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Preface

The present volume, the thirty-third in the series, surveys research on organic reaction mechanisms described in the literature dated December 1996 to November 1997. In order to limit the size of the volume, we must necessarily exclude or restrict overlap with other publications which review specialist areas (e.g. photochemical reactions, biosynthesis, electrochemistry, organometallic chemistry, surface chemistry, and heterogeneous catalysis). In order to minimize duplication, while ensuring a comprehensive coverage, the Editors conduct a survey of all relevant literature and allocate publications to appropriate chapters. While a particular reference may be allocated to more than one chapter, we do assume that readers will be aware of the alternative chapters to which a borderline topic of interest may have been preferentially assigned.

We regret that publication has been delayed by late arrival of manuscripts, but once again wish to thank the production staff of John Wiley & Sons and our team of experienced contributors (now joined by Drs A. Dobbs and J. Martin as authors of Radical Reactions: Part 2) for their efforts to ensure that the standards of this series are sustained.

A.C.K.
W.E.W.

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CHAPTER 1

Reactions of Aldehydes and Ketones and their Derivatives

B. A. MURRAY

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Formation and Reactions of Acetals and Related Species

Intramolecular general acid catalysis has been reported for hydrolysis of simple dialkyl acetals of benzaldehyde, with both carboxylic acid and ammonium catalytic functions,[1] e.g. (**1**) and (**2**). Effective molarities of the order of 10^3 mol dm^{-3} are reported for both, with (**1**) showing a high absolute reactivity: $t_{1/2} = 1.15$ s at 20 °C, with significant build-up of hemiacetal intermediate. Efficient catalysis depends on the development of a strong transition-state hydrogen bond, but such bonding should not be present in the reactant. Hence it can be 'designed in' by having such a bond in the product. The implications for enzyme catalytic systems are discussed.

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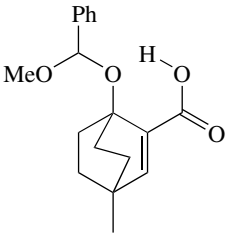
pH–rate profiles have been constructed for the hydrolysis of *o*-carboxybenzaldehyde 1,2-cyclohexanediyl acetals[2] (**3**; *cis*- and *trans*-isomers) in water at 50 °C. The complex behaviour observed is consistent with neighbouring-group participation in the ring opening of the acetal. This is supported by the fact that the analogous *para*-substituted compound has a much simpler rate profile, and ring opens 220 times slower. The implications for the mechanism of lysozyme-catalysed reactions are discussed.



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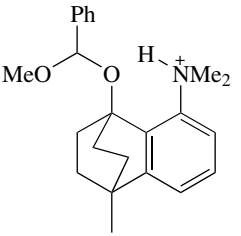

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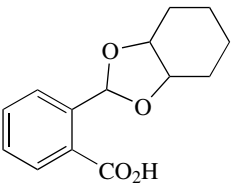

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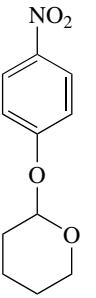
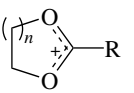


(**4**)

(**5**)



(**6**)

Acetal (**4**) undergoes S_N1 hydrolysis in aqueous solution; at high pH, it is easily monitored via the *p*-nitrophenoxide chromophore produced.[3] The reaction has been used to probe hydration effects in 'co-solvents': alcohols, amino acids, and peptides—the last two as models for such effects in enzymes. Primary alcohols retard the reaction in proportion to their carbon number, but the amino acids and peptides show more complex effects, which are interpreted in terms of interactions between the overlapping hydration shells of the amino and carboxylate groups.

The kinetics of the aqueous formaldehyde–ethylene glycol–1,3-dioxolane system have been investigated, including its acid catalysis.[4]

Equilibrium constants for hydration and hemiacetal formation have been calculated for representative highly fluorinated ketones.[5] Both reactions were substantially more favourable in cyclic than acyclic systems.

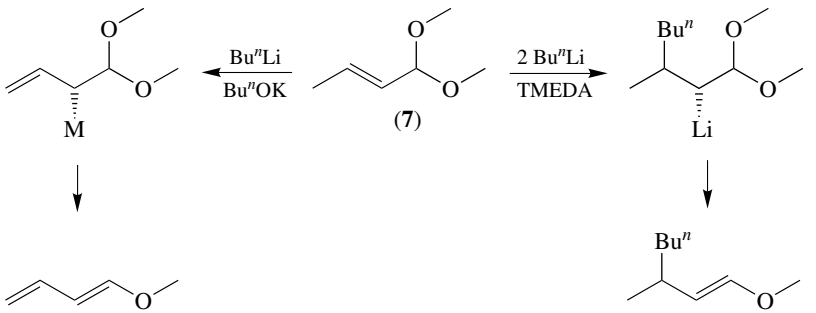
Free energies of hemi(thio)acetalization of hydrated aldehydes have been measured by a ^{1}H-NMR method, and compared with AM1 calculations.[6] The role of $n \rightarrow \sigma^*$ delocalizations in determining the overall free energy is discussed. The reactions are disfavoured by electronegative substituents in either reactant; when present in both, the effects are synergistic.

Acylphosphonates, e.g. (**5**), possess highly reactive carbonyl groups and—somewhat like trihalomethyl ketones—exhibit both ketone and carboxy character, forming oximes and adducts, and also carboxylate derivatives via C—P bond cleavage.[7] Their hemiacetal derivatives have been studied by ^{31}P-NMR in the presence of alcohols, for the representative acetyl and benzoyl compounds (**5**; R = Me, Ph). Equilibrium and

forward and reverse rate constants have been measured. These results, and a separation of the enthalpic and entropic contributions, suggest a substantially reactant-like transition state. The contribution of the $PO(OMe)_2$ group to the reactivity is underlined by an MNDO calculation of $\sigma^* = 2.65$ for this moiety.

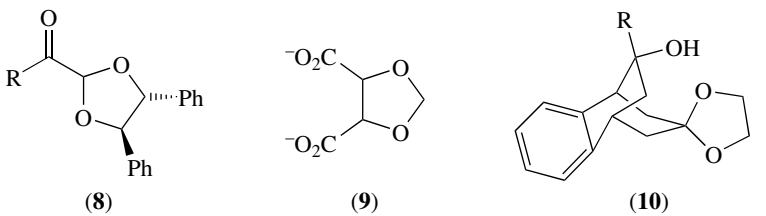
'Ionic ketals' (**6**), more strictly acetal cations, can be formed in the gas phase[8] by reaction of acylium ions $R-\overset{+}{C}=O$ with diols or other difunctional molecules $HO(CH_2)_nCH_2X$ ($n = 1$–3, X = OH, OMe, NH_2). Identified by MS, the method has applications in the detection of functional groups that give rise to acylium ions, or in the protection or elimination of such ions.

Crotonaldehyde dimethyl acetal (**7**; Scheme 1) can undergo metallo-dehydrogenation or nucleophilic addition:[9] for the example of *n*-butyllithium, the products of different experimental conditions are shown. The alternative pathways have been modelled computationally by examining the reactions of (**7**) with methyllithium and methylpotassium. The role of the potassium alkoxide in diverting the reaction towards diene is twofold: it de-aggregates $(RLi)_n$, and promotes a partial cleavage of the carbon–lithium bond.



SCHEME 1

α-Ketoacetals (**8**) undergo diastereoselective addition of alkylmagnesium bromides to give hydroxyacetals.[10] The role of the magnesium coordination of the carbonyl and one or other of the acetal oxygens is discussed.



(**8**) (**9**) (**10**)

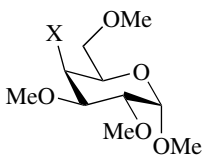
Pyrolysis of the ethylene acetal of bicyclo[4.2.0]octa-4,7-diene-2,3-dione yields α-(2-hydroxyphenyl)-γ-butyrolactone;[11] a mechanism involving a phenyl ketene acetal is proposed. Tartrate reacts with methanediol (formaldehyde hydrate) in alkaline solution to give an acetal-type species (**9**);[12] the formation constant was measured as ca 0.15 by ^{1}H-NMR. Hydroxyacetal (**10a**) exists mainly in a boat–chair conformation (boat cycloheptanol ring), whereas the methyl derivative (**10b**) is chair–boat,[13] as shown by ^{1}H-NMR, supported by molecular mechanics calculations.

Reactions of Glucosides and Nucleosides

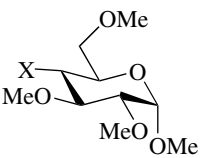
A number of fundamental studies of the nature of the anomeric effect have been undertaken, probed via kinetics and *exo*-/*endo*-regioselectivities.

Rates of acetolysis have been measured for methyl 2,3,6-tri-*O*-methyl-α-D-galacto- (**11a**) and -gluco-pyranoside (**11b**), with substituents X = OMe, OAc, and NHAc in the 4-position.[14] In both series, the most electronegative substituent (methoxy) is associated with the fast rates, and the least electronegative (acetamido) is the slowest. However, the ratio of fastest to slowest is only ca 3 in the gluco series, but is over 40 for the galactosides. This much greater sensitivity to substituent electronegativity when they are axially oriented is explained by an electron-donation process to the incipient oxocarbenium ion. It is thus claimed that the data strongly support the antiperiplanar lone-pair hypothesis.

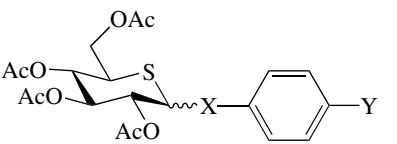
The roles of nucleophilic assistance and stereoelectronic control in determining *endo*- versus *exo*-cyclic cleavage of pyranoside acetals have been investigated for a series of α- and β-anomers.[15] Exocyclic cleavage of α-anomers, via a cyclic oxocarbenium ion, is predicted by the theory of stereoelectronic control, and was found exclusively for the cases studied. The endocyclic route, with an acyclic ion, is predicted for the β-structures, and a measurable amount was found in all cases, but its extent was dependent on temperature, solvent, and the nature of the aglycone group.



(**11a**)



(**11b**)



(**12**)

The relative nucleophilicity of the two sulfur atoms in a dithioglycoside has been probed in a study of the anomeric effect in sulfur analogues of pyranoses.[16a] In a previous study, the regioselectivity of the *S*-oxidation of α- and β-1,5-dithioglucopyranosides (**12**; X = S, Y = H) by *m*-chloroperbenzoic acid was shown to switch from predominantly *exo*-*S* for the α-anomer to *endo*-*S* for the β-anomer.[16b] Now, the origin of the differences in nucleophilicity has been further investigated by a kinetic study of the peracetic acid oxidation of the 5-thio compounds (**12**; X = O) with a range of Y substituents. The results are explained by a combination of classical anomeric arguments involving the relative $n \rightarrow \sigma^*$ *endo* and *exo* effects in the α- and β-structures, together with the inherently reduced nucleophilicity of the ring heteroatoms.

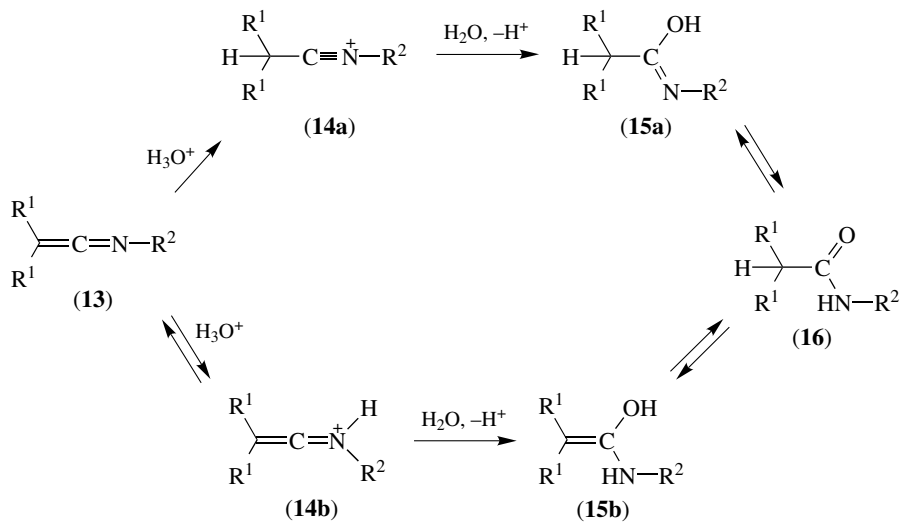
In other studies, analysis of the products of reaction between formaldehyde and guanosine at moderate pH shows a new adduct—formed by condensing two molecules of each reactant—which has implications for the mechanism of DNA cross-linking by formaldehyde,[17] while the kinetics of the mutarotation of *N*-(*p*-chlorophenyl)-β-D-glucopyranosylamine have been measured in methanolic benzoate buffers.[18] For a stereoselective aldol reaction of a ketene acetal, see the next section.

Reactions of Ketenes

Acetylketene (MeCOCH=C=O)—generated by flash photolysis—showed the following selectivities towards functional groups: amines > alcohols (primary > secondary > tertiary) ≫ aldehydes ≈ ketones.[19] The results accord with the *ab initio* calculations, which suggest planar, pseudo-pericyclic transition states. An imidoylketene, PrN=C(Me)CH=C=O, was also generated and showed similar selectivities.

Nucleophilic additions to mesitylphenylketene [Ph(Mes)C=C=O, Mes = 2,4,6-$Me_3C_6H_2$] and the related vinyl cation, Ph(Mes)C=$\overset{+}{C}$Mes, proceed as if the mesityl group was effectively *smaller* than the phenyl group.[20] The effect is explained by calculations that show that the phenyl is coplanar with the carbon–carbon double bond, while the mesityl is twisted: the in-plane nucleophilic attack prefers the mesityl side.

Acidic hydrolysis of ketenimines [**13**; Scheme 2 (adapted[21])] proceeds via either (i) rate-determining *β-C*-protonation to nitrilium ion (**14a**) followed by formation of iminol (**15a**) or (ii) pre-equilibrium *N*-protonation to give keteniminium ion (**14b**), then rate-determining hydration to give a hemiaminal (**15b**), formally an enol of an amide.[21] The final step in both routes is tautomerization to the amide (**16**). The *C*-protonation route is the 'normal' one, and is observed for e.g. diphenylketenimines (**13**; R^1 = Ph). However, highly hindered substrates with R^1 = mesityl or pentamethylphenyl switch over to the *N*-route, involving the hemiaminal (**15b**). This is confirmed by isotope effects, and also the observation of the corresponding ethane-1,1-diol, a product of the fragmentation of (**15b**), which competes with tautomerization to (**16**).



SCHEME 2

The cycloaddition of formaldehyde and ketene has been studied by *ab initio* methods.[22] A two-step zwitterionic mechanism is suggested for dichloromethane solvent, while the gas-phase reaction is concerted but asynchronous.

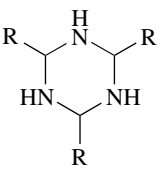
A stereoselective Mukaiyama-type aldol reaction of bis(trimethylsilyl)ketene acetals produces silyl aldols with *syn* stereoselectivity, predominantly due to steric effects.[23]

Formation and Reactions of Nitrogen Derivatives

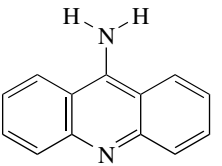
Imines

Propanal reacts with ammonia in acetonitrile to give a hexahydrotriazine (**17**; R = Et); chloroethanal (**17**; R = CH_2Cl) reacts similarly, but in lower yield.[24] The reactions proceed via carbinolamines, but increasing chloro substitution (**17**; R = $CHCl_2/CCl_3$) stabilizes the intermediate and disfavours trimerization. In the case of propanal, forward and reverse rate and equilibrium data are reported, with dehydration of the carbinolamine rate determining. The course of the reactions with some primary amines is also reported.

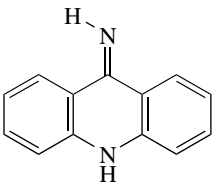
A kinetic study of the Schiff base condensation of *m*-toluidine with salicylaldehyde has examined the effects of proton, hydroxide, general base, and transition metal catalysts, and also solvent effects.[25]



(**17**)



(**18b**)



(**18b**)

Rates of [1,3]-proton shift isomerization in imines derived from $PhCH_2COCF_3$ have been measured, with electron-withdrawing ring substituents in *N*-benzylimines being particularly activating.[26]

Semiempirical calculations have been used to calculate kinetic, transition-state, thermodynamic, and physicochemical parameters for acridin-9-amine (**18a**) and its tautomer, acridin-9(10*H*)-imine (**18b**).[27]

Several reports deal with the aziridination of imines. Metal-catalysed aziridination—using ethyl diazoacetate as the carbene fragment donor—has been explored, particularly with respect to the catalytic properties of different Lewis acids, and the stereoselectivity of the reactions.[28] A variety of imines, activated by Lewis acids, react with the 'semi-stabilized' sulfonium ylid, $Ph_2\overset{+}{S}—\bar{C}HR$ (R = CH=CHSiMe$_3$, C≡CSiMe$_3$) to yield *cis*-vinyl- or *cis*-ethynyl-aziridines in high yields.[29] For many *N*-arylimines, no *trans* isomer was detected. The origin of the *cis* selectivity is discussed. Aziridines have been prepared by Lewis acid-catalysed reaction of simple imines with ethyl aminoacetate,[30] with two isomeric β-imino esters being formed as by-products: these in turn tautomerize to hydrogen-bonded *cis*-amino-α, β-unsaturated esters. Chiral *N*-sulfinyl-imines have been aziridinated diastereoselectively.[31]

Activation of aldimines with lanthanide Lewis acid catalysts has received considerable attention in recent years.[32a] Aldehydes are typically more reactive towards nucleophilic addition, but this order is reversed using ytterbium(III) triflate.[32b] This reagent complexes selectively with aldimines (as shown by ^{13}C-NMR), and catalysis is sufficiently efficient that high yields of aldimine adduct are obtained with modest amounts of catalyst, even in the presence of aldehydes. The reversal in reactivity clearly depends on this complexation, as the effect is very general: additions of silyl enol ethers, ketene silyl acetals, allyltributylsilane, and cyanotrimethylsilane all proceed with $>99:1$ ratio of aldimine adduct:aldehyde adduct, under conditions where other Lewis acids give the exact opposite result. While claiming the aldimine-selectivity as 'unprecedented', the authors do acknowledge a related aldehyde/imine reactivity reversal in a palladium-catalysed allylation.[32a] Not surprisingly, the reversal is optimized at low temperature.[33] The scope for such reversals in other nucleophilic additions—and with other substrate types—is clearly considerable. A further related case of lanthanide catalysis of a Baylis–Hilman condensation is described later under Aldol and Related Reactions.

Hydrolysis of Schiff bases derived from benzidine (4,4′-diaminobiphenyl) and from substituted benzaldehydes has been studied in aqueous ethanol;[34] attack of water molecules on the protonated substrates is suggested as the rate-determining step.

Addition of phosphates to chiral sulfinimines derived from aromatic aldehydes has been used to prepare α-amino phosphonate esters asymmetrically.[35] The sulfinimines employed, *p*-MePhS*(=O)N=CHAr, have sufficiently bulky substituents to prevent inversion, as shown by ^{1}H-NMR over a wide range of temperatures.

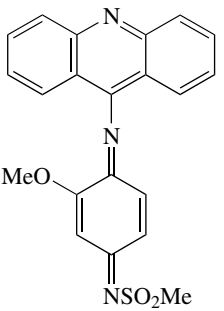
Stoichiometric and catalytic asymmetric reactions of lithium enolate esters with imines have been developed using an external chiral ether ligand that links the components to form a ternary complex.[36] The method affords *β*-lactams in high enantiomeric excess.

Extensive kinetic studies of addition of thiophenols to an *N*-acridinyl quinonediimide (**19**) are interpreted in terms of: (i) acridine nitrogen protonation followed by thiophenol addition at low pH and (ii) thiophenolate addition to neutral (**19**) at moderate to high pH.[37] For hydrolysis, a similar mechanistic competition was observed,[38] i.e. (i) water attack on acridinium substrate at low pH and (ii) hydroxide attack on (**19**) at higher pH.

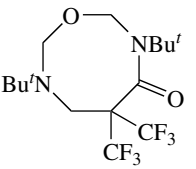
Ab initio MO methods have been used to predict the stereochemistry of aldol-type addition of boron enolates to imines, with due allowance for the degree and type of substitution, and the geometry (*E* or *Z*) of both the enolate and imine reactants.[39] Only two important transition states were identified—both cyclic—one chair-like and the other boat-like. The results are compared with the stereoselections reported in various experimental methodologies.

N-Benzylamines derived from di-*O*-protonated glyceraldehydes react with phenylmagnesium bromide to give protected aminodiols with total diastereoselectivity: the nature of the *O*-protecting group determines the direction of the selectivity.[40]

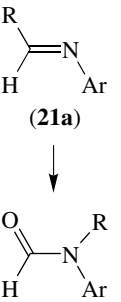
An azomethine intermediate has been implicated in the reaction of *N*-methylene-*t*-butylamine with octafluoroisobutylene to give (**20**) in wet diethyl ether;[41] (**20**) is not formed under anhydrous conditions.



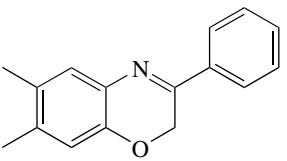
(**19**)



(**20**)



(**21a**) (**21b**)



(**22**)

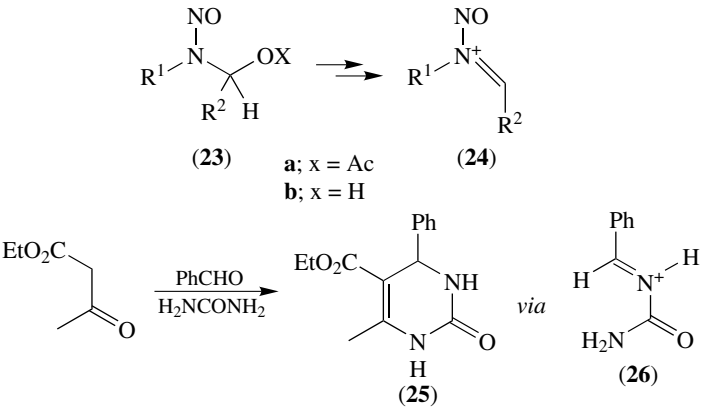
N-Arylimines (**21a**) can be oxidatively rearranged to formamides (**21b**) with sodium perborate.[42] The reaction works best for secondary or aryl R groups. An oxaziridine intermediate is proposed. Results with chiral secondary R groups indicate epimerization, suggested to occur via equilibration of (**21a**) with its enamine tautomer.

Treatment of arylimine (**22**) with alkyllithiums results in a range of single-electron-transfer reactions, substitution on the phenyl ring, and nucleophilic addition to the imine bond.[43]

Iminium Ions and Related Species

Rate constants have been determined for the reaction of four iminium ions ($Me_2\overset{+}{N}{=}CH_2$, $Pr^i_2\overset{+}{N}{=}CH_2$, $Ph(Me)\overset{+}{N}{=}CH_2$, and $Me_2\overset{+}{N}{=}CHCl$) with a range of nucleophiles.[44] The results allow calculation of electrophilicity parameters for these ions, helping to predict whether a particular aminomethylation reaction is likely to work.

α-Acetoxydialkylnitrosamines (**23a**) can generate the corresponding α-hydroxynitrosamines (**23b**) *in vivo* and *in vitro*,[45] the latter compounds being of interest as the products of enzymatic activation of dialkylnitrosamines, $R^1N(NO)CH_2R^2$; (**23b**), in turn, can ultimately cleave to yield a diazonium ion (which can alkylate DNA), plus hydroxide and aldehyde. Four acetoxy substrates ($R^1 = Pr^i/Bu^i$; $R^2 = H/Et$) and their mono-/di-deuterated analogues have been examined in aqueous solution, and their pH-independent rates of decay have been measured. Secondary isotope effects of 1.1–1.2 (k_H/k_D, per hydrogen) suggest the formation of *N*-nitrosonium ions (**24**) in—or prior to—the rate-limiting step.



SCHEME 3

The Biginelli synthesis (Scheme 3) is an important route to dihydropyrimidines, e.g. (**25**),[46a] with many variants of the original reactants now established. The mechanism has now been re-investigated using ^{1}H- and ^{13}C-NMR.[46b] The first step does *not* appear to involve aldol condensation or a carbenium-ion intermediate; rather, condensation of benzaldehyde and urea gives an *N*-acyliminium ion intermediate (**26**), which *then* goes on to react with ethyl acetoacetate.

Oximes, Hydrazones, and Related Species

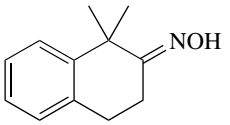
Diethylaminosulfur trifluoride (DAST, Et_2NSF_3) α-cleaves cyclic ketoximes to give fluorinated carbonitriles,[47] e.g. (**27**)→(**28**). Two mechanisms are proposed, one for substrates with substituents that can stabilize an α-carbocation, and an iminium cation route for ketoximes without such groups.

Three *O*-substituted benzophenone oximes (**29**; X = OMe, F, Cl) have been subjected to aminolysis by pyrrolidine and piperidine, in benzene solution.[48a] Kinetics were third order in amine, and involved two routes: one accelerates with a rise in temperature, the other decelerates. Of the many mechanisms proposed for this reaction in non-polar media, the results support Hirst's mechanism of electrophilic catalysis[48b] in this instance.

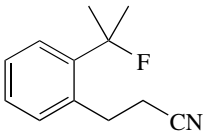
1,4-Benzoquinone oximes (**30**) exhibit 'sidedness': the structures exhibit anomalous ^{1}H-NMR coupling constants (J_{23} can exceed J_{56} by 0.6 Hz), and its additions show a *syn* selectivity.[49] The apparent stereoelectronic effect is concluded to be primarily steric in origin.

Synthesis of α-substituted and α, β-disubstituted amines with high stereoselectivity has been achieved by addition of alkyllithiums to chiral hydrazones.[50]

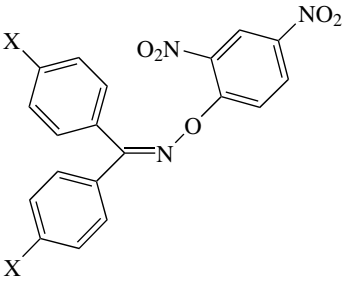
Kinetics of reactions of cyclic secondary amines with benzohydrazonyl halides (**31**) have been measured in benzene[51] at 30 °C. The products result from nucleophilic substitution at the halo-carbon via an associative addition–elimination mechanism. For X = Cl or Br, the rate equation has significant terms that are both first and second order in amine, whereas two amine molecules are essential for the fluoro compounds to react.



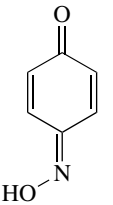
(**27**)



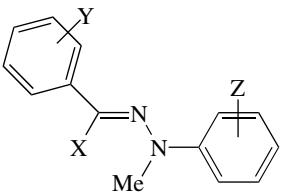
(**28**)



(**29**)



(**30**)



(**31**)

C—C Bond Formation and Fission: Aldol and Related Reactions

Regio-, Enantio-, and Diastereo-selective Aldol Reactions

Formyl hydrogen bonds, in which the C—H bond of a formyl group acts as an acceptor (typically to oxygen), have recently been identified in Lewis acid-catalysed reactions of aldehydes.[52a] An X-ray crystal structure of such a complex has been reported.[52b] This type of hydrogen bond is now suggested as a likely organizing stereochemical element in a variety of enantioselective aldol, allylation, and Diels–Alder reactions catalysed by Lewis acids reported in the literature.[52c] Further examples of such reactions are also discussed.[53]

Asymmetric aldol additions of geometrically defined trichlorosilyl enolates of ketones to aliphatic and aromatic aldehydes have been carried out uncatalysed, and with a chiral phosphoramide as Lewis base promoter.[54] Significant differences in rates and diastereoselectivities are interpreted in terms of the changeover from a boat-like transition state, with pentacoordinate siliconate, to a chair-like transition state with hexacoordination.

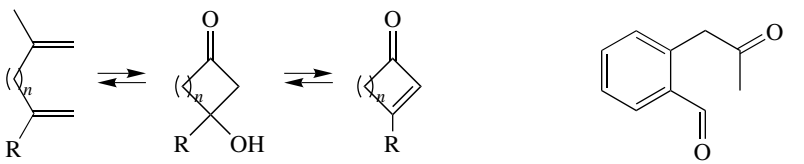
1,5-Asymmetric induction is reported in the addition of enolates of methyl ketones to aldehydes.[55] Double stereo-differentiation—in which simultaneous 1,3-control can be obtained in the aldehyde moiety—is shown to be achievable with proper selection of the aldol type.

π-Stacking interactions in the transition state are one factor suggested for the highly diastereoselective synthesis of *syn*- and *anti*-aldols from the reaction of an arylsulfonamidoindanyl titanium enolate with 'bidentate' aldehydes.[56]

Chiral 2-sulfinylcyclohexanones react with lithium alkyl acetates (i.e. lithium ester enolates) to produce alcohols with four contiguous chiral centres.[57] This stereoselective aldol reaction is proposed to depend upon tricoordination by lithium of the enolate, sulfinyl, and carbonyl oxygens of the substrates.

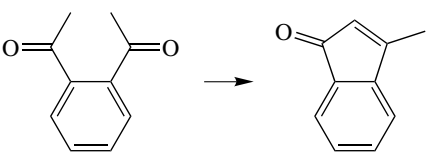
Boron aldol reactions have been used to stereoselectively construct the *anti*-3-hydroxy-2-methylcarbonyl system from carboxylate esters,[58] and to combine α-hetero-substituted thioacetates with aldehydes or silyl imines enantio- and/or diastereo-selectively.[59]

Rate and equilibrium constants have been measured for representative intramolecular aldol condensations of dicarbonyls.[60a] For the four substrates studied (**32**; $n = 2$, R = Me; $n = 3$, R = H/Me/Ph), results have been obtained for both the aldol addition to give ketol (**33**), and the elimination to the enone (**34**). A rate–equilibrium mismatch for the overall process is examined in the context of Baldwin's rules. The data are also compared with Richard and co-workers' study of 2-(2-oxopropyl)benzaldehyde (**35**), for which the enone condensation product tautomerizes to the dienol[60b] (i.e. *β*-naphthol). In all cases, Marcus theory can be applied to these intramolecular aldol reactions, and it predicts essentially the same intrinsic barrier as for their intermolecular counterparts.



(**32**) (**33**) (**34**) (**35**)

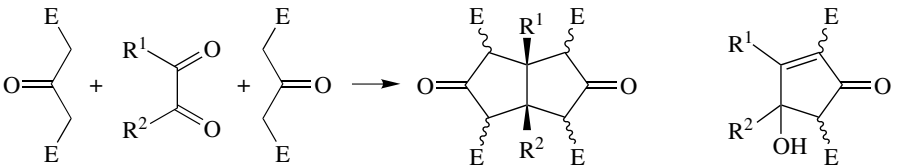
Base-catalysed cyclization of proximate diacetyl aromatics [e.g. *o*-diacetylbenzene (**36**)] gives the corresponding enone (**37**). Relative rates, activation parameters, and isotope effects are reported for (**36**), and also for 1,8-diacetylnaphthalene, 4,5-diacetylphenanthrene, and 2,2′-diacetylbiphenyl, in aqueous DMSO.[61] Reaction proceeds via enolate formation (rate determining for the latter three substrates), followed by intramolecular nucleophilic attack [rate determining for (**36**)], and finally dehydration.



(**36**) (**37**)

Miscellaneous Aldol-type Reactions

In the Weiss reaction (Scheme 4), an α-dicarbonyl compound (**38**) condenses with two molecules of dimethyl 3-oxoglutarate (**39**; E = CO_2Me) to give a *cis*-bicyclo[3.3.0]octane-3,7-dione tetraester (**40**); the one-pot reaction produces considerable complexity, with the sequential formation of four C—C bonds. Simple acid treatment removes the carbomethoxy groups, if desired. While the reaction involves aldol and Michael sequences, the intermediacy of a cyclopentenone [4-hydroxycyclopent-2-enone (**41**)] has up to now been unproven. A series of such 1 : 1 adducts has now been reported for a variety of diketones, together with evidence that they are indeed intermediates en route to the bicyclo system.[62] Electronic and steric effects on the reaction are also discussed in detail.

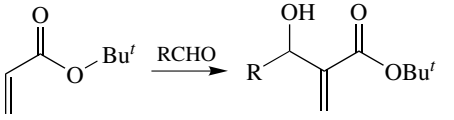


(**39**) (**38**) (**39**) (**40**) (**41**)

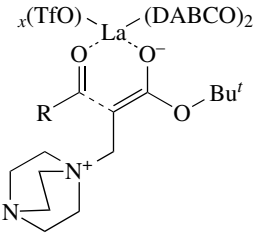
SCHEME 4

A clean, high-yielding asymmetric Baylis–Hillman reaction has been reported: employing Oppolzer's sultam,[63a,b] it couples acrylates with a variety of aldehydes at 0 °C, with >99% *ee* in all cases described.[63c] Another new, practical variant of the reaction employs a phosphine catalyst,[64] and here the temperature effect is critical: the rate increases in either direction from room temperature, with a dramatic improvement observed at 0 °C. This unusual observation is explained in terms of a temperature-dependent equilibrium between efficient and inefficient intermediates.

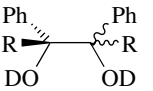
Some Baylis–Hillman reactions are *very* slow: for example, condensation of *t*-butyl acrylate (**42**) with representative aldehydes can take 28 days to complete the formation of vinyl ester (**43**).[65a] Another new approach to achieving practical rates of conversion is to combine the usual tertiary amine catalyst, 1,4-diazabicyclo[2.2.2]octane (DABCO), with a Lewis acid catalyst, in order to activate the aldehyde. However, sometimes this slows the reaction further, as many acids just sequester the amine. Several lanthanide(III) triflates (especially La, Sm) give modest accelerations,[65b] so they are 'amine-compatible' catalysts, contributing to a type of 'push-pull' catalysis via an intermediate such as (**44**). The strategy of avoiding deceleration by using the oxophilic lanthanide is further emphasized by the effect of adding diols, such as binaphthol; the reaction is further accelerated. Presumably, the *O*-ligand displaces the *N*-ligand [in (**44**)], with a chelate effect also contributing. Although the total acceleration achieved was only a factor of 18, this is of practical significance for such an intrinsically slow reaction.



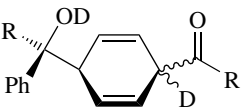
(**42**) (**43**)



(**44**)



(**45**)



(**46**)

The McMurry alkene synthesis reductively couples two molecules of ketone. It has recently been reviewed.[66a] The same authors have claimed that the reaction proceeds via a nucleophilic (rather than a radical) mechanism when carried out with Zn/Cu in dimethoxyethane solvent.[66b,c,d] Calculations using density functional theory now support their hypothesis,[66e] at least for the stated reaction conditions. The reaction is also frequently carried out using low-valency titanium reagents, and is presumed to proceed in such cases via a metallopinacol intermediate, formed by dimerization of a ketyl radical. Evidence has now been presented that even if metallopinacols are present, they are not necessarily precursors to the alkene.[67] Rather, the ketyl radical could be deoxygenated to a (metallo)carbinol, which could then couple to the second molecule of ketone. The replacement of titanium(or samarium)(II) with uranium species has also been explored: UCl_3 and $Cp_3U(THF)$ have been used to couple benzoyl compounds[68] PhCOR (R = H, Me, Pr^i, and Bu^t). After deuterolysis of the organometallic products, pinacol (**45**) was obtained, but so also was keto alcohol (**46**)—the product of *para* coupling. The organometallic precursors of these products appear to be in equilibrium under the reaction conditions, with the product ratio being determined by steric factors.

The mechanism of addition of lithium pinacolone enolate, $H_2C{=}C(OLi)Bu^t$, to benzaldehyde has been investigated by the determination of kinetic isotope effects[69] (phenyl-d_5 and carbonyl-^{13}C); C—C bond formation occurs in the rate-determining step (a result supported by MO calculations), in contrast to addition of MeLi or PhLi, which proceed via electron transfer. Further carbonyl-^{13}C isotopic studies on substituted benzaldehydes (including equilibrium effects) by the same authors confirmed these conclusions.[70]

Horner–Wadsworth–Emmons reactions of ketones and aldehydes with phosphonoacetate esters, $(R^2O)_2P(=O)CH_2CO_2R^1$, produce *E*/*Z* mixtures of α,β-unsaturated esters. Use of the conventional reagent, sodium hydride, gives some selectivity. The combination of tin(II) triflate and *N*-ethylpiperidine enhances—and sometimes also reverses—the selectivity in most cases studied.[71] Six-membered oxo-coordinated tin intermediates are proposed to control the selectivities observed. A similarly selective synthesis of trisubstituted exocyclic alkenes from cyclic ketones has been reported.[72]

The Henry reaction (addition of a nitroalkane to a carbonyl) is synthetically very useful, as the nitro group of the nitro alcohol product provides many routes to a variety of functional groups. An *ab initio* study of the stereochemical outcomes of the reaction yields the following:[73]

(i) with free nitronate anions and aldehydes, an antiperiplanar transition state is predicted, with carbonyl and nitro dipoles *anti*-parallel, leading to an *anti* product;

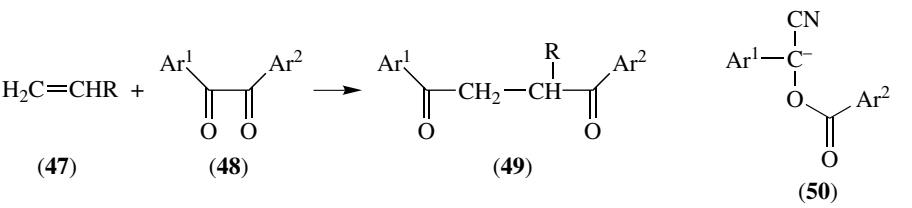
(ii) lithium nitronates and aldehydes produce *syn* product, but stereo-control is difficult;

(iii) reaction with a di-metalated nitronate has a lower barrier, allowing less electrophilic carbonyls, such as ketones, to react.

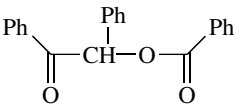
Bis(1,2-diamine)copper(II) complexes undergo condensations with formaldehyde and nitroethane to give acyclic/macrocyclic products containing —$NHCH_2C(Me)(NO_2)CH_2NH$—linkages: steric effects in the copper ligands significantly affect the product ratio.[74]

The mechanism, stereoselectivity, and synthetic applications of the nitrile aldol reaction have been reviewed.[75]

A Michael-type addition has been used[76] to insert suitable Michael acceptors (**47**; R = CN, COMe, CO_2Me/Et) between the carbonyls of benzils (**48**), to give a range of 1,4-diketones (**49**). The reaction is catalysed by cyanide (typically as Bu_4NCN), and the aryl rings can bear substituents such as chloro or methoxy. Reminiscent of the Benzoin condensation, the reaction proceeds through an *O*-aroylmandelonitrile anion (**50**). The reaction has also been extended to C—O rather than C—C insertion: benzaldehyde inserts into benzil under the same conditions to give an α-aroyloxy-ketone (**51**).



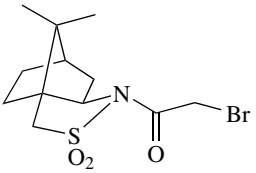
(**47**) (**48**) (**49**) (**50**)



(**51**)

A chiral enolate derived from a bromoacetyl camphor sultam [(**52**); in turn prepared from Oppolzer's sultam[63a,b]] undergoes an aza-Darzens reaction with modified amines to produce aziridine derivatives in high *de*.[77] Cleavage yields aziridine carboxylates.

An open-transition-state model is proposed for the Darzens condensation of ketones with (−)-8-phenylmenthyl α-chloroacetate: the diastereoselectivity observed is explained in terms of a π-aryl interaction between the enolate and phenyl moieties.[78]



(**52**)

1,3-Allylic strain is employed in the Paterno–Büchi reaction of a silyl enol ether and benzaldehyde.[79] Using a bulky or polar substituent γ to the ether as stereogenic locus, diastereomerically pure oxetanes with four contiguous chiral centres have been prepared.

A mechanism has been proposed for the enantioselective Mikami ene reaction of a terminal alkene with a glyoxylic aldehyde using a chiral binaphthol as Lewis acid.[80]

Stereoselective synthesis of β-amino esters via asymmetric aldol-type and aza-Diels–Alder reactions has been reviewed.[81] Siliranes react cleanly with benzaldehyde to produce oxasilacyclopentanes—with inversion—under conditions of Bu^{t}OK catalysis; enolizable aldehydes yield silyl enol ethers.[82]

Copper(II) triflate—a Lewis acid that is stable in aqueous media—has been employed as a catalyst for a variety of aldol and allylation reactions.[83]

For a stereoselective aldol of bis(trimethylsilyl)ketene acetals,[23] see Reactions of Ketenes earlier.

Allylation Reactions

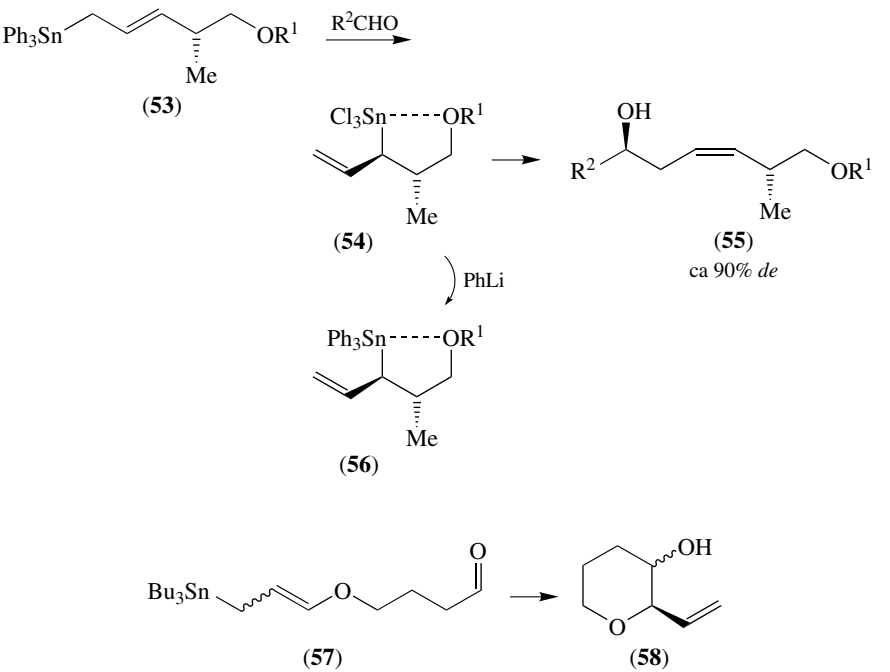
Many allylations are still built around stannanes, but other metals are becoming more widely used.

The $SnCl_4$-mediated addition of alkoxyallylstannanes can be carried out with 1,5-/6-/7-asymmetric induction, depending on the position of the alkoxy substituent.[84a] For example, the (5-alkoxypent-2-enyl)stannane (**53**) gives 1,5-*anti*-(*Z*)-alkenol (**55**).[84b] The 'remote' oxygen has been suggested to act by coordinating the electron-deficient tin of a trichlorotin intermediate (**54**). Evidence for this species has now been provided by a trapping experiment using phenyllithium,[84c] which produces the triphenyl derivative (**56**).

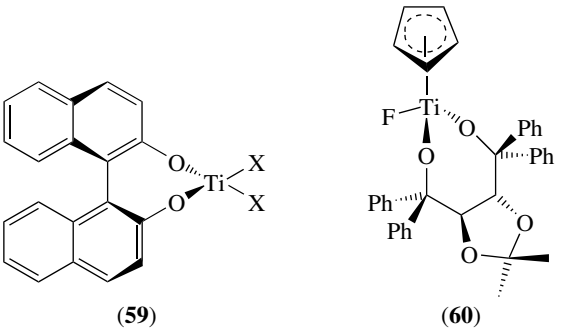
(γ-Alkoxyallyl)stannane aldehydes (**57**) can cyclize either thermally or with Lewis or protic acid catalysis to give cyclic ethers (**58**).[85] The interrelationship of the reactant and product stereochemistries has been investigated, as have the methods used to promote the reaction. For both thermal and proton-promoted reactions, [(*Z*)-**57** gave (*cis*-**58**), and [(*E*)-**57**] gave (*trans*-**58**), whereas (*trans*-**58**) was the predominant or exclusive product of Lewis acid mediation, regardless of the double bond geometry of (**57**). Mechanisms are proposed.

Methanol promotes addition of allylstannanes to aldehydes and ketones, to give homoallylic alcohols without added catalyst.[86] Aldehydes are significantly more reactive. It is suggested that the primary activating influence is hydrogen bonding to the carbonyl.

Chiral binaphthol(BINAP)-titanates (**59**; X = OR) have been used as asymmetric catalysts of additions to aldehydes, and show evidence of oligomeric Ti—O—Ti



bridging.[87a] The corresponding difluoro compound (**59**; X = F) catalyses allylsilane addition[87b], and may also involve oligomers as effective catalytic species. Using these observations, a new fluorotitanium-TADDOLate (**60**; TADDOL = tetraaryldihydroxydioxolane) has been reported to catalyse the reduction of benzaldehyde efficiently[87c] at −78 °C. Conversion of 60% with 78% *ee* is found with 0.5 mol% (**60**), and this rises to 77% with 93% *ee* for 2.0 mol%, again suggesting an oligomeric contribution to catalysis.



Allyltitanium compounds typically react with aldehydes at the most substituted allylic position; however, ring-strain effects and also substituents capable of coordinating titanium can dramatically alter the regiochemistry.[88]

Indium mediates the coupling of α,α-difluoroallyl carbanion with aldehydes, to give *gem*-difluorohomoallyl alcohols.[89] In contrast to many comparable allylations of carbonyl compounds, ketones do not react.

(*S*)-Proline-derived phosphoramides catalyse enantioselective allylation of aromatic aldehydes with allylic trichlorosilanes.[90] Chiral α-aminoaldehydes have been allylated diastereoselectively with various reagents.[91]

Ab initio calculations on the reaction of enoxysilanes with formaldehyde have been used to characterize the electron-donating and -accepting strength of the different functions in the enoxysilane.[92] This useful type of aldol reaction is also compared with the corresponding allylsilane version.

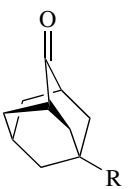
Other Addition Reactions

General and Theoretical

^{17}O-NMR chemical-shift values are proposed as the basis of an electrophilicity (polarity) scale for carbonyl groups, based on data for 35 types of benzoyl compound, PhCOX, and a Hammett–Taft analysis of 23 of them for which *para*-substituted series, *p*-YC_6H_4COX, are available.[93] Similar measurements—plus ^{13}C-carbonyl values—have been made for a wide variety of RCOX: X = H, Me, SiR_3, SR, Cl, F, OMe, OH, O^-, NH_2; R = H, Me.[94] The oxygen shift depends on the electron donor/acceptor properties of the X group, while the carbon shift values are also determined by other factors. The difference between the two shift movements has been identified as mainly related to the energy of the $n \rightarrow \pi^*$ excitation. Similar differences were found in *p*-YC_6H_4COX, but not in the aroyl cations, *p*-$YC_6H_4CO^+$, where the $n \rightarrow \pi^*$-type excitation is absent, due to symmetry.

Placing two methyl groups *ortho* to the carbonyl of acetophenone should twist the phenyl out of the C=O plane. The extent to which this affects gas- and solution-phase basicities of a series of *para*-substituted acetophenones is reported.[95]

4-Substituted norsnoutanes (**61**) have been introduced as substrates with sterically unbiased π-faces, which allow electronic effects in π-facial selectivity of nucleophilic additions to be evaluated.[96] Examples indicate how this system allows separation of long-range electronic effects into orbital and electrostatic contributions.



(**61**)

An extensive study of reactions of a variety of non-cyclic esters, aldehydes, and ketones with a range of nucleophiles has been undertaken in an attempt to find reliable rules for predicting 1,3-stereochemistry in the products.[97] Despite comparison of the

results with molecular mechanics calculations of the lowest energy reactant conformations, clear-cut open-chain stereo-control outside well-defined subsets of reactants remains elusive.

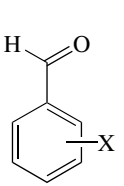
Nucleophilic addition/ring-closure sequences—especially additions to aldehydes, ketones, and aldimines—have been reviewed in the context of heterocyclic synthesis.[98]

N-Trimethylsilylbis(trifluoromethanesulfonyl)imide, $Me_3SiN(SO_2CF_3)_2$, has been reported as a better carbonyl activator than trimethylsilyl triflate.[99]

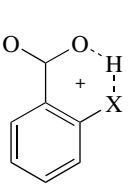
Density functional theory has been used to analyse the relative stability of tetrahedral intermediates formed when sulfhydryl or hydroxide anions attack carbonyl compounds.[100]

Protonation

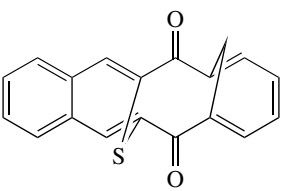
Gas-phase basicities of several substituted benzaldehydes (**62**; X = *o*-/*m*-/*p*-Me/F, *o*-/*m*-Cl) have been measured, relative to benzaldehyde or mesitylene as reference bases, over a range of temperatures.[101] The tolualdehydes are more basic than benzaldehyde, the halobenzaldehydes less so, following classical aromatic substituent effects. The data also correlate well with solution-based linear-free-energy substituent constants, as well as with theoretical (MNDO) calculations. Some deviations are noteworthy: (i) the *o*-halobenzaldehydes (especially chloro) have higher basicities than predicted, but calculations tend to rule out the hydrogen-bonded isomer (**63**), which is also contra-indicated by a 'normal' ΔS value, inconsistent with the expected restriction of —$\overset{+}{C}$HOH rotation in such a structure; (ii) anomalies in the high-temperature behaviour of *m*-fluorobenzaldehyde in the presence of mesitylene reference base are consistent with a specific catalysed isomerization to the *ortho*- or *para*-isomer.



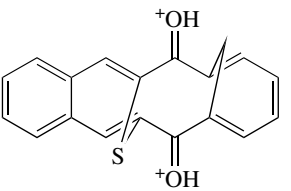
(**62**)



(**63**)



(**64**)

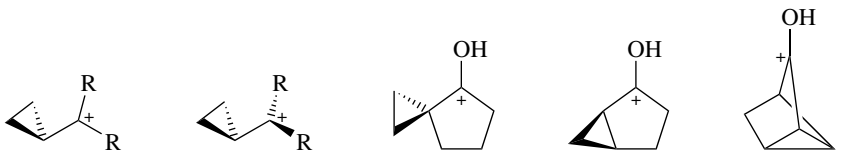


(**65**)

An X-ray crystal structure of annulene-dione (**64**) indicates an *anti*,*anti* configuration between the methylene and sulfur bridges.[102] Diprotonation gives highly localized positive charges in the dication (**65**), mainly due to unfavourable *p*-orbital overlap.

The stabilities of protonated cyclopropylcarbinyl ketones are a long-standing puzzle. Richie[103a] provided evidence that the 'bisected' cyclopropylcarbinyl carbenium ion (**66a**) was the more stable conformation, rather than the 'perpendicular' geometry (**66b**). Of the protonated, rigid ketones, (**67**), (**68**), and (**69**), spiro compound (**67**) is most stable, but the bicyclo compound (**68**) proved more stable than the nortricyclic system (**69**), although the latter has a bisected geometry, while (**68**) is unable to achieve this.[103a] The anomaly appears to have been resolved by semiempirical calculations of heats of formation of the ketones and ions, and an analysis of the effects of *syn*- and

anti-OH^+ versus -cyclopropyl orientations.[103b] While oxygen plays important roles, some of the effects cancel: the corresponding *hydrocarbon* carbenium ions show similar orders of stability.

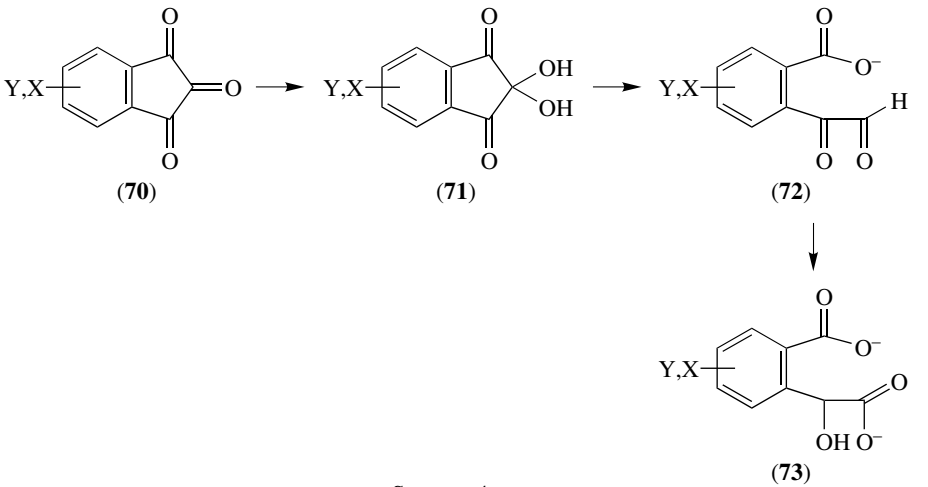


(**66a**) Bisected (**66b**) Perpendicular (**67**) (**68**) (**69**)

Ab initio MO methods have predicted geometrical changes in 3-halocyclohexanones accompanying complexation of the oxygen by a proton or lithium cation.[104] From these changes, the preferred face for attack by a nucleophile can be predicted.

Hydration and Hydrate Anions

Hydration of several 1,2,3-triones including indane derivatives (**70**; Scheme 4) has been studied in dioxane–water mixtures.[105a] Monohydration gives a 2,2-diol (**71**): forward rates and equilibrium constants have been measured over a wide range of solvent composition. Based on activation parameters, kinetic isotope effects, a Hammett treatment, and a second-order rate dependence on water, two water molecules are suggested to play distinct roles, one as nucleophile, the other as general acid–base, similar to dialdehydes.[105b,c]



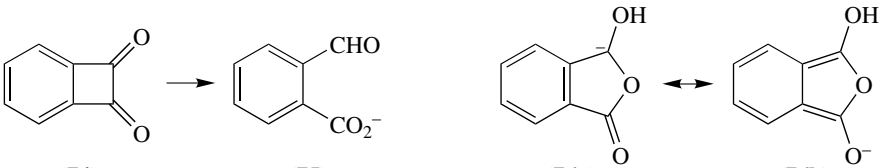
(**70**) (**71**) (**72**) (**73**)

SCHEME 4

The base-catalysed ring fission of several substituted 2,2-dihydroxyindane-1,3-diones [(**71**) in Scheme 4, i.e. hydrates of the indanetrione system (**70**)] has been studied in aqueous dioxane.[106] Rate constants, thermodynamic parameters, substituent, salt,

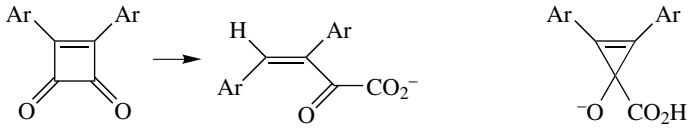
solvent, and solvent isotope effects are reported. The ring opens to give an *o*-carboxyphenylglyoxal (**72**), which rearranges to the *o*-carboxymandelate (**73**); build-up of (**72**) was clearly evident in the kinetic measurements. No evidence for a lactone pathway was found.

Benzocyclobutene-1,2-dione (**74**) undergoes base-catalysed ring fission between the carbonyls to give 2-formylbenzoate (**75**). Rate constants, activation parameters, isotope effects, and substituent effects have been measured in water.[107] Rapid reversible addition of hydroxide to one carbonyl is followed by intramolecular nucleophilic attack on the other, giving a resonance-stabilized carbanionic intermediate (**76a**)↔(**76b**).



(**74**) (**75**) (**76a**) (**76b**)

A similar investigation of the base-catalysed ring opening of 3,4-diphenylcyclobut-3-ene-1,2-diones (**77**) to give (*Z*)-2-oxo-3,4-diphenylbut-3-enoates (**78**) has been carried out in aqueous DMSO.[108] The evidence points towards a rapid, reversible addition of hydroxide to one carbonyl, followed by a benzilic acid-type rearrangement to give a cyclopropene intermediate (**79**), which ring opens.



(**77**) (**78**) (**79**)

Hydration of highly fluorinated ketones has been referred to under Acetals above.[5] 2-Acetyl-1-methylpyridinium ion is 8% hydrated in water: see Enolization below.

Addition of Organometallics

The mechanism of conjugate addition of lithium dialkylcuprates to enones has been explored by the determination of ^{13}C kinetic isotope effects by an NMR method: reductive elimination from Cu is implicated as the rate-determining step.[109]

Several papers deal with diethylzinc: a chiral titanate complex with helical ligands catalyses enantioselective addition to benzaldehyde, where approach to the Lewis acid centre is guarded by flanking aryl rings;[110] new chiral thiaprolinol amino alcohols have been used as ligands for enantioselective borane reduction of ketones and diethylzinc addition to aldehydes, with reasonable *ee*;[111] AM1 molecular-modelling studies have been used to guide the design of an improved chiral piperidine alcohol which acts as an

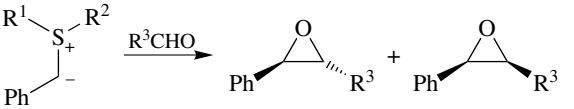
enantioselective catalyst;[112] (*S*)-2-(*N*,*N*-disubstituted-aminomethyl)pyrrolidines have been employed as enantioselective catalysts.[113]

Aryltrimethylstannanes arylate aldehydes in the presence of a cationic rhodium complex, $[Rh(cycloocta\text{-}1,5\text{-}diene)(MeCN)_2]^+$, yielding secondary alcohols.[114]

Addition of Carbon Nucleophiles containing N, S, P, or Bi Substituents

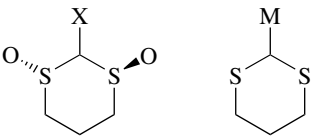
An AM1 method has been used to investigate nucleophilic addition of malononitrile anion to carbonyl compounds.[115]

Addition of sulfonium ylids to aldehydes is a useful method of synthesizing epoxides, and can be carried out with high enantioselectivity, given appropriate chiral substituents on sulfur. The reaction has been investigated using a range of benzylsulfonium ylids in various solvents,[116] with both aliphatic and aromatic aldehydes (Scheme 5). Epoxide formation is found to be under kinetic control, with a finely balanced stereochemical outcome. The *trans*-epoxide is formed directly via irreversible formation of the *anti*-betaine, or indirectly via reversible formation of *syn*-betaine, while *cis*-epoxide forms via partial reversible formation of *syn*-betaine. This reversibility in formation of the *syn*-structure is greater for aromatic aldehydes (thus giving higher *trans* selectivity), and also increases in more polar solvents.



SCHEME 5

2-Halo-1,3-dithiane *trans*-1,3-dioxides (**80**; X = Cl, Br) act as diastereoselective carbonyl anion equivalents in reactions with aldehydes.[117] The scope of the reaction has been explored by varying the temperature, the aldehyde, and the metal used as counter-ion. Similarly, metal 1,3-dithianides (**81**; M = Li, Cu^I) can be added diastereoselectively to chiral aldehydes; subsequent hydrolysis yields an α-hydroxyaldehyde.[118]

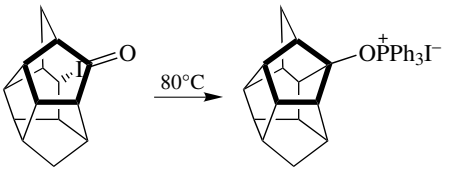


(**80**) (**81**)

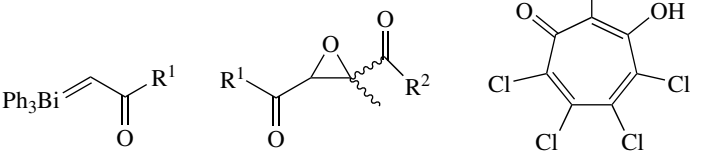
Examples of 1,13- and 1,14-asymmetric inductions are reported in the case of the addition of sulfone carbanions to benzaldehyde.[119]

The Wittig and related reactions have been reviewed in the context of natural product synthesis;[120] mechanistic studies of the Wittig reaction have also been reviewed with particular reference to asymmetric induction.[121]

Transannular interactions have been examined in the hexacyclo-[6.6.0.0^{2,6}.0^{3,13}.0^{4,11}.0^{5,9}]-tetradecane system.[122] For example, the 14-iodo-10-one derivative (**82**) reacts with triphenylphosphine to give the salt (**83**), via C(10)—C(14) bond formation. In contrast, the 10,14-dione does not react.



(**82**) (**83**)



(**84**) (**85**) (**86**)

Treatment of the salt, $[Ph_3\overset{+}{B}iCH_2COR^1]\ BF_4^-$ with base generates triphenylbismuthonium 2-oxoalkylide (**84**; $R^1 = Bu^t$, Ph). This reacts with 1,2-dicarbonyls to give 2,3-diacyloxiranes (**85**; from acyclic reactants, $MeCOCOR^2$, R^2 = Me, OEt) or 2-acyl-3-hydroxytropones [e.g. (**86**), from the tetrachloro-*o*-quinone].[123] Both reaction types are of considerable synthetic utility, and both are in marked contrast to the routes followed by the corresponding phosphonium ylids.

Miscellaneous Additions

Two moles of aromatic aldehyde react with ethyl diazoacetate to form diastereomeric 1,3-dioxolanes.[124] The reaction is catalysed by dirhodium(II) species, and proceeds via a carbonyl ylid. Stereo-control can be achieved using a bulky diazo substrate, and electronic effects of aromatic substituents are important. Different reactions show evidence of either a metal-stabilized ylid, a free ylid, or competition between the two.

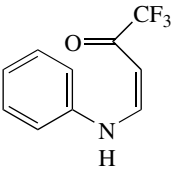
The mechanism of the alkaline decomposition of methyl ethynyl ketone—to acetate and ethyne—has been probed using AM1 calculations.[125]

Aminoenone (**87**), when heated with phosphoryl chloride, cyclizes to 2-(trifluoromethyl)quinoline, rather than the expected 4-isomer.[126] A series of crossover experiments using different perfluoroalkyl and aniline moieties suggest an amine exchange process. A 1,3-diaminoallyl cation (**88**), i.e. a vinylogous formidinium salt, is proposed to act as 'turntable' in the process.

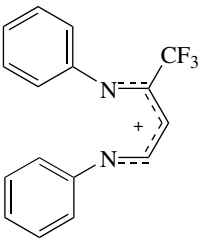
The kinetics of the reactions between *p*-benzoquinone and an amino acid have been investigated as a function of pH, temperature, and amino group basicity.[127]

4-Oxochromene-3-carboxaldehydes (**89**) react with triazoles and primary amides to give a new family of heterocyclic compounds;[128] the initial adduct of the triazole to the aldehyde can be isolated.

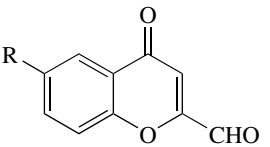
Factors affecting whether quinones undergo addition or reduction in their reactions with some organometallics, and with HN_3, are discussed under Redox Reactions later.



(**87**)



(**88**)



(**89**)

Enolization and Related Reactions

Isomer stabilities and activation energies have been calculated for keto–enol tautomerization of simple carbonyl compounds, MeC(R)=X (X = O; R = H, Me);[129] both specific and bulk solvent effects have been analysed. Related isomerizations of acid derivatives (R = F, CN) and other related structures (R = H; X = CH_2, NH, S) are compared.

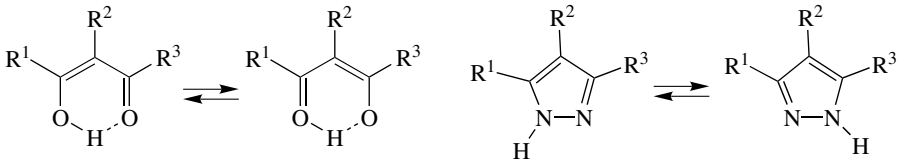
Ab initio methods have been used to compare enzyme-catalysed enolization mechanisms.[130] Acid- and base-catalysed stepwise mechanisms have been compared with the concerted reaction; the latter is favoured by several hydrogen-bonding interactions.

Simple enols stabilized by bulky aryl groups have been reviewed.[131] Amide enols, $tip_2C{=}C(OH)NR^1R^2$ (tip = 2,4,6-triisopropylphenyl), can be generated by reaction of amines with ditipyl ketene, are observable by NMR, and slowly tautomerize. Vinyl alcohols with two or three bulky aryls have propeller conformations and are chiral, but are not easily resolved.

Acyclic perfluoroenols are strongly destabilized relative to their cyclic counterparts;[132] the result is general for alkene systems.[133]

Acetoacetic acid, $MeCOCH_2CO_2H$, can enolize via its ketone- or acid-carbonyl groups: calculations suggest the former route is thermodynamically more favourable[134] by 11.3 kcal mol^{-1}.

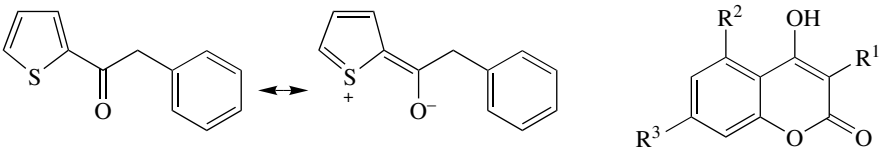
Unsymmetrical β-diketones can form two β-keto–enol tautomers, (**90a**), (**90b**). The corresponding N*H*-pyrazoles—readily synthesized from the diketones—exhibit annular tautomerism, (**91a**), (**91b**). These tautomerisms have been probed via AM1 semiempirical calculations that show that the two phenomena are related:[135] in each case the position of equilibrium is strongly influenced by whether or not the CC double bond is part of (another) ring system (the Mills–Nixon effect).



(**90a**) (**90b**) (**91a**) (**91b**)

SCHEME 6

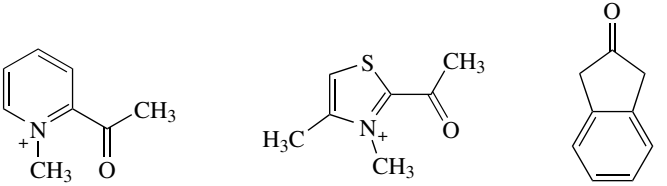
Kinetic and thermodynamic measurements show that 2-phenylacetylthiophene (**92a**) has a low enol content: $K_T = 3.55 \times 10^{-7}$ (or $pK_T = 6.45$).[136] The keto and enol tautomers have pK_a values of 14.60 and 8.15, respectively. Relative to a phenyl or furanyl substituent at the carbonyl carbon, the thiophene increases the acidity of the enol tautomer, but stabilizes the ketone, probably via the resonance contribution (**92b**). Thus 2-thiophenyl stabilizes the enolate by electron attraction, but the ketone by donation. Effects of micelles on the equilibria are also reported.



(**92a**) (**92b**) (**93**)

A series of 4-hydroxycoumarins (**93**) have been synthesized and their tautomeric equilibria with the 2,4-dione and 2-hydroxy-4-keto forms have been studied by NMR and by MNDO calculations.[137]

Enolization of cationic ketones is accelerated by electrostatic stabilization of the enolate anion. Rate constants for water-, acetate-, and hydroxide ion-catalysed enolization of 2-acetyl-1-methylpyridinium ion (**94**) have been measured[138a] and compared with a 2-acetylthiazolium ion (**95**), a simple analogue of 2-acetylthiamine pyrophosphate.[138b] For (**94**), $k_{OH} = 1.9 \times 10^2\ M^{-1}\ s^{-1}$, about 1.1×10^6 times that for a typical methyl ketone such as acetone. Thermodynamically, it is $>10^8$ times more acidic (pK_a values of 11.1 vs 19.3). These increases in kinetic and thermodynamic acidity are derived from through-bond and through-space effects, and the implications for enzymatic catalytic sites with proximal, protonatable nitrogen are discussed. The results for (**94**) suggest a pK_a value of 8.8 for (**95**), a value that cannot be measured directly due to competing hydrolysis.



(**94**) (**95**) (**96**)

Catalysis of the enolization of indan-2-one (**96**; $pK_a = 12.2$) by α-, *β*-, *γ*-, and modified cyclodextrins (of similar pK_a) indicate that the latter act as general bases.[139] There is also an inclusion component to the catalysis: saturation kinetics consistent with 1 : 1 binding are observed for enolate formation.

Rates of acid-catalysed enolization of isobutyrophenone and its α-*d* analogue have been measured in H_2O and D_2O, by bromine scavenging.[140a] Results include a *solvent* isotope effect, k_{H^+}/k_{D^+}, of 0.56, and a *substrate* isotope effect, k_H/k_D, of 6.2 (both for the enolization reaction). Combination of the data with that for ketonization in D_2O[140b] gives the first isotope effect for the keto–enol equilibrium of a simple ketone: $K_E(H_2O)/K_E(D_2O) = 0.92$. The results are discussed in terms of the isotopic fractionation factors and the medium effect.

Rates of enolization of 4-oxophenylbutanoic acids, $XC_6H_4COCH_2CH_2CO_2H$, have been measured in 75% acetic acid[141] at 30 °C. A Hammett ρ value of −0.78 was found. *Ortho* substituents significantly enhance the rate; ^{1}H- and ^{13}C-NMR suggest that this is because they twist the benzene ring out of conjugation with the carbonyl.

Keto–enol equilibrium constants for simple *β*-dicarbonyl compounds, $RCOCH_2COX$ (R = X = Me; R = Me, Ph for X = OEt) have been measured in water[142a] by a micelle perturbation method previously reported for benzoylacetone[142b] (R = Ph, X = Me). The results have been combined with kinetic data for nitrosation by NO^+, ClNO, BrNO, and SCNNO: in all cases, reaction with the enol was found to be rate limiting.

When benzyl bromide is reacted with acetophenone using a phase-transfer catalyst (but no solvent), the double benzylation product, $PhCOCH(CH_2Ph)_2$, is produced almost exclusively.[143] The change in substrate acidity does not appear to explain the result. Rather, a π–π interaction in the transition state between mono- and di-benzyl products is proposed. A further investigation[144] has more accurately characterized which substrates will display the effect, and has also identified the π–π interaction (or, more properly, a σ–π interaction between two π-systems) as being of the edge-to-face geometry.

α, *β*-Unsaturated ketones, *β*-keto esters, and some uracil derivatives undergo α-iodination with iodine in the presence of bis(tetra-*n*-butylammonium) peroxodisulfate $[(Bu^n_4N^+)_2\ {}^-OS(=O)_2OOS(=O)_2O^-]$ in good yield.[145] It is suggested that $SO_4^{\cdot-}$ is generated by homolytic cleavage of peroxodisulfate, and that this converts iodine to $I_2^{+\cdot}$, which acts as the iodinating species.

Aryllead triacetates α-arylate ketones highly selectively, working well for tertiary α-carbons, or secondary ones activated by a phenyl group,[146] thus favouring arylation of positions that are typically already crowded, making the reaction very useful synthetically.

The regiochemistry of deuteration of polycyclic carbonyl compounds such as methyl derivatives of benz[*de*]anthracen-6- and -7-one is subject to orbital control.[147] Charge alternation and deuterium isotope effects in these and related compounds were studied by NMR and MNDO methods.

Intramolecular proton transfer rates in acetylacetone have been calculated.[148]

Iodination of acetone is slowed by increasing magnetic field strength.[149]

Enolates

Recent developments in enantioselective protonation of enolates and enols have been reviewed, illustrating the reactions' utility in asymmetric synthesis of carbonyl compounds with pharmaceutical or other industrial applications.[150] Enolate protonation may require use of an auxiliary in stoichiometric amount, but it is typically readily recoverable. In contrast, the chiral reagent is not consumed in protonation of enols, so a catalytic quantity may suffice. Another variant is the protonation of a complex of the enolate and the auxiliary by an achiral proton source. Differentiation of these three possibilities may be difficult, due to reversible proton exchange reactions.

To distinguish isomeric anions such as alkoxides and enolates in the gas phase, a flowing-afterglow MS technique has been developed, using a probe reagent to distinguish such species by chemical reactivity.[151] Dimethyl sulfide proved particularly useful. Alkoxide anions react as 'hard' bases, eliminating across the C—S bond, whereas enolates were 'softer', attacking at sulfur. The scope and limitations of other probes such as methyl nitrite and methanol-*O*-*d* are outlined.

Proton abstraction from a model carbon acid, hydroxyacetaldehyde, by formate anion has been examined theoretically for the gas phase and for aqueous solution.[152] The reaction shows an early transition state, whereas its enzymatic equivalent has a late transition state. Solvation brings the transition state forward. The factors that contribute to producing the later transition state in enzymes are discussed.

Highly selective kinetic enolate formation, via the deprotonation of representative ketones with analogues of lithium diisopropyl amide (LDA) bases, has been reported.[153] The strategy involves varying the nature of the lithium amide substituents to bias protonation towards (*E*)- or (*Z*)-enolate. Combinations of phenyl, trimethylsilyl, and alkyl groups of varying bulk were employed. Excellent *E*-selectivity was achieved with steric control [e.g. using lithium *N*-*t*-butyl(trimethylsilyl)amide], while high *Z*-yield requires *two* electron-withdrawing groups, as in the case of the *N*-(trimethylsilyl)anilide base; both of these modified forms of LDA should be of considerable synthetic utility.

Another new LDA-based strategy for regioselective alkylation of unsymmetrical ketones involves the combined use of LDA and aluminium tris(2,6-diphenylphenoxide): the latter complexes the less hindered side of the ketone, blocking the LDA and 're-directing' it by default to the more hindered side.[154]

1,2-Diphenylcycloalkanols undergo base-catalysed ring opening to give enolates, with some fragmentation.[155] Mechanisms and rate-limiting steps within them change considerably with ring size. Rings of 5–8 carbons have been studied, as have the corresponding acyclic structures. A very wide range of reactivity is observed, but comparisons with strain release and entropy change give poor correlations.

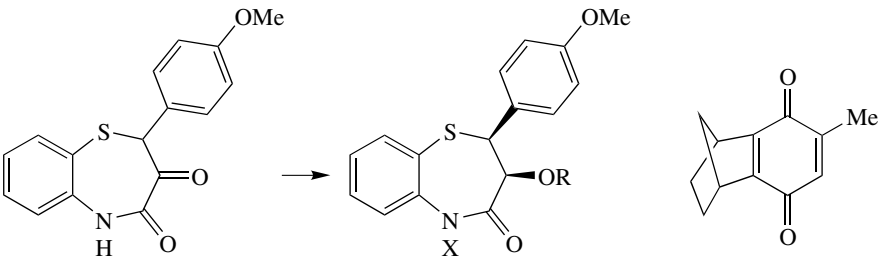
The diastereoselectivity of protonation of enolate anions has been studied by H/D exchange.[156] β-Substituted ethyl butanoates were chosen as substrates, with conditions that rigorously excluded ion-pairing and aggregation effects. Stereoelectronic effects were found typically to produce higher stereoselection than purely steric effects. In the specific case of H/D exchange in 3-ethoxybutanoate in ethanol-*d*, protonation of the enolate of 3-fluorobutanoate was chosen as a computational model.[157] Similar

diastereoselectivities were observed for *cis*- and *trans*-enolates, and the transition state for each has the C—F bond *anti* to the incipient C—H bond, perhaps due to a stabilizing orbital interaction.

Oxidation and Reduction of Carbonyl Compounds

Regio-, Enantio-, and Diastereo-selective Redox Reactions

In a new synthesis of diltiazem (**98b**; R = Ac, X = $CH_2CH_2NMe_2$), a calcium antagonist used in the treatment of hypertension, the key step is the diastereoselective reduction of α-ketolactam (**97**) to the alcohol precursor (**98a**; R = X = H).[158] The reduction of the 1,5-benzothiazepine (**97**) was achieved using an $NaBH_4$–(*S*)-amino acid combination; (*S*)-*t*-leucine was most efficient, and was readily recovered unracemized.



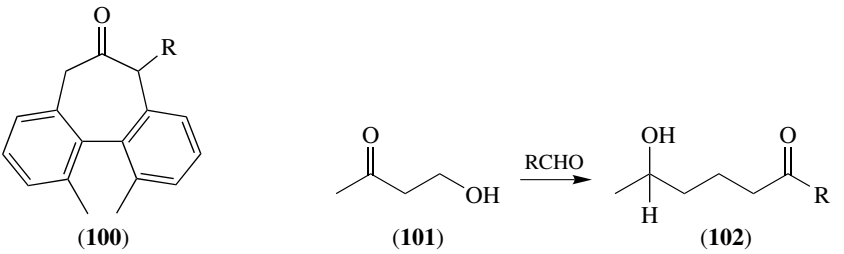
The regiochemistry of borohydride reduction of cyclic enediones such as (**99**) was markedly affected by addition of cerium(III): whether a complexation site was accessible to the Lewis acid appears to be the main factor involved.[159]

α, β-Unsaturated ketones have been converted into the corresponding saturated chiral alcohols in high yield and high *ee* using a mercaptoisoborneol as auxiliary.[160] Michael addition is followed by an intramolecular Meerwein–Ponndorf–Verley reduction involving a 1,7-hydride shift and the formation of a 10-membered cyclic chelate.

A series of 2-substituted cyclohexanones was studied over a wide range of temperature in an attempt to optimize the diastereoselectivity of diisobutylaluminium phenoxides in the reduction of ketones.[161] Hydride transfer dominates at high temperature, but a Meerwein–Ponndorf–Verley-type interconversion of the aluminium alcoholate intermediates (via the reactant ketone) is an important factor in diastereoselection at low temperature.

The face-selectivity of hydride reductions of the conformationally-rigid ketone series (**100**) has been examined for pure axial and equatorial isomers with four different R groups, viz. Me, Cl, OMe, and SMe.[162] The reactivities show Taft correlations with the inductive effects of the substituents. Only through-bond and -space electrostatic interactions are used to explain the results: neither Cieplak nor Anh antiperiplanar effects are invoked.

Reaction of organometallics such as alkyllithiums or Grignard reagents with *p*-quinones can give an addition product, or a hydroquinone (i.e. reduction product). The



(**100**) (**101**) (**102**)

SCHEME 7

reaction is shown to occur via a concerted single-electron transfer to give quinone radical anion and alkyl radical.[163] Radical coupling gives the addition product, but bulky R groups allow radical separation by diffusion, leading to reduction. Similarly, conjugate addition of HN_3 to quinones can yield either aminoquinones or azidohydroquinones, and the parameters and conditions required to select between outcomes have been characterized.[164]

β-Hydroxy ketones can be reduced with aldehydes in a Tishchenko-type reaction, (**101**) → (**102**), using a zirconocene catalyst.[165] The reaction provides a stereoselective route to *anti*-1,3-diols. A labelling experiment with $CpZrH_2$ and MeCDO indicated that the aldehydic hydrogen ends up on the alcohol carbon. The kinetic isotope effect of ca 1.8 suggests that hydride transfer may be rate limiting.

In other reports, β-cyclodextrins have been used to induce asymmetry in borohydride reduction of ketones,[166] a diastereoselective reduction has been controlled[167] by a π-allyltricarbonyliron lactone 'tether', a phosphinamide has been combined with a dioxaborolidine unit as an activated, directed catalyst for ketone reduction,[168] reductive amination using benzylamine–cyanoborohydride converts 3-hydroxy ketones into *syn*-1,3-amino alcohols,[169] 1-(3,4-dimethoxyphenyl)-2-(2-methoxyphenoxy)propan-1-one has been reduced diastereoselectively,[170] and production of chiral alcohols via (i) Itsuno–Corey and Brown procedures[171] and (ii) lithium aluminium hydride modified by chiral nucleophiles[172] has been reviewed.

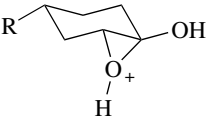
Use of thiaprolinol amino alcohols as ligands for enantioselective borane reduction of ketones[111] and of a fluorotitanium-TADDOLate to catalyse reduction of benzaldehyde[87c] has been described above under Organometallics and Allylation Reactions, respectively.

Other Redox Reactions

The Cannizzaro disproportionation, $2RCHO + HO^- \rightarrow RCH_2O^- + RCO_2H$, has been studied in the gas phase by a variety of MS techniques, for R = Bu^t and Ph,[173] and results have been compared with calculations on the prototypical system, i.e. R = H.

Cyclohexanone and some alkyl derivatives can ring contract to the corresponding cyclopentanecarboxylic acid; the reaction is promoted by thallium(III). Alternative mechanisms which have been proposed by (i) Wiberg and Koch[174a] and (ii) McKillop *et al.*[174b] involve a 2-thallyl ketone hydrate which either (i) loses Tl^+ and a proton in ring contraction or (ii) loses Tl^+ first, giving rise to a protonated hydroxyoxirane

intermediate (**103**). The stereochemical outcomes are different, and examination of the products of ring contraction of 3- and 4-methyl- and -*t*-butyl-cyclohexanones[174c] tends to favour the proposal of McKillop *et al.*



(**103**)

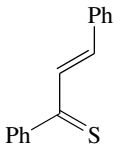
Rate equations for the oxidation of aldehydes, RCHO (R = H, Me_2CH, Ph, *p*-$MeOC_6H_4$), by Fenton's reagent (Fe^{2+}–H_2O_2–H^+) have been determined.[175] The reactions were first order in ferrous ion, peroxide, and aldehyde, except for aromatic aldehydes, where the order in peroxide was measured as 0.5.

Other reports of kinetic studies deal with mechanisms of thermal oxidation of a variety of simple ketones monitored via gas evolution (CO, CO_2, H_2, etc.),[176] alkaline oxidation of aldehydes with copper and silver tellurates,[177] $[M^{III}(H_2TeO_6)_2]^{5-}$, and oxidation of acetals of simple aldehydes in aqueous acetic acid with (i) *N*-chlorobenzamide (H_2OCl^+ is the oxidant inferred)[178] and (ii) *N*-chlorosaccharin.[179]

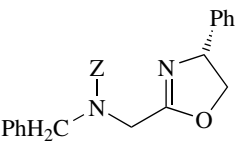
Accounts of the reductive coupling of two molecules of ketone via the McMurry alkene synthesis have been described[66–68] earlier under Miscellaneous Aldols.

Other Reactions

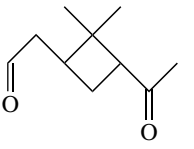
A 1-thiabuta-1,3-diene (**104**) undergoes highly stereoselective hetero-Diels–Alder cycloadditions with chiral *N*-acryloyloxazolidinones.[180]



(**104**)



(**105**)



(**106**)

Alkylation of chiral 2-(aminomethyl)oxazoline (**105**; Z = CH_2Ph) at the exocyclic carbon—using *n*-butyllithium and an alkyl halide—proceeds with negligible *de*. However, when the amine reactant is changed to a carbamate, e.g. (**105**; Z = CO_2Ph), the products exhibit up to 92% *de*.[181] This is ascribed to a preferred formation of an *E*-enolate-type intermediate during deprotonation, due to complexation of the lithium by the carbamate carbonyl.

Rate constants for the reaction of pinonaldehyde (**106**), an oxidation product of α-pinene, with OH, NO_3, and O_3 have been measured in the gas phase.[182]

Boron cations, Me_2B^+ and $(MeO)_2B^+$, are highly reactive towards carbonyl compounds, but are not easily studied in condensed phase. In the gas phase, two pathways compete:[183] (i) C=O cleavage, with OH abstraction leaving behind a

hydrocarbon cation corresponding to the entire carbon skeleton of the reactant; (ii) C—C cleavage, involving abstraction of a small aldehyde with elimination of a neutral alkene. Pathway (i) is thermodynamically favoured, and dominant for long-chain substrates. Pathway (ii) competes kinetically for shorter chains, and the product structures can identify the carbonyl substrate involved.

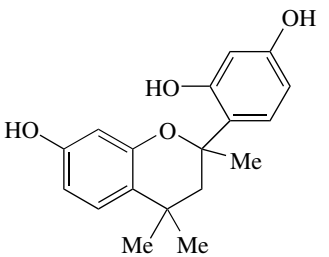
Hydrogenated furans can be prepared from the reaction of α-olefins with formaldehyde in trifluoroacetic acid: kinetics suggest that the reactions proceed via equilibrium addition of the protonated aldehyde.[184]

Structural factors in the reactants and the reaction pH have both been varied to optimize the electrophilic condensation of pyrimidines with cyclic ketones such as *N*-substituted piperidones and 4-substituted cyclohexanones.[185]

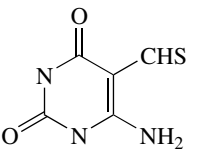
Muonium is a light isotope of hydrogen (<0.1 amu), and its muon nucleus is short-lived (ca 2 μs). Kinetic isotope effects of 10^4, relative to ^{1}H, are known. Reaction of muonium atoms with carbonyl compounds has been studied in aqueous solution.[186a] For acetone,[186b] the major pathways are addition [$Mu^{\cdot} + Me_2CO \rightarrow HMu + Me_2C^{\cdot}(OMu)$] and abstraction [$\ldots \rightarrow HMu + MeCOCH_2^{\cdot}$]. At 22 °C, the rate of muonium reaction with butanone, 3-pentanone, cyclohexanone, di-*t*-butyl ketone, and the previously measured acetone[186b] has an approximately invariant value of 1×10^8 M^{-1} s^{-1} (±20%), and even acetaldehyde reacts at $< 2 \times 10^8$ M^{-1} s^{-1}. This lack of rate dependence on structure is in marked contrast to the rates of reaction of $H^{\cdot}$, where even the closely related acetone and butanone differ by 22-fold,[186c] and reaction is slower than $Mu^{\cdot}$. It appears that abstraction, which is often the dominant reaction in the case of ^{1}H, is practically absent for Mu. Presumably tunnelling is more important for addition, whereas the heavier ^{1}H wins out in the abstraction reaction as transition states involving muonium have higher zero-point vibrational energy. As muonium isotope effects are used to investigate mechanisms of many reaction types, the example underlines the importance of identifying the products of kinetic studies, whether 'ordinary' or 'exotic' species are involved.

The balance of the two pathways for muonium and acetone described here is reversed when the acetone is localized in micelles.[187]

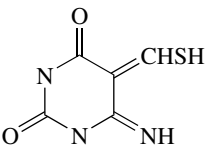
The structure of the product of the reaction of resorcinol (*m*-dihydroxybenzene) with acetone—uncertain for over a century—has been confirmed[188] as (**107**). The mechanism is proposed to involve initial formation of mesityl oxide ($Me_2C{=}CH{-}CHCOMe$), as reaction of authentic oxide with resorcinol produces the same product.



(**107**)



(**108a**)



(**108b**)

6-Amino-5-thioformyluracils, e.g. (**108a**), have their thioaldehyde function stabilized by the amino group; this may involve tautomerization to an imino-mercaptomethylene structure (**108b**). The reactivity of (**108a**) with enamines has been investigated.[189]

Several bicyclo[2.2.1]heptane derivatives with a 1,4-dicarbonyl moiety undergo C—C bond cleavage via intramolecular pinacol coupling, promoted by samarium(II) iodide.[190]

Kinetics of isomerization of glyceraldehyde to dihydroxyacetone—and the formation of pyruvaldehyde from both—have been studied in sub- and super-critical water.[191]

Formaldehyde reacts with isoeugenol [1-(3-methoxy-4-hydroxyphenyl)propene] in alkaline medium to give a 1,3-dioxane derivative via an unusual Prins-type reaction.[192]

The potential-energy surface for the equilibrium, $HCO + HCN \rightleftarrows H_2CO + CN$, has been calculated[193] by *ab initio* methods.

References

[1] Brown, C. J. and Kirby, A. J., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1081.
[2] Fife, T. H., Bembi, R., and Natarajan, R., *J. Am. Chem. Soc.*, **118**, 12956 (1996).
[3] Streefland, L., Blandamer, M. J., and Engberts, J. B. F. N., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 769.
[4] Balashov, A. L., Danov, S. M., and Chubarov, G. A., *Zh. Fiz. Chim.*, **70**, 1375 (1996); *Chem. Abs.*, **126**, 18488 (1997).
[5] Lindner, P. E. and Lemal, D. M., *Tetrahedron Lett.*, **37**, 9165 (1996).
[6] Fan, Y.-H. and Haseltine, J., *Tetrahedron Lett.*, **37**, 9279 (1996).
[7] Katzhendler, J., Ringel, I., Karaman, R., Zaher, H., and Breuer, E., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 341.
[8] Moraes, L. A. B., Pimpim, R. S., and Eberlin, M. N., *J. Org. Chem.*, **61**, 8726 (1996).
[9] Fossey, J., Ghigo, G., Tonachini, G., and Venturello, P., *Tetrahedron*, **53**, 7937 (1997).
[10] Akhoon, K. M. and Myles, D. C., *J. Org. Chem.*, **62**, 6041 (1997).
[11] Oda, M., Kamata, Y., Satoshi, N., Miyatake, R., Kuroda, S., and Oda, M., *Recl. Trav. Chim. Pays-Bas*, **115**, 445 (1996); *Chem. Abs.*, **126**, 74691 (1997).
[12] Norkus, E., Vaskelis, A., Butkus, E., and Pauliukaite, R., *J. Chem. Res. (S)*, **1997**, 126.
[13] Camps, P., Görbig, D., Muñoz-Torrero, V., and Pérez, F., *Collect. Czech. Chem. Commun.*, **62**, 1585 (1997).
[14] Miljkovic, M., Yeagley, D., Deslongchamps, P., and Dory, Y. L., *J. Org. Chem.*, **62**, 7597 (1997).
[15] Liras, J. L., Lynch, V. M., and Anslyn, E. V., *J. Am. Chem. Soc.*, **119**, 8191 (1997).
[16] (a) Yuasa, H., Kamata, Y., and Hashimoto, H., *Angew. Chem., Int. Ed. Engl.*, **36**, 868 (1997); (b) Yuasa, H. and Hashimoto, H., *Tetrahedron*, **49**, 8977 (1993).
[17] Kennedy, G., Slaich, P. K., Golding, B. T., and Wilson, W. P., *Chem.–Biol. Interact.*, **102**, 93 (1996); *Chem. Abs.*, **126**, 60270 (1997).
[18] Smiataczowa, K., Maj, K., and Korewa, R., *Pol. J. Chem.*, **71**, 831 (1997); *Chem. Abs.*, **127**, 95491 (1997).
[19] Birney, D. M., Xu, X., Ham, S., and Huang, X., *J. Org. Chem.*, **62**, 7114 (1997).
[20] Yamataka, H., Aleksiuk, O., Biali, S. E., and Rappoport, Z., *J. Am. Chem. Soc.*, **118**, 12580 (1996).
[21] Hegarty, A. F., Kelly, J. G., and Relihan, C. M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1175.
[22] Fang, D.-C. and Fu, X.-Y., *Chem. Phys. Lett.*, **259**, 265 (1996); *Chem. Abs.*, **125**, 246929 (1996).
[23] Bellassoued, M., Reboul, E., and Dumas, F., *Tetrahedron Lett.*, **38**, 5631 (1997).
[24] Crampton, M. R., Lord, S. D., and Millar, R., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 909.
[25] El-Taher, M. A., *Aswan Sci. Technol. Bull.*, **17**, 163 (1996); *Chem. Abs.*, **126**, 131093 (1997).
[26] Soloshonok, V. A. and Ono, T., *Synlett*, **1996**, 919; *Chem. Abs.*, **125**, 327885 (1997).
[27] Rak, J., Skurski, P., Józwiak, L., and Blazejowski, J., *Aust. J. Chem.*, **50**, 97 (1997).
[28] Rasmussen, K. G. and Jørgensen, K. A., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1287.
[29] Wang, D.-K., Dai, L.-X., and Hou, X.-L., *J. Chem. Soc., Chem. Commun.*, **1997**, 1231.
[30] Casarrubios, L., Pérez, J. A., Brookhart, M., and Templeton, J. L., *J. Org. Chem.*, **61**, 8358 (1996).
[31] García Ruano, J. L., Fernández, I., del Prado Catalina, M., and Alcudia Cruz, A., *Tetrahedron: Asymmetry*, **7**, 3407 (1996).
[32] (a) Nakamura, H., Iwama, H., and Yamamoto, Y., *J. Chem. Soc., Chem. Commun.*, **1996**, 1459 and *J. Am. Chem. Soc.*, **118**, 6641 (1996), as cited in *Org. React. Mech.*, **1996**, 18 and 8, respectively; (b) Kobayashi, S. and Nagayama, S., *J. Am. Chem. Soc.*, **119**, 10049 (1997).

[33] Kobayashi, S. and Nagayama, S., *J. Org. Chem.*, **62**, 232 (1997).
[34] El-Taher, M. A., *Aswan Sci. Technol. Bull.*, **17**, 150 (1996); *Chem. Abs.*, **126**, 143826 (1997).
[35] Lefebvre, I. M. and Evans, S. A., *J. Org. Chem.*, **62**, 7532 (1997).
[36] Fujieda, H., Kanai, M., Kambara, T., Iida, A., and Tomioka, K., *J. Am. Chem. Soc.*, **119**, 2060 (1997).
[37] Kim, T. R., Chung, D. I., and Pyun, S. Y., *Bull. Korean Chem. Soc.*, **18**, 374 (1997); *Chem. Abs.*, **127**, 65359 (1997).
[38] Kim, T. R., Chung, D. I., and Pyun, S. Y., *J. Korean Chem. Soc.*, **40**, 733 (1996); *Chem. Abs.*, **126**, 143822 (1997).
[39] Bernardi, A., Gennari, C., Raimondi, L., and Villa, M. B., *Tetrahedron*, **53**, 7705 (1997).
[40] Badorrey, R., Cativiela, C., Díaz-de-Villegas, M. D., and Gálvez, J. A., *Tetrahedron*, **53**, 1411 (1997).
[41] Golovanov, A. V. and Krutikov, V. I., *Zh. Obshch. Khim.*, **66**, 344 (1996); *Chem. Abs.*, **125**, 247793 (1996).
[42] Nongkunsarn, P. and Ramsden, C. A., *Tetrahedron*, **53**, 3805 (1997).
[43] Brown, D. W., Lindquist, M., Mahon, M. F., Malm, B., Nilsson, G. N., Ninan, A., Sainsbury, M., and Westerlund, C., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2337.
[44] (a) Biginelli, P., *Gazz. Chim. Ital.*, **23**, 1893 (1893); (b) Mayr, H. and Ofial, A. R., *Tetrahedron Lett.*, **38**, 3503 (1997).
[45] Cai, H. and Fishbein, J. C., *Tetrahedron*, **53**, 10671 (1997).
[46] Kappe, C. O., *J. Org. Chem.*, **62**, 7201 (1997).
[47] Kirihara, M., Niimi, K., and Momose, T., *J. Chem. Soc., Chem. Commun.*, **1997**, 599.
[48] (a) Jain, A. K., Singh, P., and Sahoo, B. B., *J. Phys. Org. Chem.*, **9**, 770 (1996); (b) Hirst, J., Onuoha, G. N., and Onyido, I., *J. Chem. Soc., Perkin Trans. 2*, **1988**, 971; Akinyele, E. T., Onyido, I., and Hirst, J., *J. Chem. Soc., Perkin Trans. 2*, **1988**, 1859.
[49] (a) Baldwin, J. E. and Norris, R. K., *J. Org. Chem.*, **46**, 697 (1981); (b) Perrin, C. L. and Engler, R. E., *J. Org. Chem.*, **62**, 687 (1997).
[50] Enders, D., Nübling, C., and Schubert, H., *Liebigs Ann./Recl.*, **1997**, 1089.
[51] Rowe, J. E. and Lee, K., *Aust. J. Chem.*, **50**, 849 (1997).
[52] (a) Corey, E. J. and Rohde, J. J., *Tetrahedron Lett.*, **38**, 37 (1997); (b) Corey, E. J., Rohde, J. J., Fischer, A., and Azimioara, M. D., *Tetrahedron Lett.*, **38**, 33 (1997); (c) Corey, E. J., Barnes-Seeman, D., and Lee, T. W., *Tetrahedron Lett.*, **38**, 1699 (1997).
[53] Corey, E. J., Barnes-Seeman, B., and Lee, T. W., *Tetrahedron Lett.*, **38**, 4351 (1997).
[54] Denmark, S. E., Wong, K.-T., and Stavenger, R. A., *J. Am. Chem. Soc.*, **119**, 2333 (1997).
[55] Evans, D. A., Coleman, P. J., and Côté, B., *J. Org. Chem.*, **62**, 788 (1997).
[56] Ghosh, A. K., Fidanze, S., Onishi, M., and Hussain, K. A., *Tetrahedron Lett.*, **38**, 7171 (1997).
[57] García Ruano, J. L., Barros, D., Maestro, M. C., Araya-Maturana, R., and Fischer, J., *J. Org. Chem.*, **61**, 9462 (1996).
[58] Abiko, A., Liu, J.-F., and Masamune, S., *J. Am. Chem. Soc.*, **119**, 2586 (1997).
[59] Gennari, C., Vulpetti, A., and Pain, G., *Tetrahedron*, **53**, 5909 (1997).
[60] (a) Guthrie, J. P. and Guo, J., *J. Am. Chem. Soc.*, **118**, 11472 (1996); (b) Nagorski, R. W., Mizerski, T., and Richard, J. P., *J. Am. Chem. Soc.*, **117**, 4718 (1995), as cited in *Org. React. Mech.*, **1995**, 10.
[61] Bowden, K. and Brownhill, A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 997.
[62] Van Ornum, S. G., Li, J., Kubiak, G. G., and Cook, J. M., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 3471.
[63] (a) Oppolzer, W., *Pure Appl. Chem.*, **62**, 1241 (1990); (b) Spivey, A. C., *Encyclopedia of Reagents for Organic Synthesis* 1995, Vol. 2, p. 975 [review of Oppolzer's sultam]; (c) Brzezinski, L. J., Rafel, S., and Leahy, J. W., *J. Am. Chem. Soc.*, **119**, 4317 (1997).
[64] Rafel, S. and Leahy, J. W., *J. Org. Chem.*, **62**, 1521 (1997).
[65] (a) Fort, Y., Berthe, M. C., and Caubere, P., *Tetrahedron*, **48**, 6371 (1992); (b) Aggarwal, V. K., Tarver, G. J., and McCague, R., *J. Chem. Soc., Chem. Commun.*, **1996**, 2713.
[66] (a) Fürstner, A. and Bogdanović, B., *Angew. Chem., Int. Ed. Engl.*, **35**, 2442 (1996); (b) Fürstner, A. and Jumbam, D. N., *Tetrahedron*, **48**, 5991 (1992); (c) Fürstner, A., Hupperts, A., Prock, A., and Janssen, E., *J. Org. Chem.*, **59**, 5215 (1994); (d) Bogdanović, B., *Angew. Chem., Int. Ed. Engl.*, **35**, 2442 (1996); (e) Stahl, M., Pidun, U., and Frenking, G., *Angew. Chem., Int. Ed. Engl.*, **36**, 2234 (1997).
[67] Villiers, C. and Ephritikhine, M., *Angew. Chem., Int. Ed. Engl.*, **36**, 2380 (1997).
[68] Maury, O., Villiers, C., and Ephritikhine, M., *Tetrahedron Lett.*, **38**, 6591 (1997).
[69] Yamataka, H., Sasaki, D., Kuwatani, Y., Mishima, M., and Tsuno, Y., *Chem. Lett.*, **1997**, 271.
[70] Yamataka, H., Sasaki, D., Kuwatani, Y., Mishima, M., and Tsuno, Y., *J. Am. Chem. Soc.*, **119**, 9975 (1997).
[71] Sano, S., Yokoyama, K., Fukushima, M., Yagi, T., and Nagao, Y., *J. Chem. Soc., Chem. Commun.*, **1997**, 559.
[72] Lampe, T. F. J. and Hoffmann, H. M. R., *J. Chem. Soc., Chem. Commun.*, **1996**, 2637.
[73] Lecea, B., Arrieta, A., Morao, I., and Cossío, F. P., *Chemistry*, **3**, 20 (1997).

[74] Rossignoli, M., Lawrance, G. A., Maeder, M., Hockless, D. C. R., Skelton, B. W., and White, A. H., *Aust. J. Chem.*, **49**, 1307 (1996).
[75] Carlier, P. R., Lo, K. M., Lo, M. M.-C., and Lam, W. W.-F., *Youji Huaxue*, **17**, 57 (1997); *Chem. Abs.*, **126**, 185838 (1997).
[76] Miyashita, A., Numata, A., Suzuki, Y., Iwamoto, K.-I., and Higashino, T., *Chem. Lett.*, **1997**, 697.
[77] Cantrill, A. A., Hall, L. D., Jarvis, A. N., Osborn, H. M. I., Raphy, J., and Sweeney, J. B., *J. Chem. Soc., Chem. Commun.*, **1996**, 2631.
[78] Ohkata, K., Kimura, J., Shinohara, Y., Takagi, R., and Hiraga, Y., *J. Chem. Soc., Chem. Commun.*, **1996**, 2411; *Chem. Abs.*, **126**, 18723 (1997).
[79] Bach, T., Jödicke, K., Kather, K., and Fröhlich, R., *J. Am. Chem. Soc.*, **119**, 2437 (1997).
[80] Corey, E. J., Barnes-Seeman, D., Lee, T. W., and Goodman, S. N., *Tetrahedron Lett.*, **38**, 6513 (1997).
[81] Ishihara, K., Hattori, K., and Yamamoto, H., *Enantiosel. Synth. β-Amino Acids*, **1997**, 159; *Chem. Abs.*, **127**, 191007 (1997).
[82] Bodnar, P. M., Palmer, W. S., Ridgway, B. H., Shaw, J. T., Smitrovich, J. H., and Woerpel, K. A., *J. Org. Chem.*, **62**, 4737 (1997).
[83] Kobayashi, S., Nagayama, S., and Busujima, T., *Chem. Lett.*, **1997**, 959.
[84] (a) Thomas, E. J., *J. Chem. Soc., Chem. Commun.*, **1997**, 411; (b) Carey, J. S. and Thomas, E. J., *Synlett*, **1992**, 585; (c) Beddoes, R. L., Hobson, L. A., and Thomas, E. J., *J. Chem. Soc., Chem. Commun.*, **1997**, 1929.
[85] Kadota, I., Kawada, M., Gevorgyan, V., and Yamamoto, Y., *J. Org. Chem.*, **62**, 7439 (1997).
[86] Cokley, T. M., Harvey, P. J., Marshall, R. L., McCluskey, A., and Young, D. J., *J. Org. Chem.*, **62**, 1961 (1997).
[87] (a) Keck, G. E., Tarbet, K. H., and Geraci, L. S., *J. Am. Chem. Soc.*, **115**, 8467 (1993); (b) Gauthier, D. R. and Carreira, E. M., *Angew. Chem., Int. Ed. Engl.*, **35**, 2363 (1996); (c) Duthaler, R. O. and Hafner, A., *Angew. Chem., Int. Ed. Engl.*, **36**, 43 (1997).
[88] Kasatkin, A. and Sato, F., *Angew. Chem., Int. Ed. Engl.*, **35**, 2848 (1996).
[89] Kirihara, M., Takuwa, T., Takizawa, S., and Momose, T., *Tetrahedron Lett.*, **38**, 2853 (1997).
[90] Iseki, K., Kuroki, Y., Takahashi, M., Kishimoto, S., and Kobayashi, Y., *Tetrahedron*, **53**, 3513 (1997).
[91] Gryko, D., Urbańczyk-Lipkowska, Z., and Jurczak, J., *Tetrahedron*, **53**, 13373 (1997).
[92] Omoto, K. and Fujimoto, H., *J. Am. Chem. Soc.*, **119**, 5366 (1997).
[93] Dahn, H., Péchy, P., and Toan, V. V., *Magn. Reson. Chem.*, **35**, 589 (1997).
[94] Dahn, H. and Carrupt, P.-A., *Magn. Reson. Chem.*, **35**, 577 (1997).
[95] Dell'Erba, C., Mugnoli, A., Noto, R., Novi, M., Occhiucci, G., Petrillo, G., Sancassan, F., and Spinelli, D., *Tetrahedron*, **53**, 731 (1997).
[96] Mehta, G., Ravikrishna, C., Ganguly, B., and Chandrasekhar, J., *J. Chem. Soc., Chem. Commun.*, **1997**, 75.
[97] Barbero, A., Blakemore, D. C., Fleming, I., and Wesley, R. N., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1329.
[98] Perlmutter, P., *Top. Curr. Chem.*, **190**, 87 (1997); *Chem. Abs.*, **127**, 205484 (1997).
[99] Mathieu, B. and Ghosez, L., *Tetrahedron Lett.*, **38**, 5497 (1997).
[100] Shokhen, M. and Arad, D., *J. Mol. Model.*, **2**, 399 (1996) [*http://science.springer.de/jmm.abstracts/1996/6020399.html*]; *Chem. Abs.*, **126**, 292963 (1997).
[101] Anderson, P. D. J., Fernandez, M. T., Pocsfalvi, G., and Mason, R. S., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 873.
[102] Kuroda, S., Oda, M., Kuramoto, S., Fukuta, A., Mizukami, Y., Nozawa, Y., Miyatake, R., Izawa, M., and Shimao, I., *Tetrahedron Lett.*, **38**, 8291 (1997).
[103] (a) Richie, H. G., in *Carbonium Ions* (Eds Schleyer, P. v. R. and Olah, G. A.), Wiley–Interscience, New York, 1970, Vol. 2, pp. 1201–1294; (b) Buckley, N., *J. Org. Chem.*, **62**, 2205 (1997).
[104] Jeyaraj, A. and Yadav, V. K., *Tetrahedron Lett.*, **38**, 6095 (1997).
[105] (a) Bowden, K., El-Kaissi, F. A., and Nadvi, N. S., *J. Chem. Soc., Perkin Trans. 2*, **1979**, 642; (b) Anvia, F. and Bowden, K., *J. Chem. Soc., Perkin Trans. 2*, **1990**, 2093; (c) Bowden, K. and Rumpal, S., *J. Chem. Res. (S)*, **1997**, 35.
[106] Bowden, K. and Rumpal, S., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 983.
[107] Bowden, K. and Horri, M. V., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 989.
[108] Al-Najja, A., Bowden, K., and Horri, M. V., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 993.
[109] Frantz, D. E., Singleton, D. A., and Snyder, J. P., *J. Am. Chem. Soc.*, **119**, 3383 (1997).
[110] Guo, C., Qiu, J., and Zhang, X., *Tetrahedron*, **53**, 4145 (1997).
[111] Huang, H.-L., Lin, Y.-C., Chen, S.-F., Wang, C.-L. J., and Liu, L. T., *Tetrahedron: Asymmetry*, **7**, 3067 (1996).
[112] Vidal-Ferran, A., Moyano, A., Pericás, M. A., and Riera, A., *Tetrahedron Lett.*, **38**, 8773 (1997).
[113] Asami, M. and Inoue, S., *Bull. Chem. Soc. Jpn.*, **70**, 1687 (1997).

[114] Oi, S., Moro, M., and Inoue, Y., *J. Chem. Soc., Chem. Commun.*, **1997**, 1621.
[115] El-Taher, S., *Int. J. Quantum Chem.*, **62**, 419 (1997); *Chem. Abs.*, **126**, 317074 (1997).
[116] Aggarwal, V. K., Calamai, S., and Ford, J. G., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 593.
[117] Aggarwal, V. K., Boccardo, G., Worrall, J. M., Adams, H., and Alexander, R., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 11.
[118] Shimizu, M., Wakioka, I., and Fujisawa, T., *Tetrahedron Lett.*, **38**, 6027 (1997).
[119] Magnus, N. and Magnus, P., *Tetrahedron Lett.*, **38**, 3491 (1997).
[120] Nicolaou, K.C., Härter, M. W., Gunzner, J. L., and Nadin, A., *Liebigs Ann./Recl.*, **1997**, 1283.
[121] Walker, B. J., *Organophosphorus Chem.*, **27**, 264 (1996); *Chem. Abs.*, **126**, 89422 (1997).
[122] Chow, T. J., Li, L.-P., Lee, V. Y. R., Lin, K.-J., and Chen, C.-Y., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2681.
[123] Matano, Y. and Suzuki, H., *J. Chem. Soc., Chem. Commun.*, **1996**, 2697.
[124] Doyle, M. P., Forbes, D. C., Protopopova, M. N., Stanley, S. A., Vasbinder, M. M., and Xavier, K. R., *J. Org. Chem.*, **62**, 7210 (1997).
[125] Ivanova, N. M. and Shchelkunov, A. V., *Zh. Org. Khim.*, **32**, 685 (1996); *Chem. Abs.*, **126**, 31016 (1997).
[126] Schlosser, M., Keller, H., Sumida, S., and Yang, J., *Tetrahedron Lett.*, **38**, 8523 (1997).
[127] Iskander, M. L. and Medien, H. A. A., *An. Quim. Int. Ed*, **93**, 3 (1997); *Chem. Abs.*, **126**, 343820 (1997).
[128] Stankovicová, H., Gasparová, R., Lácová, M., and Chovancová, J., *Collect. Czech. Chem. Commun.*, **62**, 781 (1997).
[129] Lee, D., Kim, C. K., Lee, B.-S., Lee, I., and Lee, B. S., *J. Comput. Chem.*, **18**, 56 (1997); *Chem. Abs.*, **126**, 103730 (1997).
[130] Sargent, A. L., Rollog, M. E., Almlof, J. E., Gassman, P. G., and Gerlt, J. A., *THEOCHEM*, **388**, 145 (1996); *Chem. Abs.*, **126**, 171137 (1997).
[131] Rappoport, Z., Frey, J., Sigalov, M., and Rochlin, E., *Pure Appl. Chem.*, **69**, 1933 (1997).
[132] Lindner, P. E. and Lemal, D. A., *J. Am. Chem. Soc.*, **119**, 3259 (1997).
[133] Lindner, P. E. and Lemal, D. A., *J. Am. Chem. Soc.*, **119**, 3267 (1997).
[134] Hoz, S. and Kresge, A. J., *J. Phys. Org. Chem.*, **10**, 182 (1997).
[135] Ramos, M., Alkorta, I., and Elguero, J., *Tetrahedron*, **53**, 1403 (1997).
[136] De Maria, P., Fontana, A., and Cerichelli, G., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2329.
[137] Traven, V. F., Negrebetsky, V. V., Vorobjeva, L. I., and Carberry, E. A., *Can. J. Chem.*, **75**, 377 (1997).
[138] (a) Halkides, C. J., Frey, P. A., and Tobin, J. B., *J. Am. Chem. Soc.*, **115**, 3332 (1993); (b) Tobin, J. B. and Frey, P. A., *J. Am. Chem. Soc.*, **118**, 12253 (1996).
[139] Tee, O. S. and Donga, R. A., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2763.
[140] (a) Chiang, Y., Kresge, A. J., and Walsh, P. A., *Z. Naturforsch.*, **44A**, 406 (1989); (b) Keeffe, J. R. and Kresge, A. J., *Can. J. Chem.*, **74**, 2481 (1996).
[141] Pillay, M. K. and Banumathi, K., *J. Chem. Res. (S)*, **1997**, 225.
[142] (a) Iglesias, E., *J. Phys. Chem.*, **100**, 12592 (1996); (b) Iglesias, E., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 431.
[143] Díez-Barra, E., de la Hoz, A., Loupy, A., Martínez-González, A., Martínez-Merino, V., Merino, S., Paugam, R., Sánchez-Verdú, P., Sansoulet, J., and Torres, J., *Tetrahedron*, **53**, 3659 (1997).
[144] Díez-Barra, E., Merino, S., Sánchez-Verdú, P., and Torres, J., *Tetrahedron*, **53**, 11437 (1997).
[145] Whang, J. P., Yang, S. G., and Kim, Y. H., *J. Chem. Soc., Chem. Commun.*, **1997**, 1355.
[146] Morgan, J., Pinhey, J. T., and Rowe, B. A., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1005.
[147] Negrebetski, V. V., Safronov, A. I., and Kuroda, S., *Zh. Obshch. Khim.*, **66**, 1030 (1996); *Chem. Abs.*, **126**, 7541 (1997).
[148] Hinsen, K. and Roux, B., *J. Chem. Phys.*, **106**, 3567 (1997); *Chem. Abs.*, **126**, 224966 (1997).
[149] Zhang, S., Tang, M., and Xie, W., *Daxue Huaxue*, **11**, 31 (1996); *Chem. Abs.*, **126**, 238030 (1997).
[150] Fehr, C., *Angew. Chem., Int. Ed. Engl.*, **35**, 2566 (1996).
[151] Lee, J. K. and Grabowski, J. J., *J. Org. Chem.*, **61**, 9422 (1996).
[152] Peräkylä, M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2185.
[153] Xie, L., Isenberger, K. M., Held, G., and Dahl, L. M., *J. Org. Chem.*, **62**, 7516 (1997).
[154] Saito, S., Ito, M., and Yamamoto, H., *J. Am. Chem. Soc.*, **119**, 611 (1997).
[155] Moosavi, S. M., Beddoes, R. S., and Watt, C. I. F., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1585.
[156] Mohrig, J. R., Rosenberg, R. E., Apostol, J. W., Bastienaansen, M., Evans, J. W., Franklin, S. J., Frisbie, C. D., Fu, S. S., Hamm, M. L., Hirose, C. B., Hunstad, D. A., James, T. L., King, R. W., Larson, C. J., Latham, H. A., Owen, D. A., Stein, K. A., and Warnet, R., *J. Am. Chem. Soc.*, **119**, 479 (1997).
[157] Rosenberg, R. E. and Mohrig, J. R., *J. Am. Chem. Soc.*, **119**, 487 (1997).
[158] Yamada, S., Mori, Y., Morimatsu, K., Ishizu, Y., Osaki, Y., Yoshioka, R., Nakatani, T., and Seko, H., *J. Org. Chem.*, **61**, 8586 (1996).
[159] Liu, C. and Burnell, D. J., *Tetrahedron Lett.*, **38**, 6573 (1997).
[160] Nishide, K., Shigeta, Y., Obata, K., and Node, M., *J. Am. Chem. Soc.*, **118**, 13103 (1996).

[161] Meyer-Stork, M. A., Haag, D., and Scharf, H.-D., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 593.
[162] Fraser, R. R., Faibish, N. C., Kong, F., and Bednarski, K., *J. Org. Chem.*, **62**, 6164 (1997).
[163] McKinley, J., Aponick, A., Raber, J. C., Frintz, C., Montgomery, D., and Wigal, C. T., *J. Org. Chem.*, **62**, 4874 (1997).
[164] Couladouros, E. A., Plyta, Z. F., Haroutounian, S. A., and Papageorgiou, V. P., *J. Org. Chem.*, **62**, 6 (1997).
[165] Umekawa, Y., Sakaguchi, S., Nishiyama, Y., and Ishii, Y., *J. Org. Chem.*, **62**, 3409 (1997).
[166] Park, K. K., Sim, W.-J., and Park, J. W., *J. Inclus. Phenom. Mol. Recogn. Chem.*, **27**, 41 (1997); *Chem. Abs.*, **126**, 305434 (1997).
[167] Ley, S. V. and Meek, G., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1125.
[168] Gamble, M. P., Studley, J. R., and Wills, M., *Tetrahedron: Asymmetry*, **7**, 3071 (1996).
[169] Haddad, M., Dorbais, J., and Larchevêque, M., *Tetrahedron Lett.*, **38**, 5981 (1997).
[170] Collier, W. E., Fisher, T. H., and Schultz, T. P., *Holzforschung*, **51**, 169 (1997); *Chem. Abs.*, **127**, 220421(1997).
[171] Srivastava, N. and Kumar, A., *J. Indian Counc. Chem.*, **11**, 62 (1995); *Chem. Abs.*, **125**, 300629 (1996).
[172] King, A. O., Mathre, D. J., Tschaen, D. M., and Shinkai, I., *ACS Symp. Ser.*, **641**, 98 (1996); *Chem. Abs.*, **125**, 247640 (1996).
[173] Sheldon, J. C., Bowie, J. H., Dua, S., Smith, J. D., and O'Hair, R. A. J., *J. Org. Chem.*, **62**, 3931 (1997).
[174] (a) Wiberg, K. B. and Koch, W., *Tetrahedron Lett.*, **1966**, 1779; (b) McKillop, A., Hunt, J. D., and Taylor, E. C., *J. Org. Chem.*, **37**, 3381 (1972); (c) Ferraz, H. M. C. and Silva, L. F., *Tetrahedron Lett.*, **38**, 1899 (1997).
[175] Isak, V. G., Sychev, A. Y., and Anikina, Zh. O., *Zh. Fiz. Chim.*, **70**, 1534 (1996); *Chem. Abs.*, **125**, 327902 (1997).
[176] Borisov, I. M., Zimin, Y. S., and Sharafutdinova, Z. F., *Izv. Vyssh. Uchebn. Zaved., Khim. Khim. Technol.*, **39**, 65 (1996); *Chem. Abs.*, **126**, 211743 (1997).
[177] Gupta, K. K. S., Nandy, B. K., Bera, A. K., and Gupta, S. S., *Indian J. Chem.*, **36A**, 190 (1997); *Chem. Abs.*, **127**, 50200 (1997).
[178] Ahamed, K. A. B., *Indian J. Chem.*, **36A**, 222 (1997); *Chem. Abs.*, **127**, 50201 (1997).
[179] Basheer Ahamed, K. A. B., Sheik Dawood, S., Baskaran, P., and Nambi, K., *J. Indian Chem. Soc.*, **73**, 687 (1996); *Chem. Abs.*, **127**, 94949 (1997).
[180] Saito, T., Suda, H., Kawamura, M., Nishimura, J., and Yamaya, A., *Tetrahedron Lett.*, **38**, 6035 (1997).
[181] Le Bail, M., Aitken, D. J., Vergne, F., and Husson, H.-P., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1681.
[182] Glasius, M., Calogirou, A., Jensen, N. R., Hjorth, J., and Nielsen, C. J., *Int. J. Chem. Kinet.*, **29**, 527 (1997).
[183] Ranatunga, T. D., Kennady, J. M., and Kenttämaa, H. I., *J. Am. Chem. Soc.*, **119**, 5200 (1997).
[184] Talipov, R. F., Safarov., I. M., Talipova, G. R., and Safarova, M. G., *React. Kinet. Catal. Lett.*, **61**, 63 (1997); *Chem. Abs.*, **127**, 234000 (1997).
[185] Lee, O. and Wang, H., *Tetrahedron Lett.*, **38**, 6401 (1997).
[186] (a) Stadlbauer, J. M., Venkateswaran, K., and Walker, D. C., *Can. J. Chem.*, **75**, 74 (1997); (b) Percival, P. W., Roduner, E., Fischer, H., Camani, M., Gygax, F. N., and Schenck, A., *Chem. Phys. Lett.*, **47**, 11 (1977); (c) Mezyk, S. P. and Bartels, D. M., *Can. J. Chem.*, **72**, 2516 (1994).
[187] (a) Percival, P. W., Roduner, E., Fischer, H., Camani, M., Gygax, F. N., and Schenck, A., *Can. J. Chem.*, **47**, 11 (1977); (b) Mezyk, S. P. and Bartels, D. M., *Can. J. Chem.*, **72**, 2516 (1994); (c) Stadlbauer, J. M., Venkateswaran, K., Gillis, H. A., Porter, G. B., and Walker, D. C., *Can. J. Chem.*, **74**, 1945 (1996).
[188] Livant, P. Webb, T. R., and Xu, W., *J. Org. Chem.*, **62**, 737 (1997).
[189] Hirota, K., Kubo, K., Sajiki, H., Kitade, Y., Sako, M., and Maki, Y., *J. Org. Chem.*, **62**, 2999 (1997).
[190] Haque, A. and Ghosh, S., *J. Chem. Soc., Chem. Commun.*, **1997**, 2039.
[191] Kabyemela, B. M., Adschiri, T., Malaluan, R., and Arai, K., *Ind. Eng. Chem. Res.*, **36**, 2025 (1997); *Chem. Abs.*, **126**, 277105 (1997).
[192] Singh, V. and Prathap, S., *J. Chem. Res. (S)*, **1997**, 422.
[193] Feng, W. L., Wang, Y., Zhang, S. W., and Pang, X. Y., *Chem. Phys. Lett.*, **266**, 43 (1997); *Chem. Abs.*, **126**, 199145 (1997).

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CHAPTER 2

Reactions of Carboxylic, Phosphoric and Sulfonic Acids and their Derivatives

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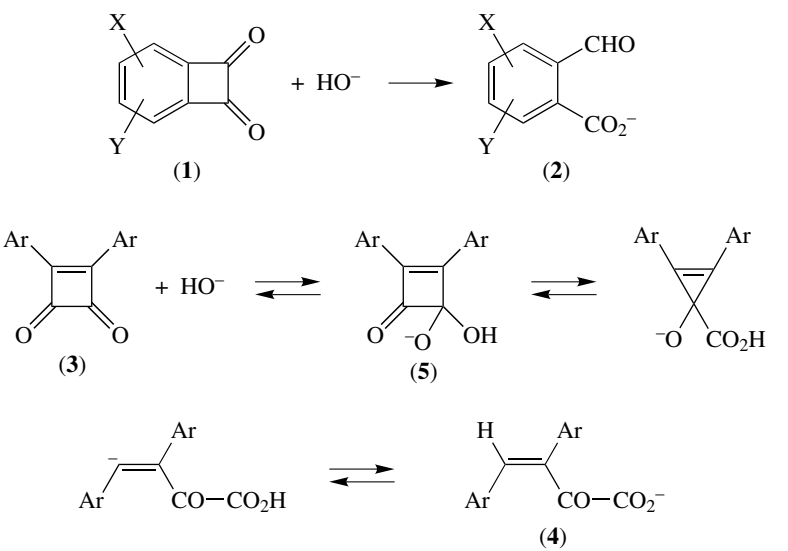
CARBOXYLIC ACIDS

Tetrahedral Intermediates

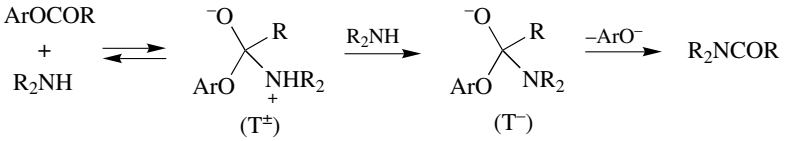
Base-catalysed ring fission of a series of substituted benzocyclobutenediones (**1**) to give the corresponding 2-formylbenzoic acids (**2**) proceeds via a rapid reversible addition of hydroxide ion to the dione giving an anionic tetrahedral adduct followed by intramolecular nucleophilic attack on the second carbonyl group. ^{18}O experiments support the formation of the tetrahedral intermediate.[1] These authors have also studied the base-catalysed ring fission of the related 3,4-diphenylcyclobut-3-ene-1,2-diones (**3**) to give the corresponding (*Z*)-2-oxo-3,4-diphenylbut-3-enoic acids (**4**) via the sequence shown in Scheme 1, which involves the tetrahedral intermediate (**5**).[2]

Measurement of Hammett ρ values for the hydroxide and phenoxide attack on 4-nitrophenyl esters of substituted benzoic acids shows that there is a large change in hybridization at the carbonyl carbon atom and the transition state for the concerted reaction which has a substantial tetrahedral geometry corresponding to a change from sp^2 to sp^3 at the carbon.[3]

A large body of work has indicated the involvement of zwitterionic tetrahedral intermediates in a number of systems. The *n*-butylaminolysis of substituted phenyl esters (Scheme 2) in acetonitrile has been studied by Williams' group.[4] A zwitterionic tetrahedral intermediate ($T^{\pm}$) is implicated in the mechanism and its formation may be



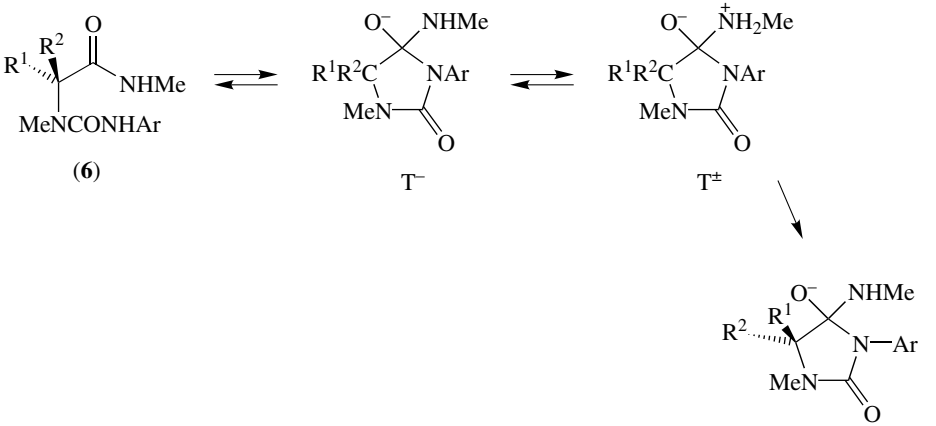
SCHEME 1



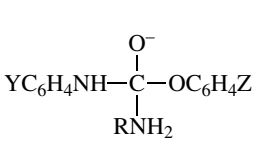
SCHEME 2

slow for one of the paths involved or C−OAr bond fission may be rate limiting in another path. The cyclization of the hydantoinamides (**6**) involves the mechanism shown in Scheme 3 with the participation of zwitterionic and first an anionic tetrahedral intermediate. At high pH, T^- is in equilibrium with the reactants and the rate is controlled by proton transfers producing $T^{\pm}$.[5] The aminolysis with benzylamines of *p*-nitrophenyl *N*-phenylcarbamates goes by a stepwise mechanism involving breakdown of intermediate (**7**) as the rate-limiting step by deprotonation at the amino group of the benzylamine. Hammett studies including the measurement of the cross-interaction constant and kinetic isotope effects with *N*-deuteriated benzylamine support this mechanism.[6] Rate-determining breakdown of the $T^{\pm}$ (**8**) is again the crucial step in the aminolysis with benzylamines of phenyl 2-furoates in acetonitrile.[7] The intermediate (**9**) is involved in the reactions of anilines, *N*,*N*-dimethylanilines, and benzylamines with phenyl dithioacetates in acetonitrile.[8] For the first two sets of bases the mechanism is rate-determining expulsion of the leaving group but, for the benzylamines, the slow step is attack by the base.

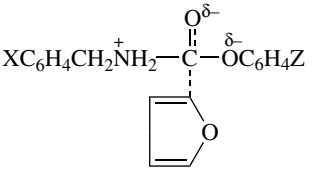
The pyridinolysis of 2,4-dinitro- and 2,4,6-trinitrophenyl *O*-ethyl dithiocarbonates (**10**) involves tetrahedral zwitterionic intermediates in stepwise reactions.[9] The reaction of pyrrolidine with (**10**; Ar = X-phenyl) in aqueous ethanol involves slow formation of a zwitterionic tetrahedral intermediate. There are major differences in this reaction compared to that involving piperidine as the base.[10] The $T^{\pm}$ (**11**) is involved in the reactions of phenyl and 4-nitrophenyl chlorothionoformates with secondary alicyclic amines.[11] The formation of the intermediate is the slow step. The reaction of the aryl



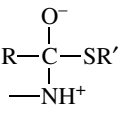
SCHEME 3



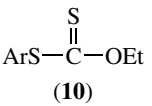
(**7**)



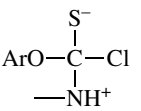
(**8**)



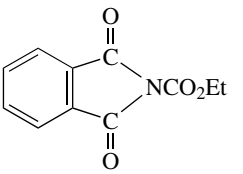
(**9**)



(**10**)

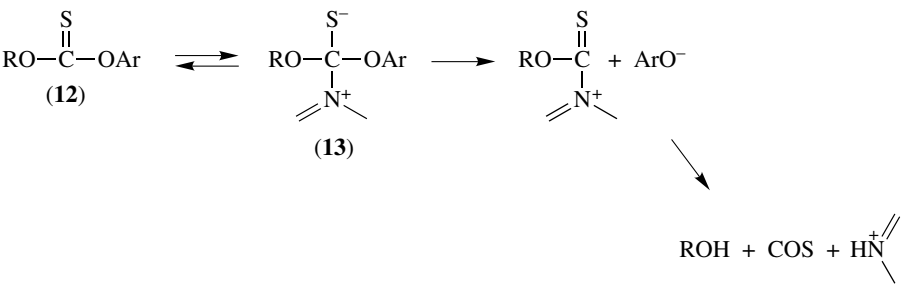


(**11**)



(**14**)

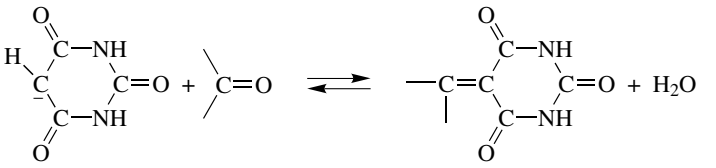
thionocarbonates (**12**) is shown in Scheme 4 and a tetrahedral zwitterionic intermediate (**13**) is seen to be involved.[12] The reaction of *N*-ethoxycarbonylphthalimide (**14**) with MeNHOH involves a zwitterionic tetrahedral intermediate formed by base attack at one of the carbonyl carbons of (**14**).[13]



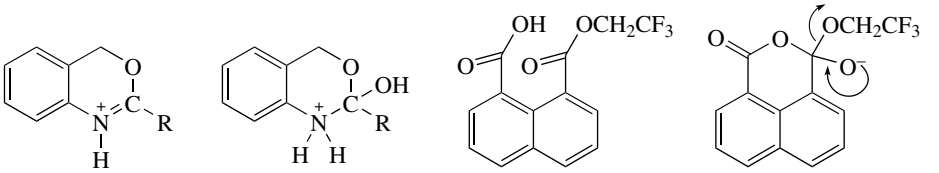
SCHEME 4

The reaction of barbiturate and 1,3-dimethylbarbiturate ions with 2- and 4-nitrobenzaldehyde and 2,4-dinitrobenzaldehyde represented generally in Scheme 5 involves a diffusion-controlled (viscosity effects on rates) proton transfer from hydronium ion to an addition intermediate T^- in the slow step.[14] The addition of water and ring-opening reactions of the protonated benzoxazines (**14**) involves the cyclic intermediate (**15**). At low buffer concentrations buffer-catalysed collapse of the intermediate is rate limiting but, at high buffer concentrations, the addition of water is the rate-limiting step.[15] The anionic tetrahedral intermediate (**16**) is involved in the hydrolysis of the 2′, 2′, 2′-trifluoroethyl monoester of 1,8-naphthalic acid (**17**).[16]

A series of molecules potentially capable of forming anionic tetrahedral adducts at the active site (**18**) have been assessed as sources of transition state analogues and as inhibitors of the class C β-lactamase of *Enterobacter cloacae* P99.[17]

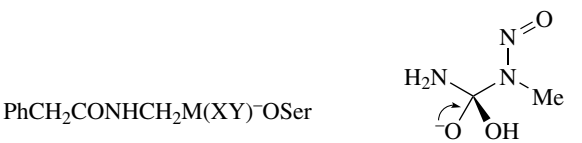


SCHEME 5



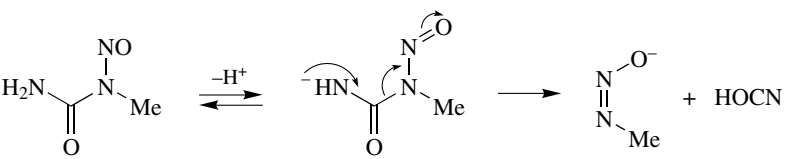
(**14**) (**15**) (**17**) (**16**)

The different behaviour of sulfhydryl (HS^-) and hydroxyl (HO^-) anions in their nucleophilic addition reactions to carbonyl groups has been examined using *ab initio* calculations.[18] All the anionic tetrahedral adducts formed by the sulfhydryl ion are characterized by higher charge transfer but are significantly less stable than the analogous tetrahedral adducts formed by hydroxyl ion. This phenomenon can be explained using density functional theory (DFT). The mechanism of decomposition of the carcinogen *N*-methyl-*N*-nitrosourea (MNU) (**19**) in water involves the tetrahedral intermediate (**20**) resulting from attack of hydroxide ion at the carbamoyl carbon atom. The overall reaction sequence is shown in Scheme 6.[19] The carcinogenicity of (**19**) arises from its ability to methylate DNA and this work has implications for the understanding of this action.



(**18**) (**20**)

Other references involving tetrahedral intermediates are 21, 38, 49, 54, 55, 96, 103, 105, 128, 211, 212 and 216.



(**19**)

SCHEME 6

Intermolecular Catalysis and Reactions

Reactions in Hydroxylic Solvents

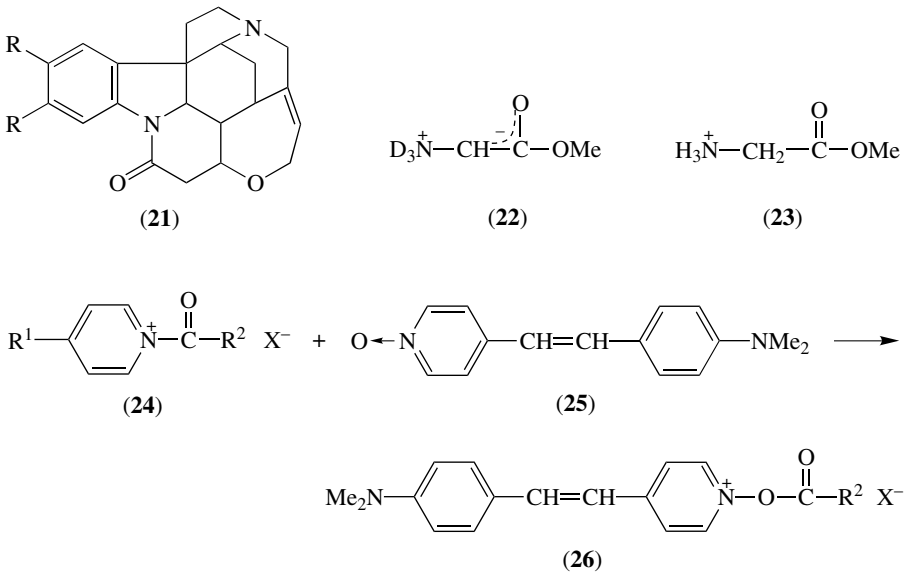
(a) *General*

MO calculations have shown that the acylation rate of amines is mainly influenced by the donor activity of the unshared electron pair on the N atom of the amine.[20] The rates of hydrolysis in aqueous NaOH of the alkaloid strychnine (**21**; R = H) and seven of its derivatives (**21**) have been determined and it has been found that the quantitative effect of positively and negatively charged groups are in approximate agreement with calculations using the Kirkwood–Westheimer theory.[21] The point is also made that strychnine is a good subject for physical organic studies, being cheap and undergoing a diversity of reactions. Hammett σ_m and σ_p values have been found to correlate very well with critical points (CPs) determined from a molecular electrostatic potential (MESP) topography study of monosubstituted benzenes.[22] The range of σ values correlated runs from ca 0.7 to ca -0.7.

(b) *Esters*

(i) *Formation* The effect of dielectric properties in a continuous flow system under microwave irradiation of esterification has been studied.[23] Base-catalysed deprotonation of *N*-protonated glycine methyl ester (**23**) at neutral pD gives the amino acid ester enolate (**22**).[24] Iodine catalyses the acetylation of amines, phenols, and alcohols with acetic anhydride in excellent yields. The mechanism may involve complexation of the iodine with the acetic anhydride followed by nucleophilic attack to give acetate and an unstable acylhypohalite MeCOOI which eliminates iodine to continue the reaction.[25] The main variables controlling the lipase-catalysed enantioselective esterification of 2-arylpropionic acids are enzyme content, amount of water, temperature, stirring speed, and solvent. Immobilized lipase from *Rhizomucor miehei* (lipozyme IM) was used in this study. A new and convenient parameter (enantiomeric factor, EF) is defined for assessing the enantioselectivity of the reaction.[26]

(ii) *Transesterification* The kinetics in acetonitrile of the acyl group transfer from the pyridinium salts (**24**) to 4-(*p*-dimethylaminostyryl)pyridine *N*-oxide (**25**) to give (**26**) have been determined and activation parameters also calculated (Scheme 7).[27] The acyloin (**27**) can be resolved using lipase–triethylamine-mediated dynamic transesterification to give optically pure (**28**). The method is a new route to optically pure oxodicyclopentadiene.[28] Direct elimination, as shown in (**29**), rather than an ene mechanism is favoured for the transfer of succinyl from aryl enolsuccinates to the enolates of aryl ketones (**30**). Semiempirical calculations and the results of a deuterium-labelling experiment support this view.[29] The rates of exchange of the 2,4,6-trimethylphenolate ion between dimeric lithium 2,4,6-trimethylphenolate-d_9, represented as (**31**), and a series of esters (**32**) have been determined in various organic solvents. The dimer does not dissociate and the rates of transesterification increase with increasing solvent donicity.[30]



(**21**) (**22**) (**23**)

(**24**) (**25**)

(**26**)

SCHEME 7

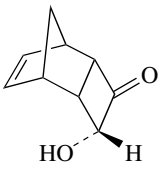
(iii) *Other reactions* Disolvated lithium diisopropylamide (LDA) deprotonates (**33**) to give the enol (**34**) in THF–toluene via a cyclic transition state. The mechanism involves complexation of (**33**) and LDA.THF monomer to give LDA. $(THF)_2$ (**33**), which decomposes to give (**34**).[31] The kinetics of pyrolysis of methyl ricinoleate to give methyl undecylenate (**35**) and heptanol (**36**) have been reported on.[32] The effect of boric acid on the kinetics of hydrolysis of *p*-nitrophenyl esters of dihydroxybenzoic acids has been studied.[33] Boric acid inhibits the hydrolysis of 2,3-dihydroxybenzoic acid *p*-nitrophenyl ester but it does not affect the hydrolysis of the 3,4-dihydroxy ester. This contrasts with the effect of boric acid on the hydrolysis of the salicylate ester and simulates borate inhibition of serine proteases.

The rates of acid-catalysed methoxy exchange between methanol and the three diastereomers of 2-methoxy-4,6-dimethyl-1,3-dioxalane (**37a**–**c**) were measured in benzene and methanol–chloroform. Rate constants were evaluated in a novel way using 1D-EXSY NMR pulse sequence and a weighted least-squares analysis. The critical intermediate is (**38**) and rates of methanol attack on it in benzene show a 24-fold axial selectivity whereas in methanol–chloroform the selectivity difference is ninefold.[34]

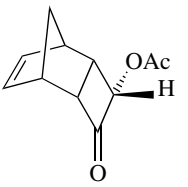
Potential energy profiles have been determined for two series of reactions:

(i) $X^- + HCOY$ where $X = Y =$ H, F, or Cl and
(ii) $X^- + RCOX$ where X = F or Cl and R = SiH_3, Me, CN, or NO_2

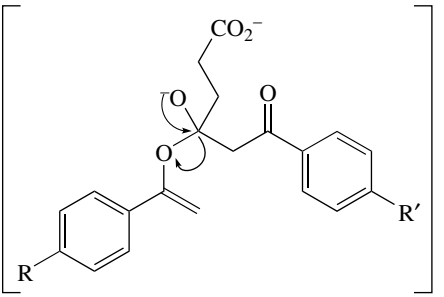
Energies of all stationary points were evaluated at the Hartree–Fock and the second-order Möller–Plesset (MP2) correlation levels with 6–3111++G** for (i) and 6–31+G* for (ii). Acyl transfers can proceed through single-, double-, or triple-well energy profiles in the gas phase depending on X^-, the nucleofuge Y^-, and the R group.[35] Comparative molecular field analysis (CoMFA) has been used in an unusual



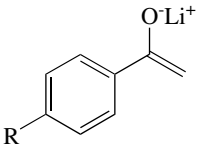
(**27**)



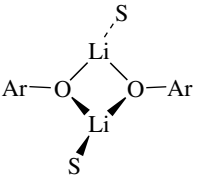
(–)-(**28**)



(**29**)



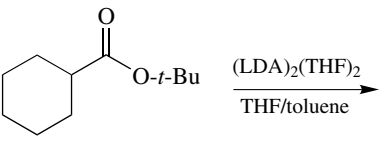
(**30**)



(**31**)

2,4,6-$Me_3C_6H_2CO_2CH_2R$

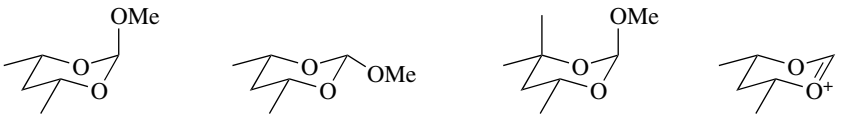
(**32**)



(**33**) (**34**)

$CH_2{=}CH(CH_2)_8CO_2Me$ $Me(CH_2)_5CHO$

(**35**) (**36**)

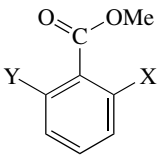


(**37a**) (**37b**) (**37c**) (**38**)

way to examine transition state conformations and the reactivity of 4-nitrophenyl benzoate and its sulfur analogues with anionic nucleophiles.[36] The analysis showed that both steric and electrostatic effects are important.

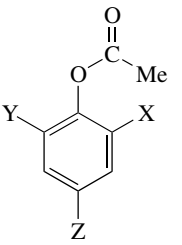
A $B_{AC}2$ mechanism is proposed for the saponification of ethyl benzoate in ethanol–water.[37] The reactions of aryl benzoates in absolute ethanol with ethoxide, aryloxides and acetophenone oximates occur via a stepwise mechanism in which the formation of the tetrahedral intermediate is rate determining.[38] A stepwise mechanism is also supported for the reactions of *p*-nitrophenyl-substituted benzoates with hydroxide and *p*-chlorophenoxide. The evidence comes from breaks in Hammett plots as the acyl

substituent becomes a strong electron withdrawer.[39] In related work on the reactions of phenoxide ions with substituted phenyl benzoates in absolute ethanol, the same group also support a stepwise mechanism.[40] They also determined by a kinetic method the pK_a values for 10 substituted phenols in ethanol. Neighbouring-group participation by acyl carbonyl groups has been demonstrated in the hydrolysis of the benzoates (**39**) and the phenyl acetates (**40**) by studying the alkaline hydrolysis of (**39**) and the neutral and alkaline hydrolysis of (**40**) and comparing the relative rates and activation parameters.[41] The same group has examined the sulfur analogous of (**39**) and (**40**). Thus, the alkaline hydrolysis of (**39**; Y = H, X = SMe, SOMe, SO_2Me) and [**40**; Y = H, X same as in (**39**)] have been studied and the relative rates and activation parameters indicate the importance of polar and steric effects in the hydrolysis.[42] The effect of solvent on the α-effect has been probed in the reaction of *p*-nitrophenyl acetate with *m*-chlorophenoxide and benzohydroxamates in MeCN–water.[43] The hydroxamates exert a large α-effect in water. Thermodynamic functions of activation of the alkaline hydrolysis of ethyl benzoate and of ethyl *p*-nitrobenzoate (**41**) in ethanol–water mixtures have been studied.[44] The hydrolysis of a series of *N*-methylpiperidinyl and tropinyl (**42**) esters in 70% DMSO has been investigated and correlated fairly well in regression equations with terms for electronic (Taft σ^*), hydrophobic (log k_w), and steric (molecular volume) effects. A correlation coefficient of 0.94 was obtained.[45]



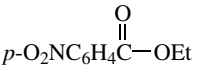
(**39**)

X = CHO, Y = H
X,Y = CHO
X = C(CF$_3$)O, Y = H



(**40**)

X = CHO, Y = Z = H
X,Y = CHO, Z = Me
X = C(CF$_3$)O, Y = Z = H



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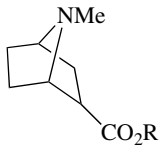

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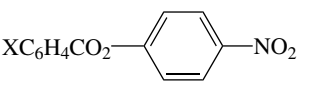

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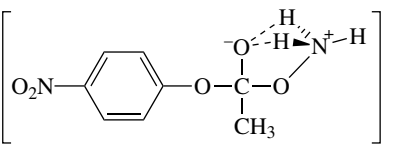


(**44**)

The reaction of 2,4-dinitrophenyl benzoate with secondary cyclic amines in DMSO–water shows a break in a Brønsted plot near pK_a 9.1 and the microconstants for the various stages in the reaction have been obtained and these gave good straight line Brønsted plots.[46] The α-effect was observed as a positive deviation in the linear log *k* vs pK_a plot for the reaction of *p*-nitrophenyl X-substituted benzoates (**43**) with primary

amines, the two amines that deviated being hydrazine and hydroxylamine.[47] The acyl transfer reaction from *p*-nitrophenyl acetate to hydroxylamine at pH 6 and 12 has been examined for kinetic isotope (leaving group ^{18}O, carbonyl oxygen ^{18}O, β-deuterium, carbonyl carbon ^{13}C and nitro group ^{15}N) effects. The results obtained have been interpreted in terms of slow breakdown of the intermediate (**44**) at low pH and attack of hydroxylamine with concerted expulsion of nitrophenolate at high pH.[48] Heavy atom isotope effects have also been looked at in the hydrazinolysis of methyl formate. At pH 8 the slow step is the breakdown of a tetrahedral intermediate to products but at pH 10 the formation of the intermediate is the slow step.[49]

(c) *Lactones and derivatives*

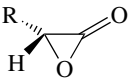
The enthalpy of formation of the oxiranone (**45**) has been estimated as -190 ± 10 kJ mol^{-1} by means of *ab initio* MO calculations at the QCISD(T) = full/6–3111G(2df,p)//MP2 = full/6–311G(d,p) level of theory and this corresponds to a ring strain energy of 169 kJ mol^{-1}. The calculated enthalpy of formation of cyclopropanone is 6.3 kJ mol^{-1}. The oxiranone ring is believed to be slightly less strained than the cyclopropanone ring.[50] The same workers have carried out theoretical calculations on the reaction pathway for the elimination of halide from the α-halocarboxylates (**46**) giving (**47**).[51] The α-chloroacetate has an S_N2 type transition state but the chloropropionate is more S_N1-like. Finally they have looked at the structure and stability of the hydroxyoxiranone (**48**) using MO methods.[52] The standard enthalpy of formation is -377 ± 10 kJ mol^{-1} and this corresponds to a ring strain of 104 kJ mol^{-1}. The hydroxy substituent on (**48**) stabilizes the α-lactone by 65 kJ mol^{-1}. Semiempirical MO calculations (AM1 and PM3) on the addition of nucleophiles to unsaturated five- (**49**) and six-membered (**50**) bislactones of the Pechmann dye type indicate that a similar mechanism operates for the two reactions.[53] The slow step is the addition of a second nucleophile to the enol of the ring-opened monolactone. The compounds (**49**) are found to be more reactive than (**50**). The rate-determining step is considered to be the formation of a tetrahedral intermediate in the alkaline hydrolysis of the unsaturated lactones and esters (**51**)–(**56**).[54] The base-catalysed hydrolysis of a series of γ-lactones (**57**) in 70% aqueous dioxane to give the 2-acetylbenzoates (**58**) has been examined for a very wide range of compounds (**57**) and the results can be related to an electrostatic field model.[55]

Cyclization to a morpholinolactone (**59**) occurs in the hydrolysis reaction of the di-*N*-hydroxylethylated compound (**60**). Compound (**59**) is rapidly hydrolysed by water to (**61**) but in the presence of equimolar amounts of amines (RNH_2) or amino acid derivatives (**62**) forms.[56] A novel reaction of cyclic 2-diazo-1,3-dicarbonyl compounds (**63**) with lactones (**64**) affords the products (**65**) in the presence of rhodium acetate, $Rh_2(OAc)_4$.[57] Lewis acid-promoted intramolecular additions of allylsilanes to β-lactones gave substituted cyclopentanes.[58] A proposed transition state guided efforts to improve the stereoselectivity of the reaction. The reaction of a series of β-lactone derivatives, such as (**66**)–(**68**), has been studied and they have been ring cleaved; the reaction outcome is both Lewis acid and structure dependent.[59]

(**45**)

$XCHRCO_2^-$

(**46**)



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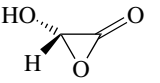
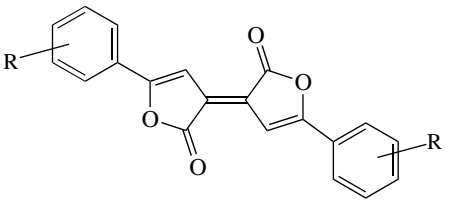
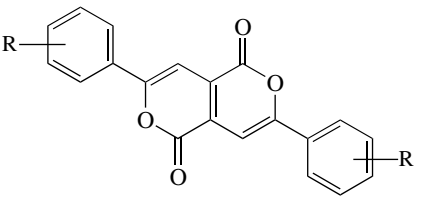


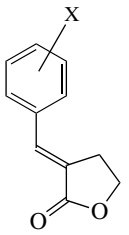
(**48**)



(**49**)



(**50**)



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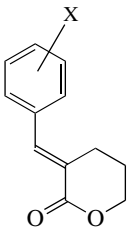

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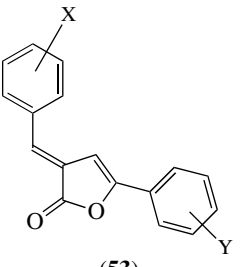

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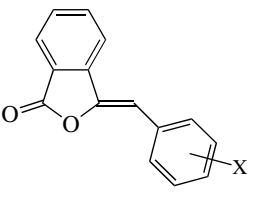

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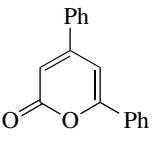

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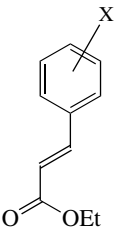
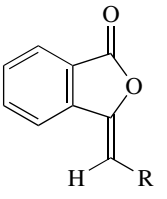


(**56**)

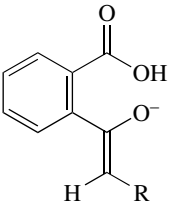
The reaction of α-peroxylactones (**69**) with C, N, P, and S nucleophiles via S_N2 attack at the more electrophilic alkoxy oxygen of the peroxide bond leads to a variety of products including oxygen transfer and addition products and catalytic Grob-type fragmentation.[60] Dyotropic ring enlargements of *β*-lactones to *γ*-lactones follow a concerted mechanism involving inversion at the C(4) atom.[61]

(d) *Acids and anhydrides*

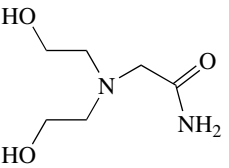
Ab initio calculations have been carried out on the decomposition of mandelic acid (**70**) at the MP2/6–31G** level.[62] Three competitive pathways have been characterized. Two are stepwise processes with the formation of an α-lactone intermediate and ring



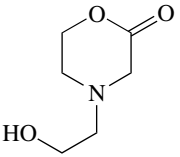
(**57**)



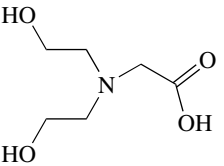
(**58**)



(**59**)



(**60**)



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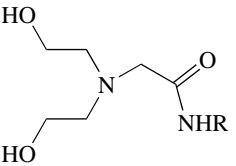

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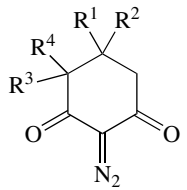

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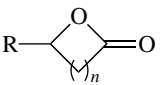

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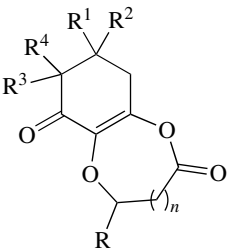

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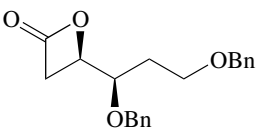

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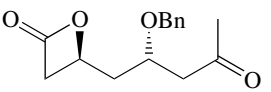

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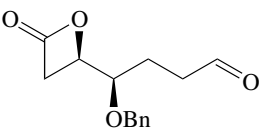

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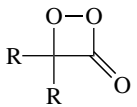

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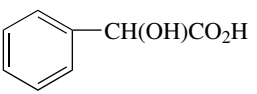
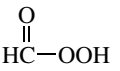


(**70**)



(**71**)

opening and the third mechanism is a one-step process. The peroxyformic acid (**71**) decomposition in the hydrogen peroxide–formic acid system has been mathematically analysed.[63]

The kinetics and mechanism of the reaction of carboxylic acids with phosgene $COCl_2$ in DMF in benzene were zero-order in substrate and proceeded via rapid formation of

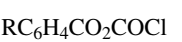
(**72**) and the rate-limiting step was the reaction of (**72**) with phosgene to give the intermediate (**73**), which rapidly decarboxylated to give RC_6H_4COCl.[64] Decarboxylation also occurred in the thermal decomposition of various haloacetic acids (**74**; X = Y = Z = F; X = Y = H, Z = Cl; X = H, Y = Z = Cl; X = Y = Z = Cl; X = Y = H, Z = Br; X = Y = H, Z = I). Semiempirical calculations gave activation energies for the various processes.[65]

Solvent effects on the dissociation of 11 2,6-disubstituted benzoic acids have been analysed by chemometric analysis.[66] The acid–base behaviour of the three zwitterionic pyridinecarboxylic acids (picolinic, nicotinic, and isonicotinic acid) has been studied. The cationic form of picolinic acid converts partially into the corresponding zwitterion within a borderline acidity range (pH/acidity function). The various pK_a values were determined for the three isomers by spectrophotometric and potentiometric methods and reasonable agreement was found.[67]

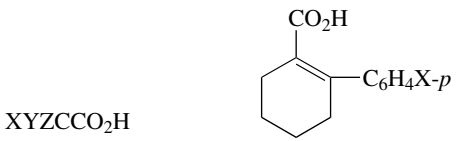
Kinetic data for the reactions of diazodiphenylmethane in 10 different alcohols with 2-(4-phenyl substituted)cyclohex-1-enylcarboxylic acids (**75**) were correlated using the extended Hammett equation.[68] Reaction of the species (**76**)–(**78**) with the light radioactive H isotope, the muonium atom, has been studied.[69] The largest primary kinetic isotope effects ever reported (ca 850) are seen in this work for the addition of muonium to one of the C=O groups.

The reaction of benzoic acid with *n*-butyllithium goes by nucleophilic addition of *n*-butyllithium to benzoic acid giving (**79**) and then the ketone (**80**), which reacts with another molecule of *n*-butyllithium to give (**81**), which can hydrolyse to the final alcohol.[70] Reaction of a set of substituted benzoic acids in toluene with the carbinol base of Crystal Violet have been investigated spectrophotometrically.[71] The rate constant for the forward step of the acid-carbinol reaction was found to be an appropriate criterion for assessing acidities in toluene and these acidities were found to be much more dependent on the substituents in the benzoic acids than aqueous phase acidities are. The acid-catalysed breakdown of *N*-(2-aminophenyl)phthalamic acid (**82**) has been studied in dilute aqueous acids in the pH range 0–6.[72] The main reaction gives *N*-(2-aminophenyl)phthalimide (**83**) which rearranges to 2-(2-carboxyphenyl)benzimidazole (**84**).

(**72**)



(**73**)

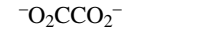


(**74**)

(**75**)

(**76**)

(**77**)



(**78**)

(**79**)

The kinetics of the reaction of acrylic acid with aqueous ammonia giving β-alanine have been investigated.[73]

The kinetics of the nucleophilic substitution reactions of benzoic anhydrides with anilines in acetonitrile–water have been studied.[74] A frontside S_N2 mechanism with a four-membered ring transition state has been proposed.

(e) *Acid halides*

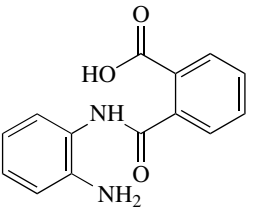
The reactions of ketene and dimethylketene with hydrogen halides giving the acylium (**85**) and vinylium (**86**) halides have been examined theoretically.[75] The formation of (**85**; R = H, X = Cl) was more favourable than that of (**86**; R, X same) by 112 kJ mol^{-1}. An S_N2 mechanism was operative in the nucleophilic substitution reactions of phenacyl halides, ArCOX, with pyridines in MeOH–MeCN mixtures. A product-like TS was predicted from a quantum mechanical model.[76] A Costa Rican group has assessed the relative reactivity for 2-propanolysis of a series of chlorides and found that the following was the order of reaction: PhSCl>PhCOCl>$PhSO_2Cl$> $PhCH_2Cl$>PhCl. The rate coefficient ratios were in the same order.[77] Two papers by Kevill's group deal with the solvolysis of phenyl chloroformate (**87**)[78] and phenyl chlorothioformate (**88**).[79] The specific rates of solvolysis of (**87**) have been measured in 21 solvents and can be easily correlated using the Grunwald–Winstein (G–W) equation including the N_T parameter for solvent nucleophilicity and the Y_{Cl} solvent ionizing parameter. The coefficients of these are 1.68 and 0.57, respectively. An addition–elimination pathway with addition being slow is proposed. A similar type of study has been undertaken with (**88**) and again using the G–W extended equation dual reaction pathways are proposed for the solvolysis of (**88**).[79] They involve again an addition–elimination mechanism in solvents of low ionizing power and/or high nucleophilicity but, in solvents 'rich' in fluoro-alcohol and in water, a mechanism involving ionization with a high degree of stabilization of the TS by solvation of the developing acylium ion is operative.

$Ph(Bu^n)CO$

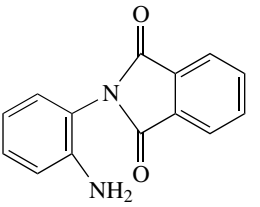
(**80**)

$Ph(Bu^n)COLi$

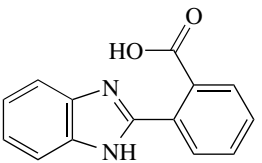
(**81**)



(**82**)



(**83**)



(**84**)

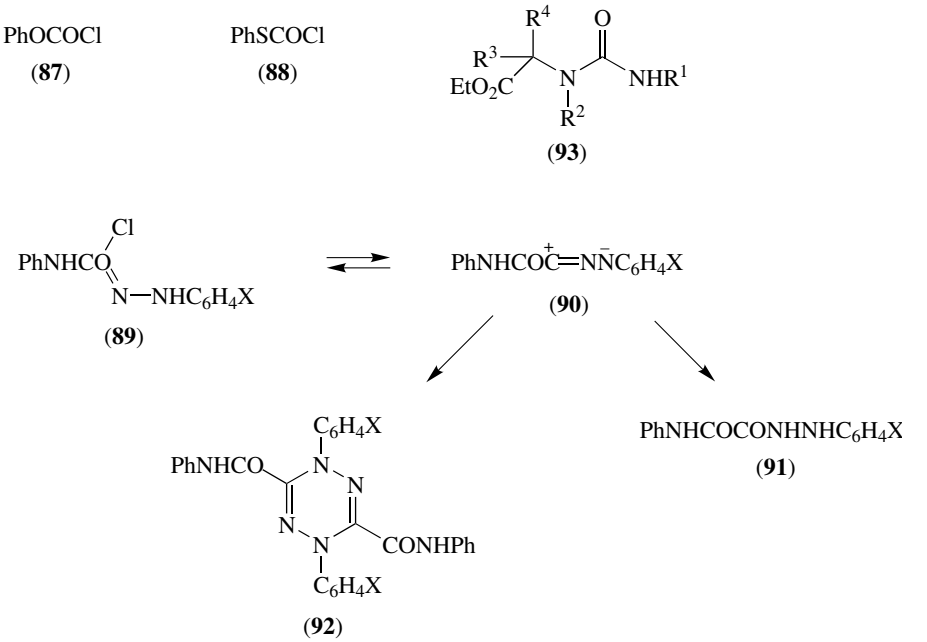
$R_2CH\overset{+}{C}{=}O\ X^-$

(**85**)

$R_2C{=}\overset{+}{C}OH\ X^-$

(**86**)

The kinetics and mechanism of the dechlorination of *N*-aryl 2-oxo-2-phenylamino-ethanehydrazonyl chlorides (**89**) in triethylamine in aqueous dioxane at 25 °C giving the oxanilic hydrazide (**91**) and 1,4-diaryl-1,2,4,5-tetrazine (**92**) have been examined.[80] The slow step of this interesting reaction is considered to be the breakup of the nitrilium imide (**90**).

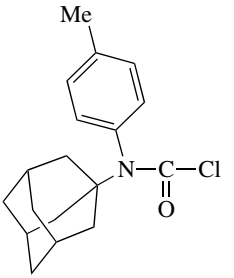


(f) *Ureas, carbamates, hydroxylamine, and derivatives*

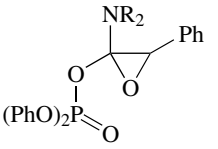
The NH acidities of some sterically hindered ureas, namely the ureido esters (**93**), have been reported.[81] The kinetics and mechanism of the alkaline hydrolysis of urea and sodium cyanate, NaCNO, have been studied at a number of temperatures.[82] Urea hydrolysis follows an irreversible first-order consecutive reaction path. Tetrahedral intermediates are not involved and an elimination–addition mechanism operates. Sodium cyanate follows irreversible pseudo-first-order kinetics. The decomposition of the carcinogen *N*-methyl-*N*-nitrosourea (**19**) was dealt with earlier.[19] The pyrolysis of *N*-acetylurea goes by a unimolecular first-order elimination reaction.[83]

There are five papers on carbamate chemistry of interest.[6,84–87] The mechanism of the reaction in MeCN of *N*-methyl-*N*-phenylcarbamoyl chlorides (**94**) with benzylamines is believed to be S_N2 based on Hammett ρ values, a cross-interaction constant ρ_{xy} of -0.14, k_H/k_D values for the *N*-deuteriated benzylamines all <1, and low activation enthalpies.[84] The aminolysis of *p*-nitrophenyl *N*-phenylcarbamates in acetonitrile involving the $T^{\pm}$ (**7**) was discussed earlier.[6] Solvolysis–decomposition of *N*-1-adamantyl-*N*-*p*-tolylcarbamoyl chloride (**95**) in hydroxylic solvents involves a facile slow ionization (S_N1 mechanism) giving a cation which eliminates ArNCO to

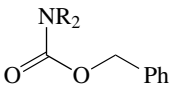
(**94**)



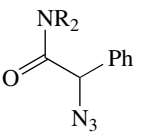
(**95**)



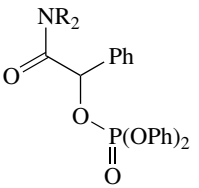
(**96**)



(**97**)

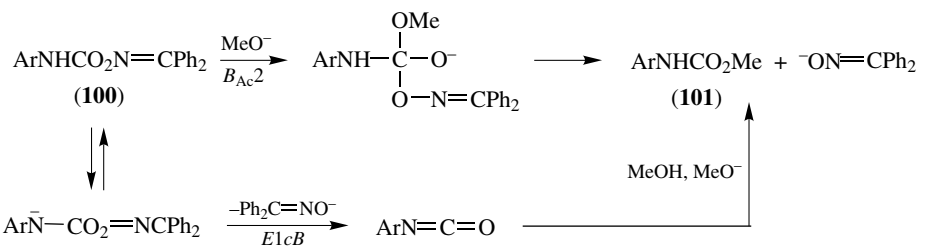


(**98**)

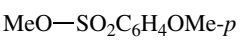


(**99**)

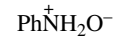
give adamantyl chloride or is attacked by solvent to give ether.[85] The oxirane intermediate (**96**) is crucial in the reactions of benzyl carbamates (**97**) with LDA, diphenyl phosphorochloridate, and sodium azide yielding α-azidobenzeneacetamides (**98**) and the phosphate (**99**).[86] The kinetics and mechanism of reaction of methoxide ion with nine different *O*-(*N*-arylcarbamoyl)benzophenone oximes (**100**) has been examined (Scheme 8).[87] The experimental results can be equally well interpreted in favour of the two mechanisms shown in the scheme. However, the authors have devised a test to support the *E*1*cB* path. Using *n*-butylamine in the reaction they diverted part of the reaction path and *N*-butyl-*N*′-(3-nitrophenyl)urea product also forms together with the usual carbamate product (**101**). In experiments involving equimolar methoxide ion and *n*-butylamine in MeOH and the same amount of *n*-butylamine in MeOH the ratio of urea to (**101**) products remains the same. Had a $B_{AC}2$ mechanism operated, the authors argue that the amount of (**101**) formed should be two orders of magnitude smaller in the second experiment.



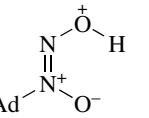
SCHEME 8



(**102**)

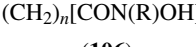


(**103**)

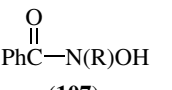


(**104**)

(**105**)



(**106**)



(**107**)

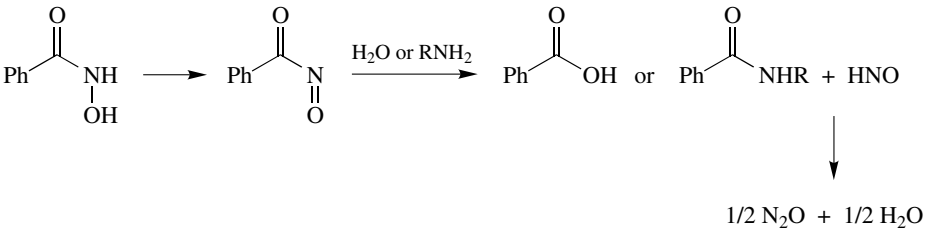
Two papers have appeared on hydroxylamines.[88,89] Methylation of *N*-phenylhydroxylamine PhNHOH with methyl 4-methoxyphenylsulfonate (**102**) and related sulfonates in DMSO gave alkylation of the O atom rather than the N atom. The crucial role of the zwitterion (**103**) is examined.[88] The fragmentation of the *N*-nitrosohydroxylamines (**104**) is stepwise and not concerted and NO is liberated in the reactions.[89] These conclusions were reached from kinetic, millimetre-wave spectroscopy and ^{17}O NMR studies.

Hydroxamic acids have been the subject of six papers.[43,90–94] Earlier the operation of the α-effect in the reaction of *p*-nitrophenyl acetate with benzohydroxamates in aqueous MeCN was discussed.[43] The conformational behaviour of series of mono- (**105**) and dihydroxamic acids (**106**) in MeOH, DMSO, and chloroform and in the solid state has been examined with IR and NMR spectroscopy.[90] X-ray crystal structure determinations of (**105**; X = Me, R = Me) and the monohydrate of glutarodihydroxamic acid (**106**; n = 3, R = H) together with *ab initio* MO calculations for several hydrated and non-hydrated acids have been performed. The *cis-Z* conformation of the hydroxamate groups is preferentially stabilized by H-bonding with water.

Three papers from Ghosh's group deal with the hydrolysis of benzohydroxamic acids in acidic[91,92] and alkaline[93] conditions. A pre-equilibrium protonation followed by a slow *A*-2 type nucleophilic attack by water is seen as the mechanism of the acid-catalysed hydrolysis of *p*-chlorophenylbenzohydroxamic acid (**107**; R = *p*-ClC_6H_4) by mineral acids (HCl, $HClO_4$) in 20% aqueous dioxane.[91] An *A*-2 mechanism was also supported for the reaction of (**107**; R = Me) under comparable conditions.[92] The alkaline hydrolysis under micellar conditions of (**107**; R = Ph) and a series of *para*-substituted derivatives has been investigated in the presence of cationic and anionic micelles in 5% dioxane–water medium at 55 °C.[93] Cationic surfactants exerted a catalytic effect and anionic surfactants were inhibitory. The rate–surfactant profiles were analysed in terms of the pseudophase and Piszkiewicz models. The detection of N_2O in the products of the oxidation of hydroxamic acids suggests the intermediacy of nitroxyl, HNO, in the process.[94] Scheme 9 may represent the pathway followed.

(g) *Amides and anilides*

An *ab initio* study of *N*- vs *O*-protonation using formamide (**108**), the somewhat strained *N*-formylazetidine (**109**), highly strained *N*-formylaziridine (**110**), and various



SCHEME 9

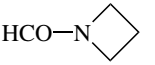
protonated tautomers has been made. The electron correlation effect was found to be important in determining the protonation sites since it helps to stabilize *N*-protonation somewhat more than *O*-protonation. *O*-Protonation is highly favoured in (**109**) and in (**108**), but *N*-protonation is favoured in (**110**).[95] Another *ab initio* study, this time on the alkaline hydrolysis of amides, has been reported.[96] The three amides, *N*-methylacetamide (**111**), acetanilide (**112**), and *N*-acetylimidazole (**113**) have been investigated. For (**111**) and (**112**) in the gas phase a route involving a tetrahedral intermediate and a cyclic transition state is supported. The thermal decomposition of some *N*,*N*-dialkylamides giving rise to acids, ketones, amides, and imides has been investigated at 215 °C.[97]

An H_- acidity function scale has been constructed for methoxide ion in methanol and its mixtures with DMSO (10–80%, v/v) using the dissociation of 11 amides (**114**) as the anchors for the scale.[98] The degradation pathways of the anti-flammatory and analgesic lornoxicam (**115**), which contains an amide bond, have been examined[99] recently. In acid, cleavage of the amide bond was the main reaction path and in alkaline and neutral solution the proton shift of the enolic hydroxyl initiated the major degradation pathway. The mechanism of hydrolysis of some *N*-nitrobenzamides (**116**) in strong acid follow an *A*-1 mechanism with *O*-protonation but, in more moderate acid, they exhibit a neutral water-catalysed mechanism. *N*-Methyl-*N*-nitroacetamide (**117**) shows only the neutral water-catalysed process. Nitrourea follows an *A*-1 acid-catalysed mechanism.[100]

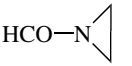
The alkaline hydrolysis of the compounds (**118**)–(**123**) in 70% (v/v) dioxane–water at various temperatures has been investigated.[101] Intramolecular catalysis by the neighbouring carbonyl group occurs in the alkaline hydrolysis of (**118**)–(**121**) and the alkaline hydrolysis of (**122**) and (**123**) is rapid owing to their lactone structures. The hydrolyses of *C*-terminal amides of α-amino acids was dealt with earlier.[56] Also, the acid-catalysed cleavage of *N*-(2-aminophenyl)phthalamic acid (**82**) was discussed earlier.[72]

An interesting triethylamine-catalysed acyl exchange has been reported by a Japanese group;[102] (**124**) with 1-naphthoyl chloride (**125**) gives (**126**) which has undergone both intramolecular acyl exchange and attack by the chloride at the N. The water-catalysed hydrolysis of *p*-nitrotrifluoroacetanilide (**127**) and trifluoracetanilide (**128**) involve rate-limiting concerted or nearly concerted formation of a diol, possibly of type (**129**), which is a tetrahedral intermediate, and this or a related species then undergoes C−N cleavage in preference to OH expulsion.[103]

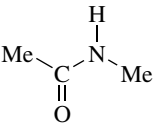
(**108**)



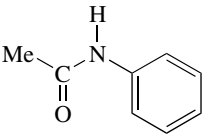
(**109**)



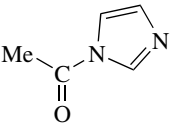
(**110**)



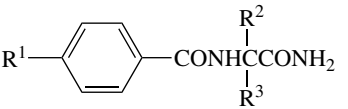
(**111**)



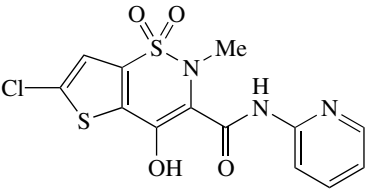
(**112**)



(**113**)



(**114**)



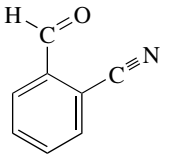
(**115**)

$XC_6H_4CONHNO_2$

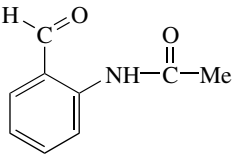
(**116**)

$MeCON(Me)NO_2$

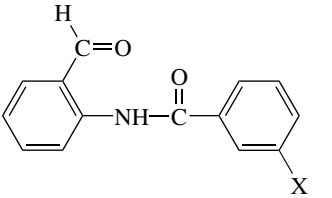
(**117**)



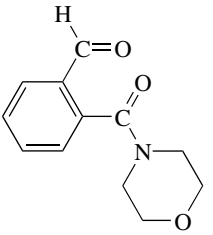
(**118**)



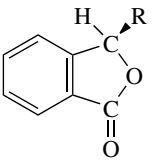
(**119**)



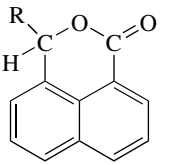
(**120**)



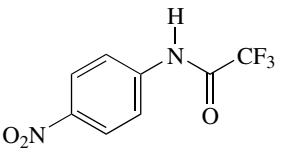
(**121**)



(**122**)



(**123**)



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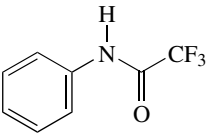

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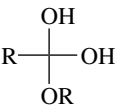
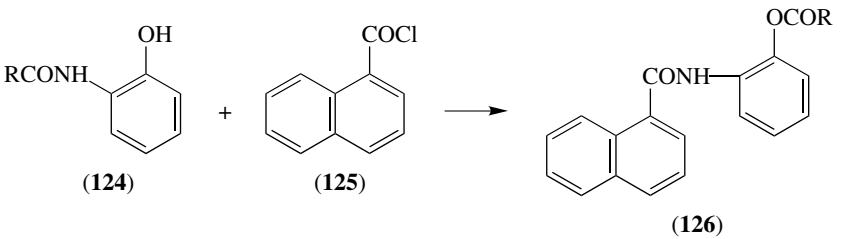


(**129**)



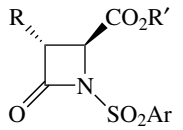
SCHEME 10

(h) *Lactams*

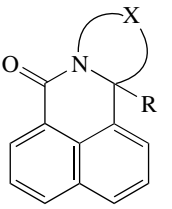
A Spanish group has been carrying out theoretical calculations on the hydrolysis of the *β*-lactam ring.[104–106] In the first study on the alkaline hydrolysis in the gas phase of penicillin G, the AM1 method predicted the opening of the thiazolidine ring to yield the corresponding imine and enamine.[104] A thorough study using *ab initio* MO calculations on the alkaline and acidic hydrolysis of the *β*-lactam ring of azetidin-2-one has been made.[105] Alkaline hydrolysis was studied assuming a $B_{AC}2$ mechanism involving a tetrahedral intermediate, while the acid hydrolysis was studied through an *A*-1 mechanism. The influence of solvent on the alkaline hydrolysis of the *β*-lactam ring of azetidin-2-one was investigated using the reaction field method (SCRF). The TS was found to correspond to a structure where the HO^- ion lies at a distance of 1.927 Å from the C=O group of the lactam ring and exhibits a potential barrier of 13.6 kcal mol^{-1}.[106]

Two mechanisms (i.e. direct hydrolysis and alternatively a path via an unstable acyl phosphate intermediate) are involved in the hydrolysis in phosphate buffer of *N*-arylsulfonyl *β*-lactams such as (**130**).[107] The acyl phosphate intermediate can be trapped with hydrazine. The alkaline hydrolysis of some torsionally distorted lactams, i.e. the bridged benz[*de*]isoquinolin-1-ones (**131**), in 70% (v/v) DMSO–water has been compared under the same conditions with the hydrolysis of *N*,*N*-dimethyl-1-naphthamide (**132**). The relative rates of reaction and activation parameters indicate the effect of torsional distortion.[108] The reaction of the tricyclic azetidinones (**133**) with trifluoroacetic acid gives the bicyclic thioesters (**135**). The mechanism may involve acid-catalysed elimination of methanethiol to give an azetinone intermediate (**134**) which, after nucleophilic attack of the thiol, is converted into (**135**).[109]

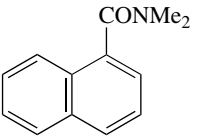
The degradation of several commercial penicillin antibiotics has been reported.[110–113] Thus the kinetics and mechanism of decomposition of cefazolin ester (**136**) in phosphate buffers[110] and the effect of hexadecyltrimethylammonium bromide-based microemulsions on the decomposition of the antibiotic cephalosporin, cephaclor (**137**)[111] have been reported. Reaction of the latter can occur intramolecularly or intermolecularly by hydroxide attack. Degradation in the solid state of cephaclor (**137**) has also been reported.[112] The same group has looked at the decomposition under aqueous acidic conditions.[113] The degradation pathways that have been recognized are (i) hydrolysis of the *β*-lactam carbonyl with subsequent rearrangement, (ii) ring contraction of the six-membered cephem nucleus to five-membered thiazole derivatives through an episulfonium ion intermediate, and (iii) attack of the primary amine of the phenylglycyl side chain on the 'masked' aldehyde at C(6) to form pyrazines.



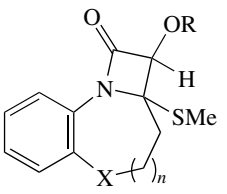
(**130**)



(**131**)



(**132**)



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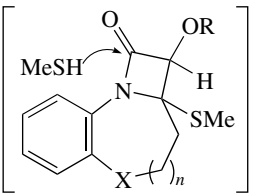
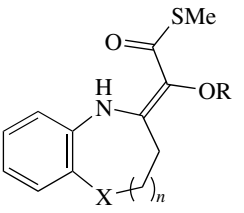
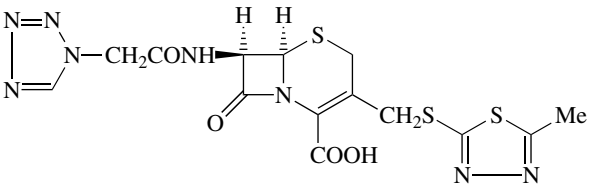


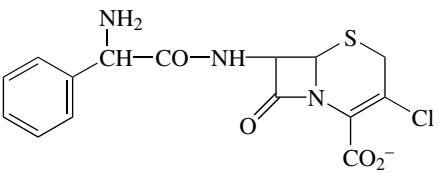
(**134**)



(**135**)



(**136**)

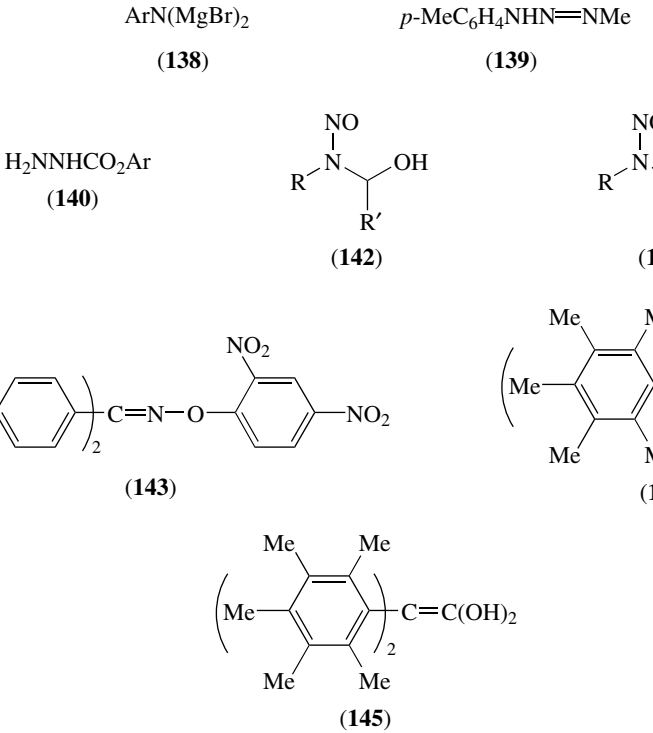


(**137**)

(i) *Non-heterocyclic nitrogen centres*

The kinetics and mechanism of the phosphorus-catalysed dimerization of acrylonitrile to give 1,4-dicyanobut-1-ene and 2,4-dicyanobut-1-ene have been studied.[114] The reactions of aryliminodimagnesium (**138**) with *p*′-substituted *p*-cyanobenzophenones, 1-cyano-9-fluorenenone, *o*-, *m*-, and *p*-dicyanobenzenes, and *o*-, *m*-, and *p*-nitrobenzonitriles have been examined.[115] The effect of pressure on the reaction of 3-methyl-1-(4-tolyl)triazene (**139**) and benzoic acid in chloroform and acetonitrile has been studied.[116] The effect of acids on the rate of urethane formation from alcohols and isocyanates in the presence of alkyltin carboxylates has been examined.[117] A Hammett σ value has been reported for the amidine group N=CHNMe$_2$ and used for the prediction of the basicity of sites in bifunctional amidines.[118]

Aryl carbazates (**140**) containing a methyl group in the 2-position hydrolyse by a $B_{AC}2$ mechanism but the others hydrolyse by an *E*1*cB* mechanism.[119] This conclusion was reached from a study of a wide range of ring-substituted compounds.

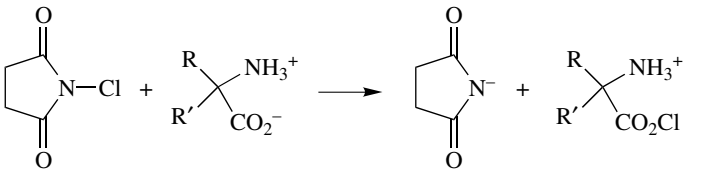


Kinetic evidence for the involvement of α-hydroxydialkylnitrosamines (**142**) in the pH-independent solvolysis of the α-(acyloxy)dialkylnitrosamines (**141**) has been obtained.[120] The aminolysis in benzene of *O*-(2,4-dinitrophenyl)-*p*,*p*-disubstituted benzophenone oximes (**143**) with pyrrolidine and piperidine are third order in amine.[121] Hirst's mechanism involving electrophilic catalysis operates and can explain the various effects observed. The bis(pentamethylphenyl)-*N*-isopropylketenimine (**144**) undergoes pre-equilibrium *N*-protonation in aqueous acetonitrile followed by water attack. An inverse solvent isotope effect and the observation of the diol (**145**) confirm this.[122]

(j) *Other heterocyclic nitrogen centres*

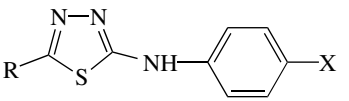
Cl^+ transfer from *N*-chlorosuccinimide (**146**) to an amine or amino acid to form an *N*-chloro compound is seen as the key step in the reactions of (**146**) with glycine, sarcosine, 2-methylalanine, proline, and pyrrolidine (Scheme 11). The reaction was first order in (**146**), first order in amine/amino acid and first order in proton.[123] The aminolysis of *N*-ethoxycarbonylphthalimide (**14**) was mentioned earlier in this review.[13] Twelve of the thiadiazoles (**147**) were prepared by the acid-catalysed intramolecular

dehydrative cyclization of the corresponding 4-(4-halophenyl)-1-(isomeric pyridyl) thiosemicarbazones. The effect of structure on reactivity with respect to the halogen atom and a reaction mechanism for the intramolecular cyclization are discussed.[124] The kinetics and mechanism of the hydrolysis of the thiadiazole (**148**) at pH 2–13 have been examined.[125] At pH 10–13 an S_N2 mechanism is favoured whereas at pH 2–8 an S_N1 mechanism finds support.

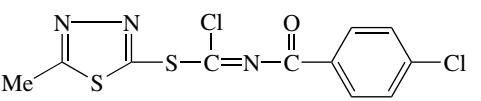


(**146**)

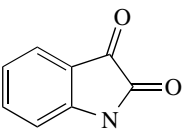
SCHEME 11



(**147**)



(**148**)

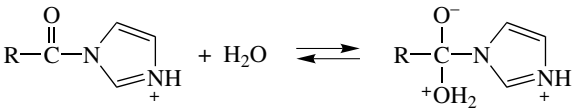


(**149**)

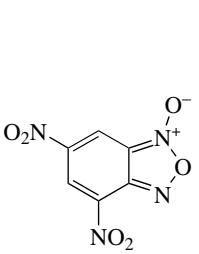
Two papers on the aminolysis[126] and hydrolysis[127] of isatin (**149**) have appeared. In the aminolysis study using piperidine, the reaction rate was much faster in water than in aqueous MeOH or aqueous MeCN. A multi-step mechanism was proposed. In the hydrolysis study the focus was again on the effect of solvent on rate in base hydrolysis, both ethanol and ethylene glycol being used. The reaction rate decreases with increasing ethanol content and it passes through a minimum at about 30% ethylene glycol.[127]

The hydrolysis of acetyl- (**150**; R = MeCO) and benzoyl-imidazoles (**150**; R = PhCO) involves the reversible addition of water to the imidazole to give the $T^{\pm}$. At low acidities the decomposition of this is the slow step but, as the acidity increases and water activity decreases, its formation becomes rate determining.[128] By contrast, the hydrolysis reactions of the *N*-acyl derivatives of 2,4,5-triphenylimidazole proceed in a concerted manner and do not involve tetrahedral intermediates.[129]

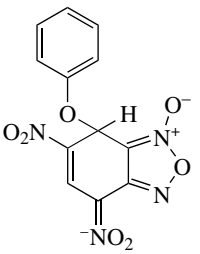
Some interesting reactions of the super-electrophile 4,6-dinitrobenzofuroxan (**151**) with aryloxide ions have been reported;[130] (**151**) with phenoxide ion gives the *O*-bonded σ-adduct (**152**) which has been fully characterized for the first time. On



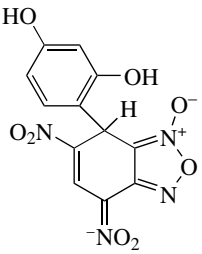
(**150**)



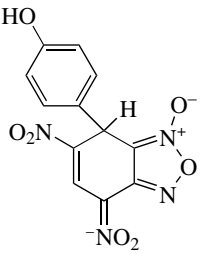
(**151**)



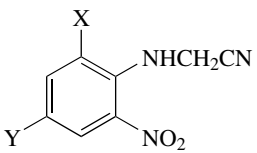
(**152**)



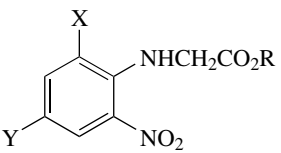
(**153**)



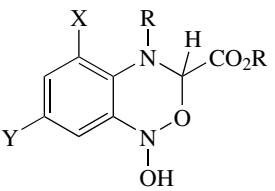
(**154**)



(**155**)



(**156**)

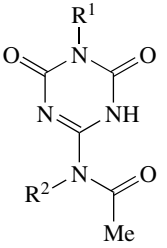


(**157**)

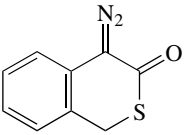
warming the solution, (**152**) yields (**153**) and (**154**). The base-catalysed cyclizations of the *N*-(*o*-nitrophenyl)glycine derivatives (**155**) and (**156**) may involve a common 2,1,4-benzoxadiazine intermediate (**157**).[131] The hydrolysis of a wide range of *N*-alkyl-6-acetylaminotriazinediones (**158**) over the full pH range has revealed four distinct regions in rate–pH profiles for the reaction corresponding to cationic, neutral, and anionic species and a region for attack of hydroxide on the anion. As the pH increases, increasing C−O bond formation in the TS occurs along the sequence from cationic to neutral to anionic, but C−N bond breaking is out of line and is largely dependent on conformational factors.[132]

The acid-catalysed hydrolysis of the cyclic diazothiolactone, 4-diazoisochroman-3-one (**159**) to a ring-contracted product involves protonation of the diazo carbon in the slow step.[133] A variable-temperature NMR study has been undertaken to study the reaction of the pyrazine (**160**) giving (**161a**; R = OH, Me, H). Spectral evidence has been obtained supporting the involvement of the dihydroimidazopyrazine ring system (**161b**).[134] Work by Edward and co-workers on the alkaline hydrolysis of strychnine and some of its derivatives was dealt with earlier.[21]

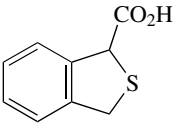
The mechanism of 2-phenylbenzoxazole (**162**) formation from benzoic acid and *o*-aminophenol in polyphosphoric acid has been studied by NMR and chemical analysis.[135] Initially benzoic acid reacts with (**162**) to form benzoic phosphoric anhydride and benzoic polyphosphoric anhydride. When *o*-aminophenol dissolves in

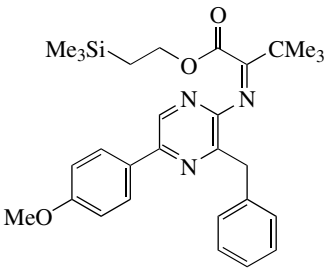


(**158**)

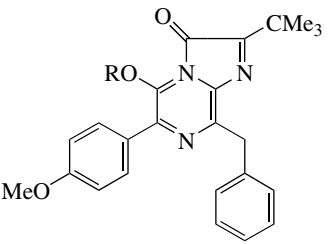


(**159**)

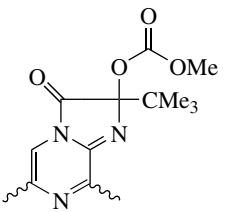




(**160**)



(**161a**)



(**161b**)

the polyphosphoric acid, part of the hydroxyl group is converted to phosphate ester. Dynamic equilibria exist between the polyphosphoric acid, *o*-aminophenol and its phosphate ester and also between benzoic acid, mixed anhydride and polyphosphoric acid. The mixed anhydride and *o*-aminophenol react to form 2-aminophenyl benzoate as the first reaction intermediate and this undergoes rapid acyl migration to give 2-hydroxybenzanilide. Ring closure of the latter, which is acid-catalysed, completes the sequence, yielding (**162**).

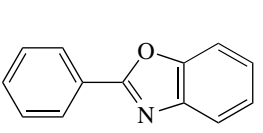
Reactions in Aprotic Solvents

Several reactions that have been conducted in aprotic solvents have been dealt with earlier; see references 4, 7, 8, 27, 64, 71, 84, and 88. The following references ahead will also deal with reactions in aprotic solvents: 116, 273, 275–278, 281, 289, 305, and 306.

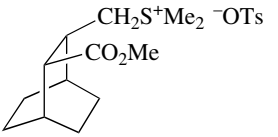
Intramolecular Catalysis and Neighbouring-group Participation

The sulfonium entity in the bicyclooctane compound (**163**) exercises a neighbouring-group effect in the hydrolysis of this compound. Rates and activation parameters were very similar for both *Z*-isomer (**163**) and the *E*-isomer, lending support to the theoretical prediction that charge–dipole and charge–charge separation in both isomers are not significantly different.[136] Two examples of amide group anchimeric assistance have been reported.[137,138] In the first example, a neighbouring amide group participates in competitive reactions of (**164**) giving by intramolecular cyclization (**165**) and by hydrolytic cleavage of the ether link (**166**); (**164**) is the well known herbicide,

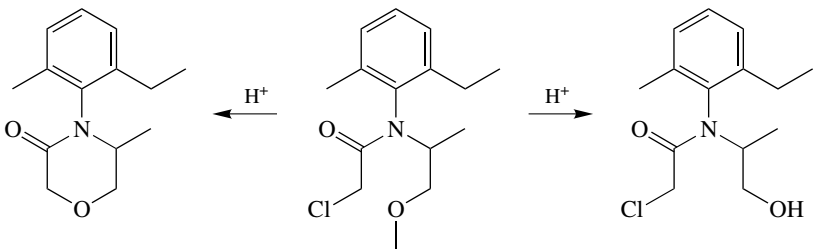
metolachlor.[137] Acid hydrolysis of the phosphinic ester (**167**) is facilitated by the *β*-carboxamido group. The promotion of the hydrolysis is dependent on the electron density of the amide, indicating the intermediacy of the cyclic imidate (**168**) in this reaction.[138] Phosphinic esters can inhibit metalloproteases and this gives further interest to this work.



(**162**)



(**163**)

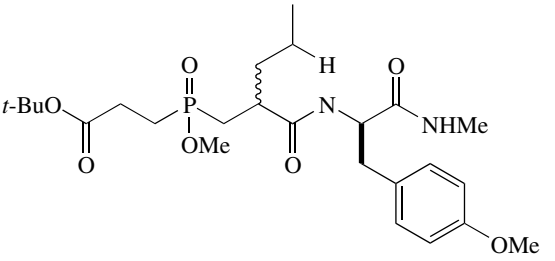


(**165**) (**164**) (**166**)

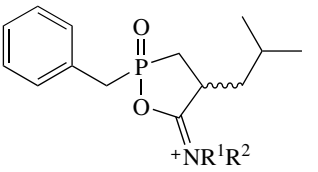
There are a number of papers involving participation by carbonyl groups. Two of these have been noted earlier.[41,101] Neighbouring-group participation by a keto carbonyl group is indicated from studies of the alkaline hydrolysis of the 2,3-diphenylacrylates (**169**) by Bowden's group. They compared relative rates, activation parameters and substituent effects for (**169**) with those for the corresponding ring (pseudo) esters (**170**).[139] In further work from the same group,[140] intramolecular catalysis by a neighbouring carbonyl group has been detected in the alkaline hydrolysis of compounds (**171**)–(**174**). Methanolysis of *p*-methoxyphenyl 2-formylbenzenesulfonate (**175**; $R^1 = CHO$, $R^2 = H$) in the presence of anhydrous potassium carbonate at ambient temperature in dry methanol gives the acetal (**176**); however, under identical conditions, the 4-formylsulfonate (**175**; $R^1 = H$, $R^2 = CHO$) does not react.[141] This supports the operation of intramolecular nucleophilic catalysis during nucleophilic substitution at sulfonyl sulfur in the 2-formylsulfonate.

The *o*-carboxyl group in the acetal (**177**) enhances the rate of acetal ring opening by a factor of 220 compared with the analogous *p*-isomer.[142] Compounds with other *o*- and *p*-derivatives (e.g. CO_2Me) have straightforward pH–log (rate constant) profiles with slopes of ca -1.0.

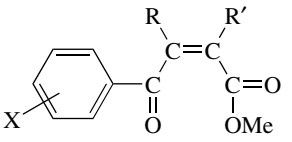
Intramolecular catalysis of amide bond isomerization is believed to play a key role in the folding of several proteins and this process has now been demonstrated experimentally including evidence for an H-bond between the side-chain and the prolyl N_a in a *cis*-proline peptidomimetic.[143] The amide (**178**) and the ester (**179**) have been used as substrates for these studies. Support for intramolecular nucleophilic attack



(**167**)



(**168**)



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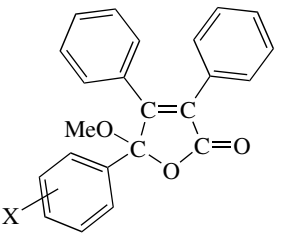
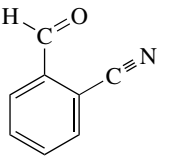
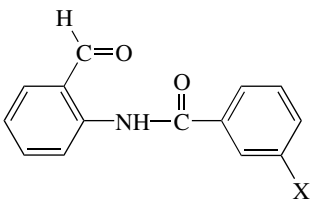


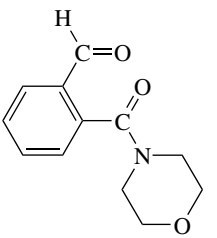
(**170**)



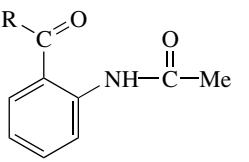
(**171**)



(**172**)



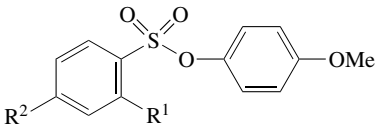
(**173**)

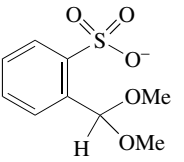


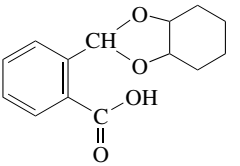
(**174**)

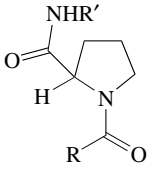
in the base-catalysed fission of a series of substituted 2,2-dihydroxyindane-1,3-diones (**180**) in 30% (v/v) dioxane–water has been obtained from kinetic and product studies.[144] Base-catalysed cyclization of (**181**)–(**183**) involves in each case ionization to the enolate anion, followed by rapid intramolecular nucleophilic attack and dehydration to give the corresponding enones.[145] The kinetics and mechanism of intramolecular general base-catalysed methanolysis of ionized phenyl salicylate in mixed MeOH–MeCN solvents with a fixed water content have been reported.[146] The MeOH exists in monomeric, dimeric, and polymeric forms in these solvents. The effects of various alkali metal ions have also been looked at. Intramolecular general base catalysis in the acetylation of a family of α,ω-amino alcohols (**184**; $n = 0$–3) by acetylimidazole has been reported.[147] The order of reactivity does not follow the order of basicity of the amino groups in (**184**); instead it follows the ease of formation of intramolecular H-bonds and thus enforced intramolecular H-bonding facilitates the reaction.

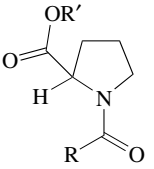
Reference 306 also deals with a neighbouring-group effect.

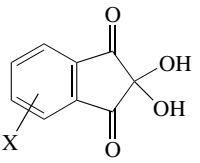

(**175**)

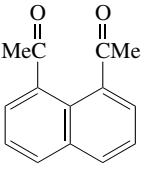

(**176**)

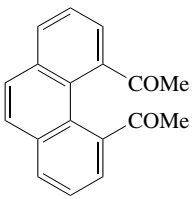

(**177**)


(**178**)


(**179**)


(**180**)


(**181**)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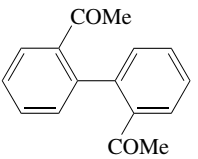
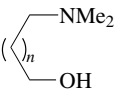
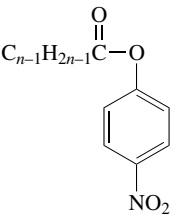

(**183**)

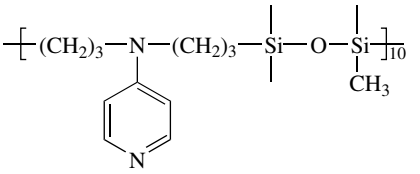

(**184**)


(**185**)

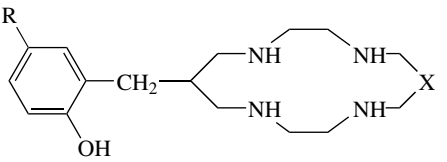
Association-prefaced Catalysis

A quantitative assessment of the effects of head group bulk on S_N2 and $E2$ reactions in cationic micelles has been made.[148] The kinetics of the acid-catalysed hydrolysis of methyl acetate in the presence of cationic, anionic, and non-ionic surfactants has been reported on.[149] The alkaline hydrolysis of *n*-butyl acetate with cetyltrimethylammonium bromide has also been investigated.[150] The alkaline hydrolysis of aromatic and aliphatic ethyl esters in anionic and non-ionic surfactants has been studied.[151] Specific salting-in effects that lead to striking substrate selectivity were observed for the hydrolysis of *p*-nitrophenyl alkanoates (**185**; $n = 2$–16) catalysed by the 4-(dialkylamino)pyridine-functionalized polymer (**186**) in aqueous Tris buffer solution at pH 8 and 30 °C. The formation of a reactive catalyst–substrate complex, (**185**)–(**186**), seems to be promoted by the presence of tris(hydroxymethyl)methylammonium ion.[152]

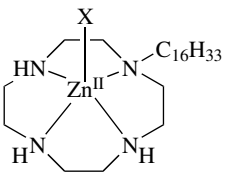
Three new macrocyclic ligands (**187**) when complexed with zinc(II) could promote ester hydrolysis and a kinetic study of the hydrolysis of 4-nitrophenyl acetate in Tris buffer at pH 8.63 in 10% (v/v) MeCN was carried out with these.[153] The hydrolysis of lipophilic esters is also catalysed by zinc(II) in a complex of a long alkyl-pendant macrocyclic tetraamine (**188**) in micellar solution.[154] A study with a copper chloride-containing micelle has compared its effectiveness in the hydrolysis of esters and amides.[155]



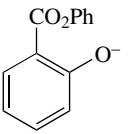
(**186**)



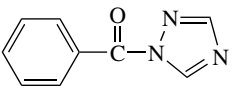
(**187**)



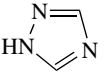
(**188**)



(**189**)



(**190**)



(**191**)

The aminolysis[156] and methanolysis[157–159] of ionized phenyl salicylate (**189**) have been examined under micellar conditions. The effect of CTABr on the rates of aminolysis of (**189**) by *n*-butylamine, piperidine, and pyrrolidine is to bring about a rate decrease (up to 17-fold with pyrrolidine). The results are interpreted in terms of binding constants for the amines with CTABr and the pseudo-phase model.[156] The effects of mixed surfactants SDS and CTABr on the methanolysis of (**189**) and the alkaline hydrolysis of phenyl benzoate suggest that micellar aggregates are involved in the processes.[157] The effects of NaOH and KBr on the intramolecular general base-catalysed methanolysis of (**189**) in the presence of CTABr has been investigated.[158] Pseudo-first-order rate constants were not affected by either additive but other changes were noted.[158] The effect of mixed MeCN–water solvents on the same reaction has also been probed.[159]

Three papers from the same group deal with micellar hydroxamic acid hydrolysis.[93,160,161] Micellar effects on the alkaline hydrolysis of (**107**; R = Ph) were discussed[93] earlier. Similar type results are reported in the other two papers.[160,161]

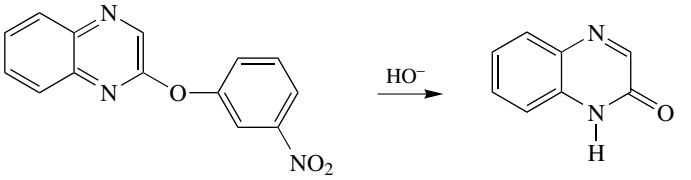
Alkyl (Me, Et, *n*-Pr, *n*-Bu), alkyldimethyl, and alkyltrimethylammonium bromides retard the neutral hydrolysis of 1-benzoyl-1,2,4-triazole (**190**) to benzoic acid and the triazole (**191**).[162] This effect is attributed to a dominant stabilization of the initial state through hydrophobic interactions with the co-solute. The effects of cetylpyridinium bromide on the hydrolysis of 2,4-dinitrochlorobenzene by hydroxide ion in water have been reported.[163]

The effects of cationic head groups on the alkaline hydrolysis of the quinoxaline (**192**) to give (**193**) have been looked at using the surfactants (**194**; R = Me, Et, *n*-Pr, *n*-Bu; X = Cl, OH).[164] The reactivity increases with increasing head-group size and is related to the disruption of the hydration of the HO^- ion. An earlier paper from the same group describes the synthesis of (**192**) and some micellar effects on its basic hydrolysis.[165] A novel site-selection functionalization reaction is facilitated by histidine side-chains in helical structures which can catalyse the acylation by mono-*p*-nitrophenyl

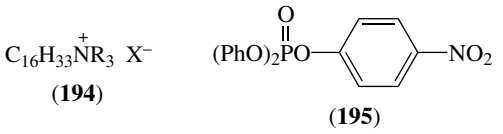
fumarate of flanking lysine, ornithine, and 1,3-diaminobutyric acid residues. This method increases the potential of polypeptide and protein design.[166]

The effect of hexadecyltrimethylammonium bromide (CTABr)-based microemulsions on the decomposition of the *β*-lactam antibiotic cephaclor (**137**) was described earlier.[111]

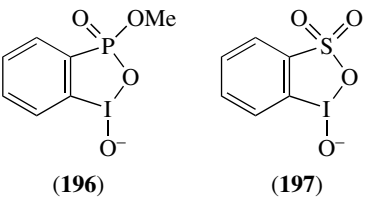
p-Nitrodiphenyl phosphate (**195**) in aqueous micellar hexadecyltrimethylammonium chloride (CTACl) in phosphate buffer at pH 8 is cleaved by 1,3-dihydro-1-oxido-3-methyl-1,2,3-benziodoxaphosphole 3-oxide (**196**) and by 1-*H*-1-oxido-5-methyl-1,2,3-benzodoxathiole 3,3-dioxide (**197**);[167] (**196**) and (**197**) were about 50 times less reactive towards *o*-iodosobenzoate (**198**).



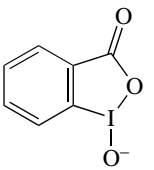
(**192**) (**193**)



(**194**) (**195**)



(**196**) (**197**)

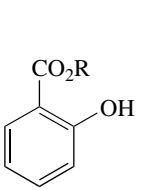


(**198**)

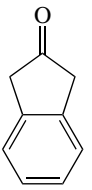
A review with ca 500 references has appeared on the stability of cyclodextrin complexes in solution. The principal headings in it are: nature of cyclodextrins (CDs); binding equilibria and kinetics; strengths of CD complexes; structures of CD complexes; sources of CD complex stability; and prediction of CD stability.[168]

The effects of *β*-CD on the kinetics of hydrolysis of salicylic acid esters (**199**; R = Me, *m*-nitrophenyl and *p*-nitrophenyl) have been examined, as has the Smiles rearrangement of (**199**; R = Me). The latter was accelerated by *β*-CD but its hydrolysis was not affected. Various other effects are reported for the other esters.[169]

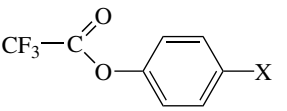
Tee's group has reported on the catalysis of enolization of indan-2-one (**200**) by α-CD, *β*-CD, *γ*-CD, hydroxyethyl-*β*-CD, and hydroxypropyl-*β*-CD, all of which accelerate the reaction by up to 22-fold, but dimethyl-*β*-CD slows it by about half.[170] These workers have also looked at the effect of alcohols on the basic cleavage of *m*-nitrophenyl hexanoate by *β*-CD.[171] Finally, they have been examining the reaction of α-amino acid anions with *p*-nitrophenyl acetate and hexanoate in the presence of *β*-CD.[172]



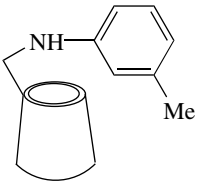
(**199**)



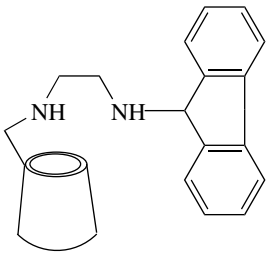
(**200**)



(**201**)



(**202**)



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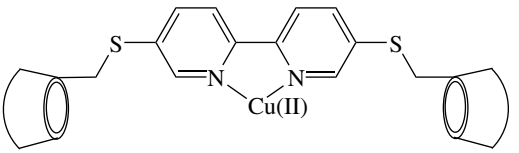
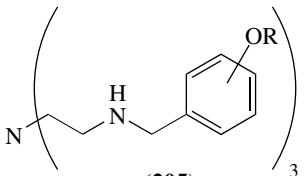
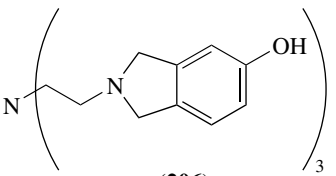


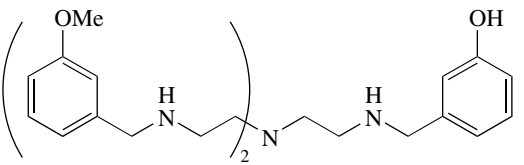
(**204**)



(**205**)



(**206**)



(**207**)

The rates of hydrolysis of the trifluoroacetates (**201**; X = H, Me) increase in a non-linear fashion in the presence of β-CD. Some differences in rate between the two substrates have been explained as being due to different modes of inclusion.[173] The novel CDs (**202**) and (**203**) have been synthesized in 45% and 66% yields, respectively, and their complexation with various L/D amino acids have been examined. Importantly, (**202**) and (**203**) can be detected by fluorescence spectroscopy and they can recognize the size and shape but also the chirality of the amino acids.[174] A β-CD dimer with a linking bipyridyl group (**204**) has been synthesized and shown to bind both ends of potential substrates into two different cavities of the CD holding the substrate ester carbonyl group directly above a Cu(II) ion bound to the bipyridyl unit. This achieves

very effective hydrolysis (accelerations of 10^4–10^5-fold) and good turnover (ca 50 times) catalysis.[175]

Metal-ion Catalysis

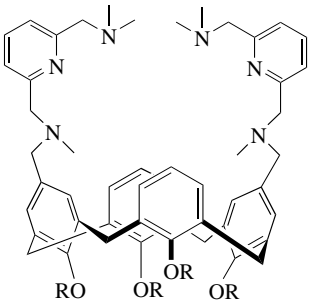
Several papers on zinc(II)-catalysed reactions have appeared during the period of review.[154,176–178] The hydrolysis of esters achieved with the zinc(II) complex (**188**) was mentioned earlier.[154] Tris(2-aminoethyl)amine functionalized with phenolic residues giving molecules such as (**205**; OR = *p*-OH and *m*-OH and OR = *m*-OMe), (**206**) and (**207**) can form stable complexes with zinc(II) ions at pH > 6–6.5. These complexes behave as molecular receptors of *p*-nitrophenyl esters of carboxylic acids and can catalyse their hydrolysis up to 60 times faster than in normal solution. The most efficient complex was (**205**; OR = *m*-OH)–Zn(II).[176] A calix[4]arene-based dinuclear zinc(II) catalyst from the ligand (**208**) produces a 23 000-fold rate enhancement in the catalytic cyclization of the RNA model substrate 2-(hydroxypropyl)-*p*-nitrophenyl phosphate (**209**) at pH 7 at 25 °C. This is the largest rate acceleration reported for nuclease mimics using this substrate.[177] The effects of nickel(II), zinc(II), and copper(II) on the hydrolysis of methyl derivatives of salicyl anil (salicylanilide) (**210**) have been reported. The accelerating effect occurs in the sequence Ni > Zn > Cu.[178] The use of copper-containing micelles to catalyse ester and amide hydrolysis was discussed earlier.[155] The oxidation of 34 different sulfides, R−S−R′, by bis(2,2′-bipyridyl)copper(II) permanganate giving the corresponding sulfoxides RS(O)R′ has been examined kinetically.[179] The reaction was first order in catalyst and is catalysed by H^+ also. Michaelis–Menten-type kinetics were observed with respect to the sulfides. Some of the kinetic results were analyzed in terms of the Taft–Pavelich equation.

Organozinc reagents and tetrakis(triphenylphosphine)palladium catalyst have been employed to convert (*S*)- and (*R*)-propargylic carbonates of type (**211**) into chiral allenes such as (**212a**,**b**) with *ee* of 82–85%.[180]

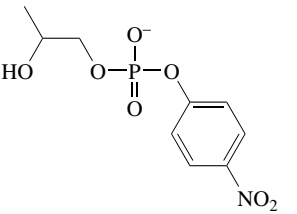
The vanadium(V) oxidation of the sulfide PhCH=CHSPh has been studied in aqueous acetic acid containing perchloric acid. The reaction is first order in vanadium(V) and fractional order in sulfide. An intermediate complex of vanadium and the sulfide forms and its decomposition is the slow step of the reaction.[181] Two Indian groups have reported on the use of ruthenium(VI) and ruthenium(III).[182,183] The kinetics and mechanism of the oxidation of diethylene glycol by aqueous alkaline potassium bromate in the presence of Ru(VI)[182] and the Ru(III)-catalysed oxidation of aliphatic alcohols by trichloroisocyanuric acid[183] have been examined.

The effect of cation-complexing agents on the barium(II)-assisted basic ethanolysis of phenyl acetate has been looked at.[184] Addition of various crown ethers yields ternary complexes of 1:1:1 crown–metal–ethoxide composition and a definite cation activation takes place. Cryptand 222 removes the catalytic activity.

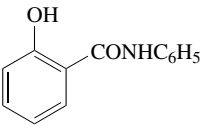
Catalysis by cobalt(III) has been the subject of several papers.[185–187] The *N*,*N*-bis(salicyldene)ethylnediaminocobalt(III)-catalysed oxidative carbonylation of *o*-, *m*- and *p*-substituted primary aromatic amines in MeOH gives ureas, isocyanates, carbamates, and azo derivatives. A Hammett ρ value of −0.5 for the reaction indicates that electrophilic attack of CO at a nitrogen anion complexed to Co in the TS is



(**208**)



(**209**)



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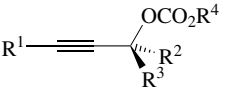

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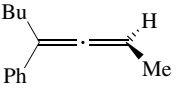
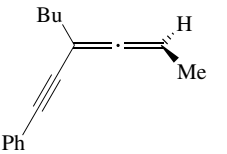
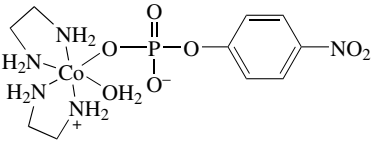


(**212a**)



(**212b**)



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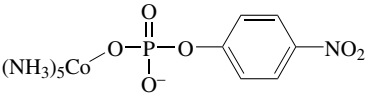

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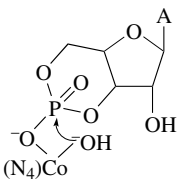
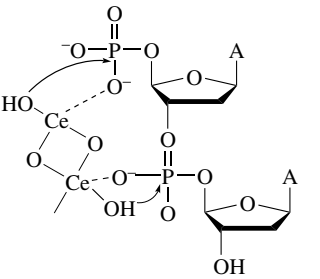


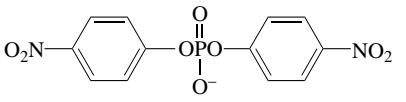
(**216**)

$[Co(N_4)(H_2O)_2]^{3+}$

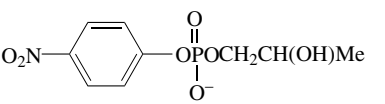
(**215**)



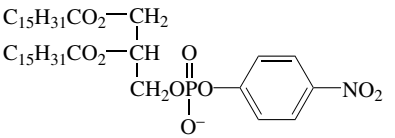
(**217**)



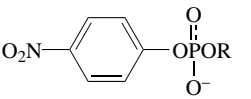
(**218**)



(**219**)



(**220**)



(**221**)

occurring.[185] Substantial TS cleavage in the rate-limiting step is indicated from a study of heavy-atom isotope effects (^{18}O-non-bridge, ^{18}O-bridge, ^{15}N of the nitrophenyl) for the reactions of the stable Co(III) complexes (**213**) and (**214**) of *p*-nitrophenyl phosphate.[186] Hydrolysis of adenosine 3′,5′-cyclic monophosphate (cAMP) by cobalt complexes (**215**; $N_4 = 2$ diamines or 1 tetraamine) has been studied at pH 7 and 50 °C. Catalytic activity and product distribution are highly dependent on the nature of the amine ligand and a 10^{10}-fold acceleration has been observed; (**216**) shows the proposed mechanism in which a hydroxide ion coordinates to Co(III) in the *cis* position to the cAMP and intramolecularly attacks the P atom of cAMP.[187]

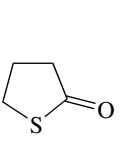
The reaction between an unsaturated ester and an aldehyde catalysed by DABCO (the Baylis–Hillman reaction) is catalysed by lanthanides and Group III triflates, particularly La and Sm, and additional acceleration can be obtained by addition of diol ligands.[188]

Ce(IV) ions efficiently catalyse the hydrolysis of phospho monoesters in nucleotides under physiological conditions. The proposed mechanism for the hydrolysis is illustrated in (**217**).[189] Uranyl cations (UO_2^{2+}) catalyse the hydrolysis of aggregated and non-aggregated *p*-nitrophenyl phosphodiesters such as (**218**)/(**219**) and (**220**), respectively.[190] Bis(*p*-nitrophenyl) phosphate (**218**) hydrolysis is accelerated ca 2.8×10^9-fold by Th(IV) cations in aqueous Brij micelles.[191] The reactivity of Th(IV) towards (**219**) and (**221**; R = Et, $C_{16}H_{33}$) also exceeds that of uranyl ion[190] and is comparable to that of Ce(IV) and exceeds that of other metal cations.

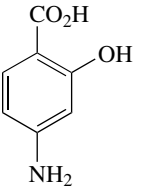
An intermediate involving oxidant, substrate, and catalyst is formed in the Cr(III)-catalysed oxidation of formic acid by Ce(IV) in aqueous sulfuric acid medium. A Cr(III)/Cr(IV) catalytic cycle operates in the reaction.[192]

Decarboxylation

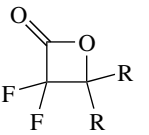
The structures and isomerization and decomposition mechanisms of oxalic acid have been studied using density functional theory and *ab initio* calculations. Unimolecular formation of carbon dioxide and dihydroxycarbene, $(HO)_2C$: has an activation barrier of 31 kcal mol^{-1} and unimolecular formation of formic acid from dihydroxycarbene has an activation barrier 31 kcal mol^{-1} higher. The most favourable unimolecular decomposition channel appears to be the formation of carbon dioxide, carbon monoxide and water.[193] The decomposition of 2-chloropropionic acid in the gas phase to form HCl, CO, and MeCHO has been examined theoretically and a two-step mechanism involving the formation of an α-propiolactone intermediate is envisaged.[194] The same Spanish group has looked at the reaction mechanism for the decomposition of α-hydroxycarboxylic acids (glycolic, lactic, and 2-hydroxyisobutyric acid) in the gas phase, giving CO, water and the corresponding carbonyl compounds.[195] Again a two-step mechanism with a lactone intermediate is supported. The gas-phase decomposition of *β*-ketocarboxylic acids, $XCOCH_2COOH$ (X = H, OH, Me), has been studied by *ab initio* MO theory.[196] Six-membered-ring transition structures are energetically favoured over four-membered ones in all cases. The thermal decomposition of *γ*-thiobutyrolactone (**222**) has been explored by *ab initio* methods. Decarbonylation leading to CO, $CH_2{=}CH_2$ and MeS is the main process, but decarboxylation leading to COS and $CH_2{=}CHMe$ is a minor process.[197]



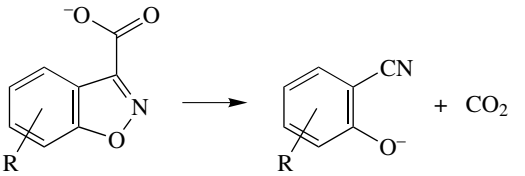
(**222**)



(**224**)



(**223**)

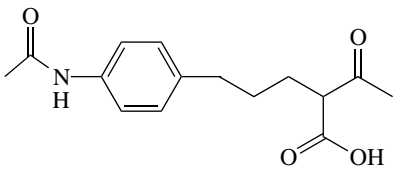


(**225**) (**226**)

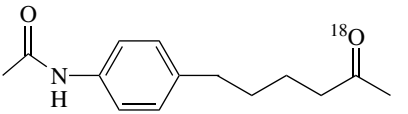
SCHEME 12

A kinetic study of the thermal decarboxylation of α,α-difluoro β-lactones (**223**; R = H, Me) in the gas phase and in various solvents has been reported.[198] *Ab initio* calculations have also been carried out.

Fluorodecarboxylation of arylchloroformates in the vapour phase to give fluorobenzene and its analogues can be achieved in high yield using anhydrous HF.[199] Reaction occurs quickly at 300–400 °C using chromium and aluminium oxyfluoride. The effects of micelles on the decarboxylation of *p*-aminosalicylic acid (**224**) have been examined.[200]



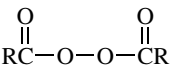
(**227**)



(**228**)

$H_2NCH_2CH_2NH_2$

(**229**)



(**230**)

The decarboxylation of 3-carboxybenzisoxazole (**225**; R = H, NO_2) gives CO_2 and (**226**). This reaction has been studied using ^{13}C and ^{15}N kinetic isotope effects.[201] The isotope effects were modelled theoretically at the semiempirical and *ab initio* levels, but comparison of experimental and theoretical results shows that the former cannot be successfully predicted by theory at the level of calculation employed. The kinetics of decarboxylation and deamination of DL-leucine by acidic permanganate in the presence of silver ion in moderately concentrated sulfuric acid is a two-stage process.[202] The

reaction is first order in amino acid and permanganate and displays a fractional order in silver ion. A water molecule acts as a proton transfer agent in the slow step.

The decarboxylation of the acetoacetic acid (**227**) to the hexan-2-one (**228**) in the presence of ^{18}O-labelled water revealed obligatory incorporation of ^{18}O in the antibody-catalysed reaction which is consistent with the decarboxylation proceeding through an imine intermediate.[203]

The carboxylation of ethylenediamine (**229**) is first order in protonated (**229**) and the rate constant was an order of magnitude lower than that for (**229**) under identical conditions.[204] The effects of solvents on the decomposition kinetics of some diacyl peroxidases (**230**) was assessed using time-resolved FTIR spectroscopy at $\leq$3 kbar and $\leq$155 °C.[205]

The decomposition of mandelic acid (**70**),[62] the elimination of CO_2 from the intermediate in the reaction of phosgene with carboxylic acids,[64] the thermal decomposition of haloacetic acids (**74**),[65] and the hydrolysis of aryl carbazates (**140**)[119] were discussed earlier.

Enzymic Catalysis

General

Comprehensive Biological Catalysis—a Mechanistic Reference Volume has recently been published.[206] The full contents list (approximate number of references in parentheses) is as follows: *S*-adenosylmethionine-dependent methyltransferases (110); prenyl transfer and the enzymes of terpenoid and steroid biosynthesis (330); glycosyl transfer (800); mechanism of folate-requiring enzymes in one-carbon metabolism (260); hydride and alkyl group shifts in the reactions of aldehydes and ketones (150); phosphoenolpyruvate as an electrophile: carboxyvinyl transfer reactions (140); physical organic chemistry of acyl transfer reactions (220); catalytic mechanisms of the aspartic proteinases (90); the serine proteinases (135); cysteine proteinases (350); zinc proteinases (200); esterases and lipases (160); reactions of carbon at the carbon dioxide level of oxidation (390); transfer of the PO_3^{2-} group (230); phosphate diesterases and triesterases (160); ribozymes (70); catalysis of tRNA aminoacylation by class I and class II aminoacyl-tRNA synthetases (220); thio–disulfide exchange of divalent sulfur (150); and S^{IV} sulfotransferases (50).

Bioinorganic enzymology has been reviewed under the following major headings: catalysis without electron transfer—new developments in zinc and iron–sulfur enzymes; catalysis with electron transfer—biological electron transfer; carbon metabolism; oxygen metabolism; nitrogen metabolism; and hydrogen metabolism.[207]

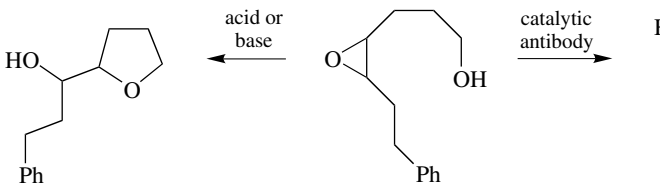
The calculated [using a quantized classical path (QCP) approach] and observed isotope effects and rate constants are in good agreement for the proton-transfer step in the catalytic reaction of carbonic anhydrase. This approach takes account of the role of quantum mechanical nuclear motions in enzyme reactions.[208]

Using the idea of a ‘theoenzyme’, that is a theoretical enzyme which contains a suitable array of functional groups that quantum mechanical calculations predict would be capable of catalysing a reaction, Houk’s group has shown how the reaction of a

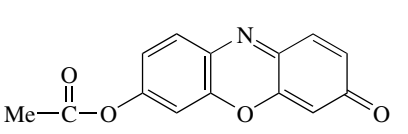
hydroxypropyl epoxide (**231**) catalysed by an antibody gives a tetrahydropyran (**232**) rather than the THF derivative (**233**) mainly arising with acid or base.[209]

Serine Proteinases

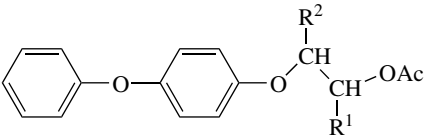
A reaction looked at earlier simulates borate inhibition of serine proteinases.[33] Resorufin acetate (**234**) is proposed as an attractive substrate to use with chymotrypsin since the absorbance of the product is several times more intense than that formed when the more usual *p*-nitrophenyl acetate is used as a substrate. The steady-state k_{cat} values are the same for the two substrates, which is expected if the slow deacylation step involves a common intermediate. Experiments show that the acetate can bind to chymotrypsin other than at the active site.[210] Brownian dynamics simulations of the encounter kinetics between the active site of an acetylcholinesterase and a charged substrate together with *ab initio* quantum chemical calculations using the 3–21G set to probe the transformation of the Michaelis complex into a covalently bound tetrahedral intermediate have been carried out.[211] The Glu 199 residue located near the enzyme active triad boosts acetylcholinesterase activity by increasing the encounter rate due to the favourable modification of the electric field inside the enzyme and by stabilization of the TS for the first chemical step of catalysis.[211]



(**233**) (**231**) (**232**)



(**234**)



(**235**)

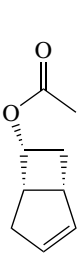
Lipases and β-Lactamases

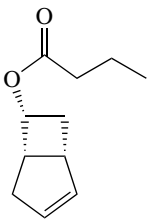
The enantioselective esterification of 2-arylpropionic acids catalysed by a lipase was discussed earlier.[26] Steady-state kinetics of the *Pseudomonas cepacia* lipase-catalysed hydrolysis of five analogous chiral and achiral esters (*R*)- and (*S*)-(**235**; $R^1 =$ Me, $R^2 = H$), (*R*)- and (*S*)-(**235**; $R^1 = H$, $R^2 =$ Me), and (**235**; $R^1 = R^2 = H$) were studied in emulsified reaction mixtures of water-insoluble substrates.[212] The K_m values were all the same and the apparent k_{cat} values reflected the binding abilities of the alcoholate ions for the fast-reacting enantiomers. All the substrates are believed to be

bound to the enzyme in the same manner and the breakdown of the tetrahedral intermediate is rate limiting.

The kinetic results for the lipase-catalysed enantioselective hydrolysis of the esters (**236**)–(**240**) can be interpreted in terms of frontier orbital localization.[213] The porcine pancreatic lipase (PPL)-mediated optical resolution of 18 racemic esters can be explained by a mechanistic model involving a W-shaped active conformation of the substrate lying in a diastereo-discriminating plane.[214]

TS analogues and inhibitors of the class C β-lactamase of *Enterobacter cloacae* P99 have been mentioned earlier.[17] The same enzyme from the same bacteria has been used to hydrolyse cephalexin (**241**) at pD 6.4 and 8.[215] The hydrolysis product is the cephalosporoate intermediate (**242**) which undergoes tautomerization of the double bond in the dihydrothiazine ring from position 3/4 to 4/5 and there is the uptake of a proton at C(3).


(**236**)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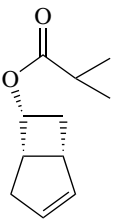
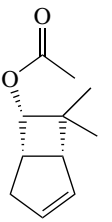
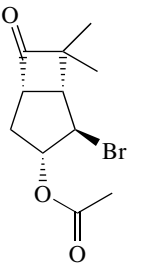
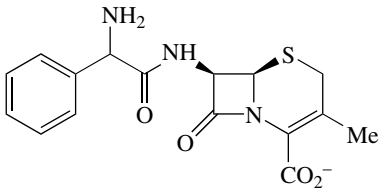

(**238**)


(**239**)



(**240**)



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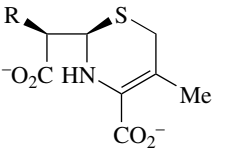


(**242**)

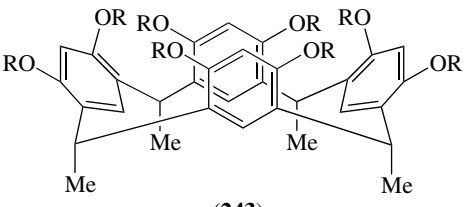
Other Enzymes

A concerted rather than a stepwise reaction involving a tetrahedral intermediate is supported for the papain-catalysed hydrolysis of amides. The TS for the hydrolysis has been determined by using a hybrid quantum mechanical/molecular mechanical potential, QM(AM1)/MM.[216]

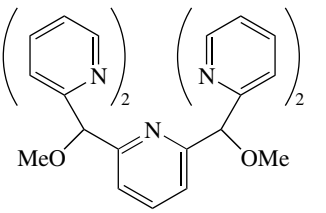
An octa(dimethylaminopropyl)calixresorcin[4]arene [**243**; R = $CH_2CONH(CH_2)_3NMe_2$] is a primitive artificial esterase for 4-nitrophenyl esters of various carboxylic acids. The overall mechanism is thought to involve complexation of substrate with the arene in its neutral form followed by intracomplex reaction of a dimethylamino function

with the ester.[217] Methane monooxygenases (MNO), a group of enzymes used to oxidize methane, have been theoretically modelled to predict an intermediate metal–oxo core like the one observed experimentally.[218] Quantum chemical methods were used to construct this MNO model.

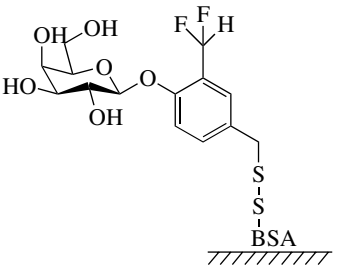
The iron enzymes, the lipoxygenases, catalyse the oxidation of 1,4-diene fatty acids to alkyl hydroperoxides and the slow step of the reaction involves H atom abstraction from the carbon adjacent to the two double bonds of the fatty acid by a $Fe(OH)_3$ species. This mechanism has now been shown to be correct by use of the lipoxygenase model (**244**).[219] Two papers discussed earlier are relevant to this section.[138,175]



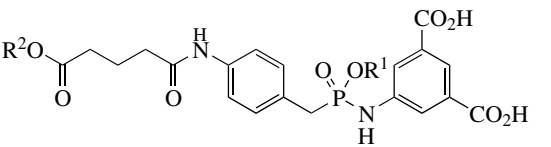
(**243**)



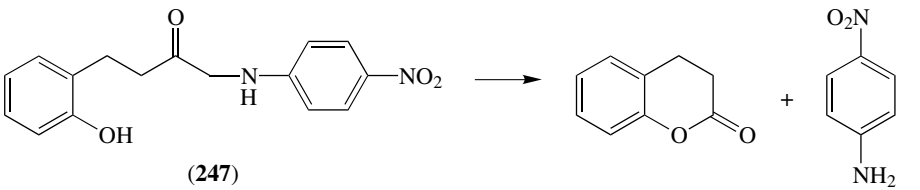
(**244**)



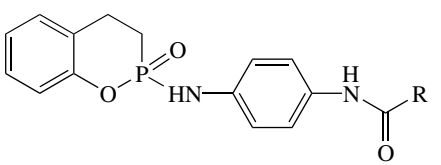
(**245**)



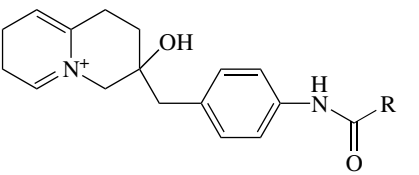
(**246**)



(**247**)



(**248**)



(**249**)

Catalytic Antibodies

A review (>150 references) entitled 'Binding energy and catalysis: the implications for transition-state analogs and catalytic antibodies' has appeared.[220] The principal sections are: transition-state theory and catalysis; protein–ligand interactions; forces available for binding and catalysis; transition-state analog inhibitors; qualitative and quantitative analysis and transition-state analogs; and catalytic antibodies. Lerner and co-workers[221] have reviewed (>40 references) antibody-catalysed cationic reactions: rerouting of chemical transformations via antibody catalysis. A trapping reagent (**245**; BSA = bovine serum albumin) which can identify antibodies with glycosidase activity has been reported by the same group.[222]

Catalysis by an antibody of the hydroxylpropyl epoxide (**231**) was discussed earlier within this enzymic catalysis section.[209] The decarboxylation of β-keto acids by catalytic antibodies was also mentioned earlier.[203] The generation of a monoclonal antibody that can catalyse carbamate hydrolysis by the highly disfavoured $B_{AC}2$ process, rather than the more usual addition–elimination $E1cB$ process, has been reported.[223] The haptens used were (**246**; R^1 = Et, H and R^2 = succinimidyl). The N → O acyl-transfer reaction of (**247**) has been successfully mediated by an antibody working from the haptens shown (**248**) and (**249**).[224] Rate enhancements of greater than 10^4-fold have been achieved in the hydrolysis of *p*-nitrophenyl glucopyranoside and galactopyranoside using five-membered ring iminocyclitol (**250**) antibodies generated by *in vitro* immunization.[225] A catalytic antibody can accelerate the cyclodehydration step of Robinson annulation and it will be the first commercially available antibody.[226] The antibody developed by Lerner and co-workers is called 38C2 and apart from annulation it can catalyse many other processes. In the Robinson annulation the acceleration is about a factor of 3.6×10^6. A pentacoordinate oxorhenium(V) metallochelate elicits antibody catalysts for phosphodiester cleavage. The TS is shown in (**251**; R = uracil-1-yl, H).[227]

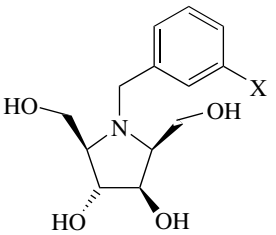
NON-CARBOXYLIC ACIDS

Phosphorus-containing Acids

Phosphates and Phosphonates

A review (91 references) on electrophilic and nucleophilic reactions of trivalent phosphorus acid derivatives, reactions of two-coordinate phosphorus compounds, and miscellaneous reactions has appeared.[228] Earlier in this review we looked at the heavy-atom isotope effects on reactions of Co(III)-bound *p*-nitrophenyl phosphate,[186] the uranyl ion hydrolysis of *p*-nitrophenyl phosphodiesters (**218**)–(**220**),[190] and the Th(IV) hydrolysis of these.[191]

Recently, theoretical calculations suggested that the rate of HO^- attack on the neutral phosphate monoester is very fast.[229] Earlier studies underestimated this rate and the present result indicates that the hydrolysis of phosphate monoesters in aqueous solution is not inconsistent with a mechanism that involves proton transfer to the phosphate oxygen followed by nucleophilic attack on the phosphorus. The hydrolysis of



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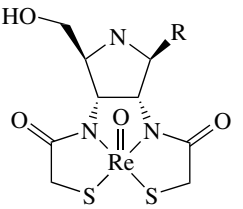

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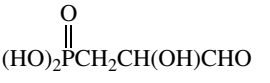
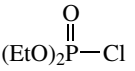
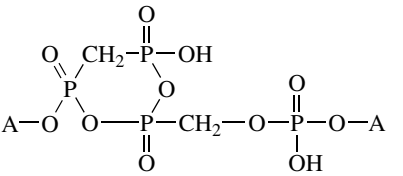


(**252**)

(**254**)



(**255**)



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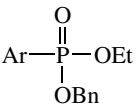

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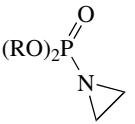

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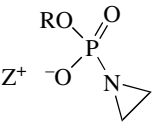

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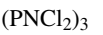
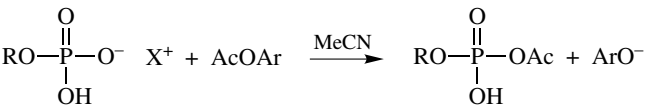


(**260**)

glyceraldehyde-3-phosphate (**252**) proceeds through an *E*1*cB* irreversible mechanism with slow C(2) deprotonation, giving an enediolate intermediate which expels the phosphate trianion.[230] The reaction between 2,4-dinitrophenyl acetate and *n*-decyl phosphate (**253**; R = *n*-decyl, $X^+ = BnMe_3N^+$) in dipolar aprotic media gives a system which allows the facile formation of acetyl phosphate derivatives (Scheme 13).[231] By restricting water in the system nucleophilic attack by water on the phosphate is inhibited.



(**253**)

SCHEME 13

The generation of alkyl-substituted monomeric metaphosphoric acid esters (**254**) has been described using two different methods and the metaphosphate produced spontaneously self-condensed to give polymeric P−O−P bonds. In the presence of styrene polymerization is avoided and trapping occurs instead to give a diastereomeric mixture of 2-alkoxy-1,3,2-dioxophospholane-2-oxides with (**254**; R = Me).[232] Pyridine *N*-oxide–triethylamine mixtures individually or together catalyse the phosphorylation of

nitrophenols and 2-[(4-dimethylamino)phenylazo]benzoic acid with diethyl chlorophosphate (**255**).[233] A strong synergistic effect was observed when the two bases were used and a mechanism for this has been suggested and supported.

Second-order rate constants for reactions of hydroxide ion and butane-2,3-dione monoximate ion with various phosphate, phosphinate, and thiophosphinate esters pass through minima with decreasing water content of water–MeCN and water–*t*-BuOH mixtures. The initial inhibition is offset by stabilization of the charge-delocalized TSs.[234]

A few papers on phosphonate chemistry have appeared.[235–237] The synthesis of the novel nucleoside bicyclic trisanhydrides (**256**; A = adenosin-*t*′-yl) has been reported.[235] A kinetic study of the alkaline hydrolysis of 4-substituted phenyl ethyl benzyl phosphonates (**257**) supports an associative *A–E* mechanism for the hydrolysis.[236] The direct preparation of the esters of *p*-nitrobenzylphosphonic acid from *p*-nitrobenzyl halides has been reported.[237]

A review (ca 300 references) on quinquevalent phosphorus acids dealing with derivatives of phosphoric, phosphonic, and phosphinic acids has been published.[238]

Phosphorus–Nitrogen Centres

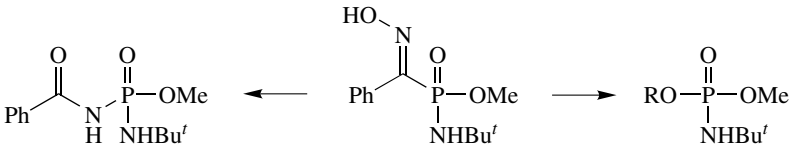
The phosphoramidates (**258**; R = Et, Me) do not undergo *N*-alkylation but when they were converted into the corresponding monoanionic salts (**259**; Z^+ = Li) they showed a high reactivity with benzyl chloride leading to a complex mixture of products, but with methyl iodide the simple *N*-methylated product was obtained.[239] ^{31}P NMR has been used to study the hydrolysis mechanism of phosphonitrilic chloride dimer (**260**) in acidic and basic solutions. First the substitution of Cl by OH occurs and then the replacement of ring nitrogens by oxygen and then the breakup of the six-membered ring takes place.[240]

Methyl *N*-*t*-butyl α-hydroxyiminobenzylphosphonamidate (**261**) rearranges in aprotic solvents to give the Beckmann rearrangement product (**262**) but in alcohols it undergoes fragmentation to give PhCN and (**263**). The involvement of the nitrilium ion species (**264**) is suggested as an intermediate in both reactions.[241]

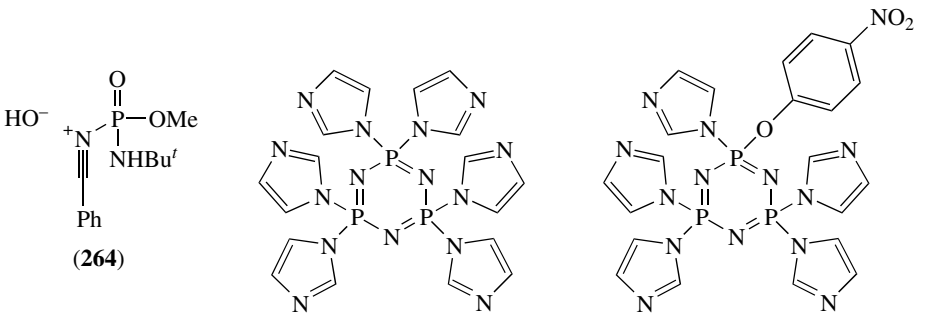
The kinetics of the nucleophilic monosubstitution of imidazole by *p*-nitrophenolate in hexaimidazolylcyclotriphosphazene (**265**) in water–THF have been studied.[242] A two-step mechanism involving the cleavage of a pentacoordinated intermediate to (**266**) in a general acid-catalysed reaction is proposed. As expected for such a mechanism, a change in the slow step occurs at pH > 7 when the [buffer] increases and k_{obs} becomes independent of [buffer].

The kinetics and mechanism of hydrolysis of monobutylaniline phosphate (**267**) in acidic media have been reported on.[243] The mechanism of hydrolysis of monophenylhydrazophosphate, as its barium salt, was investigated.[244]

The rearrangement of the *N*-phosphinoyl-*O*-sulfonylhydroxylamine (**268**) (with 57% enrichment with one ^{18}O atom in the SO_2 group) to the sulfonamide (**269**) (43.7% enriched with one ^{18}O atom) occurs with Bu^tNH_2 in dichloromethane via the phosphonamidic–sulfonic anhydride intermediate (**270**).[245] The rearrangement of the *O*-phosphinoyl compound (**271**) with *t*-butoxide gives the phosphonamidic–phosphinic



(**262**) (**261**) (**263**)



(**264**) (**265**) (**266**)

mixed anhydride (**272**). A concerted mechanism with a TS like (**273**) is proposed to explain the results.[246] The *N*- and *O*-phosphinoyl groups can interchange prior to rearrangement in (**274**) and (**275**) giving mixtures of (**276**) and (**277**), and phosphoranes (**278**) and (**279**) are suggested as intermediates.[247]

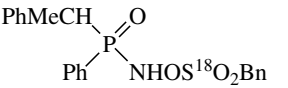
Phosphorus–Oxygen and Phosphorus–Sulfur Centres

The thionation of 2-substituted-4-aryl-5,5-dimethyl-1,3,2-dioxaphosphorinanones with Lawessen's reagent proceeded predominantly with retention of configuration and a cyclic pentacoordinated intermediate was proposed.[248] Both P−N bond cleavage in acidic solution and P−C and P−O bond cleavage in basic solution occur in the hydrolysis of *N*-(methoxycarbonyl)carbamoylmethoxyphosphonyl)-α-amino acid ester. Only P−O bond cleavage occurs with the *N*-(isopropylcarbamoyl) compound.[249]

The V-type nerve agents (**280**; $R^1 = Et$, $R^2 = Pr^i$) and (**280**; $R^1 = Bu^i$, $R^2 = Et$) react by exclusive P−S bond cleavage with an equimolar amount of water to give the corresponding phosphonic acid (**281**) and the 2-aminoethanethiol (**282**).[250] The mechanism may involve nucleophilic attack of the deprotonated phosphonic acid on protonated (**280**) to produce a diphosphonate intermediate (**283**) that rapidly hydrolyses to regenerate phosphonic acid. Reactions of the very toxic agent VX (**284**; $R = CH_2CH_2NPr^i_2$) and the mildly toxic (**284**; R = Et) with HO_2^-, HO^-, RO^-, and an oximate ion are seen as $S_N2(P)$ concerted reactions rather than stepwise with the formation of trigonal bipyramidal intermediates.[251]

The ester exchange reactions of the oxyphosphoranes (**285**; R = R = Ph, Me, 4-nitrophenyl) with several alcohols, models for nucleosides, have been investigated.[252] The oxidative hydrolysis of the phosphorus(V) esters of thiols such as (**286**)–(**289**) with

(**267**)



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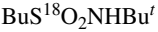

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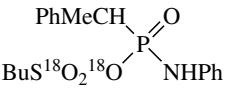

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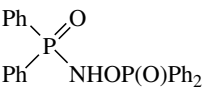

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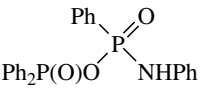

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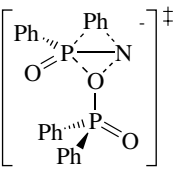

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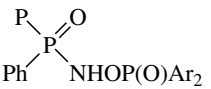

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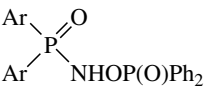

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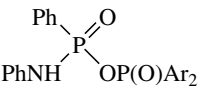

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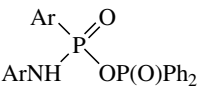

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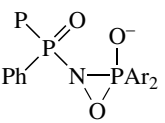

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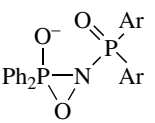

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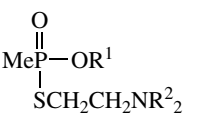

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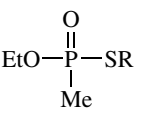

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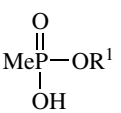
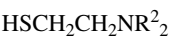
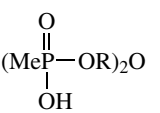


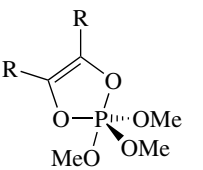
(**281**)



(**282**)



(**283**)



(**285**)

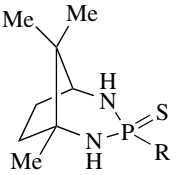
peroxymonosulfate ion, HSO_5^-, have been investigated.[253] Cleavage of the phosphate diester di-*S*-butyl phosphorothioate involves P−S fission.[254] The cyclization of the diaminocyclopentane (**290**) with thiophosphorodichlorides $RP(S)Cl_2$ may involve a trigonal bipyrimidal intermediate.[255] The mechanism of hydrolysis of diethyl dithiophosphate in aqueous acid has been explored.[256] The mechanism of the isomerization/chlorination of *O*,*O*-dialkylthiophosphate (**291**) with phosphorus oxychloride has been discussed in the light of a trigonal bipyrimidal intermediate.[257]

$Ph_2P(O)SC_6H_4X$ (**286**)

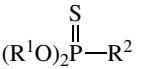
$(EtO)_2P(O)SPh$ (**287**)

$Ph_2P(O)SEt$ (**288**)

$PhP(O)(OEt)SEt$ (**289**)



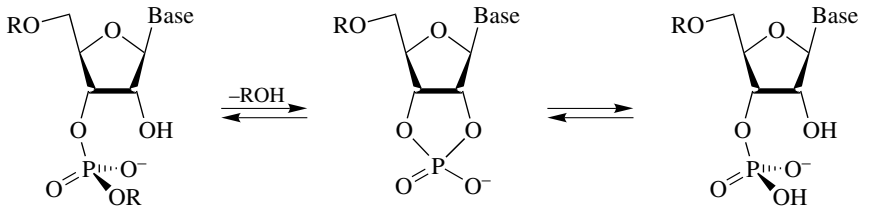
(**290**)



(**291**)

Biologically Important Reactions

The hydrolysis of adenosine 3′,5′-cyclic monophosphate (cAMP) by the cobalt complexes (**215**) was considered here earlier,[187] as was the Ce(IV)-catalysed hydrolysis of phospho monoesters in nucleotides.[189] A review (ca 100 references) on current data on the mechanism of cleavage–transesterification of RNA has appeared.[258] In this review special attention was focused on the two crucial steps in the hydrolysis of RNA, i.e. cleavage–transesterification and hydrolysis of the cyclic phosphodiester (Scheme 14). The catalysis of various amines for the hydrolysis of RNA has been looked at and ethylenediamine and propane-1,3-diamine are highly active under physiological conditions because they exist as the catalytically active monocation forms.[259]

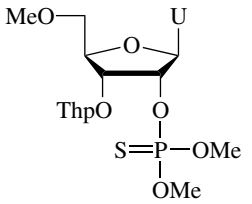


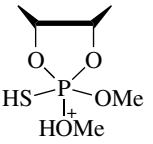
SCHEME 14

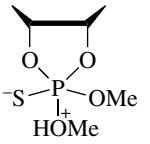
An enzyme that catalyses ATP-dependent 2′-phosphorylation and acetyl-CoA-dependent 6′-acetylation of the antibacterial aminoglycosides has been reported.[260] Because of its complementary spectrum of two enzymic reactions, this bifunctional enzyme has a wide breadth of activity. Pentacoordinated thiophosphorane intermediates such as (**292a**) and (**292b**) are involved in the hydrolytic reactions of the monothioate analogues of 5′-*O*-methyluridine 2′- and 3′-dimethylphosphates, (**293**) and (**294**), which have been studied over a wide range of HCl acidities, $H_0 = -1.7$ to pH9.[261]

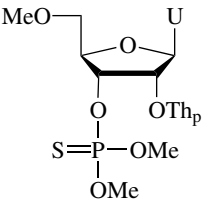
A quantum mechanical method has been used to study the TSs of the uridine phosphorylation reaction and an acid-catalysed S_N2 is the main mode of reaction.[262]

The ribonucleotide sulfur analogue 2′-deoxy-2′-thiouridine 3′-(*p*-nitrophenyl phosphate) (**295**) undergoes transphosphorylation to give 2′,3′-cyclic phosphorothioate (**296**) followed by hydrolysis to give 2′-deoxy-2′-thiouridine 2′-phosphorothioate (**297**)

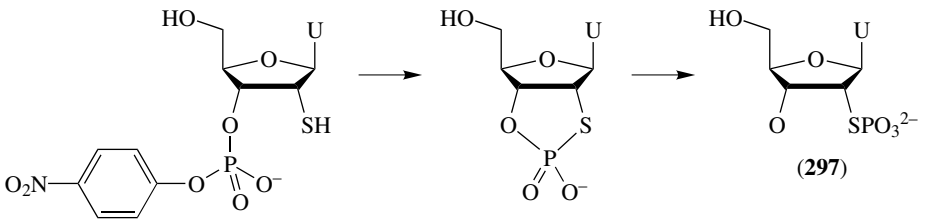

(**293**)


(**292a**)


(**292b**)


(**294**)

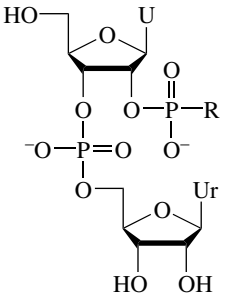
(Scheme 15). The reaction pathway of (**295**) is similar to that of ribonucleotides but there are some differences noted in this paper; for example, (**295**) hydrolyses 27-fold slower than its 2′-hydroxyl analogue.[263] 2′-Phosphorylated (**298**; R = OH) and 2′-thiophosphorylated (**298**; R = SH) dinucleotides were found to dephosphorylate readily at 90 °C in neutral aqueous solution to give UpU.[264] The neighbouring 3′–5′ phosphodiester function is thought to facilitate the 2′-dephosphorylation.


(**295**) (**296**) (**297**)

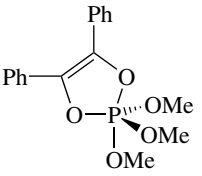
SCHEME 15

The hydrolysis reactions of *N*-phospho amino acids seen as models for protein dephosphorylation have been studied in Tris–HCl buffer (pH 7.5)–DMSO. The reactions were first order and the rates were very much faster than those of simple phosphoamidates. A pentacoordinated phosphorus intermediate is proposed on the reaction pathway.[265] The rates of ester exchange reactions of alcohols (nucleoside models) with the oxyphosphorane (**299**) have been studied and the rates of exchange are much faster for diols than for mono-alcohols.[266]

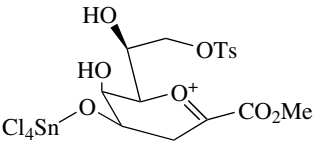
Using 1*H*-tetrazole, a more efficient procedure for the synthesis of nucleoside diphosphate sugars from nucleoside 5′-monophosphomorpholidate and glycosyl phosphate has been reported.[267] A stepwise mechanism involving the formation of a transient oxocarbenium ion intermediate (**300**) in the intramolecular condensation of two models for Kdo8P synthase, the enzyme that catalyses the unusual condensation of D-arabinose 5-phosphate with phosphoenol pyruvate to form Kdo8P, is supported in recent studies.[268] Low Brønsted β_{nuc} values of 0.08 ($\log k_{cat}$ vs pK_a) and 0.07 ($\log k_{cat}/K_m$ vs pK_a) for the protein tyrosine kinase Csk-catalysed phosphorylation of a peptide substrate family strongly support a dissociative mechanism since β_{nuc} values for non-enzymatic dissociative phosphoryl transfers of phosphate monoesters are in the range 0–0.3 and for associative phosphoryl transfers of phosphate triesters the values are ≥ 0.5.[269]



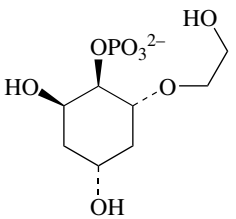
(**298**)



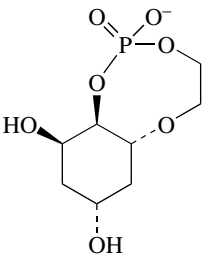
(**299**)



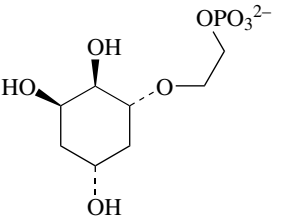
(**300**)



(**301**)

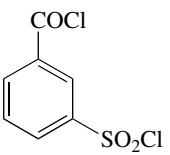


(**302**)



(**303**)

The phosphate derivatives (**301**)–(**303**) of 6-*O*-(2-hydroxyethyl)cyclohexane-1,2,4,6-tetraol have been synthesized as inositol monophosphatase inhibitors, the putative target for lithium therapy.[270] Compounds (**303**) and (**302**) are the most potent examples of a primary alkyl phosphate and phosphate monanion inhibitor so far reported.



(**304**)

$(p\text{-}ClSO_2C_6H_4)_2Z$

(**305**)

$C_nH_{2n-1}CH_2OSO_2C_6H_4Z$

(**306**)

The TS for the tyrosine phosphate hydrolysis by the enzyme protein tyrosine phosphatase (PTP1B) has been determined using a hybrid QM(PM3)/MM potential.[271] The reaction was found to be dissociative in character with no P−S bond formation in the TS but extensive P−O bond lengthening.

Sulfur-containing Acids

Sulfur–Oxygen Compounds

General base ($\beta_{nuc} = 0.19$) and nucleophilic catalysis mechanisms have been established for the hydrolysis of benzenesulfonyl chloride. Two-parameter LFERs were found for each route and electronic effects were seen to be greater than steric.[272]

The solvolysis and methanolysis of $PhSO_2Cl$ in MeCN with tertiary amine catalysts has been explored and a series of 4-substituted phenols and again both general base and nucleophilic catalysis paths were recognized.[273] The reactivity of 3-sulfobenzoyl dichloride (**304**) with substituted anilines leading to the 3-(chlorosulfonyl)benzanilides in approximately 90% yield has been probed.[274] The kinetics of the sulfonylation of aniline with the aryldisulfonyl chlorides (**305**; Z = O, S) reveals that the reactivity of (**305**) exceeded that of $PhSO_2Cl$ significantly but was less than that of $(4\text{-}ClSO_2)_2C_6H_4$.[275] The relative reactivity of PhSCl and $PhSO_2Cl$ compared with non-sulfur-containing chlorides was looked at earlier.[77]

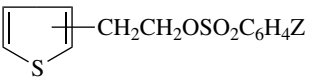
Methanolysis of the sulfonates (**175**)[141] and the reaction of the sulfonate ester (**102**) with hydroxylamine (**103**)[88] were looked at earlier. Yoh and co-workers have looked at the reactions of (Z)-phenylethyl (X)-benzenesulfonates with (Y)-pyridines in acetonitrile under pressure and the structure–reactivity relationships established show that as the pressure is increased the mechanism moves from a dissociative S_N2 to early-type concerted S_N2.[276] In other studies also under pressure the same group found that a mechanistic change from associative S_N2 to late-type S_N2 occurs as the pressure is increased in the reaction of (Z)-phenacyl (X)-benzenesulfonates with (Y)-pyridines in acetone.[277]

Lee's group has published extensive results on aminolysis of sulfonates.[278–281] Thus the reactions of anilines with 2-cyano-2-propyl and 1-cyanocyclooctylarenesulfonates in acetonitrile have been studied.[278] A dissociative S_N2 mechanism with a loose TS is supported from the usual LFERs. An S_N2 mechanism is also found for the reaction in acetone of (Z)-benzyl (X)-benzenesulfonates with (Y)-pyridines.[279] Nucleophilic substitutions with the cycloalkylmethylsulfonates (**306**) and anilines in MeOH were also studied.[280] Finally the reaction of thiopheneethyl arenesulfonates (**307**) with anilines and *N*,*N*-dimethylanilines in MeCN has been reported on.[281] Frontside-attack in an S_N2 mechanism with a four-centre TS is supported.

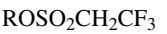
King and Gill have been studying the reaction of alkyl 2,2,2-trifluoroethanesulfonate esters (tresylates) (**308**) in aqueous base (pH > 9) in the presence of a primary or secondary amine.[282] Reaction with hydroxide is found to be a reversible *E*1*cB* process and reaction with water is the normal sulfonic ester hydrolysis.

The hydrolysis/alcoholysis of (**309**; R = Pr^n, Bu^i, allyl, propargyl) with various alcohols and water caused only a slight difference in the heat of activation for R but, for a fixed R the variation was much greater. The kinetics could be described by a Taft–Pavelich equation.[283]

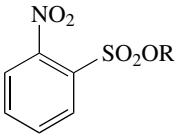
The reactivity of amines and imidazolide anions with aryl 4-toluenesulfonates (**310**) in 80% aqueous DMSO has been studied and Brønsted β_{nuc} values of ca 0.7 and ca 1.0, respectively, were found.[284] The points for both the amines and the imidazolides can all be accommodated on the same Brønsted plot. S−O rather than C−O cleavage occurs in the reaction. In a useful aside to this work the authors have shown that plots of pK_a data in water are linear with those in DMSO or 80% DMSO and these can be used to obtain unknown pK_a values. The same Ukrainian group has obtained deviations from Brønsted plots for the reaction of (**310**) with highly basic nucleophiles such as imidazoles and arenesulfonamides. The β_{nuc} value goes from 0.79 for $pK_a < 11$ to 0–0.1 for $pK_a > 11.0$.[285]



(**307**)



(**308**)



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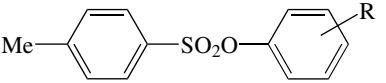

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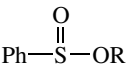
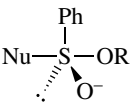


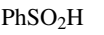
(**311**)

(**314**)

(**315**)



(**313**)



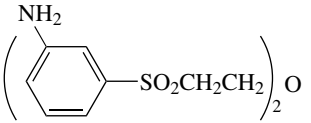
(**312**)

Buffer catalysis of the hydrolysis of phenyl (**311**; R = Ph) and methyl (**311**; R = Me) benzenesulfinates to give the sulfinic acid (**312**) and alcohol ROH is strongly accelerated by both carboxylate and amine components of the buffer which give Brønsted β values of approximately unity on separate lines. The carboxylates are about 44 times more effective than amines of similar basicity. A concerted S_N2 mechanism with a hypervalent intermediate (**313**) is proposed for the nucleophilic reaction of these esters.[286] The reaction of the thiosulfinate esters (**314**) with sulfenyl chlorides RSCl and sulfenate esters (**315**) to give sulfinyl chlorides and disulfides and sulfinate esters and disulfides, respectively, has been studied.[287] Hydrolysis of 2-(3-aminophenyl)sulfonylethanol hydrogensulfate gives under different conditions various products such as the ether (**316**) and the sulfone (**317**).[288]

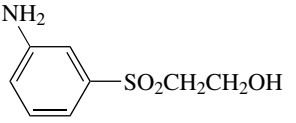
The mechanism by which α,β-unsaturated ketones (see Scheme 16), β-keto esters, and uracil derivatives react with iodine in the presence of bis(tetra-*n*-butylammonium) peroxydisulfate (**318**) in acetonitrile to give the appropriate iodinated products in good yields is unclear.[289] The mechanism may involve the cleavage of (**318**) to give an *n*-butylammonium sulfate radical, which can react to form a cationic iodine radical and sulfate anion; the substrate then reacts with the iodine radical to form an iodine-bridged intermediate.

Sulfur–Nitrogen Compounds

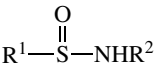
Ab initio calculations have been carried out on the gas-phase acid-catalysed hydrolysis reactions of sulfinamide (**319**) using the 3–21G* sets.[290] The first step in the acid-catalysed hydrolysis of *N*-methylmethanesulfinamide (**319**; $R^1 = R^2 = Me$) is *O*-protonation and this form is then transformed by addition of water to the sulfurane intermediate (**320**). Intramolecular proton transfer from O to N follows and then slow N−S bond cleavage to give products.[290] Studies with (**319**; $R^1 = Me$, $R^2 =$ aryl) also



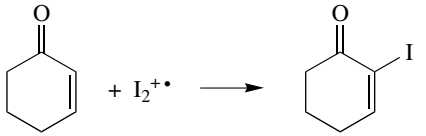
(**316**)



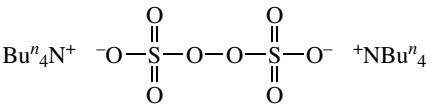
(**317**)



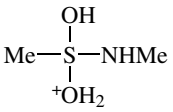
(**319**)



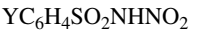
SCHEME 16



(**318**)



(**320**)



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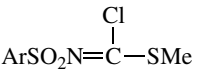


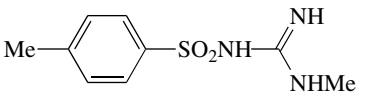
(**322a**)

indicate that N−S bond cleavage is rate determining. Rate constants have also been obtained for the hydrolysis of (**319**; $R^1 = C_6H_4X$, $R^2 = C_6H_4Y$) in the presence of halide ions.[291] The acid- and nucleophile-catalysed hydrolyses of (**319**; $R^1 = C_6H_4X$, $R^2 = C_6H_4Y$) have been studied and a hypervalent intermediate is implicated in the mechanism in certain cases.[292]

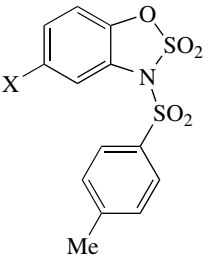
The acid-catalysed reactions of *N*-nitrobenzenesulfonamides (**321**) via an *A*-1 mechanism gives either $YC_6H_4SO_2^+$ and NH_2NO_2 or $YC_6H_4SO_2NH_2$ and NO_2^-.[100] Data on the alkylation of amines with the sulfonamide (**322a**) have been re-interpreted[293] with a multiparameter LFER incorporating dielectric properties, polarizability, Palm basicity, etc. Kinetic studies on the nitrosation of *N*-methyl-4-tolylsulfonylguanidine (**322b**) suggest a mechanism involving rapid nitrosation of the *N*-methyl nitrogen followed by slow general base-catalysed proton transfer.[294]

A bimolecular reaction has been proposed for the reaction with hydroxide ion and imidazole in aqueous acetonitrile and aqueous EtOH solutions of the 1,2,3-benzoxathiazole 2,2-dioxides (**323**) under various pressures.[295] The effect of *N*-methyl substituents in the cyclization of 2-methoxycarbonylphenylsulfamides (**324**) to give (1*H*)-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxides has been examined.[296]

The reversible formation of a monoanionic trigonal bipyrimidal intermediate with hypervalent sulfur (**325**) has been supported in the alkaline hydrolysis of the β-sultam (**326**).[297] A second deprotonation by hydroxide takes place to give (**327**) before the



(**322b**)



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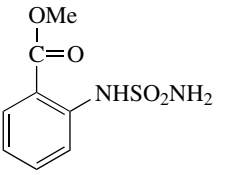

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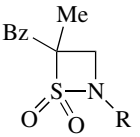

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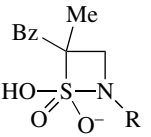

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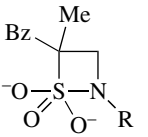

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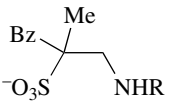

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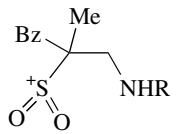

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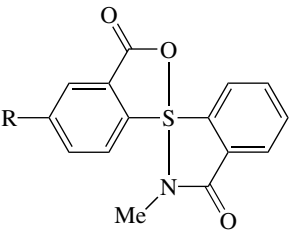

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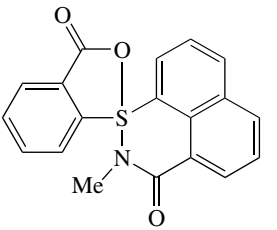
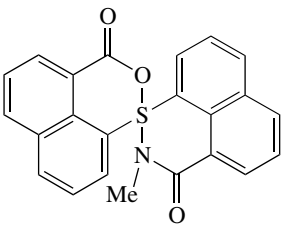
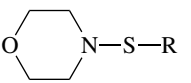


(**331**)



(**332**)



(**333**)

RSNO

(**334**)

intermediate collapses to product (**328**). The acid-catalysed hydrolysis of (**326**) involves a sulfonylium ion intermediate (**329**).

The hydrolysis of a series of spiro-λ^4-sulfanes such as (**330**)–(**332**) leads to sulfoxides in dioxane–water solutions. A mechanism involving slow nucleophilic attack of water on the positively polarized sulfur atom and simultaneous O−H and S−N bond cleavage is proposed.[298] The photo-oxidation of the sulfenamides (**333**; R = Me, Et, Ph, Bn, etc.) has been reported.[299]

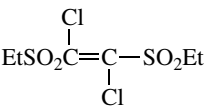
The kinetics of reaction of a number of *S*-nitrosothiols (**334**) in water with mercury(II) salts have been reported. Reaction is first order in both reactants and the products are nitrous acid and the corresponding thiol–Hg^{2+} complex. The mechanism involves slow attack by water at the nitrogen atom in the complex.[300] The same group has also studied the copper(II)-catalysed decomposition of the *S*-nitrosothiols derived from penicillamine, cysteamine, thiomalic acid, *N*-acetylpenicillamine, and cysteine.[301]

Sulfur–Carbon Compounds and Other Sulfur-containing Functionalities

Aminolysis of phenyl dithioacetates,[8] pyridinolysis of *O*-ethyl dithiocarbonates,[9] reaction of pyrrolidine with *O*-ethyl *S*-aryl dithiocarbonates,[10] aminolysis of chlorothionformates,[11] pyridinolysis of alkyl aryl thioncarbonates,[12] reaction of anionic nucleophiles with nitrophenyl benzoate and its sulfur analogues,[36] hydrolysis of methyl benzoate and phenyl acetate containing SMe, SOMe and SO_2Me substituents,[42] solvolysis of phenyl chlorothioformate,[79] synthesis of new thiadiazoles,[124] examination of a neighbouring sulfonium group in ester hydrolysis,[136] hydrolysis of V-type nerve agents,[250] and the reactions of peroxymonosulfate ion with phosphorus(V) esters have all been looked at previously in this review.

A low-temperature study in superacid media of mono-, di-, and tri-protonated thiourea has been carried out.[302] The experimental results were confirmed by theoretical calculations. Monoprotonation occurs at sulfur and, whereas the mono- and di-protonated forms are thermodynamically stable, the triprotonated ion is only kinetically stable. The pyrolysis of *N*-acetylthiourea and *N*,*N*′-diacetylthiourea (**335**) are unimolecular first-order eliminations.[83] Acid-catalysed ethanolysis of *N*,*N*′-di- and tri-substituted aryl- and alkylaryl-thioureas gives *O*-ethyl *N*-aryl thiocarbamates and amines.[303] The acid-catalysed hydrolysis of thiourea was first order in thiourea and acid.[304]

(**335**)



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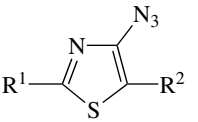
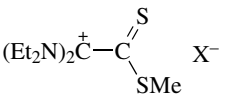
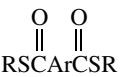


(**337**)

(**338**)



(**339**)



(**340**)

The aminolysis of *trans*-1,2-bis(ethylsulfonyl)-1,2-dichloroethene (**336**) by primary and secondary aliphatic amines in acetonitrile has been studied.[305] Thermolysis in *p*-xylene solution of 4-azidothiazoles (**337**) displayed some interesting neighbouring-group effects,[306] e.g. in (**337**) with $R^1 = Ph$, $R^2 =$ (acceleration produced in parentheses) NO_2 (19-fold), phenyliminomethyl (16-fold), formyl (4.5-fold), and acetyl (2.2-fold). Rate data for nucleophilic attack on phenyldimethylsulfonium ions by

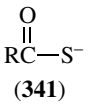
common nucleophiles correlates with pK_{lg}^{Me} and comparison with nucleophilic attack on methyl arenesulfonates shows that different leaving-group behaviour takes place.[307]

The reaction of alkyl isothiocyanates, RNCS, with diphenylphosphinic hydrazide (**338**) in benzene has been reported.[308] The bis(diethylamino)[(methylthio)thiocarbonyl]carbenium salts (**339**; X = I or BF_4) display ambident reactivity and can react either at carbenium carbon (hard nucleophiles) or at the thiocarbonyl sulfur atom (soft nucleophiles).[309] Electrochemically generated superoxide reacts with dithioic *S*,*S*′-diesters (dicarbothiolates) (**340**; Ar = C_5H_3N or C_6H_4) to give the monocarboxylate anions in 100% yield before giving the dicarboxylate anions.[310]

The addition of aromatic thiols, ArS^-, to cyanamide, $NCNH_2$, is general acid catalysed, giving isothiourea as product.[311] A significant movement of a hydron in the TS to the cyano nitrogen atom is indicated. The reactivity of sulfur towards thiocarboxylate ions (**341**; R = Ph, Me, Bu^t) has been looked at and among the species formed are $S_3^{\cdot-}/S_8^{2-}$ polysulfide ions (**342**) and (**343**).[312]

Catalysis by phosphate buffers of various active acyl compounds (**344**; X = O, S), (**345**; X = O, S) and (**346**) has been examined to assess its role as a nucleophile and general base.[313] In water at pH 8.5 phosphate dianion functions as both nucleophile and base towards (**344**; X = S); the Nu^- role accounts for about 80–93% of the reaction. In D_2O the process is totally nucleophilic. For (**345**; X = S), the Nu^- role is 40–50% of the reaction and for (**346**) the phosphate dianion adopts an entirely nucleophilic role, while the monoanion acts as a general base.

Some reactions of the 4′-thionucleoside (**347**) which is isoelectronic with natural thymidine (**348**) have been reported together with reactions of the sulfone of (**347**).[314]



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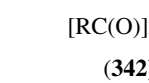

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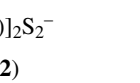

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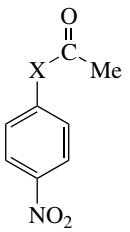

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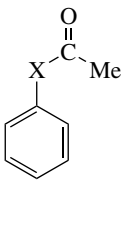

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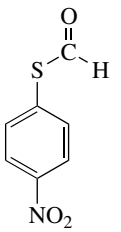
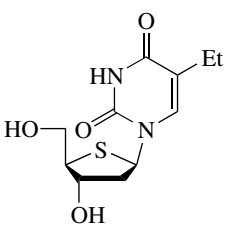


(**346**)



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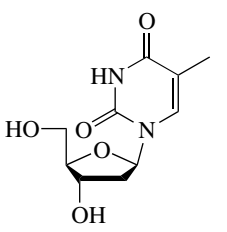
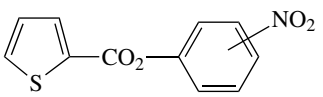


(**348**)



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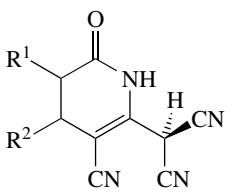
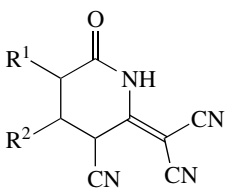


(**350**)



(**351**)

The study of the reaction of alkali metal alkoxides in absolute EtOH with nitrophenyl 2-thiophenecarboxylates (**349**) shows that the reactivity depends on the size of the alkali metal ions.[315] The ions form complexes at the TS more strongly than in the ground state.

Seven papers reviewed earlier here deal with chemistry about P−S bonds,[251,254–257,261,263] i.e. the peroxyhydrolysis of nerve agent (**284**),[251] the hydrolysis of di-*S*-butyl phosphorothioate,[254] the formation of (**290**),[255] hydrolysis of diethyl dithiophosphate,[256] the isomerization/chlorination of *O*,*O*-dialkylthiophosphate (**291**),[257] the hydrolysis of the monothioate analogues of 5′-*O*-methyluridine 2′- and 3′-dimethylphosphates (**293**) and (**294**),[261] and the reactivity of the ribonucleotide analogue (**295**).[263]

Other Acids

Evidence is presented to support the presence of the *endo* isomer (**350**), which is a key intermediate in the cyclization of the 1,5-dinitrile system present in (**351**; $R^1 = Me$, $R^2 = H$; $R^1 = H$, $R^2 = Me$; $R^1 = Ph$, $R^2 = H$; $R^1 = H$, $R^2 = Ph$).[316]

The insertion reaction of GeH_2 into a Ge−H bond of triethylgermane (**352**) in the gas phase has an activation energy of -10.6 ± 1.1 kJ mol^{-1} measured over the range 292–557 K.[317] This is the first activation energy measured for a germylene reaction. The results parallel those for Si−H insertions and the negative activation energy points to an H-bonded intermediate complex on the reaction pathway.

Et_3GeH (**352**) $\quad$ $PhCOCH_2NO_2$ (**353**) $\quad$ $PhCOCH(Ph)NO_2$ (**354**)

$$RCF(CF_3)COF\ (\mathbf{355}) \longrightarrow RCF(CF_3)CO_2Na\ (\mathbf{356}) \longrightarrow RFC{=}CF_2\ (\mathbf{357}) + RCHFCF_3\ (\mathbf{358})$$

SCHEME 17

The kinetics of proton transfer in aqueous DMSO from benzoylnitromethane (**353**) and 1,2-diphenyl-2-nitroethanone (**354**) to various bases has recently been examined.[318]

In diglyme or 2-hydroxyethanol, perfluoropropyl vinyl ether [**355**; $R = F(CF_2)_3O$] reacts with sodium carbonate to give (**356**; same R) which on heating at 113–132 °C gives rise to (**357**; same R) and (**358**; same R) via parallel mechanisms.[319]

References

1 Bowden, K. and Horri, M. V., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 989.
2 Al-Najjar, A., Bowden, K., and Horri, M. V., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 993.
3 Colthurst, M. J. and Willams, A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1493.
4 Maude, A. B. and Williams, A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 179.
5 Koedjikov, A. H., Blagoeva, I. B., Pojarlieff, I. G., and Kirby, A. J., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2479.
6 Koh, H. J., Kim, O. S., Lee, H. W., and Lee, I., *J. Phys. Org. Chem.*, **10**, 725 (1997).
7 Koh, H. J., Lee, J.-W., Lee, H. W., and Lee, I., *New J. Chem.*, **21**, 447 (1997).
8 Oh, H. K., Woo, S. Y., Shin, C. H., Park, Y. S., and Lee, I., *J. Org. Chem.*, **62**, 5780 (1997).

[9] Castro, E. A., Araneda, C. A., and Santos, J. G., *J. Org. Chem.*, **62**, 126 (1997).
[10] Castro, E. A., Cabrera, M., and Santos, J. G., *Int. J. Chem. Kinet.*, **29**, 113 (1997).
[11] Castro, E. A., Cubillos, M., and Santos, J. G., *J. Org. Chem.*, **62**, 4395 (1997).
[12] Castro, E. A., Cubillos, M., Santos, J. G., and Tellez, J., *J. Org. Chem.*, **62**, 2512 (1997).
[13] Khan, M. N., *Int. J. Chem. Kinet.*, **29**, 647 (1997).
[14] Baumann, K. D., Brighente, I. M. C., Pizzolatti, M. G., and Yunes, R. A., *J. Phys. Org. Chem.*, **9**, 545 (1996).
[15] Dixon, W. J., Hibbert, F., and Mills, J. F., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1503.
[16] Yunes, S. F., Gesser, J. C., Chaimovich, H., and Nome, F., *J. Phys. Org. Chem.*, **10**, 461 (1997).
[17] Curley, K. and Pratt, R. F., *J. Am. Chem. Soc.*, **119**, 1529 (1997).
[18] Shokhaen, M. and Arad, D., *J. Mol. Model. (Electron. Publ.)*, **2** 399 (1996); *Chem. Abs.*, **126**, 292963 (1997).
[19] Golding, B. T., Bleasdale, C., McGinnis, J., Muller, S., Rees, H. T., Rees, N. H., Farmer, P. B., and Watson, W. P., *Tetrahedron*, **53**, 4063 (1997).
[20] Yuldasheva, G. A., Ergozhin, E. E., Gabdrakipov, V. Z., and Kurmanaliev, M. K., *Izv. Nauk Akad. Nauk Resp. Kaz., Ser. Khim.*, **1995**, 46; *Chem. Abs.*, **126**, 103735 (1997).
[21] Abbas, K. A., Hurst, P., and Edward, J. T., *Can. J. Chem.*, **75**, 441 (1997).
[22] Gadre, S. R. and Suresh, C. H., *J. Org. Chem.*, **62**, 2625 (1997).
[23] Li, S., Li, F., Duan, X., and Wang, Z., *Beijing Huagong Daxue Xuebao Ziran Kexueban*, **24**, 54 (1997); *Chem. Abs.*, **127**, 190351 (1997).
[24] Rios, A. and Richard, J. P., *J. Am. Chem. Soc.*, **119**, 8375 (1997).
[25] Borah, R., Deka, N., and Sarma, J. C., *J. Chem. Res. (S)*, **1997**, 110.
[26] Lopez-Belmonte, M. T., Alcantara, A. R., and Sinisterra, J. V., *J. Org. Chem.*, **62**, 1831 (1997).
[27] Rybachenko, V. I., Shreder, G., Titov, E. A., Choti, K. Yu., Semenova, R. G., and Makarova, R. A., *Zh. Obshch. Khim.*, **66**, 1007 (1996); *Chem. Abs.*, **125**, 327845 (1996).
[28] Taniguchi, T. and Ogasawura, K., *J. Chem. Soc., Chem. Commun.*, **1997**, 1399.
[29] Murray, W. V., Turchi, I. J., and Bussolari, J. C., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2715.
[30] Jackman, L. M. and Chen, X., *J. Am. Chem. Soc.*, **119**, 8681 (1997).
[31] Sun, X., Kenkre, S. L., Remenar, J. F., Gilchrist, J. H., and Collum, D. B., *J. Am. Chem. Soc.*, **119**, 4765 (1997).
[32] Han, G., Liu, Z., Yao, S., and Wen, R., *Zhongguo Liangyou Xuebao*, **11**, 22 (1996); *Chem. Abs.*, **126**, 293008 (1997).
[33] Bezudnova, E. Yu., Sakodynskaya, I. K., and Yatsimirskii, A. K., *Kinet. Catal.*, **37**, 534 (1996).
[34] Perrin, C. L. and Engler, R. E., *J. Am. Chem. Soc.*, **119**, 585 (1997).
[35] Lee, I., Lee, D., and Kim, C. K., *J. Phys. Chem.*, **101**, 879 (1997).
[36] Yoo, S.-e. and Cha, O. K., *Bull. Korean Chem. Soc.*, **17**, 653 (1996); *Chem. Abs*., **125**, 327812 (1996).
[37] Hu, X.-G., Lin, R.-S., and Zong, H.-X., *Huaxue Xuebao*, **54**, 1060 (1996); *Chem. Abs.*, **126**, 46795 (1997).
[38] Um, I.-H., Oh, S.-J., and Kwon, D.-S., *Bull. Korean Chem. Soc.*, **17**, 802 (1996); *Chem. Abs.*, **125**, 327830 (1996).
[39] Um, I.-H., Chung, E.-K., and Kwon, D.-S., *Tetrahedron Lett.*, **38**, 4787 (1997).
[40] Um, I.-H., Hong, Y.-J., and Kwon, D.-S., *Tetrahedron*, **53**, 5073 (1997).
[41] Bowden, K., Izadi, J., and Powell, S. L., *J. Chem. Res. (S)*, **1997**, 404.
[42] Bowden, K. and Rehman, S., *J. Chem. Res. (S)*, **1997**, 406.
[43] Um, I.-H., Yoon, H.-W., Lee, J.-S., Moon, H.-J., and Kwon, D.-S., *J. Org. Chem.*, **62**, 5939 (1997).
[44] Moseley, P. G. N. and Ohag, M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 509.
[45] Xu, R. and Go, M.-L., *Chem. Pharm. Bull.*, **45**, 476 (1997).
[46] Um, I.-H., Kim, M.-J., Min, J.-S., and Kwon, D.-S., *Bull. Korean Chem. Soc.*, **18**, 523 (1997); *Chem. Abs*., **127**, 135433 (1997).
[47] Um, I.-H., Chung, E.-K., Kwon, H.-J., and Kwon, D.-S., *Bull. Korean Chem. Soc.*, **18**, 911 (1997); *Chem. Abs*., **127**, 346022 (1997).
[48] Hess, R. A., Hengge, A. C., and Cleland, W. W., *J. Am. Chem. Soc.*, **119**, 6980 (1997).
[49] Marlier, J. F., Haptonstall, B. A., Johnson, A. J., and Sacksteder, K. A., *J. Am. Chem. Soc.*, **119**, 8838 (1997).
[50] Rodriquez, C. F. and Williams, I. H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 953.
[51] Rodriquez, C. F. and Williams, I. H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 959.
[52] Firth-Clark, S., Rodriquez, C. F., and Williams, I. H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1943.
[53] Bowden, K., Fabian, W. M. F., and Kollenz, G., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 547.
[54] Agnihotri, K. and Bowden, K., *J. Chem. Res. (S)*, **1997**, 308.

[55] Bowden, K., Agnihotri, K., Ranson, R. J., Perjessy, A., Hrnciar, P., Prokes, I., and Fabian, W. M. F., *J. Phys. Org. Chem.*, **10**, 841 (1997).
[56] Suggs, J. W. and Pires, R. M., *Tetrahedron Lett.*, **38**, 2227 (1997).
[57] Cunningham, P. D., Geraghty, N. W. A., McArdle, P. J., Murphy, P. V., and O'Sullivan, T. J., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1.
[58] Zhao, C. and Romo, D., *Tetrahedron Lett.*, **38**, 6537 (1997).
[59] White, D., Zemribo, R., and Mead, K. T., *Tetrahedron Lett.*, **38**, 2223 (1997).
[60] Adam, W. and Blancafort, L., *J. Org. Chem.*, **62**, 1623 (1997).
[61] Mulzer, J., Hoyer, K., and Muller-Fahrnow, A., *Angew. Chem., Int. Ed. Engl.*, **36**, 1476 (1997).
[62] Domingo, L. R., Picher, M. T., Andreas, J., Safont, V. S., and Chuchani, G., *Chem. Phys. Lett.*, **274**, 422 (1997).
[63] Bugai, B. I., Kopachm, G. E., Mokrii, E. M., and Sapunov, V. M., *Dopov. Nats. Akad. Nauk Ukr.*, **1995**, 97; *Chem. Abs.*, **125**, 247077 (1996).
[64] Bulakh, E. L. and Militsin, I. A., *Zh. Org. Khim.*, **32**, 1756 (1996); *Chem. Abs.*, **126**, 305333 (1996).
[65] Hettema, H., Hore, N. R., Renner, N. D., and Russell, D. K., *Aust. J. Chem.*, **50**, 363 (1997).
[66] Kulhanek, J. and Pytela, O., *Collect. Czech. Chem. Commun.*, **62**, 913 (1997).
[67] Garcia, B., Ibeas, S., and Leal, J. M., *J. Phys. Org. Chem.*, **9**, 593 (1996).
[68] Uscumlic, G. S. and Krstic, V. V., *J. Serb. Chem. Soc.*, **61**, 621 (1996); *Chem. Abs.*, **125**, 300265 (1996).
[69] Stadlbauer, J. M., Barnabas, M. V., and Walker, D. C., *J. Phys. Chem.*, **101A**, 2442 (1997).
[70] Beak, P. and Pfeifer, L. A., *J. Phys. Org. Chem.*, **10**, 537 (1997).
[71] Sen Gupta, S. K. and Arvind, U., *J. Phys. Org. Chem.*, **10**, 406 (1997).
[72] Perry, C. J., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 977.
[73] Lu, N., Wu, L., Zhang, K., Xu, H., and Wan, J., *Huaxue Fanying Gongcheng Yu Gongyi*, **12**, 144 (1996); *Chem. Abs.*, **125**, 248378 (1996).
[74] Lee, B.-C., Shin, Y.-K., Lee, S. W., and Lee, W. H., *J. Korean Chem. Soc.*, **41**, 69 ; *Chem. Abs.*, **126**, 211717 (1997).
[75] Lyashchuk, S. N. and Skrypnik, Yu. G., *Zh. Org. Khim.*, **32**, 487 (1996); *Chem. Abs.*, **125**, 327839 (1997).
[76] Koo, I. S., Yang, K. P., Park, J. K., and Lee, I., *J. Korean Chem. Soc.*, **41**, 46 (1997); *Chem. Abs.*, **126**, 185686 (1997).
[77] Hirata, R., Kiyan, N. Z., and Miller, J., *Quim. Nova*, **20**, 238 (1997); *Chem. Abs.*, **127**, 65344 (1997).
[78] Kevill, D. N. and D'Souza, M. J., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1721.
[79] Kevill, D. N., Bond, M. W., and D'Souza, M. J., *J. Org. Chem.*, **62**, 7869 (1997).
[80] Shawali, A. S., Elwan, N. M., and Awad, A. M., *J. Chem. Res. (S)*, **1997**, 268.
[81] Pojarlieff, I. G., Blagoeva, I. B., Kirby, A. J., Mikhova, B. P., and Atay, E., *J. Chem. Res. (S)*, **1997**, 220.
[82] Khan, Z., Ratiquee, M. Z. A., Kabir-ud-din, Niaz, M. A., and Khan, A. A., *Indian J. Chem.*, **35A**, 1116 (1996).
[83] Al-Awadi, N., Elnagdi, M. H., Mathew, T., and El-Gamry, I., *Heteroat. Chem.*, **7**, 417 (1996); *Chem. Abs.*, **126**, 31015 (1997).
[84] Koh, H. J., Lee, H. C., Lee, H. W., and Lee, I., *Bull. Korean Chem. Soc.*, **17**, 712 (1996); *Chem. Abs*., **125**, 275018, (1996).
[85] Kevill, D. N. and Upadhyay, V., *J. Phys. Org. Chem.*, **10**, 600 (1997).
[86] Strassler, C. and Heimgartner, H., *Helv. Chim. Acta*, **80**, 2058 (1997).
[87] Kozeny, V., Mindl, J., and Sterba, V., *Chem. Pap.*, **51**, 29 (1997); *Chem. Abs.*, **126**, 343213 (1997).
[88] Fountain, K. R., White, R. D., Patel, K. D., New, D. G., Xu, Y., and Cassely, A. J., *J. Org. Chem.*, **61**, 9434 (1996).
[89] Haider, J., Hill, M. N. S., Mewweer, I. D., Maskill, H., and Smith, J. G., *J. Chem. Soc., Chem. Commun.*, **1997**, 1571.
[90] Brown, D. A., Coogan, R. A., Fitzpatrick, N. J., Glass, W. K., Abukshima, D. E., Shiels, L., Ahlgren, M., Smolander, K., Pakkanen, T. T., Pakkanen, T. A., and Perakyla, M., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2673.
[91] Ghosh, K. K. and Sar, S. K., *J. Indian Chem. Soc.*, **74**, 187 (1997).
[92] Ghosh, K. K., Rajput, S. K., and Sar, S. K., *J. Indian Chem. Soc.*, **73**, 684 (1996).
[93] Ghosh, K. K. and Roy, S., *Bull. Chem. Soc. Jpn*, **69**, 3417 (1996).
[94] Atkinson, R. N., Storey, B. M., and King, S. B., *Tetrahedron Lett.*, **37**, 9287 (1996).
[95] Cho, S. J., Cui, C., Lee, J. Y., Park, J. K., Suh, S. B., Park, J., Kim, B. H., and Kim, K. S., *J. Org. Chem.*, **62**, 4068 (1997).
[96] Hori, K., Kamimura, A., Ando, K., Mizumura, M., and Ihara, Y., *Tetrahedron*, **53**, 4317 (1997).
[97] Dagnac, T., Guillot, J. M., and Le Cloirec, P., *J. Anal. Appl. Pyrol.*, **42**, 53 (1997); *Chem. Abs.*, **127**, 148884 (1997).
[98] Mitas, P., Kavalek, J., and Pytela, O., *Collect. Czech. Chem. Commun.*, **62**, 1562 (1997).

[99] Adachi, T., Yokoo, C., Koizumi, N., Yunoki, N., Ito, Y., and Hayashi, D., *Drug Stab.*, **1**, 166 (1996); *Chem. Abs.*, **126**, 203648 (1997).
[100] Cox, R. A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1743.
[101] Bowden, K., Hiscocks, S. P., and Reddy, M. K., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1133.
[102] Iijima, T., Sakurai, T., Kubo, K., and Inoue, H., *Nippon Kagaku Kaishi*, **1997**, 163; *Chem. Abs.*, **126**, 157071 (1997).
[103] Slebocka-Tilk, H., Rescorla, C. G., Shirin, S., Bennet, A. J., and Brown, R. S., *J. Am. Chem. Soc.*, **119**, 10969 (1997).
[104] Frau, J., Donoso, J., Munoz, F., and Garcia-Blanco, F., *THEOCHEM*, **390**, 255 (1997).
[105] Frau, J., Coll, M., Donoso, J., Munoz, F., Vilanova, B., and Garcia-Blanco, F., *J. Electron Theor. Chem.*, **2**, 56 (1997); *Chem. Abs.*, **127**, 205369 (1997).
[106] Frau, J., Donoso, J., Munoz, F., Vilanova, B., and Garcia-Blanco, F., *Helv. Chim. Acta*, **80**, 739 (1997).
[107] Westwood, N. J., Schofield, C. J., and Claridge, T. D. W., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2725.
[108] Bowden, K. and Hiscocks, S. P., *J. Chem. Res. (S)*, **1997**, 96.
[109] Pippich, S., Bartsch, H., and Holzer, W., *Tetrahedron*, **53**, 8439 (1997).
[110] Yamazaki, Y., McEntagart, J., Shinozaki, K., and Yazawa, H., *Chem. Pharm. Bull.*, **44**, 599 (1996).
[111] Gomes De Oliveira, A., Scarpa, M. V., and Chaimovich, H., *J. Pharm. Sci.*, **86**, 616 (1997).
[112] Dorman, D. E., Lorenz, L. K., Occolowitz, J. L., Spangle, L. A., Collins, M. W., Bashore, F. N., and Baertschi, S. W., *J. Pharm. Sci.*, **86**, 540 (1997).
[113] Baertschi, S. W., Dorman, D. E., Occolowitz, J. L., Collins, M. W., Spangle, L. A., Stephenson, G. A., and Lorernz, L. J., *J. Pharm. Sci.*, **86**, 526 (1997).
[114] Hall, C. D., Lowther, N., Tweedy, B. R., Kayhanian, R., Piffl, M., and Shaw, G., *Phosphorus Sulfur Silicon Relat. Elem.*, **1996**, 109; *Chem. Abs.*, **126**, 74379 (1997).
[115] Okubo, M., Sakata, M., Iwatsiu, Y., Tsurusaki, N., Nakashima, S., Iwamoto, Y., Nonaka, H., Yamauchi, A., and Matsuo, K., *J. Phys. Org. Chem.*, **10**, 242 (1997).
[116] Laila, A. and Isaacs, N. S., *J. Prakt. Chem./Chem.-Ztg.*, **338**, 691 (1996).
[117] Chirkov, Yu. N., Tiger, R. P., Entelis, S. G., Draye, A.-C., Watelet, M., and Tondeur, J.-J., *Bull. Soc. Chim. Belg.*, **105**, 477 (1996).
[118] Raczynska, E. D., *J. Chem. Res. (S)*, **1997**, 214.
[119] Vlasak, P. and Mindl, J., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1401.
[120] Chahoua, L., Mesic, M., Revis, C. L., Vigroux, A., and Fishbein, J. C., *J. Org. Chem.*, **62**, 2500 (1997).
[121] Jain, A. K., Singh, P., and Sahoo, B. B., *J. Phys. Org. Chem.*, **10**, 770 (1996).
[122] Hegarty, A. F., Kelly, J. G., and Relihan, C. M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1175.
[123] Antelo, J. M., Arce, F., Crugeiras, J., and Parajo, M., *J. Phys. Org. Chem.*, **10**, 631 (1997).
[124] Iqbal, R., Rama, N. H., Yunus, U., Saeed, A., and Zamani, K., *J. Chem. Soc. Pak.*, **19**, 77 (1997); *Chem. Abs.*, **127**, 248060 (1997).
[125] Kwon, K.-S., Heo, J.-N., Kim, C.-S., Lee, Y.-G., and Sung, N.-D., *J. Korean Chem. Soc.*, **41**, 362 (1997); *Chem. Abs.*, **127**, 247761 (1997).
[126] Samarkandy, A.-R., Al-Thabaiti, S., Hamed, E. A., and Sidahmed, I. M., *Alexandria J. Pharm. Sci.*, **10**, 161 (1996); *Chem. Abs.*, **126**, 103755 (1997).
[127] El-Nader, H. M. A. and Moussa, M. N. H., *Chem. Pharm. Bull.*, **44**, 1641 (1996).
[128] Cox, R. A., *Can. J. Chem.*, **75**, 1093 (1997).
[129] Lee, J. P., Bembi, R., and Fife, T. H., *J. Org. Chem.*, **62**, 2872 (1997).
[130] Buncel, E., Manderville, R. A., and Dust, J. M., *J. Chem. Soc., Perkin Trans. 2*, **1997**. 1019.
[131] Collins Cafiero, P. A., French, C. S., McFarlane, M. D., Mackie, R. K., and Smith, D. M., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1375.
[132] Nicholson, S. and Taylor, P. J., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1771.
[133] Jefferson, E. A., Kresge, A. J., and Paine, S. W., *Can. J. Chem.*, **75**, 56 (1997).
[134] Teranishi, K., Hisamatsu, M., and Yamada, T., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1831.
[135] So, Y.-H. and Heeshen, J. P., *J. Org. Chem.*, **62**, 3552 (1997).
[136] Casanova, J., Cooper, R., Bahe, E. J., and Servis, K. L., *Croat. Chem. Acta*, **69**, 1455 (1996); *Chem. Abs.*, **126**, 185682 (1997).
[137] Arcelli, A., Papa, M., Porzi, G., and Sandri, S., *Tetrahedron*, **53**, 10513 (1997).
[138] Reiter, L. A. and Jones, B. P., *J. Org. Chem.*, **62**, 2808 (1997).
[139] Bowden, K. and Byrne, J. M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 123.
[140] Bowden, K., Hiscocks, S. P., and Reddy, M. K., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1133.
[141] Shashidhar, M. S., Rajeev, K. G., and Bhatt, M. V., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 559.
[142] Fife, T. H., Bembi, R., and Natarajan, R., *J. Am. Chem. Soc.*, **118**, 12956 (1996).
[143] Cox, C., Young, V. G., and Lectka, T., *J. Am. Chem. Soc.*, **119**, 2307 (1997).
[144] Bowden, K. and Rumpal, S., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 983.

[145] Bowden, K. and Brownhill, A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 997.
[146] Khan, M. N., *Indian J. Chem.*, **35B**, 1047 (1996).
[147] Madder, A., De Clercq, P. J., and Maskill, H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 851.
[148] Brinchi, L., Profio, P. D., Germani, R., Savelli, G., and Bunton, C. A., *Langmuir*, **13**, 4583 (1997).
[149] Mishra, S., Panigrahi, A. K., and Sinha, B. K., *J. Indian Chem. Soc.*, **74**, 408 (1997).
[150] Asai, S., Nakamura, H., and Yamada, M., *Chem. Eng. J. (Lausanne)*, **67**, 19 (1997); *Chem. Abs.*, **127**, 262346 (1997).
[151] Li, Q., Meng, X., Zeng, X., Qin, Z., and Zhou, P., *Sichuan Daxue Xuebao, Ziran Kexueban*, **34**, 71 (1997); *Chem. Abs.*, **127**, 176070 (1997).
[152] Wang, G.-J., Ye, D., and Fife, W. K., *J. Am. Chem. Soc.*, **118**, 12536 (1996).
[153] Lin, H.-K., Kou, F. P., Zhu, S.-R., and Chen, R.-T., *Gaodeng Xuexiao Huaxue Xuebao*, **18**, 513 (1997); *Chem. Abs.*, **127**, 148830 (1997).
[154] Kimura, E., Hashimoto, H., and Koike, T., *J. Am. Chem. Soc.*, **118**, 10963 (1996).
[155] Broxton, T. J. and Nasser, A., *Can. J. Chem.*, **75**, 202 (1997).
[156] Khan, M. N., Arifin, Z., Lasidek, M. N., Hanifiah, M. A. M., and Alex, G., *Langmuir*, **13**, 3959 (1997).
[157] Khan, M. N., *J. Colloid Interface Sci.*, **182**, 602 (1996).
[158] Khan, M. N., *J. Org. Chem.*, **62**, 3190 (1997).
[159] Khan, N. M. and Arifin, Z., *Colloids Surf. A*, **125**, 149 (1997).
[160] Ghosh, K. K. and Sar, S. K., *React. Kinet. Catal. Lett.*, **61**, 193 (1997).
[161] Ghosh, K. K. and Roy, S., *Indian J. Chem.*, **36B**, 324 (1997).
[162] Hol, P., Streefland, L., Blandamer, M. J., and Engberts, J. B. F. N., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 485.
[163] Shen, J.-J., Zhao, Z.-G., and Ma, J.-M., *Gaodeng Xuexiao Huaxue Xuebao*, **18**, 1527 (1997); *Chem. Abs.*, **127**, 247762 (1997).
[164] Cuenca, A., *Tetrahedron*, **53**, 12361 (1997).
[165] Cuenca, A. and Strubinger, A., *Tetrahedron*, **52**, 11665 (1996).
[166] Broo, K., Allert, M., Andersson, L., Erlandsson, P., Stenhagen, G., Wigstrom, J., Ahlberg, P., and Baltzer, L., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 397.
[167] Moss, R. A., Bose, S., and Krogh-Jesperen, K., *J. Phys. Org. Chem.*, **10**, 27 (1997).
[168] Connors, K. A., *Chem. Rev.*, **97**, 1325 (1997).
[169] Yatsimirsky, A. K. and Bezsoudnova, K. Yu., *Izv. Akad. Nauk, Ser. Khim.*, **1996**, 2658; *Chem. Abs.*, **126**, 157079 (1997).
[170] Tee, O. S. and Donga, R. A., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2763.
[171] Tee, O. S. and Giorgi, J. B., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1013.
[172] Tee, O. S., Gadosy, T. A., and Giorgi, J. B., *Can. J. Chem.*, **75**, 83 (1997).
[173] Fernandez, M. A. and de Rossi, R. H., *J. Org. Chem.*, **62**, 7554 (1997).
[174] Liu, Y., Zhang, Y.-M., Qi, A.-D., Chen, R.-T., Yamamoto, K., Wada, T., and Inoue, Y., *J. Org. Chem.*, **62**, 1826 (1997).
[175] Zhang, B. and Breslow, R., *J. Am. Chem. Soc.*, **119**, 1676 (1997).
[176] Tecilla, P., Tonellato, U., Veronese, A., Felluga, F., and Scrimin, P. A., *J. Org. Chem.*, **62**, 7621 (1997).
[177] Molenveld, P., Kapsabelis, S., Engbersen, J. F. J., and Reinhoudt, D. N., *J. Am. Chem. Soc.*, **119**, 2948 (1997).
[178] Prabhu, D. V. and Laxmeshwar, N. B., *Asian J. Chem.*, **9**, 70 (1997); *Chem. Abs.*, **126**, 157062 (1997).
[179] Bohra, A., Sharma, P. K., and Banerji, K. K., *J. Org. Chem.*, **62**, 3562 (1997).
[180] Dixneuf, P. H., Guyot, T., Ness, M. D., and Roberts, S. M., *J. Chem. Soc., Chem. Commun.*, **1997**, 2083.
[181] Karunakaran, K. and Elango, K. P., *J. Indian Chem. Soc.*, **74**, 299 (1997).
[182] Singh, R. A. and Singh, R. S., *Oxid. Commun.*, **20**, 248 (1997).
[183] Mohan, R. V. G. K. and Sondu, S., *React. Kinet. Catal. Lett.*, **61**, 167 (1997).
[184] Cacciapaglia, R., Mandolini, L., and Van Axel Castelli, V., *J. Org. Chem.*, **62**, 3089 (1997).
[185] Bolzacchini, E., Meinardi, S., Orlandi, M., and Rindone, B., *J. Mol. Catal. A*, **111**, 281 (1996).
[186] Rawlings, J., Hengge, A. C., and Cleland, W. W., *J. Am. Chem. Soc.*, **119**, 542 (1997).
[187] Komiyama, M., Sumaoka, J., Yonezawa, K., Matsumoto, Y., and Yashiro, J., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 75.
[188] Aggarwal, V. K., Tarver, G. J., and McCague, R., *J. Chem. Soc., Chem. Commun.*, **1996**, 2713.
[189] Miyama, S., Asanuma, H., and Komiyama, M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1685.
[190] Moss, R. A., Bracken, K., and Zhang, J., *J. Chem. Soc., Chem. Commun.*, **1997**, 563.
[191] Moss, R. A., Zhang, J., and Bracken, K., *J. Chem. Soc., Chem. Commun.*, **1997**, 1639.
[192] Saha, P. N., Mondal, S. K., Kar, D., Das, M., Das, A. K., and Mohanty, R. K., *J. Chem. Res. (S)*, **1997**, 364.
[193] Higgins, J., Zhou, X., Liu, R., and Huang, T. T.-S., *J. Phys. Chem.*, **101A**, 2702 (1997).

[194] Safont, V. S., Moliner, V., Andres, J., and Domingo, L. R., *J. Phys. Chem.*, **101A**, 1859 (1997).
[195] Domingo, L. R., Andres, J., Moliner, V., and Safont, V. S., *J. Am. Chem. Soc.*, **119**, 6415 (1997).
[196] Huang, C.-L., Wu, C.-C., and Lien, M.-H., *J. Phys. Chem.*, **101A**, 7867 (1997).
[197] Huang, H. H., Fan, K. N., Huang, W., Li, Z. H., Mok, C. Y., Wang, W. N., and Chin, W. S., *Chem. Phys. Lett.*, **265**, 508 (1997).
[198] Ocampo, R., Dolbier, W. R., Bartberger, M. D., and Paredes, R., *J. Org. Chem.*, **62**, 109 (1997).
[199] Garcia, H., Gilbert, L., Perrod, M.-C., Ratton, S., and Rochin, C., *Ind. Chem. Libr.*, **1996**, 301; *Chem. Abs.*, **126**, 18595 (1997).
[200] Plamondon, J. E. and Nairn, J. G., *J. Pharm. Sci.*, **86**, 205 (1997).
[201] Czyryca, P. and Paneth, P., *J. Org. Chem.*, **62**, 7305 (1997).
[202] Chourey, V. R., Pande, S., Shastry, L. V., and Shastry, V. R., *Asian J. Chem.*, **9**, 435 (1997).
[203] Bjornestedt, R., Zhong, G., Lerner, R. A., and Barbas, C. F., *J. Am. Chem. Soc.*, **118**, 11720 (1996).
[204] Teramoto, M., Nakatani, R., Huang, Q., and Watari, T., *J. Chem. Eng. Jpn*, **30**, 176 (1997); *Chem. Abs.*, **126**, 224895 (1997).
[205] Buback, M. and Hinton, C., *Z. Phys. Chem. (Munich)*, **199**, 229 (1997).
[206] Sinnott, M. (Ed.) *Comprehensive Biological Catalysis, a Mechanistic Reference*, Vol. 1, Academic Press, New York, 1998.
[207] Holm, R. H. and Solomon, E. I., *Chem. Rev.*, **96**, 2237 (1996).
[208] Hwang, J.-K. and Warshel, A., *J. Am. Chem. Soc.*, **118**, 11745 (1996).
[209] Na, J. and Houk, K. N., *J. Am. Chem. Soc.*, **118**, 9204 (1996).
[210] Kitson, T. M., *Bioorg. Chem.*, **24**, 331 (1996).
[211] Wlodek, S. T., Antosiewicz, J., and Briggs, J. M., *J. Am. Chem. Soc.*, **119**, 8159 (1997).
[212] Nishizawa, K., Ohgami, Y., Matsuo, N., Kisida, H., and Hirohara, H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1293.
[213] Parve, O., Vallikivr, I., Metsala, A., Lille, U., Tougu, V., Sikk, P., Kaambre, T., Vija, H., and Pehk, T., *Tetrahedron*, **53**, 4889 (1997).
[214] Serebryakov, E. P. and Gamalevich, G. D., *Mendeleev Commun.*, **1996**, 222.
[215] Vilanova, B., Frau, J., Donoso, J., Munoz, F., and Garcia Blanco, F., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2439.
[216] Harrison, M. J., Burton, N. A., Hillier, I. H., and Gould, I. R., *J. Chem. Soc., Chem. Commun.*, **1996**, 2769.
[217] Pirrincioglu, N., Zaman, F., and Williams, A., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2561.
[218] Siegbahn, P. E. M. and Crabtree, R. H., *J. Am. Chem. Soc.*, **119**, 3103 (1997).
[219] Jonas, R. T. and Stack, T. D. P., *J. Am. Chem. Soc.*, **119**, 8566 (1997).
[220] Mader, M. M. and Bartlett, P. A., *Chem. Rev.*, **97**, 1281 (1997).
[221] Li, T., Lerner, R. A., and Janda, K. D., *Acc. Chem. Res.*, **30**, 115 (1997).
[222] Janda, K. D., Lo, L.-C., Lo, C.-H. L., Sim, M.-M., Wang, R., Wong, C.-H., and Lerner, R. A., *Science*, **275**, 945 (1997).
[223] Wentworth, P., Datta, A., Smith, S., Marshall, A., Partridge, L. J., and Blackburn, M. G., *J. Am. Chem. Soc.*, **119**, 2315 (1997).
[224] Ersoy, O., Fleck, R., Sinskey, A., and Masamune, S., *J. Am. Chem. Soc.*, **118**, 13077 (1996).
[225] Yu, J., Choi, S. Y., Lee, S., Yoon, H. J., Jeong, S., Mun, H., Park, H., and Schultz, P. G., *J. Chem. Soc., Chem. Commun.*, **1997**, 1957.
[226] Zhong, G., Hoffmann, T., Lerner, R. A., Danishefsky, S., and Barbas, C. F., *J. Am. Chem. Soc.*, **119**, 8131 (1997).
[227] Weiner, D. P., Wiemann, T., Wolfe, M. M., Wentworth, P., and Janda, K. D., *J. Am. Chem. Soc.*, **119**, 4088 (1997).
[228] Dahl, O., *Organophosphorus Chem.*, **27**, 78 (1996).
[229] Florian, J. and Warshel, A., *J. Am. Chem. Soc.*, **119**, 5473 (1997).
[230] Humeres, E., *Gazz. Chim. Ital.*, **126**, 449 (1996).
[231] Machadu, V. G. and Nome, F., *J. Chem. Soc., Chem. Commun.*, **1997**, 1917.
[232] Banks, M. R., Gosney, I., Kilgour, D., Cadogan, J. I. G., and Hodgson, P. K. G., *Heteroat. Chem.*, **7**, 503 (1996).
[233] Simanenko, Yu. S., Belousova, I. A., and Savelova, V. A., *Zh. Org. Khim.*, **32**, 613 (1996).
[234] Bunton, C. A., Gillitt, N. D., and Kumar, A., *Proc. ERDEC Sci., Conf. Chem. Biol. Def. Res.*, **1995**, 405; *Chem. Abs.*, **127**, 108989 (1997).
[235] Pankiewicz, K. W., Lesiak, K., and Watanbe, K. A., *J. Am. Chem. Soc.*, **119**, 3691 (1997).
[236] Shon, K.-H., Park, K.-K., Lee, B.-Y., and Shin, G.-C., *J. Korean Chem. Soc.*, **41**, 299 (1997); *Chem. Abs.*, **127**, 161890 (1997).
[237] Witt, D. and Rachion, J., *Heteroat. Chem.*, **7**, 359 (1996).

[238] Edmundson, R. S., *Organophosphorus Chem.*, **27**, 100 (1996).
[239] Le Roux, C., Modro, A. M., and Modro, T. A., *J. Chem. Res. (S)*, **1997**, 100.
[240] Murray, M. and Boulajoun, I., *Phosphorus Res. Bull.*, **6**, 155 (1996); *Chem. Abs.*, **127**, 149250 (1997).
[241] Kehler, J. and Breuer, E., *J. Chem. Soc., Chem. Commun.*, **1997**, 1751.
[242] Nunez, A. and Nunez, O., *J. Org. Chem.*, **61**, 8386 (1996).
[243] Chauhan, J. S., Shinde, C. P., and Patil, R., *Asian J. Chem.*, **8**, 411 (1996).
[244] Patil, R., Shinde, C. P., Dass, K. B., and Chauhan, J. S., *Asian J. Chem.*, **8**, 197 (1996).
[245] Harger, M. J. P., *J. Chem. Soc., Chem. Commun.*, **1997**, 403.
[246] Harger, M. J. P., *J. Chem. Soc., Chem. Commun.*, **1997**, 1503.
[247] Harger, M. J. P., *Tetrahedron Lett.*, **38**, 4507 (1997).
[248] Shao, R. T. L., Miao, W. S., and Yang, G. F., *Chin. Chem. Lett.*, **8**, 269 (1997); *Chem. Abs.*, **127**, 81506 (1997).
[249] Li, H.-Y., Chen, R.-Y., and Ren, K.-T., *Phosphorus Sulfur Silicon Relat. Elem.*, **119**, 279 (1996).
[250] Yang, Y.-C., Szafraniec, L. L., Beaudry, W. T., Rohrbaugh, D. K., Procell, L. R., and Samuel, J. B., *J. Org. Chem.*, **62**, 8407 (1996).
[251] Yang, Y.-C., Berg, F. J., Szafraniec, L. L., Beaudry, W. T., Bunton, C. A., and Kumar, A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 607.
[252] Chen, X., Zhang, N.-J., and Zhao, Y.-F., *Bioorg. Chem.*, **25**, 23 (1997).
[253] Blasko, A., Bunton, C. A., and Kumar, A., *J. Phys. Org. Chem.*, **10**, 427 (1997).
[254] Patil, R., Shinde, C. P., and Samadhiya, A., *Asian J. Chem.*, **9**, 403 (1997).
[255] Tang, C.-C., Lang, H.-F., He, Z.-J., and Chen, R.-Y., *Phosphorus Sulfur Silicon Relat. Elem.*, **114**, 123 (1996).
[256] Patil, R., Shinde, C. P., and Samadhai, A., *Asian J. Chem.*, **9**, 407 (1997).
[257] Tang, C.-C., Ma, F.-P., and He, Z.-J., *Gaodeng Xuexiao Huaxue Xuebao*, **18**, 229 (1997); *Chem. Abs.*, **126**, 238430 (1997).
[258] Perreault, D. M. and Anslyn, E. V., *Angew. Chem., Int. Ed. Engl.*, **36**, 432 (1997).
[259] Komiyama, M. and Yoshinari, K., *J. Org. Chem.*, **62**, 2155 (1997).
[260] Azucena, E., Grapsas, I., and Mobashery, S., *J. Am. Chem. Soc.*, **119**, 2317 (1997).
[261] Ora, M., Oivanen, M., and Lonnberg, H., *J. Org. Chem.*, **62**, 3246 (1997).
[262] Zhao, S.-R., Chen, K.-X., Jiang, H.-L., Wang, Q.-M., and Ji, R.-Y., *Chin. J. Chem.*, **15**, 84 (1997).
[263] Dantzman, C. L. and Kiessling, L. L., *J. Am. Chem. Soc.*, **118**, 11715 (1996).
[264] Tsuruoka, H., Shohda, K., Wada, T., and Sekine, M., *J. Org. Chem.*, **62**, 2813 (1997).
[265] Li, Y., Zhou, W., Wang, Q., Liu, H., and Zhao, Y., *Phosphorus Sulfur Silicon Relat. Elem.*, **116**, 15 (1996).
[266] Chen, X., Zhang, N.-J., and Xhao, Y.-F., *Bioorg. Chem.*, **25**, 23 (1997).
[267] Wittmann, V. and Wong, C.-W., *J. Org. Chem.*, **62**, 2144 (1997).
[268] Du, S., Plat, D., Belakhov, V., and Baasov, T., *J. Org. Chem.*, **62**, 794 (1997).
[269] Kim, K. and Cole, P. A., *J. Am. Chem. Soc.*, **119**, 11096 (1997).
[270] Schulz, J. and Gani, D., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 657.
[271] Hart, J. C., Burton, N. A., Hillier, I. H., Harrison, M. J., and Jewsbury, P., *J. Chem. Soc., Chem. Commun.*, **1997**, 1431.
[272] Bezrodnyi, V. P., Kiprya, A. V., and Skrypnik, Yu. G., *Zh. Org. Khim.*, **32**, 533 (1996); *Chem. Abs.*, **125**, 327840 (1996).
[273] Bezrodnyi, V. P., Kiprya, A. V., and Skrypnik, Yu. G., *Zh. Org. Khim.*, **32**, 540 (1996); *Chem. Abs.*, **125**, 327841 (1996).
[274] Moskvichev, Yu. A., Timoshenko, G. N., Grigorichev, A. K., Tarasov, A. V., Smirnova, T. M., and Frolova, O. B., *Izv. Vyssh. Uchebn. Zaved. Khim. Khim. Tekhnol.*, **39**, 82 (1996); *Chem. Abs.*, **126**, 7547 (1997).
[275] Kuritsyn, L. V., Kustova, T. P., Moskvichev, Y. A., and Nikiforov, A. V., *Izv. Vyssh. Uchebn. Zaved., Khim. Khim. Tekhnol.*, **39**, 183 (1996); *Chem. Abs.*, **126**, 211710 (1997).
[276] Park, H.-Y., Son, K.-J., Cheong, D.-Y., and Yoh, S.-D., *Bull. Korean Chem. Soc.*, **18**, 1010 (1997).
[277] Park, H.-Y., Son, K.-J., Cheong, D.-Y., and Yoh, S.-D., *Bull. Korean Chem. Soc.*, **18**, 1179 (1997).
[278] Oh, H. K., Kwon, Y. B., Chung, D. S., and Lee, I., *J. Phys. Org. Chem.*, **9**, 683 (1996).
[279] Yoh, S.-D. and Cheong, D.-Y., *J. Phys. Org. Chem.*, **9**, 701 (1996).
[280] Oh, H. K., Song, S. J., Jo, D.-S., and Lee, I., *J. Phys. Org. Chem.*, **10**, 91 (1997).
[281] Oh, H. K., Yun, J. H., Cho, I. H., and Lee, I., *Bull. Korean Chem. Soc.*, **18**, 390 (1997).
[282] King, J. F. and Gill, M., *J. Org. Chem.*, **61**, 7250 (1996).
[283] Sendega, R. V., Majitra, R. G., and Pirig, Ya. N., *Zh. Org. Chem.*, **32**, 1491 (1996); *Chem. Abs.*, **126**, 305331 (1997).
[284] Savelova, V. A., Zubareva, T. M., and Simanenko, Yu. S., *Zh. Org. Khim.*, **32**, 1545 (1996); *Chem. Abs.*, **126**, 305332 (1997).

[285] Savelova, V. A., Karpichev, E. A., Simanenko, Yu. S., Prokop'eva, T. M., Lobachev, V. L., and Belousova, I. A., *Zh. Org. Khim.*, **32**, 551 (1996); *Chem. Abs.*, **125**, 327842 (1996).
[286] Okuyama, T., *Bull. Chem. Soc. Jpn*, **69**, 3281 (1996).
[287] Brown, C. and Evans, G. R., *Tetrahedron Lett.*, **37**, 9101 (1996).
[288] Pan, S., Ren, P., and Dong, T., *Fudan Xuebao, Ziran Kexueban*, **35**, 274 (1996); *Chem. Abs.*, **126**, 103884 (1997).
[289] Whang, J. P., Yang, S. G., and Kim, Y. H., *J. Chem. Soc., Chem. Commun.*, **1997**, 1355.
[290] Kim, C. Y. and Lee, I., *Bull. Korean Chem. Soc.*, **18**, 880 (1997).
[291] Lee, J.-P., Uhm, T.-S., Sung, D.-D., and Lee, I., *J. Korean Chem. Soc.*, **40**, 594 (1996); *Chem. Abs.*, **125**, 275017 (1996).
[292] Lee, J.-P. and Uhm, T.-S., *J. Korean Chem. Soc.*, **41**, 39 (1997); *Chem. Abs.*, **126**, 185685 (1997).
[293] Makitra, R. G., Vasyutyn, Ya. M., and Pirigin, Ya. N., *Zh. Org. Khim.*, **32**, 861 (1996); *Chem. Abs.*, **126**, 211713 (1997).
[294] Leis, J. R., Norberto, F., Moreira, J. A., and Iley, J., *J. Chem. Res. (S)*, **1997**, 88.
[295] Andersen, K. K., Hubbard, C. D., Gerhard, A., van Eldik, R., and Kociolek, M. G., *J. Phys. Org. Chem.*, **10**, 175 (1997).
[296] Sedlak, M., Kavalek, J., Machacek, V., and Sterba, V., *Molecules*, **1**, 170 (1996); *Chem. Abs.*, **127**, 50184 (1997).
[297] Baxter, N. J., Laws, A. P., Rigoreau, L., and Page, M. I., *J. Chem. Soc., Chem. Commun.*, **1997**, 2037.
[298] Vass, E., Ruff, F., Kapovits, I., Szabo, D., and Kucsman, A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2061.
[299] Clennan, E. L. and Greer, A., *Tetrahedron Lett.*, **37**, 6093 (1996).
[300] Swift, H. R. and Williams, D. L. H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1933.
[301] Dicks, A. P., Beloso, P. H., and Williams, D. L. H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1429.
[302] Olah, G. A., Burrichter, A., Rasul, G., Christe, K. O., and Prakash, G. K. S., *J. Am. Chem. Soc.*, **119**, 4345 (1997).
[303] Derume, A., Egg, H., and Koenig, R., *Sci. Pharm.*, **64**, 327 (1996); *Chem. Abs.*, **125**, 275045 (1996).
[304] Prokuev, V. A., and Zhdanova, O. V., *Izv. Vyssh. Uchebn. Zaved. Khim. Khim. Tekhnol.*, **40**, 61 (1997); *Chem. Abs.*, **127**, 148841 (1997).
[305] Kravchenko, V. V., Popov, A. F., Dontsova, N. E., Litvinov, V. P., and Lutsyuk, A. F., *Ukr. Khim. Zh.*, **62**, 104 (1996); *Chem. Abs.*, **126**, 343214 (1997).
[306] Ceulemans, E., Vercauteren, K., Dyall, L. K., Buelens, D., and Dehaen, W., *Tetrahedron*, **53**, 9657 (1997).
[307] Fountain, K. R., Dunkin, T. W., and Patel, K. D., *J. Org. Chem.*, **62**, 3711 (1997).
[308] Yanchuk, N. I., *Zh. Obshch. Khim.*, **66**, 1473 (1996); *Chem. Abs.*, **126**, 144327 (1997).
[309] Nakayama, J., Otani, T., Sugihara, Y., and Ishii, A., *Tetrahedron Lett.*, **38**, 5013 (1997).
[310] Webster, R. D. and Bond, A. M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1075.
[311] Dalby, K. N. and Jencks, W. P., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1555.
[312] Robert, J., Anouti, M., and Paris, J., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 473.
[313] Gill, M. S., Neverov, A. A., and Brown, R. S., *J. Org. Chem.*, **62**, 7351 (1997).
[314] Hancox, E. I. and Walker, R. T., *Nucleosides Nucleotides*, **15**, 135 (1996).
[315] Um, I.-H., Nahm, J.-H., Lee, Y.-J., and Kwon, D.-S., *Bull. Korean Chem. Soc.*, **17**, 840 (1996).
[316] Teixido, J., Borrell, J. I., Serra, B., Colominas, C., Batllori, X., Piniella, J. F., and Alvarez-Larena, A., *Tetrahedron*, **53**, 4487 (1997).
[317] Becerra, R., Boganov, S. E., Egorov, M. P., Nefedov, O. M., and Walsh, R., *Mendeleev Commun.*, **1997**, 87.
[318] Bernasconi, C. F. and Montanez, R. L., *J. Org. Chem.*, **62**, 8162 (1997).
[319] Yuminov, V. G., *Zh. Org. Khim.*, **31**, 1142 (1995); *Chem. Abs.*, **124**, 342454 (1996).

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CHAPTER 3

Radical Reactions: Part 1

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Introduction

Both intermolecular and intramolecular additions of carbon radicals to alkenes and alkynes continue to be a widely investigated method for carbon–carbon bond formation and has been the subject of a number of review articles.[1,2] In particular, the inter- and intra-molecular additions of vinyl, heteroatomic and metal-centred radicals to alkynes have been reported[1] and also the factors which influence the addition reactions of carbon radicals to unsaturated carbon–carbon bonds.[2] The stereochemical outcome of such additions continues to attract interest. The generation and use of alkoxy radicals in both asymmetric cyclizations and skeletal rearrangements has been reviewed[3] and the use of free radical reactions in the stereoselective synthesis of α-amino acid derivatives has appeared in two reports.[4,5] The stereochemical features and synthetic potential of the [1,2]-Wittig rearrangement has also been reviewed.[6] In addition, a review of some recent applications of free radical chain reactions in organic and polymer synthesis has appeared.[7] The effect of solvent upon the reactions of neutral free radicals has also recently been reviewed.[8]

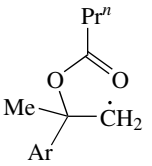
A study of the addition reactions of radicals to fullerenes (C_{60}/C_{70}) by EPR has appeared and the dynamic effects in the EPR spectra of fullerenyl radicals due to hindered rotation and the multi-addition of radicals to fullerenes are described.[9] Other review articles which have appeared this year include recent advances in the radical substitution reactions of alkyl, aryl, and vinyl halides[10] and the substitution and photochemical reactions of heterocyclic *N*-oxides.[11] The mechanisms for the oxidation of hydrocarbons, lipids, and low-density lipoproteins have been reviewed.[12]

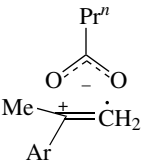
Rearrangements

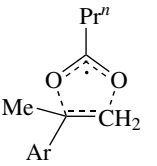
Group Migration

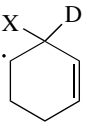
The mechanisms of the (*β*-acyloxy)alkyl and (*β*-phosphatoxy)alkyl radical migrations continue to attract attention. The mechanism of the (*β*-acyloxy)alkyl radical rearrangement has been studied in a range of solvents using a number of substituted aryl and O^{17}-labelled derivatives (**1a**–**c**).[13] A relationship between the electronic structure of the radical, the solvent and the rate and degree of O^{17} scrambling was found indicating that the radicals (**1a**–**c**) can undergo an acyloxy shift by more than one mechanism depending upon the solvent and their electronic structure. For example, considerable O^{17} scrambling occurred for (**1a**) under conditions that would favour a polar TS (e.g. MeOH), suggesting a dissociative radical cation–anion pair mechanism (**2**). Reaction of (**1a**) in benzene indicated the five-membered cyclic TS mechanism (**3**). In contrast, related investigations into (*β*-acyloxy)alkyl radical rearrangements using the substrate (**4a**) in various solvents provided no evidence for any dissociative mechanism, highlighting that the mechanistic pathway chosen is highly substrate dependent.[14] However, rearrangement of the phosphatoxy deuteriated probe (**4b**) in various solvents did show a mechanistic solvent dependence. Rearrangement of (**4b**) in benzene was concluded to occur via a non-dissociative pathway while a fragmentation/recombination mechanism was postulated for its reaction in Bu^tOH. Crossover experiments indicated the intermediacy of a tight ion pair.[14] Both the (*β*-acyloxy)methyl and (*β*-

phosphatoxy)methyl radical migrations have been investigated by theoretical treatments.[15,16]


(**1**)


(**2**)


(**3**)


(**4**)

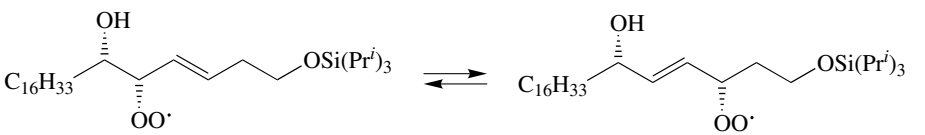
a; Ar = C_6H_5
b; Ar = *p*-$MeOC_6H_4$
c; Ar = *p*-NCC_6H_4

a; X = OC(O)Ph
b; X = OP(O)(OEt)$_2$

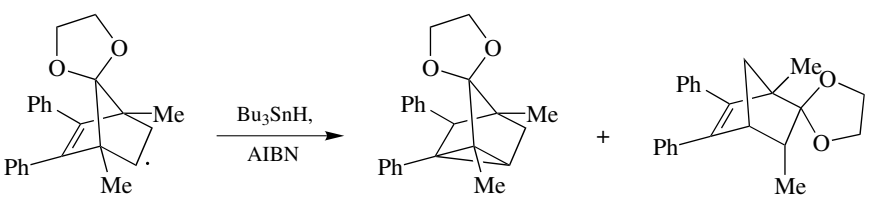
The asymmetric rearrangement of peroxy radical (**5**) has recently been used as the key step in the asymmetric synthesis of Plakorin (Scheme 1).[17] The thermal isomerization of buta-1,2- to buta-1,3-diene has been studied using *ab initio* calculations and the mechanism concluded to proceed stepwise via radical intermediates.[18] The competition between cyclopropyl formation and the homoallyl–homoallyl radical rearrangement has been studied in the radical (**6**) and found to give the 3-*exo* cyclization product (**7**) and the rearranged product (**8**) in a 1 : 5 ratio, respectively, under the conditions shown (Scheme 2).[19]

β-Scission (Ring Opening)

The ring opening of a range of cyclopropylcarbinyl radicals has been investigated.[20–22] The relative rates of opening were found to be in good agreement with experimental data and the use of HF/6–31G* and PMP2/6–31G* methods proved adequate to


(**5**)

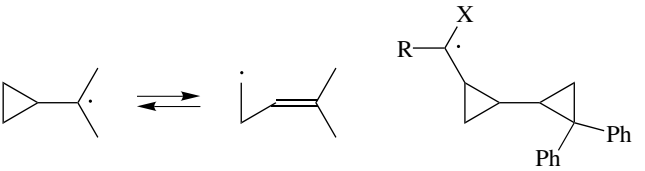
SCHEME 1


(**6**) (**7**) (**8**)

(**7**) : (**8**) = 1 : 5

SCHEME 2

describe the reactions.[20] The effect of substituents upon the ring-opening reactions was explained in steric not electronic terms. The rate of ring opening of the tertiary cyclopropylmethyl radical (**9**) has been reinvestigated using methods based upon trapping of radical (**9**) with PhSH, ABNO, and TEMPO. While the first two methods utilized H-abstraction from PhSH, and ABNO by the $Bu^{t\cdot}$ as a model to calculate the rate of ring opening of (**9**), the last reaction with TEMPO utilized trapping of the 2,3-dimethylbutyl radical as a more accurate model.[21] Laser flash photolysis kinetic studies on the fragmentation of the secondary ethoxycarbonyl radical (**10a**) shows that ring opening proceeds faster than for the analogous alkyl radical (**10b**) counterpart. However, the related tertiary ester radical (**10c**) fragmented slower than its alkyl analogue (**10d**). These results highlighted the need to take into consideration transition state polarity and steric effects in fragmentation reactions. Owing to the relative ease of acrylate-derived ring opening, the authors indicated that researchers should be 'aware of the possibility that equilibration of an acrylate adduct via fragmentation could occur.'[22]

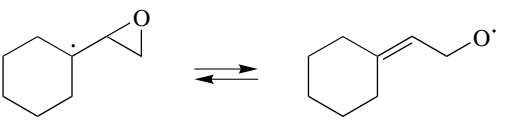


(**9**) (**10**)

a; R = H, X = CO_2Et
b; R = H, X = Me
c; R = Me, X = CO_2Et
d; R = Me, X = Me

Ring-opening reactions of aryl substituted oxiranylcarbinyl radicals have shown that C−C bond cleavage is reversible and in competition with C−O bond cleavage even when no products arising from C−C bond cleavage are obtained.[23] The related cyclohexyl-derived radical (**11**) undergoes fragmentation at 25–30 °C at a rate of 3.2×10^{10} s^{-1} as calculated from PhSH trapping experiments (Scheme 3).[24] The figure is in good agreement with that predicted by theoretical treatments.

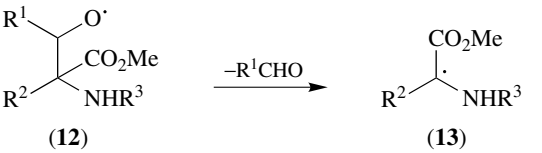
β-Scission of alkoxy radicals (**12**) generated from nitrate esters and Bu_3SnH furnish α-amino acid radicals (**13**) (Scheme 4). This new method for forming α-amino acid radicals may be useful for generating site-specific radicals in peptides.[25] The reactions of C(2) glyceryl radicals (**14**) have been observed by EPR. Whereas the phosphate derived radical (**14a**) gave the reduced product (**15a**) in 70% yield, the unsubstituted



(**11**)

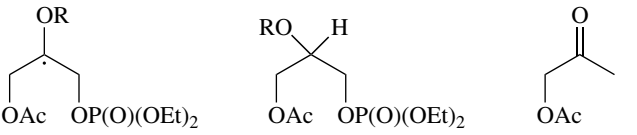
SCHEME 3

derivative (**14b**) furnished a significant amount of elimination products (**16**). The results indicate a new possible radical β-elimination mechanism for lipid damage of lysolecithins via the corresponding C(2) lysolecithin radicals.[26]



(**12**) (**13**)

SCHEME 4



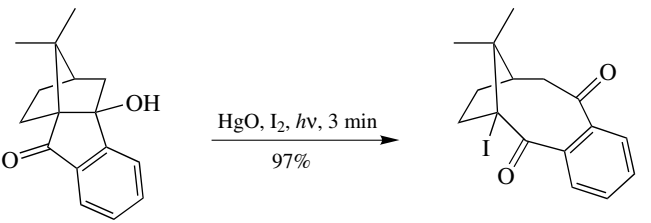
(**14**) (**15**) (**16**)

a; R = Ac
b; R = H

a; R = Ac
b; R = H

Ring Expansion

Regioselective β-fragmentation of the alkoxy radical (**17**) furnishes the ring-expanded iodide (**18**) in good yield under HgO–I_2–irradiation conditions (Scheme 5).[27] Similar transformations could not be accomplished under ionic conditions.



(**17**) (**18**)

SCHEME 5

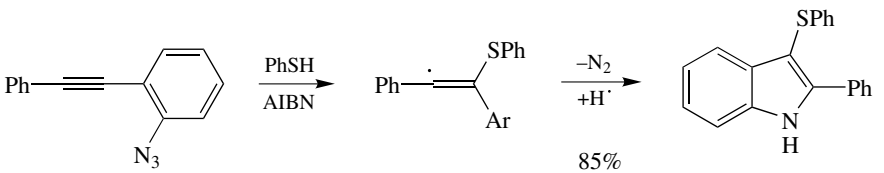
The kinetics of 5-*exo* and 6-*endo* acyl radical cyclizations have been investigated under a variety of reaction conditions.[28] The presence of the 6-*endo* product was found to arise either by a direct cyclization (2.0×10^4 s^{-1}) or by a ring expansion (4.2×10^3 s^{-1}) from the 5-*exo* radical product (1.6×10^5 s^{-1}). Consequently, cyclization in the presence of high concentrations of fast H-donors (e.g. Bu_3SnH) furnished 5-*exo* products whereas reactions under high dilution conditions or with poor H-donors gave rise to 6-*endo* products.

Intramolecular Addition

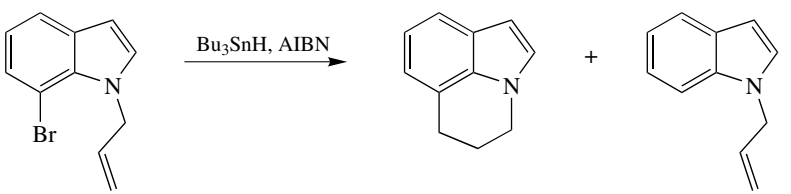
Cyclization

The cyclization of alkyl radicals to give five- and six-membered rings continues to be a rich area of chemistry. The formation of vinyl radicals from the addition of sulfur-derived radicals to alkynes and their consequent reactions with unsaturated functional groups have been reported by two different groups.[29,30] Vinyl radicals, formed from addition of alkyl or arylthiyl radicals to alkynes, undergo cyclization on to the azide functional group (Scheme 6).[29] Caddick *et al*.[30] reported the use of sulfonyl radicals as triggers to mediate cyclizations. Reaction of TsBr with AIBN furnishes sulfonyl radicals which add to alkynes to form vinyl radicals which can undergo further 5-*exo* cyclization on to alkynes. The products are electron-deficient sulfonyl dienes and may well find use in Diels–Alder reactions. Although 5-*exo* cyclizations are normally the favoured mode of carbon radical cyclization, the reactive aryl radical prepared from Bu_3SnH-mediated reaction of 7-bromo-*N*-substituted indole derivative (**19**) undergoes competitive 6-*endo* cyclization and reduction to give (**20**) and (**21**), respectively (Scheme 7).[31] No products from 5-*exo* cyclization were detected, presumably owing to unfavourable geometric constraints. A study into the regioselectivity of cyclization of allyl radicals has appeared.[32] Cyclization of the allyl radical generated from (**22**) proceeded exclusively at the γ-carbon to give the bicycle (**23**) (Scheme 8). The regioselectivity was rationalized on the basis of spin density calculations on the SOMO using PM3 calculations.[32]

The formation of ring sizes other than five- and six-membered rings has been reported, in particular the formation of three- and four-membered rings by 3-*exo* and 4-*exo* radical cyclization, respectively.[33,34] High-yielding 3-*exo* cyclizations have been reported when the cyclized radical contains a radical-stabilizing group.[33] The effects of



SCHEME 6



(**19**) (**20**) (**21**)

(**20**) : (**21**) = 1 : 2

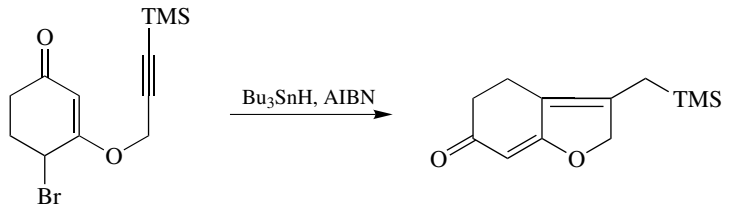
SCHEME 7

various *gem*-disubstituent groups on the rate of 4-*exo* cyclization of carbon radicals have been studied.[34] Optimum yields of 4-*exo* products were obtained with acetals as geminal substituents with the nature of the acetal ring size proving to be crucial for the success of the reaction (Scheme 9). Oxiranylmethyl radicals prepared by 3-*exo*-*trig* cyclization of alkyl alkoxy radicals have been trapped by the Bu^{t}ONO spin trap and their EPR details reported.[35]

The cyclizations of radicals on to the C−N unsaturated bonds of oxime ethers and hydrazones[36] and imines[37] are possible. Addition of the $Bu_3Sn^{\cdot}$ to the digonal carbon of the allene (**24**) forms an allyl radical (**25**) which undergoes 5-*exo* cyclization on to nitrogen-containing multiple bonds.[36] The rate constants for the irreversible 5-*exo* and 6-*endo* cyclization of alkyl radicals on to imines have been determined to be approximately 6.0×10^6 and 6.7×10^5 s^{-1} at 80 °C, respectively.[37] Semi-empirical calculations (MOPAC) indicate that the cyclization rates could be dependent upon the electron density at the iminyl carbon atom.[38] Competition studies involving cyclization of alkyl radicals on to either alkenes or benzyl oxime ethers have indicated that the rates of 5-*exo* (6.8×10^7 s^{-1}) and 6-*exo* (4.1×10^6 s^{-1}) cyclization on to oxime ethers at 80 °C are greater than on to the corresponding imines and are comparable to hydrazone cyclization rates.[38]

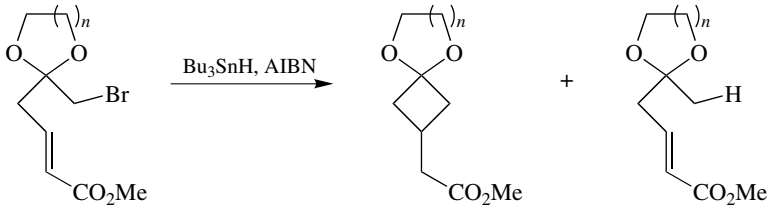
Ab initio studies (UHF/6–31G*) have been used to investigate the 5-*endo* cyclization of various substituted radicals including the 5-oxapenta-2,4-dienoyl radical. The results show that the 5-*endo* cyclization is both kinetically and thermodynamically favoured.[39]

The cyclization of a range of α-heteroatom-functionalized radicals has been studied. Both α-sulfonyl and α-sulfinyl radicals can undergo 5-*exo* cyclization on to alkenes.[40]



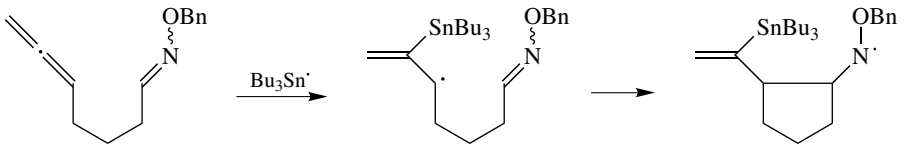
(**22**) (**23**)

SCHEME 8



$n = 1$	0	:	100
$n = 2$	97	:	3

SCHEME 9



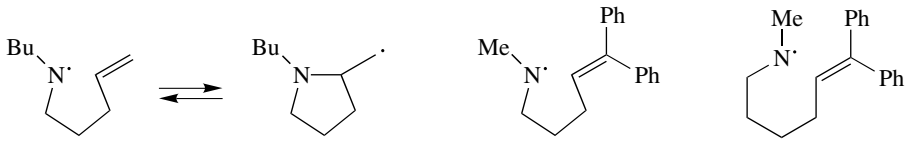
(**24**) (**25**)

SCHEME 10

The chirality of the sulfoxide led to only moderate control of stereoselectivity. α-Alkoxy radicals also undergo cyclization in a 5-*exo* and 6-*exo* mode, again with little control of stereoselectivity.[41]

The transition-state geometries for the cyclization of a range of electrophilic radicals have been obtained by MNDO semiempirical calculations.[42] The regioselectivities observed were rationalized using a frontier orbital approach. Semiempirical calculations were not suited for describing the cyclization of the pent-4-en-1-oxyl radical.[43] Instead, results indicated that *ab initio* (UHF/6–31G*) and (UBP/DZVP) were more reliable.

The kinetics and mechanism of the cyclization/ring opening of *N*-alkylpent-4-enaminyl radicals (**26**) have been re-examined by Newcomb *et al.*[44] in the light of a recent previous report by Maxwell and Tsanaktsidis (Scheme 11). The latter authors claimed that the cyclization was very slow and irreversible and that the reaction was catalysed by $(Bu_3Sn)_2O$. This was in conflict with previous reports which suggested a modestly fast and reversible cyclization. Results from the re-examined study indicated a reversible reaction not catalysed by $(Bu_3Sn)_2O$ with a forward rate of $(5 \pm 1) \times 10^4$ s^{-1} at 50 °C. The origin of the conflicting results was speculated to arise from small amounts of disulfide or selenide impurities in the radical precursors used by Maxwell and Tsanaktsidis which upon subjection to the reaction conditions (Bu_3SnH) underwent reduction to the superior H-donor PhSH or PhSeH. The catalytic effect of $(Bu_3Sn)_2O$ noted in the original study was suggested to arise by the sequestering of these undesired H-donors. The effects of complexed Lewis acid ($LiBF_4$, $MgBr_2$, BF_3) on the rate constants for the 5-*exo* and 6-*exo* cyclization of (**27**) and (**28**) have been determined by laser flash photolysis.[45]



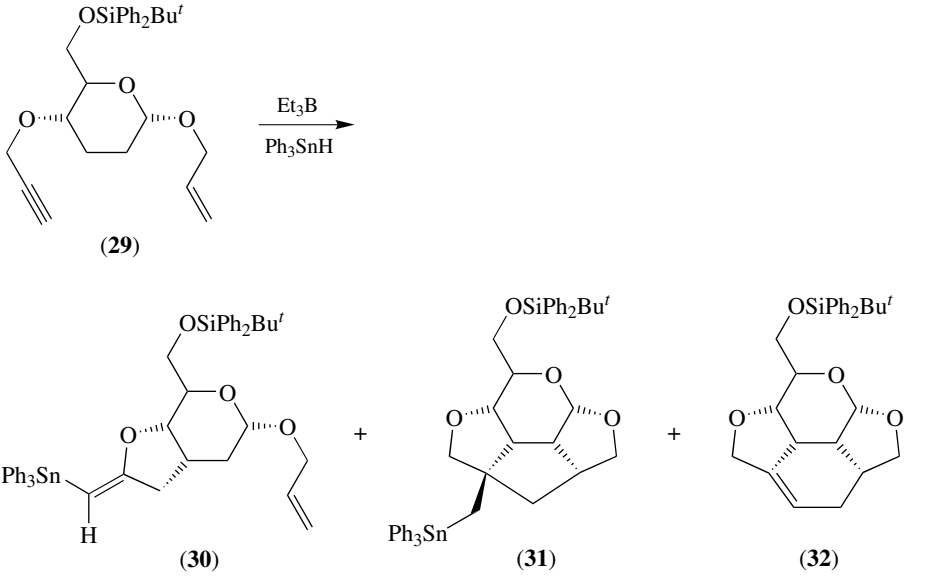
(**26**) (**27**) (**28**)

SCHEME 11

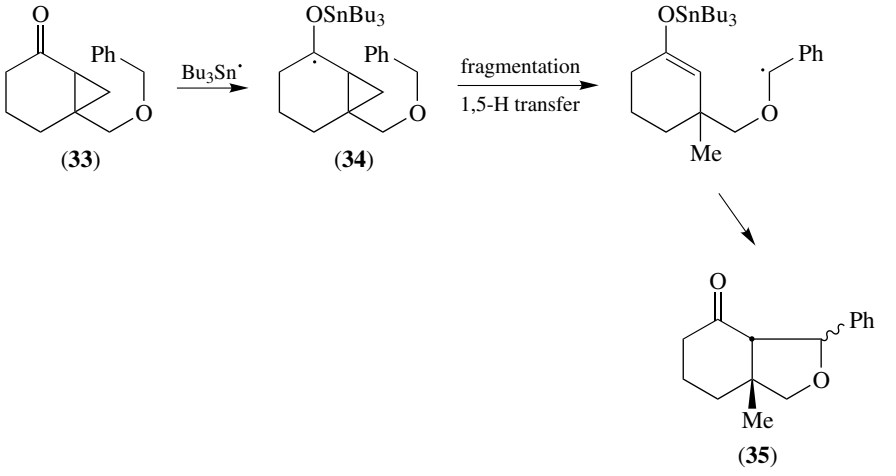
Tandem Reactions

The use of tandem reactions continues to be an efficient method for the construction of complex molecules. While tandem cyclization reactions such as the reaction of dodeca-1,6-dien-11-yne (**29**) with Et_3B–Ph_3SnH to furnish the products (**30**)–(**32**)

(Scheme 12)[46] continue to be reported, the sequencing of other cascade processes such as addition, fragmentation, and radical translocation pathways has started to become increasingly popular. For example, reaction of (**33**) with Bu_3SnH–AIBN via a syringe pump leads to initial $Bu_3Sn^{\cdot}$ addition to the C=O to give (**34**) followed by fragmentation of the cyclopropylmethyl radical, 1,5-H-atom transfer, 5-*exo* cyclization and elimination of $Bu_3Sn^{\cdot}$ to give (**35**) (Scheme 13).[47]

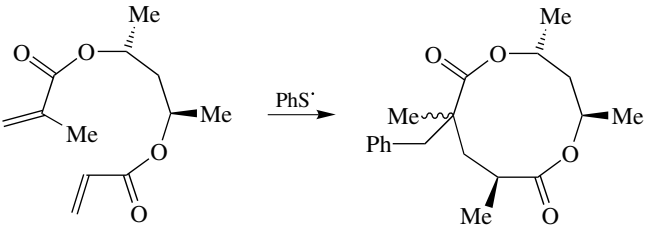


SCHEME 12



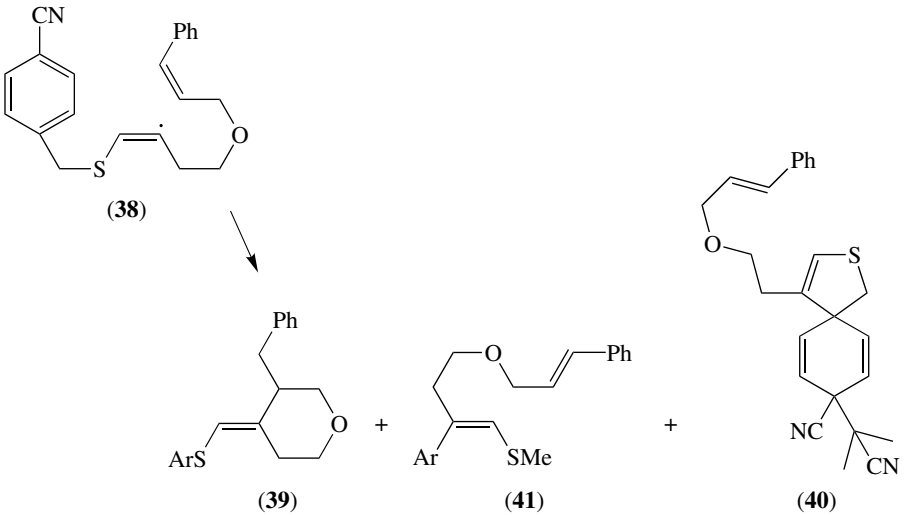
SCHEME 13

The addition of thiyl radicals to alkenes or alkynes to initiate tandem sequences has also been explored. A highly stereo-controlled phenyl thiyl radical addition, 10-*endo* macrocyclization, termination process has been used to furnish the macrocycle (**37**) from the dimethylacrylic ester (**36**).[48] In other work the vinyl radical (**38**) formed from addition of a thiyl radical to an enyne gives a mixture of the three products (**39**)–(**41**) formed either by 6-*exo* cyclization (**39**), addition into the aromatic ring followed by trapping with AIBN (**40**), or rearomatization and fragmentation to give the sulfide (**41**) (Scheme 15).[49]



(**36**) (**37**)

SCHEME 14



(**38**) (**39**) (**41**) (**40**)

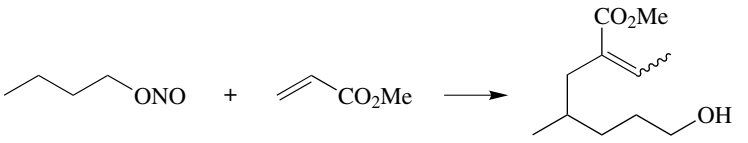
SCHEME 15

Electrochemically generated $^{\cdot}NO_3$ has been reported to add to medium-ring alkynes and alkynones to furnish bicyclic ketones and epoxy ketones, respectively.[50] The postulated mechanism involves the addition of $^{\cdot}NO_3$ to the alkyne followed by transannular cyclization/elimination of $^{\cdot}NO_3$.

Upon photolysis, the alkyl nitrate (**42**) undergoes 1,5-H transfer to furnish the δ-radical, which in the presence of a large excess of electron-deficient alkenes undergoes addition followed by NO quenching to give (**43**) (Scheme 16).[51]

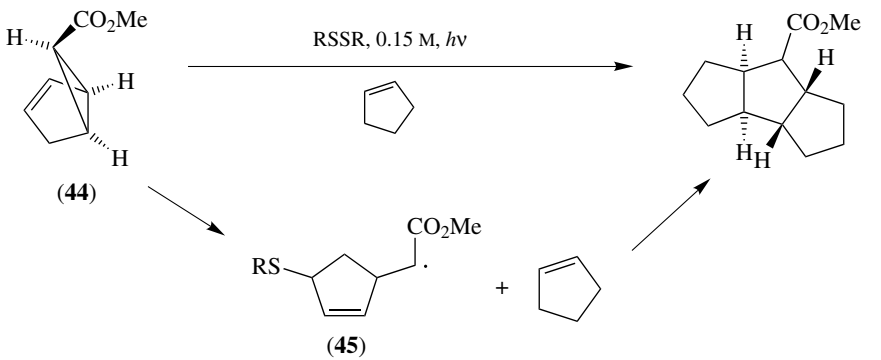
Radical Annulation

Reaction of alkylthiyl radicals with alkenyl cyclopropanes (**44**) furnishes intermediate radicals (**45**) after addition and ring opening. Addition of a further radical acceptor leads to tricyclic [5,5,*n*] systems via addition followed by cyclization and elimination (Scheme 17).[52]



(**42**) (**43**)

SCHEME 16

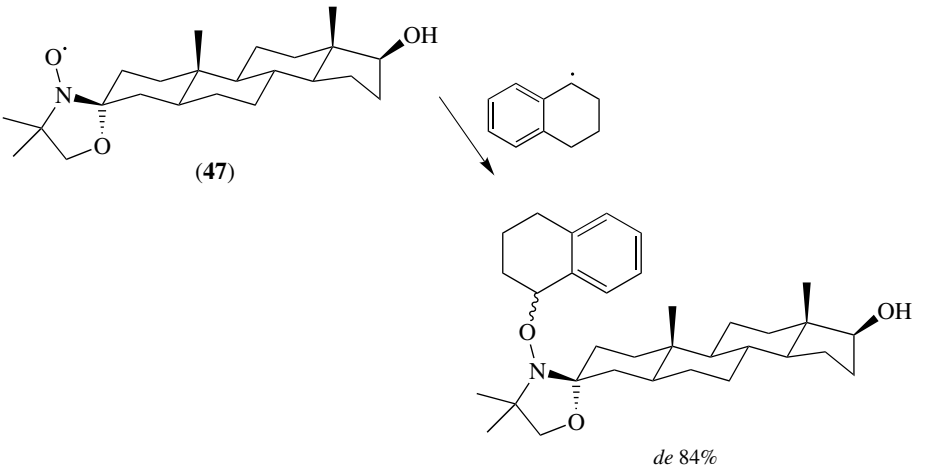


(**44**) (**45**)

SCHEME 17

Fragmentation, Recombination, and Homolysis

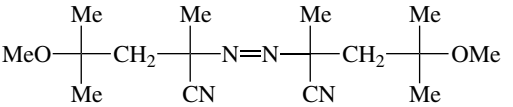
The recombination of radicals has been investigated by a number of methods including laser flash photolysis[53,54] infrared spectroscopy[55] and theoretical means.[56] The rates of self-recombination of $FC(O)O^{\cdot}$[53] $[(7.0 \pm 1.1) \times 10^{-13}\ cm^3\ mol^{-1}\ s^{-1}]$ and $Ph^{\cdot}$[54] between 300 and 500 K $[(1.39 \pm 0.11) \times 10^{-13}\ cm^3\ mol^{-1}\ s^{-1}]$ have been reported. The kinetics of the radical–radical reaction between $Cl^{\cdot}$ and $MeCO^{\cdot}$ to give ketene and HCl has been studied over the pressure range 10–200 Torr.[55] The kinetics of the reaction between the $CF_3O_2^{\cdot}$ and $^{\cdot}OH$ have been investigated using a discharge flow tube with resonance fluorescence detection of $^{\cdot}OH$.[57] Both BAC-MP4 and BAC-MP2 methods have been used to investigate the mechanism in which 2-cyclopentadienyl radicals combine to form naphthalene. Mechanistic information suggests initial formation of dihydrofulvalene followed by loss of $H^{\cdot}$ and rearrangement via ring closure/opening.[56] The coupling of prochiral radicals to a number of chiral nitroxyl radicals has been reported.[58] The best results were with the conformationally restrained nitroxyl radical (**47**) (Scheme 18).



(**47**)

de 84%

SCHEME 18

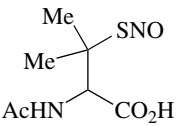


(**48**)

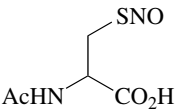
Substituent effects upon bond dissociation energies in a range of substituted methanes[59] and benzyl bromides and *t*-butylbenzenes[60] have been studied using density functional methods [B3LYP with 6–31G(d,p) basis set] and photoacoustic calorimetry, respectively. The theoretical results were in close agreement with published experimental data and similar to that arrived at by more elaborate *ab initio* techniques. The investigation of the dissociation energies of benzyl bromides in both solution and the gas phase concluded that there were no detectable substituent effects in either phase. These conclusions were in contrast to earlier reports. The activation energies for the generation of radicals by reactions between alkanes and alkenes has been examined and the role of these reactions in hydrocarbon cracking and olefin polymerisation and oxidation has been examined.[61] The homolytic cleavage of a range of new radical initiators have been examined including peroxides[62,63] and azo compounds.[64] The initiator azobis(2,4-dimethyl-4-methoxyvaleronitrile) (**48**), used to mediate carbon radical additions to alkenes at room temperature, was found to be superior to other initiators such as AIBN, BPO, or Et_3B.[64]

The observed greater thermal stability of SNAP (**49**) over SNAC (**50**) has been investigated by *ab initio* calculations and DSC and TGA measurements.[65] Results indicate a two-step procedure for decomposition with the enhanced thermal stability of SNAP (**49**) directly related to the steric interaction in the dimerisation reaction leading to disulfide formation. The methyl groups were found to have no substantial effect on the N−S bond strength.[65] *Ab initio* calculations have also been used to study the mechanism of decomposition of $AcONO_2$. Results indicated that the most thermo-

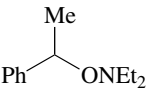
dynamically stable process involved initial cleavage of the O–NO_2 bond with simultaneous decarboxylation to give Me$^{\bullet}$ and $^{\bullet}NO_2$.[66] Density functional calculations have been used to study the deuterium isotope effect of the decomposition of dimethylnitramine (a model for nitramine explosives).[67] The thermolysis of alkoxyamine (**51**) has been studied (>150 °C). Two disproportionation pathways were detected: (a) back to styrene and diethylhydroxylamine, and (b) back to ethylbenzene and nitrone (**52**).[68]



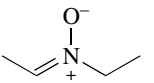
(**49**)



(**50**)

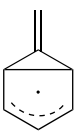


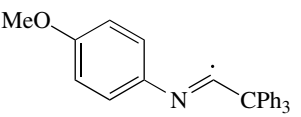
(**51**)



(**52**)

The rates of decomposition of alkoxy and β-hydroxyalkoxy radicals (key intermediates in the degradation of alkanes and alkenes in the atmosphere) have been investigated.[69] A mechanism involving 2- and 3-hexyl radical intermediates has been proposed to account for the decomposition of the 1-hexyl radical to give various C(2)–C(5) *n*-alkenes.[70] The unimolecular decomposition of Ph$^{\bullet}$ has been studied by *ab initio* molecular orbital and statistical-theory calculations.[71,72] Four possible mechanisms for the decomposition of the benzyl radical have been postulated on the basis of theoretical and shock-tube studies.[73] Results were consistent with a direct ring-opening pathway via a 6-methylenebicyclo[3.1.0]hex-3-en-2-yl intermediate (**53**). Imidoyl radicals substituted with the triphenyl methyl group (**54**) undergo novel homolytic α-fragmentation to release the stable triphenylmethyl radical and furnish isonitriles.[74]


(**53**)



(**54**)

The oxidation of thiols of biological importance by oxidizing radicals has been studied.[75] The resulting thiyl radicals were found to decompose rapidly to give C-radicals in the absence of oxygen but to form RSOO$^{\bullet}$ in the presence of oxygen.[75] The electrocyclic ring opening of α-fluorobicyclopropyl radicals to give allyl radicals has been evaluated both experimentally and theoretically.[76] The reaction of dimethyldioxirane and cumene has been studied between 22–52 °C by chemiluminescence and kinetic UV spectroscopy. The process was found to be inhibited by O_2.[77] The rate coefficients for the addition of benzyl radicals to O_3 (2.8×10^{13} cm^3 mol^{-1} s^{-1} and NO_3 (1.93×10^{12} cm^3 mol^{-1} s^{-1}) have been measured in a discharge-flow reactor. The main products from both the reactions were benzene and benzaldehyde, suggesting the intermediacy of the benzyloxy radical.[78]

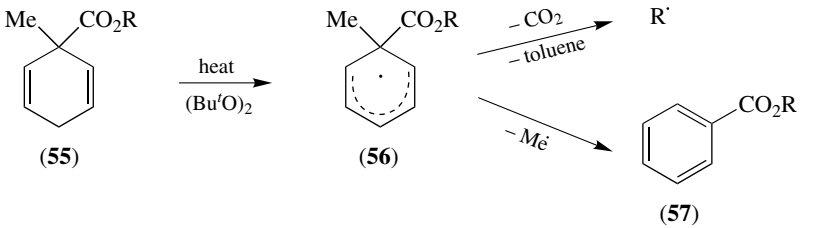
Atom Abstraction Reactions

Hydrogen Abstraction by Carbon-centred Radicals

The selective oxidation of C−H bonds in alkanes under mild conditions continues to attract interest from researchers. A new procedure based upon mild generation of perfluoroalkyl radicals from their corresponding anhydrides with either H_2O_2, *m*-CPBA, AIBN, or $PbEt_4$ has been described. Oxidation of ethane under the reported conditions furnishes propionic acid and other fluorinated products.[79] While some previously reported methods have involved metal-mediated functionalization of alkanes using trifluoroacetic acid/anhydride as solvent, these latter results indicate that the solvent itself without metal catalysis can react as an oxidant. As a consequence, results of these metal-mediated reactions should be treated with caution. The absolute rate constants for H-abstraction from Bu_3SnH by perfluorinated *n*-alkyl radicals have been measured and the trends were found to be qualitatively similar to that of their addition reactions to alkenes.[80] α,α-Difluorinated radicals were found to have enhanced reactivities and this was explained as being due to their pyramidal nature while multifluorinated radicals were more reactive still, owing to their electrophilic nature.[80]

A number of theoretical studies into H-abstraction reactions have been published.[81–87] Both *ab initio* and density functional theory have been used to investigate the reactions of the trichloromethyl radical with a number of alkanes[82] and the reaction of the methyl radical with halogenated alkanes,[83] while *ab initio* methods alone have been used to study the H-abstraction from HCN by the formyl radical[84] and from H_2O by the methyl radical.[85] Transition-state energies for H-abstractions have been predicted using density functional theory (with functionals BLYP, BP86, B3LYP, B3P86), with the last two hybrid functionals giving the most accurate results.[86] The relative merits of the Roberts and Steel empirical algorithm and the Zavitsas semiempirical method for determining activation energies of H-abstractions have continued to attract controversy. The Roberts and Steel empirical algorithm has been compared with the Zavitsas approach and also with *ab initio* and experimental data. Conclusions indicated that the empirical and semiempirical methods had 'a role to play in understanding the factors that influence the rates of radical reactions,'[87] although, owing to the failure of the Zavitsas procedure to model the activation energy for the reaction between $H_3Si^{\cdot}$ and H_4Si, doubts concerning the generality of the latter procedure were raised. The rates of reaction of ethyl radicals with HBr have been reported at low pressures using VLPR.[88] The use of 3-methylcyclohexa-1,4-diene-3-carboxylic acid derivatives (**55**) as precursors for C-radicals has been explored and the reaction characterized by EPR.[89] The rate constant for $H^{\cdot}$ abstraction from (**55**) by hexenyl radicals was determined (0.82×10^5 dm^3 mol^{-1} s^{-1} at 140 °C) and found to be slower than for Bu_3SnH. At high temperatures (>80 °C), loss of methyl radical from (**56**) was competitive with decarboxylation (Scheme 19).

The mechanism of oxidation of alkanes with dimethyldioxirane has been examined by measurement of the primary kinetic isotope effect for the oxidation of cyclohexane and methylcyclohexane in solution and in the gas phase. These experiments indicated that the major products (cyclohexanol and methylcyclohexanol) are probably formed via an electrophilic oxygen-insertion reaction while minor by-products may arise from radical reactions.[90]



(**55**) (**56**) (**57**)

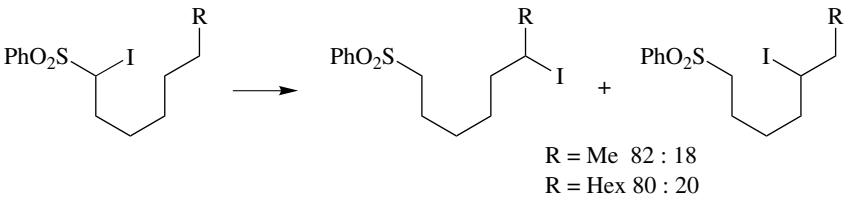
SCHEME 19

Intramolecular H-abstraction (radical translocation) has attracted a lot of attention this year. 1,2–1,5 H-atom transfer reactions have been studied theoretically using UHF–AM1 methods. The predicted activation energies were compared to experimentally measured data.[91] *Ab initio* studies into the 1,2–1,6 translocation of the 2-methylhexyl radical predicted that 1,5-H-transfer would be the fastest isomerization process.[92] The effects of various groups (dioxolane, acetoxy, TBS ether) on the relative ability of 1,5–1,7 radical translocation have been examined.[93]

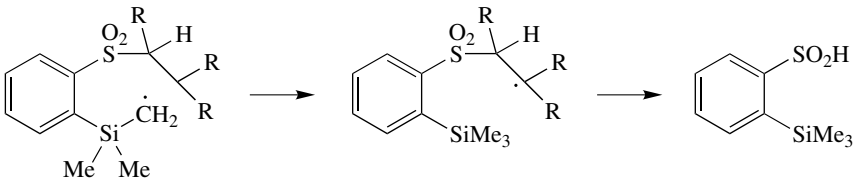
1,5-Hydrogen atom transfer from α-phenylsulphonyl radicals has been synthetically exploited (Scheme 20). In cases where R = Me or hexyl, competing 1,6-radical translocation was observed.[94] The α-silyl radical (**58**), derived from tributylstannane–AIBN mediated homolysis of the corresponding *o*-(bromomethyl)dimethylsilyl aryl sulfone, undergoes an unusual 1,8-hydrogen translocation followed by *β*-elimination of the sulfur group to give (**59**) (Scheme 21). In contrast, *β*-silyl radical (**60**) undergoes intramolecular attack at the sulfone (Scheme 22).[95]

Hydrogen Abstraction by Heteroatom-centred Radicals

The effect and role of the $Cl^{\cdot}$ in ozone depletion in the stratosphere have highlighted the need for knowledge of how it reacts with atmospheric species and pollutants. As a consequence, the H-abstraction reactions of $Cl^{\cdot}$ with a large variety of non-halogenated hydrocarbons including alkanes,[96–98] alkenes,[99,100] dienes,[101,102] aromatics,[103] and ketones[104] as well as halogenated hydrocarbons[105–108] have been investigated by a number of different research teams. The analytical potential energy surface for the $Cl^{\cdot}$ mediated hydrogen abstraction from methane has been determined using the application of variational transition state theory and the study of kinetic isotope effects.[98] The abstraction reactions from methane, ethane and other simple alkanes have been compared by two groups.[96,97] The latter measured absolute rate constants for the H-abstraction from alkanes between 292 and 700 K by laser photolysis/continuous wave IR long-path absorption spectroscopy. While the reaction with methane showed a significant curvature of the Arrhenius plot, the reaction with propane was independent over the temperature range.[97] The reaction of $Cl^{\cdot}$ with both ethene[98] and propene[100] has been reported over a variable temperature range. For propene, observations indicated that the major reaction pathway to form HCl is via H-abstraction with only a small contribution to its formation via an addition/elimination mechanism.[100] For the reaction with ethene, the addition pathway was found to be dominant at room temperature while the H-abstraction pathway dominated at elevated temperatures (>500 K).[99] Both the

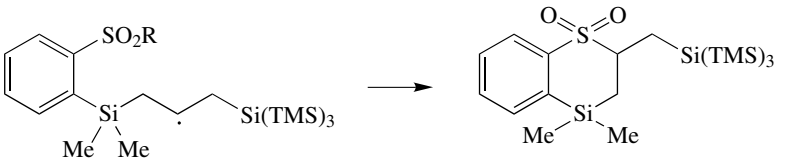


SCHEME 20



(**58**) (**59**)

SCHEME 21



(**60**)

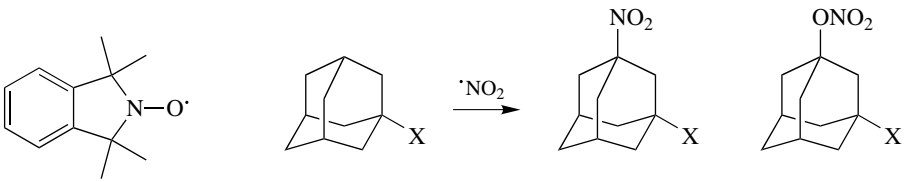
SCHEME 22

atmospheric implication of H-abstraction from 2-methylbuta-1,3-diene[102] and buta-2,3-diene[101] as well as the rate data for these reactions with the $Cl^{\cdot}$ have been reported. Reactions with acetone[101] and other ketones[104] have indicated that the carbonyl group lowers the reactivity towards α-hydrogen abstraction by $Cl^{\cdot}$ compared with related alkanes. Absolute rate constants for the reactions of $Cl^{\cdot}$ with $CHBr_3$, CH_2Br_2, and CH_3Br have been measured and found to be 2.12 ± 0.25, 2.91 ± 0.2, and 3.21 ± 0.3 cm^3 $molecule^{-1}$ s^{-1} at 273 °C, respectively,[106] with the activation energy for H-abstraction decreasing with an increasing degree of bromine substitution. The reaction between $Cl^{\cdot}$ and MeI has been studied theoretically.[107] Direct measurements of rates of H-abstraction from MeF and CF_3CH_2F (HFC-134a), an industrial substitute for CFCs, by $Cl^{\cdot}$ and $F^{\cdot}$ have been carried out experimentally using discharge flow/mass spectroscopy.[108] Rate enthalpies and activation energies were also calculated using *ab initio* methods [MP2/6–31G(d,p)] and found to be in good agreement with experimentally measured values. The reactions between $Cl^{\cdot}$ and H_2S, MeSH,[109] and MeSSMe[110] have been studied. The last reaction has been investigated at various temperatures and was found to proceed by two reaction pathways consisting of either H-abstraction or the formation of MeSCl and $MeS^{\cdot}$ via an intermediate MeS(Cl)SMe

adduct. Both of these types of reaction channel (abstraction and adduct formation) have also been experimentally determined for the reaction of F$^{\cdot}$ with CH_2BrCl, a potential substitute to the fire-extinguishing reagent Halon 1301,1211.[111] The reactions of F$^{\cdot}$ with CF_3CF_2H[112] and Br$^{\cdot}$ with MeOH[113] have been studied experimentally. The latter gave a value for the heat of formation of $^{\cdot}CH_2OH$ as -16.6 ± 1.3 kJ mol^{-1}.

Studies examining H-abstraction by various oxygen-centred radicals have been reported. Activation energies[114] and rate constants[115] for the processes of abstraction from alkyl, vinyl, and aryl hydrocarbons have been calculated with abstraction from aliphatic C−H bonds proceeding with the highest activation energies.

One of the most popular nitroxide-based radicals (TEMPO) has been shown to abstract H-atoms from activated C−H bonds. However, the nitroxide itself is easily photo-degraded. In order to examine more photochemically stable alternatives to TEMPO in abstraction reactions, the related isoindoline nitroxide radical (**61**) has been examined.[116] Abstractions from unactivated primary, secondary, and tertiary C−H alkane bonds were all achieved.



(**61**) SCHEME 23

The factors which effect the reactivity of nitrogen-centred aminyl radicals with OH, NH, and SH bonds have been studied with the activation energies for each process calculated under thermoneutral conditions.[117] The reaction of adamantane derivatives with nitrogen dioxide and ozone has been reported to yield varying proportions of the *N*- and *O*-functionalized products, respectively (Scheme 23). Initial H-abstraction by the $^{\cdot}NO_3$ followed by trapping with NO_2 furnishes the observed products. Interestingly, strongly electron-withdrawing substituents (X) were found to lead to the *O*-functionalized products whereas weaker electron-withdrawing groups (X) favoured the *N*-functionalized compounds.[118] The reaction between the $^{\cdot}NO_3$ and a number of aliphatic aldehydes has also been reported. The rate coefficients were determined and compared with those of the reaction between the same aldehydes and $^{\cdot}OH$.[119] Monodiazines have been shown to be good H-atom donors towards alkyl radicals with rates determined to be at least 3.2×10^6 M^{-1} s^{-1}.[120]

Activation energies and rate constants for the H-abstraction reaction by H$^{\cdot}$ from simple aliphatic ketones in water has been calculated by EPR FID attenuation measurements.[121]

Halogen Abstraction

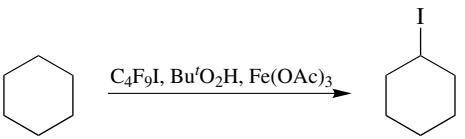
The design of an efficient chain reaction to facilitate the reduction of secondary alkyl iodides adjacent to electron-withdrawing groups has been accomplished by reaction

with dilauryl peroxide in cyclohexane.[122] Abstraction of the iodide by the cyclohexyl radical produces relatively unstabilized electrophilic radicals which can abstract hydrogen atoms from the solvent and thus establish an efficient chain process. The rates of dechlorination of a range of chlorinated phenols by Fenton's reagent has been found to be effected by the position of the chlorine atom relative to the phenoxy hydroxyl group. Hence dechlorination in the *meta* position was found to be faster than at the *para* position, which in turn was faster than at the *ortho* position. With trichlorophenols steric hindrance proved important in deciding the relative rates of dechlorination.[123]

The mechanisms and rate constants for the reaction of $Cl^{\cdot}$ with HOCl, MeOCl, and C_4H_9OCl have been measured and shown to proceed primarily via $Cl^{\cdot}$ abstraction pathways.[124] The experimental activation energies[125] and the temperature dependence of the rate constants[126] of halogen abstraction from a variety of alkyl halides have been reported. For simple abstractions from R−X or H−X results indicated that the activation energies were proportional to the force constant of the C−X bond. The reaction of $H^{\cdot}$ with alkyl iodides was investigated using flash-photolysis resonance fluorescence, with the results indicating that the major reaction pathway was I-abstraction with a minor contribution from I-substitution and H-abstraction reactions.[126]

Halogenation

A new method for the direct homolytic iodination of alkanes has been reported by Minisci *et al*.[127] While direct free radical iodination by iodine is not feasible owing to its large positive enthalpy, the new procedure takes advantage of the ease of H-abstraction from alkanes by perfluoroalkyl radicals (eq. 1) and the effective iodine abstraction by alkyl radicals from alkyl iodides (eq. 2) (Scheme 24). The regio-selectivity of bromination by NBS of a range of methylated 3-methoxypyridazine derivatives has been predicted based upon the stability of the free radical intermediate by semiempirical calculations using the PM3 Hamiltonian. Excellent agreement with experimental results indicates that this may provide a good method to predict the bromination selectivity in novel heterocyclic analogues of the neurotransmitters GABA and glutamate.[128] The effects of various solvents upon the concurrent chlorination of tetrachloroethene and 1,2-dichloroethane have been studied.[129]



SCHEME 24

$$R_f^{\cdot} + H\text{-}R \longrightarrow R_f\text{-}H + R^{\cdot} \qquad (1)$$

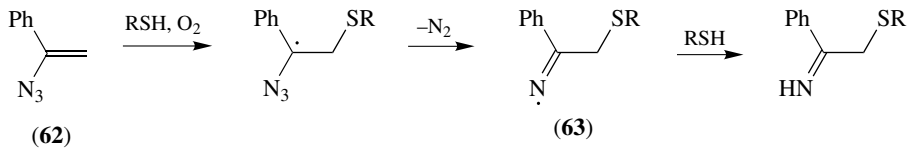
$$R^{\cdot} + I\text{-}R_f \longrightarrow R_f^{\cdot} + R\text{-}H \qquad (2)$$

Addition Reactions

Addition to Alkenes/Alkynes

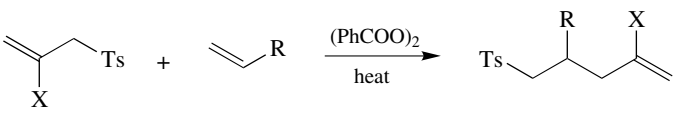
The addition reactions of carbon-centred radicals with alkenes and alkynes continue to be of great importance in both synthetic organic and polymer chemistry, as do methods for determining the rate constants of these important reactions. The use of time-resolved frequency modulation spectroscopy in the measurement of the rate of gas-phase reactions has been described.[130] By way of illustration of the technique, the reaction of $^{\cdot}$CN with ethene was studied and the rate [$(2.5 \pm 0.2) \times 10^{-10}$ cm^3 s^{-1}] found to be in good agreement with other published data.[130] The importance of polar effects in the addition of radicals to alkenes has been demonstrated by the measurement of the relative reactivities for the addition of trichloromethyl radicals to styrene, α,β,β-trifluorostyrene, and phenylacetylene, respectively.[131] The reactions of the 1-adamantyl radical with a range of electron-deficient alkenes and protonated heteroaromatic bases have been found to be much faster (10^2–10^3) than that of the related *t*-butyl radical.[132] This interesting effect was explained as due to the increased nucleophilic character of the 1-adamantyl radical with respect to the *t*-butyl radical. Some controversial aspects of the Gif reaction mechanism, such as why 1-adamantyl radicals can be trapped by pyridinium ions whereas 2-adamantyl radicals can not, can now be explained as due to the observed large difference in reactivity of these two types of radicals with protonated heteroaromatic bases. In other work the relative rates of addition of the *t*-butyl radical to a variety of 2-substituted allyl chlorides have been measured with the correlation of $\log k/k_0$ vs. σ_m giving a ρ value of 3.59.[133]

Benzenethiols have been reported to add to α-azidostyrene (**62**) to give β-sulfonylated imines via the intermediacy of 2-sulfanyliminyl radicals (**63**) produced from sulfanyl radical attack at the β-carbon of the styrene followed by nitrogen extrusion (Scheme 25).[134] Allyl sulfones (**64**) containing electron-withdrawing C(2) substituents (X) undergo addition to monosubstituted alkenes in good yield (Scheme 26). Both electron-donating and -withdrawing substituents are tolerated in the alkene partner.[135] The addition of the phenyl radical to 1,1-diphenylethylene[136] and vinyl radicals to acetylene and deuteriated acetylene[137] have both been studied by laser photolysis techniques.



(**62**) (**63**)

SCHEME 25



(**64**)

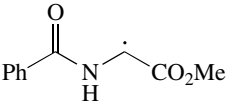
SCHEME 26

A number of studies on the addition of fluorinated radicals to unsaturated carbon–carbon bonds as well as conventional radical addition to fluorinated radical acceptors have appeared.[138] For example, the relative rates of addition of the $CF_3^{\cdot}$ to 14 *para*-substituted phenylacetylenes have been studied in cyclohexane at 55 °C. The study concluded that a spin effect was operating in the transition state for the reaction.[138] The regioselectivity of addition of $Me^{\cdot}$ and $CF_3^{\cdot}$ radicals to alkenes has been rationalized using local reactivity indices obtained from density functional theory.[139] The reaction of difluorinated ethers with amino acid-derived radicals has been reported to give novel *gem*-difluoromethylene-linked analogues of serine-derived glycopeptides.[140] In addition the rate coefficients for the reaction of $^{\cdot}NO_3$ with 3-fluoropropene have been measured using laser-induced fluorescence. The results were used to estimate the half-life of 3-fluoropropene in the troposphere at typical night and day concentrations of $^{\cdot}NO_3$ and $^{\cdot}OH$.[141] The major products in the halogen-initiated oxidation of trichloroethylene have been determined ($CHXClCOCl$, $CHClO$, and CCl_2O) and the rate coefficients for the reaction determined.[142]

The design and use of new initiators to mediate addition reactions has attracted some attention with new peroxide[62,63] and azo-derived[64] initiators being described. The additions of 2-cyanoisopropyl radicals (derived from homolysis of the common radical initiator AIBN) to a range of alkynes have been examined.[143] The reactions were regioselective with alkynes bearing electron-withdrawing substituents but failed with hindered or alkylacetylenes. The same radical addition to C_{60} has been studied by EPR. Two different types of adduct radicals were proposed.[144]

The addition of silanes across alkenes has been investigated both experimentally[145] and theoretically.[146] The effect of optically active thiol catalysts to catalyse radical hydrosilylation (polarity reversal catalysis) has been studied. The use of 2,3,4,6-tetra-*O*-acetyl-thio-*β*-D-glucopyranose as the chiral thiol (used to reduce the intermediate carbon-based radicals) furnished the hydrosilylated alkenes in low to moderate enantiomeric excesses.[145] In addition to this work a theoretical study on the reactions of SiH_3 with ethene and propene has been undertaken using PMP2(6–31G*) and QCISD(T)(6–31G**) methods. Results indicated that the alkene-addition pathway is favoured over the alternative possible mode of reaction (H-abstraction). This is contrary to that previously suggested for the reaction of SiH_3 with propene.[146]

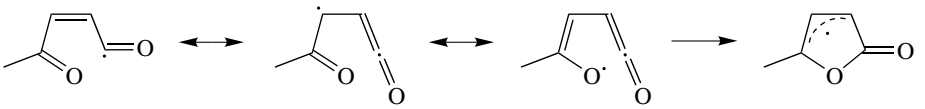
Other research in the area of addition reactions onto unsaturated carbon–carbon bonds has included measurement of the rate coefficients for the addition of $^{\cdot}NO_3$ to chloro- and trichloro-ethene,[147] relative rate measurement for $^{\cdot}NO_3$ addition to isoprene,[148] TF-μSR-measured muonium addition to vinyl aromatics[12] and EPR studied addition of radical (**65**) to alkenes.[150] In this latter study a linear dependence of the rate constant of addition with the donor/acceptor properties of the alkene partner was highlighted.



(**65**)

Addition to Oxygen-containing Multiple Bonds

Ab initio studies (UHF/6–31G*) have been used to investigate the 5-*endo* cyclization of various substituted radicals including the 5-oxapenta-2,4-dienoyl radical (**66**).[39] The results show that the 5-*endo* cyclization of (**66**) is both kinetically and thermodynamically favoured. Three major features of the reaction were recognized: (1) the geometry of the lowest energy conformer has the radical set favourably for cyclization; (2) owing to delocalization the reaction is best considered as a carbonyl oxygen radical (**67**) addition to a ketene, not an acyl radical (**66**) cyclization on to a carbonyl group; and (3) the cyclized carbon radical helps to stabilize the transition state as it acts like a delocalized cyclopentadienyl radical (**68**).



(**66**) (**67**) (**68**)

SCHEME 27

Addition to Nitrogen-containing Multiple Bonds

The rate constants for the 5-*exo* and 6-*exo* cyclization of alkyl radicals on to imines[37] and oxime ethers[38] have been reported, as have the cyclizations of alkyl radicals on to azides[29] and hydrazones.[36]

Addition to Thiocarbonyl Bonds

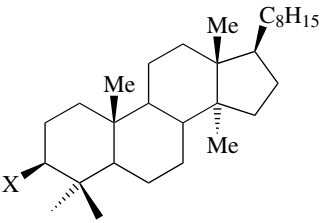
The unexpected formation of the methoxy ether (**69b**) in the reaction of lanosterol 5-methyl dithiocarbonate (**69a**) with Bu_3SnH has been reported.[151] Studies using Bu_3SnD indicated that a hydrogen within the methoxy group originated from the organostannane reagent. A possible mechanism (Scheme 28) was postulated to explain these observations.[151]

Photolysis of PTOC imidate esters generated amidyl radicals which can undergo intramolecular homolytic substitution reactions (Scheme 29).[152] The ratio of *exo* to *endo* products observed for the reaction of each of the thiocarbonylimidazolide diastereomers (**70**) and (**71**) with Bu_3SnH was found to be different indicating that the intermediate radical (**72**) produced in each case was generated and reacted in a different conformation, respectively (Scheme 30).[153]

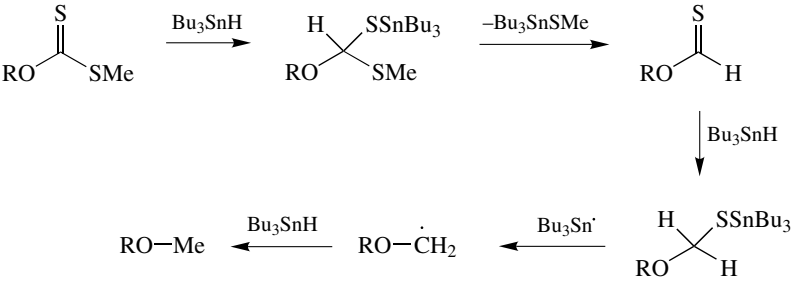
Homolytic Substitution

Aromatic Substitution

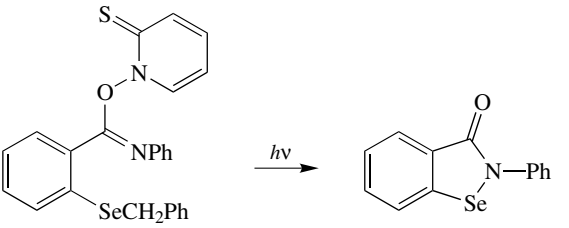
The effects of different substituents (R) (both steric and electronic) on the 1,5-*ipso* substitution reactions of radicals of the type (**73**) to give (**74**) and finally biaryls (**75**) after loss of SO_2 have been examined (Scheme 31).[154,155] The results indicated that the introduction of either an electron-donating or -releasing group in the *ortho* position



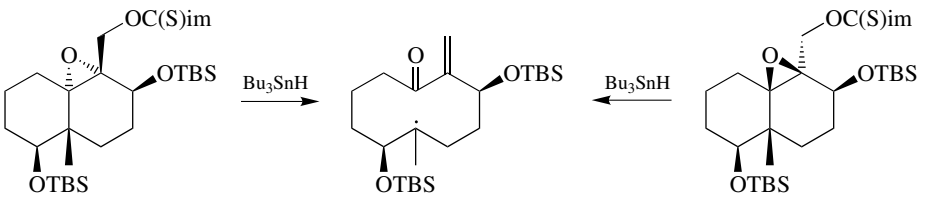
(**69**)
a; X = OC(S)SMe
b; X = OMe



SCHEME 28

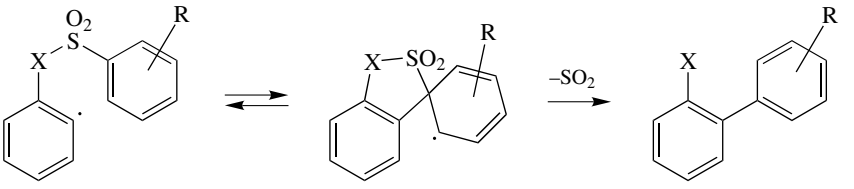


SCHEME 29



(**70**) (**72**) (**71**)

SCHEME 30



(**73**) (**74**) (**75**)

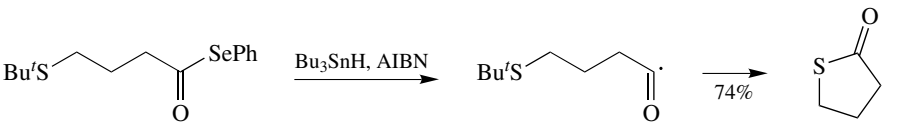
SCHEME 31

facilitated the reaction. This approach to furnishing *ortho*-functionalised biaryl systems complements other alternative metal-mediated coupling approaches. In addition to the substituent effects mentioned above, the nature and length of the tethers upon the success or otherwise of the reactions was investigated.[155] For benzylic sulfonates and sulfonamides the [1,7]-addition pathway was favoured instead of the [1,6]-*ipso* substitution pathway. The formation of nitrothiazoles by reaction of 2-nitropropane anions and 2-methyl-4-chloromethyl-5-nitrothiazole has been determined to proceed via the $S_{RN}1$ mechanism[156] as has the photo-stimulated reactions of iodobenzene and iodonaphthalene with the anions of *N*-acetylthiomorpholine.[157] In competition experiments it was discovered that the acetophenone enolate was 1.4 times more reactive than *N*-acetylthiomorpholine in the above reaction.

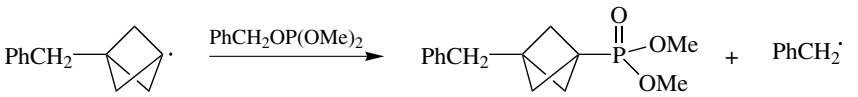
The rate of fluorine displacement from fluorotoluenes by H-atoms has been measured in single-pulse shock tubes at 988–114 K.[158] The addition of $^{\cdot}CF_3$ to C_6F_5Cl has been studied.[159] The intermediate adduct radical $(CF_3C_6F_5Cl)^{\cdot}$ was shown to react with an additional $^{\cdot}CF_3$ to give CF_3Cl and $C_6F_5CF_3$. A range of fluorinated biphenyls can be produced by the reaction of pentafluorobenzene radicals with both electron-rich and -poor aromatics. The isomeric ratios of biphenyls produced indicated an efficient homolytic chain process.[160]

S_H2 and Related Reactions

Acyl radicals derived from phenylselenyl esters (**76**) can undergo S_H2 reactions onto sulfides to form γ-thiolactones (Scheme 32). The rate of reaction was found to be approximately $7.5 \times 10^3\ s^{-1}$ at 25 °C which is reasonably fast with respect to decarboxylation.[161] Acyl radicals can be generated from thiol esters under non-reducing conditions by reaction with I_2 and diazonium salts. The generated aromatic radicals undergo intramolecular homolytic substitution at sulfur with liberation of an acyl radical. After cyclization the intermediate alkyl radical undergoes trapping with iodine followed by elimination of HI.[162] The reaction of bicyclo[1.1.1]pent-1-yl radicals (**77**), generated from addition of alkyl radicals to the strained hydrocarbon [1.1.1]propellane, add to tricoordinate phosphonites in a free radical Arbuzov reaction (Scheme 33). The 3-substituted bicyclo[1.1.1]pent-1-yl radicals (**77**) were found to have a greater propensity to undergo reactions than primary alkyl radicals and were closer in reactivity to phenyl radicals.[163]



SCHEME 32



SCHEME 33

The mechanism of reduction of unsymmetrical alkyl sulfides with atomic hydrogen has been probed and is consistent with an S_H2 mechanism or a 9-S-3 fragmentation.[164] The kinetics of the reaction of F· with $MeONO_2$ has been determined in low-pressure flow systems. Results indicate that the initial step may be F atom addition to the N atom rather than H-abstraction and that the reaction itself leads to a clean source of MeO·.[164]

Reactivity Effects

Polarity and Philicity

The rates of bromine atom abstraction by tris(trimethylsilyl)silyl radicals from a range of *para*-substituted benzyl bromides has indicated that the silyl radical is nucleophilic. In addition both the polar and spin-delocalization effects of the substituents play a role in the abstraction reaction with the latter effect greater than for H-atom abstractions.[166] The perfluoroalkylation of aromatics and alkenes has been investigated using C_4F_9I as the source of $^{\cdot}C_4F_9$. Measurement of rate constants indicated that perfluoroalkyl radicals were 2–3 orders of magnitude more reactive than the corresponding alkyl radicals. This was attributed primarily to the reaction enthalpy and far less to the electrophilic nature of the radicals.[167]

Stability of Radicals

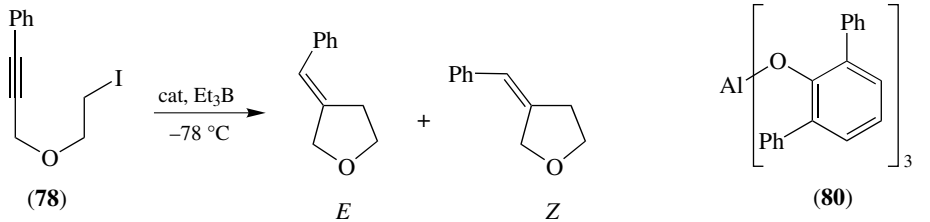
EPR experiments on carbon-centred radicals with either α- or β-boronic ester substituents have been reported.[168] While the α-substituted radicals were modestly thermodynamically stable, the β-substituted radicals underwent easy β-elimination. An EPR experiment on the photo-oxidation of phenolic compounds containing at least one free *ortho* position has indicated the formation of persistent secondary radicals derived from dimerization or polymerization from C–O coupling.[169] The structure of the succinimidyl radical has been re-examined using density functional theory with a variety of basis sets. The electronic ground state was found to be of σ-symmetry allowing for facile β-scission. These conclusions were also predicted using MP2 but

complete active space (CAS) calculations predicted the Π–N state to be of lowest energy.[170]

Stereoselectivity in Radical Reactions

Stereoselectivity in Cyclization

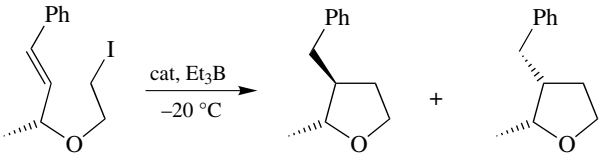
The use of Lewis acids in controlling the stereoselective outcome of radical cyclization reactions has been explored, in particular the effect of aluminium-based Lewis acids using low temperature Et_3B/Bu_3SnH-initiated procedures.[171,172] For example, cyclization of propargyl ether (**78**) or allyl ether (**79**) in the presence of Lewis acid (**80**) can completely reverse the normal selectivity (Scheme 34).[171] The effect of aluminium Lewis acids on the diastereoselectivity of 6-*exo* cyclization of unsaturated chiral menthol esters has been studied.[172] Cyclization at low temperature in the presence of the Lewis acid MAD modified the *de* of the reaction from 31 to 98%.



(**78**) (**80**)

	E		*Z*
no (**80**)	61	:	39
with (**80**)	14	:	86

SCHEME 34

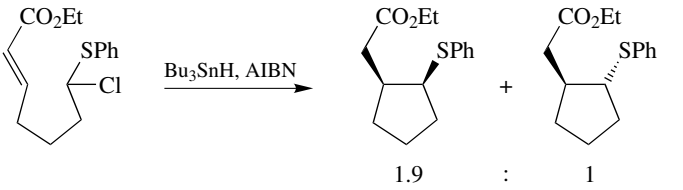


(**79**)

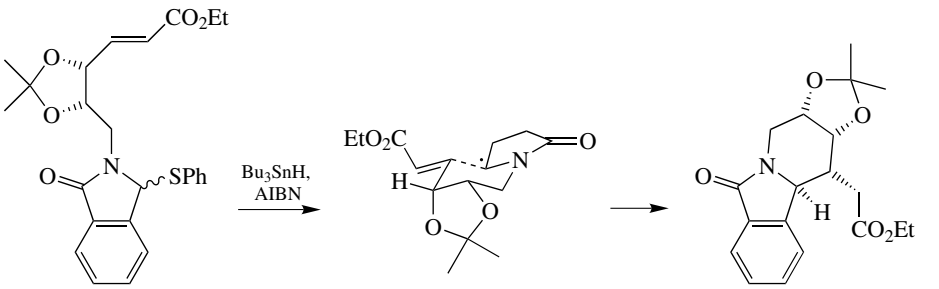
	trans		*cis*
no (**80**)	97	:	3
with (**80**)	8	:	92

SCHEME 35

The diastereoselectivity in 5-*exo* cyclization of a range of chiral acyl radical equivalents derived from 1,3-dioxolanes and dioxanes has been investigated. Results indicate that selectivity was poor for radicals which cyclised via a twist-boat conformation but high when 1,3-dioan-2-yl radicals containing an imposed chair-like conformation were used.[173] The 5-*exo* cyclizations of α-phenylsulfenyl radicals,



SCHEME 36



(**81**) (**82**) (**83**)

SCHEME 37

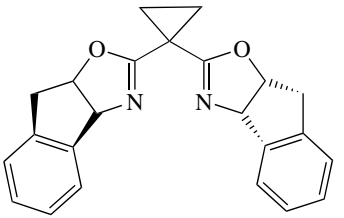
generated from chloro sulfides, on to ester-functionalized alkenes have been reported to give rise to *cis* isomers as the major products (Scheme 36). With alkyl-substituted alkenes the *trans* isomers were predominantly formed.[174] In addition, α-sulfonyl and sulfinyl radicals also undergo 5-*exo* radical cyclizations mediated by Bu_3SnH. The chirality of the sulfoxide was found to have only moderate control of the stereoselectivity of the cyclization.[40] Cyclization of the thio ether (**81**) furnishes the all-*cis* isomer (**83**) in 70% yield. The transition state (**82**) was postulated to explain the observed stereochemistry (Scheme 37).[175]

Stereoselectivity in Addition to Alkenes

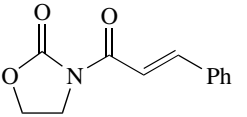
Quantum mechanical calculations have shown that both nucleophilic and electrophilic alkyl radicals undergo addition to alkenes at tetrahedral trajectories. The effects of this mode of attack on asymmetric induction and reaction stereochemistry in addition reactions has been discussed.[176] The use of chiral Lewis acids to mediate asymmetric radical additions to alkenes has been extensively investigated. Enantioselective alkylation of chiral Lewis acid-complexed α-oxazolidinone radicals has been reported to give products in up to 34% *ee*.[177] Various Lewis acids prepared from $AlMe_3$ and chiral diols/diamides were screened. A model to explain the observed selectivity was postulated.[177] By far the most popular ligands for chiral Lewis acids seem to be the bisoxazolines.[177–180] A number of such MgI_2 complexes have been investigated in the radical alkylation of oxazolidinones (**85**).[178] The best *ee* values were for the cyclopropyl analogue (**84**) with 97% at −78 °C. However, the use of 30 mol% of LiI as catalyst also

proceeded with a high *ee* of 94%, thus allowing efficient asymmetric additions at ambient temperature.[178] The stereoselectivity of allyl-transfer reactions from allylsilanes and allylstannanes in the presence of chiral bisoxazoline ligands (**86**) has been investigated by Porter and co-workers.[179,180] The configuration of the products were found to be dependent upon the nature of the Lewis acid, with MgI_2 and $Zn(OTf)_2$ giving opposite enantiomers. More interesting was the discovery that allylsilanes furnished better *ee*s than with the corresponding allylstannanes. In fact, the addition of excess Me_3SnBr caused the *ee* of the reactions to fall linearly indicating that allyl silanes are the allyl-transfer agents of choice.[179] Good to average levels of stereoselectivity have been observed in the zinc Lewis acid-promoted allyl-transfer reactions of radical (**87**) with ligands (**86**). Correlation of the selectivity against the Taft steric parameters for the alkyl group (R) was observed.[180]

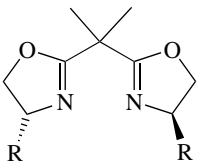
A potential method for the preparation of novel amino acids via the highly selective addition of radicals to the glyoxylic oxime derivative of Oppolzer's camphor sultam (**88**) has been reported.[181] Both Lewis acid and non-Lewis acid-mediated reaction conditions for the addition of alkyl radicals generated from alkyl iodides and Et_3B/Bu_3SnH were examined. A new chiral auxiliary based upon (*R*,*R*)-2,5-diphenylpyrrolidine has been used in the addition of phenylthiyl radicals to unsaturated methacrylamides. The selectivity was found to be better than that reported for the structurally related 2,5-dimethylpyrrolidine derivative.[182]



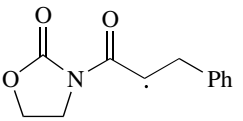
(**84**)



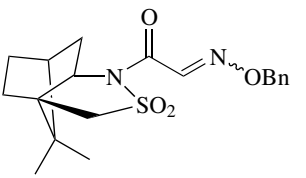
(**85**)



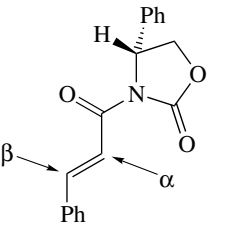
(**86**)



(**87**)



(**88**)



(**89**)

An investigation into the stereoselectivity of addition of radicals to cinnamyl-4-phenyloxazolidine-2-ones has shown that the regioselectivity of the process was dependent upon at least three factors, including the stability of the adduct radical,

electrophilicity of the adding radicals, and the method of their generation.[183] For example, while addition of electrophilic $^{\cdot}CCl_3$ to (**89**) at 80 °C gave only products arising from α-attack, addition of the nucleophilic $^{i}Pr^{\cdot}$ gave a 2.3 : 1 ratio at 80 °C and 1 : 3 at 20 °C.

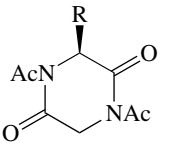
Stereoselectivity of Atom Transfer

A quantitative study of the relative reactivities of piperazine-2,5-dienes (**90**) towards *N*-bromosuccinimide reactions was determined by competition studies and indicated that the glycyl centres of piperazine-2,5-dienes are more reactive than α-substituted amino-acid centres.[184] Radical deuteriation of the *syn*- and *anti*-α-selenyl-β-silyl sulfoxides (**91**) lead to the *syn*,*syn* isomer products irrespective of the stereochemistry of the sulfinyl precursor (Scheme 38). In addition, the steric nature of the silyl group had little effect on the *de*. The stereochemistry was rationalized using the Felkin–Ahn model.[185] The stereochemistry of reduction of alkynes using unimolecular chain-transfer reactions (UMCT) has been reported with complementary alkene geometries being obtained from reduction of vinyl radicals generated by a 5-*exo* cyclization of an alkyl radical onto an alkyne. The use of UMCT (**92**) gives the *E*-isomer exclusively whereas (**93**) gives the *Z*-isomer with reduction occurring away from the bulky silicon group (Scheme 39).[186]

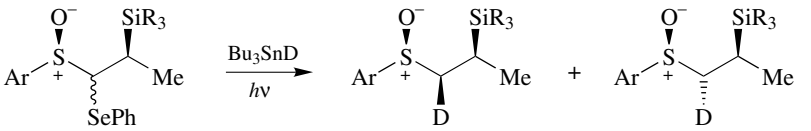
Redox Reactions

Manganese-promoted cyclizations have been reported by two groups. 4-*Exo* radical cyclization of variously substituted enamides to β-lactams has been promoted by $Mn^{III}(OAc)_3$ (Scheme 40).[187] The acetoacetyl-derived cyclization precursors (R = Me) reacted much faster than the β-keto ester analogues (R = OMe). The formation of (**94**) from the reaction is primarily due to oxidation of the intermediate radical to the corresponding cation.[187] Reaction of 2-halophenyl ethers and amines with Bu_3MnLi or $Bu_3MnMgBr$ furnishes benzofuran or indoline derivatives, respectively. A mechanism involving intermediate aryl radical cyclization trapping by manganese followed by dehydromanganation was postulated.[188] Recent studies on the tetrahydrofulvalene-mediated radical polar cross-over reactions of benzenediazonium salts have discounted the alternative totally ionic mechanism.[189] *Ipso* radical cyclization of *N*-benzyl-substituted trichloroacetamides with Ni–AcOH occurs to give spirolactams. The yield of the reactions was found to increase with increasing steric bulk at the nitrogen (Scheme 41).[190]

The synthesis of mixed peroxides formed from *t*-butyl hydroperoxide and carbon-centred radicals has been studied. The reactions were strongly effected by solvents as well as catalytic amounts of Cu^{II}/Fe^{III}. The kinetic data suggest that the conditions for the Ingold–Fischer 'persistent radical effect' are fulfilled in these cases.[191] The use of Cu^{I}/Cu^{II} redox couples in mediating 'living' radical polymerization continues to be of interest. The kinetics of atom-transfer radical polymerization (ATRP) of styrene with CuBr and bipyridine have been investigated. The polymer reactions were found to be first order with respect to monomer, initiator and CuBr concentration, with the optimum CuBr : Bipy ratio found to be 2 : 1.[192] In related work using CuBr–*N*-pentyl-2-

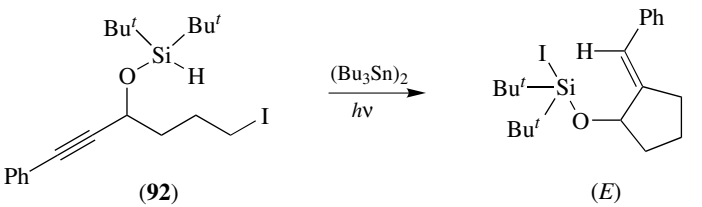


(**90**)

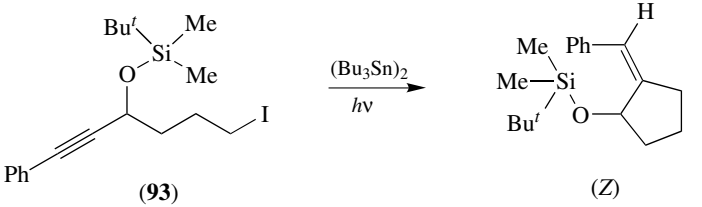


(**91**) *syn/syn* *anti/anti*

SCHEME 38



(**92**) (*E*)

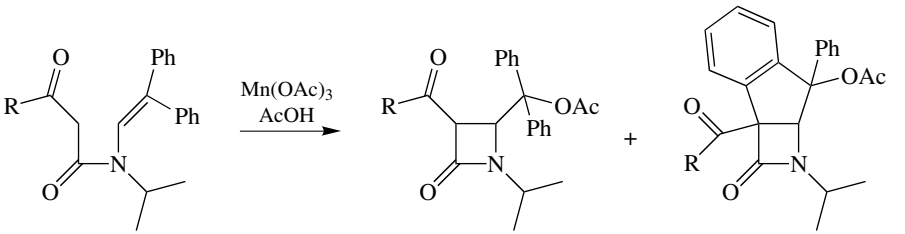


(**93**) (*Z*)

SCHEME 39

pyridylmethanimine ligands, the rate of ATRP of methyl methacrylate was found to be enhanced by the addition of substituted phenols, traditionally used as radical inhibitors. This provided evidence that the propagation of the polymerization reaction did not take place via a carbon-centred free radical casting doubt as to the true mechanism of ATRP.[193]

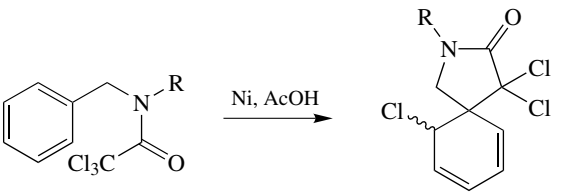
Photo-induced H-abstraction of anthraquinone from xanthene has been studied using nuclear polarization-detected EPR and the structure of the resulting short-lived radical pair determined.[194] The 'retrodisproportionation' reactions of a variety of styrenes with 9,10-dihydroanthracene (DHA), xanthene (XAN), and 9,10-dihydroacridine (DHAc) have been studied in order to determine if there was any evidence of the alternative hydride-transfer mechanism in competition with the proposed H-atom-transfer mechanism. No such evidence was found.[195] The reaction between azulene and DHAC



(**94**)

R = Me	26%	28%
R = OMe	50%	–

SCHEME 40



R = $PhCH_2$	30%
R = Pr^i	41%
R = Bu^t	65%

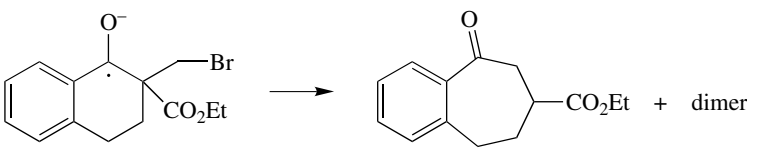
SCHEME 41

has also been studied and gives two isomeric octahydroazulenes as well as naphthalene and tetralin as products. Kinetic studies, isotopic labelling, and semiempirical calculations all indicate a mechanism initiated by an H atom transfer step.[196] The uncatalysed thermal hydrogen-transfer reactions above have recently been reviewed.[197]

Radical Ions

Anion Radicals

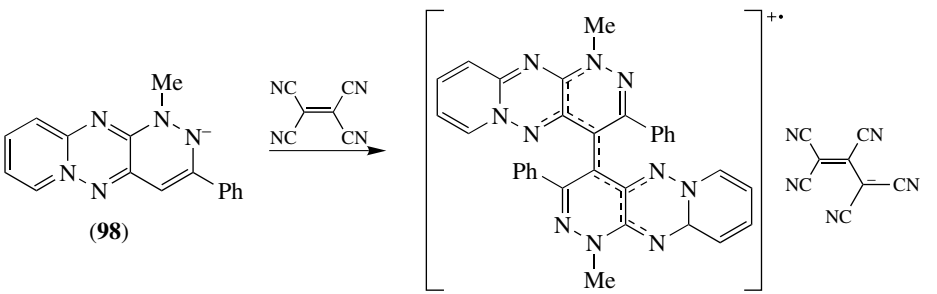
The radical anion (**95**), generated from photo-induced electron transfer of halogenated benzocycloalkanes, furnishes ring-expanded products (**96**) in addition to reduced species and dimers.[198]



(**95**) (**96**)

Cation Radicals

The unexpected formation of the blue crystalline radical cation (**97**) from the reaction of triazinium salt (**98**) with tetracyanoethylene has been reported and the product identified by its EPR spectrum and by X-ray crystallography (Scheme 42).[199] Carboxylic acids react with the photochemically produced excited state of *N*-*t*-α-phenynitrone (PBN) to furnish acyloxy spin adducts RCOOPBN. The reaction was assumed to proceed via ET oxidation of PBN to give the PBN radical cation followed by reaction with RCO_2H.[200] The mechanism of the protodiazoniation of 4-nitrobenzenediazonium fluoroborate to nitrobenzene in DMF has been studied.[201] Trapping experiments were consistent with kinetic isotope effects calculated for the DMF radical cation. The effect of the coupling of radicals with different sulfur radical cations in diazadithiafulvalenes has been investigated.[202]



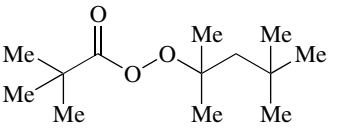
SCHEME 42

Peroxides, Peroxyl, and Hydroxyl Radicals

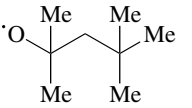
Peroxides

The reactions and decomposition of peroxides has been studied by a range of techniques including time-resolved Raman spectroscopy,[203] CIDNP,[204] and theoretical methods.[205] The kinetics of pyrolysis of dimethyl, diethyl and di-*t*-butyl peroxides have been measured. The free energies of activation for the three diacyl peroxides were found to increase in the order listed above.[206] The thermolysis of acetyl propionyl peroxide and the lifetimes of the intermediate radicals have been studied using CIDNP.[204] A range of theoretical methods have been compared to ascertain which calculations are in best agreement with bond dissociative energies of a range of peroxides.[205] The decomposition of *t*-butyl hydroperoxide in the presence of Co^{II} 2-ethylhexanoate has been studied.[207] Evidence was presented to indicate the intermediacy of a bridged dicobalt species in the catalytic cycle. This postulated mechanism differs substantially from the accepted Haber and Weiss cycle as no alkoxy radical is generated. The use of 1,1,3,3-tetramethylbutylperoxy pivalate (**99**) has been

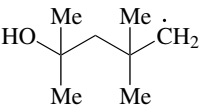
examined as an initiator in the polymerization of methyl methacrylate and styrene in the presence of the radical scavenger 1,1,3,3-tetramethyl-2,3-dihydro-1*H*-isoindol-2-yloxyl.[62] After initial homolysis of the initiator the main reactions of the resulting *t*-ocyloxy radicals (**100**) are unimolecular 1,5-H transfer to (**101**) and fragmentation to (**102**). These latter alkyl radicals undergo addition to monomers far faster than the parent radical (**100**).[62,63]



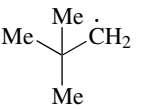
(**99**)



(**100**)



(**101**)



(**102**)

Peroxyl Radicals

The regiospecificity of peroxyl radical addition to (*E*)-retinoic acid has been studied in micelles. The major product was found to be the 5,6-epoxyretinoic acid suggesting initial addition at C(5) or C(6) yielding an endocyclic tertiary allylic or tertiary carbon centred radical, respectively. Elimination of an alkoxy radical then furnishes the observed epoxide. Computational studies were also carried out to gain insights into the mechanism of the process.[208] Theoretical calculations have also been carried out to determine the possible mechanism for oxidation of the methoxy radical to formaldehyde. Results indicated that oxidation is likely to occur via the intermediate $MeO_3^{\cdot}$ rather than by a straightforward H-abstraction reaction.[209] The reactions of the triphenylmethyl radical,[210] *n*-pentyl radical[211] and the acetyl radical[212] with O_2 have been investigated. The latter reaction was studied at 298 K as a function of pressure using FTIR spectroscopy. The reaction of the triphenylmethyl radical with O_2 was found to proceed with a negative activation energy (-4.1 kcal mol^{-1}). The rate constants for the addition of $CF_3O_2^{\cdot}$ to O(3P)[213] and *p*-phenylenediamine[214] have been reported to be $(6.3 \pm 1) \times 10^{-11}$ cm^3 molecule^{-1} s^{-1} [213] and 2×10^4 l mol^{-1} s^{-1},[214] respectively.

The self-recombination reactions of $HO_2^{\cdot}$, $CF_3CFHO^{\cdot}$, and $CF_3O_2^{\cdot}$ have been studied using pulse radiolysis/time-resolved UV absorption spectroscopy.[215] The addition of the cumylperoxy radical to a range of alkyl-substituted biphenyls has been studied and the rate constants compared with reactions with related monosubstituted benzenes.[216]

The reaction of 2,2,6,6-tetramethylpiperidyl radical with O_2 has been studied using EPR at low temperature. Evidence indicates a possible reversible reaction with initial formation of the piperidylperoxyl radical followed by conversion to the aminoxyl

radical.[217] Kinetic studies on the oxidation of dimethyl ether (a possible alternative to diesel fuel) have been reported.[218]

Hydroxyl Radical

The role and behaviour of organic nitrates[219–221] and acetates[222] in the troposphere have been studied by a number of groups. Relative rate coefficients for the reactions of methyl and ethyl nitrate with ˙OH have been determined and compared with other literature data.[219] The reactions of a variety of alkyl nitrates have been studied using pulsed laser photolysis[221] and discharge-flow/resonance fluorescence.[220] The latter work studied the reaction over the pressure range 1–20 Torr and temperature range 300–400 K and concluded that the rate constants were invariant with pressure but did increase with increasing temperature, suggesting an abstraction process. The temperature dependence of the reaction between ˙OH and alkyl acetates (used as solvents, perfumes, and flavourings) has been studied over the temperature range 253–372 K.[222]

There has been a lot of interest into the reactions of ˙OH with fluorinated and chlorinated organic molecules. The atmospheric chemistry of hydrofluoroethers (HFEs), possible replacements to CFCs in numerous applications, has been evaluated.[223] The reaction of C_4F_9OMe (HFE-7100) with ˙OH and the fate of the intermediate radicals $C_4F_9OCH_2^{\cdot}$, $C_4F_9OCH_2O_2^{\cdot}$, and $C_4F_9OCH_2O^{\cdot}$ have been studied and an atmospheric lifetime of 5 years was determined for HFE-7100. Reactions of ˙OH with $MeCF_2Cl$,[224] fluorinated alkenes,[225] and CH_2Cl_2[226] have been reported. The last report allowed for a reanalysis of reaction values for the reaction of ˙OH with various CFCs.[226] The reaction-pathway dynamics of hydrogen abstraction from ethane and haloethanes by ˙OH have been determined using vibrational TS theory augmented with multidimensional semiclassical tunnelling approximations.[227]

The rates of reaction of ˙OH with methane, deuteriated methanes,[228] cyclohexane,[229] and 1-bromopropane[230] have been measured and the atmospheric implication of the results discussed. The latter study assessed the global warming potential of the industrial solvent 1-bromopropane at 20, 100 and 500 years.

The reaction of a series of dimethylbenzaldehydes and trimethylphenols[231] (constituents of wood smoke and tobacco smoke, respectively) with ˙OH have been studied as well as with other aromatic molecules such as indene, fluorene, and 9,10-dihydroanthracene,[232] and atmospheric implications determined.[231]

The rate constants for the reactions between ˙OH and a range of ethers and hydroxy ethers have been reported at 298 K[233] as well as those for reactions between dimethyl ether and methyl *t*-butyl ether over the range 295–750 K.[234] Data from the former study show deviations from simple structure–activity relationships which were postulated to arise due to H-bonding in the reaction transition states.[233] The atmospheric lifetime of methyl ethyl ether has been determined to be approximately 2 days.[235] Theoretical studies on the H-abstraction from propan-2-ol (a model for deoxyribose) by ˙OH have been reported using *ab initio* methods (MP2/6–31G*).[236] The temperature dependence (233–272 K) of the rate coefficients for the reaction of ˙OH with methyl, ethyl, *n*-propyl, *n*-butyl, and *t*-butyl formate has been measured and structure–activity

relationships discussed. Results indicated tropospheric lifetimes of 66.9, 13.6, 6.4, 3.3, and 15.5 days, respectively.[237]

Volatile siloxanes have shown promise as environmentally friendly alternatives to volatile organic solvents and lubricants. As a consequence, the rate constants for the reactions of a number of siloxanes with ·OH have been determined.[238] A number of unusual cyclic siloxane products were observed in the reactions with hexamethyldisiloxane, octamethyltrisiloxane, and decamethyltetrasiloxane.

Carbon monoxide has been used to scavenge ·OH formed from the ozonolysis of alkenes. The CO_2 thus generated was detected by FTIR spectroscopy and the ·OH yields for individual reactions were calculated.[239] The significance of the ·OH-induced intramolecular transformation of glutathione thiyl radicals to α-aminoalkyl radicals has been discussed with respect to its biological implications.[240] The kinetics and mechanism of the process indicated that it could be a significant pathway for the self-removal of glutathione thiyl radicals *in vivo*.

References

[1] Chatgilialoglu, C. and Ferreri, C., *Chem. Triple-Bonded Funct. Groups*, **2**, 917 (1994); *Chem. Abs.*, **125**, 327741 (1996).
[2] Fischer, H., *NATO ASI Ser., Ser. 3*, **27**, 63 (1997); *Chem. Abs.*, **127**, 4739 (1997).
[3] Nishida, A. and Nishida, M., *Rev. Heteroatom. Chem.*, **16**, 287 (1997); *Chem. Abs.*, **127**, 94835 (1997).
[4] Easton, C.J., *Chem. Rev.*, **97**, 53 (1997); *Chem. Abs.*, **126**, 75194 (1997).
[5] Easton, C. J., *Pure Appl. Chem.*, **69**, 489 (1997).
[6] Tomooka, K. and Nakai, T., *Yuki Gosei Kagaku Kyokaishi*, **54**, 1000 (1996); *Chem. Abs.*, **126**, 18412 (1997).
[7] Chatgilialoglu, C., *NATO ASI Ser., Ser. 3*, **27**, 263 (1996); *Chem. Abs.*, **125**, 30155 (1996).
[8] Tonko, J. M. and Suleman, N. K., *Struct. Energ. React. Chem. Ser.*, **1996**, 224; *Chem. Abs.*, **125**, 274936 (1996).
[9] Tumanski, B. L., *Izv. Akad. Nauk, Ser. Khim.*, **1996**, 2396; *Chem. Abs.*, **126**, 156988 (1997).
[10] Rossi, R. A., Pierini, A. B., and Penenory, A., *Chem Halides Pseudo-Halides Azides*, **1995**, 1395; *Chem. Abs.*, **125**, 246846 (1996).
[11] Ciurla, H., *Pr. Nauk. Akad. Ekon. im Oskara Langego Wroclawiu*, **728**, 83 (1996); *Chem. Abs.*, **127**, 34159 (1997).
[12] Porter, N. A., Havrilla, C. M., and Kenar, J. A., *NATO ASI Ser., Ser. 3*, **27**, 121 (1997); *Chem. Abs.*, **127**, 17848 (1997).
[13] Beckwith, A. L. J. and Duggan, P. J., *J. Am. Chem. Soc.*, **118**, 12838 (1996).
[14] Crich, D., Escalante, J., and Jiao, X.-Y., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 627.
[15] Zipse, H., *J. Am. Chem. Soc.*, **119**, 2889 (1997).
[16] Zipse, H., *J. Am. Chem. Soc.*, **119**, 1087 (1997).
[17] Dussault, P. H. and Woller, K. R., *J. Am. Chem. Soc.*, **119**, 3824 (1997).
[18] Feng, W. L., Lei, M., Wang, Y., and Qian, Y., *Chin. Chem. Lett.*, **8**, 71 (1997); *Chem. Abs.*, **126**, 224912 (1997).
[19] Srikrishina, A., Viswajanani, R., Jagadeeswar, R. T., Vijaykumar, D., and Praveen Kumar, P., *J. Org. Chem.*, **62**, 5232 (1997).
[20] Martinez, F. N., Schlegel, H. B., and Newcomb, M., *J. Org. Chem.*, **61**, 8547 (1996).
[21] Engel, P. S., He, S.-H., Banks, J. T., Ingold, K. U., and Lusztyk, J., *J. Org. Chem.*, **62**, 1210 (1997).
[22] Newcomb, M., Horner, J. H., and Emanuel, C. J., *J. Am. Chem. Soc.*, **119**, 7147 (1997).
[23] Marples, B. A., Rudderhan, J. A., Slawin, A. M. Z., Edwards, A. J., and Hird, N. W., *Tetrahedron Lett.*, **38**, 3599 (1997).
[24] Krishnamurthy, V. and Rawal, V. H., *J. Org. Chem.*, **62**, 5486 (1997).
[25] Easton, C. J., Ivorty, A. I., and Smith, C. A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 503.
[26] Müller, S. N., Batra, R., Senn, M., Giese, B., Kisel, M., and Shadyro, O., *J. Am. Chem. Soc.*, **119**, 2795 (1997).
[27] Saicic, R. N., *Tetrahedron Lett.*, **38**, 295 (1997).

[28] Chatgilialoglu, C., *Chem. Eur. J.*, **1997**, 377.
[29] Montevecchi, P. C., Navacchia, M. L., and Spagnolo, P., *Tetrahedron Lett.*, **38**, 7913 (1997).
[30] Caddick, S., Shering, C. L., and Wadman, S. N., *J. Chem. Soc., Chem. Commun.*, **1997**, 171.
[31] Dobbs, A. P., Jones, K., and Veal, K. T., *Tetrahedron Lett.*, **38**, 5379 (1997).
[32] Sha, C.-K., Tseng, W.-H., Huang, K.-T., Liu, K.-M., Lin, H.-Y., and Chu, S.-Y., *J. Chem. Soc., Chem. Commun.*, **1997**, 239.
[33] Srikrishna, A. and Veera Raghava Sharma, G., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 177.
[34] Jung, M. E. and Marques, R., *Tetrahedron Lett.*, **38**, 6521 (1997).
[35] Grossi, L. and Strazzari, S., *J. Chem. Soc., Chem. Commun.*, **1997**, 917.
[36] Krishnamurthy, V. and Rawal, V. H., *J. Org. Chem.*, **62**, 1572 (1997).
[37] Kim, S., Yoon, K. S., and Kim, Y. S., *Tetrahedron*, **53**, 73 (1997).
[38] Kim, S., Yoon, K. S., and Kim, Y. S., *Tetrahedron Lett.*, **38**, 2487 (1997).
[39] Yamamoto, Y., Ohno, M., and Eguchi, S., *J. Org. Chem.*, **61**, 9264 (1996).
[40] Ke, B.-W., Lin, C.-H., and Tsai, Y.-M., *Tetrahedron*, **53**, 7805 (1997).
[41] Parsons, A. F., and Pettife, R. M., *Tetrahedron Lett.*, **38**, 5907 (1997).
[42] Keseru, G. M., Toke, L., Hell, Z., Jaszay, Z. M., Petnehazy, I., and Korecz, L., *THEOCHEM*, **392**, 95 (1997); *Chem. Abs.*, **127**, 94877 (1997).
[43] Hartung, J., Stowasser, R., Vitt, D., and Bringmann, G., *Angew. Chem., Int. Ed. Engl.*, **35**, 2820 (1996).
[44] Newcomb, M., Musa, O. M., Martinez, F. N., and Horner, J. H., *J. Am. Chem. Soc.*, **119**, 4569 (1997).
[45] Ha, C., Musa, O. M., Martinez, F. N., and Newcomb, M., *J. Org. Chem.*, **62**, 2704 (1997).
[46] Marco-Conteles, J., *J. Chem. Soc., Chem. Commun.*, **1996**, 2629.
[47] Chambournier, G., Krishnamurthy, V., and Rawal, V. H., *Tetrahedron Lett.*, **38**, 6313 (1997).
[48] Sugimura, T., Nagaro, S., and Tai, A., *Tetrahedron Lett.*, **38**, 3547 (1997).
[49] Montevecchi, P. C. and Navacchia, M. L., *J. Org. Chem.*, **62**, 5600 (1997).
[50] Wille, U. and Plath, C., *Liebigs Ann./Recl.*, 1997, 111.
[51] Petrovic, G. and Cekovic, Z., *Tetrahedron Lett.*, **38**, 627 (1997).
[52] Jung, M. E. and Rayle, H. L., *J. Org. Chem.*, **62**, 4601 (1997).
[53] Croce, A. E., Cobos, C. J., and Castellano, E., *Chem. Phys.*, **211**, 215 (1996); *Chem. Abs.*, **126**, 7546 (1997).
[54] Park, J. and Lin, M. C., *J. Phys. Chem.*, **101A**, 14 (1997).
[55] Marico, M. N., Ball, J. C., Straccia, A. M., and Szente, J. J., *Int. J. Chem. Kinet.*, **29**, 412 (1997).
[56] Melius, C. F., Colvin, M. E., Marinov, N. M., Pitz, W. J., and Senkan, S. M., *Symp. (Int.) Combust., (Proc.)*, **26**, 685 (1996); *Chem. Abs.*, **126**, 293005 (1997).
[57] Biggs, P., Canosa-Mas, C. E., Shallcross, D. E., Vipond, A., and Wayne, R. P., *J. Chem. Soc., Faraday Trans.*, **93**, 2701 (1997).
[58] Breslan, R., Burrill, L. C., Mahal, L. K., and Wedeking, T., *Angew. Chem., Int. Ed. Engl.*, **36**, 237 (1997).
[59] Korth, H.-G. and Sicking, W., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 715.
[60] Laarhoven, J. J. J., Born, J. G. P., Arends, I. W. C. E., and Mulder, P., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2307.
[61] Denisov, E. T., *Neftekhimiya*, **37**, 23 (1997); *Chem. Abs.*, **127**, 17296 (1997).
[62] Nakamura, T., Busfiled, W. K., Jenkins, I. D., Rizzardo, E., Thang, S. H., and Suyamas, S., *J. Am. Chem. Soc.*, **119**, 10987 (1997).
[63] Nakamura, T., Busfiled, W. K., Jenkins, I. D., Rizzardo, E., Thang, S. H., and Suyamas, S., *J. Org. Chem.*, **62**, 5578 (1997).
[64] Kita, Y., Sano, A., Yamaguch, T., Oka, M., Gotanda, K., and Matsugi, M., *Tetrahedron Lett.*, **38**, 3549 (1997).
[65] Binbnigge, N., Butler, A. R., and Gorbitz, C. H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 351.
[66] Antonovskii, V. L. and Bozhenko, K. V., *Dokl. Akad. Nauk*, **343**, 337 (1995); *Chem. Abs.*, **126**, 305366 (1997).
[67] Harris, N. J. and Lammertsma, K., *J. Phys. Chem.*, **101A**, 1370 (1997).
[68] Engel, P. S., Duan, S., and Arhancet, G. B., *J. Org. Chem.*, **62**, 3537 (1997).
[69] Atkinson, R., *Int. J. Chem. Kinet.*, **29**, 99 (1997).
[70] Tsang, W., Walker, J. A., and Manion, J. A., *Chem. Phys. Processes Combust.*, **1996**, 515; *Chem. Abs.*, **126**, 131091 (1997).
[71] Madden, L. K., Moskaleve, L. V., Kristyan, S., and Lin, M. C., *J. Phys. Chem.*, **101A**, 6790 (1997).
[72] Huang, J.-H., Han, K.-L., Deng, W.-Q., and He, G.-Z., *Chem. Phys. Lett.*, **273**, 205 (1997); *Chem. Abs.*, **127**, 190315 (1997).
[73] Jones, J., Backsay, G. B., and Mackie, J. C., *J. Phys. Chem.*, **101A**, 7105 (1997).
[74] Nanni, D., Pareschi, P., and Tundo, A., *Tetrahedron Lett.*, **37**, 9337 (1996).
[75] Abedinzadeh, Z., *J. Chim. Phys.-Chem. Biol.*, **94**, 262 (1997); *Chem. Abs.*, **126**, 292908 (1997).

[76] LaFracois, C. J. and Shevlin, P. B., *Tetrahedron*, **53**, 10071 (1997).
[77] Kazakov, D. V., Kabal'nova, N. N., Khursan, S. L., and Shereshovets, V. V., *Russ. Chem. Bull.,* transl. *Izv. Akad. Nauk, Ser. Khim.*, **46**, 663 (1997); *Chem. Abs.*, **127**, 220338 (1997).
[78] Olzmann, M. and Viskolcz, B., *Ber. Bunsen-Ges.*, **101**, 538 (1997); *Chem. Abs.*, **126**, 343240 (1997).
[79] Hogan, T. and Sen, A., *J. Am. Chem. Soc.*, **119**, 2642 (1997).
[80] Bartberger, M. D., Dolbier, W. R., Lusztyk, J., and Ingold, K. U., *Tetrahedron*, **53**, 9857 (1997).
[81] Basch, H. and Hoz, S., *J. Phys. Chem.*, **101A**, 4416 (1997).
[82] Jursic, B. S., *THEOCHEM*, **365**, 75 (1996); *Chem. Abs.*, **126**, 274960 (1996).
[83] Bernardi, F. and Bottoni, A., *J. Phys. Chem.*, **101A**, 1912 (1997).
[84] Pang, X.-Y., Wang, Y., Feng, W.-L., Zham, S.-W., and Xi, H.-W., *Jiegou Huaxue*, **15**, 466 (1996); *Chem. Abs.*, **126**, 59497 (1997).
[85] Ma, S. and Liu, R., *Sci. Chin., Ser. B: Chem.*, **39**, 37 (1996); *Chem. Abs.*, **126**, 18462 (1997).
[86] Skokov, S. and Wheeler, R. A., *Chem. Phys. Lett.*, **271**, 271 (1997); Chem. Abs., **127**, 80970 (1997).
[87] Roberts, B. P., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2719.
[88] Dobis, O. and Benzon, S. W., *J. Phys. Chem.*, **101A**, 6030 (1997).
[89] Binmore, G., Cardellini, L., and Walton, J. C., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 757.
[90] Asensio, G., Mello, R., Gonzalez-Nuez, M. E., Boix, C., and Royo, J., *Tetrahedron Lett.*, **38**, 2373 (1997).
[91] Kortvelyesi, T. and Seres, L., *React. Kinet. Catal. Lett.*, **58**, 27 (1996); *Chem. Abs.*, **126**, 30978 (1997).
[92] Viskolcz, B., Lenduay, G., and Seres, L., *J. Phys. Chem.*, **101A**, 7119 (1997).
[93] Gross, A., Fensterbank, L., Bogen, S., Thouvenot, R., and Malacria, M., *Tetrahedron*, **53**, 13797 (1997).
[94] Masnyk, M., *Tetrahedron Lett.*, **38**, 879 (1997).
[95] Van Dort, P. C. and Fuchs, P. L., *J. Org. Chem.*, **62**, 7142 (1997).
[96] Kandel, S. A., Rakitis, T. P., Lev-On, T., and Zare, R. N., *J. Chem. Phys.*, **105**, 7550 (1996); *Chem. Abs.*, **125**, 300284 (1996).
[97] Pilgrim, J. S., McLlroy, A., and Taatjes, C. A., *J. Phys. Chem.*, **101A**, 1873 (1997).
[98] Espinosa-Garcia, J. and Corchado, J. C., *J. Chem. Phys.*, **105**, 3 517 (1996); *Chem. Abs.*, **125**, 246935 (1996).
[99] Pilgrim, J. S. and Taatjes, C. A., *J. Phys. Chem.*, **101A**, 4172 (1997).
[100] Pilgrim, J. S. and Taatjes, C. A., *J. Phys. Chem.*, **101A**, 5776 (1997).
[101] Olsson, B. E. R., Hallquist, M., Ljungstroem, E., and Davidsson, J., *Risoe Natl. Lab. [Rep.] Risne-R*, **1996**, 38; *Chem. Abs.*, **126**, 131094 (1997).
[102] Regains, M. L. and Finlayson-Pitts, B. J., *J. Phys. Chem.*, **101A**, 1509 (1997).
[103] Shi, J. and Bernhard, M. J., *Int. J. Chem. Kinet.*, **29**, 349 (1997).
[104] Olsson, B. E. R., Hallquist, M., and Ljungström, E., *Int. J. Chem. Kinet.*, **29**, 195 (1997).
[105] Rosenman, E. and McKee, M. L., *J. Am. Chem. Soc.*, **119**, 9033 (1997).
[106] Kambanis, K. G., Lazarou, Y. G., and Papagiannakopoulos, P., *J. Phys. Chem.*, **101A**, 8496 (1997).
[107] Kambanis, K. G., Lazarou, Y. G., and Papagiannakopoulos, P., *Chem. Phys. Lett.*, **268**, 498 (1997); *Chem. Abs.*, **126**, 317101 (1997).
[108] Louis, F., Talhaoui, A., Sawerysyn, J.-P., Rayel, M.-T., and Rayez, J. C., *J. Phys. Chem.*, **101A**, 8503 (1997).
[109] Wilson, C. and Hirst, D. M., *J. Chem. Soc., Faraday Trans.*, **93**, 2831 (1997).
[110] Kambanis, K. G., Lazarov, Y. G., and Papagiannakopoulos, P., *J. Chem. Soc., Faraday Trans.*, **92**, 4905 (1996).
[111] Bilde, M., Sehested, J., Nielsen, O. J., and Wallington, J. J., *J. Phys. Chem.*, **101A**, 5477 (1997).
[112] Hasson, A. S., Moore, C. M., and Smith, I. W. M., *J. Chem. Soc., Faraday Trans.*, **93**, 2693 (1997).
[113] Dóbé, S., Bérces, T., Turányi, T., Márta, F., Grussdorf, J., Temps, F., and Wagener, H., *J. Phys. Chem.*, **100A**, 19864 (1996).
[114] Denisov, E. T. and Tumanov, V. E., *Khim. Fiz.*, **15**, 132 (1996); *Chem. Abs.*, **125**, 327786 (1997).
[115] Denisov, E. T. and Drozdova, T. I., *Kinet. Catal.* transl. *Kinet. Katal.*, **38**, 35 (1997); *Chem. Abs.*, **126**, 292953 (1997).
[116] Bottle, S. E., Chand, U., and Micallef, A. S., *Chem. Lett.*, **1997**, 857.
[117] Denisov, E. T. and Drozdova, T. I., *Kinet. Catal.* transl. *Kinet. Katal.*, **38**, 14 (1997); *Chem. Abs.*, **126**, 292952 (1997).
[118] Suzuki, H. and Nanoyama, N., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2965.
[119] D'Anna, B. and Nielsen, C. J., *J. Chem. Soc., Faraday Trans.*, **93**, 3479 (1997).
[120] Myers, A. G., Movassaghi, M., and Zheng, B., *Tetrahedron Lett.*, **38**, 6569 (1997).
[121] Mezyk, M. P., Lossack, A., and Bartles, D. M., *Can. J. Chem.*, **75**, 1114 (1997).
[122] Boivin, J., Quiclet-Sire, B., Ramos, L., and Zard, S. Z., *J. Chem. Soc., Chem. Commun.*, **1997**, 353.
[123] Tang, W. Z. and Huang, C. P., *Waste Manage. (N.Y.)*, **15**, 1615 (1995); *Chem. Abs.*, **126**, 18509 (1997).

[124] Kukui, A., Roggenbuck, J., and Schindler, R. N., *Ber. Bunsen-Ges.*, **101**, 281 (1997); *Chem. Abs.*, **126**, 298066 (1997).
[125] Denisov, E. T. and Tumanov, V. E., *Kinet. Catal.* transl. *Kinet. Katal.*, **38**, 345 (1997); *Chem. Abs.*, **127**, 148829 (1997).
[126] Yuan, J., Wells, L., and Marshall, P., *J. Phys. Chem.*, **101A**, 3542 (1997).
[127] Liguori, L., Bjørsvik, H.-R., Bravo, A., Fontana, F., and Minisci, F., *J. Chem. Soc., Chem. Commun.*, **1997**, 1501.
[128] Greenwood, J. R., Vaccarella, G., Capper, H. R., Mewett, K. N., Allan, R. D., and Johnston, G. A. R., *THEOCHEM*, **368**, 235 (1996); *Chem. Abs.*, **126**, 88959 (1997).
[129] Avery'yanov, V. A., Ryl'tsova, S. V., and Alferov, V. A., *Kinet. Catal.* transl. *Kinet. Katal.*, **38**, 14 (1997); *Chem. Abs.*, **126**, 1292951 (1997).
[130] North, S. W., Fei, R., Sears, T. T., and Hall, G. E., *Int. J. Chem. Kinet.*, **29**, 127 (1997).
[131] Jiang, X.-K., Zhang, Y.-H., and Ding, W. F.-X., *J. Chem. Res. (S)*, **1997**, 6.
[132] Recupero, F., Bravo, A., Bjøorsvik, H.-R., Fontana, F., Minisci, F., and Piredda, M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2399.
[133] Wu, Y. W., *J. Chin. Chem. Soc. (Taipei)*, **43**, 507 (1996); *Chem. Abs.*, **126**, 185674 (1997).
[134] Montevecchi, P. C., Navaccia, M. L., and Spagnolo, P., *J. Org. Chem.*, **62**, 5846 (1997).
[135] Harvey, I. W., Phillips, E. D., and Whitham, G. H., *Tetrahedron*, **53**, 6493 (1997).
[136] Weldon, D., Holland, S., and Scaiano, J. C., *J. Org. Chem.*, **61**, 8544 (1996).
[137] Knyasez, V., Stoliarov, S. I., and Slagle, I. R., *Symp. (Int.) Combust., (Proc.)*, **1996**, 513; *Chem. Abs.*, **126**, 277052 (1997).
[138] Jiang, X.-K., Ji, G.-Z., and Xie, J. R.-Y., *J. Fluorine Chem.*, **79**, 133 (1996); *Chem. Abs.*, **126**, 7543 (1997).
[139] Chandra, A. K. and Nguyen, M. T., *J. Chem. Soc., Chem. Commun.*, **1997**, 1415.
[140] Herpin, T. F., Motherwell, W. B., and Weibel, J. M., *J. Chem. Soc., Chem. Commun.*, **1997**, 923.
[141] Martinez, E., Carbnas, B., Avanda, A., Martin, P., and Salgado, S., *Int. J. Chem. Kinet.*, **29**, 927 (1997).
[142] Catoire, V., Ariya, P. A., Niki, H., and Harris, G. W., *Int. J. Chem. Kinet.*, **29**, 695 (1997).
[143] Montevecchio, P. C., Navacchia, M. L., and Spagnolo, P., *Tetrahedron*, **53**, 7929 (1997).
[144] Chen, X.-Y., Wu, M.-F., Han, Y., Qi, L., and Xu, Z., *Youji Huaxue*, **16**, 453 (1996); *Chem. Abs.*, **126**, 31147 (1997).
[145] Haque, M. B. and Roberts, B. P., *Tetrahedron Lett.*, **37**, 9123 (1997).
[146] Bottoni, A., *J. Phys. Chem.*, **101A**, 4402 (1997).
[147] Noremsaure, I. M. W., Langer, S., Ljungström, E., and Nielsen, C. J., *J. Chem. Soc., Faraday Trans.*, **93**, 525 (1997).
[148] Berndt, T. and Böge, O., *Int. J. Chem. Kinet.*, **29**, 755 (1997).
[149] Rhodes, C. J., Morris, H., and Reid, I. D., *Hyperfine Interact.*, **106**, 203 (1997); *Chem. Abs.*, **127**, 33732 (1997).
[150] Gasonov, R. G., *Izv. Akad. Nauk, Ser. Khim.*, **1996**, 2124; *Chem. Abs.*, **126**, 30971 (1997).
[151] Bensassan, C. S., Cornforth, J., Du, M.-H., and Hanson, J. R., *J. Chem. Soc., Chem. Commun.*, **1997**, 1509.
[152] Fong, M. C. and Schieseer, C. H., *J. Org. Chem.*, **62**, 3103 (1997).
[153] Nishida, A., Kakimoto, Y.-I., Ogasawara, Y., Kawahara, N., Nishida, M., and Takayanagi, H., *Tetrahedron Lett.*, **38**, 5519 (1997).
[154] da Mata, M. L. E. D., Motherwell, W. B., and Ujjainwalla, F., *Tetrahedron Lett.*, **38**, 137 (1997).
[155] da Mata, M. L. E. D., Motherwell, W. B., and Ujjainwalla, F., *Tetrahedron Lett.*, **38**, 141 (1997).
[156] Gellis, A., Vanelle, P., Kaafarani, M., Benakli, K., and Crozet, P., *Tetrahedron*, **53**, 5471 (1997).
[157] Murguia, M. C. and Rossi, R. A., *Tetrahedron Lett.*, **38**, 1355 (1997).
[158] Manion, J. A. and Tsang, W., *Isr. J. Chem.*, **36**, 263 (1996); *Chem. Abs.*, **126**, 305347 (1997).
[159] Nieto, J. D. and Oexler, E. V., *Ber. Bunsen-Ges.*, **101**, 868 (1997); *Chem. Abs.*, **127**, 33740 (1997).
[160] Kosynkin, D., Bockman, T. M., and Kochi, J. K., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2003.
[161] Ryu, I., Okuda, T., Nagahara, K., Kambe, N., Komatsu, M., and Sonoda, N., *J. Org. Chem.*, **62**, 7550 (1997).
[162] Crich, D. and Hao, X., *J. Org. Chem.*, **62**, 5982 (1997).
[163] Dockery, K. P. and Bentrude, W. G., *J. Am. Chem. Soc.*, **119**, 1388 (1997).
[164] Taner, D. D., Koppula, S., and Kandanarachchi, P., *J. Org. Chem.*, **62**, 4210 (1997).
[165] Biggs, P., Canosa-Mas, C. E., Fracheboi, J.-M., Shallcross, D. E., and Wayne, R. P., *J. Chem. Soc., Faraday Trans.*, **93**, 2481 (1997).
[166] Jiang, X.-K., Ding, W. F.-X., and Zhang, Y.-H., *Tetrahedron*, **53**, 8479 (1997).
[167] Bravo, A., Bjørsvik, H.-R., Fontana, F., Liguori, L., Mele, A., and Minisci, F., *J. Org. Chem.*, **62**, 7128 (1997).

[168] McCarroll, A., Walton, J. C., Nziengui, R., and Carboni, B., *J. Chem. Soc., Chem. Commun.*, **1997**, 2075.
[169] Magnaterra, F., Pedrielli, P., and Pedulli, G. F., *Gazz. Chim. Ital.*, **126**, 673 (1996); *Chem. Abs.*, **126**, 7601.
[170] Gainsforth, J. L., Klobikowski, M., and Tanner, D. D., *J. Am. Chem. Soc.*, **119**, 3339 (1997).
[171] Ooi, T., Hokke, Y., and Maruoka, K., *Angew. Chem., Int. Ed. Engl.*, **36**, 1181 (1997).
[172] Ihara, M., Katsumata, A., and Fukumoto, K., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 991.
[173] Stien, D., Samy, R., Nouguier, R., Crich, D., and Bertrand, M. P., *J. Org. Chem.*, **62**, 272 (1997).
[174] Tsai, Y.-M., Chang, F.-C., Huang, J., Shiu, C.-L., Kao, C.-L., and Liu, J.-S., *Tetrahedron*, **53**, 4291 (1997).
[175] Clauss, R. and Hunter, R., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 71.
[176] Giese, B., *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)*, **38**, 639 (1997); *Chem. Abs.*, **126**, 224879 (1997).
[177] Fhal, A.-R. and Renaud, P., *Tetrahedron Lett.*, **38**, 2661 (1997).
[178] Sibi, M. P. and Ji, J., *J. Org. Chem.*, **62**, 3800 (1997).
[179] Porter, N. A., Wu, J. H., Zhang, G., and Reed, A. D., *J. Org. Chem.*, **62**, 6702 (1997).
[180] Wu, J. H., Zhang, G., and Porter, N. A., *Tetrahedron Lett.*, **38**, 2067 (1997).
[181] Miyabe, H., Ushira, C., and Naito, T., *J. Chem. Soc., Chem. Commun.*, **1997**, 1798.
[182] Taber, D. F., Gorski, G. J., Liable-Sands, L. M., and Rheingold, A. L., *Tetrahedron Lett.*, **38**, 6317 (1997).
[183] Tararov, V. I., Kuznetzov, N. Y., Balchnutov, V. I., Ikonnikov, N. S., Bubnov, Y. N., Khrustalev, V. N., Saveleva, T. F., and Belokon, Y. N., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 310 (1997).
[184] Chai, C. L. L., Hockless, D. C. R., and King, A. R., *Aust. J. Chem.*, **49**, 1229 (1996).
[185] Angelaud, R. and Landais, Y., *Tetrahedron Lett.*, **38**, 233 (1997).
[186] Martinez-Grau, A. and Curran, D. P., *Tetrahedron*, **53**, 5679 (1997).
[187] D'Annibale, A., Pesce, A., Resta, S., and Trogolo, C., *Tetrahedron*, **53**, 13129 (1997).
[188] Inoue, R., Nakao, J., Shiokubo, H., and Oshima, K., *Bull. Chem. Soc. Jpn*, **70**, 2039 (1997).
[189] Bashir, N., Callaghan, O., Murphy, J. A., Ravishanker, T., and Roome, S. J., *Tetrahedron Lett.*, **38**, 6255 (1997).
[190] Boivin, J., Yousfi, M., and Zard, S. Z., *Tetrahedron Lett.*, **38**, 5985 (1997).
[191] Bravo, A., Bjørsvik, H.-F., Fontana, F., Liguoori, L., and Minisci, F., *J. Org. Chem.*, **62**, 3849 (1997).
[192] Matyjaszewki, K., Palten, T. E., and Xia, J., *J. Am. Chem. Soc.*, **119**, 674 (1997).
[193] Haddleton, D. M., Clark, A. J., Crossman, M. C., Duncalf, D. J., Heming, A. M., Morsley, S. R., and Shooter, A. J., *J. Chem. Soc., Chem. Commun.*, **1997**, 1173.
[194] Shindo, K., Yamamoto, K., Maeda, K., and Azumi, T., *Bull. Chem. Soc. Jpn*, **69**, 2731 (1996).
[195] Friebolin, H., Roers, R., Ebenhoch, J., Gerst, M., and Richardt, C., *Liebigs Ann./Recl.*, **1997**, 385.
[196] Keller, F., Beckhaus, H.-D., and Richardt, C., *Liebigs Ann./Recl.*, **1997**, 2055.
[197] Richardt, C., Gerst, M., and Ebenhoch, J., *Angew. Chem., Int. Ed. Engl.*, **36**, 1406 (1997).
[198] Hasegawa, E., Tamura, Y., and Tosaka, E., *J. Chem. Soc., Chem. Commun.*, 1997, 1895.
[199] Riedl, Z., Hajós, G., Messmer, A., Rockkenbauer, A., Korecz, L., Kollenze, G., Fabian, W. M. F., Peters, K., and Peters, E.-M., *J. Chem. Soc., Chem. Commun.*, **1997**, 757.
[200] Eberson, L. and Persson, O., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1689.
[201] Markgraf, J. H., Chang, R., Cort, J. R., Durant, J. L., Jr, Finkelstein, M., Gross, A. W., Lavyne, M. H., Moore, W. M., Petersen, R. C., and Ross, S. D., *Tetrahedron*, **53**, 1009 (1997).
[202] Murphy, J. A., Koizumi, T., and Bashir, N., *Tetrahedron Lett.*, **38**, 7635 (1997).
[203] Jacob, P., Wehling, B., Hill, W., and Klockow, D., *Appl. Spectroac.*, **51**, 74 (1997); *Chem. Abs.*, **126**, 277115 (1997).
[204] Skakovski, E. D., Stankevich, A. I., Lamotkin, S. A., Tychinskaya, L. Y., and Rykov, S. V., *Zh. Obshch. Khim.*, **66**, 881 (1996); *Chem. Abs.*, **125**, 327945 (1997).
[205] Brankos, S., *THEOCHEM*, **370**, 65 (1996); *Chem. Abs.*, **126**, 224860 (1997).
[206] Lee, S.-Y. and Shin, Y.-J., *Hwakak Konghak*, **35**, 592 (1996); *Chem. Abs.*, **126**, 199210 (1997).
[207] Harris, P. G., Houghton, R. P., and Taylor, P. L., *Polyhedron*, **16**, 2651 (1997); *Chem. Abs.*, **127**, 121437 (1997).
[208] Samokyszyn, V. M., Freyaldenhoven, M. A., Chang, H. C., Freeman, J. P., and Compadne, R. L., *Chem. Res. Toxicol.*, **10**, 795 (1997); *Chem. Abs.*, **127**, 65959 (1997).
[209] Jungkamp, T. P. W. and Seinfeld, J. H., *Chem. Phys. Lett.*, **263**, 371 (1996); *Chem. Abs.*, **126**, 59554 (1997).
[210] Wang, H. and Parker, V. D., *Acta Chem. Scand.*, **51**, 865 (1997).
[211] Vedennev, V. I. and Cherysheva, A. V., *Kinet. Catal.,* transl. *Kinet. Katal.*, **37**, 469 (1996); *Chem. Abs.*, **125**, 247008 (1997).
[212] Tyndall, G. S., Orlando, J. J., Wallington, T. J., and Hurley, M. D., *Int. J. Chem. Kinet.*, **29**, 655 (1997).
[213] Biggs, P., Canosa-Mas, C. E., Shallcross, D. E., Vipond, A., and Wayne, R. P., *J. Chem. Soc., Faraday Trans.*, **93**, 2477 (1997).

[214] Zolotova, N. V. and Kharitonov, V. V., *Izv. Akad. Nauk, Ser. Khim.*, **12**, 2902 (1996); *Chem. Abs.*, **126**, 305354 (1997).
[215] Sehested, J., Møgelberg, T., Fagerström, K., Mahmoud, G., and Wallington, T. J., *Int. J. Chem. Kinet.*, **29**, 673 (1997).
[216] Efimova, I. V., Matvienko, A. G., Romantsevich, A. M., Zaraiskii, A. P., and Opeida, I. A., *Zh. Org. Khim.*, **32**, 516 (1996); *Chem. Abs.*, **125**, 3328024 (1996).
[217] Gottinger, H. A., Zubarev, V. E., and Brede, O., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2167.
[218] Maricq, M. M., Szente, J. J., and Hybl, J. D., *J. Phys. Chem.*, **101A**, 5155 (1997).
[219] Kakesu, M., Bandow, H., Takenaka, N., Maeda, Y., and Washida, N., *Int. J. Chem. Kinet.*, **29**, 933 (1997).
[220] Shallcross, D. E., Biggs, P., Canosa-Mas, C. E., Clemitshaw, K. C., Harrison, M. G., Alanon, M. R. L., Pyles, J. A., Vipond, A., and Wayne, R. P., *J. Chem. Soc., Faraday Trans.*, **93**, 2807 (1997).
[221] Talukdar, R. K., Herridon, S. C., Burkholder, J. B., Roberts, J. M., and Ravishankara, A. R., *J. Chem. Soc., Faraday Trans.*, **93**, 2787 (1997).
[222] LeCalvé, S., LeBras, G., and Mellouki, A., *Int. J. Chem. Kinet.*, **29**, 683 (1997).
[223] Wallington, J. J., Schneider, W. F., Shested, J. H., Bilde, M., Polatz, J., Nielsen, O. J., Christensen, J., Bilde, M., Platz, J., Nielsen, O. J., Christensen, L. K., Molina, M. J., Milina, L. T., and Wooldridge, P. W., *J. Phys. Chem.*, **101A**, 8264 (1997).
[224] Fang, T. D., Taylor, P. H., Dellingger, B., Ehlers, C. J., and Berry, R. J., *J. Phys. Chem.*, **101A**, 5758 (1997).
[225] Dhanya, S. and Sainin, R. D., *Int. J. Chem. Kinet.*, **29**, 187 (1997).
[226] Villenave, E., Orkinb, V. L., Hine, R. E., and Kurylo, M. J., *J. Phys. Chem.*, **101A**, 8513 (1997).
[227] Sekusak, S., Liedl, K. R., Rode, B. M., and Sabljic, A., *J. Phys. Chem.*, **101A**, 4245 (1997).
[228] Gierczak, T., Talukadar, R. K., Herndon, S. C., Vaghjiani, G. L., and Ravishankara, A. R., *J. Phys. Chem.*, **101A**, 3125 (1997).
[229] Aschmann, S. M., Chew, A. A., Arey, J., and Atkinson, R., *J. Phys. Chem.*, **101A**, 8042 (1997).
[230] Nelson, D. D., Wormhoudt, J. C., Zahniser, M. S., Kolb, C. E., Ko, M. K. W., and Weisentein, D. K., *J. Phys. Chem.*, **101A**, 4987 (1997).
[231] Tse, C. W., Flagan, R. C., and Seinfeld, J. H., *Int. J. Chem. Kinet.*, **29**, 523 (1997).
[232] Kwok, E. S. C., Atkinson, R., and Arey, J., *Int. J. Chem. Kinet.*, **29**, 299 (1997).
[233] Porter, E., Wenger, J., Treacy, J., Sidebottom, H., Mellouki, A., Téton, S., and LeBras, G., *J. Phys. Chem.*, **101A**, 5770 (1997).
[234] Arif, M., Dellinger, B., and Taylor, P. H., *J. Phys. Chem.*, **101A**, 2436 (1997).
[235] Starkey, D. P., Holbrook, K. A., Oldershaw, G. A., and Walker, R. W., *Int. J. Chem. Kinet.*, **29**, 231 (1997).
[236] Luo, N., Kombo, D. C., and Osman, R., *J. Phys. Chem.*, **101A**, 926 (1997).
[237] LeCalvé, S., LeBras, G., and Mellouki, A., *J. Phys. Chem.*, **101A**, 5489 (1997).
[238] Stewart, J., Markgraf, J., and Wells, J. R., *Int. J. Chem. Kinet.*, **29**, 445 (1997).
[239] Eutbrod, R., Meyers, S., Rahman, N. M., and Schindler, R. N., *Int. J. Chem. Kinet.*, **29**, 717 (1997).
[240] Zhao, R., Lind, J., Merengi, G., and Erikson, T. E., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 569.

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CHAPTER 4

Radical Reactions: Part 2

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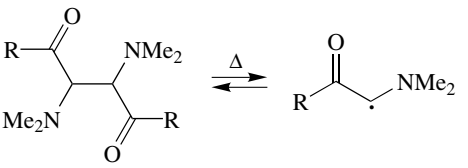
Structure and Stability

Carbon-centred Radicals

The energetics of free radicals[1,2] and estimation of their heats of formation by kinetic methods have been reviewed,[3] along with the mechanism of magnetic isotope effects in radical reactions.[4] Three-electron-bonded radicals (or σ^* radicals) are the subject of a review which details methods of preparation and detection as well as examples of homo- and hetero-nuclear σ^* radicals.[5]

The homolytic bond dissociation energies (BDEs) of phenolic O—H bonds has been the subject of a computational study focusing on substituent effects by *ab initio* and density functional theory (DFT) methods.[6] Consistent overestimation of the BDEs by MP2 and MP4 calculations was associated with spin contamination in the reference UHF wave functions, whilst the DFT calculations (particularly the B3LYP/6–31G** level of theory) were relatively unaffected. *Ab initio* calculations of the photosensitized C—C BDEs of β-phenethyl ethers has revealed a significant configurational

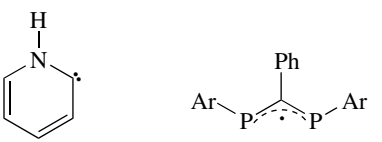
dependence.[7] The $CH_3\dot{C}HOH$ radical has been identified and characterized by UV photoelectron spectroscopy from the reaction of fluorine atoms and ethanol.[8] Dissociation of the amide dimers (**1**) generated the corresponding captodative α-aminocarbonyl radicals (**2**) which were characterized by electron spin resonance (ESR) spectroscopy (Scheme 1).[9] Kinetic and equilibrium data for these C—C cleavage reactions were used to calculate radical stabilization energies (RSEs) which compare favourably with values from *ab initio* calculations.



(**1**) (**2**)

The stabilization of methyl radicals by geminal donor and acceptor substituents has been analysed by calculations at the MP2/6–31G* level which revealed a substantial stabilization for the combination of hydroxyl and carbonyl or amino and carbonyl substitution.[10] The geometries, excitation energies and vibrational spectra of the excited electronic states of the methyl radical have also been calculated.[11] An *ab initio* study of the decomposition of formaldehyde has compared the energetics of formation of H_2 and CO with a competing radical reaction pathway via $H^{\cdot}$ and $HCO^{\cdot}$, using Hartree–Foch (H–F) and MP2 calculations on geometry-optimized intermediates and products.[12] Differences in the *ab initio* calculated heats of formation, BDEs and stabilization energies of vinyl and formyl halides have been associated with the relative C—X bond lengths.[13] Molecular structures, vibrational frequencies, and enthalpies of formation were determined in an *ab initio* study of radicals formed from methyl and methylene chlorides and fluorides.[14] A new theoretical study suggested that triarylvinyl radicals are linear or an average linear structure by rapid *E–Z* interconversion.[15] The bent form was the minimum energy structure for a number of vinyl radicals bearing σ-type substituents, whereas π-type substituted radicals preferred the linear structure.[16]

Azacyclohexatriene-2-ylidene (**3**), the 2-isomer of pyridine, has been generated by one-electron oxidation of the corresponding radical cation in neutralization–re-ionization mass spectrometry.[17] It was determined by *ab initio* H–F calculations that the charge polarization of the radical formed by H-abstraction from pyrazine can be



(**3**) (**4**)

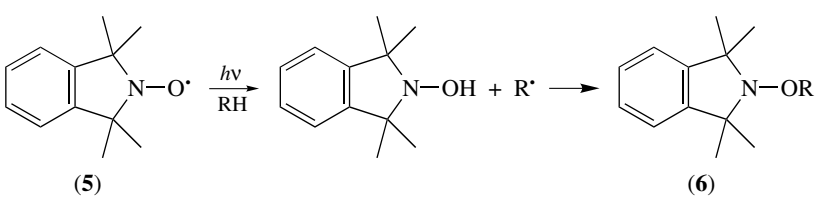
relatively easily deformed by an external electrostatic field, whereas the acetone radical was relatively unaffected.[18]

Miscellaneous Radicals

A room-temperature-stable 1,3-diphosphaallyl radical (**4**) has been isolated and characterized by mass spectrometry and ESR spectroscopy.[19] A DFT study at the B3LYP and QCSID levels is reported for neutral sulfur radicals $HS^{\cdot}$ and $H\dot{S}O_3$ and the sulfur oxide radical anions, $^{\cdot-}SO_x$ ($x = 2$–4).[20] There is close agreement with experimental data for geometries and electron affinities but calculated ESR hyperfine coupling constants (HFCs) show significant deviation. It was found that the exchange of a hydrogen atom for NH_2 on aniline or amide nitrogens to give the hydrazine or hydrazide respectively has a significant N—H bond weakening effect towards homolysis, but a negligible effect on the acidity.[21] Fourier transform ESR spectroscopy has been used to determine the sign of the exchange interaction (and thus the ferro- or antiferro-magnetic nature) of many radical ion pairs. Interestingly, addition of the Lewis acid BF_3 to the $DABCO^{+\cdot}$ and 4,4-dimethoxybenzophenone radical anion results in a change of the interaction (J) sign from positive to negative, indicating a change to ferromagnetic interaction (although the magnitude of J was not evaluated). No other Lewis acids are investigated, but the formation of the $R^{\cdot-}$ BF_3 adduct is confirmed by laser flash photolysis.[22]

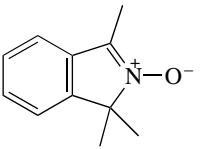
Nitroxides and Spin Trapping

Under photo-stimulation, isoindolyloxyl radical (**5**) abstracts primary, secondary, or tertiary hydrogens from unactivated hydrocarbons including cyclohexane, isobutane, or *n*-butane (Scheme 1).[23] The nitroxide (**5**) traps the resultant carbon-centred radical ($R^{\cdot}$) and so afford the *N*-alkoxyisoindoles (**6**). Blank photolysis experiments with no added hydrocarbon have shown some unprecedented β-fragmentation of (**5**) to afford the nitrone (**7**). A number of C^{60} nitroxide derivatives have been synthesized and characterized by ESR spectroscopy which show features common to nitroxide radicals.[24] Reaction of nitroxide and thionitroxide radicals with thiyl radicals have been observed, from which sulfinyl, sulfonyl, and sulfonyloxy radicals were generated.[25] The diisopropyl nitroxide radical was generated in the reaction of lithium diisopropylamide with α-fluoroacetate esters.[26]

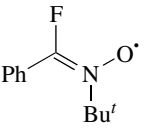


(**5**) (**6**)

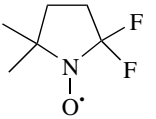
SCHEME 1



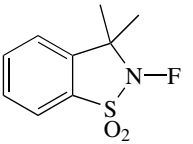
(**7**)



(**8**)



(**9**)



(**10**)

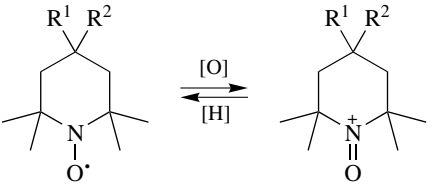
A new ^{15}N-labelled imidazole *N*-oxide spin trap has been synthesized and successfully trapped a number of oxygen- and carbon-centred as well as thiyl and sulfite-derived radicals.[27] The superoxide anion (O_2^-) was reacted with 5,5-dimethyl-1-pyrroline 1-oxide (DMPO) and the resultant adduct was found to be sufficiently stable for detection by EPR.[28] The iminyl radicals formed by H abstraction by *t*-butoxyl radicals from the *N*-substituted benzylidene amines were trapped with 2-methyl-2-nitrosopropane and their ESR spectra recorded. The absolute rate constant for these abstractions were calculated on the basis of competitive experiments with addition of *t*-butyloxy radicals to the spin trap.[29] Two methods of synthesizing fluorinated spin adducts from nitrones have been reported.[30] The reaction of *N*-*t*-butyl-α-phenyl nitrone (PBN) with XeF_2 proceeds via initial formation of the nitrone radical cation followed by reaction with F^- ('inverted spin trapping') to afford the α-fluoro nitroxide (**8**). The reaction of DMPO with XeF_2 which affords only the known α,α-difluoro nitroxide (**9**) and α-difluorination is the only observed product of the reaction of PBN with AgF_2. The α-monofluoro nitroxide (**8**) was also formed by reaction with a sulfonamide fluorinating agent (**10**) and it is believed to proceed by the Forrester–Hepburn mechanism via the hydroxylamine. These workers also proposed this mechanism for the formation of spin adducts in the acid-catalysed thermal reaction between PBN and trichloroacetonitrile.[31] The spin adducts formed between heteroaromatic bases and DMPO or PBN under oxidizing conditions have been studied by EPR. The adducts form by the Forrester–Hepburn mechanism, the oxidants being too weak to initiate the necessary electron transfer of the competing radical cation-mediated pathway.[32] Phosphorus-centred radicals were generated by the reaction of dibenzoyl peroxide with organophosphorus compounds and were trapped by PBN or DMPO.[33] The ESR hyperfine coupling constants of the spin adducts were used in a conformational analysis.

Radical cations of PBN and derivatives were generated photolytically and identified from their ESR spectra.[34] The radical cations of PBN, DMPO, and 3,3,5,5-tetramethylpyrroline 1-oxide (TMPO) spin traps were detected by EPR spectroscopy after exposure of dilute solutions to ionizing radiation in dry $CFCl_3$ at 77 K.[35,36] The same radical cations were detected using matrices containing water and on melting formed the HO$^\bullet$ radical adducts.

An investigation into the initiation mechanism of copolymerization of ethyl vinyl ether and acrylonitrile by *t*-butoxyl radicals has shown that the reaction between the two monomers competes successfully with radical trapping by the nitroxide radical trap (**5**).[37] The *t*-butoxyl radicals react 3–6 times faster with ethyl vinyl ether than acrylonitrile; the authors proposed that this is due to selective interaction of one monomer with the radical species rather than a solvent polarity effect.

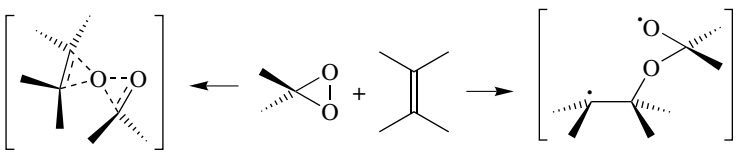
Oxidation and Reduction

A review presents the generation of radicals by one-electron oxidation with metallic oxidants and their application to C—C bond formation.[38] Three articles discuss oxidation by radical mechanisms, including the role of radicals in the chain propagation of hydrocarbon oxidation,[39] hydrocarbon oxidation by peroxyl radicals,[40] and the mechanisms of chain termination in the oxidation of a number of organic compounds, including hydrocarbons and alcohols.[41] The oxidation of primary and secondary alcohols using oxoammonium salts [e.g. (**11**) derived from nitroxyl radical (**12**); (Scheme 2)] is covered in a review, which begins with the first publication of this reaction from 1965.[42] A variety of methods in organic and aqueous media is discussed and the review includes mechanistic studies and experimental procedures.



(**12**) (**11**)

SCHEME 2

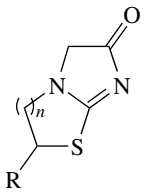


(**14**) (**13**) (**15**)

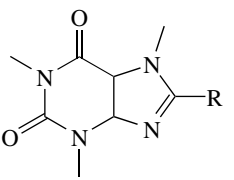
SCHEME 3

The epoxidation of alkenes and hydroxylation of alkanes by dioxiranes [e.g. DMDO (**13**)] has been the subject of a detailed mechanistic investigation.[43] The study concludes that, provided the oxidant is handled with care to avoid conditions which trigger its decomposition, neither reaction mechanism involves radical participation. These results support reaction via the spirocyclic transition state (**14**) rather than the originally proposed biradical transition state (**15**) (Scheme 3). A structure–activity study reports rate constants of the gas-phase epoxidation of 17 alkenes with five peroxy radicals.[44] Elsewhere, the temperature dependence of rate constants for the reaction of oxygen atoms with four alkenes is described.[45] An *ab initio* study of the singlet oxygen reactions of alkenes, enol ethers, and enamines suggest only alkenes react via a radical mechanism, in which hydroperoxides, dioxetanes, and other alkenes are formed from a biradical intermediate.[46] Oxidation of nitrosobenzene by NO_2 has been re-examined and found to occur via a radical mechanism, in which an oxygen atom is added to the nitroso nitrogen.[47] This unstable aminoxyl radical decomposes to the corresponding nitrobenzene and NO.

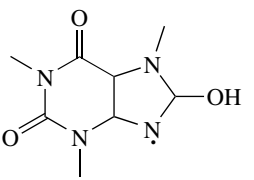
The kinetics of the addition reaction of the allylic isobutenyl radical with molecular oxygen have been analysed by computational methods (MOPAC-PM3 and *ab initio*) according to quantum Rice–Ramsperger–Kassel (QRRK) theory.[48] Predictions were in good agreement with experimental data. The antioxidant butylated hydroxytoluene (BHT) was found to react slowly with singlet oxygen and a number of radical species in a study using time-resolved luminescence and pulse radiolysis.[49] The 2-thiohydantoins (**16**) and related structures were found only to be weak antioxidants towards scavenging hydroxyl radicals.[50] The oxidation of caffeine (**17**) by peroxodisulfate and hydroxyl radicals was studied by EPR spectroscopy and HPLC analysis which revealed 1,3,7-trimethyluric acid (**18**) as the major product in each case via a C(8)—OH radical intermediate (**19**).[51]



(**16**)



(**17**) R = H
(**18**) R = OH



(**19**)

The photo-oxidation of *n*-butane has been modelled by *ab initio* and DFT computational methods, in which the key role of 1- and 2-butoxyl radicals was confirmed.[52] These radicals, formed from the reaction of the corresponding butyl radicals with molecular oxygen, account for the formation of the major oxidation products including hydrocarbons, peroxides, aldehydes, and peroxyaldehydes. The differing behaviour of *n*-pentane and cyclopentane towards autoignition at 873 K has been found to depend on the relative concentrations of resonance-stabilized radicals in the reaction medium.[53] The manganese-mediated oxidation of dihydroanthracene to anthracene has been reported via hydrogen atom abstraction.[54] The oxidation reactions of hydrocarbon radicals and their OH adducts are reported.[55]

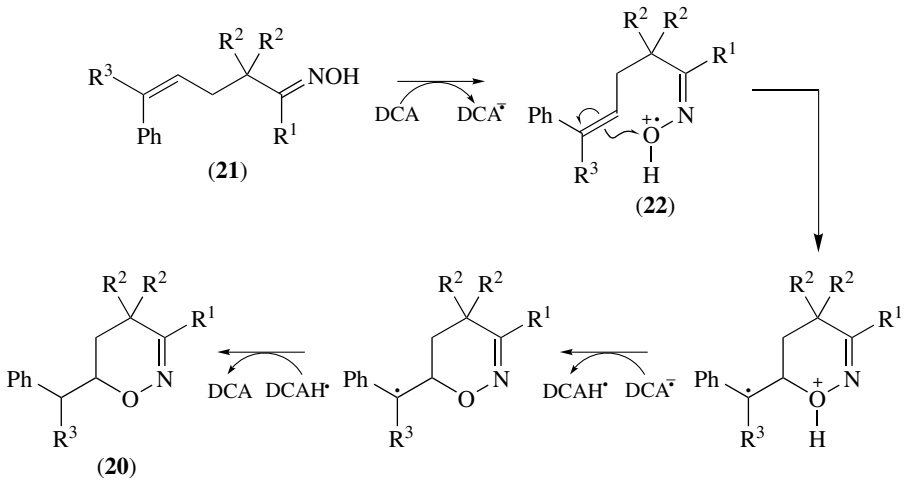
The corrinoid-mediated reduction of polyhaloethenes has been the subject of a recent study, which reports reaction via homolytic C–halogen bond fission. The elimination of a further halogen radical affords haloalkynes, which lead to acetylene itself.[56] The electron transfer-induced reductive cleavage of alkyl phenyl ethers with lithium naphthalenide has been re-examined in a study which showed that it is possible to reverse regioselectivity of the cleavage (i.e. ArOR to ArH or ArOH) by introduction of a positive charge adjacent to the alkyl ether bond.[57] A radical intermediate has been detected by ESR spectroscopy in the reduction of imines to amines with formic acid[58] which infers reacts takes place via Lukasiewicz's mechanism.[59]

Electron-transfer Reactions

Photo-induced Electron Transfers

The catalytic effect of acid or metal ions on the thermal or photo-induced electron-transfer reactions has been reviewed.[60]

A novel synthesis of 5,6-dihydro-4*H*-1,2-oxazines (**20**) is presented via the photo-induced cyclization of γ,δ-unsaturated oximes (**21**); see Scheme 4. Irradiation of (**21**) in the presence of 9,10-dicyanoanthracene (DCA) led to the heterocycle (**20**) only. The proposed mechanism proceeds via the radical cation (**22**), generated by single-electron transfer (SET) from the oxime (**21**) to the excited sensitizer (DCA. Cyclization of (**22**) affords the oxazine (**20**) after proton transfer to the DCA radical anion ($DCA^{\bullet-}$) and H abstraction.[61]



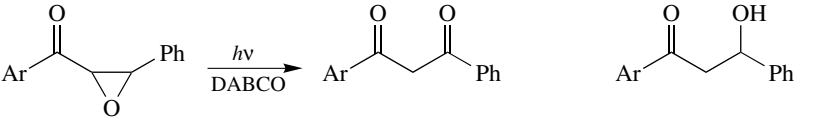
SCHEME 4

Irradiation of benzilates [$ArC(OH)CO_2^-$] or aryl acetates ($ArCH_2CO_2^-$) with methyl viologen (MV^{2+}) at 366 nm was examined by femtosecond time-resolved spectroscopy.[62] The transient photo-generated radical pairs ($MV^{+\bullet}$, $RCO_2^{\bullet}$) undergo electron transfer to regenerate the original ion pair or, in a competing process, the acyloxy radical ($RCO_2^{\bullet}$) undergoes rapid decarboxylation (10^{-9}–10^{-15} s).

The photo-induced electron transfer of 1,4-bis(methylene)cyclohexane in acetonitrile–methanol solution with 1,4-dicyanobenzene (DCB) affords two products, both consistent with nucleophilic attack on the radical cation followed by reduction and protonation or by combination with $DCB^{\bullet-}$).[63] In the absence of a nucleophile, the product mixture is highly complex, as is the case under electro-oxidative conditions. Under UV irradiation, *trans*-stilbene undergoes dimerization and oxygenation (to benzaldehyde) by a single-electron mechanism in the presence of a sensitizer such as 2,4,6-triphenylpyrilium tetrafluoroborate (TPT).[64] This reaction was found to yield a similar product mixture with the sulfur analogue of TPT and their relative merits as well as electrochemical and photophysical properties are discussed.

The selective two-electron reduction of C_{60} to $C_{60}H_2$ has been achieved by photo-induced electron transfer in benzonitrile–TFA solution with 10-methyl-9,10-dihydroacridine ($AcrH_2$).[65] The proposed mechanism begins with electron transfer from $AcrH_2$ to C_{60} to afford the radical ion pair ($C_{60}^{\bullet-}$, $AcrH_2^{+\bullet}$). The strongly acidic $AcrH_2^{+\bullet}$ species protonates $C_{60}^{\bullet-}$ to afford the $C_{60}H^{\bullet}$ radical which is rapidly converted into the dihydrofullerene ($C_{60}H_2$) by electron transfer from $AcrH^{\bullet-}$ in the presence of TFA. The

fullerene radical anion ($C_{60}^{\cdot}$), dianion (C_{60}^{2-}) and radical trianion ($C_{60}^{\cdot 3-}$) were generated from C_{60} using the radical anion of naphthalene as an electron-transfer reductant.[66] The dianion was reacted with alkyl halides to yield the dialkyl fullerene via the radical anion ($R_2C_{60}^{\cdot -}$)).



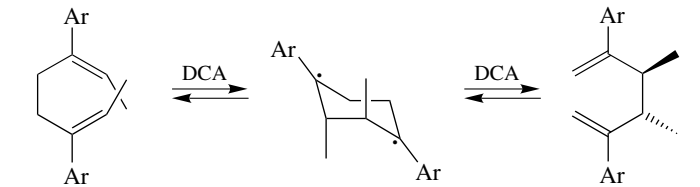
(**23**)
Ar = *p*-NCPh

(**24**) (**25**)

The reported photo-reaction of α,β-epoxy ketone (**23**) with 1,4-diazabicyclo[2.2.2]octane (DABCO) gave exclusively the β-diketone (**24**) and no trace of the related β-hydroxy ketone (**25**).[67] The authors claim the strong dependence of the product ratio on the nature of the solvent and amine reagent suggests that the diketone is formed via the radical cation-assisted β-H abstraction from the ring-opened epoxy ketone radical cation. Information from this study was applied to the optimization of the conversion of α,β-epoxy ketones to the analogous β-hydroxy ketones with samarium diiodide. The photo-stimulated electron-transfer Cope rearrangement of (*E*,*E*)-2,5-bis(4-methoxyphenyl)octa-1,5-dienes (**26**) with DCA afforded quantitatively the racemic hexadienes (**27**) by a kinetically controlled reaction, via the biradicals (**28**) (Scheme 5).[68]

The photo-reactions of a number of organosilanes have been reported. The photo-induced electron transfer of dibenzo-7-silabicyclo[2.2.1]hepta-2,5-diene (**29**) with TPT leads to difluromesitylsilane (F_2SiR_2, R = mesityl).[69] In the proposed mechanism, an Si—C bond of the bridged structure is cleaved by BF_4^- to afford a radical species, which fragments to neutral anthracene and $F\dot{S}iR_2$. This fluorosilyl radical may undergo further single-electron oxidation to the silyl cation and reaction with BF_4^- affords F_2SiR_2. Elsewhere, photo-induced silylene-transfer reactions have been studied with cyclic organosilanes and phenanthraquinone (PQ) in which (**30**) was formed from dodecamethylcyclohexasilane via a radical intermediate.[70]

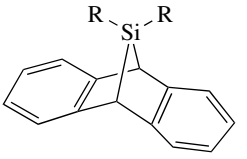
The reaction of CO_2 with phenol has been studied using a number of photo-catalysts. It was found that 2-hydroxybenzoic acid and catechol were the main products and some selectivity was achieved by judicious choice of the photo-catalyst.[71]



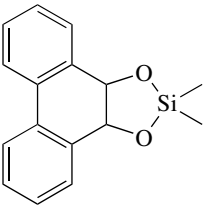
(**26**)
Ar = 4-$MeOC_6H_4$

(**28**) (**27**)

SCHEME 5

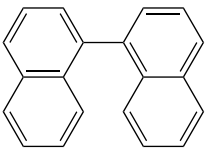


(**29**)
R = mesityl

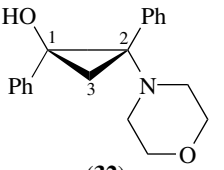


(**30**)

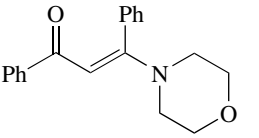
A paper reports the photo-inductive reaction of di- and tri-naphthyl phosphates in the presence of sensitized DCA to afford 1,1-binaphthyl (**31**). No reaction was observed with mono-1-naphthyl or di- and tri-phenyl phosphate esters.[72]



(**31**)

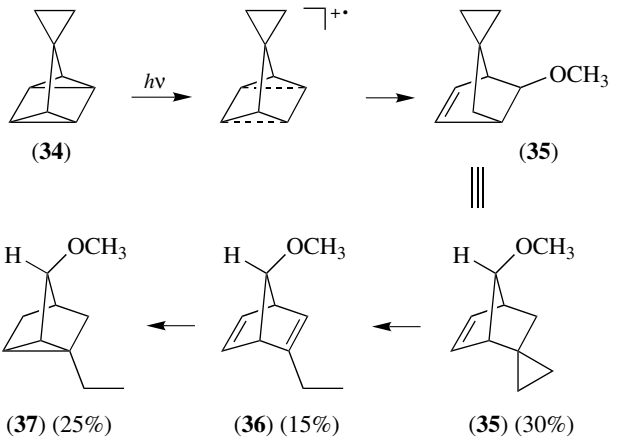


(**32**)



(**33**)

The irradiation of 2-morpholino-2,3-diphenylcyclopropanol (**32**) in the presence of DCA or TPT and triplet oxygen afforded the β-amino enone (**33**), whereas the 1,3-diphenyl isomer of (**32**) afforded the α-phenyl-substituted product. In the proposed mechanism, both products arise via the radical cation of (**32**) before a ring-opening reaction with $^3O_2$ in which the C—C bond which breaks is determined by the position of the relative positions of the phenyl groups.[73] The photo-stimulated electron-transfer reaction of 7-(spiracyclopropane)quadricyclane (**34**) with methanol produces the radical cation (**34**$^{+\cdot}$) which undergoes stereo- and regio-specific attack on one of the trisubstituted cyclopropane rings (Scheme 6). A subsequent cycloproylcarbinyl to

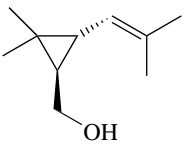


(**34**) (**35**)

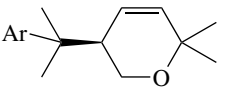
(**37**) (25%) (**36**) (15%) (**35**) (30%)

SCHEME 6

butenyl rearrangement affords (**35**), which gives (**36**) by H abstraction and cyclopropyl ring opening, and (**37**) via a second electron-transfer reaction. This conversion is supported by the observation that prolonged irradiation of a mixture depletes (**36**) in favour of (**37**).[74] The photo-induced rearrangement of (1*R*,3*S*)-*cis*-chrysanthemol (**38**) to the dihydropyran (**39**) occurs with significant retention of configuration which is rationalized by unprecedented vinylcyclopropane reaction via a radical cation intermediate in a mechanism strongly influenced by ring strain and its avoidance.[75] Nucleophilic attack of the alcohol moiety on the cationic radical precipitates ejection of an isopropyl radical in an apparent S_N2' reaction to afford the cyclic ether (**39**) after radical capture with DCB.



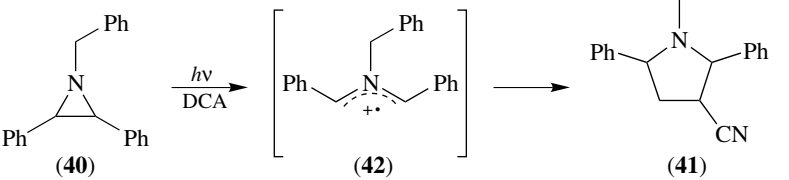
(**38**)



(**39**)

Photo-stimulated reactions of neopentyl iodide with several carbanionic nucleophiles have been studied in which inhibition experiments with the TEMPO radical trap suggest the reaction occurs via an $S_{RN}1$ mechanism.[76] Comparison of 22 nucleophiles in their $S_{RN}1$ reactions with iodobenzene by Fe(II)- and photo-induction has revealed that both are enhanced by high electron-donation ability of the nucleophile. The radical anion $PhI^{\cdot-}$ is a key intermediate.[77] The SET reactions of perfluoroalkyl iodides have been reviewed.[78] Flash photolysis of H_2O_2 was used to generate $HO^{\cdot}$ and $O^{\cdot-}$ radicals which were reacted with α,α,α-trifluorotoluene (TFT) and 4-fluorotoluene (4FT) and the rate constants calculated.[79] The diminished reactivity of TFT towards $HO^{\cdot}$ or $O^{\cdot-}$ with respect to toluene or benzene was consistent with radical addition to the aromatic ring, whilst the reactivity of 4FT was of the same order as electron-deficient toluenes, which favour H abstraction from the aliphatic side-chain.

A number of electrocyclic reactions under PET conditions have been reported. In this way, *N*-benzyl-2,3-diphenylaziridine (**40**) underwent a 3 + 2-cycloaddition with alkene and alkyne dipolarophiles to afford substituted pyrrole cycloadducts (**41**) via the radical cation intermediate (**42**); see Scheme 7.[80] Elsewhere, novel arylallenes have been used as dienophiles in a radical cation-catalysed Diels–Alder cycloaddition reaction with 1,2,3,4,5-pentaflurometh ylcyclopentadiene, which often occurred with peri-, chemo-, facial- and stereo-selectivity.[81]



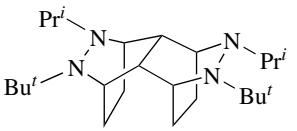
(**40**) (**42**) (**41**)

SCHEME 7

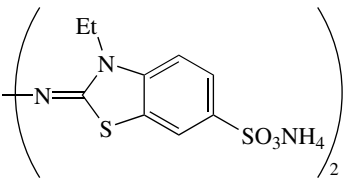
Other electron transfers

A review has focused on differentiation between polar and SET mechanisms through kinetic analysis.[82] In two separate reviews, the effects of solute–solvent interactions on electron-transfer reactions have been described.[83,84] A review of the behaviour of radical cations in liquid hydrocarbons has given particular emphasis to those with high mobility.[85] A paper presents selected studies in the formation of radicals by oxidation with manganese- or cerium-based reagents and their application to C—C bond formation by SET processes.[86]

Marcus has introduced a model for S_N2 reactions of the ET type based on two interacting states which takes into account the relevant bond energies, standard electrode potentials, solvent contributions, and steric effects.[87] The rate constant for intramolecular electron transfer between reduced and oxidized hydrazine units in the radical cation of the tetraazahexacyclotetradecane derivative (**43**) and its analogues has been determined by simulation of their variable temperature ESR spectra.[88] The same researchers also reported their studies of the SET processes of other polycyclic dihydrazine systems.[89,90]



(**43**)

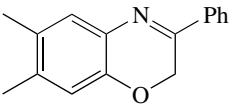


(**44**)

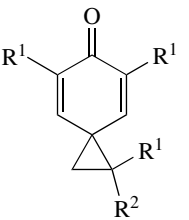
The self-exchange electron-transfer (SEET) process, in which a radical is trapped by the parent molecule, has been studied using the intersecting-state model (ISM).[91] Absolute rate constants of SEET for a number organic molecules from ISM show a significant improvement over classical Marcus theory[92–94] in the ability to predict experimental SEET values. A combination of Marcus theory and the Rips and Jortner approach was applied to the estimation of the amount of charge transferred in the intramolecular ET reactions of isodisubstituted aromatic compounds.[95]

The electron-transfer reactions of a number of organosulfur compounds have been reported. Amongst these, cumyl phenyl sulfide was reduced by aromatic radical anions to form mainly bicumyl rather than cumyllithium, contrary to an earlier report.[96] The proposed mechanism invokes SET from cumyllithium to the disulfide substrate to give thiophenoxide and two cumyl radicals which couple to form the product.[97] In accordance with previous findings, the mechanism of addition to the vinyl double bond of aryl vinyl sulfides, ethers, and selenides has been shown to occur via electrophlilic addition rather than radical cation-mediated electron transfer.[98] The rate constants for the addition reactions correlated more closely with the Hammett σ values (electrophilic) than the Brown σ^+ values (electron transfer) and were supported by *ab initio* SCF MO calculations. This agrees with the generalization that, for a σ^+ correlation, there must be a direct resonance interaction between a *para* resonance electron-donating group and a positively charged reaction site. The radical cation of azinothiazoline (**44**) reacts with

phenols with rate constants unrelated to the structure of the phenol, by an initial rapid electron transfer to form the phenoxy radicals ($ArO^{\cdot}$) before self-combination or reaction with further ($\mathbf{44}^{+\cdot}$).[99] Other examples of nucleophilic addition to radicals include the products isolated from the reaction between Grignard reagents and thiocarbonyl compounds[100] or benzoquinone[101] as well as Reformatsky reagents and 1,1-dicyanoalkenes.[102] In each case, there are clear indications of reaction via a SET process. The treatment of arylimine (**45**) with cyclohexyllithium affords the expected product of nucleophilic addition to the C of the imine C=N bond, along with a number of minor by-products. Studies with *t*-butyllithium have shown that other imine substrates may undergo SET reactions and conjugate substitution in the aryl ring, giving rise to rearranged and oxidized products, including dimers and 4 + 2-cycloadducts.[103] A study of the utility of spirocyclopropyl radical probes (**46**) and (**47**) concludes that they can be highly useful to determine the presence of SET processes in polar, aprotic solvents but fail in protic media.[104]

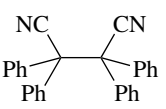


(**45**)

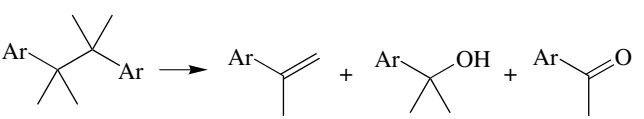


(**46**) R^1 = H
(**47**) R^1 = Me

Many SET reactions involving alkyl and aryl halides have been studied. The reaction between $LiAlH_4$ (LAH) and alkyl halides has been re-examined after challenges suggested a cyclic intermediate in an S_N2 mechanism rather than SET.[105,106] Reaction of an alkyl iodide that cannot cyclize with LAH and $LiAlD_4$ (LAD) implicates reaction via a SET mechanism only.[106] The preparation of *p*-nitrobenzylphosphonic acids from the corresponding nitrobenzyl halides suggests a SET mechanism from product and radical-trapping studies.[107] A study of the alkaline hydrolysis of *p*-chloranil has the first evidence of an electron-transfer mechanism involving a radical anion intermediate from UV and ESR spectra.[108] Fourier transform ioncyclotron resonance spectrometry (FT-ICR) of the reaction of halomethanes with the atomic oxygen radical anion suggests the major reaction pathways are abstraction of $H^{\cdot}$ or $H_2^{+\cdot}$ and nucleophilic substitution.[109] The reaction of $CHBr_3$, CCl_4, and $CHCl_3$ with α-cyanodiphenylmethide anion afforded dimer (**48**) by a SET mechanism, whereas $CHCl_2$ gave an S_N2 product.[110] The competition between $S_{RN}1$ and S_N2 mechanisms was investigated for the reaction of α-chloro-*p*-nitrophenylethane with a nitronate or thiocarbamate anion, and showed that both nucleophiles afford the products of each mechanistic pathway.[111]



(**48**)



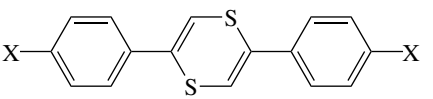
(**49**)

Calculated enthalpies (MP2/3–21G* and MP2/6–311G**) have shown that the gas-phase SET Cannizaro-type reaction between formaldehyde or benzaldehyde and their corresponding radical anions is unlikely to occur spontaneously.[112] The reaction between *O*-alkylated di- and tri-nitrophenylhydroxylamines and the 2,2-diphenyl-1-picrylhydrazyl radical has been re-investigated and, in accordance with the literature, the observed products arise via addition at the *para* position of one of the two phenyl rings on the hydrazine moiety. The intermediacy of radical species is proposed through ESR spectroscopic evidence.[113] The ozone-mediated reaction of bicumenes (**49**) with NO_2 results in almost exclusive substrate C—C homolysis over ring nitration.[114] The results are rationalized in terms of ET between NO_3 formed *in situ* and the substrate to form the radical cation ($\mathbf{49}^{+\cdot}$) followed by benzylic C—C scission to afford a mixture of alkene, alcohol, or ketone products. The relevance of this mechanism to the Kyodai nitration is suggested. The failure of the Crigee mechanism for ozonation of alkenes to account for radical intermediates is highlighted in a paper which uses the linear correlation between rate constant and ionization potential data to suggest a SET mechanism which proceeds via a radical cationic intermediate.[115]

Heterocyclic substrates in SET processes have been widely studied, including the reactions of dihydronicotinamide,[116] pyridine, and quinoline[117] and also phenoxazine and phenothiazines.[118] Phenothiazine has also been shown by ESR analysis to undergo an electron-transfer reaction with its radical cation with an appreciable $^{15}N/^{14}N$ isotope effect.[119] The reaction of phenazine di-*N*-oxide radical cations with hydrocarbons shows evidence of non-radical processes.[120]

Radical Cations

The mechanistic aspects of aromatic[121] and alkene[122] radical cation reactions have been reviewed. A second review article covers the structure and properties of hydrocarbon radical cations, as revealed by low-temperature ESR and IR spectroscopy.[123] A review of the reactivity of trivalent phosphorus radical cations has appeared which discusses ionic and SET processes and their kinetics.[124] The structure and reactivity of distonic radical cations have been reviewed, including experimental and calculated heats of formation, structures, reactivity, and mechanisms.[122,125]

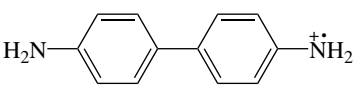


(**50**)

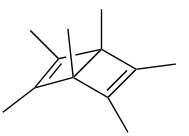
X = H, Me, OMe, Cl, NO_2

The electrochemical oxidation of 2,5-diaryl-1,4-dithiins (**50**) has been studied using various voltametric techniques and all compounds were found to undergo quasi-reversible one-electron transfers to the radical cations and dications.[126] The first formal redox potential and the lifetime of the radical cation were found to decrease with increasing electron donation from the aryl ring. The major products were the 2,2′-dimers, which result via reaction of two radical cations for which rate constants are given. Dibenzothiophene radical cations reacted with tetranitromethane under

photolytic conditions to yield the corresponding sulfoxide as the major product, along with the 2-nitro compound and various products of tetranitromethane addition. The sulfoxide also predominates by nitration with NO_2 or nitrous acid, whilst silver(II)-mediated oxidation in acetic acid affords the 1- and 4-acetoxydibenzothiophenes.[127] These workers have also reported the ESR spectra of substituted dibenzothiophene radical cations, prepared by Tl(III)-mediated oxidation.[128] The trithiocarbenium ion $[C(SH)_3]^+$ and its radical dication $[C(SH)_3]^{\cdot 2+}$ have been the subject of an investigation of the effect of electron correlation and spin projection on rotational barriers.[129] Planar geometries were calculated for the radical cations of HSSH and MeSSMe as part of a study of the unknown thiosulfoxide species.[130] The pulse radiolysis of aliphatic δ-amino sulfides in aqueous solution has been used to generate a series of radical cations, most notably a cyclic two-centre, three-electron (S∴N) species. *Ab initio* molecular-orbital calculations and DFT methods were employed to provide structure and property information on these species by assignment and interpretation of transient ESR and resonance Raman spectra. High-level calculations on model systems call into question the ability of hybrid DFT methods to provide a reliable description of S∴N species.[131] Diaryl disulfide radical cations $[(ArSSAr)^{+\cdot}]$ reacted with six functionalized benzenes (PhX) to afford predominantly the *para*-substituted diaryl sulfides $[p\text{-}(ArS)C_6H_4X]$.[132]



(**51**)

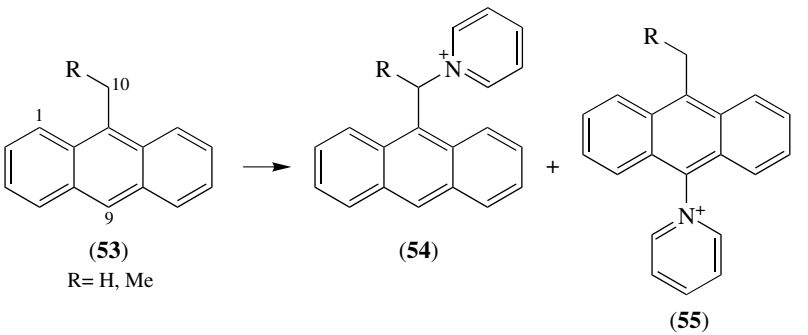


(**52**)

Benzidene has been oxidized to its radical cation (**51**) using a number of common oxidants, including cerium(IV), permanganate, dichromate, potassium peroxomono- and di-sulfates, and halogens.[133] The rate constants for formation of (**51**) and further oxidation to the biradical cation were estimated and showed good agreement with those calculated using Marcus theory. The facile rearrangement of the radical cation of hexamethyl Dewar benzene (**52**) has made it an elusive study subject. Assignment of the ESR spectra of ($\mathbf{52}^{+\cdot}$) and related species has been made through DFT calculations which show close agreement with experiment.[134] These workers have described the effect of halocarbon matrices on the rearrangement of propene radical cations into allyl radicals by *ab initio* and semiempirical calculations.[135] By *ab initio* calculations, the barrier to the rearrangement of 1,3-hexadien-5-yne radical cations is lower for a five-membered ring than for the classical benzene structure.[136] The radical anion of methylacetylene has been generated by γ-radiolysis and characterized by ESR and MO studies, which assign a *trans*-bent structure.[137] Density functional theory (DFT) has been used to calculate the structure and vibrational frequencies for the radical cation and anion of biphenyl.[138]

The mechanism of base-catalysed deprotonation of the α-CH of 4-methoxybenzyl alcohol radical cations in water has been examined. There is no direct attack of HO^- at the α-CH as was believed, but reaction occurs via deprotonation of the OH to produce the benzyloxy radical, which then forms the carbon-centred radical by a 1,2-hydrogen

atom shift.[139] The main product of the radical cation-mediated reaction of 9-methyl- or 9-ethyl-anthracene (**53**) by pyridine–iodine arises from nucleophilic attack at the open C(10) position leading to the ring oxidation product (**54**) rather than deprotonation to oxidize the side-chain forming the 9-substituted product (**55**); see Scheme 8.[140] The reactivity is rationalized in terms of stereoelectronic effects rather than substrate acidity, such that deprotonation is the dominant pathway under careful conformation control, e.g. bulky trimethylsilyl substituent introduced at C(1). The formation of neutral radicals from deprotonation of the radical cations of α- and *β*-pinene was found to be efficient when performed on a redox-active zeolite (NaZSM-5), but led to complex mixtures of products in solution.[141]



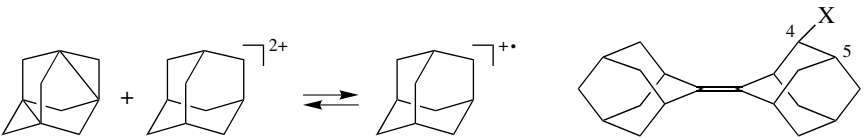
SCHEME 8

A mechanism has been proposed for the liquid-phase formation of aliphatic alcohol radicals ($R\dot{C}HOH$) by a proton-transfer mechanism from the corresponding distonic cation radicals which, calculations suggest, are more stable than the classical cation radicals ($RCH_2OH^{+\cdot}$).[142] A paper reports a low-temperature ESR and UV–VIS study of the radical cation of 2,6-di-*t*-butyl-4-methylphenol, generated by electron-transfer oxidation with matrix alkyl halide radical cations.[143] A theoretical study of the structure of the methanol radical cation by MP2 methods has revealed an artificially short C—O bond length of 1.3 Å, compared with 1.37 Å at higher levels of theory.[144] The isotropic hyperfine coupling constants (IHFCs) of the radical cations of hydroquinone and tetrahydroquinone have been studied by UB3LYP and UB3PW91 DFT calculations whilst testing the ability of various basis sets to reproduce the experimental values. A significant temperature dependence of the hydroxyl proton IHFC is predicted.[145]

The structure of diphosphallenic radical cations, generated from the allene ArP=C=PAr by electrochemical oxidation, has been examined using EPR spectroscopy. *Ab initio* calculations including correlation effects at the MP2 and MCSCF levels have determined that two rotamers exist compatible with Jahn–Teller distortion of the allene.[146] Anodically generated radical cations of alkyl phosphites [$(RO)_3P$] and silylphosphites [$(RO)_2POSiMe_3$] reacted with alkenes by initial attack at the C=C bond followed by electron transfer, deprotonation, and elimination of an alkyl or trimethylsilyl cation to form identical alkyl phosphate adducts.[147] The electron ionization-induced McLafferty rearrangement of *n*-hexylphosphine afford the α-distonic radical cation $^{\cdot}CH_2PH_3^+$, the distinct reactivity of which suggests there is no

interconversion between this radical and the more conventional isomer $CH_3PH_2^{+\cdot}$.[148] The distonic radical undergoes proton transfer, atom, and group abstraction reactions with neutral molecules, in contrast to $CH_3PH_2^{+\cdot}$, which reacts predominantly by an electron-transfer process.

The concept of aromaticity in three dimensions has been studied by a theoretical examination of the electronic structure of a number of ions formed from pentacyclo[3.3.1.1^{3,7}.0^{1,3}.0^{5,7}]decane (**56**). The dication (**57**) belongs to a small group of compounds exhibiting three-dimensional electron delocalization and H–F, MP2, and DFT calculations suggest it is stable with respect to a localized structure, but less stable than the radical cation (**58**).[149] Charge and spin delocalization in 1,4-diphenylpiperazine radical cations was found to be suppressed on introduction of a *p*-methoxy group in each phenyl ring.[150] A paper introduces the concept of anchimeric spin delocalization in the tryptophan radical cation after the observation by H–F/DFT calculations of a through-space interaction between the π-system of the indole and the alanyl side-chain.[151]

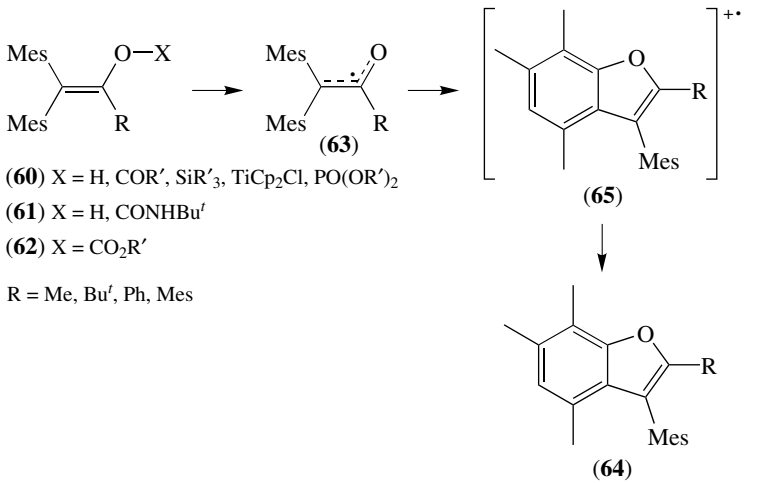


(**56**) (**57**) (**58**) (**59**)

The ease of electrochemical oxidation of a number of 4-halogenated diadamantanes (**59**) to their radical cations was found to agree with AM1 predictions and is attributed to a resonance contribution through the σ framework.[152] The structure of the four-centre, three-electron cyclobutane radical cations of pagodane-type molecules was the subject of a review which combines an *ab initio* study.[153] Both the parent cyclobutane and the rearranged diene forms of the radical cations are discussed as intermediates in a 2 + 1-cycloaddition reaction coordinate. A paper describes the asymmetric distortion of several alkane radical cations as studied by EPR at low temperatures in various matrices.[154] The direction of the distortion is unique to each system and is not affected by the matrix used, although the magnitude of distortion shows some matrix dependence. A paper reports CIDNP characterization of the radical cations of both the *syn*- and *anti*-isomers of the bridged dicyclopropane system tricyclo[5.1.0.0]-octane.[155] The quadricyclane radical cation is a closely related system and its rearrangement to the corresponding norbornadiene radical has been studied[156] by comparison of *ab initio* methods with the principles of radical electrocyclic reactions. The calculated activation energy agreed with the work of Bach *et al.*,[157] at about twice the current experimental estimate.

The AM1-calculated structure and charge distribution of radical the trication of β-carotene have been reported and its UV absorption spectrum estimated from INDO/S methods.[158] The decomposition of the furan radical cation proceeds by two separate pathways according to a recent theoretical study, one via formation of propene radical cation and CO, the other a lower energy process via acetylene and a ketene radical cation.[159] As a result of a reflection mass spectrometric study, a likely mechanism is

proposed for the elimination of H_2 from ethene radical cations by the tunnelling of hydrogen atoms through a transfer barrier.[160] The rearrangement of the dimesityl enol derivatives (**60**),[161] and the corresponding enol carbamates (**61**) and carbonates (**62**)[162] proceeds via a proposed radical intermediate (**63**) to afford the benzofurans (**64**) (Scheme 9). The radical cations (**65**) were characterized by ESR and ENDOR.[163] The reaction of acetylene and its radical cation has been studied theoretically in a paper that suggests that a low-energy pathway exists in which an initial T-shaped ion–molecule complex forms. Delocalization of the spin and charge collapses the complex to the cyclobutadienyl radical cation via a linear complex or a cyclopropenylcarbene cation.[164] The formation of dihydropyrene radical cations and their potential application to NMR studies of polycyclic aromatic hydrocarbons (PAHs) is reported.[165] Nanosecond laser photolysis of bis(*p*-methylphenyl)diazomethane generated the radical cation from which a carbene radical cation formed. Reactions of this radical species with a number of nucleophiles and radicalophiles are reported.[166]

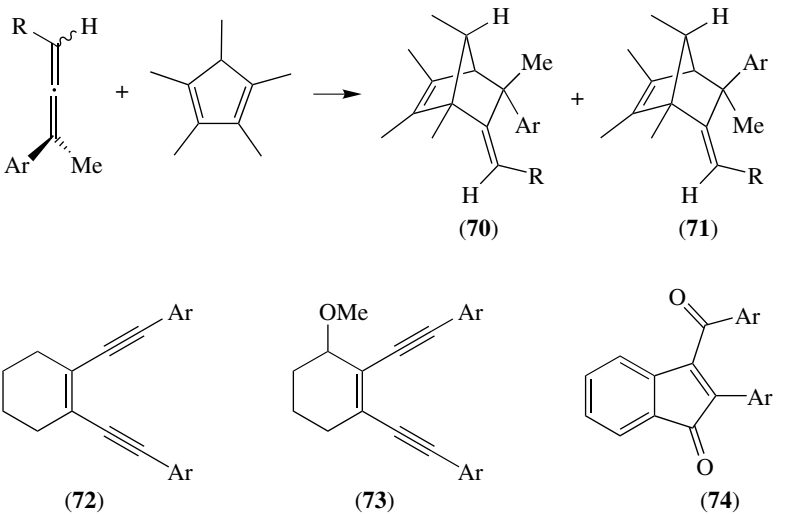


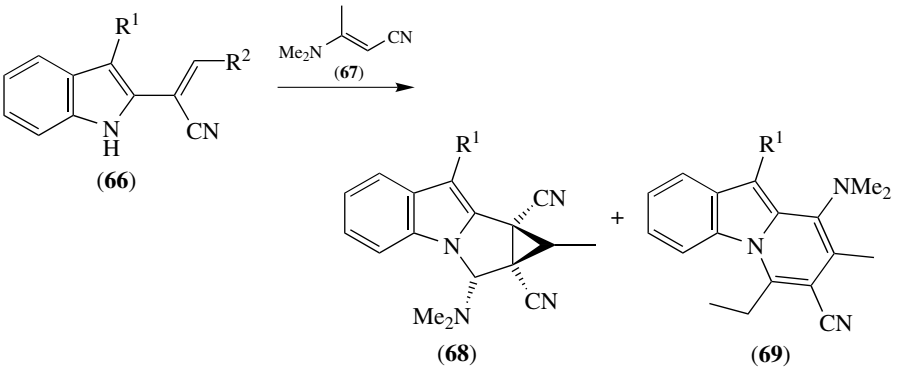
SCHEME 9

A paper reports an *ab initio* study of the structure and vibrational spectra of the radical cations generated from *N*,*N*,*N*′,*N*′-tetramethyl-*p*-phenylenediamine (TMPD) and piperidine and piperazine diamines. It was shown that, whilst the hydrid H–F/DFT (B3LYP) calculations are the best practical method for aromatic diamines, DFT theory calculations (BLYP) are far superior for piperidine and piperazine diamines owing to the tendency of the former to localize the positive charge on one of the amino groups.[167] A series of linear and branched high-spin radical di- and tri-cations of aniline oligomers have been synthesized and characterized as potential polaronic ferromagnets.[168] The radical cations of novel 18-π aromatic azines were generated by oxidation with $AgClO_4$ and characterized by their ESR spectra and the effect of substitution on their spin densities and oxidation potentials is discussed.[169] Anodic oxidation of 2,6-bis(*N*,*N*-dimethylamino)anthracene (DMA) with tetrabutylammmonium acetate resulted in formation of products derived from initial attack of the acetate ion at the 9-position of the DMA radical dication ($DMA^{\cdot 2+}$).[170] Kinetic data for the

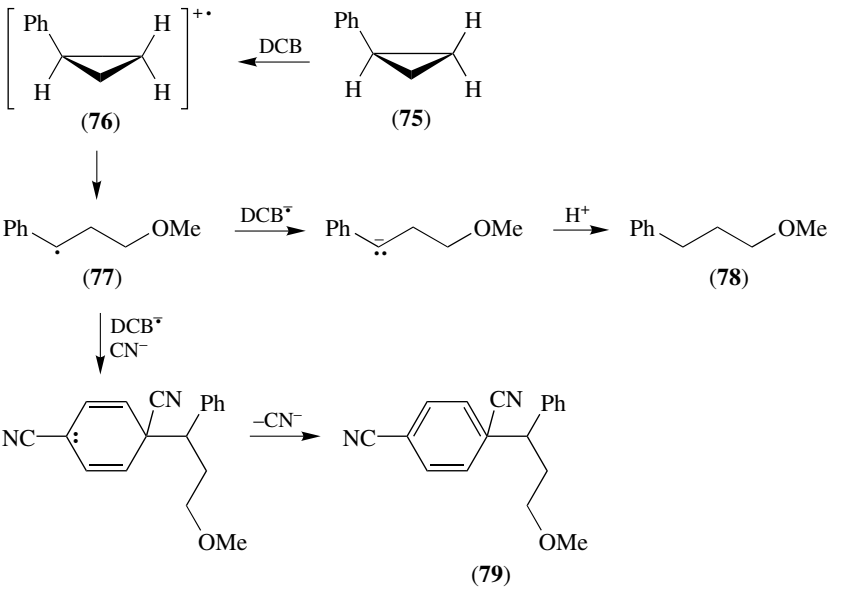
combination of $DMA^{\cdot 2+}$. with acetate ions and nitrogen nucleophiles are presented. The 4,5-diphenylimidazole radical cation has been generated by UV irradiation of the parent molecule with $Hg(TFA)_2$ and characterized by ESR and ENDOR.[171] ^{15}N-CIDNP investigations of the nitration of anisole with nitric acid suggests formation of 2- and 4-nitroanisole by a recombination reaction of the anisole radical cation with NO_2.[172]

The radical cation-initiated cycloaddition reactions of 2-vinylindole heterodienes (**66**) and *β*-substituted enaminonitriles (**67**) have been examined. The electrochemically generated radical cation ($\mathbf{66}^{+\cdot}$) affords either the cyclopropyl-substituted adducts (**68**) or the formal product (**69**) of a 4 + 2-cycloaddition followed by a 1,4-dialkylamino shift; see Scheme 10. The product isolated depends strongly on the substitution pattern of the two reactants and judicious choice of substituents may lead to product selectivity.[173] In a related report, the gas-phase reaction of *o*-quinodimethane and styrene radical cations towards propene was found to include 4 + 2-cycloaddition products.[174] The major isolated products of the reaction between 2-pyridylhydrazones with radical cations were formed either by intramolecular cyclization or intermolecular cycloaddition.[175] The formation of (**70**) and (**71**) during the reaction of variously substituted allenes with pentamethylcyclopentadiene has been explained by a radical cation-mediated 4 + 2-cycloaddition which shows high facial-, chemo-, and stereo-selectivities.[176] Three novel radical probes have been developed which apply the cyclobutanation or Diels–Alder cycloaddition chemistry of photo-generated arylalkene radical cations with varying success.[177] An *ab initio* study of the nature of Frontier MOs of 1,3-dipoles has concluded that ozone and diazomethane are amongst those which exhibit significant biradical character,[178] in contrast to the widely accepted mechanism.[179,180] The oxidation of the novel enediynes (**72**) under SET conditions in methanol affords the 3-methoxy enediyne (**73**) and the corresponding 3-keto enediyne[181] rather than the cyclization product (**74**) recently reported for a similar system.[182] The structures of α-ammonium distonic radicals cations and their reactivity towards 5- or 6-*exo* radical cyclizations have been described.[183,184]





SCHEME 10



SCHEME 11

A study of the photo-sensitized ring-opening reactions of the radical cations (**76**) of arylcyclopropanes (**75**) with methanol, water, and cyanide nucleophiles suggests a three-electron S_N2 mechanism (Scheme 11).[185] The isolated products are methyl propyl ethers, derived from nucleophilic attack of methanol on the radical cation (**76**). They were detected by UV–VIS spectroscopy and shown to react with nucleophiles by transient kinetic methods. The benzyl radical (**77**) reacts with the DCB radical anion to afford monoaromatic ether (**78**) by oxidation and protonation or the disubstituted ether (**79**) by addition of DCB$^{\cdot}$. Regio- and stereo-selectivity of the substitution were complete; regiochemistry and rate constant were profoundly effected by the electronic nature of the aryl substituents.[186] Elsewhere, a combined *ab initio* and CIDNP study

has been made of the structure and reactivity of three bicyclic cyclopropane radical cations,[187] whilst the nucleophilic ring-opening reactions of naphthylcyclopropyl radical cations have been explored.[188] Examination of the ring cleavage of the cycloabutadiene radical cation using H–F, DFT and correlated MO calculations found *cis*-butadiene is formed via a concerted, unsymmetric pathway.[189] A combination of the valence bond configurational model and CASPT2 calculations agreed with experimental findings in the regiochemistry of addition of nucleophiles to the radical cations of non-alternant systems, such as dibenzofuran and azulene.[190] A paper reports the nucleophile-assisted cleavage of benzyltrialkysilane radical cations. The absolute rate constants were determined for C—Si bond lysis and decreased by up to four orders of magnitude by increased steric bulk at Si, with a similar but smaller effect by increasing crowded nucleophiles.[191] Conjugated diene radical cations have been generated by photolytic methods for characterization by flash photolysis and their reactions with anionic nucleophiles discussed.[192] Studies of the reactivity of 9-substituted-anthracene radical cations towards nitrogen nucleophiles with emphasis on the nucleophile structure and the nature of the 9-alkyl or aryl substituent have concluded that the configuration mixing model[193] does not apply.[194,195] High-level *ab initio* calculations on the ethane radical cation at the CCSD(T)/TZ (2df,2pd) and CCSD(t)/TZ2P levels have shown the ^2A_g state (C_{2h} symmetry, C—C bond length ca 1.7 Å) and the $^2A_{1g}$ state (D_{3d}, C—C bond length ca 1.9 Å) to be almost degenerate in energy. The transition state separating these minima is very low in energy, giving rise to an equilibrium between these two structures and only one averaged structure is observed.[196]

A study of a number of aryl bromide and α-phenoxyacetophenone radical cations has found a linear correlation between Hammett plots of cleavage rate constants versus σ-values for a selection of analogous radicals.[197] The reaction of vinyl chloride and bromide radical cations with ammonia was studied by FT-ion cyclotron resonance spectrometry and *ab initio* calculations. In this way it was established that halide substitution is the dominant pathway via a highly exothermic reaction.[198] An *ab initio* study of the effect of neutral bases on the isomerization of methyl radical cations ($CH_3X^{+\cdot}$) to their distonic isomers ($^{\cdot}CH_3\overset{+}{X}H$) found the mechanism to be largely determined by the relative proton affinities of the base and the parent radical $^{\cdot}CH_2X$.[199] Methyl radicals are reported to be released by the radical cation of 1-methyl-1,3-dioxacyclohexane before hydrogen abstraction at the carbon atom adjacent to both oxygens, as determined by deuteration studies.[200] The radical cations of substituted indol-3-ylacetic acids undergo a substituent-dependent decarboxylation with radical lifetimes of 10^{-6}–10^{-3} s.[201] The photo-induced fragmentation of α-anilino carboxylates proceeds by way of the radical cation which decarboxylates to a radical which self-terminates to the diamine or combines with the DCB sensitizer.[202]

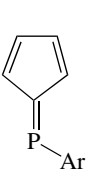
Radical Anions

A review has examined the use of radical anions in elucidation of the role of electron transfer in nucleophilic reactions through the determination of rates of electron-transfer reactions or obtaining reduction potentials of short-lived radical species.[203] The control of conjugation and high-spin formation of radical anions of linear and ladder-type π-

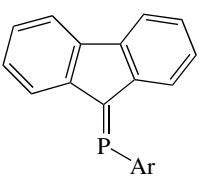
systems has been reviewed.[204] A review of the literature has been combined with *ab initio* calculations to conclude that aromatic radical anions containing fluorine substituents do not readily dissociate to the aryl radical and fluoride ions.[205]

A B3P86 hybrid H–F/DFT computational method using the 6–31-G(d) basis set was used to determine the structure, spin properties, and vibrational frequencies and mode assignments for the radical anions of *p*-chloranil, *p*-fluoranil, and *p*-benzoquinone.[206] There is good agreement between calculated and published neutral structures and the radical anion bond lengths are consistent with a shift towards a more phenolic structure. The calculated spin and vibrational properties show good qualitative correlation but fail to reproduce several important details. The stabilities, properties, and AM1-calculated C—Cl bond dissociation energies of a range of halohydrocarbon radical anions are reported.[207] A related paper made an *ab initio* study of the formation of the radical anions of mono- and tri-chloromethylbenzenes and their 4-pyridyl isomers, which adopt identical planar geometries.[208] The only significant factor to effect the C—Cl BDEs of these radical anions was found to be the number of chlorine atoms at the radical centre. The reductive cleavage of C—F bonds in trifluoromethylarenes led to completely defluorinated products. In contrast to other polyhalomethyl compounds, the initially formed radical anion rapidly protonates to afford the hydrogenolysis product rather than defluorination to the carbene probably due to the increased strength of C—F over other C—halogen bonds.[209] The halide elimination from haloethanol substrates affords a ketyl radical anion which has found application as a mechanistic probe in the radical reaction mechanisms of galactose oxidase.[210] An *ab initio* study found competing electron-transfer and substitution mechanisms for the reaction of ketyl anion radicals with chloromethane.[211] An MP2/3–21G theoretical study of the radical anions and dianions of cyclooctene analogues reports planar conjugation and varying degrees of aromaticity.[212]

The radical anions of phosphafulvene (**80**) and dibenzophosphafulvene (**81**) were generated by electrochemical reduction and their EPR spectra recorded between 110 K and room temperature.[213] Comparisons of calculated spin densities and charge distributions are presented along with experimental data. The radical anions of *o*-, *m*-, or *p*-thiobenzoate esters were generated by electro-reduction and found by their ESR spectra to be persistent.[214]



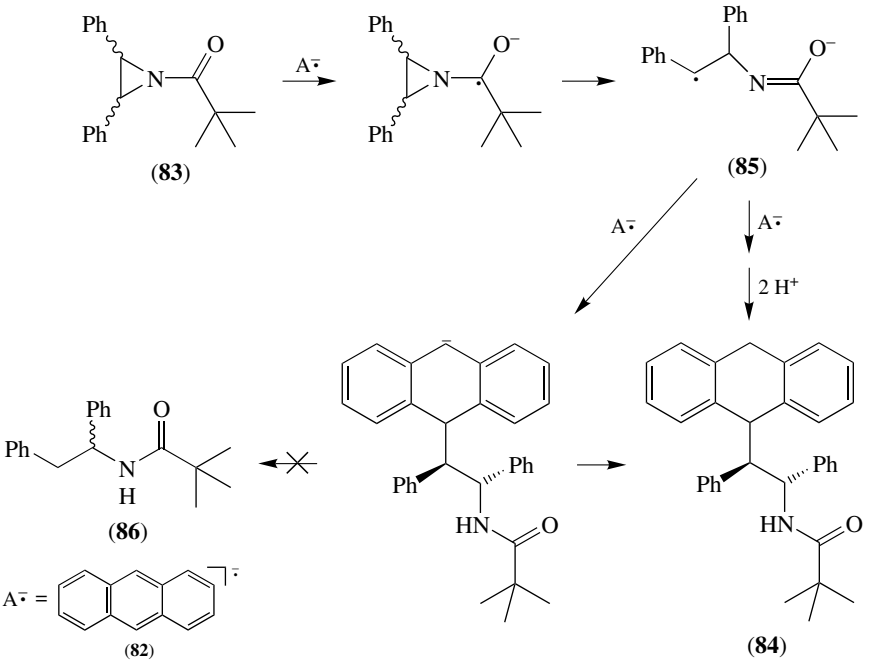
(**80**)



(**81**)

The role of radical anions in the detonation of nitroaromatic explosives has been examined.[215] The potassium salts of such radicals were formed by mono-, di-, and tri-nitrobenzenes and -toluenes in liquid ammonia solution and, on removal of the solvent, render the material highly susceptible to loss of the metal nitrite, which increases with nitro substitution. Cleavage of the C—NO_2^- M^+ bond follows the 'regioconserved' or

heterolytic mode and it seems likely that radical anion contamination of field explosives may be responsible for 'chemically induced hot-spots' that lead to inadvertent explosion. A number of *gem*-nitronitroso radical dianions have been prepared from the reaction of sodium nitrite with sulfur-containing compounds in the presence of ascorbic acid in the dark.[216] The initially formed anionic intermediates are reduced to the observed radicals once the reaction mixtures are made alkaline.



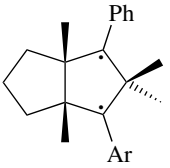
SCHEME 12

Reaction of anthracenide radical anion (**82**) with *cis*- and *trans*-1-pivaloyl-2,3-diphenylaziridines (**83**) yields the same product, *erythro*-(**84**).[217] The loss of steric differentiation is attributed to homolytic ring cleavage to give the same radical anion (**85**). Very rapid reaction (< 10 s) gives rise to exclusively *erythro* products, the *threo* compound being discounted on the basis of electrostatic repulsion between $A^{\cdot-}$ and the anionic tail. These short reaction times mean that radical coupling is not always complete and so (**85**) is also observed. Longer reaction times ensure radical coupling is completed at the expense of (**86**); see Scheme 12.

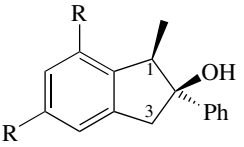
Biradicals

The photochemically generated cyclopentane-1,3-diyl diradials (**87**) were part of a study of spin delocalization through the EPR *D*-parameter. These biradicals were a model system for cumyl and benzyl radicals and experimental data were combined with MO calculations to map the electronic effects on *D* by varying the aromatic substituent (Ar = heterocycle).[218] This parameter was also measured for a related series of

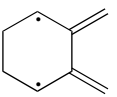
cyclopentene biradicals in which the aromatic groups were chosen from a range of mono- or di-substituted benzenes.[219−222] A paper discusses the structural dependence of spin–orbit coupling in biradicals, covering the importance of through-bond coupling and the origin of substituent effects, in particular heavy atoms.[223]



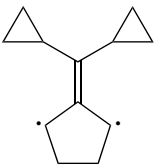
(**87**)



(**88**)
R = H or Et



(**89**)



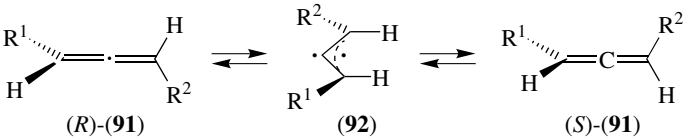
(**90**)

The biradical benzo-1,2 : 4,5-bis(1,3,2-dithiazolyl) (BBDTA) is known in the literature but characterization is incomplete. A new study reports the electronic, molecular, and solid-state structure of BBDTA.[224] The lifetime of an alkyl phenylglyoxalate-derived 1,4-biradical has been estimated, using the cyclopropylmethyl 'radical clock', to be in the range 35–40 ns.[225] The indanols (**88**) and their C(3) methyl and trideuteromethyl analogues have been prepared from phenyl benzyl ketone via photo-cyclization of an intermediate 1,5-biradical species.[226,227] Selectivity for these products over their C(1) epimers is high but is profoundly effected by substitution in the benzyl ring or the alkyl side-chain. The findings are rationalized in terms of the conformational preference of the intermediate 1,5-biradicals.

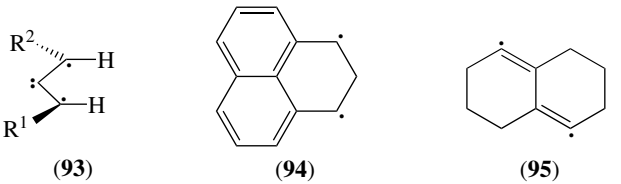
It has been shown that the singlet and triplet states of 2,3-dimethylmethylenecyclohexane-1,4-diyl (**89**) are almost degenerate, in agreement with computational results.[228] The modelling of simple non-Kekulé hydrocarbons such as trimethylenemethane using a dicyclopropyl derivative (**90**) has been extended to conformational analysis from its ESR hyperfine splitting pattern.[229] Semiempirical quantum chemical calculations (AM1/CI and PM3/CI) on 3,4-dimethylenepyrrole biradicals have shown that electron-withdrawing substituents on N should create a near-zero energy separation of the singlet and triplet states.[230] Most notably, the *N*-tosylpyrrole biradical was prepared by photolysis of the corresponding diazene and found to possess persistent triplet and singlet species. An *ab initio* study has been made at the ROHF, GVB, and CASSCF levels with the 6–31G* basis sets of *m*-phenylenediamine and 2,4-diamino-1,3,5-triazine dication biradicals as models of potential high-spin polymers.[231]

The gas-phase ionization of 2,4,6-tribromobenzene in the presence of *m*-fluoropyridine afforded the *N*-aryl-*m*-fluoropyridine adduct from which the biradical cation was generated by loss of two bromine radicals.[232] This biradical species was isolated and characterized using Fourier transform ion cyclotron resonance (FT-ICR) mass spectrometry and its chemical properties are discussed. FT-ICR was also used to isolate and characterize the products of electron ionization of fluorinated acetyl compounds, which included a biradical anion.[233]

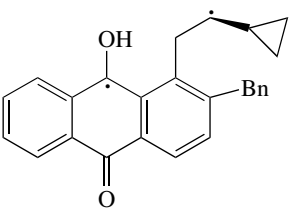
The thermal racemization of vinyl- and phenyl-substituted allenes (**91**) has been studied, which suggests the involvement of a biradical intermediate (**92**) (Scheme 13).[234] The experimentally determined racemization enthalpies are lower than the



SCHEME 13



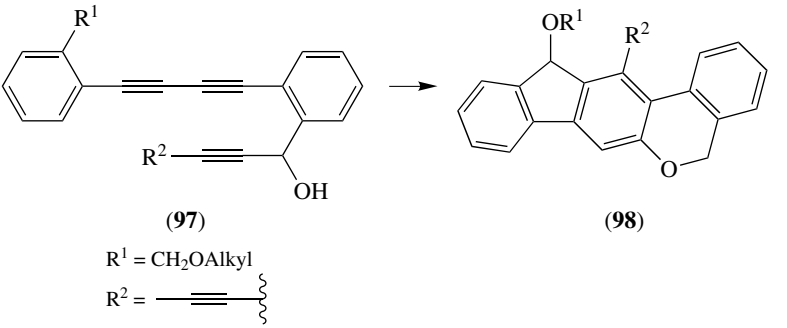
estimate derived from the parent system after correction for the extra stabilization of the biradical intermediate. The authors claim this is indicative of increasing importance of further stabilization by the carbene-type structure (**93**). These workers also determined the energy profile for the equilibrium between 1,8-naphthoquinodimethane and its thermally generated biradical (**94**).[235] Furthermore, they established that a thermal equilibrium exists between 1,6-cyclobutadiene and the bicyclic biradical (**95**) by isolation of radical-trapping products with NO and O_2; the enthalpy of formation of (**95**) is 116.2 kcal mol^{-1}.[236] The lifetimes of the triplet state of biradical (**96**) and a related structure, photogenerated from the analogous anthraquinones, have been determined using cyclopropylmethyl-derived radical clocks as 1–2 ns.[237] The reactivity of these biradicals is discussed and a mechanistic pathway for their formation is proposed.



(**96**)

The tandem radical cyclization of tetrayne (**97**) and its derivatives has been performed to generate the polycyclic pyran (**98**) via a biradical intermediate.[238] The cycloaddition reaction of a biradical species (or diyl) and a multiply bonded species (the diylophile)[239] has been observed with unique allene diylophiles.[240] The short-lived biradical formed by the irradiation of the diazene (**99**) is trapped by an allene diester to form a second biradical species (**100**). Intramolecular cyclization occurs such that all steric interactions are minimized and so enforces stereocontrol in the formation of the cycloadduct (**101**); see Scheme 14. A paper reports the rearrangement of 2-vinylmethylenecyclopropane (**102**) to 3-methylcyclopentene (**103**) via the triplet biradical (**104**), which has been characterized for the first time by IR spectroscopy.[241]

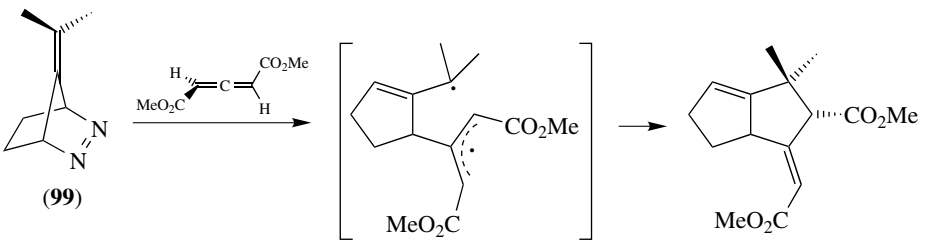
The photo-reaction is strongly dependent on the wavelength of irradiation and (**103**) is only observed in the presence of Br_2.



(**97**) (**98**)

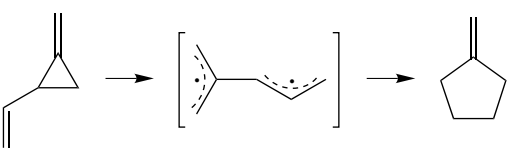
$R^1 = CH_2OAlkyl$

$R^2 =$



(**99**) (**100**) (**101**)

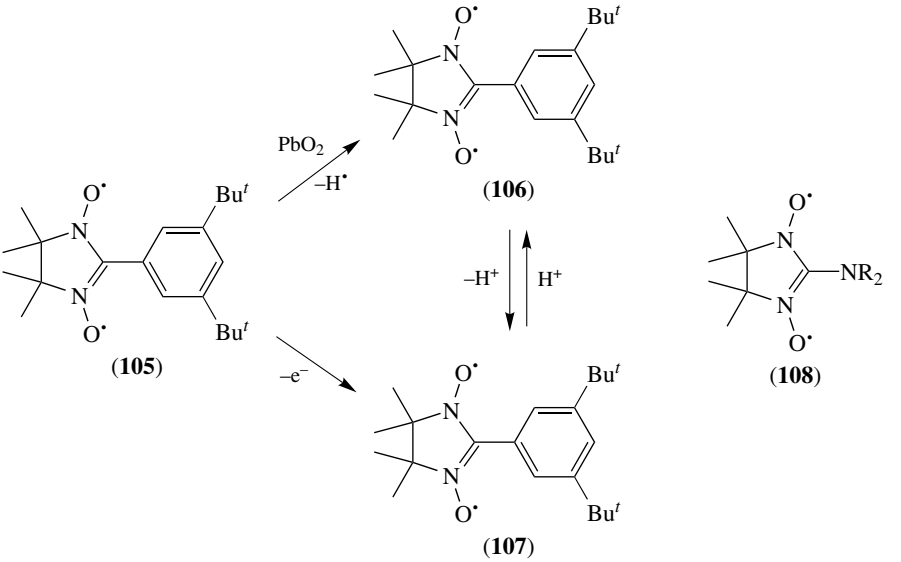
SCHEME 14



(**102**) (**104**) (**103**)

Nitroxides are the most common of the oxygen-centred biradicals to be reported. As a model for spin-crossover molecules, the nitronyl nitroxide (**105**) was prepared and by oxidation with PbO_2 afforded the triplet biradical (**106**) which was characterized by ESR (Scheme 15).[242] The one-electron oxidation of (**105**) afforded the singlet cation (**107**) which was seen to exist in equilibrium with (**106**) in solution. The authors claim that pH-controlled interconversion between two species of different spin multiplicities in this way may provide the basis for novel magnetic switches or pH sensors. The *N*,*N*-dialkylamino nitronyl nitroxides (**108**) were prepared and afforded the triplet-state biradical cation species by one-electron oxidation with iodine.[243] The authors propose that, by the similarity of the electronic structures, these structures can be regarded as hetero-analogues of trimethylenemethane. A paper confirms the conversion of 3,3-dimethyldioxetane into the corresponding ring-opened 1,2-diol but refutes the

intermediacy of the 1,4-dioxy radical, proposing instead ring cleavage by a radical species to a radical intermediate rather than O—O homolysis as the initial step.[244]

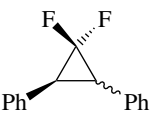


SCHEME 15

Pyrolysis and Thermolysis

Formation of stable radical species from cellulose, starch and sucrose during cooking has been reviewed.[245]

Thermolysis of 1,1-difluoro-2,3-diphenylcyclopropane in supercritical CO_2 has allowed the rate of geometrical isomerization [i.e. *cis*-(**109**) to *trans*-(**109**)] and racemization [i.e. (*R*)-(**109**) to (*S*)-(**109**)] to be determined from O_2 dependence of the trapping rate of the postulated intermediate 1,3-biradical.[246] Above 150 °C, the formation of 2,2-difluoroindane and its decomposition products is reported. A similar thermally induced equilibrating series of stereomutations has been observed with the analogous non-fluorinated cyclopropane in which rate constants and deuterium exchange isotope effects are reported.[247] Theoretical studies of this isomerization have focused on classical[248] and quasi-classical trajectories.[249]



(**109**)

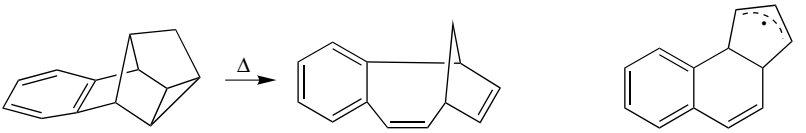
Single-pulse shock-tube thermal decomposition of furonitrile (1135–1380 K) affords primarily but-2-yne 1-nitrile via a radical intermediate.[250] Radicals are also implicated in the thermolysis of furan-2,3-dione analogues.[251] Explosive-driven shock waves of up

to 16 GPa and accompanying temperatures of 900–1400 K have been used for the measurement of the rates of a number of organic reactions. It was reported that, whilst extreme pressure favours reaction via an ionic mechanism, homolytic mechanisms are favoured by extreme temperatures. Thus, neopentyl nitrate afforded 2-nitro-2-methylpropane after thermally induced homolysis, β-scission and recombination.[252]

Time-of-flight (TOF) mass spectrometric analysis of the pyrolysis fragments of di-*t*-butyl peroxide suggests *t*-BuCO$^{\cdot}$ as the primary product, followed by decomposition of this radical into $CH_3^{\cdot}$.[253] Elsewhere, the kinetics of the pyrolysis of dimethyl, diethyl, and di-*t*-butyl peroxides in a modified adiabatic bomb calorimeter have been investigated.[254] The lifetime of acyloxy radicals, generated by the photolysis or thermolysis of acetyl propionyl peroxide, have been studied. Chemical nuclear polarization has been used to determine the rate constant for the decarboxylation of these radical intermediates.[255]

A number of papers report investigations of the pyrolytic cleavage of aromatic hydrocarbons. The oxidation and pyrolysis of anisole at 1000 K have revealed first-order decay in oxygen exclusively via homolysis of the O—CH_3 bond to afford phenol, cresols, methylcyclopentadiene, and CO as the major products.[256] A study of PAH radical anion salts revealed that CH_4 and H_2 are evolved from carbene formation and anionic polymerization of the radical species, respectively.[257] Pyrolysis of allylpropargyltosylamine was studied at temperatures of 460–500 °C and pressures of 10–16 Torr. The product mixture was dominated by hydrocarbon fragments but also contained SO_2 from a proposed thermolysis of an intermediate aldimine by radical processes.[258]

The kinetics of the pyrolysis of *n*-butenes with propane and *n*-butane were studied to obtain the relative rate constants and so calculate the effective relative reactivities towards Me$^{\cdot}$ and H$^{\cdot}$.[259] As part of a detailed study on hydrocarbon cracking, UHF calculations of the thermolysis of alkanes have shown that the modelled values agree well with the generally accepted free-radical mechanism.[260] The BDE for C—C homolytic fission has been calculated as 95 kcal mol^{-1} at the MP2/6–31G* level and 89 kcal mol^{-1} at the B3LYP/6–31G* level. The decomposition of cyclopentadiene was investigated by pyrolysis in argon using a single-pulse shock-tube (1080–1550 K, 1.7–9.6 atm).[261] Gas chromatographic analysis determined the main products in order of abundance to be acetylene, ethylene, methane, allene, propyne, butadiene, propylene, and benzene and reaction occurs via the cyclopentadienyl radical in the proposed mechanism. Pyrolysis of benzotricyclene (**110**) revealed the benzocyclooctene (**111**) as the initial product by GC/MS which was converted into α- and β-allylnaphthalenes via radical (**112**).[262]



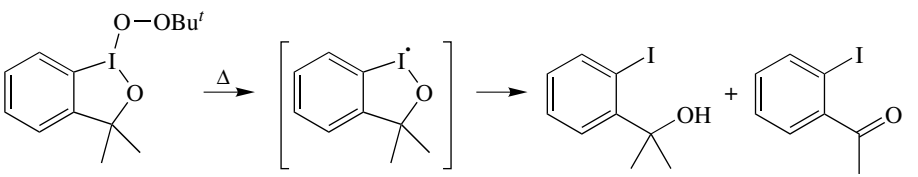
(**110**) (**111**) (**112**)

A paper reporting the pyrolysis of pyrazine, pyrimidine, and pyridine combined with laser-Schlieren densitometry and TOF mass spectrometry proposes decomposition via a

radical mechanism. It is suggested that the C—H homolytic BDEs of these heteroaromatic structures are lower than that for benzene owing to stabilization in the heterocyclic radicals by interaction of the N lone pair with adjacent C—H.[263] The thermal decomposition of azomethane has been the subject of an *ab initio* study, which predicted the lowest energy pathway to be homolytic C—N cleavage to afford $CH_3^{\cdot}$ and $CH_3N_2^{\cdot}$ using DZP and TZ2P basis sets. The calculations also indicated the *trans*-azomethane isomer to be more stable than the *cis*-isomer by 9.3 kcal mol^{-1}.[264] In the single-pulse shock-tube pyrolysis of 3-picoline, HCN, acetylene, benzene, methane, pyridine, and cyanoacetylene were isolated. *Ab initio* analysis of the enthalpy of formation of the intermediate 3-picolyl radical indicates a value lower than that for 2-picolyl, suggesting 3-picolyl decomposition more closely resembles that of toluene than of the 2-isomer.[265]

The products of the thermolysis of 3-phenyl-5-(arylamino)-1,2,4-oxadiazoles and thiazoles have been accounted for by a radical mechanism.[266] Flash vacuum pyrolysis of 1,3-dithiolane-1-oxides has led to thiocarbonyl compounds, but the transformation is not general.[267] In an ongoing study of silacyclobutane pyrolysis, CASSF(4,4), MR-CI and CASSCF(4,4)+MP2 calculations using the 3–21G* and 6–31G* basis sets have modelled the reaction between silenes and ethylene, suggesting a cyclic transition state from which silacyclobutane or a *trans*-biradical are formed.[268] An AM1 study of the thermolysis of 1,3,3-trinitroazacyclobutane and its derivatives has identified *gem*-dinitro C—N bond homolysis as the initial reaction.[269] Similar AM1 analysis has determined the activation energy of the formation of $^{\cdot}NO_2$ from methyl nitrate.[270] Thermal decomposition of nitromethane in a shock tube (1050–1400 K, 0.2–40 atm) was studied spectrophotometrically, allowing determination of rate constants.[271]

A re-examination of the pyrolysis of TFA has used FTIR spectoscopy to confirm the postulated mechanistic pathway, which proceeds via initial loss of HF to give the biradical $^{\cdot}CF_2CO_2^{\cdot}$. The authors claim the first direct observation of HF produced from this reaction from which the principal products were CHF_3, CF_3COF, and CO_2.[272] Elsewhere, the equilibrium and rate constants for the homolytic pyrolysis of a number of polyhalomethanes are reported.[273,274] Shock-tube pyrolysis of methyl iodide has been studied by I-atom atomic resonance spectrometry combined with unimolecular theoretical analysis.[275] The intermediacy of iodine radicals has been proposed in the thermolysis of *t*-butylperoxyiodinanes (**113**).[276] The products and kinetic data for decomposition of (**113**) in various organic solvents suggest thermolysis proceeds via initial I—O bond homolytic fission to give radical (**114**) from which the isolated iodinated aromatic alcohols (**115**) or ketones (**116**) were formed; see Scheme 16.

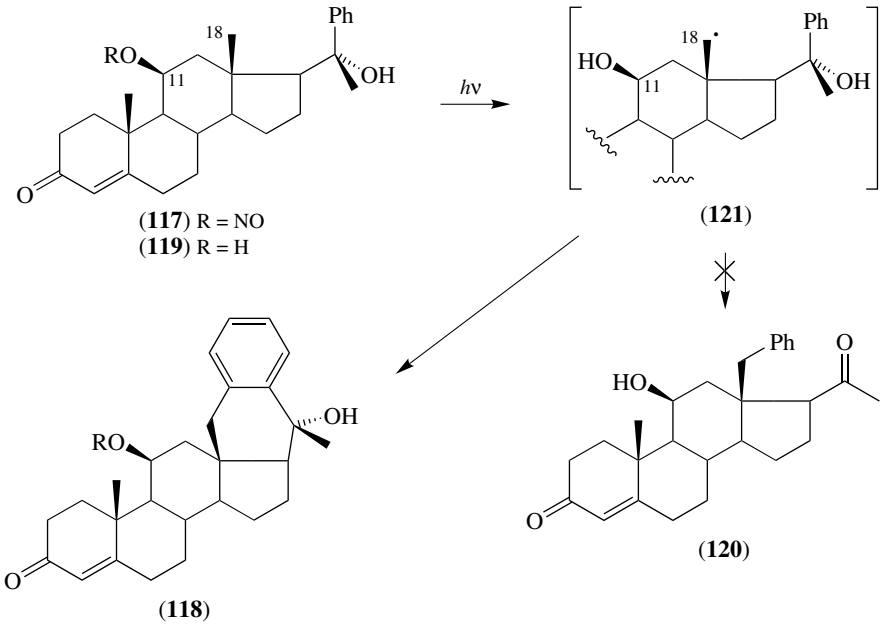


(**113**) (**114**) (**115**) (**116**)

SCHEME 16

Photolysis

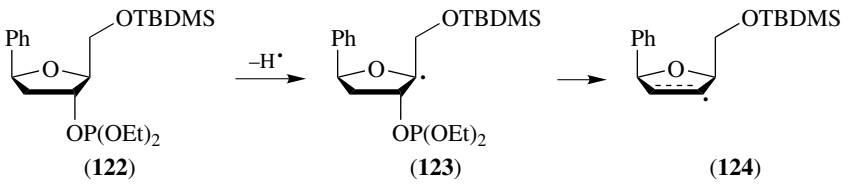
The photolysis of nitrosopregnone steroid (**117**) afforded the 18,20-benzo-fused compound (**118**) as the major product (24%) along with the diol (**119**) (6%), whilst the expected C(18) rearranged product (**120**) is not isolated (Scheme 17).[277] Reaction proceeds via the C(18) alkyl radical (**121**), formed in accordance with the accepted C(11) O—NO bond homolysis and H-abstraction pathway, before either addition of C(11) radical (**121**) to the aromatic ring to afford (**118**) or H abstraction to give (**119**).



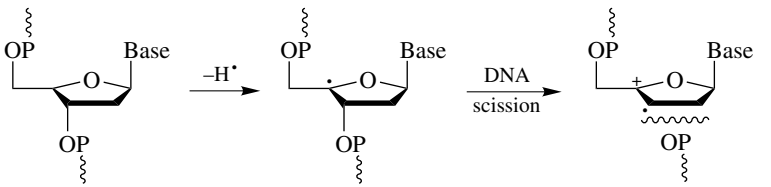
SCHEME 17

The photolytic cleavage of alkyl aryl sulfoxides has been shown to occur via initial C—S bond homolysis, in accordance with the common mechanistic assumption.[278] Secondary and tertiary alkyl groups show high chemoselectivity for alkyl C—S cleavage. Uniquely, alkene products have been isolated, formed by disproportionation of the initial alkyl radical, with the formation of benzaldehyde and racemization of primary alkyl compounds. An investigation into the photochemical conversion of *N*-propylsulfobenzoic imides into amides in various solvents revealed a solvent dependence of the observed mechanism.[279] In ethanol, sulfur dioxide extrusion forms a biradical which abstracts a hydrogen atom from the solvent, whereas in aromatic solvents biradical formation by a single electron transfer is implicated. The photolysis and thermolysis of 1,9-bis(alkylthio)dibenzothiophenes[280] and *p*-aminophenyl disulfide[281] have been studied.

The allylic radical (**124**) has been characterized by ESR as an intermediate in the photolysis of the deoxyribose phosphate (**122**), a model system for DNA cleavage by antitumour antibiotics (Scheme 18).[282] The proposed mechanistic pathway follows that

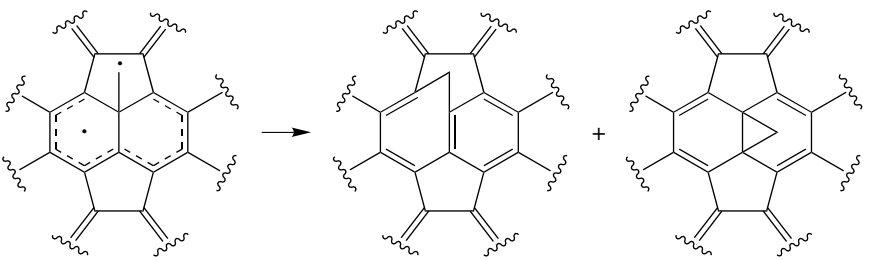


SCHEME 18



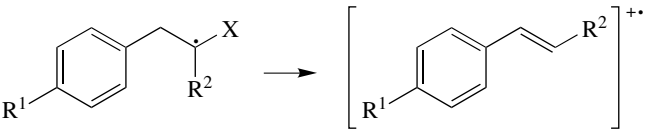
assumed for natural DNA, whereby the initially formed radical (**123**) undergoes dephosphorylation to afford a radical cation, from which the detected allylic radical (**124**) is formed by simple deprotonation of this acidic species. In a related report, a similar deoxyribophosphate moiety was photolysed, affording dihydrofuran and acetal products via an identical mechanism.[283]

The photolysis of aromatic species with tetranitromethane in perfluoro alcohol solvent has been studied, in which the radical cations were observed by EPR spectroscopy.[284] Photo-stimulated reaction of 1- and 2-haloadamantanes and 1,2- and 1,3-dihaloadamantanes with various carbanionic nucleophiles afforded products rationalized through an $S_{RN}1$ mechanism.[285,286] Photolysis of the cycloadduct formed between a functionalized derivative of C_{60} and diazomethane has been shown to afford a pair of ring-opened structures (**125**) and (**126**) via a proposed biradical intermediate (**127**) (Scheme 19). The UV-photolytic fragments of *t*-butyl iodide (I˙ and *t*-Bu˙) have been ionized by resonance-enhanced multiphoton ionization for TOF mass spectrometric analysis.[287] A two-dimensional position-sensitive detector provided angular distribution and translational energy data.



SCHEME 19

Recombination fluorescence has been used to study the decay of radical ion pairs generated photolytically.[288] Simulation of quantum beats caused by hyperfine interaction in the $R^{-\cdot}$ and $R^{+\cdot}$ enable the values of hfc to be determined for very short-lived species. In the case of one $R^{-\cdot}$ excellent agreement with the value of hfc as determined by ESR is reported. The primary reaction in the photolysis of 1-arylalkyl radicals (**128**) is the heterolytic cleavage of the β-halogen (X), generating the radical cation (**129**).[289]

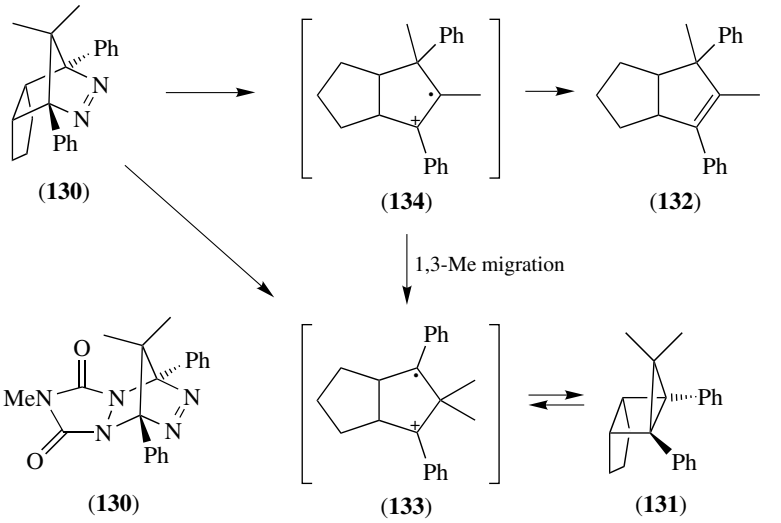


(**128**) (**129**)

Radiolysis

A review of radiolysis in liquid methanol has appeared which compares the relative abilities of methanol and water towards electron solvation.[290]

The cyclopentane-annelated azoalkane (**130**) and related housane (**131**) have previously been shown to rearrange under SET conditions to give the corresponding cyclopentene (**132**) (Scheme 20).[291293] According to a new study, the mechanism for pulse-radiolytic rearrangement of (**130**) begins by generation of the substrate radical cation and nitrogen extrusion.[294] Using time-resolved optical absorption to detect the transient radical intermediates, it has been determined that this radical cation follows two reaction pathways: (i) via the 1,2-radical cation (**134**) to give the fused

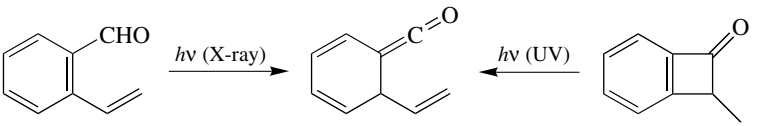


SCHEME 20

cyclopentene (**132**), or (ii) via the 1,3-distonic radical cation (**133**), which cyclizes to the housane (**131**) or undergoes a 1,3-methyl migration to generate (**134**). In contrast, radiolysis of the corresponding urazole-annelated analogue (**135**) formed the relatively stable 1,3-radical cation.[294] Radical formation rate constants, lifetimes, and optical spectra are also presented.

The radical-mediated degradation of trihalogenated acids has been studied by γ-radiolysis.[295] Irradiation of tribromoacetic acid (TBAA) in aqueous solution at pH 10 generated the radical anion $^{\cdot}CBr_3CO_2^-$. The major fate of this species was self-termination to tetrabromosuccinic acid which itself thermally decomposed to HBr, CO_2, and tribromoacrylic acid. Dibromofumaric acid, dibromomaleic acid, and CO were minor secondary products. It was observed that TBAA reacted with a number of radical species and the rate constants are presented. In contrast, trichloroacetic acid was efficiently reduced only by CO_2, whilst trifluoroacetic acid was highly stable towards γ-radiolysis. An ESR study of fluorinated benzene radical cations generated by γ-radiolysis showed close agreement between the calculated and observed hyperfine couplings.[296] The paper concludes, through *ab initio* calculations for the optimum radical geometries, that the structure and symmetry of the singly occupied molecular orbital (SOMO) are affected by the number and position of fluorine substitution. Elsewhere, radical anions were observed upon radiolysis of pentafluoroacetophenone and pentafluoronitrobenzene.[297]

X-ray ionization of *o*-vinylbenzaldehyde (**136**) in argon matrices leads to the quinoketene (**137**) via the radical cation, detected by IR spectroscopy.[298] The product identity was confirmed by the independent preparation of (**137**) and ($\mathbf{137}^{+\cdot}$) by the photo-stimulated ring-opening of 2-methylbenzocyclobutenone (**138**) (Scheme 21). The reactions of benzaldehyde, acetophenone, and benzophenone with $^{\cdot}OH$, $O^{\cdot-}$ and $SO_4^{\cdot-}$ have been studied by pulse radiolysis in aqueous solution.[299] The addition of $^{\cdot}OH$ to the carbonyl moiety of benzaldehyde predominates over addition to the aromatic ring, whereas ring addition is predominant in the case of acetophenone. Disproportionation of the exocyclic OH adduct is proposed to explain the formation of benzoic acid, which is a major product in the reaction of benzaldehyde and $^{\cdot}OH$ or $SO_4^{\cdot-}$. Rate constants for each reaction have been calculated.

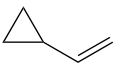


(**136**) (**137**) (**138**)

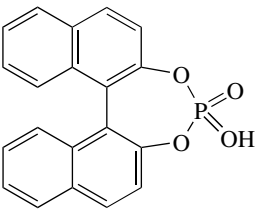
SCHEME 21

The vinylcyclopropane radical cation, generated at 77 K by X-irradiation of (**139**) in a Freon-113 matrix, was shown to rearrange at 105–110 K to afford two ring-opened distonic radical cationic species.[300] The rearrangement reactions of the radical cations of 1,3- and 1,4-pentadiene and cyclopentene and the formation of spin adducts with 2,4,6-tri-*t*-butylnitrosobenzene (BNB) are discussed. The pulse radiolysis of 1,1′-binaphthyl-2,2′-diyl hydrogenphosphate ($BiNPO_4H$) (**140**) in deaerated *t*-butanol at

pH 9.5 generated the radical anion.[301] Reaction with ·OH is reported to afford an adduct which formed the radical cation by acidic dehydroxylation. This radical cation was also produced in the reaction of (**140**) with oxidizing radicals, e.g. $SO_4^{-\cdot}$ and $Cl_2^{-\cdot}$.



(**139**)

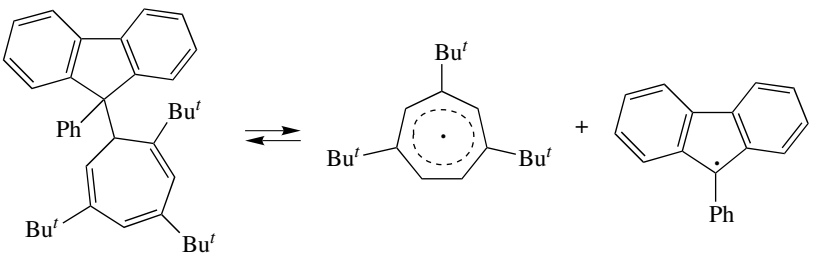


(**140**)

Pulse radiolysis has been used to afford the radical cations of thioanisole, *p*-methylthioanisole, and benzyl phenyl sulfides. The absorption spectra of these radicals and their reaction with a number of nucleophiles and electron donors are reported.[302] Exposure of trimethylphosphine sulfide to ^{60}Co γ-radiation at 77 K gave the radical anion $Me_3PS^{-\cdot}$, identified by its ESR spectrum, from which other radicals, including $Me_2\dot{P}S$, were formed at higher temperatures.[303]

Autoxidation

The autoxidation of 4-undecanone in air at 130 °C leads to the formation of hydroperoxides, which decompose at 120–160 °C via different radical pathways to give CO, CO_2, and H_2 by parallel pseudomonomolecular processes.[304] An extremely sterically crowded heptatriene (**141**) is reported to undergo autoxidation at 25 °C in cyclohexane. The isolated products were rationalized by the dissociation of (**141**) to the tropyl radical (**142**) or fluorenyl radical (**143**) and subsequent attack by molecular oxygen (Scheme 22).[305]



(**141**) (**142**) (**143**)

SCHEME 22

References

[1] Martinho Simoes, J. A., Greenberg, A., and Liebman, J. F., *Struct. Energ. React. Chem. Ser.*, **4**, 301 (1996).
[2] Francisco, J. S. and Montgomery, J. A., *Struct. Energ. React. Chem. Ser.*, **4**, 110 (1996).

[3] Tsang, W., *Struct. Energ. React. Chem. Ser.*, **4**, 22 (1996).
[4] Nakagaki, R., Fujiwara, Y., and Tanimoto, Y., *Kokagaku*, **22**, 46 (1996).
[5] Symons, M. C. R., *Acta Chem. Scand.*, **51**, 127 (1997).
[6] Brinck, T., Haeberlein, M., and Jonsson, M., *J. Am. Chem. Soc.*, **119**, 4239 (1997).
[7] Perrott, A. L., de Lijser, H. J. P., and Arnold, D. R., *Can. J. Chem.*, **75**, 384 (1997).
[8] Dyke, J. M., Groves, A. P., Lee, E. P. F., and Niavaran, M. H. Z., *J. Phys. Chem. A*, **101**, 373 (1997).
[9] Welle, F. M., Beckhaus, H. D., and Ruchardt, C., *J. Org. Chem.*, **62**, 552 (1997).
[10] Davidson, E. R., Chakravorty, S., and Gajewski, J. J., *New J. Chem.*, **21**, 533 (1997).
[11] Mebel, A. M. and Lin, S. H., *Chem. Phys.*, **215**, 329 (1997).
[12] Yu, J. S. K. and Yu, C. H., *Chem. Phys. Lett.*, **271**, 259 (1997).
[13] Glukhovtsev, M. N. and Bach, R. D., *J. Phys. Chem. A*, **101**, 3574 (1997).
[14] Cheong, B. S. and Cho, H. G., *J. Phys. Chem. A*, **101**, 7901 (1997).
[15] Galli, C., Gentili, P., Guarnieri, A., and Rappoport, Z., *J. Org. Chem.*, **61**, 8878 (1996).
[16] Galli, C., Guarnieri, A., Koch, H., Mencarelli, P., and Rappoport, Z., *J. Org. Chem.*, **62**, 4072 (1997).
[17] Lavorato, D., Terlouw, J. K., Dargel, T. K., Koch, W., McGibbon, G. A., and Schwarz, H., *J. Am. Chem. Soc.*, **118**, 11898 (1996).
[18] Morita, A. and Kato, S., *J. Am. Chem. Soc.*, **119**, 4021 (1997).
[19] Canac, Y., Baceiredo, A., Schoeller, W. W., Gigmes, D., and Bertrand, G., *J. Am. Chem. Soc.*, **119**, 7579 (1997).
[20] Martell, J. M., Eriksson, L. A., and Goddard, J. D., *Acta Chem. Scand.*, **51**, 229 (1997).
[21] Zhao, Y. Y., Bordwell, F. G., Cheng, J. P., and Wang, D. F., *J. Am. Chem. Soc.*, **119**, 9125 (1997).
[22] Sekiguchi, S., Akiyama, K., and TeroKubota, S., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1619.
[23] Bottle, S. E., Chand, U., and Micallef, A. S., *Chem. Lett.*, **1997**, 857.
[24] Arena, F., Bullo, F., Conti, F., Corvaja, C., Maggini, M., Prato, M., and Scorrano, G., *J. Am. Chem. Soc.*, **119**, 789 (1997).
[25] Carloni, P., Damiani, E., Greci, L., and Stipa, P., *Pol. J. Environ. Stud.*, **5**, 67 (1996).
[26] Welch, J. T., Plummer, J. S., and Herbert, R. W., *Res. Chem. Intermed.*, **22**, 791 (1996).
[27] Haseloff, R. F., Kirilyuk, I. A., Dikalov, S. I., Khramtsov, V. V., Darkhan, I., Blasig, I. E., and Grigor'ev, I. A., *Free Rad. Res.*, **26**, 159 (1997).
[28] Hashimoto, M., Nakai, Y., Kohno, M., Tajima, K., Kanaori, K., Endo, N., and Makino, K., *Chem. Lett.*, **1997**, 71.
[29] Janzen, E. G. and Nutter, D. E., *Magn. Reson. Chem.*, **35**, 131 (1997).
[30] Eberson, L. and Persson, O., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 893.
[31] Eberson, L., MacCullough, J. J., and Persson, O., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 133.
[32] Alberti, A., Carloni, P., Eberson, L., Greci, L., and Stipa, P., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 887.
[33] Sueishi, Y. and Miyake, Y., *Bull. Chem. Soc. Jpn*, **70**, 397 (1997).
[34] Eberson, L., Hartshorn, M. P., and Persson, O., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 195.
[35] Bhattacharjee, S., Khan, M. N., Chandra, H., and Symons, M. C. R., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2631.
[36] Bhattacharjee, S., Khan, M. N., Chandra, H., and Symons, M. C. R., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 845.
[37] Busfield, W. K., Jenkins, I. D., and Monteiro, M. J., *Aust. J. Chem.*, **50**, 1 (1997).
[38] Arai, N. and Narasaka, K., *Yukui Gosei Kagaku Kyokaishi*, **54**, 964 (1996).
[39] Mantashyan, A. A., *Khim. Fiz.*, **15**, 75 (1996).
[40] Pritzkow, W. W. and Suprun, V. Y., *Usp. Khim.*, **65**, 538 (1996).
[41] Denisov, E. T., *Usp. Khim.*, **65**, 547 (1996).
[42] de Nooy, A. E. J., Besemer, A. C., and van Bekkum, H., *Synthesis*, **1996**, 1153.
[43] Adam, W., Curci, R., Daccolti, L., Dinoi, A., Fusco, C., Gasparrini, F., Kluge, R., Paredes, R., Schulz, M., Smerz, A. K., Veloza, L. A., Weinkotz, S., and Winde, R., *Chem. Eur. J.*, **3**, 105 (1997).
[44] Stark, M. S., *J. Phys. Chem. A*, **101**, 8296 (1997).
[45] Weber, M., Hake, A., and Stuhl, F., *Int. J. Chem. Kinet.*, **29**, 149 (1997).
[46] Yoshioka, Y., Yamada, S., Kawakami, T., Nishino, M., Yamaguchi, K., and Saito, I., *Bull. Chem. Soc. Jpn*, **69**, 2683 (1996).
[47] Gowenlock, B. G., Pfab, J., and Young, V. M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1793.
[48] Chen, C.-J. and Bozzelli, J. W., *Chem. Phys. Processes Combust.*, **1996**, 519.
[49] Lambert, C. R., Black, H. S., and Truscott, T. G., *Free Rad. Biol. Med.*, **21**, 395 (1996).
[50] Kiec-Kononowicz, K., Karolak-Wojciechowska, J., and Robak, J., *Arch. Pharm., (Weinheim, Ger.)*, **330**, 85 (1997).
[51] Telo, J. P. and Vieira, A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1755.
[52] Jungkamp, T. P. W., Smith, J. N., and Seinfeld, J. H., *J. Phys. Chem. A*, **101**, 4392 (1997).

[53] Simon, V., Simon, Y., Scacchi, G., and Baronnet, F., *Can. J. Chem.*, **75**, 575 (1997).
[54] Wang, K. and Mayer, J. M., *J. Am. Chem. Soc.*, **119**, 1470 (1997).
[55] Yamada, T., Bozzelli, J. W., and Lay, T., *Chem. Phys. Processes Combust.*, **1996**, 523.
[56] Glod, G., Angst, W., Holliger, C., and Schwarzenbach, R. P., *Environ. Sci. Technol.*, **31**, 253 (1997).
[57] Azzena, U., Casado, F., Fois, P., Gallardo, I., Pisano, L., Marquet, J., and Melloni, G., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2563.
[58] Bianchini, R., Forte, C., Musumarra, G., Pinzino, C., and Sergi, C., *Tetrahedron*, **53**, 6907 (1997).
[59] Lukasiewicz, A., *Tetrahedron*, **19**, 1789 (1963).
[60] Fukuzumi, S., *Bull. Chem. Soc. Jpn*, **70**, 1 (1997).
[61] Armesto, D., Austin, M. A., Griffiths, O. J., Horspool, W. M., and Carpintero, M., *J. Chem. Soc., Chem. Commun.*, **1996**, 2715.
[62] Bockman, T. M., Hubig, S. M., and Kochi, J. K., *J. Org. Chem.*, **62**, 2210 (1997).
[63] de Lijser, H. J. P. and Arnold, D. R., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1369.
[64] Akaba, R., Kamata, M., Koike, A., Mogi, K. I., Kuriyama, Y., and Sakuragi, H., *J. Phys. Org. Chem.*, **10**, 861 (1997).
[65] Fukuzumi, S., Suenobu, T., Kawamura, S., Ishida, A., and Mikami, K., *J. Chem. Soc., Chem. Commun.*, **1997**, 291.
[66] Fukuzumi, S., Suenobu, T., Kadish, K. M., Subramanian, R., and Jones, M. T., *Proc. Electrochem. Soc.*, **1996**, 243.
[67] Hasegawa, E., Ishiyama, K., Fujita, T., Kato, T., and Abe, T., *J. Org. Chem.*, **62**, 2396 (1997).
[68] Ikeda, H., Ishida, A., Takasaki, T., Tojo, S., Takamuku, S., and Miyashi, T., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 849.
[69] Kako, M., Mori, M., Hatakenaka, K., Kakuma, S., Nakadaira, Y., Yasui, M., and Iwasaki, F., *Tetrahedron*, **53**, 1265 (1997).
[70] Kako, M., Ninomiya, M., and Nakadaira, Y., *J. Chem. Soc., Chem. Commun.*, **1997**, 1373.
[71] Sclafani, A., Palmisano, L., and Farneti, G., *J. Chem. Soc., Chem. Commun.*, **1997**, 529.
[72] Nakamura, M. and Majima, T., *J. Chem. Soc., Chem. Commun.*, **1997**, 1291.
[73] Weigel, W. and Henning, H. G., *J. Chem. Soc., Chem. Commun.*, **1997**, 1893.
[74] McIlroy, S., Weng, H. X., and Roth, H. D., *J. Phys. Org. Chem.*, **10**, 607 (1997).
[75] Herbertz, T. and Roth, H. D., *J. Am. Chem. Soc.*, **118**, 10954 (1996).
[76] Penenory, A. B. and Rossi, R. A., *Gazz. Chim. Ital.*, **125**, 605 (1995).
[77] Galli, C., Gentili, P., and Guarnieri, A., *Gazz. Chim. Ital.*, **127**, 159 (1997).
[78] Chen, Q., in *Zhongguo Youjifu Huaxue Yanjiu* (Ed. Huang, W.), Shanghai Kexue Jishu Chubanshe, Shanghai, **1996**, p. 111.
[79] Villata, L. S., Rosso, J. A., Gonzalez, M. C., and Martire, D. O., *J. Chem. Res. (S)*, **1997**, 172.
[80] Gaebert, C. and Mattay, J., *Tetrahedron*, **53**, 14297 (1997).
[81] Schmittel, M., Wohrle, C., and Bohn, I., *Chem. Eur. J.*, **2**, 1031 (1996).
[82] Patz, M. and Fukuzumi, S., *J. Phys. Org. Chem.*, **10**, 129 (1997).
[83] Matyushov, D. V., *Chem. Phys.*, **211**, 47 (1996).
[84] Zimmt, M. B., *EPA Newsl.*, **59**, 42 (1997).
[85] Trifunac, A. D., Sauer, M. C., Shkrob, I. A., and Werst, D. W., *Acta Chem. Scand.*, **51**, 158 (1997).
[86] Narasaka, K., *Pure Appl. Chem.*, **69**, 601 (1997).
[87] Marcus, R. A., *J. Phys. Chem. A*, **101**, 4072 (1997).
[88] Nelsen, S. F., Ramm, M. T., Wolff, J. J., and Powell, D. R., *J. Am. Chem. Soc.*, **119**, 6863 (1997).
[89] Nelsen, S. F., Trieber, D. A., Wolff, J. J., Powell, D. R., and Rogers Crowley, S., *J. Am. Chem. Soc.*, **119**, 6873 (1997).
[90] Nelsen, S. F., Ismagilov, R. F., and Powell, D. R., *J. Am. Chem. Soc.*, **119**, 10213 (1997).
[91] Formosinho, S. J. and Arnaut, L. G., *Bull. Chem. Soc. Jpn*, **70**, 977 (1997).
[92] Marcus, R. A., *J. Chem. Phys.*, **24**, 966 (1956).
[93] Marcus, R. A., *J. Chem. Phys.*, **26**, 867 (1957).
[94] Marcus, R. A., *J. Chem. Phys.*, **43**, 679 (1965).
[95] Candida, M., Shohoji, B. L., and Telo, J. P., *Rev. Port. Quim.*, **1**, 22 (1994).
[96] Screttas, C. G. and Micha-Screttas, M., *J. Org. Chem.*, **44**, 713 (1979).
[97] Kulkarni, V. and Cohen, T., *Tetrahedron*, **53**, 12089 (1997).
[98] Aplin, J. T. and Bauld, N. L., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 853.
[99] Campos, A. M. and Lissi, E. A., *Int. J. Chem. Kinet.*, **29**, 219 (1997).
[100] Alberti, A., Benaglia, M., Macciantelli, D., Marcaccio, M., Olmeda, A., Pedulli, G. F., and Roffia, S., *J. Org. Chem.*, **62**, 6309 (1997).
[101] McKinley, J., Aponick, A., Raber, J. C., Fritz, C., Montgomery, D., and Wigal, C. T., *J. Org. Chem.*, **62**, 4874 (1997).

[102] Ding, Y., Zhao, Z. B., and Zhou, C. M., *Tetrahedron*, **53**, 2899 (1997).
[103] Brown, D. W., Lindquist, M., Mahon, M. F., Malm, B., Nilsson, G. N., Ninan, A., Sainsbury, M., and Westerlund, C., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2337.
[104] Tanko, J. M. and Brammer, L. E., *J. Org. Chem.*, **62**, 5550 (1997).
[105] Welder, C. O. and Ashby, E. C., *J. Org. Chem.*, **62**, 4829 (1997).
[106] Ashby, E. C. and Welder, C. O., *J. Org. Chem.*, **62**, 3542 (1997).
[107] Witt, D. and Rachon, J., *Heteroat. Chem.*, **7**, 359 (1996).
[108] Lafis, S., Konidari, C. N., Veltsistas, P. G., Tzerpos, N., and Karayannis, M. I., *Int. J. Chem. Kinet.*, **29**, 385 (1997).
[109] Staneke, P. O., Kauw, J., Born, M., Ingemann, S., and Nibbering, N. M. M., *Rapid Commun. Mass Spectrom.*, **11**, 124 (1997).
[110] Zheng, Z. R. and Cheng, J. P., *Chin. Sci. Bull.*, **42**, 292 (1997).
[111] El Badraoui, K., Chanon, M., Merlet, D., Chajara, K., and Courtieu, J., *Tetrahedron Lett.*, **38**, 831 (1997).
[112] Sroubkova, L., Horak, V., and Zahradnik, R., *Collect. Czech. Chem. Commun.*, **62**, 147 (1997).
[113] Constantinescu, T., Caproiu, M. T., Zarna, N., Caragheorgheopol, A., Caldararu, H., Stanciuc, G., Radu, M., Badescu, V., and Balaban, A. T., *New J. Chem.*, **21**, 575 (1997).
[114] Suzuki, H. and Mori, T., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1265.
[115] Zhang, X. M. and Xhu, Q. Y., *J. Org. Chem.*, **62**, 5934 (1997).
[116] Takada, N., Itoh, S., and Fukuzumi, S., *Chem. Lett.*, **1996**, 1103.
[117] Wong, J. W., Natalie, K. J., Nwokogu, G. C., Pisipati, J. S., Flaherty, P. T., Greenwood, T. D., and Wolfe, J. F., *J. Org. Chem.*, **62**, 6152 (1997).
[118] Spreitzer, H., Scholz, M., Gescheidt, G., and Daub, J., *Liebigs Ann.*, **1996**, 2069.
[119] Wu, L. M., Lu, J. M., Wen, X. L., Jia, X. Q., Liu, Y. C., and Liu, Z. L., *J. Phys. Org. Chem.*, **10**, 152 (1997).
[120] Koldasheva, E. M., Strelets, V. V., Tse, Y. K., Geletii, Y. V., and Shestakov, A. F., *Russ. Chem. Bull.*, **45**, 1889 (1996).
[121] Takamuku, S., Majima, T., Ishida, A., and Tojo, S., *Mem. Inst. Sci. Ind. Res., Osaka Univ.*, **53**, 1 (1996).
[122] Johnston, L. J. and Schepp, N. P., *Adv. Electron Transfer Chem.*, **5**, 41 (1996).
[123] Feldman, V. I., *Acta Chem. Scand.*, **51**, 181 (1997).
[124] Yasui, S., *Trends Org. Chem.*, **5**, 141 (1995).
[125] Smith, R. L., Chou, P. K., and Kenttamaa, H. I., *Struct. Energ. Dyn. Org. Ions*, **1996**, 197.
[126] Andersen, M. L., Nielsen, M. F., and Hammerich, O., *Acta Chem. Scand.*, **51**, 94 (1997).
[127] Butts, C. P., Eberson, L., Hartshorn, M. P., Radner, F., Robinson, W. T., and Wood, B. R., *Acta Chem. Scand.*, **51**, 839 (1997).
[128] Eberson, L., Hartshorn, M. P., Persson, O., and Radner, F., *Acta Chem. Scand.*, **51**, 492 (1997).
[129] Glaser, R., Chen, G. S., and Grutzmacher, H., *J. Comput. Chem.*, **18**, 1023 (1997).
[130] Steudel, R., Drozdova, Y., Miaskiewicz, K., Hertwig, R. H., and Koch, W., *J. Am. Chem. Soc.*, **119**, 1990 (1997).
[131] Carmichael, I., *Acta Chem. Scand.*, **51**, 567 (1997).
[132] Takeuchi, H., Hiyama, T., Kamai, N., and Oya, H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2301.
[133] Aravindan, P., Maruthamuthu, P., and Dharmalingam, P., *Bull. Chem. Soc. Jpn*, **70**, 37 (1997).
[134] Salhi Benachenhou, N., Eriksson, L. A., and Lunell, S., *Acta Chem. Scand.*, **51**, 636 (1997).
[135] Salhi Benachenhou, N., Alvarez Idaboy, J. R., and Lunell, S., *Acta Chem. Scand.*, **51**, 242 (1997).
[136] van der Hart, W. J., *J. Am. Soc. Mass Spectrom.*, **7**, 731 (1996).
[137] Itagaki, Y., Shiotani, M., and Tachikawa, H., *Acta Chem. Scand.*, **51**, 220 (1997).
[138] Furuya, K., Torii, H., Furukawa, Y., and Tasumi, M., *Chem. Lett.*, **1996**, 913.
[139] Baciocchi, E., Bietti, M., and Steenken, S., *J. Am. Chem. Soc.*, **119**, 4078 (1997).
[140] Tolbert, L. M., Li, Z. Z., Sirimanne, S. R., and VanDerveer, D. G., *J. Org. Chem.*, **62**, 3927 (1997).
[141] Roth, H. D., Weng, H. X., Zhou, D. H., and Lakkaraju, P. S., *Acta Chem. Scand.*, **51**, 626 (1997).
[142] Belopushkin, S. I. and Belevskii, V. N., *Vestn. Mosk. Univ., Ser. 2: Khim.*, **37**, 393 (1996).
[143] Zubarev, V. E. and Brede, O., *Acta Chem. Scand.*, **51**, 224 (1997).
[144] Gauld, J. W., Glukhovtsev, M. N., and Radom, L., *Chem. Phys. Lett.*, **262**, 187 (1996).
[145] Eloranta, J., Suontamo, R., and Vuolle, M., *J. Chem. Soc., Faraday Trans.*, **93**, 3313 (1997).
[146] Chentit, M., Sidorenkova, H., Jouaiti, A., Terron, G., Geoffroy, M., and Ellinger, Y., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 921.
[147] Romakhin, A. S., Kosachev, I. P., and Nikitin, E. V., *Zh. Obshch. Khim.*, **66**, 1955 (1996).
[148] Schweighofer, A., Chou, P. K., Thoen, K. K., Nanayakkara, V. K., Keck, H., Kuchen, W., and Kenttamaa, H. I., *J. Am. Chem. Soc.*, **118**, 11893 (1996).
[149] Chan, M. S. W. and Arnold, D. R., *Can. J. Chem.*, **75**, 192 (1997).

[150] Brouwer, A. M., Wiering, P. G., Zwier, J. M., Langkilde, F. W., and Wilbrandt, R., *Acta Chem. Scand.*, **51**, 217 (1997).
[151] Walden, S. E. and Wheeler, R. A., *J. Am. Chem. Soc.*, **119**, 3175 (1997).
[152] Nelsen, S. F., Klein, S. J., Trieber, D. A., Ismagilov, R. F., and Powell, D. R., *J. Org. Chem.*, **62**, 6539 (1997).
[153] Gescheidt, G., Prinzbach, H., Davies, A. G., and Herges, R., *Acta Chem. Scand.*, **51**, 174 (1997).
[154] Toriyama, K. and Okazaki, M., *Acta Chem. Scand.*, **51**, 167 (1997).
[155] Herbertz, T. and Roth, H. D., *J. Am. Chem. Soc.*, **119**, 9574 (1997).
[156] Clark, T., *Acta Chem. Scand.*, **51**, 646 (1997).
[157] Bach, R. D., Schilke, I. L., and Schlegel, H. B., *J. Org. Chem.*, **61**, 4845 (1996).
[158] Kispert, L. D., Gao, G., Deng, Y., Konovalov, V., Jeevarajan, A. S., Jeevarajan, J. A., and Hand, E., *Acta Chem. Scand.*, **51**, 572 (1997).
[159] Feng, W. L., Wang, Y. H., Zhang, S. W., Xi, H. W., and Pang, X. Y., *Chin. Sci. Bull.*, **42**, 910 (1997).
[160] Guethe, F. and Weitzel, K.-M., *Ber. Bunsen-Ges.*, **101**, 484 (1997).
[161] Schmittel, M. and Langels, A., *Angew. Chem., Int. Ed. Engl.*, **36**, 392 (1997).
[162] Schmittel, M. and Trenkle, H., *Chem. Lett.*, **299**, (1997).
[163] Schmittel, M., Gescheidt, G., Eberson, L., and Trenkle, H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2145.
[164] Hrouda, V., Roeselova, M., and Bally, T., *J. Phys. Chem. A*, **101**, 3925 (1997).
[165] Laali, K. K. and Hansen, P. E., *Res. Chem. Intermed.*, **22**, 737 (1996).
[166] Stoub, D. G. and Goodman, J. L., *J. Am. Chem. Soc.*, **119**, 11110 (1997).
[167] Brouwer, A. M., *J. Phys. Chem. A*, **101**, 3626 (1997).
[168] Wienk, M. M. and Janssen, R. A. J., *J. Am. Chem. Soc.*, **119**, 4492 (1997).
[169] Matsumoto, K., Katsura, H., Yamauchi, J., Uchida, T., Aoyama, K., and Machiguchi, T., *Bull. Soc. Chim. Fr.*, **133**, 891 (1996).
[170] Wang, H. J., Handoo, K., and Parker, V. D., *Acta Chem. Scand.*, **51**, 963 (1997).
[171] Krull, W., Lehnig, M., and Such, P., *Acta Chem. Scand.*, **51**, 214 (1997).
[172] Lehnig, M., *Acta Chem. Scand.*, **51**, 211 (1997).
[173] Gurtler, C. F., Blechert, S., and Steckhan, E., *Chem. Eur. J.*, **3**, 447 (1997).
[174] Grutzmacher, H. F. and Barkow, A., *Acta Chem. Scand.*, **51**, 619 (1997).
[175] Park, K. H., Jun, K., Shin, S. R., and Oh, S. W., *Bull. Korean Chem. Soc.*, **18**, 604 (1997).
[176] Schmittel, M., Wohrle, C., and Bohn, I., *Acta Chem. Scand.*, **51**, 151 (1997).
[177] Schepp, N. P., Shukla, D., Sarker, H., Bauld, N. L., and Johnston, L. J., *J. Am. Chem. Soc.*, **119**, 10325 (1997).
[178] Yoshioka, Y., Yamaki, D., Maruta, G., Tsunesada, T., Takada, K., Noro, T., and Yamaguchi, K., *Bull. Chem. Soc. Jpn*, **69**, 3395 (1996).
[179] Huisgen, R., *Angew. Chem., Int. Ed. Engl.*, **2**, 633 (1963).
[180] Huisgen, R., in *1,3-Dipolar Cycloaddition Chemistry* (Ed. Padwa, A.), Wiley, New York, **1984**, Vol. 1, p. 1.
[181] Schmittel, M. and Kiau, S., *Liebigs Ann./Recl.*, **1997**, 1391.
[182] Ramkumar, D., Kalpana, M., Vargehese, B., Sankararaman, S., Jagadeesh, N., and Chandrasekhar, J., *J. Org. Chem.*, **61**, 2247 (1996).
[183] Rios, L. A., Dolbier, W. R., Paredes, R., Lusztyk, J., Ingold, K. U., and Jonsson, M., *J. Am. Chem. Soc.*, **118**, 11313 (1996).
[184] Rios, L. A., Bartberger, M. D., Dolbier, W. R., and Paredes, R., *Tetrahedron Lett.*, **38**, 7041 (1997).
[185] Dinnocenzo, J. P., Simpson, T. R., Zuilhof, H., Todd, W. P., and Heinrich, T., *J. Am. Chem. Soc.*, **119**, 987 (1997).
[186] Dinnocenzo, J. P., Zuilhof, H., Lieberman, D. R., Simpson, T. R., and McKechney, M. W., *J. Am. Chem. Soc.*, **119**, 994 (1997).
[187] Roth, H. D., Weng, H. X., and Herbertz, T., *Tetrahedron*, **53**, 10051 (1997).
[188] Wang, Y. H. and Tanko, J. M., *J. Am. Chem. Soc.*, **119**, 8201 (1997).
[189] Wiest, O., *J. Am. Chem. Soc.*, **119**, 5713 (1997).
[190] Eberson, L., GonzalezLuque, R., Merchan, M., Radner, F., Roos, B. O., and Shaik, S., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 463.
[191] Dockery, K. P., Dinnocenzo, J. P., Farid, S., Goodman, J. L., Gould, I. R., and Todd, W. P., *J. Am. Chem. Soc.*, **119**, 1876 (1997).
[192] Lew, C. S. Q., Brisson, J. R., and Johnston, L. J., *J. Org. Chem.*, **62**, 4047 (1997).
[193] Pross, A., *J. Am. Chem. Soc.*, **108**, 3537 (1986).
[194] Parker, V. D. and Reitstoen, B., *Acta Chem. Scand.*, **51**, 1035 (1997).
[195] Parker, V. D., Handoo, K., Zheng, G., and Wang, H. J., *Acta Chem. Scand.*, **51**, 869 (1997).
[196] Sulzbach, H. M., Graham, D., Stephens, J. C., and Schaefer, H. F., *Acta Chem. Scand.*, **51**, 547 (1997).

[197] Jaworski, J. S., *J. Chem. Res. (S)*, **1997**, 412.
[198] Nixdorf, A. and Grutzmacher, H. F., *J. Am. Chem. Soc.*, **119**, 6544 (1997).
[199] Gauld, J. W. and Radom, L., *J. Am. Chem. Soc.*, **119**, 9831 (1997).
[200] Kubota, S., Hishikawa, T., Makino, M., Ushida, K., Momose, T., and Shida, T., *Acta Chem. Scand.*, **51**, 579 (1997).
[201] Mehta, L. K., Porssa, M., Parrick, J., Candeias, L. P., and Wardman, P., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1487.
[202] Su, Z. Y., Falvey, D. E., Yoon, U. C., and Mariano, P. S., *J. Am. Chem. Soc.*, **119**, 5261 (1997).
[203] Lund, H., Daasbjerg, K., Lund, T., Occhialini, D., and Pedersen, S. U., *Acta Chem. Scand.*, **51**, 135 (1997).
[204] Baumgarten, M., *Acta Chem. Scand.*, **51**, 193 (1997).
[205] Denney, D. B., Denney, D. Z., and Fenelli, S. P., *Tetrahedron*, **53**, 9835 (1997).
[206] Boesch, S. E. and Wheeler, R. A., *J. Phys. Chem. A*, **101**, 8351 (1997).
[207] Taddei, F., *Gazz. Chim. Ital.*, **126**, 529 (1996).
[208] Benassi, R., Bertarini, C., and Taddei, F., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2263.
[209] Andrieux, C. P., Combellas, C., Kanoufi, F., Saveant, J. M., and Thiebault, A., *J. Am. Chem. Soc.*, **119**, 9527 (1997).
[210] Wachter, R. M., Montague Smith, M. P., and Branchaud, B. P., *J. Am. Chem. Soc.*, **119**, 7743 (1997).
[211] Shaik, S., Danovich, D., Sastry, G. N., Ayala, P. Y., and Schlegel, H. B., *J. Am. Chem. Soc.*, **119**, 9237 (1997).
[212] Salcedo, R., Sansores, L. E., and Fomina, L., *THEOCHEM*, **397**, 159 (1997).
[213] Al Badri, A., Chentit, M., Geoffroy, M., and Jouaiti, A., *J. Chem. Soc., Faraday Trans.*, **93**, 3631 (1997).
[214] Voss, J., Behrens, T., Krasmann, M., Osternack, K., and Prangova, L., *J. Chem. Res. (S)*, **1997**, 252.
[215] Batz, M. L., Garland, P. M., Reiter, R. C., Sanborn, M. D., and Stevenson, C. D., *J. Org. Chem.*, **62**, 2045 (1997).
[216] Lagercrantz, C., *Acta Chem. Scand.*, **51**, 113 (1997).
[217] Mall, T. and Stamm, H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2135.
[218] Adam, W., Emmert, O., and Harrer, H. M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 687.
[219] Adam, W., van Barneveld, C., Emmert, O., Harrer, H. M., Kita, F., Kumar, A. S., Maas, W., Nau, W. M., Reddy, S. H. K., and Wirz, J., *Pure Appl. Chem.*, **69**, 735 (1997).
[220] Adam, W., Harrer, H. M., Kita, F., and Nau, W. M., *Pure Appl. Chem.*, **69**, 91 (1997).
[221] Adam, W., Harrer, H. M., and Maas, W., *J. Org. Chem.*, **62**, 7263 (1997).
[222] Adam, W., Harrer, H. M., Kita, F., Korth, H. G., and Nau, W. M., *J. Org. Chem.*, **62**, 1419 (1997).
[223] Michl, J. and Havlas, Z., *Pure Appl. Chem.*, **69**, 785 (1997).
[224] Barclay, T. M., Cordes, A. W., de Laat, R. H., Goddard, J. D., Haddon, R. C., Jeter, D. Y., Mawhinney, R. C., Oakley, R. T., Palstra, T. T. M., Patenaude, G. W., Reed, R. W., and Westwood, N. P. C., *J. Am. Chem. Soc.*, **119**, 2633 (1997).
[225] Hu, S. K. and Neckers, D. C., *J. Org. Chem.*, **62**, 755 (1997).
[226] Wagner, P. J., Zand, A., and Park, B. S., *J. Am. Chem. Soc.*, **118**, 12856 (1996).
[227] Zand, A., Park, B. S., and Wagner, P. J., *J. Org. Chem.*, **62**, 2326 (1997).
[228] Matsuda, K. and Iwamura, H., *J. Am. Chem. Soc.*, **119**, 7412 (1997).
[229] Paul, G. C., Gajewski, J. J., Kestyn, P. A., Khorasanizadeh, S., and Lahti, P. M., *J. Org. Chem.*, **62**, 7189 (1997).
[230] Bush, L. C., Heath, R. B., Feng, X. W., Wang, P. A., Maksimovic, L., Song, A. I., Chung, W. S., Berinstain, A. B., Scaiano, J. C., and Berson, J. A., *J. Am. Chem. Soc.*, **119**, 1406 (1997).
[231] Ito, A., Miyajima, H., Yoshizawa, K., Tanaka, K., and Yamabe, T., *Synth. Met.*, **85**, 1777 (1997).
[232] Thoen, K. K. and Kenttamaa, H. I., *J. Am. Chem. Soc.*, **119**, 3832 (1997).
[233] Zhong, M. L., Chabinyc, M. L., and Brauman, J. I., *J. Am. Chem. Soc.*, **118**, 12432 (1996).
[234] Roth, W. R. and Bastigkeit, T., *Liebigs Ann.*, **1996**, 2171; [235] Roth, W. R., Unger, C., and Wasser, T., *Liebigs Ann.*, **1996**, 2155.
[236] Roth, W. R., Wasser, T., Gleiter, R., and Weigl, H., *Liebigs Ann./Recl.*, **1997**, 1329.
[237] Smart, R. P., Peelen, T. J., Blankespoor, R. L., and Ward, D. L., *J. Am. Chem. Soc.*, **119**, 461 (1997).
[238] Miyawaki, K., Suzuki, R., Kawano, T., and Ueda, I., *Tetrahedron Lett.*, **38**, 3943 (1997).
[239] Little, R. D., *Chem. Rev.*, **96**, 93 (1996).
[240] Lin, X. D. and Little, D., *Tetrahedron Lett.*, **38**, 15 (1997).
[241] Maier, G. and Senger, S., *J. Am. Chem. Soc.*, **119**, 5857 (1997).
[242] Ishiguro, K., Ozaki, M., Sekine, N., and Sawaki, Y., *J. Am. Chem. Soc.*, **119**, 3625 (1997).
[243] Sakurai, H., Kumai, R., Izuoka, A., and Sugawara, T., *Chem. Lett.*, **1996**, 879.
[244] Murphy, S. and Adam, W., *J. Am. Chem. Soc.*, **118**, 12916 (1996).
[245] Yordanov, N. D. and Stoilova-Lyanova, N. G., *Glas. Hem. Tehnol. Maked.*, **15**, 67 (1996).
[246] Roth, W. R., Wasser, T., and Boenke, M., *Liebigs Ann./Recl.*, **1997**, 1323.

[247] Asuncion, L. A. and Baldwin, J. E., *Croat. Chem. Acta*, **69**, 1421 (1996).
[248] Doubleday, C., Bolton, K., and Hase, W. L., *J. Am. Chem. Soc.*, **119**, 5251 (1997).
[249] Hrovat, D. A., Fang, S., Borden, W. T., and Carpenter, B. K., *J. Am. Chem. Soc.*, **119**, 5253 (1997).
[250] Laskin, A. and Lifshitz, A., in *Shock Waves, 20th International Symposium*, World Scientific, Singapore, **1995**, Vol. 2, p. 971.
[251] Bogdan, D., Aycard, J. P., Hnach, M., Volanschi, E., Hillebrand, M., Badescu, V., Dragoe, N., and Segal, E., *J. Thermal Anal.*, **46**, 1729 (1996).
[252] Davis, L. L. and Brower, K. R., *J. Phys. Chem.*, **100**, 18775 (1996).
[253] Liu, Z. X., Lu, J. J., Han, Z. H., Dai, Z. G., and Qin, Q. Z., *Gaodeng Xuexiao Huaxue Xuebao*, **17**, 1922 (1996).
[254] Lee, S.-Y. and Shin, Y.-J., *Hwahak Konghak*, **34**, 592 (1996).
[255] Skakovskii, E. D., Lamotkin, S. A., and Tychinskaya, L. Y., *J. Appl. Spectrosc.*, **64**, 319 (1997).
[256] Pecullan, M., Brezinsky, K., and Glassman, I., *J. Phys. Chem. A*, **101**, 3305 (1997).
[257] Stevenson, C. D., Rice, C. V., Garland, P. M., and Clark, B. K., *J. Org. Chem.*, **62**, 2193 (1997).
[258] Martin, G., Ascanio, J., and Rodriquez, J., *J. Phys. Org. Chem.*, **10**, 49 (1997).
[259] Korzun, N. V., Sizova, O. A., Tarasova, O. A., and Ravlyuk, E. E., *Zh. Fiz. Khim.*, **70**, 977 (1996).
[260] Xiao, Y. T., Longo, J. M., Hieshima, G. B., and Hill, R. J., *Ind. Eng. Chem. Res.*, **36**, 4033 (1997).
[261] Burcat, A. and Dvinyaninov, M., *Int. J. Chem. Kinet.*, **29**, 505 (1997).
[262] Banciu, M. D., Olteanu, E., Draghici, C., Petride, A., and Danila, M., *J. Anal. Appl. Pyrol.*, **37**, 151 (1996).
[263] Kiefer, J. H., Zhang, Q., Kern, R. D., Yao, J., and Jursic, B., *J. Phys. Chem. A*, **101**, 7061 (1997).
[264] Vrabel, I., Biskupic, S., and Stasko, A., *Theor. Chim. Acta*, **95**, 201 (1997).
[265] Jones, J., Bacskay, G. B., and Mackie, J. C., *Isr. J. Chem.*, **36**, 239 (1996).
[266] Gaber, A. E.-A., El Emary, T. I., and Atalla, A. A., *Heteroat. Chem.*, **8**, 287 (1997).
[267] Christensen, J. B. and Holm, A., *Acta Chem. Scand.*, **51**, 527 (1997).
[268] Schaad, L. J. and Skancke, P. N., *J. Phys. Chem. A*, **101**, 7408 (1997).
[269] Zhang, J., Zhu, C., Gong, X., and Xiao, H., *Wuli Huaxue Xuebao*, **13**, 612 (1997).
[270] Fan, J., Xiao, H., Y., L., and Hong, S., *Nanjing Ligong Daxue Xuebao*, **21**, 122 (1997).
[271] Zaslonko, I. S., Petrov, Y. P., and Smirnov, V. N., *Kinet. Catal.*, **38**, 321 (1997).
[272] Jollie, D. M. and Harrison, P. G., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1571.
[273] Skorobogatov, G. A., Dymov, B. P., and Nedozrelova, I. V., *Zh. Obshch. Khim.*, **66**, 1824 (1996).
[274] Skorobogatov, G. A., Dymov, B. P., and Nedozrelova, I. V., *Zh. Obshch. Khim.*, **66**, 1834 (1996).
[275] Kumaran, S. S., Su, M. C., and Michael, J. V., *Int. J. Chem. Kinet.*, **29**, 535 (1997).
[276] Dolenc, D. and Plesnicar, B., *J. Am. Chem. Soc.*, **119**, 2628 (1997).
[277] Kalvoda, J., Grob, J., Bjelakovic, M., Lorenc, L., and Mihailovic, M. L., *Helv. Chim. Acta*, **80**, 1221 (1997).
[278] Guo, Y. S. and Jenks, W. S., *J. Org. Chem.*, **62**, 857 (1997).
[279] Ono, I., Sato, S., Fukuda, K., and Inayoshi, T., *Bull. Chem. Soc. Jpn*, **70**, 2051 (1997).
[280] Kimura, T., Izumi, Y., Horn, E., and Furukawa, N., *Heteroat. Chem.*, **7**, 313 (1996).
[281] Hirata, Y., Niga, Y., Makita, S., and Okada, T., *J. Phys. Chem. A*, **101**, 561 (1997).
[282] Peukert, S., Batra, R., and Giese, B., *Tetrahedron Lett.*, **38**, 3507 (1997).
[283] Gugger, A., Batra, R., Rzadek, P., Rist, G., and Giese, B., *J. Am. Chem. Soc.*, **119**, 8740 (1997).
[284] Eberson, L., Persson, O., Radner, F., and Hartshorn, M. P., *Res. Chem. Intermed.*, **22**, 799 (1996).
[285] Lukach, A. E., Santiago, A. N., and Rossi, R. A., *J. Org. Chem.*, **62**, 4260 (1997).
[286] Santiago, A. N., Stahl, A. E., Rodriguez, G. L., and Rossi, R. A., *J. Org. Chem.*, **62**, 4406 (1997).
[287] Kim, Y. S., Kang, W. K., Kim, D. C., and Jung, K. H., *J. Phys. Chem. A*, **101**, 7576 (1997).
[288] Bagryansky, V. A., Borovkov, V. I., Molin, Y. N., Egorov, M. P., and Nefedov, O. M., *Mendeleev Commun.*, **1997**, 132.
[289] Cozens, F. L., Oneill, M., Bogdanova, R., and Schepp, N., *J. Am. Chem. Soc.*, **119**, 10652 (1997).
[290] Ferradini, C. and Jay-Gerin, J. P., *Radiat. Phys. Chem.*, **48**, 473 (1996).
[291] Adam, W., Walter, H., Chen, G.-F., and Williams, F., *J. Am. Chem. Soc.*, **114**, 3007 (1992).
[292] Adam, W., Sahin, C., Sendelbach, J., Walter, H., Chen, G.-F., and Williams, F., *J. Am. Chem. Soc.*, **116**, 2576 (1994).
[293] Adam, W., Hiedenfelder, T., and Sahin, C., *Synthesis*, **1995**, 1163.
[294] Adam, W., Kammel, T., Toubartz, M., and Steenken, S., *J. Am. Chem. Soc.*, **119**, 10673 (1997).
[295] Fliount, R., Makogon, O., Guldi, D. M., and Asmus, K. D., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1535.
[296] Hasegawa, A., Itagaki, Y., and Shiotani, M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1625.
[297] Shoute, L. C. T., *Radiat. Phys. Chem.*, **49**, 25 (1997).
[298] Huben, K., Zhu, Z. D., Bally, T., and Gebicki, J., *J. Am. Chem. Soc.*, **119**, 2825 (1997).

[299] Sharma, S. B., Mudaliar, M., Rao, B. S. M., Mohan, H., and Mittal, J. P., *J. Phys. Chem. A*, **101**, 8402 (1997).
[300] Belevskii, V. N. and Shchapin, I. Y., *Acta Chem. Scand.*, **51**, 1085 (1997).
[301] Shoute, L. C. T., *J. Phys. Chem. A*, **101**, 5535 (1997).
[302] Ioele, M., Steenken, S., and Baciocchi, E., *J. Phys. Chem. A*, **101**, 2979 (1997).
[303] Mishra, S. P. and Symons, M. C. R., *J. Phys. Chem. A*, **101**, 8242 (1997).
[304] Borisov, I. M., Zimin, Y. S., Garifullina, G. G., and Sharafutdinova, Z. F., *Izv. Vyssh. Uchebn. Zaved., Khim. Khim. Tekhnol.*, **39**, 61 (1996).
[305] Kitagawa, T., Miyabo, A., Fujii, H., Okazaki, T., Mori, T., Matsudou, M., Sugie, T., and Takeuchi, K., *J. Org. Chem.*, **62**, 888 (1997).

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CHAPTER 5

Oxidation and Reduction

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Oxidation by Metal Ions and Related Species

Chromium, Manganese, and Nickel

Chromyl chloride (CrO_2Cl_2) reacts with isopropylcyclopropane to generate the dimethylcyclopropylcarbinyl 'radical clock' by a mechanism probably involving initial hydrogen atom abstraction.[1] The resulting radical can be trapped by CrO_2Cl_2, to form 2-cyclopropyl-2-chloropropane or 2-cyclopropylpropan-2-ol, or ring open to give 4-methylpent-3-enyl radical which is trapped similarly. The only material observed from permanganate oxidation of this substrate is acetone, which is the product of vigorous oxidation of the ring-opened radical.

Different reactivities of some substituted oxan-4-ols on oxidation by pyridinium chlorochromate (PCC) are rationalized on the basis of their conformational features, including twist conformations.[2] A rate-determining carbon–carbon bond cleavage step in a glycol–PCC complex is proposed in the oxidation of butane-2,3-diol to acetaldehyde.[3] Steroidal 6β-hydroxy-4-en-3-one was isolated as an intermediate in the oxidation of steroidal 5-en-3β-ol with PCC.[4]

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The oxidation of diols by quinolinium dichromate (QDC) shows a first-order dependence on QDC and acid.[5] The oxidation of phenols to quinones by quinolinium dichromate in aqueous acetic acid is acid catalysed; rate-determining formation of a cationic intermediate is indicated by a ρ value of -3.79 and further analysis shows the rates to be influenced equally by both inductive and resonance effects of the substituents.[6]

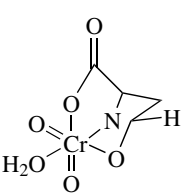
Oxidation of alkyl phenyl sulfides by pyridinium bromochromate (PBC) is accelerated by electron-donating alkyl groups or aryl substituents, indicating an electron-deficient sulfur centre in the transition state; this is accounted for in terms of rate-determining electrophilic oxygen attack from PBC to the sulfide in an S_N2-like process.[7]

The kinetics and mechanism of oxidation of benzyl alcohol by tetraethylammonium chlorochromate have been studied.[8]

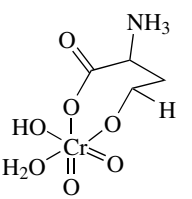
From the temperature dependence of the substantial kinetic isotope effect (KIE) observed in the oxidation of diols to hydroxycarbonyl compounds by 2,2′-bipyridinium chlorochromate (BPCC), it is proposed that hydride transfer occurs in a chromate ester intermediate, involving a six-electron Hückel-type transition state.[9] A similar conclusion is drawn for the oxidation of substituted benzyl alcohols by quinolinium chlorochromate.[10]

The kinetics of oxidation of allyl alcohol with quinolinium fluorochromate have been studied.[11] This reagent has also been used to oxidize benzyl alcohols; the activation enthalpies and entropies obtained for the substituted derivatives are linearly related, and a Hammett relationship ($\rho = -1.04 \pm 0.08$) is obeyed.[12]

The oxidation of homoserine by Cr(VI) has been compared with that of simple alcohols and 4-hydroxybutyric acid (HBA). The formation of CrO_2^{2+} during the oxidation was taken as evidence for the intermediacy of Cr(II). Whilst the rate law for homoserine has a first- and a second-order term, the rate laws for alcohols and HBA display only the second-order term. The second-order rate constants for HBA and homoserine are similar (suggesting that the amino group of homoserine does not participate in binding to the chromium in this pathway), and about 10 times lower than for the alcohols, accounted for in terms of carboxylate binding to Cr(VI) in the intermediate ester (**2**), lowering the rate. The additional first-order term seen only for homoserine must arise from involvement of the amino group and this additional pathway is proposed to proceed via a tricyclic intermediate (**1**).[13]



(**1**)



(**2**)

The pyridine-catalysed Cr(V) oxidation of organic sulfides to sulfoxides may be explained by Michaelis–Menten (MM) kinetics between intermediate Cr(V)–catalyst and Cr(V)–catalyst–substrate complexes.[14]

The orders of reaction in the oxidation of *N*,*N*-dimethylaniline by chromic acid are one and zero, respectively.[15] The reaction is catalysed by metal ions such as Cu^{2+} and Ag^{+}, but retarded by Mn^{2+}; a mechanism is proposed. In contrast, in the chromic acid oxidation of *o*-toluidine, the reaction is first order in both oxidant and substrate.[16]

Although (salen)manganese(III) complexes are widely studied, those with other metals are largely unexplored. The stereochemistry of Cr–salen-catalysed epoxidation of dimethylchromenes and styrenes was found to be highly solvent-dependent, with polar solvents giving the opposite sense of induction to non-polar.[17] This may be explained by competitive collapse of diastereomeric metalloxetanes either directly to epoxide or via a cationic intermediate.

The kinetics of surfactant-catalysed oxidation of alanine by permanganate ion have been studied.[18] An intermediate hypomanganate ester was observed in the oxidation mechanism of various cinnamic acid C=C bonds by permanganate ion.[19] Hammett plots revealed reaction constants between −1 and 0 at pH between 7 and 13. The kinetics and role of $HMnO_4$ in permanganate oxidations of alkylbenzenes have been investigated.[20] The permanganate oxidation of nucleobases is first order in MnO_4^- and fractional order in base.[21] X-ray diffraction analysis and X-ray photoelectron spectroscopy (XPS) studies of barium manganate have shown that $Mn(VI)O_4^{2-}$ is reduced to $Mn(IV)O_3^{2-}$ when it acts as an oxidant.[22] The oxidation of aldehydes by permanganate in organic solvents has been studied. Under acidic conditions, acid-catalysed nucleophilic attack of MnO_4^- occurs on the aldehyde or the hydrate form, the latter being more reactive, as indicated by the acceleration induced by addition of water. In alkaline media, electron abstraction from the alkoxy anion of the hydrate (with simultaneous H^+ elimination) is proposed to be the dominant process.[23] In the permanganate oxidation of a series of α-amino acids, $H(CH_2)_nCH(NH_2)CO_2H$ (n = 0–4) in a weak acid, a sawtooth variation in rate as a function of chain length is observed, the reasons for which are not clear.[24] Oxidative cleavage of 4-oxanones by acid permanganate has been studied.[25]

The Mn(II)-catalysed oxidation of glucose by peroxodisulfate ions occurs via a radical-chain mechanism.[26] Kinetics of oxidation of thiodiglycollic acid by (*trans*-cyclohexane-1,2-diamine-*N*, *N*, *N*′, *N*′-tetraacetato)manganate(III) have been investigated.[27] Oxidations of ketoses and aldoses by manganese(IV) in sulfuric acid media have a first-order dependence on sugar and fractional-order dependence on oxidant.[28] A mechanism has been proposed for the oxidation of L-malic acid by Mn(III) pyrophosphate in aqueous acid, involving complex formation and radicals.[29]

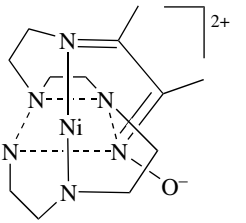
The use of Mn–salen catalysts for asymmetric epoxidation has been reviewed.[30] Oxo(salen)manganese(V) complexes, generated by the action of PhIO on the corresponding Mn(III) complexes, have been used to oxidize aryl methyl sulfides to sulfoxides.[31] The first example of C—H bond oxidation by a (μ-oxo)manganese complex has been reported.[32] The rate constants for the abstraction of $H^{\cdot}$ from dihydroanthracene correlate roughly with O—H bond strengths.

Manganese(III) Schiff base complexes, but not those of iron(III), activate dioxygen in the presence of aliphatic aldehydes.[33]

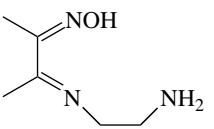
A kinetic study of the reaction of phenol and several substituted derivatives with oxomanganese(IV) tetra(2-*N*-methylpyridyl)porphyrin in aqueous solution reveals that the rate-determining step involves hydrogen atom abstraction from the phenol by the oxomanganese(IV) species, as found in the reactions of the analogous oxoiron(IV) porphyrin.[34] The manganese(III) complex of the same porphyrin has been used as a catalyst in the oxidation of 1,3-dimethylthymine with oxone.[35] Oxidation of the 5-methyl group to —CH_2OH, —CHO and —CO_2H is observed, and accounted for in terms of a hydrogen abstraction and recombination mechanism. Two additional products, *cis*-1,3-dimethylthymine-5,6-glycol and 1,3,5-trimethyl-5-hydroxybarbituric acid, may be formed either by electron transfer followed by oxygen atom transfer, or by the involvement of hydroxy radicals.

In the oxidation of substituted benzyl alcohols to aldehydes by the mild oxidant bis(2,2′-bipyridyl)copper(II) permanganate (BBCP), the formation of an intermediate complex between the alcohol and BBCP in a pre-equilibrium is followed by rate-determining decomposition to the products; this probably involves hydride transfer, based on the substantial kinetic isotope effect observed.[36] Michaelis–Menten-type kinetics were observed in the oxidation of organic sulfides by BBCP.[37] Negative polar reaction constants indicate an electron-deficient sulfur centre in the rate-determining step. Similarly MM kinetics were observed in the oxidation of diols by BBCP.[38] No primary KIE was observed for perdeuteroethane-1,2-diol. The oxidations of phosphinic, phenylphosphinic, and phosphorous acids by BBCP are catalysed by hydrogen ions.[39] Similarly, in the oxidation of glycolic, lactic, mandelic, and nine monosubstituted mandelic acids by BBCP, the rate is found to increase with $[H^+]$; a Hammett analysis was carried out and thermodynamic parameters for the formation and decomposition of hydroxy acid–BBCP complexes calculated.[40]

Nickel(III) complexes of oxime–imine ligands, such as (**3**), are oxidizing agents: the oxidation of formate and oxalate to CO_2 and of malonate to mesoxalic acid by this complex has been studied at different pH values. The higher reactivity of the carboxylic acids compared with their monoanions was attributed to the formation of a hydrogen-bonded adduct between the carboxylate hydrogen and the oximato oxygen atom (=N—O^-; the Ni(III) complex is a strong acid and is fully deprotonated under the conditions used here), providing a lower energy pathway for electron transfer from the reductant to the Ni(III) centre.[41] The oxidation of thiols to disulfides by the same complex, (**3**), has been investigated.[42]



(**3**)



(**4**)

The nickel(IV) complex of ligand (**4**) has been used to oxidize thiourea and alkyl derivatives to the respective disulfides, $NH_2C(S)NHR \rightarrow NH{=}C(NHR){-}S{-}S{-}C(NHR){=}NH$. Autocatalysis is observed around pH 4.5, whilst at pH ≥ 6, a faster Ni(IV)→Ni(III) reduction step is followed by slower Ni(III) → Ni(II) reduction. In the intervening pH region (ca 5.5), behaviour indicative of a single step two-electron-transfer reduction of the Ni(IV) is observed.[43]

Silver, Copper, and Thallium

Intramolecular electron transfer in a stepwise manner from the amine substrate to the silver(III) center in a 1 : 2 complex, $[Ag(OH)_4]^-$–*N*,*N*-dimethylaniline, has been observed.[44] The kinetics of oxidation of some aliphatic, heterocyclic, and aromatic aldehydes towards bis(dihydrogentellurato)cuprate(III) and argentate(III) in alkaline medium have been studied.[45] A negative salt effect was observed in the oxidation of aminoacetic acid by diperiodatocuprate(III) complex in alkaline medium.[46] The oxidation of glutamic acid by thallium(III) perchlorate is catalysed by Ru(III), Os(III), and Nd(III) in a free radical mechanism and the rate is inversely dependent on $[H^+]$ concentration.[47]

Cerium, Cobalt, Vanadium, Molybdenum, Rhenium, Bismuth, Palladium, and Iridium

Multinuclear NMR and ESR spectroscopy have been employed for the *in situ* detection and characterization of reactive intermediates in a variety of transition metal-catalysed oxidations.[48]

The cerium(IV) oxidation of lactyllactic acid[49] and of 4-oxopentanoic acid[50] in aqueous nitric acid solutions shows first-order dependence of the reaction on both cerium(IV) and substrate. A 1 : 1 complex formation between manganese(III) and amine, which later decomposes in the rate-limiting step, best explains the kinetics of oxidation of aliphatic amines by cerium(IV) in nitric acid medium in the presence of manganese(II).[51] The kinetics of oxidation of naphthalene, 2-methylnaphthalene, and α-naphthol with cerium(IV) in perchloric acid solutions have been studied.[52] Use of a 50-fold molar excess of cerium(IV) perchlorate results in complete oxidation of fluorophenols to CO_2, HCO_2H, and HF in 48 h at 50 °C.[53]

The kinetics of chromium(III)-catalysed oxidation of formic acid by Ce(IV) in aqueous H_2SO_4 can be rationalized in terms of initial formation of an outer-sphere complex involving oxidant, catalyst, and substrate (S), Ce(IV)(S)Cr(III), followed by an inner-sphere complex Ce(III)(S)Cr(IV). It is proposed that electron transfer occurs within this complex from substrate to Cr(IV) (with elimination of H^+) followed by fast reaction to give CO_2 (again with elimination of H^+).[54] In contrast, there was no kinetic evidence for the accumulation of a corresponding inner-sphere intermediate in the osmium(VIII)-catalysed Ce(IV) oxidation of DMSO to dimethyl sulfone: here, the observed rate law was rationalized in terms of rate-determining bimolecular electron transfer from DMSO to Os(VIII) in an outer-sphere step.[55] The kinetics of oxidation of 2-hydroxy-1-naphthalidene anil by cerium(IV) in aqueous sulfuric acid have been

studied.[56] Polymerization of acrylonitrile was used as evidence for the formation of a radical intermediate during the oxidation of 2-methylpropan-1-ol by cerium(IV) in sulfuric acid.[57]

The kinetics and product distribution of oxidation of methylmalonic acid by Ce(IV) have been studied by ^{1}H NMR spectroscopy. In the presence of at least six equivalents of Ce(IV), acetic acid is the only product whilst lower relative amounts of cerium led to hydroxymethylmalonic acid and pyruvic acid as end products, also shown to be intermediates in the formation of acetic acid.[58]

Steady-state hydroxocobaloxime(III) precursor forms a superoxocobaloxime(III) intermediate, which acts as the active oxidant in the cobaloxime(II)-catalysed oxidation of tetra-*t*-butyl-4,4′-dihydroxystilbene by atmospheric oxygen.[59] The catalytic oxygenation of alkenes and alkanes by oxygen donors catalysed by cobalt-substituted polyoxotungstate has been investigated.[60] The formation of bromocyclohexane in cyclohexane hydroxylation upon addition of CH_2Br_2 suggests the participation of cyclohexyl radical. The activation of dioxygen to form cobalt(III) superoxo complexes was shown by EPR to be enhanced by aliphatic ketones and aldehydes acting as ligands.[61] It is suggested that intramolecular H· transfer from carbonyl compound and subsequent oxygen transfer to carbonyl leads to a cobalt(IV) Co=O oxo species akin to the Fe=O formed as an intermediate in cytochrome P450 enzymes. This species is able to oxidize a wide range of substrates with a different spectrum of activity to oxidation by cobalt(salens). It is also suggested that the formation of the initial cobalt(III)–superoxo complex is aided by hydrogen bonding to the hydroxymethyl group of equatorial ligands on the cobalt complex used in these reactions.

Asymmetric epoxidation, dihydroxylation, aminohydroxylation, and aziridination reactions have been reviewed.[62] The use of the Sharpless asymmetric epoxidation method for the desymmetrization of *meso* compounds has been reviewed.[63] The conformational flexibility of nine-membered ring allylic alcohols results in *trans*-epoxide stereochemistry from *syn* epoxidation using $VO(acac)_2$–hydroperoxide systems in which the hydroxyl group still controls the facial stereoselectivity.[64] The stereoselectivity of side-chain epoxidation of a series of 22-hydroxy-Δ^{23}-sterols with C(19) side-chains incorporating allylic alcohols has been investigated, using *m*-CPBA or *t*-BuOOH in the presence of $VO(acac)_2$ or $Mo(CO)_6$.[65] The *erythro–threo* distributions of the products were determined and the effect of substituents on the three positions of the double bond (*gem* to the OH or *cis* or *trans* at the remote carbon) partially rationalized by molecular modelling.

Dependence of the rate on pH in the epoxidation of allyl chloride by sodium orthovanadate-catalysed hydrogen peroxide is indicative of the active species being H_3VO_5.[66] The kinetics of oxidation of valine by vanadium(V) has been studied in sulfuric acid.[67] In an unusual mechanism, the hydrated polyoxometalate $H_5PV_2Mo_{10}O_{40}$ oxidizes substrate thioethers. Since *t*-BuOOH oxidant only reoxidizes the reduced form of the polyoxometallate this leads to a highly selective oxidation to sulfoxide.[68] The oxidation of benzalmethyl phenyl sulfides (PhCH=CHSPh) and *para*-substituted derivatives by vanadium(V) has been investigated.[69] Vanadium-catalysed oxidation of alkenes with hydrogen peroxide in acetic acid results in the formation of the corresponding aldehydes.[70]

Molybdenum oxidoreductase enzymes are well known, but tungsten analogues less so, although they have been found in some hyperthermophilic organisms which grow at high temperatures. A model study of their activity was made using the complexes $(NEt)_4M(VI)O_2(S_2C_6H_4)_2$ (M = Mo or W, $S_2C_6H_4$ = 1, 2-benzenedithiolate) and benzoin as the substrate (oxidized cleanly to benzil).[71] The mechanisms involve rate-limiting α-H abstraction. Although the W complex reacts more slowly than the Mo complex, the difference in rate is much smaller at 100 °C than 30 °C, and the product yield is higher for the W system. This might explain the adoption of W by thermophilic organisms.

The oxidation chemistry of methylrhenium trioxide (MTO) has been reviewed.[72] The oxidation of thiophenes by hydrogen peroxide has also been studied, using MTO as a catalyst.[73] The latter reacts with H_2O_2 to generate 1 : 1 and 1 : 2 rhenium peroxides, which are able to transfer an oxygen atom to the sulfur of the substrate, to give first the sulfoxide and then the sulfone. Whilst electron-donating substituents accelerate the first oxidation, the reverse trend is observed for oxidation of the sulfoxide.

The use of much-neglected bismuth derivatives for the oxidation of organic compounds has been reviewed.[74] Bismuth(III) carboxylates, obtained by reaction of Bi_2O_3 with pyridine mono- and di-carboxylic acids and with phthalic acid, act as catalysts for the oxidation of styrene oxide to benzoic acid in DMSO in the presence of O_2.[75] It is proposed that the bismuth may activate both epoxide and oxidant in a solvate, from which dimethyl sulfide evolution and elimination leads to a ketoalkoxide–bismuth complex (and hence to the initial product, 2-hydroxyacetophenone). Further oxidation to the ketoaldehyde and acid requires molecular oxygen, but is also found to be catalysed by bismuth.

The stereochemistry of the Wacker reaction, oxidation of terminal or methyl-substituted alkenes to aldehydes and methyl ketones using stoichiometric Pd(II) at low chloride concentration, has been probed using concepts of chirality transfer.[76] The use of chiral allyl alcohols invoked the intermediacy of π-complexes in which the bulky substituent at the chiral centre is furthest away from a *cis* substituent on the other side of the C=C bond ($A^{1,3}$ strain). Upon hydroxypalladation *R* stereochemistry was transferred but at high chloride concentration isomerization resulted in an inversion of configuration in the products, implying opposite stereochemistry. Assuming that the same π-complex is involved at both high and low chloride concentrations, it was deduced that the Wacker hydroxypalladation occurs via a *syn*-type intramolecular mechanism. The kinetics of oxidation of benzyl alcohol with a palladium(II) aqua complex in perchloric acid have been studied.[77] The kinetics of palladium(II)-catalysed oxidation of digol and ethyldigol by *N*-bromosuccinimide (NBS) have been investigated.[78] The mechanism of Pd(II)-catalysed oxidation of penta-1,3-diene by hydrogen peroxide has been studied.[79]

The oxidation of trimethylene glycol and dimethyldiethylene glycol by NBS is catalysed by iridium(III) in acidic media.[80] The kinetics have been investigated in the presence of mercury(II) acetate as a bromide ion scavenger, and $[IrCl_5(H_2O)]^{2-}$ is thought to be the reactive iridium species under the conditions employed.

Group VIII Metals

The use of a catecholato iron(III) complex to catalyse the hydroxylation of 4-*t*-butylphenol to 4-*t*-butylcatechol by molecular O_2, in the presence of a hydroquinone as the proton and electron donor, has been investigated.[81] Both Fe(II) and Fe(III) species have been found to be important for effective oxidation [e.g. trapping of Fe(II) as its phenanthroline complex inhibits reaction, but use of $FeCl_2$ did not give the high yields observed with $FeCl_3$]. Electron-withdrawing groups on the catechol lead to higher yields, possibly owing to their making the metal centre a better Lewis acid towards the phenolic substrate. An iron–oxygen active intermediate is proposed, possibly relevant to the mechanism of action of tyrosine hydroxylase, where oxidation by a non-iron peroxytetrahydropterin has been put forward.

The kinetics of the potassium hexacyanoferrate(III)-catalysed oxidation of glucose with ammonium peroxodisulfate have been studied.[82] The kinetics and mechanism of oxidation of some cycloalkanols by alkaline $Fe(CN)_6^{3-}$ have been reported.[83] The same group has also studied the oxidation of cycloalkanones under comparable conditions and determined the order of reactivity as cyclohexanone > cyclopentanone > cyclo-octanone > cycloheptanone.[84] Palladium(II) has been found to catalyse the oxidation of formaldehyde, thiourea, and thioacetamide by alkaline $Fe(CN)_6^{3-}$, whereas no effect is observed in the oxidation of acetaldehyde.[85] The orders of reaction have been determined and a mechanism was proposed.

From the kinetics of oxidation of diols by $Fe(CN)_6^{3-}$ in aqueous alkali catalysed by $RuCl_3$, it is concluded that oxidation proceeds not by hydride ion transfer from alcohol to Ru(III) but via hydrogen *atom* transfer, to generate Ru(II) species and an intermediate radical which is further oxidized by more Ru(III).[86] Similar conclusions were made from a related study of the oxidation of propan-1-ol under comparable conditions.[87]

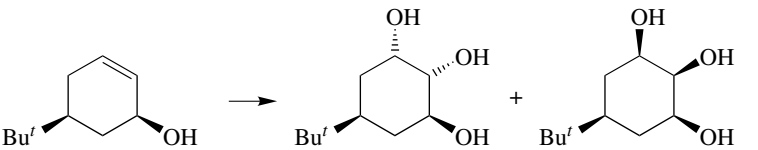
In the stoichiometric oxidation of secondary alcohols to ketones by tetraoxoferrate(VI), the second-order rate constant depends on pH. Rate acceleration at high $[HO^-]$ is attributed to formation of $HOFeO_4^{3-}$, proposed to be more susceptible to attack by nucleophiles (alcohols, R_2CHOH) than FeO_4^{2-} itself, to generate a ferrate ester, $HOFe(O^-)_4$–$OCHR_2$. A second effect accounting for the steep dependence on $[HO^-]$ is attributed to ionization of alcohols to generate the more readily oxidized alkoxide ions.[88]

The kinetics of oxidation of aldehydes by the Fenton reagent [Fe(II)–H_2O_2–OH^-] have been studied.[89] It has been suggested that different reactivities of PhIO in iron(III)–porphyrin-catalysed alkene epoxidation may be due to the formation of a more reactive iron(IV)–O–IPh complex.[90] The iron(III) complex of tetrakis(3,5-disulfonatomesityl)porphyrin catalyses the oxidative degradation of 2,4,6-trichlorophenol to 2,6-dichloro-1,4-benzoquinone with $KHSO_5$ as the oxygen atom donor; a peroxidase-type oxidation is thought to be involved.[91]

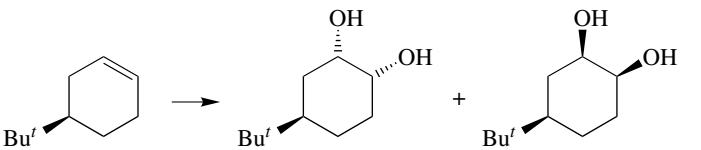
Ru(II) halosulfoxide complexes catalyse the oxidation of secondary alcohols by *N*-methylmorpholine-*N*-oxide (NMO) via a proposed Ru(IV)oxo species.[92] Ruthenium (VI) catalyses the oxidation of diethylene glycol by alkaline solution of potassium bromate.[93] Acid bromate oxidation of butylethylene glycol is catalysed by ruthenium(III).[94] Ruthenium(III) catalyses DMF oxidation by periodate in alkaline

solution.[95] The ruthenium complex $[Ru(azpy)_2(H_2O)_2]^{2+}$ has been used as a catalyst in the oxidation of several sugars by sodium bromate. The activity and selectivity of the reaction are strongly dependent on the structure of the sugar substrate.[96]

The dihydroxylation of cyclohexenols by OsO_4 alone is known to proceed with high *anti* diastereofacial selectivity. In order to determine the origin of this stereoselectivity, the oxidation of conformationally locked cyclohexenols, namely the *cis* and *trans* isomers of 5-*t*-butylcyclohex-2-enol, has been examined.[97] For catalytic OsO_4 oxidation in aqueous acetone using NMO, the *anti-syn* isomer was obtained in high diastereoselectivity, as for cyclohex-2-enol (Scheme 1). This has been attributed to the steric effect of the OH group differentiating the faces of the adjacent alkene and possible electrostatic repulsion between OH and the oxidant, favouring *anti* attack. The use of a non-hydrogen-bonding solvent (CH_2Cl_2) to encourage H-bonding between the OH and OsO_4, with the aim of reversing the *anti* selectivity, led to moderate selectivity for *syn* oxidation under catalytic conditions. That this is indeed due to intermolecular H-bonding was confirmed by the lack of such an effect when the OH group was methylated.



Condition (i) (91%)	85	:	15
Condition (ii) (50%)	45	:	55



Condition (i) (91%)	57	:	43
Condition (ii) (86%)	54	:	46

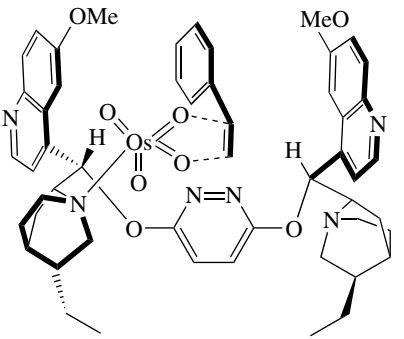
Reagents: (i) catalytic OsO_4, NMO, acetone, H_2O
(ii) OsO_4 (1 mol%), $Me_3NO{\cdot}2H_2O$ (1.3 equiv.), CH_2Cl_2

SCHEME 1

In the dihydroxylation of cyclohexene by Me_3N^+—O^-, catalysed by OsO_4, aromatic amines and aliphatic chelating (TMEDA) or bridging (DABCO, hexamine) amines were found to retard the oxidation, owing to the formation of amine adducts of the dioxomonoglycolatoosmium(VI) ester intermediates, which are more resistant to the further oxidation required for product formation.[98] Alkenes derived from Garner's aldehyde, *N*-Boc-*N*,*O*-acetonide of the aldehyde of L-serine, may be dihydroxylated by OsO_4 with excellent selectivities that may be explained by $A^{1,3}$ strain.[99]

Definitive evidence for the mechanism of Sharpless' asymmetric dihydroxylation (AD) system is still a matter for discussion. The agreement[100] of Becke3LYP[101] DFT calculations with experimental high-precision NMR-based kinetic isotope effect methods[102] has provided strong evidence to support a $3 + 2$ mechanism. H–D and $^{13/12}C$ KIEs for *t*-butylethene, chosen to avoid complications from regioisomeric $2 + 2$ transition states, using the $(DHQD)_2$–PYR–OsO_4 system agreed well with calculations on $OsO_4 \cdot NH_3$ and ethene or propene. The results predict a 3.1–3.4 kcal mol^{-1} activation energy for the $3 + 2$ mechanism as opposed to the prohibitively high 41–44 kcal mol^{-1} for the $2 + 2$ mechanism and 29–31 kcal mol^{-1} for four-ring to five-ring expansion. It should be noted, however, that a one-step $3 + 2$ cycloaddition does not explain previously observed electronic and temperature effects that supported a complex overall mechanism. These calculations are in very close agreement with earlier calculations made on the same system using both LANL2DZ and 631G* basis sets that explored systems with and without amine base ligands.[103] The conclusion was also that the $2 + 2$ pathway is prohibitively high in energy.

Corey and Noe published an extensive manifesto in support of the CCN (Criegee–Corey–Noe) $3 + 2$ model (**5**).[104] They argue convincingly that all of the evidence previously cited as being inconsistent with CCN *can* be explained using CCN. This includes non-linear Eyring temperature effects on enantioselectivity that could simply be a function of the Michaelis–Menten-like kinetics. Working on the assumption of an early transition state, much of the discussion is based on the relative geometries of the U-shaped for CCN and L-shaped for $2 + 2$ binding pockets that would be required. In support of CCN, enantioselectivities correlate better with varying alkene substrate structures fitting into a U-shaped pocket. Also in support of CCN is that *ee*s are affected



(**5**)

little by varying the spacer from, e.g., phthlazine to pyridazine, yet the 2 + 2 model requires significant interaction of this spacer with substrate. Similarly, variation of the quinoline rings does affect *ee* and this would be expected to be influential in the CCN model, although influence on the 2 + 2 L-pocket would also be expected to some lesser extent. Additional heuristic arguments are also invoked: the CCN model has proved useful in the design of novel systems for, e.g., terminal hydroxylation of higher terpenes.

Sharpless and co-workers have studied the effect of the variation of amine ligands on the dihydroxylation process and concluded that it involves a complex mixture of at least two reaction manifolds.[105] The equilibrium constant of ligand binding and the corresponding reduction potential of the amine–OsO_4 complex increase with ligand basicity induced by electron-donating substituents. However, Hammett linear free energy relationships do not apply and only slight rate variation was observed. Moreover, substituent effects on quinuclidine bases were slight. Relationships for substrate substituent effects were parabolic and this is attributed to a combination of a 3 + 2 pathway for the positive ρ value region (termed 'nucleophilic') of plots and a 2 + 2 pathway for the negative ρ value region ('electrophilic'). Thus, at high ligand concentrations with strong binding ligands the L–OsO_4 complex is nucleophilic and rates increase with electron withdrawal in the substrate. In contrast, with poorly binding ligands at low concentrations, electron-donating substituents in the alkene increase the concentration of the 16-electron osmaoxetane formed in the 2 + 2 pathway. Sharpless and co-workers conclude that the former case dominates with pyridine-type ligands but that a 2 + 2 pathway seems most likely for the low concentrations of quinuclidine used in AD systems. They also suggested that Corey and Noe's arguments based on the shape of the supposed binding pocket rely on inadequate evidence. A clear reduction in enantioselectivity and rate is observed as the substituent on styrene substrates becomes more electron withdrawing, something attributed to decreased interaction with the binding pocket of the ligand. They also dismissed the observed Michaelis–Menten kinetics as being due to a step other than osmylation and cited unpublished evidence that the kinetics are, in fact, first order with respect to substrate in the organic phase of the system. Finally, they acknowledged that observed changes in the curvature of the Hammett plots with ligand concentration imply that both pathways operate together although even this does not adequately explain all observed aspects of the system's properties and contrasts with the ligand-free system in which linear free energy relationships are clearly observed.

Reverse Sharpless selectivity for terminal over internal dihydroxylation of non-conjugated dienes can be performed using AD-mix reagent α or β provided the internal alkene is sufficiently sterically hindered, and this may be attributed to the larger size of the reagents as compared with NMO–OsO_4 systems, which show lower selectivities.[106] It should be borne in mind, however, that the interaction with key ligand faces may also have a critical and more subtle influence on regioselectivity[107] and simple steric arguments will clearly only stretch so far.

Os(VIII)-catalysed oxidation of allyl alcohols by NBS in alkaline solution was found to be of first order in NBS and in $^{\bullet}$Os(VIII) and of fractional order in allyl alcohol and in alkali.[108]

Oxidation by Compounds of Non-metallic Elements

Nitrogen, Selenium, and Sulfur

Chiral Davis oxaziridines allow the oxidation of phosphonates to α-hydroxyphosphonates in good *ee* with apparently wide generality and with a sense of induction that is well controlled by the chirality of the reagent used.[109] *m*CPBA oxidation of a bicyclic *endo*-camphorylsulfonylimine surprisingly resulted in an *exo*-camphorylsulfonyloxaziridine, whereas all other camphorylsulfonylimines resulted only in *endo*-oxaziridines.[110] Asymmetric oxidation of sulfides to sulfoxides and the α-hydroxylation of enolates were predicted by models in which steric interactions are minimized.

The oxidation of primary and secondary alcohols by stable organic nitroxyl radicals has been reviewed.[111] The kinetics of reactions of alkanes and arenes with peroxynitrous acid suggest the participation of the same active oxidizing species in both gas and aqueous phase: HOONO or its decomposition product $OONO^{\cdot}$.[112] The oxidation of the alkaloids reserpine and rescinnamine by nitric acid has been studied.[113]

The sodium salt of *N*-chloro-4-chlorobenzenesulfonamide (the *p*-chloro analogue of chloramine-T), upon addition of a 0.01–0.03 molar amount of dimethyl-2,2′-diselenodibenzoate, oxidizes secondary and β, γ-unsaturated primary alcohols to the corresponding carbonyl compounds in good yield.[114] Reaction does not proceed in the absence of the Se reagent. The compound $ArSeNHSO_2C_6H_4Cl$ was isolated under conditions of large excess of alcohol relative to oxidant and is thought to be a catalytic species in the cycle proposed. This is an unusual case of a compound of a main group element (Se) acting as a redox catalytic centre.

Swern oxidation of β-amino alcohols has been shown to be a useful alternative to metal-based oxidants, which may be chelated by the substrate.[115] *N*-Methylpyrrolidine, *N*-ethylpiperidine, or triethylamine proved optimal as bases. The reaction, although successful for β-secondary amino alcohols, gave products that readily polymerized.

The peroxomonosulfate ion HSO_5^- (as Oxone) has been used in the oxidation of phosphorus esters of thiols to generate phosphorus(V) and sulfinic acids: $Ph_2P(O)—S—C_6H_4R \rightarrow PhPO_2H + SO_3C_6H_4R$. A kinetic study using a range of substituents (R) confirms earlier suggestions that the first step in such reactions is oxidation at sulfur, followed by attack of water and P—S bond cleavage.[116] The use of HSO_5^- in the oxidation of a series of alkyl-substituted 2,6-diphenyl-4-piperidones has been described; a radical mechanism is excluded and a constrained epoxide transition state proposed.[117] The oxidation of benzene by peroxodisulfate is not an important sink for benzene in the troposphere due to the higher concentrations of $OH^{\bullet}$ radicals present.[118]

Like many fluoroxy compounds, in caesium fluoroxysulfate-mediated oxidations competition between fluorination and oxidation is often observed.[119] Cyclic and acyclic secondary alcohols gave ketones without any fluorination or oxidation although phenyl-1-naphthylmethanol gave 1-fluoronaphthalene. Primary alcohols gave acid fluorides derived from fluorination of aldehydes. Benzyl groups geminal to the hydroxyl group resulted in the formation of benzyl fluoride. Radical inhibitors retarded the rate. Hammett correlation for the oxidation of 1-phenyl-1-ethanols to acetophenones gave $\rho^+ = -0.32$. A mechanism involving initial rate-determining SET to give an alkoxy radical cation is proposed.

Halogens

The $HOF{\cdot}CH_3CN$ complex readily oxidizes sulfides to sulfones.[120] The electrophilic nature was confirmed by an X_{SO} value (see Peroxides and Peracids for a discussion of X_{SO}) of 0.45. Examples include electron-deficient sulfides that cannot be oxidized to sulfone by any other method.

The involvement of $ArSO_2NCl_2$ during the oxidation of benzhydrol (PhCHOHPh) by chloramine-T (CAT) in the presence of $RuCl_3$ is ruled out, owing to the first-order dependence of the rate on [CAT].[121] The oxidizing species here is likely to be H_2OCl^+, formed in two fast equilibria which are catalysed by H^+ and retarded by added *p*-toluenesulfonamide. Similar conclusions were drawn from an analogous study employing chloramine-B.[122] Chloramine-T oxidation of D-glucuronic acid and D-galacturonic acid involves the formation of an enediol anion followed by its oxidation in a rate-determining step.[123] The oxidation of aliphatic acetals with *N*-chlorobenzamide (NCB) follows first- and zero-order dependence in [NCB] and [acetal], respectively.[124]

The kinetics of oxidation of selected α-amino acids[125] and aliphatic aldehydes[126] by trichloroisocyanuric acid (TCICA) in aqueous acetic acid–perchloric acid is first order in both TCICA and substrate. The kinetics of Ru(III)-catalysed oxidation of aliphatic alcohols by TCICA in aqueous $HOAc–HClO_4$ are zero order in [TCICA], fractional order in alcohol and first order in Ru(III).[127]

A radical chain oxidation mechanism, involving the formation and decomposition of an intermediate hydroperoxide, is consistent with the observed kinetics in the oxidation of cumene and acenaphthene by oxygen in the presence of alkylammonium perchlorates.[128]

Belousov–Zhabotinsky (B–Z) oscillations in a 1,2-dimethoxybenzene–BrO_3^-–manganese(II)–H_2SO_4 system have been studied.[129] A system of fructose–BrO_3^-–Ce^{4+}–H_2SO_4 also gives rise to B–Z oscillations in the range 0.035–0.7 M fructose, which are promoted by tartaric acid.[130] Potassium bromate has been used to oxidize the Schiff base 2-hydroxy-1-naphthalidene anil in aqueous acetic acid, and a kinetic study made.[131] The kinetics of oxidation of formamide and dimethylformamide by $HBrO_3$ have been reported.[132]

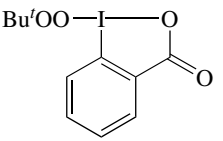
The oxidation of α-hydroxy acids by benzyltrimethylammonium tribromide (BTMAB) to the corresponding carbonyl compounds shows a substantial solvent isotope effect, $k(H_2O)/k(D_2O) = 3.57$, but no KIE for α-deuteromandelic acid.[133] The oxidation of glucose by hypobromous acid is first order in glucose and the acid.[134] [1,1-$^2H_2$]Ethanol shows a substantial kinetic isotope effect when oxidized by hexamethylenetetramine–bromine (HABR) in acetic acid to aldehyde.[135] Kinetics of the oxidation of aliphatic aldehydes by hexamethylenetetramine–bromine have been studied by the same group.[136] Dioxoane dibromide oxidizes γ-tocopherol to 5-bromomethyl-γ-tocopherylquinone, which spontaneously cyclizes to 5-formyl-γ-tocopherol.[137]

The kinetics of oxidation of caffeine by sodium *N*-bromo-*p*-toluenesulfonamide (bromamine-T) in dilute HCl have been studied.[138] In the oxidation of α-phenylbenzenemethanols by bromamine-T catalysed by ruthenium(III), the reaction constant ρ is -2.1 for electron-releasing substituents.[139] It is proposed that the

oxidation of indigo carmine by bromamine-T at pH 5 proceeds via initial formation of dibromamine-T ($ArSO_2NBr_2$) in two fast equilibria, followed by its attack on the substrate in a rate-determining step.[140] The oxidation of primary amines with bromamine-B (BAB) in the presence of OsO_4 under alkaline conditions leads to the corresponding aldehydes. A kinetic study reveals that $PhSO_2NBr^-$ is the likely reactive species, which forms a complex intermediate with OsO_4 in a rate-determining step, accounting for the lack of dependence on amine concentration.[141] The kinetics of the oxidation of cyclopentanone and cyclohexanone by BAB in perchloric acid are first order in ketone.[142] A kinetic study of the oxidation of six aryl-substituted phenethyl alcohols by BAB has been made, including a Hammett analysis.[143] The kinetics of oxidation of acetophenone and substituted acetophenones by *N*-bromophthalimide (NBP) in aqueous acetic acid are first order in substrate.[144]

Oxidation of arylmethyl ketoximes by phenyliodoso diacetate in glacial acetic acid was second order overall, first order each in substrate and oxidant.[145] Iodine allowed the oxidative dimerization of glycine ester enolates with low to moderate diastereoselectivity that is consistent with kinetic control.[146] Although malonic acid is not oxidized by iodate under acidic conditions, oxidation proceeds in the presence of catalytic ruthenium(III). A mechanism is put forward to account for the observed orders of reaction.[147] The rate of periodate oxidation of *m*-toluidine in acetone–water increases with ionic strength.[148]

Further to its ability to perform allylic and benzylic oxidations,[149] *t*-butylperoxyiodane (**6**) effects radical oxidation of 4-alkylphenols to give 2,5-cyclohexadien-1-ones under mild conditions in good yields.[150] *o*,*o*-Coupling dimers as side products and inhibition of the reaction by added galvinoxyl radical scavenger support a radical oxidation mechanism.



(**6**)

Negative reaction constants ρ^+ for the oxidation of sulfides by [10-I-3]–(*t*-butylperoxy)iodanes are consistent with a mechanism involving rate-limiting formation of a sulfonium species by nucleophilic attack of sulfide on the iodine(III) atom followed by attack of water to give sulfoxide.[151] However, in dichloromethane, inhibition by galvinoxyl implicates a free radical mechanism perhaps by homolytic cleavage of the weak iodine(III)–peroxy bond.

The kinetics of oxidation of Dess–Martin periodinane (DMP) and its iodoxybenzoic acid (IBX) precursor have been compared to explain their often different selectivities.[152] A fast pre-equilibrium produces transient iodic esters, whose axial alkoxy structure for IBX was determined by ^1H NMR spectroscopy, which then disproportionate in a rate-limiting manner to product. As a result, steric effects in alcohol oxidation reflect a balance between opposing effects on equilibrium constants and rate constants for disproportionation. With 1,2-diols DMP gives spirobicyclic

periodinane adducts whereas IBX binds only reversibly; as a result, IBX forms an oxide that oxidizes to α-hydroxy ketones whereas DMP gives rise to C—C bond cleavage.

Ozonolysis and Ozonation

One study suggests that there are no compelling experimental data in support of HO• formation in the ozonolysis of alkenes.[153] Nevertheless, other studies have been directed towards quantifying HO• formation during ozonolysis and the use of CO as a scavenger of HO• has been reported for this purpose.[154] The resulting formation of CO_2 is monitored by FTIR spectroscopy and the HO• yields are found to be highly dependent on the alkene, with ethene displaying the lowest value.

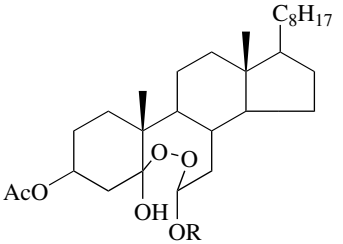
In accord with previous limited observations, a thorough investigation of ozonations of ammonia, amines, anilines, and *p*-phenylenediamines has shown that reaction occurs via a SET process.[155] Furthermore, and more controversially, the correlation of rate constants for ozonations of various alkenes and arenes with ionization potentials led the authors to suggest that these substrates also react via a rate-limiting electron-transfer mechanism prior to primary ozonide formation. In the light of these results, it is interesting that the transition state for the overall reaction of ozone with cycloalkenes is likely to be closer in structure to the biradical intermediate, rather than to the initial ozonide intermediate; the apparent contradiction with earlier results is attributed to the fact that the latter have dealt with more complex systems, where steric effects rather than changes in ring strain probably determine the reactivity.[156]

Ab initio calculations suggest that in ozonolysis, as the two fragments formed by dissociation of the primary ozonide start to move apart, a strong electrostatic attraction builds up between newly formed dipoles.[157] The torque created causes a 'flip' of one relative to the other, with formation of a dipolar complex which converts to the secondary ozonide. Thus, the authors suggest that the carbonyl oxide and carbonyl are never actually separated to a van der Waals distance. This argument goes some way to explaining some observed experimental stereoselectivities.

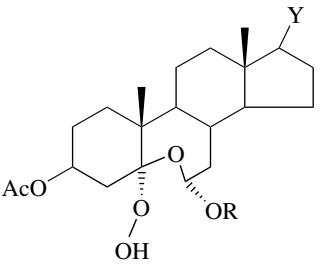
Carbonyl oxides formed in the gas-phase ozonolysis of alkylated alkenes give rise to a much larger amount of OH• radicals when there is a *syn*-positioned alkyl group.[158] This can be attributed to O—O bond cleavage being more favourable in these circumstances than decomposition to dioxirane. Isoprene, a minor atmospheric component, gives a 19% yield of OH• from ozone. The formation of α-oxo carbonyl oxides by ozonolyses of alkynes was confirmed by 3 + 2-cycloaddition trapping with carbonyl compounds and reaction of the resulting α-oxo ozonides to form corresponding *O*-methyl oximes.[159] Indeed, α-oxo carbonyl oxides were found to trap ketones readily, which carbonyl oxides from alkene ozonolysis do not.

Whilst ozonolysis of cholesterol and related steroids in non-hydroxylic solvents is known to give the expected ozonides (which may be reduced to the 5,6-diols), the product of reaction in water or alcohols has previously been assigned as the hydroxyperoxide (**7**). Conclusive crystallographic evidence is presented showing that the products formed under these conditions are in fact hydroperoxides of the form (**8**),

reinforcing spectroscopic evidence such as the presence of a low-field ^{1}H NMR signal, assigned to the OOH group.[160]



(**7**)



(**8**)

a; R = Pr^i, Y = C_8H_{17} **b**; R = Me, Y = H

The oxidation of 1,3,5-trifluorobenzene and trifluoromethylbenzene by ozone in acidic aqueous solution, and by OH$^\bullet$ radicals generated from the action of ozone on hydrogen peroxide, has been studied.[161] No hydroxylated aromatic compounds could be detected amongst the products of reaction of O_3 with 1,3,5-trifluorobenzene, presumably owing to rapid ring opening following 1,3-dipolar cycloaddition on the highly reactive intermediates initially formed. In contrast, a number of hydroxylated fluoroaromatics were obtained from the action of HO$^\bullet$ radicals, thought to arise via the intermediacy of fluorohydroxycyclohexadienyl radicals. For trifluoromethylbenzene, the products are mainly hydroxylated trifluoromethylbenzenes.

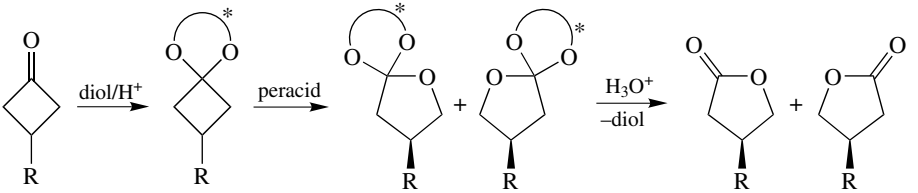
The kinetics and product distributions of ozonolysis of vinylcyclohexane and methylene cyclohexane have been investigated.[162] Steric hindrance of the cyclic substituent largely offsets electronic effects in determining the rate of reaction. The main products of ozonation of catechols were quinones, while catechol acetals gave rise to compounds with an opened benzene ring.[163] The ozonolysis of azoles such as pyrroles, oxazoles, and imidazoles has been reviewed.[164]

Peracids and Peroxides

Oxygen-transfer agents for the oxidation of organic substrates by H_2O_2 have been reviewed and categorized according to whether they are used in stoichiometric amounts (carboxylic acids, nitriles, and amides) or in catalytic amounts [e.g. transition metal compounds, metal-containing zeolites, poly(amino acid)s and enzymes].[165] When carried out in the presence of poly(amino acid)s, the epoxidation of α,β-unsaturated ketones by H_2O_2 occurs with high stereoselectivity for some substrates, but such reactions normally require triphasic systems (alkaline H_2O_2, an organic solvent, and an insoluble polymer) and the reaction times are often very long (several days), during which time the base may degrade the poly(amino acid). These problems have been circumvented using a two-phase non-aqueous system of oxidant (complex of H_2O_2 with urea or DABCO) and a non-nucleophilic base (DBU or DBN) in an organic solvent (THF and other polar aprotic solvents) with the immobilized poly(amino-acid).[166] Many substrates are transformed much more quickly (typically 50 min) with high selectivity, and substrates such as styryl methyl ketone which are unreactive under

triphasic conditions are oxidized (albeit more slowly). The diastereoselective alkylation of the resulting epoxides using MeLi/BuLi and CeI_3 leads to epoxides formally derived from allylic tertiary alcohols which, it is noted, are not readily obtainable in optically active form by Sharpless methodology.

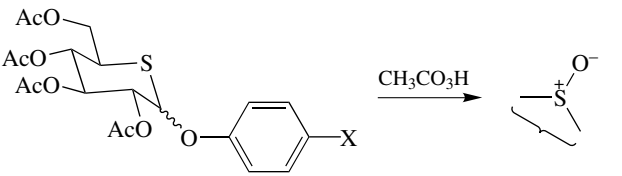
An interesting asymmetric Baeyer–Villiger reaction of prochiral ketones via chiral ketals (**9**) allowed the synthesis of chiral 3-butyrolactones in *ee*s of up to 89%.[167] An $SnCl_4$: *m*CPBA ratio of >1 in dichloromethane at −100 °C gave the best results and this is attributed to a high S_N1 character due to lowered nucleophilicity of peracid by coordination to $SnCl_4$. This is mirrored by the better selectivity of BH_3 than Et_3SiH in acetal reductions.



The Baeyer–Villiger oxidation of 1-*p*-methoxyphenyl-4-formyl-*β*-lactams to give 4-(formyloxy)-*β*-lactams is a rare example of preferred carbon over hydrogen migration in an aliphatic aldehyde; addition of 1-benzyl or 3-acyloxy/acylaza substituents gave only hydrogen-migration products.[168] A theoretical investigation of the Baeyer–Villiger reaction in non-polar solvents was carried out using *ab initio* MO calculations;[169] *p*-anisaldehyde was the substrate chosen. Addition of peroxyacetic acid to the carbonyl substrate is calculated to be the rate-determining step in the absence of catalyst and also using TFA as the catalyst. TFA also catalyses the subsequent migration step of the carbonyl adduct intermediate. Catalysis by acetic acid switches the rate-determining step from carbonyl addition to the migration. The effect of the trifluoromethyl groups on the Baeyer–Villiger reaction of di- and tri-fluoromethyl ketone derivatives has been discussed.[170]

A monocyclic methylsulfenyl ester has been suggested as a possible intermediate in the oxidation of 4-methyl-2,6,7-trioxa-1-phosphabicyclo[2,2,2]octane-1-sulfide by *m*CPBA.[171] The mole fraction of SSO_2 product (X_{SO}) was determined from the product ratio of bissulfoxide (SOSO) to sulfone (SSO_2) obtained on oxidation of thianthrene-5-oxide (SSO) by a range of peracids.[172] No significant steric effect was discerned for aliphatic peracids but a significant electronic effect for both aliphatic and benzoic peracids was observed. For example, CF_3COOOH yielded almost no sulfone whereas nucleophilic peracid anion gave exclusively sulfone. Interestingly, the more reactive oxidants are also the more selective, a finding justified by orbital control and a lower energy gap between LUMO(oxidant) and HOMO(sulfide). This study nicely demonstrates the utility of thianthrene-5-oxide as a probe of relative nucleophilicity or electrophilicity of oxidants. Whilst it is known that electrophilic oxidation of phenyl-1,5-dithioglucopyranoside gives primarily oxidation at glycosidic S(1) for the α-axial anomer, but at ring sulfur S(5) for the *β*, it has not been clear whether the reduced

nucleophilicity of the ring S(5) in the α-anomer is really due to the anomeric effect [interaction between a non-bonding (n) orbital of S(5) and the antibonding σ^* of the glycosidic bond, C(1)—S(1)]. Oxidation of 4-substituted phenyl α- and β-5-thioglucopyranosides (**10**) with *m*CPBA revealed that the rate of oxidation of the β form was 5–7 times higher than that of the α form, consistent with an n–σ^* interaction.[173] Moreover, the nucleophilicity of the ring S (as measured by the observed reaction rate constant) in the α form is 1.5 times more sensitive than that in the β form to the electronic properties of the substituent *X* (σ_P). For example, electron-withdrawing groups (NO_2) lower the energy of σ^*[C(1)—O(1)] and hence nucleophilicity of the lone pair on S_5 through increased (n–σ^*) *endo* anomeric interaction.



(**10**)

X = OMe, H, F, Cl, CF_3, NO_2

The reaction mechanism for *N*-oxidation by performic acid has been studied by AM1 calculation methods.[174] The iminium salt *N*-methyl-3,4-dihydroisoquinolinium *p*-toluenesulfonate has been used to catalyse the oxidation of the azo dye calmagite by peracetic acid. The mechanism at pH 10 involves peracid oxidation of the quinolinium ion to form an oxaziridinium salt, which then acts as an oxygen transfer agent for oxidation of calmagite.[175] The presence of lithium salts affects the course of the reaction determining the formation of benzoyl peroxide and benzoic acid as final products in the oxidation of benzaldehyde by perbenzoic acid.[176,177]

The debate about two contrasting transition states for the epoxidation of alkenes by peracids (Prilaschajew reaction) continues. An excellent study has been conducted by Houk and co-workers[178] in which the agreement of Becke3LYP[179] DFT calculations with experimental high-precision NMR-based kinetic isotope effect methods[102] using slightly asymmetric alkenes strongly supports the classical synchronous Bartlett butterfly epoxidation transition state. They also highlight the large differences between output from different calculation methods, which in some cases had suggested high asynchronicity.[180] This method clearly has great potential for tackling many other systems for which differences in interpretation remain. The α k_H/k_D KIE of 0.81 and β-secondary KIE of 0.96 reported for peracid epoxidation of 1-phenyl-3-methylbut-2-ene are consistent with a symmetrical rather than an asymmetric transition state, which would be expected to lead to a small positive β KIE due to hyperconjugative effects.[181] A rate study of peracid oxidation of several α, β-unsaturated aldehydes has revealed the dependence on the structure of both the aldehyde and peracid RCO_2OH.[182]

A modest increase in the rate of alkene epoxidation by peroxy acid in benzene occurs on addition of TCA or TFA.[183] Calculations predict a much lower activation barrier for epoxidation of ethene with fully protonated peroxyformic acid ($\Delta E^{\ddagger} = 6.4\,\text{kcal mol}^{-1}$);

however, the concentration of such an intermediate in a non-polar solvent would be low and general-acid catalysis via a cluster of HA and peracid is another possibility. In calculations this lowered the activation barrier by 3 kcal mol^{-1} to ca 15 kcal mol^{-1}.

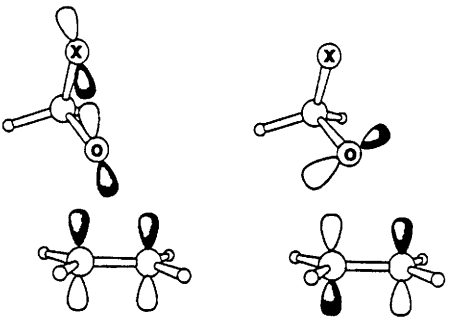
Dioxiranes, such as dimethyldioxirane (DMDO) and (trifluoromethyl)methyldioxirane (TFDO), are powerful oxidants which exhibit electrophilic oxygen transfer to nucleophilic substrates as well as oxidation of unactivated alkanes.[184] Primary k_H/k_D kinetic isotope effects of up to 6.76, determined through yields of competition experiments for the oxidation of cyclohexane and methylcyclohexane, suggest an electrophilic oxygen insertion mechanism for the oxidation of alkanes by DMDO.[185] Lowered, but still significant, KIE values and continued formation of cyclohexanone products in the gas phase suggests that direct C—H bond insertion, rather than a radical solvent-cage mechanism, is operating.

The effect of intramolecular hydrogen-bonding on the C—H bond oxygen-insertion reactions of DMDO has been investigated by measuring the rate constants for its reactions with a series of aliphatic alcohols containing a single tertiary C—H bond, separated from the OH group by varying numbers of CH_2 units.[186] The study showed that rate acceleration occurs when the distance between the reacting C—H bond and the OH group is such as to allow intramolecular H-bonding stabilization of the transition state; maximum rate acceleration (by a factor of six in acetone solution, compared with the analogous alkane incorporating CH_3 in place of the OH group) occurs when there are two interposed CH_2 groups.

DMDO produces sulfoximines efficiently while maintaining configuration and *ee* in the oxidation of optically active sulfilimines.[187] Substituent effects suggest an electrophilic oxidation and nucleophilic attack by the weakly nucleophilic sulfonium sulfur. Use of TFDO led to *N*-oxidation and hence fragmentation. The oxidation of cumene by DMDO is reported to follow a chain-radical mechanism and is inhibited by oxygen.[188] Aurones (furanones/pyranones with exocyclic C=C bonds) and dihydroflavanols can be epoxidized by DMDO.[189] Whereas furanoid systems gave epoxide products only, pyranoid structures gave largely rearranged products, presumably via epoxide formation also.

Encouraged by the good agreement between theory and experiment in their investigation of peracid epoxidations of alkenes, Houk and co-workers have extended the application of density functional theory methodology to those reactions involving DMDO, oxaziridine, and peroxynitrous acid.[190] The transition states were all predicted to be concerted and of spiro geometry. Substituents on the alkene increased the degree of asynchronicity, and created a preference for the substituent to be *anti* to the oxidant substituents, as did the transition from peroxy acid or dioxirane to oxaziridine. This may be explained by the lower leaving group ability of N versus O which favours FMO interactions (**12**) between the oxygen lone pair n orbital and the π^* of the alkene over the interaction (**11**) between π and the O—O σ^* orbital, which is involved in the S_N2-like attack of the alkene π system on the DMDO O—O bond. The $n \rightarrow \pi^*$ interaction is also responsible for the large spiro preference. The results of this transition state modelling were extended using MM2 force-field calculations and shown to correlate with observed stereoselectivities of DMDO and oxaziridines already reported in the

literature. Previous calculations with MP2/6–31G* gave a synchronous transition state for oxaziridine[191] but this was shown just to be a secondary saddle point 10.8 kcal mol^{-1} higher in energy. Short-lived peroxynitrous acid has never been observed to epoxidize alkenes but a transition state geometry that is in between those for DMDO and oxaziridine is suggested by this work to lie at a relatively accessible energy.



(**11**) (**12**)

AM1 and PM3 calculations reveal that epoxidations by DMDO and TFDO involve peroxide-bond σ^* at a very early stage and that TFDO is the most reactive dioxirane as the CF_3 group in it stabilizes this σ^* level. In accord with previous calculations a spiro transition state is predicted. Furthermore, allene is predicted to be less reactive than alkenes toward epoxidation by DMDO.[192] DFT calculations on the oxidation of primary amines by dimethyldioxirane predict a late transition state with a barrier of 17.7 kcal mol^{-1} which is drastically lowered by hydrogen bonding to the O—O bond to just 1.3 kcal mol^{-1} in protic solvents.[193]

In a study aimed at dismissing conclusively the proposition that alkene epoxidation by DMDO involves a biradical mechanism, the oxidation of α-methylstyrene, *trans*-cyclooctene and 1-vinyl-2,2-diphenylcyclopropane with DMDO was found to give the corresponding epoxide in high yield with no allylic oxidation via radical products.[194] Were radicals to be involved, the strained *trans*-cyclooctene would be predicted to undergo *trans* to *cis* isomerization on epoxidation and, for the third substrate, the classical ultrafast ring opening of the cyclopropane ring would be expected. Neither process was observed to occur, rendering the radical pathway highly unlikely.

Shi and coworkers have found[195] that pH has a dramatic effect on the epoxidation efficiency of their carbohydrate-based ketone reagent used previously[196] for asymmetric epoxidations of alkenes. Raising the pH to 10.5 allows the use of 20 mol% as opposed to the 3 equiv. It is suggested that a competing Baeyer–Villiger reaction is suppressed under these higher pH conditions; *ee*s of epoxidation remain as high.

Johnson and Taylor have shown that for the first time episulfones may be prepared by oxidation of a variety of the corresponding mono- and bi-cyclic episulfides using oxone–trifluoroacetone, although *cis*-stilbene and cyclohexene episulfides failed.[197] Preliminary mechanistic studies indicated that neither TFDO or Oxone alone was the

active oxidant. The chemistry of carbonyl oxide biradicals R_2COO and their cyclic isomers, dioxiranes, have been reviewed, including methods of generation and oxygen transfer activity.[198]

In the molybdenum-catalysed epoxidation of oct-1-ene and cyclohexene with organic hydroperoxides ROOH, the steric effect of the substituent R on the reaction rate has been studied.[199] Substitution of an alkyl group in place of one of the methyl groups in Bu^tOOH leads to a reduction in rate, the magnitude of which increases with increasing steric bulk of the substituent introduced. Substitution of a second and third methyl group in Bu^tOOH led to further reductions in rate; for example, a 99% reduction in rate is observed for Et_3COOH. These observations are rationalized in terms of nucleophilic attack of the alkene on an alkylperoxomolybdenum(VI) intermediate: the effect of bulky substituents in the alkyl hydroperoxide is to impede the approach of the olefin to the O—O bond. Oxobisperoxo molybdenum complexes with chelating pyrazolylpyridine ligands are thought to catalyse the epoxidation of alkenes by activating the oxidizing agent (Bu^tOOH or H_2O_2), rather than transferring an oxygen atom directly from an η^2-peroxo ligand to the alkene.[200,201] In the perborate oxidation of aniline to azobenzene catalysed by Mo(VI) and W(VI), H_2O_2 is the reactive species. The reaction is zero, first, and second order in oxidant, catalyst, and substrate respectively, based on which a mechanism is discussed.[202] Peroxoniobium(V) complexes oxidize $PhCH_2OH$ to PhCHO in a two-phase system of aqueous H_2O_2 as the oxidant and 1,2-dichloroethane as the organic solvent. The effect of phenylphosphonic acid and bipyridine as ligands for Nb has been investigated; in the latter case, selective oxidation to benzaldehyde (with no formation of $PhCO_2H$) was observed.[203]

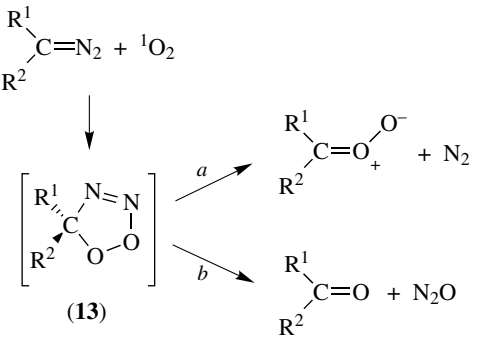
A material prepared by anchoring titanium(IV) on to the walls of a high-area, crystalline mesoporous silica (MCM41) has been used as an alkene epoxidation catalyst with alkyl hydroperoxides.[204] The effect of replacing one of the three O—Si≡ groups to which the Ti(IV) is bound by an O—Ge≡ group is reported to lead to an increase in catalytic activity of up to 18% in the epoxidation of cyclohexene, although no explanation is provided and it is notable that the selectivity towards the formation of cyclohexene oxide (versus cyclohexenol and cyclohexane-1,2-diol) was inferior to that with the non-modified system.[205]

Oxidation of 3-mercaptopropanoic acid by H_2O_2 involves rate-determining nucleophilic attack of sulfur on the peroxide, which is accelerated at high pH owing to the faster rate of attack by the dianion compared with the monoanion or acid.[206] The sulfenic acid (RSOH) so formed then undergoes fast reaction with further thiol to give the disulfide product. The kinetics (including pH dependence) of oxidation of DMS and DMSO by several hydroperoxides ROOH has been studied, with reference to their fate in the atmosphere.[207] For conversion of DMS to DMSO, the rate constant is higher for ROOH than for ROO^-. The logarithm of the rate constants for both species correlate well with the pK_a values of the corresponding alcohol (ROH) but not with the values of ROOH: an electron-withdrawing group on RO^- (stronger acid ROH) favours cleavage of the RO^- anion in the rate-determining step, thereby favouring oxygen transfer to form Me_2SOH^+, which deprotonates rapidly. The lower rate constants for ROO^- compared with ROOH then reflect the lower electrophilicity of the former in interaction with the nucleophilic sulfur of DMS. On the other hand, for the oxidation of DMSO to

dimethyl sulfone, the reaction is faster with the anion ROO^- (for most of the peroxides studied). DMSO acts here as a sulfur-based *electrophile*, and the reversal reflects the lower nucleophilicity of ROOH compared with ROO^-. Again, a good correlation of the rate constants with pK_a (ROH) is found, accounted for in terms of pre-equilibrium addition of ROO^- to S=O followed by rate-determining release of RO^- on formation of
—SO_2—.

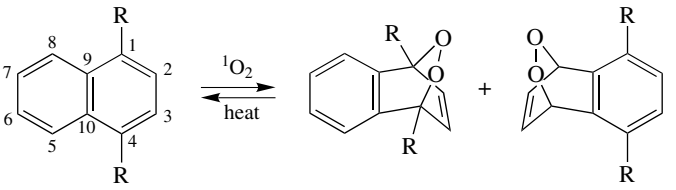
Photo-oxygenation, Singlet Oxygen, and Superoxide

Photosensitized oxygenation of significantly twisted 1,3-dienes has been studied to investigate the unusually high reactivity of vinylic hydrogens towards $^1O_2$.[208] Thermal decomposition of diphenyldiazomethane in the presence of oxygen is accompanied by chemiluminescence.[209] Laser flash photolysis to produce singlet oxygen allowed the oxidation of variously substituted diazomethanes;[210] the $N_2 : N_2O$ product ratio was determined by GC–MS and interpreted as being indicative of the ratio of formation of carbonyl oxide to ketone products. These were not affected by the use of protic solvents and appeared to be controlled by the relative stabilities of the resulting carbonyl oxides since electron-donating groups favoured their formation. A mechanism involving the intermediacy of dioxodiazole (**13**), with too short a lifetime to be observed, was suggested.



Reaction of $^1O_2$ with a water-soluble 1,4-disubstituted naphthalene (**14**) leads to a 5,8-endoperoxide (**16**), in addition to the 1,4-endoperoxide (**15**) which is normally obtained as the exclusive product in such reactions (in the absence of methyl groups at position 6, 7 or 8).[211] Formation of the 5,8-isomer is probably due to the effect of steric hindrance of the bulky substituents impairing the approach of $^1O_2$ to the more crowded

ring; the greater thermal stability of the 5,8- than the 1,4-compound is also likely to be due to steric hindrance in the butterfly structure of the latter.



(**14**) (**15**) (**16**)

R = $CH_2CH[CONCH_2CH(OH)CH_2(OH)]_2$

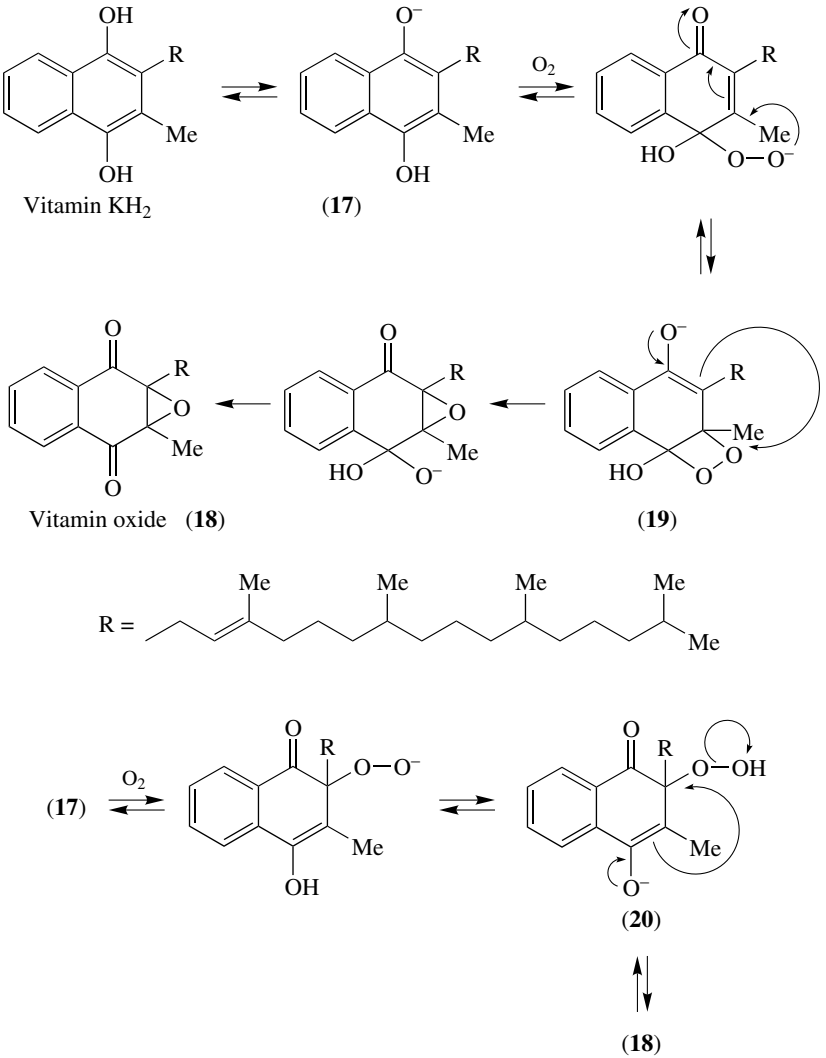
In the ene reaction of singlet oxygen with alkenes bearing an electron-withdrawing group at the *β*-position, the driving force to form the new double bond in conjugation with the allylic position in the resulting product may be counterbalanced by the electronic repulsion between perepoxide and the negatively polarized allylic functionality found in C=O-, P=O-, and S=O-containing systems.[212] This degree of counteraction appeared to vary with the degree of polarization in the order S=O > P=O > C=O. The quenching of singlet oxygen by five amines at different pressures, observed by time-resolved phosphorescence, revealed activation volumes from $-33\,cm^3\,mol^{-1}$ in non-polar to $-9\,cm^3mol^{-1}$ in polar solvents.[213] These were used to calculate dipole moments that indicate that only a partial charge transfer takes place in the quenching process.

Ab initio molecular orbital calculations, coupled with activation energies and entropies from experimental data, have been employed to determine the nature of the intermediates in the reaction of singlet oxygen with alkenes, enol ethers, and enamines.[214] Allylic alkenes probably react via a perepoxide-like conformation, whereas the more likely pathway for enamines involves a zwitterionic cycloaddition mechanism. The reactions of enol ethers are more complex, since the relative stabilities of the possible intermediates (biradical, perepoxide, and zwitterionic) here depend sensitively on the substituents and solvent polarity.

The oxidation of vitamin K hydroquinone monoanion (**17**) with labelled $^{18}O_2$ in THF leads to vitamin K oxide (**18**) in which the epoxide oxygen is fully labelled. In addition, partial incorporation of ^{18}O at the carbonyl oxygen is observed (on the basis of the mass spectrum).[215] This is most readily explained by invoking a dioxetane intermediate (**19**) as opposed to the alternative intermediacy of a 2-hydroperoxide (**20**), where only the epoxide oxygen would be expected to be labelled.

Different ratios of inter- and intra-molecular chain propagation imply involvement of α-keto hydroperoxides in the oxidation of ketones to CO_2 and CO at 120–155 °C.[216]

The role of anthraquinones as mediators of one-electron transfer to molecular oxygen has been studied by cyclic voltammetry in DMSO and DMF solution.[217] The reduction potentials of those anthraquinones containing OH groups were substantially shifted towards more positive values in the presence of O_2, whereas those without OH groups



showed no such effect. Indicative of a significant interaction with oxygen, this effect has been explained, with the aid of theoretical calculations, in terms of formation of hydroperoxide anion radicals which can be formed only by anthraquinones possessing OH groups. A study of the oxidative deamination of benzylamine to benzaldehyde catalysed by quinonoid cofactors supports the transamination mechanism of quinone-catalysed aerobic deamination involving an aminophenol intermediate that is

autoxidized to an iminoquinone during the catalytic cycle.[218] Electrochemical results suggest that an *asymmetric* orthoquinone structure is a requirement.

Ab initio and semiempirical molecular orbital calculations have been used, together with charge-transfer theories, to investigate the structures of organodioxide anions and related charge-transfer complexes between carbanions and molecular oxygen.[219]

The kinetics of quenching of $^1O_2$ by the alkaloid boldine in a number of solvents have been studied.[220] Solvent-effect correlations of the quenching rate constant suggest that the predominant mode of quenching is the formation of a charge-transfer complex between the aromatic rings and the excited oxygen. Back-electron transfer of the electron in such a complex regenerates boldine and ground-state oxygen (physical quenching with no net chemical transformation) whilst combination leads to products (chemical quenching). The rate of consumption of boldine (as measured by HPLC) reveals that the latter accounts for up to 5% of the total quenching rate.

Atomic Oxygen, Triplet Oxygen, and Autoxidation

The formation of a biradical, involving the addition of an oxygen atom to the double bond, is proposed to occur in the oxidation of acrylonitrile and crotononitrile by atomic oxygen(^3P).[221]

The oxidation of cyclohexene by means of molecular oxygen in the presence of cobalt naphthenate, vanadyl acetylacetonate, and molybdenyl acetylacetonate as catalysts has been studied.[222] The mechanism of *p*-toluenesulfonic acid-catalysed oxidation of styrene epoxide by O_2 has been discussed, including the influence of $[O_2]$ on radical formation, drawing on literature data and comparison with the reaction in the absence of O_2.[223] With the aim of acquiring a better understanding of the factors responsible for knock in spark ignition engines, the oxidation mechanisms of pentane and cyclopentane have been probed by oxidation at 873 K and chromatographic determination of the product distribution according to the time of passage in the reactor.[224]

Study of the oxidation of aromatics at high temperature is relevant to their use in augmenting the octane rating of hydrocarbon fuels. Oxidation of anisole at 1000 K is shown to proceed via the same pathway as pyrolysis under inert conditions.[225] Modelling of the experimental kinetics and product mixtures indicates that the first step is cleavage of the O—CH_3 bond to generate phenoxy and methyl radicals, from which cresols are obtained by attack of CH_3 at positions *ortho*, *meta*, or *para* to the oxygen, phenols by subsequent cleavage of the C—CH_3 bonds in the excited products, and methylcyclopentadiene by elimination of CO. A symposium has dealt with the mechanisms of oxidation of a range of aromatic and aliphatic hydrocarbons under combustion conditions, together with the role of NO.[226]

In the oxidation of octan-2-one, undecan-4-one, 1,3-diphenylacetone, and 2-phenylacetophenone, different ratios of intermolecular and intramolecular chain propagation are proposed to lie behind the varying distribution of products, CO_2, CO, H_2, hydroperoxides, and acids; a mechanism involving α-keto hydroperoxides was proposed.[227]

Other Oxidations

The oxidation of cholesteryl esters and low-density lipoproteins by free radicals has been reviewed.[228] The use of bis(pentafluorophenyl)borinic acid as a strong Lewis acid allows efficient Oppenauer oxidation of allylic and benzylic alcohols using Bu^tCHO as oxidant.[229] Saturated alcohols were only slowly oxidized and this allowed selective conversion of allylic alcohols in the presence of saturated alcohols.

The main effect of solvents on the rate of oxidation of tetrabutylammonium[230] and sodium[231] 1-acetonyl-2,4,6-trinitrocyclohexa-2,5-dienide with tetrachloro-1,4-benzoquinone were basicity, polarizability, and polarity. Selective oxidations of benzyl ethers can be achieved using DDQ.[232] Oxidation is favoured by electron-donating ether alkyl groups. Interestingly, the reaction rate is reduced by aromatic ring steric hindrance but not side-chain hindrance, which suggests an initial rate-determining aromatic stacking that is dependent on steric and electronic effects. Flavinium salts can be used as catalysts for the oxidation of benzylamines to aldimines under aerobic conditions.[233] The mechanism proceeds via addition at C(4a) followed by amine-promoted elimination before the dihydroflavin is reoxidized by atmospheric oxygen back up to the flavinium form and provides a good model for monoamine oxidase enzymes. Oxidation of veratryl alcohol by the enzyme lignin peroxidase has been studied.[234]

Reduction by Complex Hydrides

An excellent, broad review of the last 60 years of hydride reductions has been published,[235] and the use of selectrides, Li and K tri-*s*-butylborohydrides or trisiamylborohydrides, has also been reviewed.[236] A review of sodium borohydride–carboxylic acid as a reagent with novel selectivity in reductions has been written; in particular, this reagent is useful for the *N*-alkylation of primary and secondary amines, through a sequence that is believed to involve sequential carboxylic acid to aldehyde reduction followed by reductive amination.[237]

The reductive fragmentation of cyclic α-amino oximes using $NaBH_4$ in acetonitrile gave ω-amino nitriles in good yield.[238] Low stereospecificities were interpreted as being a result of the reduction of acyclic imminium intermediates. Rates and substituent effects were consistent with a preceding rate-determining synchronous ring-opening step requiring alignment of the nitrogen lone pair, scissile bond and oxime N—O bond. The requirement for aliphatic nitrile as solvent was interpreted as involvement of solvent in various B—N adduct formations to create a suitable oxime O leaving group.

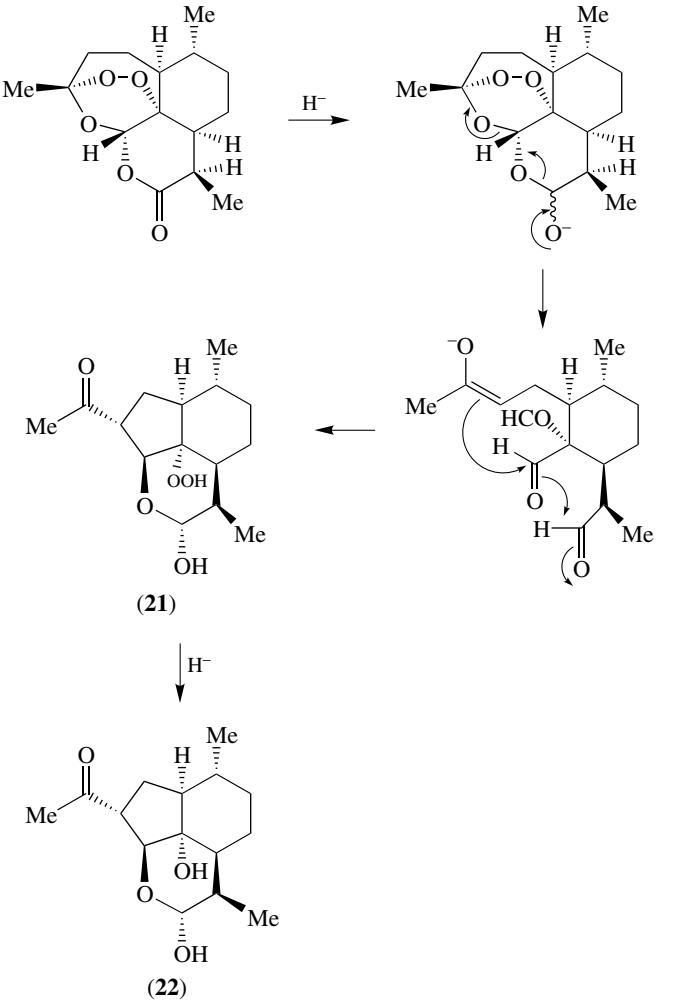
Reductions of cyclic enediones by $NaBH_4$ in the presence of $CeCl_3$ are controlled by accessibility for complexation by the Lewis acid and therefore more regioselective than those conducted without complexation.[239] This combination of reagents in MeOH has been used for the selective reduction of a decalin-based ketone from the more hindered, equatorial face of the molecule.[240] Use of 1.4 equiv. of $NaBH_4$ and 1.1 equiv. of $CeCl_3$ at high dilution (0.005 M) and low temperature (−95 °C) led to a 95 : 5 ratio of the axial to equatorial alcohol (compared with a 20 : 80 ratio in the absence of cerium).

The influence of β-cyclodextrin on the reduction of acetophenone by aqueous $NaBH_4$ is to induce a small *ee* of (*S*)-1-phenylethanol. The addition of stoichiometric amounts of triethylamine has been found to invert the absolute configuration of the main product, and substantially higher *ee* values (up to 56%) are then observed.[241] In a separate study, the stereoselectivity of the same reaction has been reversed through use of 6-deoxy-6-(ethylenediamine)-β-cyclodextrin.[242]

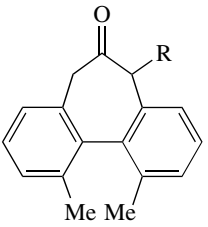
A range of 2,3-epoxyamines were prepared and reduced with sodium cyanoborohydride in the presence of $BF_3 \cdot Et_2O$.[243] Generally good selectivity in favour of the products of sequential Lewis aza-Payne rearrangement, induced by Lewis acid epoxide opening, followed by reduction was observed, although, in some cases, straight epoxide reduction products or mixtures of products from both processes resulted. *syn*-1,3-Amino alcohols were synthesized in good diastereomeric excess by reductive amination of 3-hydroxy-ketones with sodium cyanoborohydride in the presence of benzylamine.[244] The presence of a 2-alkyl substituent markedly reduces selectivity.

A thorough study of the reduction of hindered alkyl iodide by LAH has provided convincing evidence that reductive deiodination is a result of SET processes rather than S_N2 reaction.[245] Product ratios showing varying, less than complete, incorporation of deuterium in LAD reductions for a variety of proposed intermediates also discounts the idea that radical-type products are the result of impurities. The nature of the vessel hardly affected SET levels but bromide reductions showed less SET character and tosylate reductions none at all. An unusual debrominative [1,2]-hydride shift is observed in the reduction of *cis*-2-azido-1-bromoindane with LAD whereas the corresponding *cis*-1-mesylate or *trans*-1-bromide underwent the expected S_N2 displacement.[246] LAH reduction of artemisinin gave (**21**) and (**22**);[247] the suggested mechanism shown was supported by the sequential reduction of artemisinin to lactol by $NaBH_4$ and treatment with base to give (**21**).

In the so-called Exterior Frontier Orbital Extension (EFOE) model (which applies only to the spatial expanse of a frontier orbital outside the repulsive molecular surface), the location in cyclohexanone of a 'blocking wall' formed in the equatorial region of space between the C=O π^* and the 1*s* orbitals of $H_{ax}(2)$ and $H_{ax}(6)$ suggests that the stereochemistry of hydride reduction of cyclohexanone is determined at an early stage in the exterior region of the LUMO of the molecule to give axial approach.[248] The authors suggest that this second-order mixing is caused by the three methylene carbons C(3–5) and not by the orbitals of the hydrogens themselves. Interestingly, the level of mixing should also depend on the conformation of the cyclohexanone. It should be noted that the original Felkin–Anh model employed a lower level STO-3G basis set which effectively neglected such distortion effects. This work suggests that this effect appears to be as important a factor as torsional effects in the nucleophilic π-facial selectivity in such systems. *N*-Alkyloxindoles may be reduced by $LiAlH_4$ whereas those which are unsubstituted on nitrogen are unreactive, probably owing to deprotonation of the amide NH. Similar protection of the oxindole carbonyl is reported in 3-(methylthio)oxindoles, where deprotonation of the rather acidic C(3)—H similarly protects the carbonyl.[249] Interestingly, deprotonation also results in donation of electron density into the benzene ring to such an extent that an ester substituent in the ring *ortho*



to C(3) is greatly deactivated towards reduction to the alcohol, whereas forcing conditions lead to over-reduction to a methyl group. A mechanism is proposed, supported by a second study that shows that when deprotonation at C(3) is blocked by alkylation, reduction proceeds normally.[250] The relative rates of hydride addition to the carbonyl group of a conformationally locked bridged biaryl ketone and its α-methyl, α-methylthio, α-methoxy, α-chloro, and α-fluoro axial and equatorial derivatives (**23**) have been measured for each of three hydrides (LAH, $NaBH_4$, and Et_3SiH); rate constant partitioning, based on diastereoselectivities, allowed the determination of facial selectivities.[251] The results were not consistent with either Cieplak or Anh models and can be explained on the basis of through-bond and electrostatic through-space effects in the transition state.



(**23**)

Competition experiments have revealed that ionic triethylsilane-mediated reductions of alcohols exhibit dramatic substituent effects whereas only slight effects apply for ketones; this suggests that there is substantial carbocation character in the transition state for the former reaction but that counterbalancing effects on basicity and electrophilicity control the rate of the latter.[252] A helpful rule of thumb results from this work: 'ionic hydrogenation of carbonyl compounds only yields alcohols selectively under the conditions described in this work if the ethanolysis rate constants at 25 °C of the corresponding alkyl chlorides are smaller than 10^{-6} s^{-1}, otherwise the carbonyl group is immediately reduced to a methylene group,' which translates to dialkyl ketones being selectively reduced successfully to alcohols but diaryl ketones being reduced all the way to diarylmethanes regardless of the number of equivalents.

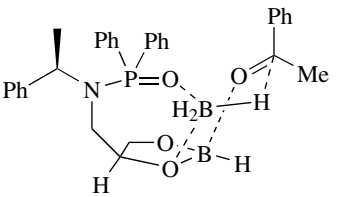
An impressive new route to enantiopure *syn*- and *anti*-1,2-diols involves sequential diastereoselective DIBAL reduction of oxalyl-di(*N*-methyl-*N*-methoxyamide) following conversion to a corresponding intermediate *β*-keto sulfoxide; a route that involved control of both reductions by the chiral sulfoxide auxiliary.[253] Comparison of *β*-hydroxy ketone systems with the *γ*-sulfoxide-*β*-keto systems used here showed this to be the first example of such asymmetric induction by a *γ*-sulfoxide substituent.

Other Reductions

An economical *in situ* method for the preparation of borane diisopinocampheylchloride (DIP-Cl or Ipc_2BCl) from $NaBH_4$, BCl_3 and 85% *ee* α-pinene has been demonstrated to be as effective as pure DIP-Cl for the reduction of aryl ketones.[254] The successful use of this lower *ee* reagent is a consequence of positive non-linear effects or asymmetric amplification which is itself a consequence of the (+)-Ipc, (–)-IpcBCl isomer being almost inactive. Interestingly, however, closer inspection showed that these effects do not precisely follow those that would be predicted if DIP-Cl isomers were formed statistically. HCl and mesylic acid increase the rate of intramolecular asymmetric reduction of *o*-amino-substituted aceto- and benzo-phenones by diisopinocampheyl-borane (DIP-H).[255] This can be explained by the formation of an initial azaborane intermediate, observed by ^{11}B NMR, which then reduces the carbonyl. Protonation of the nitrogen atom by these strong acids increases the Lewis acidity of the boron and hence accelerates the reaction.

Building on previous use of phosphonamides, a combined phosphonamide–dioxoborolidine has been prepared to operate via the predicted matched transition state (**24**) resulting in an *S* absolute configuration in product alcohols from the reduction

of acetophenone.[256] Interestingly, the low *ee* of 59% was matched by using a chiral phosphonamide and dioxoborolidine in an intermolecular combination.



(**24**)

The use of oxazaborolidines as asymmetric reduction catalysts[257] and the enantioselectivity of diphenyloxazaborolidine reduction of ketones have been reviewed.[258] Large-scale practical enantioselective reduction of prochiral ketones has been reviewed with particular emphasis on the Itsuno–Corey oxazaborolidine and Brown's *B*-chlorodiisopinocampheylborane (Ipc_2BCl) as reagents.[259] Brown himself has also reviewed the use of Ipc_2BCl.[260] Indolinoalkylboranes in the form of dimers have been confirmed by ^{11}B NMR as the products of the reduction of trifluoroacetylindoles by diborane.[261]

The deoxidation of heterocyclic *N*-oxides has been reviewed.[262] Cobalamin, cobinamide, and cobamide have been used as electron-transfer mediators for the reduction of three chlorinated alkenes using titanium salts as the terminal electron donors.[263] Dissociative one-electron transfer yields the corresponding vinyl radicals in a rate-limiting step and the direct formation of acetylene from trichloroethene is accounted for by elimination of a chloride radical from the 1,1-dichlorovinyl radical. The direct observation of a bicyclic aldimine radical by EPR supports a mechanism for the reduction of benzaldehyde imines by formic acid in which formate addition is followed by decarboxylative homolytic bond cleavage.[264] The aldimine radical formed then abstracts hydride from another imine–formate adduct to complete the chain. The observations by EPR were supported by spin trapping and NMR line broadening. The kinetics and mechanisms of reductions by ascorbic acid have been investigated in aqueous solution using *p*-benzoquinone as substrate, over the pH range 2–4.87.[265] It is proposed that ascorbate anion is the reactive species and that the highly negative volume of activation under acidic conditions relates to its formation. Fast one-electron transfer is followed by reversible and rate-determining hydrogen atom transfer, consistent with a maximum kinetic isotope effect. Proton transfer completes the reaction, accounting for the observation that only in H_2O do ascorbate reductions proceed well.

Intramolecular protonation on the more hindered face of a steroid from a neighbouring hydroxyl group best explains a reversal of diastereoselectivity in the Birch reduction of styrene double bonds.[266] The kinetics and product distribution of lithium metal reduction of benzaldehyde to benzyl alcohol in THF have been studied; electron transfer from Li to PhCHO occurs in a slow step, but absorption of the PhCHO onto the metal surface is also crucial in determining the overall kinetics. The proposed mechanism successfully accounts for the formation of minor products, benzoin and

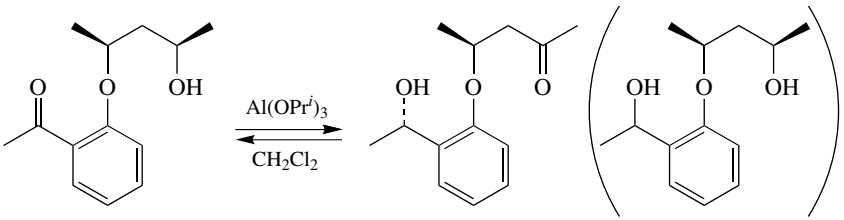
benzil.[267] A mechanism for the Clemmensen reduction of 3-arylpyruvic acid has been put forward, based on a ^{1}H NMR spectroscopic study of the enol form.[268]

Methods for the catalytic reduction of alkynes under homogeneous and heterogeneous conditions have been reviewed.[269] The catalytic reduction of {[(4-nitrophenyl)methyl]sulfonyl}acetic acid in alkaline dioxane–water proceeds via (α-hydroxy-4-nitrosobenzyl)sulfonylacetic acid and 4-nitrosobenzaldehyde as intermediates.[270] Study of the kinetics and mechanism of the hydrogenation of *N*-(1,4-dimethylpentyl)-4-nitrosobenzeneamine to *N*-(1,4-dimethylpentyl)-1,4-benzenediamine over 5% Pd/C revealed faster reaction rates with decreasing pressures of hydrogen.[271] Alkenes derived from Garner's aldehyde, *N*-Boc-*N*,*O*-acetonide of the aldehyde of L-serine, may be hydrogenated with fair selectivities explained by $A^{1,3}$ strain.[99]

π-Allyltricarbonyl iron lactone complexes bearing ketone groups in the side-chain may be reduced diastereoselectively by triisobutyl aluminium, since nucleophilic attack occurs *anti* to the bulky tricarbonyl iron unit. This has been exploited in a key step in the enantioselective synthesis of *β*-dimorphecolic acid, where diastereoselective reduction of a carbonyl-containing intermediate is thereby achieved, amounting to a 1,5-transfer of chirality.[272] The metal carbonyl $HCo(CO)_4$ reacts with cinnamaldehyde in methylcyclohexane to generate hydrocinnamaldehyde and styrene.[273] The reduction of the double bond is effected by H from the $HCo(CO)_4$ and from the solvent, in a free-radical chain mechanism. Formation of styrene arises from thermal decomposition of the initial product $PhCH_2CH_2C(O)Co(CO)_4$.

A tandem 1,4-addition–Meerwein–Ponndorf–Verley (MPV) reduction allows the reduction of α, *β*-unsaturated ketones with excellent *ee* and in good yield using a camphor-based thiol as reductant.[274] The 1,4-addition is reversible and the high *ee* stems from the subsequent 1,7-hydride shift; the overall process is thus one of dynamic kinetic resolution. A crossover experiment demonstrated that the shift is intramolecular. Subsequent reductive desulfurization yielded fully saturated compounds in an impressive overall asymmetric reductive technique with apparently wide general applicability.

Intramolecular hydride transfer under MPV reduction conditions occurs in substrate (**25**) with complete stereospecificity to generate (**26**).[275] A 2 : 1 mixture of product to reactant was observed, irrespective of reaction time or relative excess of $Al(O^iPr)_3$, indicative of an equilibrium. Intermolecular hydride transfer to give (**27**) does not occur and the absence of the epimer of (**25**) implies that complete stereodifferentiation also occurs in the reverse process (Oppenhauer oxidation). Stereodifferentiation under



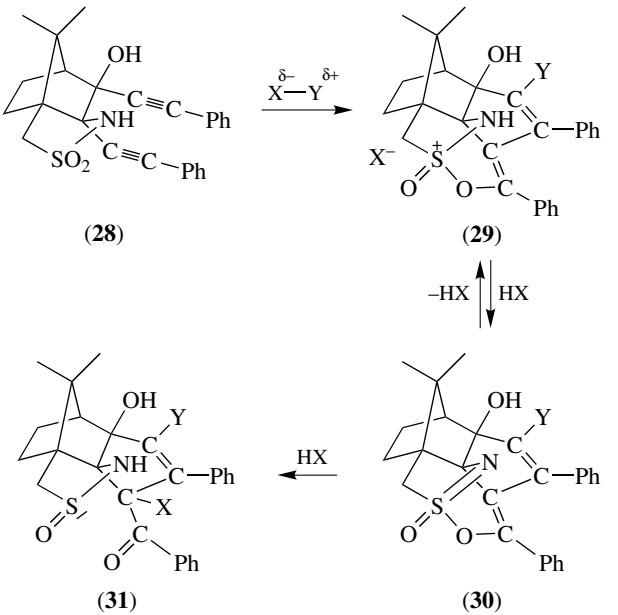
(**25**) (**26**) (**27**)

equilibrium conditions has not previously been reported for the MPV–Oppenhauer reaction and may be a consequence here of the restricted orientation of the carbonyl group and the alcohol in the intramolecular transition state; coordination to Al will also inhibit the intermolecular reaction.

The diastereoselectivity of reduction of 2-substituted cyclohexanones with 4-substituted aluminium phenoxides has been investigated over a wide temperature range (−75 to +80 °C).[276] Hydride transfer dominates at high temperature whereas an MPV-type reaction contributes at lower temperatures.

HI in acetic acid allows the reduction of *β*-peracetates of the higher sugar *N*-acetylneuraminic acid to the corresponding anomeric deoxy compounds.[277] At room temperature this method gave exclusively the α-anomer, whereas at −20 °C a 4 : 1 $\alpha:\beta$ ratio resulted. This may be explained by thermodynamic and kinetic protonation of ester enolates generated *in situ* from anomeric iodide in a manner reminiscent of previous reductions of 2-iodo sugar lactones.[278]

Cationic sulfonamides of the form (**29**) [obtained from dialkynes (**28**) upon treatment with acids or halogens] undergo stereoselective reduction of the sulfonamide group to generate a sulfinamide (**31**) under very mild conditions.[279] Indirect ^{1}H NMR evidence suggests that the reaction proceeds via the intermediate (**30**). Further reactions occur in the presence of I_2, including the reduction of the sulfinamide to a sufenamide.

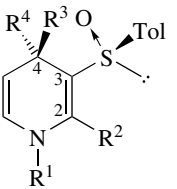


(**28**) (**29**) (**31**) (**30**)

An intramolecular model for the reductive acyl transfer catalysed by α-keto-acid dehydrogenases relies on the presence of PhHgCl to trap the thiolate generated by reduction of the lipoate disulfide bond by enamine.[280] This shows a 10-fold increase in loss of enamine UV–visible absorption over background decomposition attributed by the authors to reductive acyl transfer. However, no reaction products were isolated and

the rate is ca 10^5-fold lower than that in dehydrogenase enzyme-catalysed systems. Although it has been established that Cu^+ brings about the decomposition of *S*-nitrosothiols in aqueous solution, $2RSNO \rightarrow RSSR + 2NO$, the effect of the presence of the corresponding thiols has been unclear. In a kinetic study, large differences in behaviour have been found for five such nitrosothiols derived from 2-amino- or 2-carboxylato-thiols: in some cases, catalysis was observed by the added thiols, whereas in others, stabilization was the outcome.[281] The results have been interpreted in terms of the requirement of some thiol for reduction of Cu^{2+} to Cu^+, offset at higher thiol concentrations by complexation of the Cu^{2+}, making it less available. Studies aimed at addressing the evolutionary origin of the stereospecificity of enzymatic reactions have been reviewed.[282] Results from hydratase–dehydratase enzymes, enoyl thioester reductases and coenzyme B_{12}-dependent rearrangements are presented in support of the notion that stereospecificity is a historical contingency, arising from an arbitrary choice made early and then retained during the evolutionary process. Conversion of esters/lactones to their carbothionyl ester derivatives, followed by treatment with triphenylstannane in the presence of AIBN, gave reduced ether products, yet the use of tributylstannane failed.[283] A two-step reductive mechanism involving radicals is implicated.

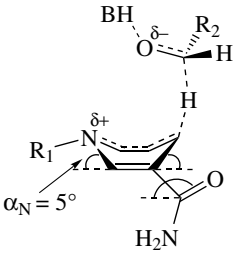
The thermodynamics and kinetics of reductions by NAD(P)H model compounds, such as 1-benzyl-1,4-dihydronicotinamide, have been investigated.[284] With xanthylium ion as the substrate, it is proposed that rate-determining electron transfer is followed by fast hydrogen atom abstraction. Imanishi's group have expanded their study of chiral sulfinyl-containing NADH models. By using (**32**) it was shown that the C(4) hydrogen *syn* to the S—O bond was stereospecifically transferred to ketones.[285] However, an observed lack of kinetic isotope effect contrasts with amide NADH models and suggests a three-step electron, proton, electron process (with initial electron transfer being rate determining) rather than direct hydride transfer. Furthermore, similar enantioselectivities and NMR data were obtained from a 2-methyl derivative (**33**), in which additional $A^{1,3}$ strain between S—O and methyl is present. This lends support to a transition state in which the S—O bond is aligned with the hydrogen that is transferred.



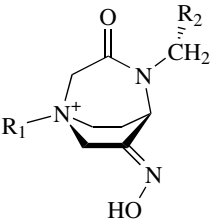
(**32**) R^1 = Bu, R^2, R^3 = H, R^4 = D

(**33**) R^1 = Bu, R^2 = Me, R^3 = H, R^4 = H

Compound (**35**) has been synthesized to mimic the NADH/NAD^+ cofactor and product in the transition-state model (**34**) of hydride transfer in dehydrogenase enzymes.[286] The intended use of (**35**) is to act as a hapten for the generation of catalytic antibodies with the potential to act as dehydrogenase mimics.



(**34**)



(**35**)

Retention of configuration and regioselectivity of PPh_3 mediated O—O bond cleavage in 1,2-dioxolanes (wherein the more sterically congested O atom is abstracted preferentially) has been attributed to biphilic insertion of PPh_3 to form a labile phospholane intermediate which equilibrates with the alternative zwitterions formed on P—O bond scission; the regiochemistry is apparently determined by the relative rates of zwitterion fragmentation.[287] Rhodium complexes of sulfonated (−)-(2*S*,4*S*)-2,4-bis(diphenylphosphino)pentane [(*S*,*S*)-(BDPP)] have been shown to be effective catalysts for the asymmetric hydrogenolysis of sodium *cis*-epoxysuccinate to sodium hydroxysuccinate in an aqueous–organic two-phase solvent system or in aqueous solution.[288]

References

1 Wang, K. and Mayer, J. M., *J. Org. Chem.*, **62**, 4248 (1997).
2 Mangalam, G., Gurumurthy, R., Arul, R., Karthikeyan, R., and Mathivanan, K., *Indian J. Heterocycl. Chem.*, **6**, 197 (1997); *Chem. Abs.*, **127**, 50207 (1997).
3 Agarwal, G. L. and Khare, S. S. J. N., *J. Indian Counc. Chem.*, **10**, 26 (1994); *Chem. Abs.*, **125**, 300323 (1996).
4 Korde, S. S., Udasi, R. A., and Trivedi, G. K., *Synth. Commun.*, **27**, 3419 (1997); *Chem. Abs.*, **127**, 262900 (1997).
5 Kuotsu, B., Tiewsoh, E., Debroy, A., and Mahanti, M. K., *J. Org. Chem.*, **61**, 8875 (1996).
6 Aruna, K. and Manikyamba, P., *Int. J. Chem. Kinet.*, **29**, 437 (1997).
7 Loonker, K., Sharma, P. K., and Banerji, K. K., *J. Chem. Res. (S)*, **1997**, 194.
8 Pandurangan, A. and Murugesan, V., *J. Indian Chem. Soc.*, **73**, 484 (1996); *Chem. Abs.*, **125**, 300311 (1996).
9 Loonker, K., Sharma, P. K., and Banerji, K. K., *J. Chem. Res. (S)*, **1997**, 242.
10 Ozgun, H. B. and Degirmenbasi, N., *J. Chem. Res. (S)*, **1997**, 32.
11 Agarwal, G. L. and Jain, R., *Oxid. Commun.*, **20**, 273 (1997); *Chem. Abs.*, **127**, 176090 (1997).
12 Pandurangan, A. and Murugesan, V., *Oxid. Commun.*, **20**, 93 (1997); *Chem. Abs.*, **126**, 330334 (1997).
13 Palopoli, C., Signorella, S., and Sala, L. F., *New J. Chem.*, **21**, 343 (1997).
14 Bharathy, J. B., Ganesan, T. K., Sheriff, A. I. A. M., and Rajagopal, S., *Tetrahedron*, **53**, 1131 (1997).
15 Singh, R. and Shrivastava, K. B. L., *Asian J. Chem.*, **8**, 649 (1996); *Chem. Abs.*, **126**, 88975 (1997).
16 Singh, R., *Asian J. Chem.*, **9**, 52 (1997); *Chem. Abs.*, **126**, 131112 (1997).
17 Imanishi, H. and Katsuki, T., *Tetrahedron Lett.*, **38**, 251 (1997).
18 Gaur, D. S., *J. Indian Chem. Soc.*, **74**, 545 (1997); *Chem. Abs.*, **127**, 220954 (1997).
19 Wang, L., *Huaxue Yanjiu Yu Yingyong*, **9**, 45 (1997); *Chem. Abs.*, **127**, 50214 (1997).
20 Rudakov, E. S., Lobachev, V. L., and Zaichuk, E. V., *Kinet. Catal. (transl. Kinet. Katal.)*, **37**, 500 (1996); *Chem. Abs.*, **125**, 275079 (1996).
21 Rao, K. V., Rao, M. T., and Adinarayana, M., *Indian J. Chem.*, **35A**, 856 (1996); *Chem. Abs.*, **125**, 300676 (1996).
22 Srivastava, R. G. and Venkataramani, P. S., *Indian J. Chem.*, **35B**, 1163 (1996); *Chem. Abs.*, **125**, 327903 (1996).

[23] Jaky, M. and Szammer, J., *J. Phys. Org. Chem.*, **10**, 420 (1997).
[24] Arrizabalaga, A., Andres-Ordax, F. J., Fernandez-Aranguiz, M. Y., and Peche, R., *Int. J. Chem. Kinet.*, **29**, 181 (1997).
[25] Mangalam, G., Gurumurthy, R., Arul, R., and Karthikeyan, R., *Oxid. Commun.*, **20**, 107 (1997); *Chem. Abs.*, **127**, 17293 (!997).
[26] Kislenko, V. N., Berlin, A. A., and Litovchenko, N. V., *Kinet. Catal. (transl. Kinet. Katal.)*, **38**, 359 (1997); *Chem. Abs.*, **127**, 149329 (1997).
[27] Elango, K. P. and Karunakaran, K., *Oxid. Commun.*, **20**, 243 (1997); *Chem. Abs.*, **127**, 176085.
[28] Ram Reddy, M. K., Nagi Reddy, K., Rajanna, K. C., and Saiprakash, P. K., *Oxid. Commun.*, **19**, 381 (1996); *Chem. Abs.*, **125**, 329138 (1996).
[29] Tripathi, R. S. and Gupta, R. P., *Asian J. Chem.*, **8**, 665 (1996); *Chem. Abs.*, **126**, 88976 (1997).
[30] Katsuki, T., *J. Mol. Catal. A*, **113**, 87 (1996); *Chem. Abs.*, 126, 18718 (1997).
[31] Chellamani, A., Alhaji, N. M. I., and Rajagopal, S., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 299.
[32] Wang, K. and Mayer, J. M., *J. Am. Chem. Soc.*, **119**, 1470 (1997).
[33] Suzuki, M., Ishikawa, T., Harada, A., Ohba, S., Sakamoto, M., and Nishida, Y., *Polyhedron*, **16**, 2553 (1997); *Chem. Abs.*, **127**, 108640 (1997).
[34] Kamp, N. W. J. and Smith, J. R. L., *J. Mol. Catal. A: Chem.*, **113**, 131 (1996); *Chem. Abs.*, **126**, 46812 (1997).
[35] Chauhan, S. M. S., Gupta, M., Gulati, A., and Nizar, P. N. H., *Indian J. Chem.*, **35B**, 1267 (1996); *Chem. Abs.*, **126**, 47024 (1997).
[36] Vyas, V. K., Kothari, S., and Banerji, K. K., *Int. J. Chem. Kinet.*, **29**, 9 (1997).
[37] Bohra, A., Sharma, P. K., and Banerji, K. K., *J. Org. Chem.*, **62**, 3562 (1997).
[38] Mohnot, K., Sharma, P. K., and Banerji, K. K., *Proc. Indian Acad. Sci., Chem. Sci.*, **108**, 421 (1996); *Chem. Abs.*, **126**, 18507 (1997).
[39] Mohnot, K., Sharma, P. K., and Banerji, K. K., *J. Indian Chem. Soc.*, **74**, 12 (1997); *Chem. Abs.*, **126**, 212182 (1997).
[40] Satasngi, B. K. and Kothari, S., *J. Indian Chem. Soc.*, **74**, 16 (1997); *Chem. Abs.*, **126**, 199195 (1997).
[41] Saha, B., Dutta, A., Gangopadhyay, S., and Banerjee, P., *Int. J. Chem. Kinet.*, **29**, 225 (1997).
[42] Dutta, A., Saha, B., Ali, M., and Banerjee, P., *J. Chem. Res. (S)* **1997**, 186.
[43] Bhattacharya, S., Dutta, A., and Banerjee, P., *Acta Chem. Scand.*, **51**, 676 (1997).
[44] Kumar, A. and Panwar, A., *Oxid. Commun.*, **20**, 258 (1997); *Chem. Abs.*, **127**, 176088 (1997).
[45] Gupta, K. K. S., Nandy, B. K., Bera, A. K., and Gupta, S. S., *Indian J. Chem.*, **36A**, 190 (1997); *Chem. Abs.*, **127**, 50200 (1997).
[46] Shan, J., Zhao, J., Shen, S., and Lu, Y., *Hebei Daxue Xuebao, Ziran Kexueban*, **16**, 29 (1996); *Chem. Abs.*, **127**, 94957 (1997).
[47] Asthana, S. K., Mishra, S. K., and Nand, K. C., *Oxid. Commun.*, **20**, 132 (1997); *Chem. Abs.*, **126**, 343823 (1997).
[48] Talsi, E. P., *New J. Chem.*, **21**, 709 (1997).
[49] Saxena, R. B. and Joshi, P. R., *J. Indian Counc. Chem.*, **10**, 1 (1994); *Chem. Abs.*, **125**, 300322 (1996).
[50] Venkateswarlu, K. C. and Rao, M. A., *Acta Cienc. Indica, Chem.*, **22**, 135 (1996); *Chem. Abs.*, **127**, 81077 (1997).
[51] Venkateswarlu, K. C. and Rao, M. A., *Acta Cienc. Indica, Chem.*, **22**, 140 (1996); *Chem. Abs.*, **127**, 81078 (1997).
[52] Steglinska, V., Gzheidzyak, A. and Dzegets, Y., *Zh. Obshch. Khim.*, **66**, 847 (1996); *Chem. Abs.*, **125**, 327926 (1996).
[53] Prawicki, K. and Dziegiec, J., *Zh. Obshch. Khim.*, **66**, 2003 (1996); *Chem. Abs.*, **126**, 293001 (1997).
[54] Saha, P. N., Mondal, S. K., Kar, D., Das, M., Das, A. K., and Mohanty, R. K., *J. Chem. Res.*, **1997**, 364.
[55] Mohanty, R. K., Das, M., and Das, A. K., *Transition Met. Chem.*, **22**, 487 (1997).
[56] Yamgar, R. S., Pol, U. N., and Dodwad, S. S., *Asian J. Chem.*, **9**, 195 (1997); *Chem. Abs.*, **126**, 343233 (1997).
[57] Jameel, A. A., *J. Indian Chem. Soc.*, **74**, 405 (1997); *Chem. Abs.*, **127**, 176095 (1997).
[58] Kvernberg, P. O., Hansen, E. W., Pedersen, B., Rasmussen, A., and Ruoff, P., *J. Phys. Chem. A*, **101**, 2327 (1997).
[59] Simandi, L. I. and Simandi, T. L., *J. Mol. Catal. A: Chem.*, **117**, 299 (1997); *Chem. Abs.*, **126**, 224920 (1997).
[60] Nam, W., Yang, S. J., and Kim, H., *Bull. Korean Chem. Soc.*, **17**, 625 (1996); *Chem. Abs.*, **125**, 327664 (1996).
[61] Punniyamurthy, T., Bhatia, B., Reddy, M. M., Maikap, G. C., and Iqbal, J., *Tetrahedron*, **53**, 7649 (1997).
[62] Lin, G. and Wang, Z., *Huaxue*, **54**, 105 (1996); *Chem. Abs.*, **126**, 171081 (1997).
[63] Stephenson, G. R., *Adv. Asymm. Synth.*, 367 (1996); *Chem. Abs.*, **125**, 246825 (1996).

[64] Collado, I. G., Hanson, J. R., Hitchcock, P. B., and Macías-Sanchez, A. J., *J. Org. Chem.*, **62**, 1965 (1997).
[65] Back, T. G. and Baron, D. L., *Can. J. Chem.*, **74**, 1857 (1996).
[66] Agrawal, G. L., *J. Indian Counc. Chem.*, **12**, 4 (1996); *Chem. Abs.*, **127**, 190380 (1997).
[67] Bhargava, N., Pandey, A., and Sharma, K., *J. Indian Counc. Chem.*, **11**, 68 (1995); *Chem. Abs.*, **127**, 176686 (1997).
[68] Gall, R. D., Faraj, M., and Hill, C. L., *Proc. ERDEC Sci. Conf. Chem. Biol. Def. Res., 1994*, **1996**, 263; *Chem. Abs.*, **127**, 33778 (1997).
[69] Karunakaran, K. and Elango, K. P., *J. Indian Chem. Soc.*, **74**, 299 (1997); *Chem. Abs.*, **127**, 176081 (1997).
[70] Gekhman, A. E., Moiseeva, N. I., Moiseev, I. I., and Kurnakov, N. S., *Dokl. Akad. Nauk*, **349**, 53 (1996); *Chem. Abs.*, **126**, 7580 (1997).
[71] Oku, H., Ueyama, N., and Nakamura, A., *Chem. Lett.*, **1996**, 1131.
[72] Gable, K. P., *Adv. Organomet. Chem.*, **41**, 127 (1997); *Chem. Abs.*, **127**, 220683 (1997).
[73] Brown, K. N. and Espenson, J. H., *Inorg. Chem.*, **35**, 7211 (1996); *Chem. Abs.*, **126**, 30981 (1997).
[74] Postel, M. and Dunach, E., *Coord. Chem. Rev.*, **155**, 127 (1996); *Chem. Abs.*, **126**, 18403 (1997).
[75] Coin, C., Zevaco, T., Duach, E., and Postel, M., *Bull. Soc. Chim. Fr.*, **133**, 913 (1996).
[76] Hamed, O., Thompson, C., and Henry, P. M., *J. Org. Chem.*, **62**, 7082 (1997).
[77] Ukraintsev, V. B., Potekhin, V. V., and Avetikyan, G. B., *Zh. Obshch. Khim.*, **66**, 716 (1996); *Chem. Abs.*, **125**, 275103 (1996).
[78] Singh, B., Singh, M., and Kesarwani, D., *Oxid. Commun.*, **20**, 267 (1997); *Chem. Abs.*, **127**, 176089 (1997).
[79] Belozerov, V. E., Flid, V. R., Finashina, E. D., and Belov, A. P., *Kinet. Catal. (transl. Kinet. Katal.)*, **38**, 355 (1997); *Chem. Abs.*, **127**, 148869 (1997).
[80] Singh, B., Singh, M., Singh, A. K., and Prakash, V., *Oxid. Commun.*, **19**, 559 (1996); *Chem. Abs.*, **126**, 185718 (1997).
[81] Funabiki, T., Yokomizo, T., Suzuki, S., and Yoshida, Y., *Chem. Commun.*, **1997**, 151.
[82] Kislenko, V. N., Berlin, A. A., and Litovchenko, N. V., *Zh. Obshch. Khim.*, **66**, 854 (1996); *Chem. Abs.*, **125**, 329140 (1996).
[83] Sati, M. K., Singh, P., Tewary, G., and Mehta, S. P. S., *Asian J. Chem.*, **8**, 621 (1996); *Chem. Abs.*, **126**, 88974 (1997).
[84] Sati, M. K., Singh, P., Tewary, G., and Mehta, S. P. S., *Asian J. Chem.*, **9**, 78 (1997); *Chem. Abs.*, **126**, 131114 (1997).
[85] Bajpai, P., Shukla, A., and Upadhyay, S. K., *Oxid. Commun.*, **19**, 529 (1996); *Chem. Abs.*, **126**, 171197 (1997).
[86] Mucientes Balado, A., Santiago Jimenez, F., Poblete Martin, F. J., and Varon Castellanos, R., *Int. J. Chem. Kinet.*, **29**, 1 (1997).
[87] Mucientes, A. E., Poblete, F. J., Rodriguez, M. A., and Santiago, F., *J. Phys. Org. Chem.*, **10**, 662 (1997).
[88] Norcross, B. E., Lewis, W. C., Gai, H., Noureldin, N. A., and Lee, D. G., *Can. J. Chem.*, **75**, 129 (1997).
[89] Isak, V. G., Sychev, A. Ya., and Anikina, Z. O., *Zh. Fiz. Khim.*, **70**, 1534 (1996); *Chem. Abs.*, **125**, 327902 (1996).
[90] Le, K. A. and Nam, W., *Bull. Korean Chem. Soc.*, **17**, 669 (1996); *Chem. Abs.*, **125**, 300300 (1996).
[91] Shukla, R. S., Robert, A., and Meunier, B., *J. Mol. Catal. A: Chem.*, **113**, 45 (1996); *Chem. Abs.*, **126**, 46813 (1997).
[92] Tony, K. J., Rajaram, J., Mahadevan, V., and Swamy, C. S., *React. Kinet. Catal. Lett.*, **60**, 145 (1997); *Chem. Abs.*, **127**, 65395 (1997).
[93] Singh, R. A. and Singh, R. S., *Oxid. Commun.*, **20**, 248 (1997); *Chem. Abs.*, **127**, 176086 (1997).
[94] Singh, B., Ratan, A., Prakash, V., and Kesarwani, D. M., *Oxid. Commun.*, **19**, 552 (1996); *Chem. Abs.*, **126**, 185717 (1997).
[95] Timmanagoudar, P. L., Hiremath, G. A., and Nandibewoor, S. T., *J. Indian Chem. Soc.*, **74**, 296 (1997); *Chem. Abs.*, **127**, 161415 (1997).
[96] Boelrijk, A. E. M., Dorst, J. T., and Reedijk, J., *Recl. Trav. Chim. Pays-Bas*, **115**, 536 (1996); *Chem. Abs.*, **126**, 144485 (1997).
[97] Donohoe, T. J., Moore, P. R., and Beddoes, R. L., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 43.
[98] Erdik, E. and Kahya, D., *Int. J. Chem. Kinet.*, **29**, 359 (1997).
[99] Kauppinen, P. M. and Koskinen, A. M. P., *Tetrahedron Lett.*, **38**, 3103 (1997).
[100] DelMonte, A. J., Haller, J., Houk, K. N., Sharpless, K. B., Singleton, D. A., Strassner, T., and Thomas, A. A., *J. Am. Chem. Soc.*, **119**, 9907 (1997).
[101] Becke, A. D., *J. Chem. Phys.*, **98**, 5648 (1993).
[102] Singleton, D. A. and Thomas, A. A., *J. Am. Chem. Soc.*, **117**, 9357 (1995).

[103] Dappich, S., Ujaque, G., Maseras, F., Lledós, A., Musaeev, D. G., and Morokuma, K., *J. Am. Chem. Soc.*, **118**, 11660 (1996).
[104] Corey, E. J. and Noe, M. C., *J. Am. Chem. Soc.*, **118**, 11038 (1996).
[105] Nelson, D. W., Gypser, A., Ho, P. T., Kolb, H. C., Kondo, T., Kwong, H.-L., McGrath, D. V., Rubin, A. E., Norrby, P.-O., Gable, K. P., and Sharpless, K. B., *J. Am. Chem. Soc.*, **119**, 1840 (1997).
[106] Andrus, M. B., Lepore, S. D., and Sclafani, J. A., *Tetrahedron Lett.*, **38**, 4043 (1997).
[107] Corey, E. J., Noe, M. C., and Lin, S., *Tetrahedron Lett.*, **36**, 8741 (1995).
[108] Chougale, R. B., Kamble, D. L., and Nandibewoor, S. T., *Pol. J. Chem.*, **71**, 986 (1997); *Chem. Abs.*, **127**, 121436 (1997).
[109] Pogatchnik, D. M. and Wiemer, D. F., *Tetrahedron Lett.*, **38**, 3495 (1997).
[110] Davis, F. A., Reddy, B. A., Kasu, P. V. N., Portonovo, P. S., and Carroll, P. J., *J. Org. Chem.*, **62**, 3625 (1997).
[111] De Nooy, A. E. J., Besemer, A. C., and Van Bekkum, H., *Synthesis*, **1996**, 1153; *Chem. Abs.*, **125**, 300167 (1996).
[112] Rudakov, E. S., Lobachev, V. L., Geletii, Yu. V., and Balavoine, G. G. A., *Zh. Org. Khim.*, **32**, 522 (1996); *Chem. Abs.*, **125**, 327912 (1996).
[113] Khan, M. A. and Azeem, S. W., *Pak. J. Sci. Ind. Res.*, **38**, **1995**, 127; *Chem. Abs.*, **125**, 276273 (1996).
[114] Onami, T., Ikeda, M., and Woodard, S. S., *Bull. Chem. Soc. Jpn*, **69**, 3601 (1996).
[115] Chrisman, W. and Singaram, B., *Tetrahedron Lett.*, **38**, 2053 (1997).
[116] Blasko, A., Bunton, C. A., and Kumar, A., *J. Phys. Org. Chem.*, **10**, 427 (1997).
[117] Meenal, Kr. and Vimala, G. R., *J. Indian Chem. Soc.*, **74**, 43 (1997); *Chem. Abs.*, **126**, 199197 (1997).
[118] Brandt, C., Berndt, T., Rolle, W., Herrmann, H., Jacobi, H.-W., Reese, A., and Zellner, R., *Proc. EUROTRAC Symp. '96: Transp. Transform. Pollut. Troposphere, 1996*, **1**, 413 (1997); *Chem. Abs.*, **127**, 277880 (1997).
[119] Stavber, S., Kosir, I., and Zupan, M., *J. Org. Chem.*, **62**, 4916 (1997).
[120] Rozen, S. and Bareket, Y., *J. Org. Chem.*, **62**, 1457 (1997).
[121] Ramachandra, H., Mahadevappa, D. S., Rangappa, K. S., and Made Gowda, N. M., *Int. J. Chem. Kinet.*, **29**, 773 (1997).
[122] Rangappa, K. S., Ramachandra, H., and Mahadevappa, D. S., *J. Phys. Org. Chem.*, **10**, 159 (1997).
[123] Raghavendra, M. P., Mahadevappa, D. S., and Rangappa, K. S., *Indian J. Chem.*, **35A**, 1079 (1996); *Chem. Abs.*, **126**, 157733 (1997).
[124] Ahamed, K. A. B., *Indian J. Chem.*, **36A**, 222 (1997); *Chem. Abs.*, **127**, 50201 (1997).
[125] Mohan, R. V. G. K. and Sondu, S., *Acta Cienc. Indica, Chem.*, **22**, 13 (1996); *Chem. Abs.*, **127**, 95563 (1997).
[126] Mohan, R. V. G. K. and Sondu, S., *Acta Cienc. Indica, Chem.*, **22**, 3 (1996); *Chem. Abs.*, **127**, 81075 (1997).
[127] Mohan, R. V. G. K. and Sondu, S., *React. Kinet. Catal. Lett.*, **61**, 167 (1997); *Chem. Abs.*, **127**, 220340 (1997).
[128] Opeida, I. A. and Zalevskaya, N. M., *Zh. Org. Khim.*, **32**, 545 (1996); *Chem. Abs.*, **125**, 327913 (1996).
[129] Sugihara, M. and Tsukada, M., *Juntendo Igaku*, **42**, S37 (1997); *Chem. Abs.*, **127**, 161418 (1997).
[130] Rastogi, R. P., Khare, R., Misra, G. P., and Srivastava, S., *Indian J. Chem.*, **36A**, 19 (1997); *Chem. Abs.*, **126**, 204179 (1997).
[131] Pol, U. N., Yamgar, R. S., and Dodwad, S. S., *Asian J. Chem.*, **9**, 58 (1997); *Chem. Abs.*, **126**, 131113 (1997).
[132] Veeraiah, T. and Sondu, S., *J. Indian Chem. Soc.*, **74**, 402 (1997); *Chem. Abs.*, **127**, 176094 (1997).
[133] Goel, S., Kothari, S., and Banerji, K., *Indian J. Chem.*, **35B**, 1180 (1996); *Chem. Abs.*, **125**, 300315 (1996).
[134] Yang, H., Shen, B., Peng, T., Wang, G., Tang, Y., and Zhang, P., *Hangzhou Daxue Xuebao, Ziran Kexueban*, **23**, 168 (1996); *Chem. Abs.*, **125**, 248236 (1996).
[135] Pareek, A., Kothari, S., and Banerji, K. K., *Indian J. Chem.*, **35B**, 970 (1996); *Chem. Abs.*, **125**, 275068 (1996).
[136] Pareek, A., Varshney, S., and Banerji, K. K., *React. Kinet. Catal. Lett.*, **60**, 127 (1997); *Chem. Abs.*, **127**, 33775 (1997).
[137] Witkowski, S. and Poplawski, J., *Pol. J. Chem.*, **70**, 1448 (1996); *Chem. Abs.*, **126**, 60169 (1997).
[138] Puttaswamy, Mayanna, S. M., *Indian J. Chem.*, **36A**, 225 (1997); *Chem. Abs.*, **127**, 17295 (1997).
[139] Ramachandra, H., Mahadevappa, D. S., and Rangappa, K. S., *Indian J. Chem.*, **36B**, 333 (1997); *Chem. Abs.*, **127**, 161408 (1997).
[140] Ananda, S., Jagadeesha, M. B., Venkatesha, B. M., and Made Gowda, N. M., *Int. J. Chem. Kinet.*, **29**, 453 (1997).
[141] Ananda, S., Demappa, T., and Made Gowda, N. M., *Int. J. Chem. Kinet.*, **29**, 737 (1997).

[142] Mohana, K. N. and Yathirajan, H. S., *Asian J. Chem.*, **9**, 462 (1997); *Chem. Abs.*, **127**, 4773 (1997).
[143] Ramachandra, H., Mahadevappa, D. S., and Rangappa, K. S., *Proc. Indian Acad. Sci., Chem. Sci.*, **108**, 485 (1996); *Chem. Abs.*, **126**, 117660 (1997).
[144] Nair, T. D. R. and Zachariah, A., *Asian J. Chem.*, **9**, 297 (1997); *Chem. Abs.*, **126**, 343234 (1997).
[145] Bhavani, N. and Lily, K., *Oxid. Commun.*, **20**, 87 (1997); *Chem. Abs.*, **127**, 17292 (1997).
[146] Alvarez-Ibarra, C., Csák, A. G., Colmenero, B., and Quiroga, M. L., *J. Org. Chem.*, **62**, 2478 (1997).
[147] Babu, N. J. S., Sundar, B. S., and Murti, P. S. R., *J. Inst. Chem. (India)*, **68**, 81 (1996); *Chem. Abs.*, **126**, 74418 (1997).
[148] Kaushik, R. D. and Joshi, R., *Asian J. Chem.*, **9**, 527 (1997); *Chem. Abs.*, **127**, 4774 (1997).
[149] Ochiai, M., Ito, T., Takahashi, H., Nakanishi, A., Toyonari, M., Sueda, T., Goto, S., and Shiro, M., *J. Am. Chem. Soc.*, **118**, 7716 (1996).
[150] Ochiai, M., Nakanishi, A., and Yamada, A., *Tetrahedron Lett.*, **38**, 3927 (1997).
[151] Ochiai, M., Nakanishi, A., and Ito, T., *J. Org. Chem.*, **62**, 4253 (1997).
[152] De Munari, S., Frigerio, M., and Santagostino, M., *J. Org. Chem.*, **61**, 9272 (1996).
[153] Schaefer, C., Horie, O., Crowley, J. N., and Moortgat, G. K., *Geophys. Res. Lett.*, **24**, 1611 (1997); *Chem. Abs.*, **127**, 135481 (1997).
[154] Gutbrod, R., Meyer, S., Rahman, M. M., and Schindler, R. N., *Int. J. Chem. Kinet.*, **29**, 717 (1997).
[155] Zhang, X.-M. and Zhu, Q., *J. Org. Chem.*, **62**, 5934 (1997).
[156] Treacy J., Curley, M., Wenger, J., and Sidebottom, H., *J. Chem. Soc., Faraday Trans.*, **93**, 2877 (1997).
[157] Ponec, R., Yuzhakov, G., Haas, Y., and Samuni, U., *J. Org. Chem.*, **62**, 2757 (1997).
[158] Gutbord, R., Krafka, E., Schindler, R. N., and Cremer, D., *J. Am. Chem. Soc.*, **119**, 7330 (1997).
[159] Griesbaum, K., Dong, Y., and McCullough, K. J., *J. Org. Chem.*, **62**, 6129 (1997).
[160] Paryzek, Z. and Rychlewska, U., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2313.
[161] Karpel Vel Leitner, N., Ben Abdessalem, R., and Doré, M., *New J. Chem.*, **21**, 187 (1997).
[162] Grosjean, E. and Grosjean, D., *Int. J. Chem. Kinet.*, **29**, 855 (1997).
[163] Rakovsky, S., Cherneva, D., Deneva, M., and Ershov, V., *Oxid. Commun.*, **20**, 169 (1997); *Chem. Abs.*, **127**, 176083 (1997).
[164] Kashima, C., Maruyama, T., and Arao, H., *Rev. Heteroat. Chem.*, **16**, 197 (1997); *Chem. Abs.*, **127**, 95210 (1997).
[165] Mlochowski, J. and Said, S. B., *Pol. J. Chem.*, **71**, 149 (1997); *Chem. Abs.*, **126**, 224824 (1997).
[166] Bentley, P. A., Bergeron, S., Cappi, M. W., Hibbs, D. E., Hursthouse, M. B., Nugent, T. C., Pulido, R., Roberts, S. M., and Wu, L. E., *Chem. Commun.*, **1997**, 739.
[167] Sugimura, T., Fujiwara, Y., and Tai, A., *Tetrahedron Lett.*, **38**, 6019 (1997).
[168] Alcaide, B., Aly, M. F., and Sierra, M. A., *J. Org. Chem.*, **61**, 8819 (1996).
[169] Okuno, Y., *Chem. Eur. J.*, **3**, 212 (1997).
[170] Kitazume, T. and Kataoka, J., *J. Fluorine Chem.*, **80**, 157 (1996); *Chem. Abs.*, **126**, 131101 (1997).
[171] Kim, J. H., *Han'guk Nonghwa Hakhoechi*, **39**, 227 (1996); *Chem. Abs.*, **125**, 328895 (1996).
[172] Adam, W. and Golsch, D., *J. Org. Chem.*, **62**, 115 (1997).
[173] Yuasa, H., Kamata, Y., and Hashimoto, H., *Angew. Chem., Int. Ed. Engl.*, **36**, 868 (1997).
[174] Ramirez, G. G. and Rubio, A. M. F., *Mex. Rev. Latinoam. Quim.*, **25**, 22 (1996); *Chem. Abs.*, **127**, 50204 (1997).
[175] Pocalyko, D. J., Coope, J. L., Carchi, A. J., Boen, L., and Madison, S. A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 117.
[176] Ferrer, C., Echeverria, M., and Suzarte, A., *Rev. CENIC, Cienc. Quim.*, **27**, 13 (1997); *Chem. Abs.*, **127**, 234042 (1997).
[177] Ferrer, C., Echeverria, M., and Suzarte, A., *Rev. CENIC, Cienc. Quim.*, **27**, 16 (1997); *Chem. Abs.*, **127**, 234043 (1997).
[178] Singleton, D. A., Merrigan, S. R., Liu, J., and Houk, K. N., *J. Am. Chem. Soc.*, **119**, 3385 (1997).
[179] Becke, A. D., *J. Chem. Phys.*, **98**, 5648 (1993).
[180] Yamabe, S., Kondou, C., and Minato, T., *J. Org. Chem.*, **61**, 616 (1996).
[181] Angelis, Y. S. and Orfanopoulos, M., *J. Org. Chem.*, **62**, 6083 (1997).
[182] Pikh, Z. G., *Dopov. Nats. Akad. Nauk Ukr.*, **3**, 116 (1996); *Chem. Abs.*, **126**, 199203 (1997).
[183] Bach, R. D., Canepa, C., Winter, J. E., and Blanchette, P. E., *J. Org. Chem.*, **62**, 5191 (1997).
[184] Asensio, G., Mello, R., Gonzalez-Nunez, M. E., Castellano, G., and Corral, J., *Angew. Chem., Int. Ed. Engl.*, **35**, 217 (1996).
[185] Asensio, G., Mello, R., Gonzalez-Nunez, M. E., Boix, C., and Royo, J., *Tetrahedron Lett.*, **38**, 2373 (1997).
[186] Murray, R. W. and Gu, H., *J. Phys. Org. Chem.*, **9**, 751 (1996).
[187] Gaggero, N., D'Accolti, L., Colonna, S., and Curci, R., *Tetrahedron Lett.*, **38**, 5559 (1997).

[188] Kazakov, D. V., Kabal'nova, N. N., Khursan, S. L., and Shereshovets, V. V., *Russ. Chem. Bull. (transl. Izv. Akad. Nauk, Ser. Khim.)*, **46**, 663 (1997); *Chem. Abs.*, **127**, 220338 (1997).
[189] Burke, A. J. and O'Sullivan, W. I., *Tetrahedron*, **53**, 8491 (1997).
[190] Houk, K. N. Liu, J., DeMello, N. C., and Condroski, K. R., *J. Am. Chem. Soc.*, **119**, 10147 (1997).
[191] Bach, R. D., Andres, J. L., and Davis, F. A., *J. Org. Chem.*, **57**, 613 (1992).
[192] Manoharan, M. and Venuvanalingam, P., *THEOCHEM*, **394**, 41 (1997); *Chem. Abs.*, **127**, 80979 (1997).
[193] Miaskiewicz, K., Teich, N. A., and Smith, D. A., *J. Org. Chem.*, **62**, 6493 (1997).
[194] Adam, W., Curci, R., D'Accolti, L., Dinoi, A., Fusco, C., Gasparrini, F., Kluge, R., Paredes, R., Schulz, M., Smerz, A. K., Veloza, L. A., Weinkotz, S., and Winde, R., *Chem. Eur. J.*, **3**, 105 (1997).
[195] Wang, Z.-X., Tu, Y., Frohn, M., and Shi, Y., *J. Org. Chem.*, **62**, 2328 (1997).
[196] Yu, T., Wang, Z.-X., and Shi, Y., *J. Am. Chem. Soc.*, **118**, 9806 (1996).
[197] Johnson, P. and Taylor, R. J. K., *Tetrahedron Lett.*, **38**, 5873 (1997).
[198] Ishiguro, K., Nojima, T., and Sawaki, Y., *J. Phys. Org. Chem.*, **10**, 787 (1997).
[199] Lempers, H. E. B., van Crey, M. J., and Sheldon, R. A., *Recl. Trav. Chim. Pays-Bas*, **115**, 542 (1996); *Chem. Abs.*, **126**, 171191 (1997).
[200] Thiel, W. R. and Eppinger, J., *Chem. Eur. J.*, **3**, 696 (1997).
[201] Thiel, W. R., *J. Mol. Catal. A: Chem.*, **117** (1–3, Proceedings of the 6th International Symposium on the Activation of Dioxygen and Homogeneous Catalytic Oxidation (1996), **1997**, 449; *Chem. Abs.*, **126**, 224922 (1997).
[202] Karunakaran, C. and Palanisamy, P. N., *Pol. J. Chem.*, **70**, 1573 (1996); *Chem. Abs.*, **126**, 117663 (1997).
[203] De Souza Batista, C. M., De Souza Melo, S. C., Gelbard, G., and Lachter, E. R., *J. Chem. Res.*, **92** (1997).
[204] Oldroyd, R. D., Thomas, J. M., Maschmeyer, T., MacFaul, P. A., Snelgrove, D. W., Ingold, K. U., and Wayner, D. D. M., *Angew. Chem., Int. Ed. Engl.*, **35**, 2787 (1996); *Chem. Abs.*, **126**, 131335 (1997).
[205] Oldroyd, R. D., Thomas, J. M., and Sankar, G., *Chem. Commun.*, **1997**, 2025.
[206] Forlano, P., Olabe, J. A., Magallanes, J. F., and Blesa, M. A., *Can. J. Chem.*, **75**, 9 (1997).
[207] Amels, P., Elias, H., and Wannowius, K.-J., *J. Chem. Soc., Faraday Trans.*, **93**, 2537 (1997).
[208] Mori, H., Ikoma, K., and Katsumura, S., *Chem. Commun.*, **1997**, 2243.
[209] Komissarov, V. D., Nazarov, A. M., and Yamilova, G. A., *Russ. Chem. Bull. (transl. Izv. Akad. Nauk, Ser. Khim.)*, **46**, 261 (1997); *Chem. Abs.*, **127**, 148885 (1997).
[210] Nojima, T., Ishiguro, K., and Sawaki, Y., *J. Org. Chem.*, **62**, 6911 (1997).
[211] Pierlot, C. and Aubry, J.-M., *Chem. Commun.*, **1997**, 2289.
[212] Stratakis, M. and Orfanopoulis, M., *Tetrahedron Lett.*, **38**, 1067 (1997).
[213] Hild, M. and Brauer, H.-D., *Ber. Bunsen-Ges.*, **100**, 1210 (1996); *Chem. Abs.*, **125**, 247083 (1996).
[214] Yoshioka, Y., Yamada, S., Kawakami, T., Nishino, M., Yamaguchi, K., and Saito, I., *Bull. Chem. Soc. Jpn*, **69**, 2683 (1996).
[215] Ham, S. W. and Yoo, J. S., *Chem. Commun.*, **1997**, 929.
[216] Borisov, I. M., Zimin, Y. S., and Sharafutdinova, Z. F., *Izv. Vyssh. Uchebn. Zaved., Khim. Khim. Tekhnol.*, **39**, 65 (1996); *Chem. Abs.*, **126**, 211743 (1997).
[217] Jeziorek, D., Ossowski, T., Liwo, A., Dyl, D., Nowacka, M., and Woznicki, W., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 229.
[218] Kano, K., Nakagawa, M., Takagi, K., and Ikeda, T., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1111.
[219] Yoshioka, Y., Yamanaka, S., Yamada, S., Kawakami, T., Nishino, M., Yamaguchi, K., and Nishinaga, A., *Bull. Chem. Soc. Jpn*, **69**, 2701 (1996).
[220] Zanocco, A. L., Lemp, E., and Günther, G., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1299.
[221] Upadhyaya, H. P., Naik, P. D., Pavanaja, U. B., Kumar, A., Vatsa, R. K., Sapre, A. V., and Mittal, J. P., *Chem. Phys. Lett.*, **274**, 383 (1997); *Chem. Abs.*, **127**, 176091 (1997).
[222] Martinez de la Cuesta, P. J., Rus, M. E., and Romero, S. F., *Afinidad*, **54**, 309 (1997); *Chem. Abs.*, **127**, 135483 (1997).
[223] Petrov, L. V. and Solyanikov, V. M., *Dokl. Akad. Nauk*, **350**, 357 (1996); *Chem. Abs.*, **126**, 131118 (1997).
[224] Simon, V., Simon, Y., Scacchi, G., and Baronnet, F., *Can. J. Chem.*, **75**, 575 (1997).
[225] Pecullan, M., Brezinsky, K., and Glassman, I., *J. Phys. Chem. A*, **101**, 3305 (1997).
[226] *Symp. (Int.) Combust., [Proc.] 26th*, **1**, 589 *et seq*. (1996); *Chem. Abs.*, **126**, 277089–277097 (1997).
[227] Borisov, I. M., Zimin, Y. S., and Sharafutdinova, Z. F., *Izv. Vyssh. Uchebn. Zaved., Khim. Khim. Tekhnol.*, **39**, 65 (1996); *Chem. Abs.*, **126**, 211743 (1997).
[228] Porter, N. A., Havrilla, C. M., and Kenar, J. A., *NATO ASI Ser.*, **3**, *27* (Free Radicals in Biology and Environment), **1997**, 121; *Chem. Abs.*, **127**, 17848 (1997).
[229] Ishihara, K., Kurihara, H., and Yamamoto, H., *J. Org. Chem.*, **62**, 5664 (1997).
[230] Alifanova, E. N., Atroshchenko, Yu. M., Akhromushkina, I. M., Gitis, S. S., Savinova, L. N., Kaminskii, A. Ya., and Sychev, V. S., *Zh. Obshch. Khim.*, **66**, 324 (1996); *Chem. Abs.*, **125**, 275102 (1996).

[231] Alifanova, E. N., Atroshchenko, Y. M., Akhromushkina, I. M., Savinova, L. N., Gitis, S. S., and Kaminskii, A. Y., *Zh. Obshch. Khim.*, **66**, 1173 (1996); *Chem. Abs.*, **126**, 18513 (1997).
[232] Wang, W., Li, T., and Attardo, G., *J. Org. Chem.*, **62**, 6598 (1997).
[233] Hoegy, S. E. and Mariano, P. S., *Tetrahedron*, **53**, 5027 (1997).
[234] Momohara, I., *Biotechnol. Pulp Pap. Ind., Proc. Int. Conf., 6th, 1995*, 429 (1996); *Chem. Abs.*, **126**, 46814 (1997).
[235] Brown, H. C. and Ramachandran, P. V., *ACS Symp. Ser.*, **641** (Reductions in Organic Synthesis), 1 (1996); *Chem. Abs.*, **125**, 246827 (1996).
[236] Wittmann, S. and Schoenecker, B., *J. Prakt. Chem./Chem.-Ztg.*, **338**, 759 (1996); *Chem. Abs.*, **126**, 7431 (1997).
[237] Gribble, G. W., *ACS Symp. Ser.*, **641** (Reductions in Organic Synthesis), 167 (1996); *Chem. Abs.*, **125**, 246832 (1996).
[238] Petukhov, P. A. and Tkachev, A. V., *Tetrahedron*, **53**, 2535 (1997).
[239] Liu, C. and Burnell, D. J., *Tetrahedron Lett.*, **38**, 6573 (1997).
[240] Leclaire, M. and Jean, P., *Bull. Soc. Chim. Fr.*, **133**, 801 (1996).
[241] Deratani, A., Renard, E., Djedani-Pilard, F., and Perly, B., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1517.
[242] Park, K. K., Sim, W.-J., and Park, J. W., *J. Inclusion Phenom. Mol. Recognit. Chem.*, **27**, 41 (1997); *Chem. Abs.*, **126**, 305434 (1997).
[243] Harden, R. C., Hodgkinson, T. J., McKillop, A., Prowse, W. G., and Urquhart, M. W. J., *Tetrahedron*, **53**, 21 (1997).
[244] Haddad, M., Dorbais, J., and Larchevque, M., *Tetrahedron Lett.*, **34**, 5981 (1997).
[245] Ashby, E. C. and Welder, C. O., *J. Org. Chem.*, **62**, 3542 (1997).
[246] Mitrochkine, A. A., Blain, I., Bit, C., Canlet, C., Pierre, S., Courtieu, J., and Réglier, M., *J. Org. Chem.*, **62**, 6204 (1997).
[247] Sy, L.-K., Hui, S.-M., Cheubg, K.-K., and Brown, G. D., *Tetrahedron*, **53**, 7493 (1997).
[248] Tomoda, S. and Senju, T., *Tetrahedron*, **53**, 9057 (1997).
[249] Connolly, T. J. and Durst, T., *Can. J. Chem.*, **75**, 536 (1997).
[250] Connolly, T. J. and Durst, T., *Can. J. Chem.*, **75**, 542 (1997).
[251] Fraser, R. R., Faibish, N. C., Kong, F., and Bednarski, K., *J. Org. Chem.*, **62**, 6164 (1997).
[252] Mayr, H. and Dogan, B., *Tetrahedron Lett.*, **38**, 1013 (1997).
[253] Solladié, G., Hanquet, G., and Rolland, C., *Tetrahedron*, **38**, 5847 (1997).
[254] Zhao, M., King, A. O., Larsen, R. D., Verhoeven, T. R., and Reider, P. J., *Tetrahedron Lett.*, **38**, 2641 (1997).
[255] Ramachandran, P. V., Malhotra, S. V., and Brown, H. C., *Tetrahedron Lett.*, **38**, 957 (1997).
[256] Gamble, M. P., Studley, J. R., and Wills, M., *Tetrahedron: Asymmetry*, **7**, 3071 (1996).
[257] Chen, K., *Huaxue* **54**, 117 (1996); *Chem. Abs.*, **126**, 171082 (1997).
[258] Quallich, G. J., Blake, J. F., and Woodall, T. M., *ACS Symp. Ser.*, **641** (Reductions in Organic Synthesis), 112 (1996); *Chem. Abs.*, **125**, 274990 (1996).
[259] King, A. O., Mathre, D. J., Tschaen, D. M., and Shinkai, I., *ACS Symp. Ser.*, **641** (Reductions in Organic Synthesis), 98 (1996); *Chem. Abs.*, **125**, 247640 (1996).
[260] Ramachandran, P. V. and Brown, H. C., *ACS Symp. Ser.*, **641** (Reductions in Organic Synthesis), 84 (1996); *Chem. Abs.*, **125**, 246830 (1996).
[261] Biswas, K. M., Dhara, R. N., Mallik, H., Sinha-Chaudhuri, A., Halder, S., Saha, A., De, P., and Brahmachari, A. S., *Indian J. Chem.*, **36B**, 318 (1997); *Chem. Abs.*, **127**, 161660 (1997).
[262] Puszko, A. and Ciurla, H., *Pr. Nauk. Akad. Ekon. im. Oskara Langego Wroclawiu*, **728**, 55 (1996); *Chem. Abs.*, **127**, 34066 (1997).
[263] Glod, G., Angst, W., Holliger, C., and Schwarzenbach, R. P., *Environ. Sci. Technol.*, **31**, 253 (1997); *Chem. Abs.*, **126**, 30980 (1997).
[264] Bianchini, R., Forte, C., Musumarra, G., Pinzino, C., and Sergi, C., *Tetrahedron*, **53**, 6907 (1997).
[265] Isaacs, N. S. and van Eldik, R., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1465.
[266] Lin, Z., Chen, J., and Valenta, Z., *Tetrahedron Lett.*, **38**, 3863 (1997).
[267] Nudelman, N. S. and Mendiara, S., *J. Phys. Org. Chem.*, **10**, 233 (1997).
[268] Xu, Z.-L. and Wong, H. N. C., *Youji Huaxue*, **16**, 440 (1996); *Chem. Abs.*, **126**, 46915 (1997).
[269] Howarth, J., *Prep. Alkenes*, **1996**, 117; *Chem. Abs.*, **126**, 276967 (1997).
[270] Riad, Y., Asaad, A. N., El-Nahas, H. M., and Madkour, A. E., *Egypt. J. Chem.*, **39**, 353 (1996); *Chem. Abs.*, **125**, 327911 (1996).
[271] Reynolds, M. P., Chan, W. C., Raymond, M., and Russell, E., *Chem. Ind. (Dekker)*, **68** (Catalysis of Organic Reactions), 457 (1996); *Chem. Abs.*, **125**, 327921 (1996).
[272] Ley, S. V. and Meek, G., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1125.
[273] Klemm, L. H. and Orchin, M., *Int. J. Chem. Kinet.*, **29**, 473 (1997).

[274] Nishide, K., Shigeta, Y., Obata, K., and Node, M., *J. Am. Chem. Soc.*, **118**, 13103 (1997).
[275] Fujita, M., Takarada, Y., Sugimura, T., and Tai, A., *Chem. Commun.*, **1997**, 1631.
[276] Meyer-Stork, M. A., Haag, D., and Scharf, H.-D., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 593.
[277] Gervay, J. and Gregar, T. Q., *Tetrahedron Lett.*, **38**, 5921 (1997).
[278] Elliott, R. P., Fleet, G. W. J., Gyoung, Y. S., Ramsden, N. G., and Smith, C., *Tetrahedron Lett.*, **31**, 3785 (1990).
[279] Wagner, G., Herrmann, R., and Schier, A., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 701.
[280] Chiu, C. C., Chung, A., Barletta, G., and Jordan, F., *J. Am. Chem. Soc.*, **118**, 11026 (1996).
[281] Dicks, A. P., Beloso, P. H., and Williams, D. L. H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1429.
[282] Reynolds, K. A. and Holland, K. A., *Chem. Soc. Rev.*, **26**, 337 (1997).
[283] Sato, M., *Nippon Kagaku Kaishi*, **7**, 508 (1997); *Chem. Abs.*, **127**, 190574 (1997).
[284] Cheng, J.-P. and Lu, Y., *J. Phys. Org. Chem.*, **10**, 577 (1997).
[285] Obika, S., Nishiyama, T., Tatematsu, S., Miyashita, K., and Imanishi, T., *Tetrahedron*, **53**, 3073 (1997).
[286] Schröer, J., Sanner, M., Reymond, J.-L., and Lerner, R. A., *J. Org. Chem.*, **62**, 3220 (1997).
[287] Abe, M., Sumida, Y., and Nojima, M., *J. Org. Chem.*, **62**, 752 (1997).
[288] Bakos, J., Orosz, A., Cserepi, S., Toth, I., and Sinou, D., *J. Mol. Catal. A: Chem.*, **116**, 85 (1997); *Chem. Abs.*, **126**, 199306 (1997).

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CHAPTER 6

Carbenes and Nitrenes

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Reviews

Reviews have appeared on the absolute kinetics of intramolecular alkylcarbene reactions,[1] the reactions between carbenes and the O−H bond,[2] carbenes and carboranes,[3] the use of carbenes and carbenoids in the synthesis of heterocycles,[4] and the physical organic chemistry of Fischer carbene complexes.[5]

Structure and Reactivity

Energy-resolved rate constant measurements near the threshold for triplet methylene formation from ketene have been used to provide confirmation of the fundamental hypothesis of statistical transition state theory (that rates are controlled by the number of energetically accessible vibrational states at the transition state).[6] The electronic structure and aromaticity of planar singlet Π^2-carbenes has been studied by π-electron coupling perturbation theory.[7] The heats of formation of three ground-state triplet carbenes have been determined by collision-induced dissociation threshold analysis.[8] The heats of formation of methylene, vinylcarbene ($H_2C{=}CHCH$), and phenylcarbene were found to be 92.2 ± 3.7, 93.3 ± 3.4, and 102.8 ± 33.5 kcal mol^{-1}, respectively.

Ab initio and molecular orbital calculations have been used to study the interactions of organic radicals coupled by *m*-phenylene.[9,10] These methods were used to explain the low-lying excitation spectra of radical ions such as (**1**).[9] The tricarbene (**2**) was also shown to have a high-spin ground state irrespective of the value of the dihedral angle

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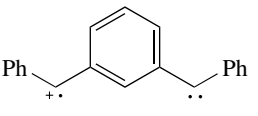
ϕ.[10] This reflects the importance of through-bond interactions in comparison to through-space effects. The chemical reactivity of the 1,2,4-triazol-5-ylidene species (**3**) has been studied.[11] Reactivity typical of a stable nucleophilic carbene was seen (insertion into OH, NH, SH bonds, protonation, nucleophilic attack on heterocumulenes).



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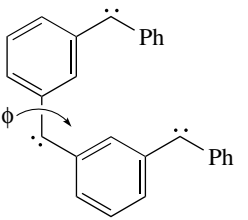

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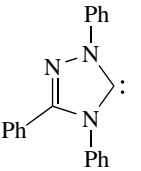
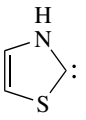


(**3**)

The dihydrothiazol-2-ylidene (**4**) was generated by photolysis of matrix-isolated thiazol-2-carboxylic acid.[12] Calculations suggested that the barrier to isomerization to thiazole is about 42.3 kcal mol^{-1} and that the carbene resembles the related imidazol-2-ylidene in structure. An *ab initio* study of hydroxyoxiranone predicted that the decarboxylation of the zwitterion (**5**) to form hydroxycarbene (**6**) would be favourable *in vacuo* but not in water.[13] A theoretical study showed that dihalosulfenes ($X_2C{=}SO_2$) are best viewed as dihalocarbene–SO_2 complexes with a carbon–sulfur bond order of approximately zero.[14] In a study directed at the elusive thionformic acid (**7**), tandem mass spectrometric methods were applied to isomeric ethyl thioformates.[15] The results suggest that the radical cations generated have the carbene structure $[(HS)C(OH)]^{+\cdot}$.



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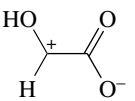
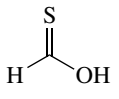


(**5**)

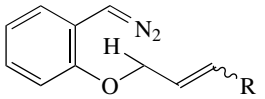
(**6**)



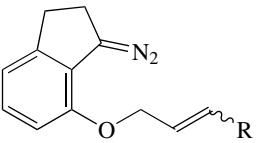
(**7**)

Analysis of the product distributions arising from both sensitized and non-sensitized irradiation of 2-allyloxyphenyldiazo species (**8**) showed that the C−H insertion product and much of the cyclopropanation arise from the triplet carbene.[16] For the singlet carbene, intermolecular O−H insertion with methanol is about 50 times faster than intramolecular addition to the double bond. In this system, intramolecular reactions and intersystem crossing of the triplet carbene proceed at similar rates. In the closely related indanyl system (**9**), the smaller RCR angle stabilizes the singlet state relative to the triplet and the intramolecular reactivity is dominated by the singlet state.[17]

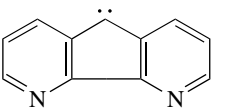
Non-stereospecific cyclopropanation reactions of the diazafluorenylidene (**10**), generated by photolysis of the diazo compound, indicated a triplet carbene.[18] Competition experiments suggested a singlet–triplet equilibrium at room temperature and a Hammett study of additions to substituted styrenes indicated that the carbene reacts as an electrophile ($\rho = -0.65$).



(**8**)

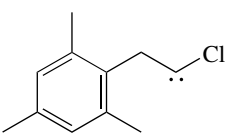


(**9**)

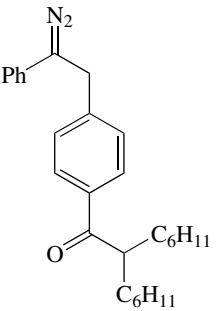


(**10**)

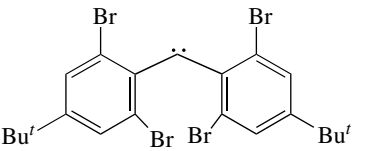
It was found that significant Arrhenius curvature arose due to the intrusion of intermolecular channels to give azine and carbene dimers during the reactions of mesitylchlorocarbene (**11**).[19] This curvature disappeared upon dilution of the diazirine precursors. The authors comment that such effects must be carefully excluded before interpreting Arrhenius curvature in similar systems. The invariance of the ratio of 1,2-H shift and intermolecular reaction with methanol on photolysis of the diazo compound (**12**) under both sensitized and non-sensitized conditions is consistent with competing reactions of a spin-equilibrated carbene.[20] The simpler diphenyl system [$PhC(N_2)CH_2Ph$] gave results consistent with some product formation via excited states of the diazo precursor. An account has appeared describing the role of steric and electronic effects in determining the reactivity of persistent triplet carbenes such as (**13**) ($t_{1/2} = 16$ s in benzene at room temperature).[21]



(**11**)



(**12**)



(**13**)

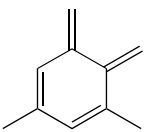
Phenylcarbene and *o*-tolylcarbene (produced by laser flash photolysis of the diazo compounds) could not be directly observed in pentane at room temperature.[22] Ylide formation in the presence of pyridine allowed the lifetimes of these species to be determined as 74 ns. In contrast, transient spectra of triplet mesitylcarbene were

observed and the lifetime measured as 500 ns. The co-product benzoquinodimethane (**14**) was observed to arise by H-atom transfer in the excited state of the diazo compound in solution and directly from the carbene in a low-temperature matrix.

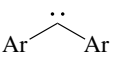
Studies of sterically crowded diarylcarbenes (**15**) have shown that dimesitylcarbene (**15**; Ar = 2,4,6-$Me_3C_6H_2$) decays by dimerization with a half-life of 160 ms.[23] Didurylcarbene (**15**; Ar = 2,3,5,6-Me_4C_6H) has a lifetime of 410 ms due to buttressing of the *o*-Me groups by the *m*-Me groups and decamethyldiphenylcarbene (**15**; Ar = Me_5C_6) has a lifetime of only 180 ms owing to an increased rate of intramolecular H-abstraction from the *o*-Me groups. The related tri(*t*-butyl)diphenylcarbene (**15**; Ar = 2,4,6-$Bu^t_3C_6H_2$) had a lifetime of 125 s and decayed by H-abstractions from the *o*-Bu^t groups. The use of bulky bicyclo[2.2.2]octyl groups gave rise to a triplet carbene (**16**) with a lifetime of 1.5 s in benzene at 20 °C.[24] Rate measurements showed that this species was actually more reactive than didurylcarbene towards typical triplet quenchers.

Density functional theory calculations showed that for vinylidenecarbenes, through-bond inductive stabilization effects were of greatest importance in determining the influence of substitution on singlet–triplet splittings.[25] For halogenated carbenes, orbital rehybridization and charge redistribution effects are large. The absolute kinetics of reactions of phenylcarbene and pentafluorophenylcarbene with various carbene quenchers was studied by laser flash photolysis.[26] Both carbenes have triplet ground states (with single–triplet splittings of 2.3 and 3.1 kcal mol^{-1}, respectively) but react in solution
at room temperature via the low-lying singlet state. Unlike the phenylnitrenes, perfluorination does not have a significant effect on the kinetics. This is probably due to the fact that phenylcarbene is a closed-shell structure whereas phenylnitrene is an open-shell ground state which can become a stabilized closed-shell form upon perfluorination.

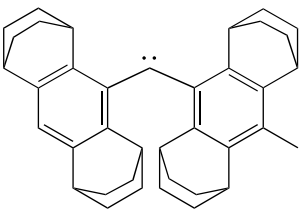
Laser flash photolysis of perfluorophenyl azide and perfluorobiphenyl azide gives the singlet nitrenes (**17**).[27] The fluorine atoms significantly raise the barrier to rearrangement of the nitrene, and increase the lifetime (32 ns for X = F and 254 ns for X = C_6F_5 at 21 °C). Absolute rate constants for intersystem crossing, ylide formation with pyridine, and rearrangement were determined. Singlet phenylnitrene has been spectroscopically observed in pentane at various temperatures.[28] The decay of this species yielded an activation energy of 6.2 ± 0.4 kcal mol^{-1} with $A = 10^{13.6\pm0.4}$ s^{-1}.



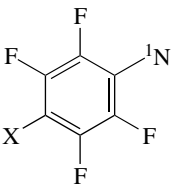
(**14**)



(**15**)



(**16**)

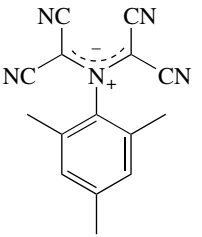


(**17**)

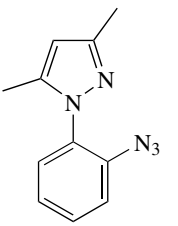
X = F or C_6F_5

The barrier to rearrangement is larger than previous deductions because intersystem crossing is much slower than originally anticipated.

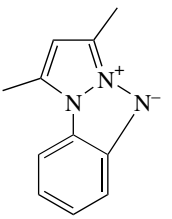
Photolysis of mesitylazide in the presence of tetracyanoethane gave rise to the azomethine ylide (**18**) by trapping of the singlet nitrene with a rate constant of approximately 10^9 mol^{-1} s^{-1}.[29] Above 200 K, photo-decomposition of the azidophenylpyrazole (**19**) gives rise to the pyrazolobenzotriazole (**20**) by cyclization of the singlet nitrene.[30] At lower temperatures the azo compound forms together with products derived from the triplet nitrene. The dehydroazepine (which would form by ring expansion of the nitrene) is not a kinetically distinguished isomer (or is in equilibrium with the singlet nitrene).



(**18**)



(**19**)

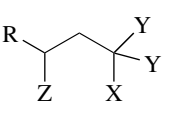


(**20**)

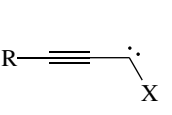
Generation

The reaction of $CHBr_3$ and $CHCl_3$ with magnesium under Grignard conditions was shown to form cyclopropanes in the presence of alkenes.[31] Treatment of 1,1,1,3-tetrahalopropanes (**21**; X = Cl, Br, F; Y, Z = Cl or Br) with $KOBu^t$ or alkali metal hydroxides under phase transfer conditions in the presence of excess alkene gave rise to cyclopropanes via a postulated alk-1-ynylhalocarbene (**22**).[32]

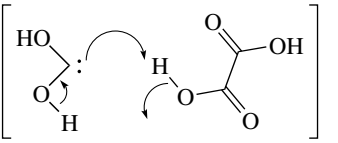
Density functional theory was used to show that unimolecular formation of CO_2 and dihydroxycarbene from oxalic acid has a barrier of 31 kcal mol^{-1}.[33] The barrier for H-migration in dihydroxycarbene to form formic acid was shown to be less than 37 kcal mol^{-1} if an exchange with oxalic acid was involved (**23**). QRRK analysis of the pyrolytic decomposition of 2-chloro-1,1,1,2-tetrafluoroethane ($F_3CCFClH$) indicated that the primary route is α-elimination of HCl to form singlet F_3CFC:.[34]



(**21**)



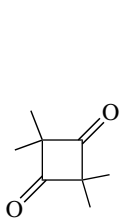
(**22**)



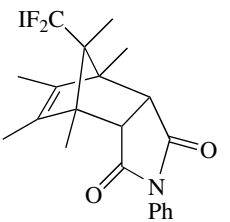
(**23**)

Electron impact mass spectrometry of the cyclobutanedione (**24**) gives rise to dimethylcarbene radical cation.[35] Appearance energy measurements and *ab initio* calculations indicated that the radical cation lies 84 kJ mol^{-1} above the propene radical cation and is separated from it by a barrier of 35 kJ mol^{-1}. Diarylcarbene radical cations have been generated by double flash photolysis of diaryldiazomethanes in the presence of a quinolinium salt (by photo-induced electron transfer followed by photo-initiated loss of N_2).[36] Absolute rate constants for reactions with alkenes showed the radicals to be highly electrophilic. In contrast to many other cation radicals, they also showed significant radicophilic properties.

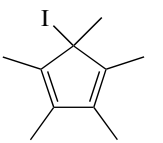
The attempted trifluoromethylation of pentamethylcyclopentadienyllithium by reaction with F_3CI in the presence of *N*-phenylmaleimide gave rise to the unexpected Diels–Alder adduct (**25**).[37] The authors proposed that the cyclopentadienyl anion captures the iodine of CF_3I to give (**26**) and trifluoromethyllithium which then produces difluorocarbene (F_2C:) which inserts into the C−I bond of (**26**) to form the difluoroiodomethylated product. The observed regioselectivity of addition of thiazyl chloride (N≡S−Cl) to 2,5-diarylfurans provided support for a mechanism involving carbene and nitrene intermediates (**27**).[38]



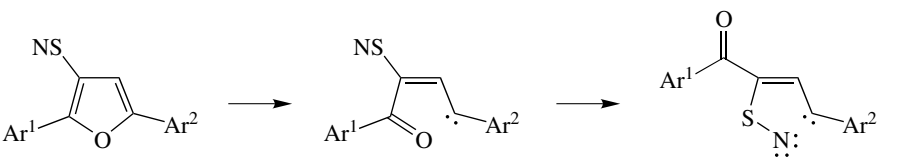
(**24**)



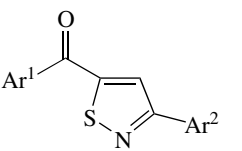
(**25**)



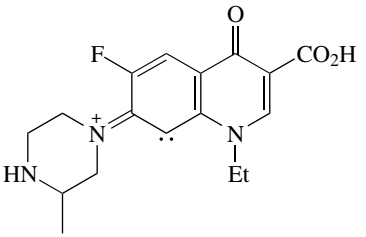
(**26**)



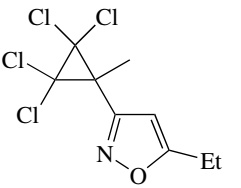
(**27**)



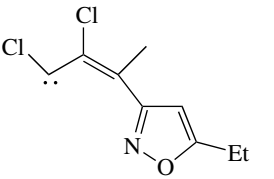
A carbene intermediate (**28**) was proposed in the photo-decomposition of the antibiotic agent lomefloxacin.[39] Treatment of isoxazole-containing tetrachlorocyclopropanes such as (**29**) with MeLi gave rise to 1-aza fulvenes via postulated vinylcarbene intermediates (**30**).[40]



(**28**)

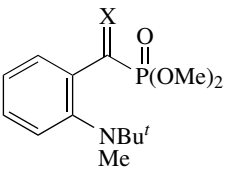


(**29**)

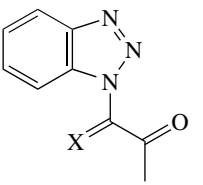


(**30**)

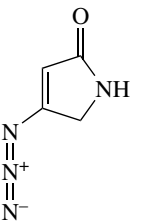
Reaction of the benzoylphosphonate (**31**; X = O) with trimethylphosphite was proposed to proceed via deoxygenation to form the carbene (**31**; X =:).[41] In a single case, flash vacuum pyrolysis of the β-oxophosphorus ylide (**32**; X = Bu_3P) gave rise (by extrusion of Bu_3P) to products derived from the corresponding carbene (**32**; X =:).[42] Similar compounds with larger groups than Me next to the carbonyl did not undergo the same chemistry perhaps due to different conformational preferences (leading to loss of Bu_3P=O instead). An *ab initio* study of the zwittazido cleavage of 4-azido-2-pyrrolines (**33**) failed to detect any nitrene intermediate.[43] Rate determining loss of N_2 from the *trans* conformer (**33**) leading to an azirine intermediate was the most favoured path.



(**31**)



(**32**)



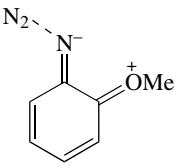
(**33**)

+R-type *para* substituents lead to large increases in the rates of thermolysis of azidobenzenes.[44] In nitrobenzene at 120 °C the rates follow the Hammett-type relationship $\log k = -5.44 - 2.33\sigma_1 - 1.44R^+$ indicating conjugative stabilization of a nitrene-like transition state. +R-type *ortho*-substituents cause even larger rate increases, suggesting a special resonance proximity effect (**34**).

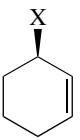
Addition

A review has appeared on the synthesis of enantiomerically enriched aziridines by the addition of nitrenes to alkenes and of carbenes to imines.[45] A study of the metal-catalysed aziridination of imines by ethyl diazoacetate found that main group complexes, early and late transition metal complexes, and rare-earth metal complexes can catalyse the reaction.[46] The proposed mechanism did not involve carbene intermediates, the role of the metal being as a Lewis acid to complex the imine lone pair. Ruthenium porphyrins were found to be efficient catalysts for the cyclopropanation of styrenes.[47] High diastereoselectivities in favour of the *anti*-product were seen but the use of chiral porphyrins gave only low *ee*s.

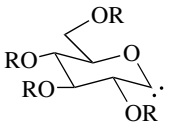
The slight preference for *syn* addition of singlet methylene to cyclohexenes (**35**; X = Cl, OMe) was attributed to a reversible interaction between the carbene and the substituent.[48] This was not, however, obviously ylide formation but could be long-range dipole–dipole interactions or a contact pair. The stereoselectivity of addition of H(Br)C: to cycloalkenes was seen to increase from cycloocta-1,3-diene (unselective), cyclohexene (1.6 : 1 *endo* : *exo*), cyclooctene (2.2–2.8 : 1), to cycloocta-1,5-diene, (*Z*)-cyclodecene, and cyclododecene (which all gave exclusively *endo* addition).[49] The authors proposed a close approach of one or more distantly bound hydrogen atoms to the double bond resulting in favourable H-bonding to the bromine of the carbenoid. The addition of glycosylidene carbenes (**36**) to dihydrofuran only gave good yields when R = pivaloyl.[50] Reactions with other enol ethers gave poor yields and/or low diastereoselectivities.



(**34**)



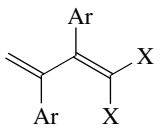
(**35**)



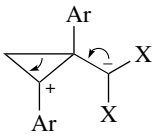
(**36**)

The production of buta-1,3-dienes (**37**) by reaction of 1,2-diarylcyclopropenes with dihalocarbenes is thought to involve electrophilic attack of the carbene to give a dipolar intermediate (**38**).[51] The addition of carbene to CO and $H_2C{=}O$ has been studied by MNDO calculations.[52] Photolysis of diethyl diazomalonate in a CO matrix at low temperature gave rise to ketenes by immediate trapping of the postulated carbene (**39**).[53] The major products of reaction between dichlorocarbene and cyclone were CO and the *gem*-dichloro species (**40**).[54] The predominance of this pathway over formation of the dichlorooxirane or the cyclopropane is attributed to the aromatic nature of the carbonyl ylide and its twist geometry.

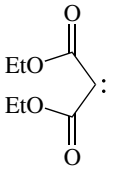
Addition of dimethoxycarbene (generated by thermolysis of the corresponding oxadiazoline) to 9-fluorenone gave rise to the unstable oxirane (observed by ^{1}H NMR).[55] This species was shown to rearrange to the ester (**41**) by an intramolecular methoxy transfer from (**42**) [and not by a 5-*endo*-*tet* methyl transfer from (**43**)].



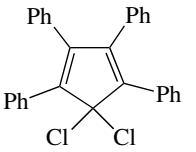
(**37**)



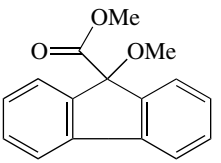
(**38**)



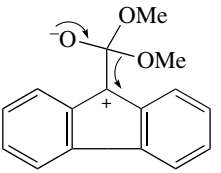
(**39**)



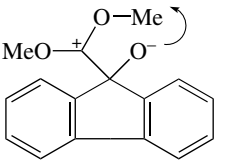
(**40**)



(**41**)



(**42**)



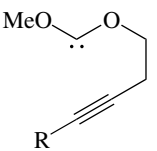
(**43**)

Dialkoxycarbenes (**44**) with a tethered triple bond undergo intramolecular cyclization to give dialkoxyvinylcarbene intermediates.[56] The regioselectivity (to give endocyclic or exocyclic carbenes by attack on the far or near end of the alkyne) is dependent on the alkyne substituent (R). Moderate to high *anti*-diastereoselectivity was observed in the attack of ethoxycarbonylnitrene on β-silylated silyl ketene acetals (**45**) to give α-amino acid derivatives.[57] A laser flash photolysis study of the reactivity of singlet pentafluorophenylnitrene showed that it is most reactive towards electron-rich alkenes.[58] The reactivity spread is, however, very small (and similar to that of phenylcarbene).

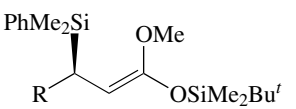
Insertion and Abstraction

No trace of any ring expanded products due to C−C insertion was seen in the reactions of methylene with strained spirobicyclic molecules (**46**) and (**47**).[59] *Ab initio* calculations on the reaction between quartet methylidyne (CH) with methane predicted a barrier of 3.5 kcal mol^{-1}.[60]

Reaction of alkynylbisiodonium ditriflates (**48**) with sodium phenoxide gave rise to good yields of benzofurans by 1,5-CH insertion of the intermediate alkylidenecarbene (**49**).[61] The selectivity of 1,5-CH insertion of carbene (**50**) was observed to be highly dependent on the method of carbene generation.[62]

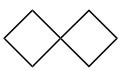


(**44**)

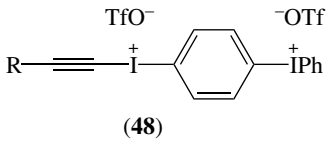


(**45**)

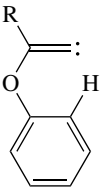
(**46**)



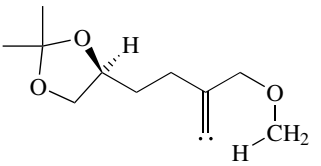
(**47**)



(**48**)

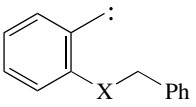


(**49**)

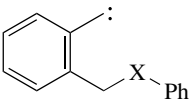


(**50**)

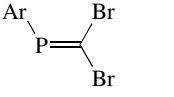
The arylcarbenes (**51**; X = CH_2, O, $SiMe_2$) underwent β-CH insertion via the triplet carbene.[63] The related systems (**52**) underwent predominant insertion into the C−X bonds. In fact, when X = $SiMe_2$, products of insertion into all four C−Si bonds were observed. Treatment of the dibromophosphinaethene (**53**) with butyllithium gave rise to the phosphanaphthalene (**54**) by 1,6-CH insertion of an intermediate phosphinidenecarbene.[64]



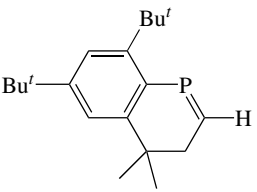
(**51**)



(**52**)

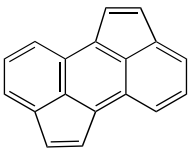


(**53**)
Ar = 2,4,6-$Bu^t{}_3C_6H_2$

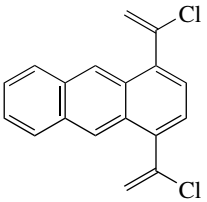


(**54**)

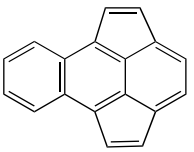
A reversible vinylidene insertion was proposed to explain the formation of (**55**) on flash vacuum pyrolysis of the anthracene derivative (**56**) at 1100 °C.[65] The expected loss of HCl followed by 1,2-H shift and 1,5-CH insertion of the resulting vinylidene species would give rise to the strained paracyclophane (**57**). This is proposed to ring open to the alternative alkylidene (**58**) before proceeding to the observed product (**55**).



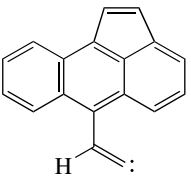
(**55**)



(**56**)



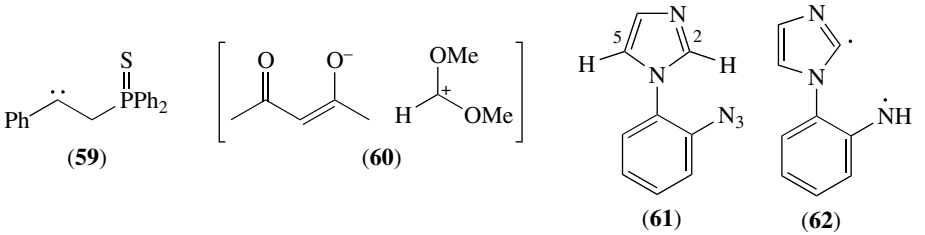
(**57**)



(**58**)

The relative rates of insertion into the OH bond of methanol and addition to 2-methylbut-2-ene indicate that the β-thiophosphinoylcarbene (**59**) has enhanced nucleophilicity.[66] This was interpreted as being due to hyperconjugative electron

donation by the C−P bond. The insertion of nucleophilic carbenes (such as dimethoxycarbene) into the acidic C−H bond of β-diketones was rationalized by proton abstraction from the enol form to give an ion pair (**60**) followed by *C*-alkylation to form the products.[67] The BF_3OEt_2-catalysed reaction between diazomethylphosphonates and disulfides or diselenides leads to insertion of the carbene $RO_2P(O)CH$: into S−S and Se−Se bonds.[68] Flash vacuum pyrolysis of the imidazole (**61**) occurs exclusively by insertion of the nitrene into the 2-CH bond.[69] A mechanism involving H-abstraction by the triplet nitrene to give the highly stabilized diradical (**62**) was proposed.



(**59**) (**60**) (**61**) (**62**)

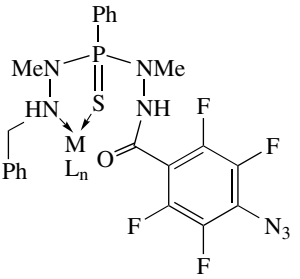
Efficient nitrene generation and insertion into the CH bonds of the solvent (cyclohexane) was observed for a series of perfluoroarylazides linked to metal-ligating systems (**63**).[70]

Rearrangement

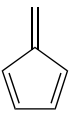
An *ab initio* study of the rearrangement of vinylidene ($H_2C{=}C$:) to acetylene found a barrier of 1.5 kcal mol^{-1}, in good agreement with experimental evidence.[71] Density functional theory has been used to study the related rearrangement of difluorovinylidene to difluoroacetylene.[72] *Ab initio* calculations indicated that, for simple acyclic dialkylcarbenes (such as ethylmethylcarbene), 1,2-H migration is preferred over 1,2-C migration and has a barrier of about 5 kcal mol^{-1}.[73] Rearrangement to a secondary alkene is favoured over that to a primary. For cyclic carbenes, the situation is more complex. For cyclobutylidene and norbornylidene the similarity between the carbene geometry and the transition state lowers the barrier for C-migration and 1,3-H shift respectively.

The rearrangement of fulvene (**64**) to benzene has been studied by theoretical methods.[74] The favoured pathway involved rearrangement to isofulvene (**65**) (barrier 41.6 kcal mol^{-1}), ring opening to cyclohexadienecarbene (**66**) (barrier 74.3 kcal mol^{-1}), and 1,2-H shift to form benzene (barrier 59 kcal mol^{-1}). The discrepancy between the calculated activation energy and the value determined by very low-pressure pyrolysis is suggested to be due to surface effects.

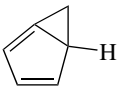
UV photoelectron spectroscopy was used to study the vacuum pyrolysis of diazothiochromanone (**67**; X = S).[75] Calculations suggest that, unlike the oxygen analogue (**67**; X = O), Wolff rearrangement to the ketene (**68**) may be concerted with



(**63**)



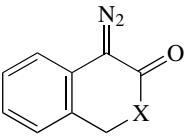
(**64**)



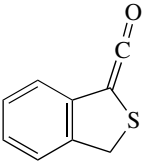
(**65**)

(**66**)

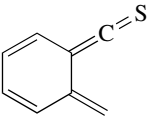
N_2 loss. The ketene (**68**) loses CO to form a carbene which undergoes ring opening to (**69**) before ring closing to a benzocyclobutenethione.



(**67**)



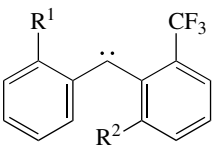
(**68**)



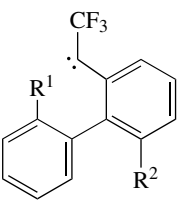
(**69**)

AM1 calculations on the gas-phase Wolff rearrangements of α-ketocarbenes indicate that there is a strong vicinal interaction between the lone pair (n) and carbonyl σ^* orbital.[76] In the bridged transition state, electronic charge is transferred from the migrating group toward the non-migrating group. No 1,2-F migration or C−F insertion was seen in a flash vacuum pyrolysis study of carbenes (**70**).[77] The almost exclusive rearrangement to (**71**) by attack at the CF_3 bearing carbon is explained by a simple FMO analysis.

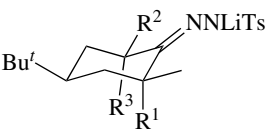
Product analysis of the products of photolysis or thermolysis of conformationally biased tosylhydrazone salts (**72**) showed that a bystander equatorial Me group promotes a geminal H-shift several times more effectively than does an axial Me.[78] The observation that the primary isotope effect for axial deuterium migration was 1.5 times that for equatorial migration in (**72**; $R^1 = R^2 = D$, $R^3 = Me$) invalidates the common assumption that these isotope effects are equal.



(**70**)



(**71**)

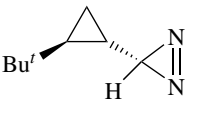


(**72**)

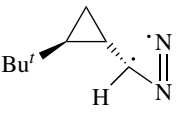
Ab initio calculations on the structures of ethylchlorocarbene and chloromethylchlorocarbene show that the equilibrium between *cis* and *trans* conformers is shifted moderately to the *trans* isomer for the ethyl derivative and strongly to the *cis* for the chloromethyl (due to a stabilizing carbene n $\rightarrow \sigma^*_{C-Cl}$ interaction).[79] The barriers to rotation around the C−C bond are lower than the barriers to 1,2-H shift which leads to the more stable (*Z*)-alkene in both cases. The rearrangement transition states are product-like and the *Z*-isomers are stabilized by a through-space interaction of the p_z orbitals localized on the terminal atoms.

Kinetic analysis of the rearrangement of benzylfluorocarbene, generated by laser flash photolysis of the corresponding diazirine, gave a rate constant of 9.2×10^6 s^{-1} at 26 °C with activation entropy −17.2 eu and activation energy 3.25 ± 0.34 kcal mol^{-1}, very similar to the values for the chlorocarbene.[80] A product analysis study of the thermolysis and photolysis of the diazirine (**73**) in the presence of tetramethylethylene showed that the ring-expanded cyclobutene and the cyclopropanation products do not arise via a common intermediate.[81] The ring expansion was proposed to occur by loss of N_2 from the diradical intermediate (**74**).

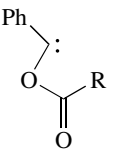
A laser flash photolysis study of phenylacyloxycarbene (**75**) allowed the measurement of the rate of 1,2-acyl shift of between 10^5 and 10^6 s^{-1} in pentane at room temperature.[82] The activation parameters were in good agreement with calculations. High-level calculations supported a carbanion-like attack by the carbene lone pair on the carbonyl (**76**) whereas the effects of substituents on the rate suggested an acyl anion-like transition state (**77**). The electron-donating, stabilizing effect of OAc slows the 1,2-C and 1,2-H shifts in alkylacetoxycarbenes (**78**),[83] allowing 1,2-acetyl shifts to compete.



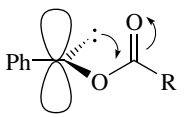
(**73**)



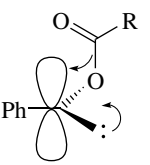
(**74**)



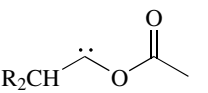
(**75**)



(**76**)

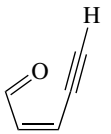


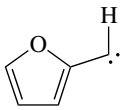
(**77**)

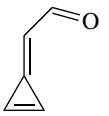


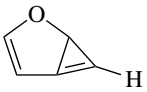
(**78**)

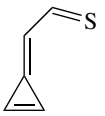
Photolysis of matrix isolated diazo(2-furyl)methane led to the aldehyde (**79**) by stereospecific rearrangement of the carbene (**80**).[84] The corresponding 3-furyl compound gave the (*s-Z*)-methylenecyclopropene (**81**) by ring closure of the initially formed vinylcarbene to give cyclopropene (**82**) followed by ring opening of the furan.


(**79**)


(**80**)

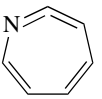

(**81**)

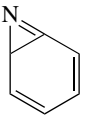

(**82**)

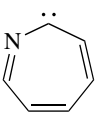

(**83**)

In an exactly analogous process, photolysis of diazo(3-thienyl) methane gave rise to the thial (**83**).[85]

Ab initio calculations predicted that the ring expansion of singlet phenylnitrene to the tetraene (**84**) proceeds by rearrangement to the bicyclic triene (**85**) with a barrier of 6 kcal mol^{-1}, followed by ring expansion with a barrier of 3 kcal mol^{-1}.[86] This is 19 kcal mol^{-1} less exothermic than ring expansion of $^1A'$ phenylcarbene but has a barrier 9 kcal mol^{-1} lower. The difference in free energy of reaction stems from the much lower energy of the nitrene compared with the carbene. The lowest singlet state of the planar carbene (**86**) lies 20 kcal mol^{-1} above (**84**) and represents the transition state for enantiomerization of this species. The ring expansion of several fluorinated phenylnitrenes was calculated to occur in two steps via the azirine, just as in the parent nitrene.[87] For 2-fluorophenylnitrene, the barrier to cyclisation towards fluorine is 3 kcal mol^{-1} higher than for away from fluorine (largely due to steric repulsion in the transition state).


(**84**)


(**85**)


(**86**)

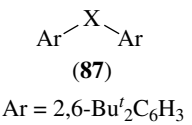
Nitrenium ions

Density functional theory predicts that the hindered diarylnitrenium ion (**87**; $X = N^+$) has a triplet ground state and that the corresponding silylene (ArSiAr) has degenerate singlet and triplet states.[88] The triplet states can more readily accommodate the large valence angle at the nitrogen or silicon. A study of transient absorption spectra using pump-probe spectroscopy of phenyl azide and 2,4,6-tribromophenyl azide showed that protonation to form the nitrenium ions ($ArNH^+$) is competitive with intersystem crossing in aqueous solution.[89]

Nucleophiles and Electrophiles

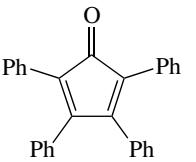
The cycloaddition of Cl_2C: to formaldehyde is calculated to be about 2.5 times faster than ylide formation at 298 K.[90] The ylide was calculated to have a lifetime of about

1 ms with respect to ring closure. Push–pull stabilization by the partially aromatic cyclopentadienide moiety and the positively charged CBr_2 group of the ylide-like transition state was proposed to explain the high yield of CO formed on reaction of the ketone (**88**) with $:CBr_2$.[91] The Rh-catalysed decomposition of α-diazo keto esters such as (**89**; X = O) led to products derived from the carbonyl ylide.[92] In the corresponding amides (**89**; X = NEt) ammonium ylide formation was found to compete with formation of the carbonyl ylide.

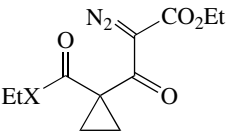


(**87**)

Ar = 2,6-$Bu^t_2C_6H_3$

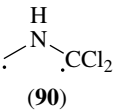


(**88**)

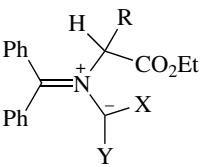


(**89**)

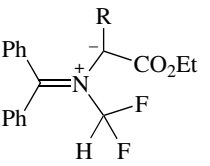
The barrier to 1,2-cycloaddition of Cl_2C: to imine $H_2C{=}NH$ was calculated to be 16.5 kcal mol^{-1}.[93] Ylide formation has a barrier of only 5 kcal mol^{-1} and the dipolar ylide rearranges to a more stable biradical (**90**) which can ring close with a barrier of 21.2 kcal mol^{-1}. Dichloro- (**91**; X = Y = Cl) and chlorofluoroylides (**91**; X = Cl, Y = F), derived from the addition of dihalocarbenes to the benzophenone Schiff bases of amino acid esters, cyclize to give aziridines.[94] The corresponding difluoroylides (**91**; X = Y = F) undergo isomerization by 1,3-H shift to form ylides (**92**) before proceeding to products.



(**90**)



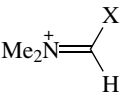
(**91**)



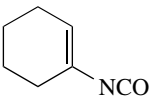
(**92**)

The oxidation of phenylhydrazine and 1,2-disubstituted hydrazines to hydrazones and diazenes by Cl_2C: proceeds via formation of unstable azomethine imines.[95] The conversion of alcohols into alkyl halides is achieved by reaction with CCl_4 (or CBr_4) in DMF under electrochemical reduction.[96] The reaction of dihalocarbene X_2C: with DMF to form a Vilsmaier reagent (**93**) is proposed as the key process. The reaction of simple isocyanates (RNCO) with dimethoxycarbene normally gives hydantoin-type products. In the reaction with vinylisocyanates such as (**94**), however, hydroindoles (**95**) are formed in good yields.[97]

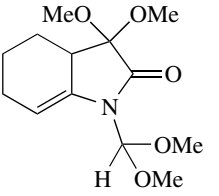
Treatment of the amidinium salt (**96**) with LDA was found to produce the alkene (**97**) and the stable carbene (**98**).[98] The dimerization of the carbene was found to be very slow and so the initial formation of alkene (**97**) was explained by reaction of the carbene



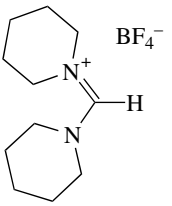
(**93**)
X = Cl or Br



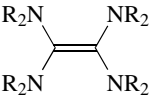
(**94**)



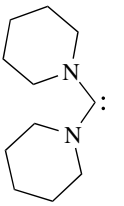
(**95**)



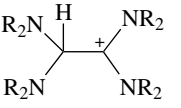
(**96**)



(**97**)



(**98**)

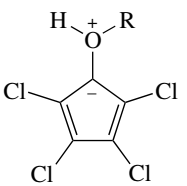


(**99**)

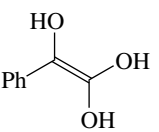
(**98**) with the starting material to form the new salt (**99**) which can lose a proton to form the alkene.

A number of minima corresponding to oxonium ylides and H-bonded structures were found on the potential-energy surface for reaction of singlet carbenes with water and alcohols.[99] Laser flash photolysis revealed that the rates of reaction between cyclopentadienylidene or fluorenylidene and alcohols increased with alcohol acidity and had linear Brønsted plots with slopes of 0.061 and 0.082, respectively.[100] These results point to protonation with a very early transition state or to concerted OH insertion. For tetrachlorocyclopentadienylidene, the results showed that ylide formation (**100**) is predominant.

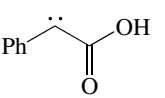
The enol form of mandelic acid (**101**) has been generated by flash photolysis of phenyldiazoacetic acid in aqueous solution.[101] The enol forms by hydration of the intermediate carbene (**102**). The reaction of chloramine-T ($TsNClNaH_2O$) with methyl *p*-tolyl sulfide to give the corresponding sulfimide (**103**) appears to proceed via a nitrene-transfer mechanism in the presence of copper(I) and a second nitrogen ligand (such as acetonitrile).[102]



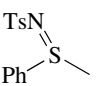
(**100**)



(**101**)



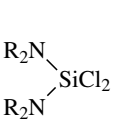
(**102**)



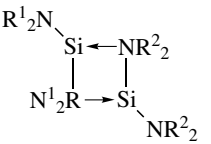
(**103**)

Silylenes and Germylenes

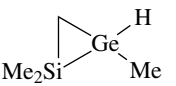
A review covering the frontier orbital control of silylene addition to alkenes has appeared.[103] The complexation energy for silylene (H_2Si:) with methanol is calculated to be 19.9 kcal mol^{-1}.[104] The overall barrier to OH insertion was found to be 0.6 kcal mol^{-1} (much less than that to C−O insertion). Silylidene ($H_2C{=}Si$) and germylidene ($H_2C{=}Ge$) have been produced by electron discharge in Me_4Si and Me_4Ge.[105] Both vinyl chloride and allyl chloride react with dichlorosilylene (Cl_2Si:) by C−Cl insertion.[106] Alkali metal reduction of bis(dialkylamino)dichlorosilanes (**104**) gave the corresponding silylenes which could be trapped by reaction with benzene, alkenes, acetylene, and hydrosilane.[107] Simultaneous generation of two different silylenes in benzene led to scrambling of the amino groups on silicon, suggesting the existence of bridged dimers (**105**).



(**104**)



(**105**)



(**106**)

A complex between difluorostannylene (F_2Sn) and chloromethane has been studied by infrared spectroscopy in an argon matrix at 12 K.[108] Calculations suggest that insertion into the C−Cl bond is energetically favourable but has a very high barrier. Products of the vacuum flow pyrolysis of $(Me_3Si)_2GeHMe$ in the presence of excess alkene suggest the generation of the α-silylgermylene, $Me_3SiGeMe$, which either inserts into a C−H bond to form a silagermirane (**106**) or dimerizes to the digermene.[109]

References

1. Moss, R. A., *Adv. Carbene Chem.*, **1**, 59 (1994); *Chem. Abs.*, **125**, 327732 (1997).
2. Kirmse, W., *Adv. Carbene Chem.*, **1**, 1 (1994); *Chem. Abs.*, **125**, 327731 (1997).
3. Jones, M., *Adv. Carbene Chem.*, **1**, 161 (1994); *Chem. Abs.*, **125**, 328816 (1997).
4. Khlebnikov, A. F., Novikov, M. S., and Kostikov, R. R., *Adv. Heterocycl. Chem.*, **65**, 93 (1996); *Chem. Abs.*, **125**, 300696 (1996).
5. Bernasconi, C. F., *Chem. Soc. Rev.*, **26**, 299 (1997).
6. Kim, S. K., Lovejoy, E. R., and Moore, C. B., *Springer Ser. Chem. Phys.*, **1995**, 61; *Chem. Abs.*, **126**, 74431 (1997).
7. Vysotskii, Yu. B., Zaikovskaya, Ya. V., and Gorban, O. A., *Teor. Eksp. Khim.*, **32**, 157 (1996); *Chem. Abs.*, **126**, 117599 (1997).
8. Poutsma, J. C., Nash, J. J., Paulino, J. A., and Squires, R. R., *J. Am. Chem. Soc.*, **119**, 4686 (1997).
9. Mizouchi, H., Ikawa, A., and Fukutome, H., *Synth. Met.*, **85**, 1760 (1997); *Chem. Abs.*, **126**, 343193 (1997).
10. Yoshizawa, K., Kuga, T., Sato, T., Hatanaka, M., Tanaka, K., and Yamabe, T., *Bull. Chem. Soc. Jpn*, **69**, 3443 (1996).
11. Enders, D., Breuer, K., Runsink, J., and Teles, J. H., *Liebigs Ann. Chem.*, **1996**, 2019.
12. Maier, G., Endres, J., and Reisenauer, H. P., *Angew. Chem., Int. Ed. Engl.*, **36**, 1709 (1997).
13. Firth-Clark, S., Rodriguez, C. F., and Williams, I. H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1943.
14. Lyashchuk, S. N., Vasileva, N. V., and Skrypnik, Yu. G., *Zh. Org. Khim.*, **32**, 509 (1996); *Chem. Abs.*, **125**, 327770 (1997).

[15] Lahem, D., Flamming, R., and Tho Nguyen, M. M., *Chem. Phys. Lett.*, **270**, 93 (1997); *Chem. Abs.*, **127**, 50224 (1997).
[16] Gotzhein, F. and Kirmse, W., *Tetrahedron Lett.*, **38**, 1373 (1997).
[17] Gothein, F. and Kirmse, W., *Tetrahedron Lett.*, **38**, 1377 (1997).
[18] Abdel-Wahab, A.-M. A., Ismail, M. T., Mohamed, O. S., Dürr, H., and Ma, Y., *Liebigs Ann. Chem.*, **1997**, 1611.
[19] Moss, R. A. and Merrer, D. C., *J. Chem. Soc., Chem. Commun.*, **1997**, 617.
[20] Motschiedler, K. R., Toscano, J. P., and Garcia-Garibay, M. A., *Tetrahedron Lett.*, **38**, 949 (1997).
[21] Tomioka, H., *Acc. Chem. Res.*, **30**, 315 (1997).
[22] Admasu, A., Platz, M. S., Marcinek, A., Michalak, J., Gudmundsdóttir, A. D., and Gebicki, J., *J. Phys. Org. Chem.*, **10**, 207 (1997).
[23] Tomioka, H., Okada, H., Watanabe, T., Banno, K., Komatsu, K., and Hirai, K., *J. Am. Chem. Soc.*, **119**, 1582 (1997).
[24] Tomioka, H., Mizuno, H., Itakura, H., and Hirai, K., *J. Chem. Soc., Chem. Commun.*, **1997**, 2261.
[25] Worthington, S. E. and Cramer, C. J., *J. Phys. Org. Chem.*, **10**, 755 (1997).
[26] Admasu, A., Gudmundsdóttir, A. D., and Platz, M. S., *J. Phys. Chem. A*, **101**, 3832 (1997).
[27] Gritsan, N. P., Zhai, H. B., Yuzawa, T., Karweik, D., Brooke, T., and Platz, M. S., *J. Phys. Chem. A*, **101**, 2833 (1997).
[28] Gritsan, N. P., Yuzawa, T., and Platz, M. S., *J. Am. Chem. Soc.*, **119**, 5059 (1997).
[29] Murata, S., Abe, S., and Tomioka, H., *J. Org. Chem.*, **62**, 3055 (1997).
[30] Albini, A., Bettinetti, G., and Minoli, G., *J. Am. Chem. Soc.*, **119**, 7308 (1997).
[31] Lin, H.-X., Xu, L.-H., and Huang, N.-J., *Huaxue Xuebao*, **54**, 819 (1996); *Chem. Abs.*, **125**, 328118 (1997).
[32] Shavrin, K. N., Gvozdev, V. D., and Nefedov, O. M., *Mendeleev Commun.*, **1997**, 144.
[33] Higgins, J., Zhou, X., Liu, R., and Huang, T. T. S., *J. Phys. Chem. A*, **101**, 2702 (1997).
[34] Difelice, J. J. and Ritter, E. R., *Combust. Sci. Technol.*, **116–117**, 5 (1996); *Chem. Abs.*, **126**, 117682 (1997).
[35] Aubry, C., Polce, M. J., Holmes, J. L., Mayer, P. M., and Radom, L., *J. Am. Chem. Soc.*, **119**, 9039 (1997).
[36] Stoub, D. G. and Goodman, J. L., *J. Am. Chem. Soc.*, **119**, 11110 (1997).
[37] Letourneau, J. E. and Burnell, D. J., *Tetrahedron Lett.*, **38**, 1353 (1997).
[38] Rees, C. W. and Yue, T.-Y., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2247.
[39] Fasani, E., Mella, M., Caccia, D., Tassi, S., Fagoni, M., and Albini, A., *J. Chem. Soc., Chem. Commun.*, **1997**, 1329.
[40] Al Dulayymi, A. R., Baird, M. S., and Clegg, W., *Tetrahedron Lett.*, **38**, 8271 (1997).
[41] Griffiths, D. V., Harris, J. E., and Whitehead, B. J., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2545.
[42] Aitken, R. A., Fairhurst, I. M., Ford, A., Milne, P. E. Y., Russell, D. W., and Whittaker, M., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 3107.
[43] Suárez, D. and Sordo, T. L., *J. Am. Chem. Soc.*, **119**, 10291 (1997).
[44] LAbbé, G., Dyall, L., and Dehaen, W., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 971.
[45] Li, A.-H. and Dai, L.-X., *Huaxue*, **54**, 157 (1996); *Chem. Abs.*, **126**, 171428 (1997).
[46] Rasmussen, K. G. and Jørgensen, K. A., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1287.
[47] Galardon, E., Le Maux, P., and Simmoneaux, G., *J. Chem. Soc., Chem. Commun.*, **1997**, 927.
[48] Cuggabe, J. W., Edelbach, B. L., Kuen, K. S., and DeLuca, J. P., *Tetrahedron*, **53**, 9823 (1997).
[49] Dehmlow, E. V. and Lustinetz, H., *Liebigs Ann. Chem.*, **1996**, 2065.
[50] Waldraff, C., Bernet, B., and Vasella, A., *Helv. Chim. Acta*, **80**, 1882 (1997).
[51] Weber, J. and Brinker, U. H., *Angew. Chem., Int. Ed. Engl.*, **36**, 1623 (1997).
[52] Tang, Z., Li, L., Sun, Z., Tian, A., Yan, G., and Zhou, H., *Sci. China, Ser. B: Chem.*, **39**, 269 (1996); *Chem. Abs.*, **126**, 46775 (1997).
[53] Visser, P., Zuhse, R., Wong, M. W., and Wentrup, C., *J. Am. Chem. Soc.*, **118**, 12598 (1996).
[54] Gun, W. X., Wang, H.-X., Pan, Y.-M., Huan, Z.-W., and Cheng, J.-P., *Gaodeng Xuexiao Huaxue Xuebao*, **18**, 238 (1997); *Chem. Abs.*, **126**, 211718 (1997).
[55] Pole, D. L. and Warkentin, J., *J. Org. Chem.*, **62**, 4065 (1997).
[56] Kassam, K. and Warkentin, J., *Can. J. Chem.*, **75**, 120 (1997).
[57] Loreto, M. A., Tardella, P. A., Tedeschi, L., and Tofani, D., *Tetrahedron Lett.*, **38**, 5717 (1997).
[58] Zhai, H. and Platz, M. S., *J. Phys. Org. Chem.*, **10**, 22 (1997).
[59] Wu, G.-X., Jones, M., Doering, W. von E., and Knox, L. H., *Tetrahedron*, **53**, 9913 (1997).
[60] Kellog, C. B., Valeev, E., Morrison, G. J., Fowler, J. E., and Schaefer, H. E., *Mol. Phys.*, **89**, 1695 (1996); *Chem. Abs.*, **126**, 117596 (1997).
[61] Kitamura, T., Zheng, L., Fukuoka, T., Fujiwara, Y., Taniguchi, H., Sakurai, M., and Tanaka, R., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1511.

[62] Taber, D. F. and Christos, T. E., *Tetrahedron Lett.*, **38**, 4927 (1997).
[63] Kirmse, W., Konrad, W., and özkir, I. S., *Tetrahedron*, **53**, 9935 (1997).
[64] Ito, S., Toyota, K., and Yoshifuji, M., *J. Chem. Soc., Chem. Commun.*, **1997**, 1637.
[65] Scott, L. T. and Necula, A., *Tetrahedron Lett.*, **38**, 1877 (1997).
[66] Lambert, J. B. and Liu, X., *Tetrahedron*, **53**, 9989 (1997).
[67] Couture, P., Pole, D. L., and Warkentin, J., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1565.
[68] Mikolajczyk, M., Mikina, M., Graczyk, P. P., and Balczewski, P., *Synthesis*, **1996**, 1232; *Chem. Abs.*, **125**, 328938 (1997).
[69] Blake, A. J., Clark, B. A. J., McNab, H., and Sommerville, C. C., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1605.
[70] Pandurangi, R. S., Karra, S. R., Katti, K. V., Kuntz, R. R., and Volkert, W. A., *J. Org. Chem.*, **62**, 2798 (1997).
[71] Chang, N.-Y., Shen, M.-Y., and Yu, C.-H., *J. Chem. Phys.*, **106**, 3237 (1997); *Chem. Abs.*, **126**, 224910 (1997).
[72] Jursic, B. S., *Int. J. Quantum Chem.*, **62**, 515 (1997); *Chem. Abs.*, **126**, 330277 (1997).
[73] Sulzbach, H. M., Platz, M. S., Schaefer, H. F., and Hadad, C. M., *J. Am. Chem. Soc.*, **119**, 5682 (1997).
[74] Madden, L. K., Mebel, A. M., Lin, M. C., and Melius, C. F., *J. Phys. Org. Chem.*, **9**, 801 (1996).
[75] Werstiuk, N. H., Ma, J., Roy, C. D., Kresge, A. J., and Jefferson, E. A., *Can. J. Chem.*, **74**, 2536 (1996).
[76] Kim, C. K. and Lee, I., *Bull. Korean Chem. Soc.*, **18**, 395 (1997); *Chem. Abs.*, **127**, 65377 (1997).
[77] Tomioka, H. and Taketsuji, K., *J. Chem. Soc., Chem. Commun.*, **1997**, 1745.
[78] Kenar, J. A. and Nickon, A., *Tetrahedron*, **53**, 14871 (1997).
[79] Shustov, G. V., Liu, M. T. H., and Rauk, A., *J. Phys. Chem. A*, **101**, 2509 (1997).
[80] Moss, R. A., Maksimovic, L., and Merrer, D. C., *Tetrahedron Lett.*, **38**, 7049 (1997).
[81] Platz, M. S., Huang, H., Ford, F., and Toscano, J., *Pure Appl. Chem.*, **69**, 803 (1997).
[82] Moss, R. A., Xue, S., Liu, W., and Krogh-Jespersen, K., *J. Am. Chem. Soc.*, **118**, 12588 (1996).
[83] Moss, R. A., Xue, S., Ma, W., and Ma, H., *Tetrahedron Lett.*, **38**, 4379 (1997).
[84] Albers, R. and Sander, W., *Liebigs Ann. Chem.*, **1997**, 897.
[85] Albers, R. and Sander, W., *J. Org. Chem.*, **62**, 761 (1997).
[86] Karney, W. L. and Borden, W. T., *J. Am. Chem. Soc.*, **119**, 1378 (1997).
[87] Karney, W. L. and Borden, W. T., *J. Am. Chem. Soc.*, **119**, 3347 (1997).
[88] Cramer, C. J. and Falvey, D. E., *Tetrahedron Lett.*, **38**, 1515 (1997).
[89] Born, R., Burda, C., Senn, P., and Wirz, J., *J. Am. Chem. Soc.*, **119**, 5061 (1997).
[90] Pliego, J. R. and De Almeida, W. B., *J. Chem. Phys.*, **106**, 3582 (1997); *Chem. Abs.*, **126**, 224905 (1997).
[91] Cheng, J.-P., Wang, H.-X., Huan, Z.-W., and Tan, C.-E., *Gaodeng Xuexiao Huaxue Xuebao*, **18**, 1067 (1997); *Chem. Abs.*, **127**, 161424 (1997).
[92] Curtis, E. A., Worsencroft, K. J., and Padwa, A., *Tetrahedron Lett.*, **38**, 3319 (1997).
[93] Pliego, J. R. and De Almeida, W. B., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2365.
[94] Khlebnikov, A. F., Novikov, M. S., and Kostikov, R. R., *Mendeleev Commun.*, **1997**, 145.
[95] Novikov, M. S., Khlebnikov, A. F., and Kostikov, R. R., *Izv. Akad. Nauk, Ser. Khim.*, **1996**, 1489; *Chem. Abs.*, **125**, 247278 (1996).
[96] Léonel, E., Paugam, J. P., and Nédélec, J. Y., *J. Org. Chem.*, **62**, 7061 (1997).
[97] Rigby, J. H., Cavezza, A., and Ahmed, G., *J. Am. Chem. Soc.*, **118**, 12848 (1996).
[98] Alder, R. W. and Blake, M. E., *J. Chem. Soc., Chem. Commun.*, **1997**, 1513.
[99] Zub, L. L. and Standard, J. M., *THEOCHEM*, **368**, 133 (1996); *Chem. Abs.*, **126**, 88926 (1997).
[100] Olson, D. R. and Platz, M. S., *J. Phys. Org. Chem.*, **9**, 759 (1996).
[101] Chiang, Y., Kresge, A. J., Popik, V. V., and Schepp, N. P., *J. Am. Chem. Soc.*, **119**, 190203 (1997).
[102] Aujla, P. S., Baird, C. P., Taylor, P. C., Mauger, H., and Vallée, Y., *Tetrahedron Lett.*, **38**, 7453 (1997).
[103] Gaspar, P. P., Li, X., Silverman, J., Haile, T., Pae, D. H., and Xiao, M., *Prog. Organosilicon Chem.*, **1993**, 247; *Chem. Abs.*, **126**, 18913 (1997).
[104] Lee, S. Y. and Boo, B. H., *THEOCHEM*, **366**, 79 (1996); *Chem. Abs.*, **125**, 327823 (1997).
[105] Harper, W. W., Ferrall, E. A., Hilliard, R. K., Stogner, S. M., Grev, R. S., and Clouthier, D. J., *J. Am. Chem. Soc.*, **119**, 8361 (1997).
[106] Chernyshev, E. A., Komalenkova, N. G., Kapitova, I. A., Bykovchenko, V. G., Khromykh, N. N., and Bochkarev, V. N., *Zh. Obshch. Khim.*, **66**, 1484 (1996); *Chem. Abs.*, **126**, 171641 (1997).
[107] Sakamoto, K., Tsutsui, S., Sakurai, H., and Kira, M., *Bull. Chem. Soc. Jpn*, **70**, 253 (1997).
[108] Boganov, S. E., Faustov, V. I., Rudyak, S. G., Egorov, M. P., and Nefedov, O. M., *Izv. Akad. Nauk, Ser. Khim.*, **1996**, 1121; *Chem. Abs.*, **126**, 18968 (1997).
[109] Lei, D., Lee, M. E., and Gaspar, P. P., *Tetrahedron*, **53**, 10179 (1997).

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CHAPTER 7

Nucleophilic Aromatic Substitution

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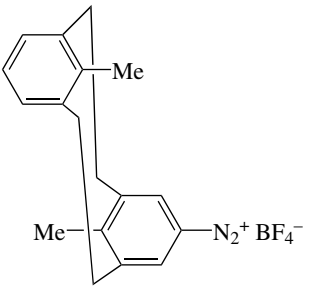
General

The host–guest complexation of crown ethers with arenediazonium ions is well known. A study of the complexation in dichloroethane of benzenediazonium ions with crown ethers containing 4–10 oxygen atoms has shown that 21-crown-7 is the strongest complexing agent. The rate constants for dediazoniation, which may involve heterolytic or homolytic pathways, are reduced by complexation. However, 12-crown-4, where the ring size is too small for complexation, destabilises benzenediazonium ions resulting in an increased rate of homolysis.[1] Evidence for transannular interaction in 5-substituted [2.2]metacyclophanes carrying a diazonio group (**1**) comes from studies of their UV spectra and from values of stability constants for their complexation with 18-crown-6.[2]

Brightly coloured 1:1 charge–transfer complexes have been observed on mixing electron-poor arenediazonium salts, such as 3,5-dinitrobenzenediazonium tetrafluoroborate, with aromatic hydrocarbons in acetonitrile. These complexes, which involve



(**1**)

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π–π interaction, may be precursors for electron-transfer activation of the diazonium ions leading to dediazoniation.[3]

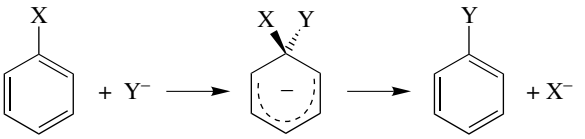
The use of iodoacetic acid as an aryl radical trapping agent has confirmed the intermediacy of aryl radicals in some hydrodediazoniation reactions, whether these are initiated or not.[4] Spontaneous hydrodediazoniation of aryldiazonium fluoroborates occurs in warm dimethylformamide (DMF). Detailed study[5] of the conversion of the 4-nitro derivative into nitrobenzene indicates a homolytic mechanism in which H-atom abstraction occurs from both sites in DMF with a formyl : methyl preference of 3.5 : 1.0. High yields of mixed perfluorinated biaryls may be obtained by the catalytic dediazoniation of pentafluorobenzenediazonium ions in acetonitrile containing aromatic substrates and small amounts of iodide salts. The catalytic role of iodide and the isomeric product distributions indicate that arylation proceeds through the pentafluorophenyl radical in an efficient homolytic chain process.[6]

There is continued interest in the $S_{RN}1$ radical chain mechanism. A comparison of the efficiencies of twenty two nucleophiles, Nu^-, in their $S_{RN}1$ reactions with iodobenzene has been made using both Fe(II)- and photo-induction.[7] The radical anion $PhNu^{\cdot-}$ is a key intermediate in this reaction and information on the energy of the MO where the unpaired electron resides may be inferred from calculations of the LUMO of the reaction product, PhNu. Substituent effects on the rate constants for cleavage of radical anions derived from a series of aryl bromides and α-phenoxyacetophenones have been correlated with the Hammett equation.[8] A variety of carbanion nucleophiles, generated using potassium amide in liquid ammonia, have been shown to react with 2-bromopyridine in a photo-stimulated $S_{RN}1$ reaction.[9] There have been reports of the electrochemically initiated reactions of aryl halides with the thiourea anion leading, after fragmentation, to the formation of aryl sulfides and diaryl sulfides,[10] and of the photo-stimulated reactions of iodobenzene and 1-iodonaphthalene with the anion of *N*-thioacetylmorpholine.[11].

The S_NAr Mechanism

There have been both experimental and theoretical studies to probe the degree of concertedness in gas-phase substitutions as shown in Scheme 1. Is (**2**) an intermediate with a finite lifetime, or are the addition and elimination steps concerted so that (**2**) is a transition state? Experimental molecular beam studies on the femtosecond time-scale have been reported for the reaction of chloride ions with the iodobenzene cation to yield chlorobenzene and iodine. The results show an 880 fs reaction time for the elimination process, indicating a highly non-concerted process, so that here the σ-complex is an intermediate rather than a transition state.[12] The reactions of halobenzene cations with ammonia have been interpreted in terms of the formation of an addition complex which may eliminate either halogen, X^-, or hydrogen halide, HX, depending on the nature of the halogen.[13]

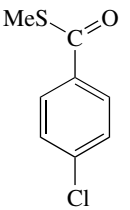
In contrast, an *ab initio* computational study of the symmetrical exchange process, X = Y = Cl, Br, I in Scheme 1, concluded that reaction would occur in a single step without the formation of an intermediate. However when X = Y = F, a two-step



(**2**)

SCHEME 1

mechanism with a discrete intermediate was predicted. The S_NAr reaction of chloride ions with 1-chloro-4-nitrobenzene was calculated to involve a concerted mechanism, while the introduction of further nitro groups resulted in a change to a two-step mechanism.[14] *Ab initio* MO theory in combination with a continuum solvent model has been used to examine the substitution reactions of 1-chloro-2,4-dinitrobenzene with thiomethoxide ions in the gas phase and in solution. Calculations, in agreement with experiment, indicate reaction via a discrete intermediate with nucleophilic attack the rate-limiting step. Here, thiomethoxide was used as a model for glutathione to probe the mode of action of glutathione-*S*-transferase. It was concluded that the main function of the transferase was to facilitate generation of the thiolate and to provide a non-aqueous environment for the reaction.[15] In a related theoretical study, the mechanism of the enzyme-catalysed dehalogenation of 4-chlorobenzoyl-CoA has been modelled using the reaction of acetate ions with (**3**). Here the calculations indicate that the σ-adduct intermediate would have low stability corresponding to the low electron-withdrawing ability of the methylthiocarbonyl group.[16]



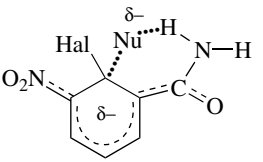
(**3**)

There has been a review of the effects of high pressure on the substitution reactions of amines with haloaromatic compounds, including polyhalobenzenes.[17] Nucleophilic substitutions by amines often proceed readily in dimethyl sulfoxide (DMSO). The pK_a values, in DMSO, have been reported for some ammonium ions derived from amines widely used as nucleophiles in S_NAr reactions.[18] Correlations have been established[19] between the oxidation potentials and the basicities of some arylamine and diarylamine anions and the rate constants for their reactions with aryl halides in DMSO.

The kinetics of the reactions of 1-halo-2,4-dinitrobenzenes with aliphatic amines have been used to probe solvent effects in mixtures of chloroform or dichloromethane with polar hydrogen-bond acceptors, such as DMSO. In these reactions, nucleophilic attack is rate limiting. Attempts to correlate reactivity with the empirical solvent

polarity parameter $E_T(30)$ were unsuccessful.[20] Solvent effects have also been examined[21] in the reaction of morpholine with 2,3-(cyclopentene-3′,5′-diyl)-*endo*-*N*-(2″,4″-dinitrophenoxy)succinimide. In non-polar solvents, association phenomena between reagents may be important and may contribute to catalytic effects. The third-order dependence in amine of the reaction between aniline and 1-chloro-2,4-dinitrobenzene in toluene has been interpreted in terms of reaction via dimers of the nucleophile.[22]

There has been an investigation into the relative activating effects of carboxamido ($CONH_2$) and carbomethoxy (CO_2Me) substituents in reactions involving displacement of halide ions by benzenethiolate and piperidine nucleophiles in methanol.[23] Generally, the carbomethoxy group is the more strongly activating. However, the high efficiency of the *o*-carboxamido group in combination with the benzenethiolate nucleophile was attributed to favourable interaction between the nucleophile and the hydrogen atoms of the $CONH_2$ group in the transition state (**4**) for nucleophilic attack. A kinetic study of the reactions of 1-*N*-crown ether-2,4-dinitrobenzenes with alkali metal hydroxides in DMSO–water has shown that cation complexation occurs rapidly and favours the formation of both 3-hydroxy σ-adducts and phenolate ions.[24] Study of the reactions of 4-nitrohalobenzenes with alkali metal phenoxides in dimethylformamide indicates enhanced reactivity for "free" phenoxide ions compared with ion-paired phenoxides,[25] and the effects of substituents in the phenoxides have been evaluated.[26] There have been reports of the kinetics of the reaction of picryl bromide with 4-(4′*N*,*N*-dimethylaminostyryl)pyridine in acetonitrile leading to the formation of an *N*-(trinitroaryl)pyridinium salt,[27] and of the reactions of aryl dichlorides with alkaline sulfides resulting in polymerization.[28]

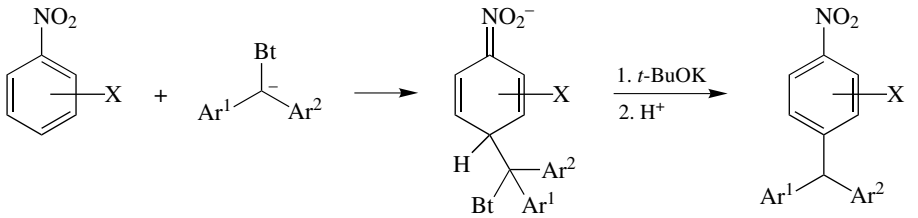


(**4**)

The reactions of oxygen, sulfur, and carbon nucleophiles with 1-fluoro-4-nitroanthraquinone have been shown to result in displacement of fluorine rather than the nitro group.[29] However replacement of either fluoride or nitrite has been observed in the reactions of 1-fluoro-2,4-dinitrobenzene with substituted lithium phenoxides in liquid ammonia.[30,31] The reaction of 1,3-dinitrobenzene with phenolate or benzenethiolate ions in DMSO or DMF may result in nitro group displacement; the mobility of the nitro group is 1.3–1.9 times higher than that of fluorine in 1-fluoro-3-nitrobenzene.[32] It has been shown that *S*,*S*-diphenylsulfilimine ($Ph_2S{=}NH$) reacts by the S_NAr mechanism with activated aryl halides; its behaviour resembles that of an amine such as piperidine.[33] Dimethoxycarbene, generated by thermolysis, may displace fluoride from aromatic compounds activated with electron-withdrawing groups; the products are unstable 'acetals' of aroyl fluorides.[34] ^{18}F-labelled perfluoronitrobenzene

has been prepared by ^{18}F for ^{19}F fluoride exchange and has been used for labelling biochemically important molecules.[35]

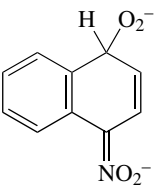
There is current interest in the nucleophilic substitution of ring hydrogen which may involve oxidative or vicarious pathways. Some applications of vicarious substitutions in syntheses have been reviewed.[36] A general synthesis of (4-nitroaryl)diarylmethanes involves vicarious substitution of hydrogen by diarylmethylbenzotriazoles in 2- or 3-substituted nitrobenzenes, as shown in Scheme 2, and makes use of the excellent leaving-group ability of the benzotriazole group. Here the diarylmethylbenzotriazole reagents are produced by condensation of benzotriazole and diaryl methanols with acid catalysis.[37] *Tele*-substitutions yielding *para*-alkylated products have been observed in the reactions of α-(benzotriazol-1-yl)alkyl aryl ketones with alkyllithium or Grignard reagents.[38]



(Bt = benzotriazole)

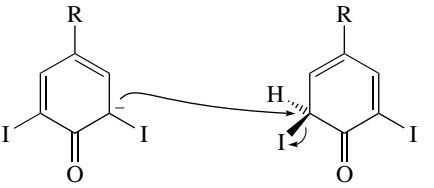
SCHEME 2

Although nitrophenols are unreactive in vicarious substitutions, it has been shown that their toluenesulfonate derivatives will react with carbanion nucleophiles carrying leaving groups. The products obtained are readily hydrolysed to yield the corresponding phenols or hydroxynitrobenzaldehydes.[39] It has been reported that the reaction of 3-chloronitrobenzene with the enolates of some chiral cyclohexylphenylsulfanyl acetates results in vicarious substitution at the 4-position and may be followed by stereoselective alkylation.[40] The hydroxylation of 1-chloro-2,4-dinitrobenzene has been achieved by reaction with cumene hydroperoxide and has been used in an efficient synthesis of 4,6-diaminoresorcinol.[41] 1-Nitro- and 1,8-dinitro-naphthalenes are hydroxylated by reaction with potassium peroxide in liquid ammonia to give mono- and di-nitronaphthols;[42] it is thought that the reaction involves oxidation by molecular oxygen of σ-adducts such as (**5**).



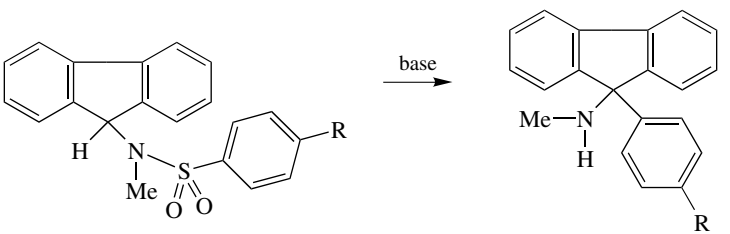
(**5**)

An unusual non-radical phenolic coupling has been observed in 4-substituted-2,6-diiodophenols.[43] It is likely that the reaction which results in the liberation of iodine involves S_N2 attack by an ambident phenolate anion (**5**) on the α-iodo keto tautomer (**6**).



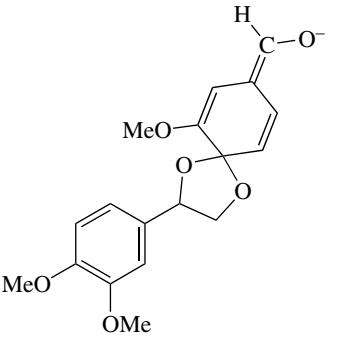
(**5**) (**6**)

The reactions with base of 9-(*N*-4-R-benzenesulfonyl-*N*-methylamino)fluorenes (**7**) result in elimination to yield imines for most R substituents. However, when R = NO_2, the product (**8**; R = NO_2) is formed. There is a large isotope effect, $k_H/k_D = 5.8$, at the 9-position indicating that hydrogen transfer is rate limiting. Product formation involves intramolecular carbanion attack at the 1-position of the nitrobenzenesulfonyl ring with loss of sulfur dioxide.[44] The reactions of pentafluorobenzaldehyde with anilines yield tetrafluoroacridines; the mechanism is thought to involve intramolecular ring-closure of 2-arylamino derivatives of Schiff bases.[45] Evidence derived from ^{17}O labelling studies has shown[46] that a *β-O*-4 to α-*O*-4 rearrangement in a lignin model compound involves intramolecular nucleophilic substitution via the intermediate (**9**). Intramolecular cyclization of conjugated carbonyl ylides (**10**) may yield benzoxepine derivatives. The rates of cyclization onto the unsubstituted phenyl group at the 2-position relative to attack on various 6-substituents have been examined by competition experiments.[47] There have been reports of the use of intramolecular hydroxydefluorinations in the synthesis of the D–O–E segment of vancomycin[48] and in the syntheses of model compounds for chloropeptins[49] and kistamycin.[50]

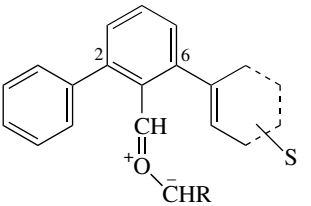


(**7**) (**8**)

There has been a study of photo-induced intramolecular cyclization of some *o*-haloarylheterylamines which may lead to pyrido[1,2-*a*]benzimidazole derivatives.[51] Several studies have been reported of photochemical nucleophile-olefin combination, aromatic substitution (photo-NOCAS) reactions with fluoride,[52] cyanide,[53] or acetonitrile[54] acting as the nucleophile. In the example illustrated in Scheme 3,

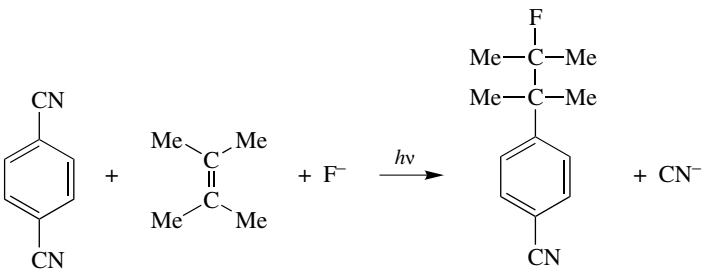


(**9**)



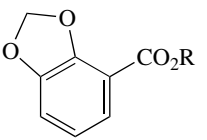
(**10**)

cyanide in 1,4-dicyanobenzene is displaced, in a photo-induced reaction, by a combination of the alkene and nucleophile.

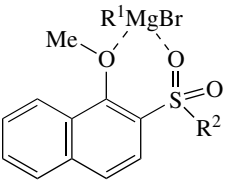


SCHEME 3

There has been a review[55] of ester-mediated substitutions including the reactions of *o*-alkoxyarylcarboxylic esters with C-, N-, and O-nucleophiles. It has been shown that the reactions of aryllithium reagents with 2,3-dialkylidenedioxybenzoic esters such as (**11**), where R = 2, 6-di-*t*-butyl-4-methylphenyl, may yield 6-hydroxy-1,1′-biphenyl-2-carboxylates in good yield.[56] The activating ability of sulfonyl groups has been compared with that of ester groups in the substitutions of 2-sulfonyl-1-methoxynaphthalenes with Grignard reagents; chelation, as in (**12**), assists reaction and both the electronic and steric effects of the 2-substituent are important.[57]



(**11**)

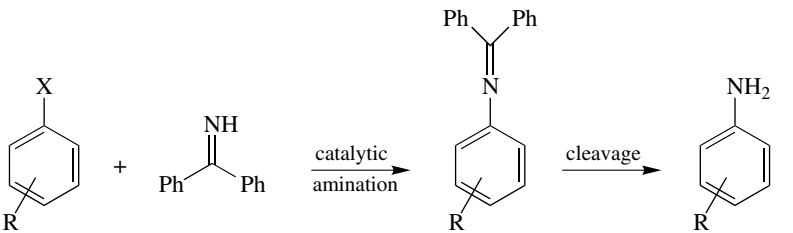


(**12**)

It has been reported that diphenyliodonium triflate reacts with the lithium enolates of some cyclic ketones in the presence of copper cyanide to yield the corresponding α-phenylated or α-diphenylated ketones.[58] There has been a detailed analysis of the products of thermal decomposition of diphenyliodonium tetrafluoroborate and hexafluorophosphate salts.[59]

The copper-catalysed, Ullman-type coupling of aryl, heteroaryl and alkenyl halides may be achieved at ambient temperature using copper(I) thiophene-2-carboxylate as catalyst.[60] A new semiconducting poly(anthraquinone-1,5-diyl) with nitro groups at the 4- and 8-positions has been prepared by Ullman-type coupling using metallic copper or a zerovalent nickel complex as catalyst.[61]

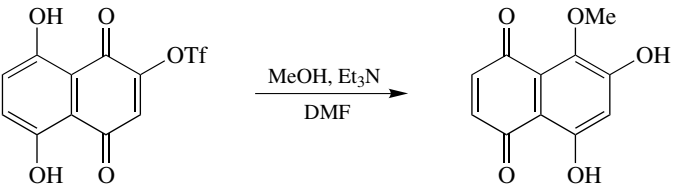
There is continued and increasing interest in palladium-catalysed substitutions, and a book has been published dealing with metal-catalysed cross-coupling reactions.[62] There have been several reports of palladium-catalysed amination reactions. The conversion of aryl triflates into the corresponding aniline derivatives may be achieved using palladium catalysts with chelating bis(phosphine) ligands and sodium *t*-butoxide as base.[63,64] There are advantages in using caesium carbonate as the base since this is compatible with a wide variety of functional groups.[65] A side reaction involving cleavage of the triflate to give phenol must be avoided. Caesium carbonate has also been used effectively in the palladium-catalysed amination of aryl bromides.[66] It has been shown that aryl chlorides will react with amines in the presence of palladium catalysts in the presence of potassium *t*-butoxide at raised temperatures.[67,68] However, the room temperature amination of aryl iodides may be achieved using crown ethers to activate the butoxide base.[69] The selective reaction with aryl halides of polyamines carrying primary amino groups has been described, again using *t*-butoxide as the base.[70] Benzophenone imine may be used as a convenient ammonia equivalent in the palladium-catalysed aminations of aryl triflates and halides[71] as shown in Scheme 4. The reaction of aryl bromides with acyclic secondary amines may be achieved using palladium catalysts carrying phosphino ether ligands.[72]



SCHEME 4

Palladium catalysts have been found which are effective in the Suzuki coupling reaction of arylboronic acids with aryl chlorides carrying electron-withdrawing groups.[73] Biaryls may also be synthesized by cross-coupling of arylboronic acids with arenediazonium salts.[74,75] There has been a report of the polymer-bound palladium-catalysed Suzuki coupling of aryl triflates with organoboron compounds.[76] Arylboronates may themselves be synthesized by the palladium-catalysed reactions of

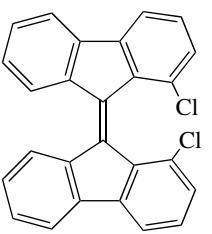
dialkoxyboranes with aryl halides,[77] or of tetra(alkoxo)diborons with aryl triflates.[78] Catalysis of Suzuki-type coupling reactions of chloroarenes with arylboronic acids by nickel complexes has been reported.[79,80] Nickel catalysis may also be useful in the formation of alkyl or silyl aryl ethers from electron-deficient aryl halides.[81] The relative efficiencies of nickel and palladium catalysts have been compared in the homo-coupling of aryl triflates to yield biaryls.[82] Unsymmetrical biaryls may be prepared by the palladium-catalysed reaction of arylmanganese chlorides with aryl halides or triflates.[83] Monoorganostannanes have been shown to be effective reagents in the palladium-catalysed Stille coupling reaction with aryl iodides.[84] The palladium-catalysed coupling of arylstannanes with naphthoquinone derivatives may yield 2-aryl-[85] or 2,3-diaryl-quinones.[86] Reaction of the naphthoquinone triflate derivative (**13**) with methanol in dimethylformamide containing triethylamine yields the methyl ether (**14**); a pathway involving a radical anion is likely.[85]



(**13**) (**14**)

It has been found that the use, as ligands, of electron-poor phosphines, such as 1,1′-bis(diphenylphosphino)ferrocene, enhances yields in the palladium-catalysed reaction of aryl bromides with sodium phenoxides to yield diaryl ethers.[87] Palladium-catalysed coupling of ethynylated derivatives of bipyridine or terpyridine with the corresponding bipyridine or terpyridine halides or triflates has been used in the synthesis of pre-organized polytopic ligands.[88]

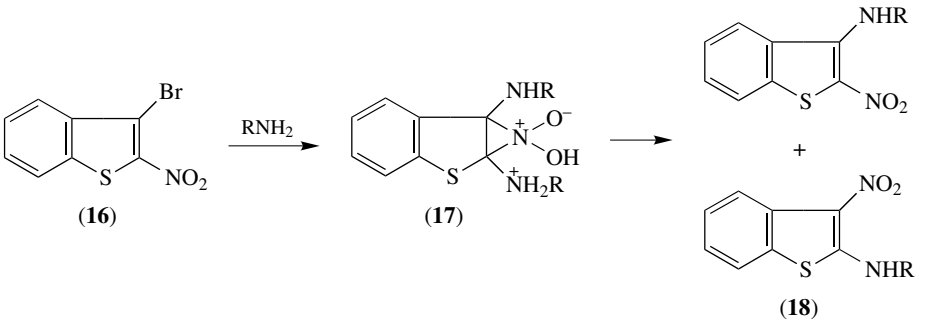
It is reported that the palladium-catalysed intramolecular aromatization of 1,1′-dichloro-9*H*-fluoren-9-ylidene (**15**) may lead to the formation of fullerene fragments.[89] The annulation reaction, under palladium catalysis, between iodoanilines and ketones may yield indole derivatives.[90] There have also been studies of the palladium-catalysed carbonylation of *o*-iodophenols with allenes which may lead to 1-benzopyran-4-one derivatives,[91] of the intramolecular coupling of phenols with aryl halides,[92] and of the intramolecular Heck arylation of cyclic enamides.[93]



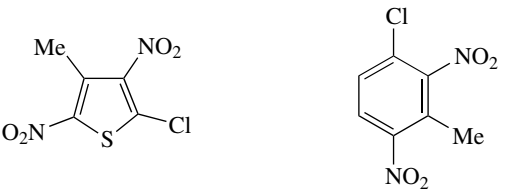
(**15**)

Heterocyclic Systems

The reaction of 3-bromo-2-nitrobenzo[*b*]thiophene (**16**) with amines may lead to a rearranged product (**18**) in addition to the product of *ipso*-substitution. ^{13}C labelling experiments[94] have ruled out a rearrangement of the carbon skeleton. The likely mechanism involves double addition of the nucleophile and a nitro group shift through intermediate (**17**). Kinetic, spectroscopic, crystallographic, and *ab initio* theoretical studies have shown[95] that secondary steric effects, between methyl and nitro groups, are considerably smaller in thiophene derivatives, such as (**19**), than in the corresponding benzene derivatives (**20**). The effects of ion association with cations, K^+, Na^+ and Li^+, have been investigated in the substitution reactions with ethanolic ethoxide of *S*-4-nitrophenol 2-thiofurate and 2-thiophenethiocarboxylate.[96]

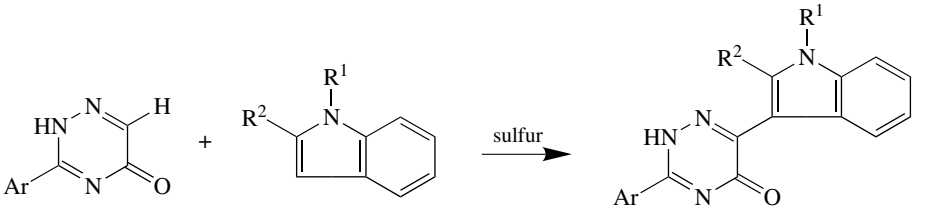


(**16**) (**17**) (**18**)



(**19**) (**20**)

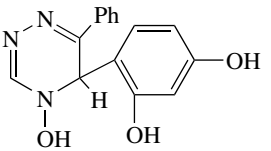
Kinetic studies of substitutions by the S_NAr mechanism have been reported for reactions of 2-chloro-3-nitro-, 2-chloro-5-nitro-,[97] and 2-chloro-3,5-dinitro-pyridines[98] with substituted arenethiolates in methanol. The reactivities of the nucleophiles are nicely correlated by their carbon basicities. An addition–elimination mechanism, with rate-limiting nucleophilic attack, is likely in the reaction of substituted pyridines, as nucleophiles, with 2,4-disubstituted-6-halo-1,3,5-triazines in acetonitrile.[99] A comparison of the activating effects of aza and nitro groups has been made using some morpholino-dechlorination reactions of pyridine and benzene derivatives.[100] It has been shown that the reaction with alkoxide ions of ring-halogenated 3-trifluoromethylpyridines may result in ring substitution or alcoholysis of the trifluoromethyl group.[101] Nucleophilic substitution of hydrogen has been observed (Scheme 5) in the reaction of 1,2,4-triazin-5-ones with indoles (**21**; R^1, R^2 = H, Me) in the presence of sulfur.[102]



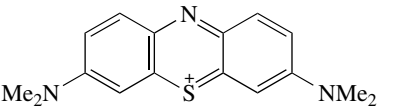
(**21**)

SCHEME 5

There have been reviews of nucleophilic substitution[103] and of deoxidative nucleophilic substitution [104] in heterocyclic *N*-oxides. Stable carbon–carbon-bonded adducts, such as (**22**), have been reported from the reactions of 6-phenyl-1,2,4-triazine 4-oxides with phenols; oxidation of the adducts may be achieved by reaction with potassium permanganate in acetone.[105]

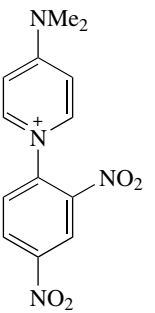


(**22**)



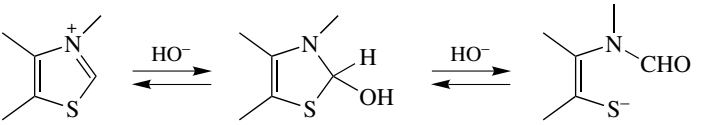
(**23**)

The special effects of a mesoionic system as a substituent have been noted[106] in the reactions with nucleophiles of 3-*N*-(4-chloro-3-nitrophenyl)sydnone. A synthesis, using two amino-debromination reactions, has been used[107] to prepare phenothiazines analogous to methylene blue (**23**). An unusual susceptibility to the nature of the counteranion has been observed[108] in the kinetics of the reaction of *N*-(2,4-dinitrophenyl)-4-dimethylaminopyridinium salts (**24**) with piperidine in acetonitrile, and may indicate participation of the anion in stabilising the intermediate. An ANRORC mechanism is implicated in the reaction of *N*-(2,4-dinitrophenyl)-4-(4-pyridyl)pyridinium cations with arylamines.[109] Ring-opening and ring-closure reactions



(**24**)

will also account for the formation of pyrimidine derivatives in the reaction of 4-acylaminopyrylium salts with ammonia or primary amines.[110] Ring opening has also been observed in the reactions of *o*-phenyldibenzofuranium and 10-phenylxanthonium cations with nucleophiles.[111] A detailed kinetic study has been reported of the reversible ring opening of thiamine derivatives (Scheme 6). A major conclusion is that the amidoenethiolates (**25**) produced may exist as two rotamers, owing to slow rotation about the N−CO amide bond, so that two separate re-closure reactions are observed.[112]

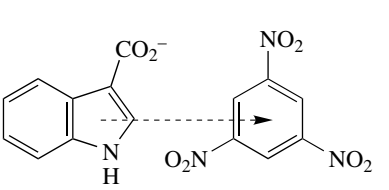


(**25**)

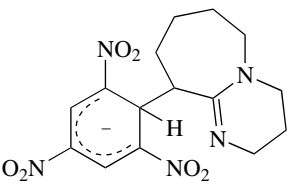
SCHEME 6

Meisenheimer and Related Adducts

Rate and equilibrium constants have been reported for the reactions of butylamine, pyrrolidine, and piperidine with trinitrobenzene, ethyl 2,4,6-trinitrophenyl ether, and phenyl 2,4,6-trinitrophenyl ether in acetonitrile. In these reactions, leading to σ-adduct formation and/or nucleophilic substitution, proton transfer may be rate limiting. Comparisons with data obtained in DMSO show that, while equilibrium constants for adduct formation are lower in acetonitrile, rate constants for proton transfer are higher. This probably reflects the stronger hydrogen bonding between DMSO and NH^+ protons in ammonium ions and in zwitterions.[113] Reaction of 1,3,5-trinitrobenzene with indole-3-carboxylate ions in methanol has been shown to yield the π-complex (**26**), which is the likely precursor of nitrogen- and carbon-bonded σ-adducts expected from the reaction.[114] There is evidence for the intermediacy of adducts similar to (**27**) from the reaction of methyl 3,5-dinitrobenzoate with 1,8-diazabicyclo[5.4.0]undec-8-ene (DBU); cyclization eventually yields 2-aminoindole derivatives.[115]



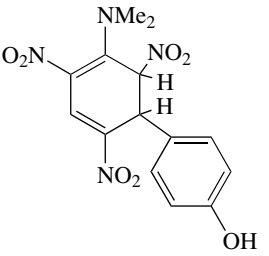
(**26**)



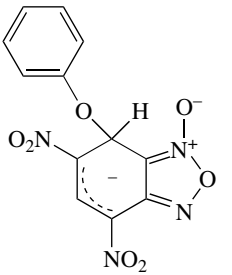
(**27**)

NMR studies of the reactions of *N*,*N*-dimethylpicramide (DMP) with phenoxide and 2,6-di-*t*-butylphenoxide nucleophiles in DMSO show that attack occurs at the 3-position of the DMP to yield *para*-carbon-bonded σ-adducts.[116] Surprisingly,

acidification led to ring protonation to give neutral adducts such as (**28**). The ready protonation ($pK_a = 6.2$ in aqueous solution) is likely to derive from charge-transfer interaction between the NMe_2 group and the adjacent nitro group, and the attendant relief of steric strain upon conversion of the (C)2 centre from sp^2 into sp^3.

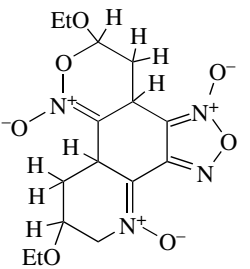


(**28**)

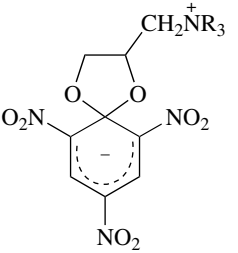


(**29**)

There have been several studies utilizing the ability of 4,6-dinitrobenzofuroxan (DNBF) to act as a 'super-electrophile.' It has been shown that the initial product of its reaction with phenoxide ions is the O-bonded adduct (**29**), although this rearranges to give the C-bonded adduct.[117] The reaction of DNBF with ethyl vinyl ether yields a dihydrooxazine *N*-oxide cycloadduct as a mixture of two diastereoisomers, and in the presence of excess ether a di-adduct (**30**) is formed.[118] Rate constants have been reported for the reaction of DNBF with 3-methoxythiophene in DMSO–water mixtures. The reaction results in a σ-adduct which is the product of S_EAr substitution in the thiophene, and the results were used to probe the carbon basicity of the thiophene derivative.[119]



(**30**)

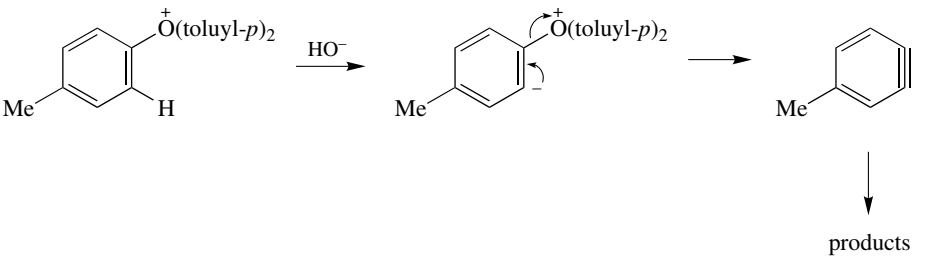


(**31**)

The reactions of picryl fluoride with (2,3-dihydroxypropyl)-ammonium or -phosphonium compounds have been found[120] to yield zwitterionic spiro-σ-adducts such as (**31**). Aromatic diazonium cations have been shown to add to the 9-position of σ-adducts of 9-nitroanthracene to yield neutral derivatives.[121] A study has been reported of the effects of ion pairing and change of solvent on the kinetics of decomposition of some anionic σ-adducts.[122]

Benzyne and Related Intermediates

There has been a review of didehydropyridines, focusing on their formation from halopyridines and base.[123] The reactions of tri-*p*-tolyloxonium salts with hydroxide in water yield a mixture of *p*- and *m*-cresols via a benzyne intermediate,[124] as shown in Scheme 7. A benzyne intermediate, generated by loss of lithium fluoride, is also implicated in the reaction of organolithium reagents with fluoro-*N*,*N*-diallylanilines leading to 3,4-disubstituted indolines.[125] The reaction of benzyne with 1,8-diethynylnaphthalene has been shown to yield benzo[*a*]pyrene.[126]



SCHEME 7

References

1 Kuokkanen, T., *J. Phys. Org. Chem.*, **10**, 67 (1997).
2 Moriguchi, T., Sakata, K., and Tsuge, A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2141.
3 Kosynkin, D., Bockman, T. M., and Kochi, J. K., *J. Org. Chem.*, **62**, 5811 (1997).
4 Wassmundt, F. W. and Kiesman, W. F., *J. Org. Chem.*, **62**, 8304 (1997).
5 Markgraf, J. H., Chang, R., Cort, J. R., Durant, J. L., Finkelstein, M., Gross, A. W., Lavyne, M. H., Moore, W. M., Petersen, R. C., and Ross, S. D., *Tetrahedron*, **53**, 10009 (1997).
6 Kosynkin, D., Bockman, T. M., and Kochi, J. K., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2003.
7 Galli, C., Gentili, P., and Guarnieri, A., *Gazz. Chim. Ital.*, **127**, 159 (1997).
8 Jaworski, J. S., *J. Chem. Res. (S)*, **1997**, 412.
9 Wong, J.-W., Natalie, K. J., Nwokogu, G. C., Pisipati, J. S., Flaherty, P. T., Greenwood, T. D., and Wolfe, J. F., *J. Org. Chem.*, **62**, 6152 (1997).
10 Combellas, C., Dellerue, S., Mathes, G., and Thiebault, A., *Tetrahedron Lett.*, **38**, 539 (1997).
11 Murguia, M. C. and Rossi, R. A., *Tetrahedron Lett.*, **38**, 1355 (1997).
12 Zhong, D., Ahmad, S., Cheng, P. Y., and Zewail, A. H., *J. Am. Chem. Soc.*, **119**, 2305 (1997).
13 Dedonder-Lardeux, C., Jouvet, C., Martrenchard-Barra, S., Solgadi, D., and Dimicoli, I., *Chem. Phys. Lett.*, **264**, 596 (1997); *Chem. Abs.*, **126**, 143823 (1997).
14 Glukhovtsev, M. N., Bach, R. D., and Laiter, S., *J. Org. Chem.*, **62**, 4036 (1997).
15 Zheng, Y.-J. and Ornstein, R. L., *J. Am. Chem. Soc.*, **119**, 648 (1997).
16 Zheng, Y.-J. and Bruice, T. C., *J. Am. Chem. Soc.*, **119**, 3868 (1997).
17 Ibata, T., *Kagaku Kogyo*, **47**, 8590 (1996); *Chem. Abs.*, **125**, 274942 (1996).
18 Crampton, M. R. and Robotham, I. A., *J. Chem. Res. (S)*, **1997**, 22.
19 Vlasov, V. M., Oskima, I. A., and Starichenko, V. F., *Zh. Org. Khim.*, **33**, 720 (1997).
20 Mancini, P. M. E., Terenzani, A., Adam, C., and Vottero, L. R., *J. Phys. Org. Chem.*, **10**, 849 (1997).
21 Bhattacharjee, G., Singh, A. K., and Gupta, A., *J. Indian Chem. Soc.*, **74**, 231 (1997); *Chem. Abs.*, **127**, 4762.
22 Nudelman, N. S., Alvaro, C. E. S., and Yankelevich, J. S., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2125.
23 Arnone, C., Consiglio, G., Frenna, V., and Spinelli, D., *J. Org. Chem.*, **62**, 3093 (1997).
24 Leska, B., Schroeder, G., and Gierczyk, B., *ACH-Models Chem.*, **133**, 461 (1996); *Chem. Abs.*, **127**, 56377 (1997).

[25] Rosca, S., Marton, A., and Rosca, S., *Rev. Chim. (Bucharest)*, **47**, 1127 (1996); *Chem. Abs.*, **126**, 185688 (1997).
[26] Rosca, S., Marton, A., Marton, G., and Rosca, S., *Rev. Chim. (Bucharest)*, **48**, 198 (1997); *Chem. Abs.*, **126**, 317093 (1997).
[27] Titskii, G. D. and Gaidash, T. S., *Ukr. Khim. Zh. (Russ. Ed.)*, **62**, 107 (1996); *Chem. Abs.*, **126**, 343215 (1997).
[28] Hedhli, L., Lesclingant, C., Fradet, A., and Marechal, E., *Macromol. Chem. Phys.*, **198**, 1 (1997); *Chem. Abs.*, **126**, 118268 (1997).
[29] Tabatskaya, A. A. and Vlasov, V. M., *Zh. Org. Khim.*, **33**, 762 (1997).
[30] Politanskaya, L. V., Malykhin, E. V., and Shteingarts, V. D., *Zh. Org. Khim.*, **32**, 1174 (1996).
[31] Politanskaya, L. V., Malykhin, E. V., and Shteingarts, V. D., *Zh. Org. Khim.*, **33**, 703 (1997).
[32] Khalfina, I. A. and Vlasov, V. M., *Zh. Org. Khim.*, **33**, 725 (1997).
[33] Sandall, J. P. B., Thompson, C., and Steel, N. J. D., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 513.
[34] Ross, J. P., Couture, P., and Warkentin, J., *Can. J. Chem.*, **75**, 1331 (1997).
[35] Hashizume, K., Tamakawa, H., Hashimoto, N., and Miyake, Y., *Chem. Lett.*, **1997**, 109.
[36] Makosza, M. and Wojciechowski, K., *Liebigs Ann./Recl.*, **1997**, 1805.
[37] Katritzky, A. R. and Toader, D., *J. Org. Chem.*, **62**, 4137 (1997).
[38] Katritzky, A. R., Wu, H., and Xie, L., *Tetrahedron Lett.*, **38**, 903 (1997).
[39] Makosza, M., Ziobrowski, T., Serebriakov, M., and Kwast, A., *Tetrahedron*, **53**, 4739 (1997).
[40] Drew, M. D., Jackson, D. A., Lawrence, N. J., Liddle, J., and Pritchard, R. G., *J. Chem. Soc., Chem. Commun.*, **1997**, 189.
[41] Pews, R. G., Lysenko, Z., and Vosejpka, P. C., *J. Org. Chem.*, **62**, 8255 (1997).
[42] Malykhin, E. V. and Shteingarts, V. D., *Zh. Org. Khim.*, **33**, 694 (1997).
[43] Bell, N. V., Bowman, W. R., Coe, P. F., Turner, A. T., and Whybrow, D., *Tetrahedron Lett.*, **38**, 2581 (1997).
[44] Meng, Q. and Thibblin, A., *J. Am. Chem. Soc.*, **119**, 1224 (1977).
[45] Adamson, A. J., Banks, R. E., Fields, R., and Tipping, A. E., *J. Chem. Res. (S)*, **1997**, 76.
[46] Criss, D. L., Ingram, L. L., Schultz, T. P., Fisher, T. H., and Saebo, D. B., *J. Org. Chem.*, **62**, 7885 (1997).
[47] O'Shea, D. F. and Sharp, J. T., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 3025.
[48] Rama Rao, A. V., Gurjar, M. K., Lakshmipathi, P., Reddy, M. M., Nagarajan, M., Pal, S., Sarma, B. V. N. B. S., and Tripathy, N. K., *Tetrahedron Lett.*, **38**, 7433 (1997).
[49] Roussi, G., Zamora, E. G., Carbonnelle, A.-C., and Beugelmans, R., *Tetrahedron Lett.*, **38**, 4401 (1997).
[50] Roussi, G., Zamora, E. G., Carbonnelle, A.-C., and Beugelmans, R., *Tetrahedron Lett.*, **38**, 4405 (1997).
[51] Frolov, A. N. and Rtishchev, N. I., *Zh. Org. Khim.*, **33**, 279 (1997).
[52] Chan, M. S. W. and Arnold, D. R., *Can. J. Chem.*, **75**, 1810 (1997).
[53] Arnold, D. R., McManus, K. A., and Chan, M. S. W., *Can. J. Chem.*, **75**, 1055 (1997).
[54] de Lijser, H. J. P. and Arnold, D. R., *J. Org. Chem.*, **62**, 8432 (1997).
[55] Hattori, T. and Miyano, S., *Yuki Gosei Kagaku Kyokaishi*, **55**, 121 (1997); *Chem. Abs.*, **126**, 199293 (1997).
[56] Koike, N., Nattori, T., Takeda, A., Okaishi, Y., and Miyano, S., *Chem. Lett.*, **1997**, 641.
[57] Hattori, T., Suzuki, M., Tomita, N., Takeda, A., and Miyano, S., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1117.
[58] Ryan, J. H. and Stang, P. J., *Tetrahedron Lett.*, **38**, 5061 (1997).
[59] McEwen, W. E. and De Massa, J. W., *Heteroatom Chem.*, **7**, 349 (1996); *Chem. Abs.*, **125**, 275114 (1996).
[60] Zhang, S., Zhang, D., and Liebeskind, L. S., *J. Org. Chem.*, **62**, 2312 (1997).
[61] Muramatsu, Y. and Yamamoto, T., *Chem. Lett.*, **1997**, 581.
[62] Stang, P. J. and Diederich, F., *Metal Catalysed Cross-Coupling Reactions*, Wiley, Chichester, 1997.
[63] Wolfe, J. P. and Buchwald, S. L., *J. Org. Chem.*, **62**, 1264 (1997).
[64] Louie, J., Driver, M. S., Hamann, B. C., and Hartwig, J. F., *J. Org. Chem.*, **62**, 1268 (1997).
[65] Ahman, J. and Buchwald, S. L., *Tetrahedron Lett.*, **38**, 6363 (1997).
[66] Wolfe, J. P. and Buchwald, S. L., *Tetrahedron Lett.*, **38**, 6359 (1997).
[67] Beller, M., Riermeier, T. H., Reisinger, C.-P., and Herrmann, W., *Tetrahedron Lett.*, **38**, 4807 (1997).
[68] Reddy, N. P. and Tanaka, M., *Tetrahedron Lett.*, **38**, 4807 (1997).
[69] Wolfe, J. P. and Buchwald, S. L., *J. Org. Chem.*, **62**, 6066 (1997).
[70] Beletskaya, I. P., Bessmertnykh, A. G., and Guilard, R., *Tetrahedron Lett.*, **38**, 2287 (1997).
[71] Wolfe, J. P., Singer, R. A., Ahman, J., and Buchwald, S. L., *Tetrahedron Lett.*, **38**, 6367 (1997).
[72] Marcoux, J.-F., Wagaw, S., and Buchwald, S. L., *J. Org. Chem.*, **62**, 1568 (1997).
[73] Shen, W., *Tetrahedron Lett.*, **38**, 5575 (1997).
[74] Sengupta, S. and Bhattacharyya, S., *J. Org. Chem.*, **62**, 3405 (1997).
[75] Darses, S., Genet, J.-P., Brayer, J.-L., and Demoute, J.-P., *Tetrahedron Lett.*, **38**, 4393 (1997).

[76] Jang, S.-B., *Tetrahedron Lett.*, **38**, 1793 (1997).
[77] Murata, M., Watanabe, S., and Masuda, Y., *J. Org. Chem.*, **62**, 6458 (1997).
[78] Ishiyama, T., Itoh, Y., Kitano, T., and Miyaura, N., *Tetrahedron Lett.*, **38**, 3447 (1997).
[79] Indolese, A. F., *Tetrahedron Lett.*, **38**, 3513 (1997).
[80] Saito, S., Oh-tani, S., and Miyaura, N., *J. Org. Chem.*, **62**, 8024 (1997).
[81] Mann, G. and Hartwig, J. F., *J. Org. Chem.*, **62**, 5413 (1997).
[82] Jutand, A. and Mosleh, A., *J. Org. Chem.*, **62**, 261 (1997).
[83] Riguet, E., Alami, M., and Cahiez, G., *Tetrahedron Lett.*, **38**, 4397 (1997).
[84] Fouquet, E., Pereyre, M., and Rodriguez, A. L., *J. Org. Chem.*, **62**, 5242 (1997).
[85] Echavarren, A. M., de Frutos, O., Tamayo, N., Noheda, P., and Calle, P., *J. Org. Chem.*, **62**, 4524 (1997).
[86] Stagliano, K. W. and Malinakova, H. C., *Tetrahedron Lett.*, **38**, 6617 (1997).
[87] Mann, G. and Hartwig, J. F., *Tetrahedron Lett.*, **38**, 8005 (1997).
[88] Grosshenny, V., Romero, F. M., and Ziessel, R., *J. Org. Chem.*, **62**, 1491 (1997).
[89] Pogodin, S., Biedermann, P. U., and Agranat, I., *J. Org. Chem.*, **62**, 2285 (1997).
[90] Chen, C., Lieberman, D. R., Larsen, R. D., Verhoeven, T. R., and Reider, P. J., *J. Org. Chem.*, **62**, 2676 (1997).
[91] Okuro, K. and Alper, H., *J. Org. Chem.*, **62**, 1566 (1997).
[92] Hennings, D. D., Iwasa, S., and Rawal, V. H., *J. Org. Chem.*, **62**, 2 (1997).
[93] Ripa, L. and Hallberg, A., *J. Org. Chem.*, **62**, 595 (1997).
[94] Spinelli, D., Zanirato, P., Di Miceli, E., Lamartina, L., and Guerrera, F., *J. Org. Chem.*, **62**, 4921 (1997).
[95] Consiglio, G., Frenna, V., Mugnoli, A., Noto, R., Pani, M., and Spinelli, D., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 309.
[96] Um, I.-H., Lee, Y.-J., Nahm, J.-H., and Kwon, D.-S., *Bull. Korean Chem. Soc.*, **18**, 749 (1997); *Chem. Abs.*, **127**, 205209 (1997).
[97] Hamed, E. A., El-Bardan, A. A., Saad, E. F., Gohar, G. A., and Hassan, G. M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2415.
[98] Hamed, E. A., *Int. J. Chem. Kinet.*, **29**, 515 (1997).
[99] Skrypka, A. V., Taran, N. A., Savelova, V. A., Mikhailov, V. A., and Drizhd, L. P., *Ukr. Khim. Zh. (Russ. Ed.)*, **62**, 116 (1996); *Chem. Abs.*, **126**, 330317 (1997).
[100] Elhegazy, F. E. Z. M., *Alexandria J. Pharm. Sci.*, **10**, 113 (1996); *Chem. Abs.*, **125**, 246984 (1996).
[101] Qian, X. and Liu, S., *J. Fluorine Chem.*, **79**, 9 (1996); *Chem. Abs.*, **125**, 246980 (1996).
[102] Zyryanov, G. V., Pilicheva, T. L., Rusinov, V. L., Chupakhin, O. N., and Neunhoeffer, H., *Zh. Org. Khim.*, **33**, 612 (1997).
[103] Puszko, A. and Lorenc, J., *Pr. Nauk. Akad. Ekon. im. Oskara Langego Wroclawiu*, **728**, 45 (1996); *Chem. Abs.*, **127**, 34156 (1997).
[104] Puszko, A. and Lorenc, J., *Pr. Nauk. Akad. Ekon. im. Oskara Langego Wroclawiu*, **728**, 61 (1996); *Chem. Abs.*, **127**, 34157 (1997).
[105] Kojevnikov, D. N., Ulomsky, E. N., Rusinov, V. L., Chupakhin, O. N., and Neunhoeffer, H., *Mendeleev Commun.*, **1997**, 116.
[106] Braz, V. R., Echevarria, A., and Miller, J., *Heterocycl. Commun.*, **2**, 507 (1996); *Chem. Abs.*, **126**, 211706 (1997).
[107] Leventis, N., Chen, M., and Sotiriou-Leventis, C., *Tetrahedron*, **53**, 10083 (1997).
[108] Titskii, G. D., Kulishova, T. P., and Mitchenko, E. S., *Zh. Org. Khim.*, **32**, 629 (1996); *Chem. Abs.*, **125**, 327844 (1997).
[109] Titskii, G. D. and Mitchenko, E. S., *Ukr. Khim. Zh. (Russ. Ed.)*, **62**, 57 (1996); *Chem. Abs.*, **126**, 330313 (1997).
[110] Shibaeva, N. V., Nechayuk, I. I., Pyshchev, A. I., and Borodaev, S. V., *Zh. Org. Khim.*, **33**, 595 (1997).
[111] Tolstaya, T. P., Bobyleva, M. S., Vanchikov, A. N., Kovalysheva, G. V., Kulikov, N. S., and Tsariev, D. A., *Russ. Chem. Bull.*, **46**, 789 (1997); *Chem. Abs.*, **127**, 205428 (1997).
[112] Carmichael, E. C., Geldart, V. D., McDonald, R. S., Moore, D. B., Rose, S., Colebrook, L. D., Spiropoulos, G. D., and Tee, O. S., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2609.
[113] Crampton, M. R. and Lord, S. D., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 369.
[114] Sepulchri, P., Goumont, R., Halle, J.-C., Buncel, E., and Terrier, F., *J. Chem. Soc., Chem. Commun.*, **1997**, 789.
[115] Sutherland, J. K., *J. Chem. Soc., Chem. Commun.*, **1997**, 325.
[116] Manderville, R. A. and Buncel, E., *J. Org. Chem.*, **62**, 7614 (1997).
[117] Buncel, E., Manderville, R. A., and Dust, J. M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1019.
[118] Halle, J.-C., Vichard, D., Pouet, M.-J., and Terrier, F., *J. Org. Chem.*, **62**, 7178 (1997).
[119] Kizilian, E., Terrier, F., Chatrousse, A.-P., Gzouli, K., and Halle, J.-C., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2667.

[120] Knyazev, V. N. and Drozd, V. N., *Zh. Org. Khim.*, **32**, 1394 (1996); *Chem. Abs.*, **126**, 317333 (1997).
[121] Blokhin, I. V., Atroshchenko, Yu. M., Gitis, S. S., Alifanova, E. N., Kaminskii, A. Ya., Grudtsyn, Yu. D., Efremov, Yu. A., Andrianov, V. F., Blokhinova, N. I., and Shakhkeldyan, I. V., *Zh. Org. Khim.*, **32**, 1531 (1996); *Chem. Abs.*, **126**, 293171 (1997).
[122] Gitis, S. S. and Stempin, N. D., *Zh. Obshch. Khim.*, **66**, 1516 (1996); *Chem. Abs.*, **126**, 211753 (1997).
[123] Yao, Z. and Cai, Z., *Daxue Huaxue*, **11**, 11 (1996); *Chem. Abs.*, **126**, 117822 (1997).
[124] Tolstaya, T. P., Tsariev, D. A., and Luzikov, Y. N., *Tetrahedron Lett.*, **38**, 4457 (1997).
[125] Bailey, W. F. and Carson, M. W., *Tetrahedron Lett.*, **38**, 1329 (1997).
[126] Cobas, A., Guitian, E., and Castedo, L., *J. Org. Chem.*, **62**, 4896 (1997).

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CHAPTER 8

Electrophilic Aromatic Substitution

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General

A contribution has been made to discussions concerning the reactivity–selectivity principle. *N*-Nitrosoamides were used to generate essentially free substituted benzyl cations of varying reactivity for the benzylation of toluene–benzene mixtures and studies of the intermolecular selectivity of these cations accorded with the principle.[1] These observations led to a critical discussion of earlier discussions[2] but do not appear to question the fundamental point concerning the incompatibility of the Hammett equation and the Hammond postulate. Conclusive evidence for the operation of the proposed mechanism of electrophilic aromatic substitution occurring within the complex formed upon addition of gaseous arenium ions to a variety of electrophile precursors including alkyl halides, alcohols, epoxides, esters, and diazoalkanes is provided by FT-ICR mass spectrometry.[3] A review covers advances in the understanding of gas-phase reactions of aromatic substrates with cationic electrophiles in thermally equilibrated systems with an emphasis on the elementary processes and the covalent and non-covalent ionic intermediates involved.[4]

A review entitled 'Electrophilic species that can react with benzene are dicationic' covers the reactions of benzene with several reactive electrophiles and developments in understanding of the mechanism of the Friedel–Crafts reaction.[5]

The quantum-chemical calculation of charge-transfer states as possible intermediates in electrophilic aromatic substitution reactions, making allowance for solvation effects, has been reviewed.[6] It has been shown that a simple scaled Hartree–Fock *ab initio* model describes the ring proton affinity of some polysubstituted benzenes, naphthalenes, biphenylenes, and large alternant aromatics, in agreement with experimental values. The simple additivity rule observed previously in smaller

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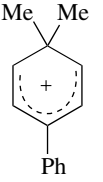
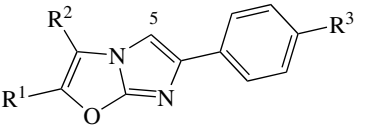
alternant systems applies to polyfluoropyrenes.[7] The proton affinities of polycyclic aromatic hydrocarbons with a five-membered ring have been calculated using the AM1 Hamiltonian comparing with experimental values from a new chemical ionization mass spectrometric method. The method thus developed was applied to indene.[8] The benzenium, toluenium, and ethylbenzenium ions have been synthesized on aluminium bromide by co-adsorption of the arenes with either hydrogen bromide or an alkyl bromide. The *p*-toluenium ion was the main isomer at 77 K but was in observable equilibrium with the *ortho* isomer at 273 K.[9] The 6,6-dimethyl-3-phenylbenzenium ion (**1**) has been generated in aqueous solution containing 20% acetonitrile. It has a half-life of ca 150 ns at 298 K when it forms 6,6-dimethyl-3-phenylcyclohexa-2,4-dien-1-ol with 2% 3,4-dimethylbiphenyl.[10]

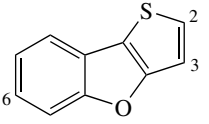
A review in Polish covers nitration, bromination, mercuration, nitrosation and diazocoupling of heterocyclic *N*-oxides.[11] The reactivity to electrophilic substitution of azoles has been assessed[12] by combining quantum-chemical calculations with a review of literature data. Both S_E2Ar and ylide mechanisms were considered. Bromination, nitration, Vilsmeier–Haack formylation and Mannich reactions of di- and tri-substituted imidazo[2,1-*b*]oxazoles (**2**) occur at the 5-position.[13] Vilsmeier formylation and acetylation of 3,3′-dipyrromethane gave the corresponding 3-acylpyrrole in a novel fragmentation reaction.[14] Bromination, formylation, acetylation, and nitration of thieno[3,2-*b*]benzofuran (**3**) takes place at position 2.[15] An electron-donating substituent in this position directs further substitution to positions 3 and 6, whereas an electron-withdrawing substituent at position 2 leads to exclusive 6-substitution. Heterocyclic analogues of benzocyclopropene (**4**) exhibit enhanced selectivity in electrophilic substitution reactions. Competition between two effects is responsible for the enhanced *β*-position activity, in concurrence with the Mills–Nixon hypothesis.[16]



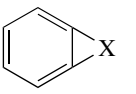
(**1**)



(**2**)



(**3**)



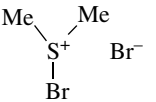
X = NH, O, S

(**4**)

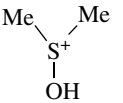
Halogenation

The role of polychlorinated *gem*-dichlorocyclohexadienones as reaction intermediates which can then produce desired *meta*-chlorinated products or undesired coupled products has been described.[17] Chlorination of phenol and sometimes the ether complicates the hydrolysis of some primary alkyl phenyl ethers in concentrated aqueous perchloric acid solution.[18] Unexpected chlorination has also been established in the reaction of 2-amino-5-chlorobenzophenone with HCl in aqueous methanol (1 : 1 v/v), 2-amino-3,5-dichlorobenzophenone being amongst the products.[19]

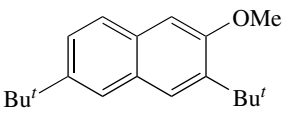
Zinc bromide supported on mesoporous silica or acid-activated montmorillonite is an efficient, selective, and reusable catalyst for the *para*-bromination of activated and moderately deactivated aromatic substrates.[20] Chlorobenzene, for example, is converted into bromochlorobenzenes (92.9% conversion, *para* : *ortho* ratio= 10) with the former system in *n*-hexane. Bromodimethylsulfonium bromide (**5**) can be generated *in situ* by treating dimethyl sulfoxide with aqueous hydrobromic acid. Studies[21] with a range of activated aromatics have shown that it is a milder more selective brominating reagent than elemental bromine. If the bromination is carried out by adding 47% HBr to stirred dimethyl sulfoxide at room temperature containing the substrate, a range of monosubstituted benzene derivatives can be monobrominated.[22] Some substrates with electron-withdrawing groups (NO_2, CHO) yield *ortho*-substituted products whereas some with electron-donating groups (NH_2, OH, CH_3) yield only *para*-bromo derivatives. It is suggested that initial electrophilic attack by the hydroxydimethylsulfonium ion (**6**) giving *ortho*-substitution via prior interaction with the substituent (for CHO, NO_2) or *para*-substitution (for NH_2, OH, CH_3) is followed by nucleophilic displacement by bromide ion. The use of benzyltrimethylammonium tribromide as a brominating agent has been reviewed (in Chinese).[23] 3,6-Di-*t*-butyl-2-methoxynaphthalene (**7**) is brominated most rapidly at the 1-position, as is 2-methoxynaphthalene.[24] Unlike with the latter, however, there is a rapid acid-catalysed reversible reaction which gives eventually 8-bromo-



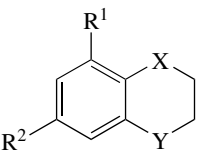
(**5**)



(**6**)

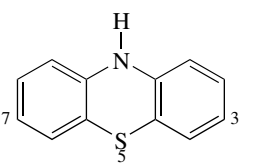


(**7**)



(**8**) **a**; X = O, S; Y = S

b; X = O, S; Y = $\overset{+}{S}$Br



(**9**)

3,6-di-*t*-butyl-2-methoxynaphthalene by an intermolecular route. The difference is attributed to steric buttressing by the 3-*t*-butyl group facilitating 1-protonation and loss of the bromonium ion.

1,4-Benzothiazines and 1,4-benzoxathianes (**8a**) undergo regiospecific bromination when treated with bromine in dry chloroform.[25] Calculations suggest that the regioselectivity is consistent with a charge-controlled electrophilic aromatic substitution where the Br^+ species comes from a monobromosulfonium ion such as (**8b**), in contrast to the behaviour of the related benzodithiane systems. Phenothiazine (**9**) reacts [26] with an excess of bromine in acetic acid to give 3,7-dibromophenothiazin-5-ium bromide, a reaction involving disubstitution followed by oxidation of the central ring by the excess of bromine.

The kinetics of iodination of a number of disubstituted phenols by iodine monochloride in aqueous methanol have been studied[27] and interpreted in terms of a proposed mechanism.

Nitration

The reported improvement in yields and selectivities in both mono- and poly-nitration of aromatic compounds using Claycop with acetic anhydride (and if necessary nitric acid) in tetrachloromethane has been investigated.[28] The reagent system is found to be modestly catalytic and regioselective in the mononitration of toluene but is neither catalytic nor regioselective in the nitration of 2-nitrotoluene.

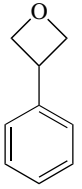
Data have been presented on the kinetics of nitration of acetanilide in mixtures of nitric and sulfuric acids.[29] A review discusses the several mechanisms operative in the nitration of phenol including *para*-selective nitrosation–oxidation and mechanisms involving phenoxy radical–nitrogen dioxide reaction yielding a 55:45 *ortho*:*para* nitration ratio.[30] The kinetics of mononitration of biphenyl-2-carboxylic acid have been investigated in several solvents. The maximum *ortho*:*para* product ratio of 8.4 is observed in tetrachloromethane.[31] Nitration products were not formed in the presence of dioxane.[31,32] Quantum-chemical AM1 calculations were performed and the predominant formation of the *ortho*-nitro product is accounted for by stabilization of the σ-complex by the carboxyl group.[33]

Nitration of naphthalene by use of cerium(IV) ammonium nitrate suspended on silica gel, or in homogeneous solution, in the presence of alcohols, sodium or tetrabutylammonium nitrite and acid gives mainly 1-alkoxy-4-nitronaphthalenes together with some of the 2-nitro isomers.[34] The results are consistent with initial attack by $NO_2\cdot$ alone or complexed with cerium(IV) ion at the 1- and 2-positions in a ratio of 5:1.

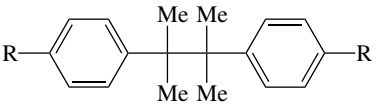
The reaction of 3-phenyloxetane (**10**) with nitric acid in dichloromethane and trichloromethane under anhydrous conditions has been investigated.[35] Quantitative conversion into 2-(nitrophenyl)propane-1,3-diol dinitrates occurs. The substrate reacts through its majority hydrogen-bonded complexed form initially by a mixture of aromatic nitration and oxetane ring opening. The nitration, perhaps surprisingly, proceeds at a rate comparable to that of *p*-dichlorobenzene.

The ozone-mediated reaction of bicumene and some derivatives (**11**) with nitrogen dioxide in dichloromethane (kyodai nitration) at low temperatures results in the cleavage of the central C−C bond to yield the benzyl nitrate and products therefrom, in contrast to the behaviour of bibenzyl.[36] This result is interpreted in terms of electron transfer from the substrate to $NO_3\cdot$ to give a radical cation species which fragments to form tertiary benzylic species in the former cases.

Nitration of 1-arylpyrroles with acetyl nitrate and 1-arylpyrroles and 1-(2-ethoxycarbonylbenzyl)pyrrole with trifluoroacetyl nitrate gave 2- and 3-nitro products. The latter were further nitrated with mixed nitric and sulfuric acids.[37]

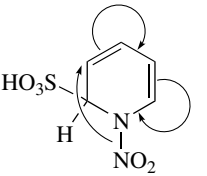


(**10**)

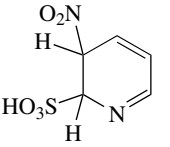


(**11**)

R = H, Me, Br



(**12**)

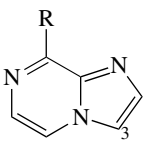


(**13**)

The mechanism of the formation of 3-nitropyridine from pyridine on reaction with dinitrogen pentaoxide in the presence of sulfur dioxide has been partially elucidated, with two stages of the reaction being separated.[38] The reaction involves the initial formation of *N*-nitropyridinium nitrate which then reacts to form transient species, one of which may be *N*-nitro-1,2-dihydropyridine-2-sulfonic acid (**12**). 3-Nitropyridine is formed from these intermediates either by extramolecular nitronium ion migration or via appropriate sigmatropic shifts [e.g. (**12**)→(**13**)]. *N*-Nitropyridinium nitrate can also be generated *in situ* from the reaction of pyridine with nitrogen dioxide and ozone in an inert organic solvent.[39] 3-Nitropyridine is then formed as above in good yield on addition of sodium hydrogen sulfite.

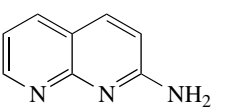
Imidazo[1,2-*a*]pyrazines (**14**) with activating alkyloxy or alkylamino substituents at the 8-position were mononitrated regiospecifically at the 3-position by nitric acid in sulfuric acid in accord with semiempirical (AM1) molecular orbital calculations.[40]

Nitration, suggested to involve nitrosation/oxidation, occurs during diazotization of some substituted 2-amino-1,8-naphthyridine derivatives (**15**).[41] The selectivity of this process was contrasted with that of the nitronium ion reaction.



(**14**)

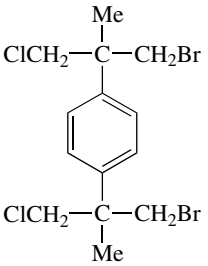
R = OR^1, NHR^1



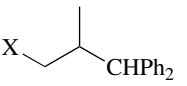
(**15**)

Alkylation, Acylation, and Related Reactions

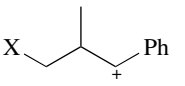
Spin coupled (SC) valence bond calculations[42] for the formation of the Wheland intermediate, $C_6H_6CH_3^+$, from CH_3^+ and benzene suggest the crossing of two SC potential energy curves, which at large separations correspond to $C_6H_6 + CH_3^+$ and $C_6H_6^+ + CH_3$, simultaneously with the rehybridization of the carbon atoms. A qualitatively correct description of complex formation is obtained by taking a linear combination of the SC solutions. Alkylation of benzene with 1,2-dibromo-3-chloro-2-methylpropane yields mainly the disubstituted benzene (**16**) with $AlCl_3$–CH_3NO_2 or K10 montmorillonite, but mainly the 1-X-2-methyl-3,3-diphenylpropanes (**17**; X = Cl, Br) with $AlCl_3$, the latter reactions involving the intermediate (**18**).[43] Simple alkanes (e.g. propane) and cycloalkanes (e.g. cyclopentane) alkylate deactivated aromatic compounds (e.g. acetophenone) in the presence of the superacid, $CBr_4.2AlBr_3$, at low temperatures.[44]



(**16**)



(**17**)



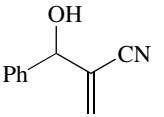
(**18**)

In contrast to the simple Friedel–Crafts reaction, scandium(III) triflate-catalysed benzylation of benzene using an aromatic aldehyde and propane-1,3-diol (or their acetal) gives selectively the diarylmethane in excellent yield.[45] The alcohol acts as a hydride ion source for incorporation into the benzylic methylene group. A related study again forming diarylmethanes[46] involves the reaction of 2-aryl-1,3-dioxane or the aromatic aldehyde and propane-1,3-diol with aromatic compounds in the presence of trifluoromethanesulfonic acid. A full competitive and non-competitive kinetic study[47] of the chloromethylation of benzene and toluene with methoxyacetyl chloride and chloromethyl methyl ether with $AlCl_3$–CH_3NO_2 or $SnCl_4$–CH_2Cl_2 suggests $CH_3OCH_2^+$ or a related ion pair as a common remarkably selective electrophile. These studies permit the rationalization of the range of chloromethylation inter- and intra-molecular selectivities in the literature.

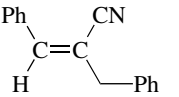
A study[48] of the direct upper-rim alkylation of calix[*n*]arenes has shown that, with $n = 8$, reaction with isopropyl chloride in 1,2-dichloroethane with $AlCl_3$ gives isopropylation, whereas when $n = 4$ hydroxyisopropylation is observed. With $n = 6$ there is a mixture of products, indicating overall an increase in phenolic behaviour as n increases from 4 to 8.

A short review in Chinese covers Friedel–Crafts reactions of alkenyl halides with aromatic hydrocarbons.[49] High yields of the allylated aromatic products have been

established[50] from reactions of arenes with allylic alcohols in the presence of catalytic amounts of cationic thiolate-bridged diruthenium complexes. The product proportions, however, do not suggest an electrophilic reaction. A simple stereoselective reaction of some unsaturated alcohols [e.g. (**19**)] with benzene in the presence of concentrated sulfuric acid has been demonstrated [e.g. to give (**20**) from (**19**).[51]

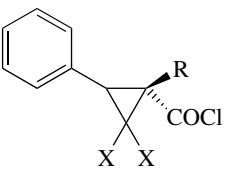


(**19**)

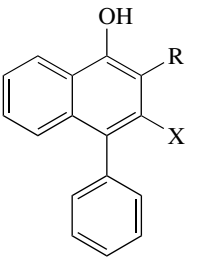


(**20**)

Novel, sequential regioselective Friedel–Crafts reactions of *gem*-dihalocyclopropanecarbonyl chlorides [e.g. (**21**)] with benzenes in the presence of $AlCl_3$ led to the synthesis of 4-aryl-1-naphthol derivatives [e.g. (**22**) from (**21**) and benzene], by a pathway involving an intramolecular cyclization [of (**21**)] followed by intermolecular coupling with benzene.[52] Errors in the structures of previously reported products from the transannular alkylation of benzene with (*Z*, *Z*)-cycloocta-1,5-diene have been corrected[53] and almost all products have the bicyclo[3.3.0]octane framework. Intramolecular alkylation of the aromatic ring in some aromatic cyclic ethers in the presence of $TiCl_4$ in CH_2Cl_2 gives a stereospecific route to substituted tetralins [e.g. (**23**)→(**24**)].[54] An efficient method for the synthesis of fused polycyclic aromatics involves a two-step sequence and the critical ring-forming step involves 4-alkoxyphenylethynyl groups and strong electrophiles such as trifluoroacetic acid and iodonium tetrafluoroborate [e.g. (**25**)→(**26**)].[55]



(**21**)
X = Cl, Br



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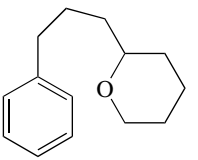
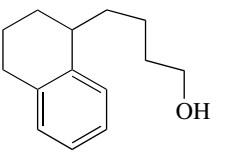
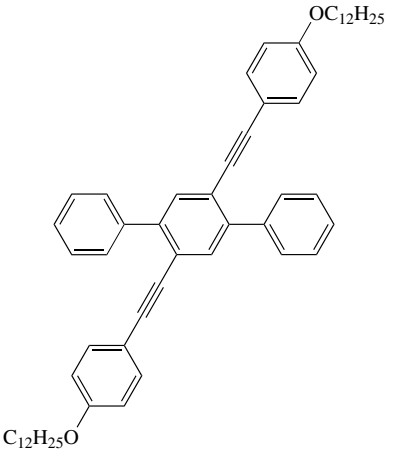


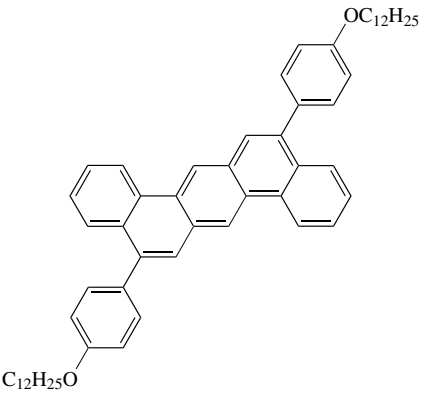
(**23**)



(**24**)

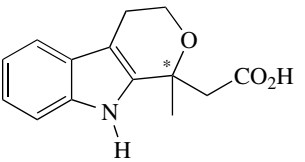


(**25**)



(**26**)

The reactions of nitrones with indoles have been applied to the formation of several *N*-hydroxylamines and symmetrical and unsymmetrical diindolylalkanes.[56] Chiral auxiliaries, alcohols derived from (1*S*)-(−)-*β*-pinene (R*OH), lead to an enantioselective synthesis when R* acetoacetate reacts with 3-(2-hydroxyethyl)indole in the presence of, for example, $BF_3.Et_2O$, forming (**27**).[57] Methyl migration follows Friedel–Crafts reaction of $(CH_3)_3SiCCl_3$ with benzene in the present of $AlCl_3$ and (**28**) is formed.[58]



(**27**)
ee can be >95%

$Cl(CH_3)_2SiCPh_2Me$

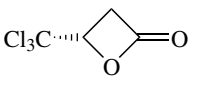
(**28**)

The first unequivocal evidence for the effective electrophile in an acylation reaction has been presented.[59] Reaction of aromatics with aroyl triflates in organic solvents needs no catalyst and allows kinetic investigation in homogeneous solution. The rate-limiting step can be either dissociation of the triflate to the acylium ion or reaction of the latter with the substrate. Kinetic measurements in the presence of base establish firmly the intermediacy of acylium ions.

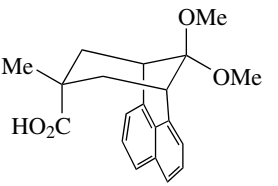
A review of formylation reactions involving methyl formate in a hydrogen fluoride–boron trifluoride medium has appeared.[60] Regioselectivity and kinetic data have been reported for Gattermann–Koch formylation in superacids and provide evidence for an intra-complex reaction where the formylation electrophile HCO^+ is generated by protonation of CO by the arenium ion.[61] The observed selectivity results from

competition between a *para*-selective intra-complex reaction and conventional reaction. Friedel–Crafts formylation, with HCOF, also appears to have an intra-complex pathway.

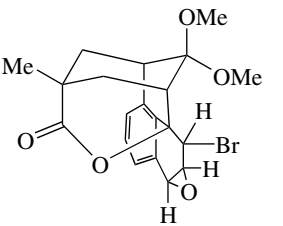
A review covers factors involved in the selection of Lewis acid catalysts for acylation reactions.[62] Bismuth(III) triflate has been shown to be a surprisingly good acylation catalyst especially for aroylation reactions,[63] and the potential of using a range of bismuth(III) salts for acylations has been reviewed.[64] A review[65] surveys Friedel–Crafts acylations of aromatic compounds with some cyclic anhydrides giving information about the regioselectivity of the ring opening and pathways of acylation. Regioselective acylations of some activated aromatics have been observed on heating with $PhCCl_3$ or PhCOCl over hydrated zirconia.[66] The use of zeolites in the acylation of anisole and veratrole by acetic anhydride under mild conditions has been reviewed,[67] as has the trifluoroacetylation of aromatics using trifluoroacetic anhydride with cobalt(II) chloride catalyst at room temperature, which appears to require the presence of at least one methoxy substituent.[68] A range of aromatic compounds are acylated by (*S*)-*β*-trichloromethyl-*β*-propiolactone (**29**) in the presence of a Lewis acid to give products retaining the stereochemical integrity of the lactone.[69] A review of the influence of the cation on the condensation of glyoxylic acid with 2-alkoxylphenols indicates that the use of tetraalkylammonium hydroxide instead of sodium hydroxide increases the *para*-selectivity of the condensation.[70]



(**29**)



(**30**)

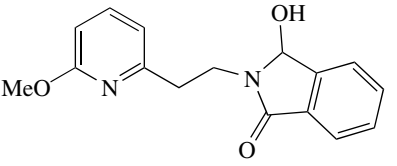


(**31**)

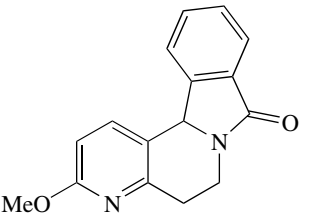
The bromination of the tetracyclic compound (**30**) affords[71] the novel compound (**31**) formed by capture of the Wheland intermediate by the neighbouring carboxylate ion. The intramolecular reaction of some activated pyridines with *N*-acyliminium ions led to some novel heterocycles [e.g. (**33**) from (**32**) in the presence of *p*-toluenesulfonic acid in benzene] by cyclization *para* to an electron-donating substituent.[72]

Other Reactions

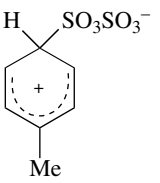
The details of protonation of several alkyl-substituted phenanthrenes by superacids have been reported.[73] The observed mono- and di-cations are usually in agreement with those predicted by AM1 MO calculations. Molecular modelling studies have suggested a multi-step pathway for the sulfonation of toluene with sulfur trioxide.[74] Intermediate π-complex, Wheland intermediate and pyrosulfonate species (**34**) are suggested, the product (*p*-toluenesulfonic acid) arising from an exothermic reaction between toluene and the acid (**35**) formed by a facile prototropic rearrangement of (**34**). The sulfur trioxide monosulfonation of isopyrene and some derivatives leads usually to sulfonated



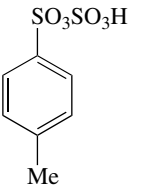
(**32**)



(**33**)

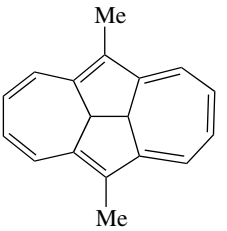


(**34**)

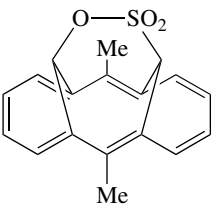


(**35**)

products[75] involving reaction at position 5. With 5,10-dimethylisopyrene (**36**), however, the sulfur trioxide may add as a bidentate electrophile to form the [14]annulene derivative (**37**). The amounts of sulfonic acids and sulfonic anhydrides formed in the sulfur trioxide sulfonation of some dialkylbenzenes and 1,ω-diarylalkanes have been investigated.[76] CNDO/2 MO theory has been applied to the prediction of the reactivity to chlorosulfonation of some phenoxyacetic acid derivatives.[77] A 3*H*-indole-3,3-bis-sulfide has been isolated from the sulfenylation of 3-phenylthioindole in the presence of triethylamine, lending support to the hypothesis that initial attack in the second sulfenylation of indole, which forms the 2,3-bis-sulfide, is initially at C(3).[78]



(**36**)

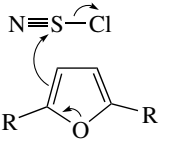


(**37**)

The nitrosation of phenol and cresols in buffer solutions involves a diffusion-controlled *C*-nitrosation followed by rate-limiting proton loss. *p*-Cresol is much less reactive than the other substrates.[79] Nitrosation in trifluoroacetic acid or in acetic–sulfuric acid mixtures is regioselective (e.g. 4-nitroso-*m*-xylene is formed from *m*-xylene) and possible non-selective nitrous acid-catalysed nitration can be eliminated by purging reaction solutions with nitric oxide.[80]

The kinetics of reaction of a number of aromatic compounds with substituted benzenediazonium ions have been studied and compared with those of other nucleophiles, kinetic isotope effect studies indicating rate-limiting attack of the diazonium ion.[81] The comparative studies permit qualitative rate predictions for such reactions. Coloured crystalline 1 : 1 complexes between electron-poor arenediazonium salts (ArN_2^+) and aromatic hydrocarbons have been successfully isolated and X-ray crystallographic studies indicate cofacial stacking of the aromatic donor on top of the aromatic ring of ArN_2^+.[82] The mechanistic implications of this have been discussed with relevance to electron-transfer arylation and electrophilic azo-coupling (see also reference 83). The reactivity of nitronaphthalenediazonium ions has been surveyed, 4-nitronaphthalenediazonium ion having the highest azo-coupling activity.[84] Low-temperature solution reactions of silylenes with aromatic compounds are reported to involve silyl cation intermediates.[85]

Evidence has been presented for initial electrophilic substitution by thiazyl chloride (NSCl) in the reaction of trithiazyl trichloride with 2,5-diarylfurans (**38**) which eventually yields 5-aroyl-3-arylisothiazoles.[86]



(**38**)

References

1 White, E. H., *Tetrahedron Lett.*, **38**, 7649 (1997).
2 Johnson, C. D. and Schofield, K., *J. Am. Chem. Soc.*, **95**, 270 (1973).
3 Aschi, M., Attina, M., and Cacace, F., *Res. Chem. Intermed.*, **22**, 645 (1996); *Chem. Abs.*, **125**, 275023 (1996).
4 Fornarini, S., *Mass Spectrom. Rev.*, **15**, 365 (1996, publ. 1997); *Chem. Abs.*, **127**, 108587 (1997).
5 Koichi, S. and Tomohiko, O., *Stable Carbocation Chemistry (Loker Hydrocarbon Res. Inst. Symp. Carbocation Chem.*), **1992** (publ. 1997), 525; Eds Prakash, G. K. S. and Schleyer, P. von R.; *Chem. Abs.*, **126**, 117577 (1997).
6 Abronin, I. A., *Khim. Fiz.*, **15**, 16 (1996); *Chem. Abs.*, **126**, 156976 (1997).
7 Maksic, Z. B., Kovacevic, B., and Kovacek, D., *J. Phys. Chem. A*, **101**, 7446 (1997).
8 Pointet, K., Milliet, A., Hoyau, S., and Renou-Gonnord, M. F., *J. Comput. Chem.*, **18**, 629 (1997); *Chem. Abs.*, **126**, 305291 (1997).
9 Xu, T., Barich, D. H., Torres, P. D., and Haw, J. F., *J. Am. Chem. Soc.*, **119**, 406 (1997).
10 McClelland, R. A., Ren, D., Ghobrial, D., and Gadosy, T. A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 451.
11 Puszko, A. and Wasylina, L., *Pr. Nauk, Akad. Ekon. im. Oskara Langego Wroclawiu*, **728**, 37 (1996); *Chem. Abs.*, **127**, 34065 (1997).
12 Belen'kii, L. I. and Chuvylkin, N. D., *Khim. Geterotsikl. Soedin.*, **1996**, 1535; *Chem. Abs.*, **126**, 224892 (1997).
13 Mekonnen, B. and Crank, G. *Tetrahedron*, **53**, 6959 (1997).
14 Leung, S. H., Nguyen, L. T., and Smith, K. M., *Heterocycl. Commun.*, **2**, 9 (1996); *Chem. Abs.*, **125**, 247518 (1996).
15 Vachal, P., Pihera, P., and Svoboda, J., *Collect. Czech. Chem. Commun.*, **62**, 1468 (1997).
16 Maksic, Z. B., Kovacek, D., and Kovacevic, B., *Electron. J. Theor. Chem.*, **1**, 65 (1996); *Chem. Abs.*, **127**, 108615 (1997).

[17] Desmurs, J.-R., Ratton, S., Jacquerot, R., Dananche, J., Besson, B., and Leblane, J.-C., *Ind. Chem. Libr.*, **8**, 129 (1996); *Chem. Abs.*, **126**, 18593 (1997).
[18] Lajunen, M., Laine, R., and Aaltonen, M., *Acta Chem. Scand.*, **51**, 1155 (1997).
[19] Nudelman, N. S. and De Waisbaum, R. G., *J. Phys. Org. Chem.*, **10**, 97 (1997).
[20] Clark, J. H., Ross, J. C., Macquarrie, D. J., Barlowe, S. J., and Bastock, T. W., *J. Chem. Soc., Chem. Commun.*, **1997**, 1203.
[21] Majetich, G., Hicks, R., and Reister, S., *J. Org. Chem.*, **62**, 4321 (1997).
[22] Srivastava, S. K., Chauhan, P. M. S., and Bhaduri, A. P., *J. Chem. Soc., Chem. Commun.*, **1996**, 2679.
[23] Kang, K. and Xie, R., *Huaxue Yanjiu Yu Yingyong*, **8**, 475 (1996); *Chem. Abs.*, **126**, 131210 (1997).
[24] Braddock, C. D., Tucker, S. C., and Brown, J. M., *Bull. Soc. Chim. Fr.*, **134**, 399 (1997).
[25] Caputo, R., De Nisco, M., Palumbo, G., Adamo, C., and Barone, V., *Gazz. Chim. Ital.*, **126**, 595 (1996); *Chem. Abs.*, **126**, 7542 (1997).
[26] Leventis, N., Chen, M. G., and Sotiriou-Leventis, C., *Tetrahedron*, **53**, 10083 (1997).
[27] Dasharath, D. and Vibhute, Y. B., *Asian J. Chem.*, **9**, 70 (1997); *Chem. Abs.*, **126**, 157063 (1997).
[28] Lancaster, N. L., Moodie, R. B., and Sandall, J. P. B., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 847.
[29] Gu, J. and Lu, C., *Hanneng Cailiao*, **4**, 132 (1996); *Chem. Abs.*, **126**, 46796 (1997).
[30] Metivier, P. and Schlama, T., *Ind. Chem. Libr.*, **8**, 368 (1996); *Chem. Abs.*, **126**, 18599 (1997).
[31] Kolobov, A. V., Sokolov, A. V., Krasovskaya, G. G., Kofanov, E. R., Mironov, G. S., and Ovchinnikov, K. L., *Kinet. Catal.* (transl. of *Kinet. Katal.*), **38**, 335 (1997); *Chem. Abs.*, **127**, 148827 (1997).
[32] Kolobov, A. V., Krasovskaya, G. G., Kofanov, E. R., and Ovchinnikov, K. L., *Izv. Vyssh. Uchebn. Zaved., Khim. Khim. Tekhnol.*, **39**, 92 (1996); *Chem. Abs.*, **125**, 246987 (1996).
[33] Kolobov, A. V., Rusakov, A. I., Sokolov, A. V., and Kofanov, E. R., *Izv. Vyssh. Uchebn. Zaved., Khim. Khim. Tekhnol.*, **39**, 44 (1996); *Chem. Abs.*, **125**, 275043 (1996).
[34] Mellor, J. M., Parkes, R., and Millar, R. W., *Tetrahedron Lett.*, **38**, 8739 (1997).
[35] Hylands, K. A. and Moodie, R. B., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 709.
[36] Suzuki, H. and Mori, T., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1265.
[37] Korakas, D. and Varvounis, G., *J. Heterocycl. Chem.*, **33**, 611 (1996).
[38] Bakke, J. M. and Ranes, E., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1919.
[39] Suzuki, H., Iwaya, M., and Mori, T., *Tetrahedron Lett.*, **38**, 5647 (1997).
[40] Vitse, O., Bonnet, P.-A., Bompart, J., Viols, H., Subra, G., Chapat, J.-P., and Grassy, G., *J. Heterocycl. Chem.*, **34**, 701 (1997).
[41] Ferrarini, P. L., Mori, C., Badawneh, M., Manera, C., Martinelli, A., Miceli, M., Romagnoli, F., and Saccomanni, G., *J. Heterocycl. Chem.*, **34**, 1501 (1997).
[42] Raos, G., Astorri, L., Raimondi, M., Cooper, D. L., Gerratt, J., and Karadakov, P. B., *J. Phys. Chem. A*, **101**, 2886 (1997).
[43] Albar, H. A., Khalaf, A. A., and Bahaffi, S. O., *J. Chem. Res. (S)*, **1997**, 20.
[44] Orlinkov, A. V., Akhrem, I. S., Afanaseva, L. V., Mysov, E. I., and Volpin, M. E., *Mendeleev Commun.*, **1997**, 61.
[45] Tsuchimoto, T., Tobita, K., Hiyama, T., and Fukuzawa, S., *J. Org. Chem.*, **62**, 6997 (1997).
[46] Fukuzawa, S., Tsuchimoto, T., and Hiyama, T., *J. Org. Chem.*, **62**, 151 (1997).
[47] DeHaan, F. P., Djaputra, M., Grinstaff, M. W., Kaufman, C. R., Keithly, J. C., Kumar, A., Kuwayama, M. K., Macknet, K. D., Na, J., Patel, B. R., Pinkerton, M. J., Tidwell, J. H., and Villahermosa, R. M., *J. Org. Chem.*, **62**, 2694 (1997).
[48] Yao, B., Bassus, J., and Lamartine, R., *Bull. Soc. Chim. Fr.*, **134**, 555 (1997).
[49] Li, Y., Zhang, X., and Peng, G., *Hebei Shifan Daxue Xuebao, Ziran Kexueban*, **20**, 75 (1996); *Chem. Abs.*, **127**, 220407 (1997).
[50] Nishibayashi, Y., Yamanashi, M., Takagi, Y., and Hidai, M., *J. Chem. Soc., Chem. Commun.*, **1997**, 859.
[51] Basavaiah, D., Krishnamacharyulu, M., Hyma, R. S., and Pandiarju, S., *Tetrahedron Lett.*, **38**, 2141 (1997).
[52] Nishii, Y. and Tanabe, Y., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 477.
[53] Tateiwa, J. and Uemura, S., *Bull. Chem. Soc. Jpn*, **70**, 1615 (1997).
[54] Harrowven, D. C. and Dainty, R. F., *Tetrahedron Lett.*, **38**, 7123 (1997).
[55] Goldfinger, M. B., Crawford, K. B., and Swager, T. M., *J. Am. Chem. Soc.*, **119**, 4578 (1997).
[56] Denis, J.-N., Mauger, H., and Vallee, Y., *Tetrahedron Lett.*, **38**, 8515 (1997).
[57] Costa, P. R. R., Cabral, L. M., Alencar, K. G., Schmidt, L. L., and Vasconcellos, M. L. A. A., *Tetrahedron Lett.*, **38**, 7021 (1997).
[58] Kornev, A. N., Semenov, V. V., and Kurskii, Yu. A., *Izv. Akad. Nauk, Ser. Khim.*, **1996**, 1511; *Chem. Abs.*, **125**, 247922 (1996).
[59] Effenberger, F., Eberhard, J. K., and Maier, A. H., *J. Am. Chem. Soc.*, **118**, 12572 (1996).
[60] Saint-Jalmes, L., Rochin, C., Janin, R., and Morel, M., *Ind. Chem. Libr.*, **8**, 325 (1996); *Chem. Abs.*, **126**, 18597 (1997).

[61] Tanaka, M., Fujiwara, M., Xu, Q., Souma, Y., Ando, H., and Laali, K. K., *J. Am. Chem. Soc.*, **119**, 5100 (1997).
[62] Ashforth, R. and Desmurs, J.-R., *Ind. Chem. Libr.*, **8**, 3 (1996); *Chem. Abs.*, **126**, 18588 (1997).
[63] Desmurs, J.-R., Labrouillere, M., Le Roux, C., Gaspard, H., Laporterie, A., and Dubac, J., *Tetrahedron Lett.*, **38**, 8871 (1997).
[64] Desmurs, J. R., Labrouillere, M., Dubac, J., Laporterie, A., Gaspard, H., and Metz, F., *Ind. Chem. Libr.*, **8**, 15 (1996); *Chem. Abs.*, **126**, 18589 (1997).
[65] Hasumoto, I., Takatoshi, K., Badea, F. D., Sawada, T., Mataka, S., and Tashiro, M., *Res. Chem. Intermed.*, **22**, 855 (1996); *Chem. Abs.*, **125**, 300505 (1996).
[66] Patil, M. L., Jnaneshwara, G. K., Sabde, D. P., Dongare, M. K., Sudalai, A., and Deshpande, V. H., *Tetrahedron Lett.*, **38**, 2137 (1997).
[67] Spagnol, M., Gilbert, L., and Alby, D., *Ind. Chem. Libr.*, **8**, 29 (1996); *Chem. Abs.*, **126**, 18590 (1997).
[68] Ruiz, J., Gilbert, L., and Astruc, D., *Ind. Chem. Libr.*, **8**, 39 (1996); *Chem. Abs.*, **126**, 18591 (1997).
[69] Fujisawa, T., Ito, T., Fujimoto, K., Shimizu, M., Wynberg, H., and Staring, E. G. J., *Tetrahedron Lett.*, **38**, 1593 (1997).
[70] Wuthrick, M.-F. and Maliverney, C., *Ind. Chem. Libr.*, **8**, 343 (1996); *Chem. Abs.*, **126**, 18598 (1997).
[71] Chen, Y. S., Kampf, J. W., and Lawton, R. G., *Tetrahedron Lett.*, **38**, 6831 (1997).
[72] Brodney, M. A. and Padwa, A., *Tetrahedron Lett.*, **38**, 6153 (1997).
[73] Laali, K. K., Hollenstein, S., and Hansen, P. E., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2207.
[74] Morley, J. O. and Roberts, D. W., *J. Org. Chem.*, **62**, 7358 (1997).
[75] Cerfontain, H., Bakker, B. H., Koeberg-Telder, A., and Wilmes, O., *Liebigs Ann./Recl.*, **1997**, 49.
[76] Cerfontain, H., Koeberg-Telder, A., van Lindert, H. C. A., and Bakker, B. H., *Liebigs Ann./Recl.*, **1997**, 2227.
[77] Dumitrascu, A., Oniscu, C., Surpateanu, G., Horoba, E., and Cascaval, D., *Bul. Inst. Politeh. Iasi, Sect. 2: Chim. Ing. Chim.*, **42**, 91 (1996); *Chem. Abs.*, **127**, 108626 (1997).
[78] Hamel, P., *Tetrahedron Lett.*, **38**, 8473 (1997).
[79] Fernández-Liencres, M. P., Calle, E., González-Mancebo, S., Casado, J., and Quintero, B., *Int. J. Chem. Kinet.*, **29**, 119 (1997).
[80] Atherton, J. H., Moodie, R. B., Noble, D. R., and O'Sullivan, B., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 663.
[81] Mayr, H., Hartnagel, M., and Grimm, K., *Liebigs Ann./Recl.*, **1997**, 55.
[82] Bockman, T. M., Kosynkin, D., and Kochi, J. K., *J. Org. Chem.*, **62**, 5811 (1997).
[83] Kosynkin, D., Bockman, T. M., and Kochi, J. K., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2003.
[84] Bagal, I. L., Luchkevich, E. P., and El'tsov, A. V., *Zh. Obshch. Khim.*, **66**, 122 (1996); *Chem. Abs.*, **126**, 31038 (1997).
[85] Lumen, R., Mournier, P. A., Powell, J. M., Saint, G. N., and Timms, P. L., *Int. Conf. Low Temp. Chem., 2nd*, **1996**, 69; *Chem. Abs.*, **127**, 262716 (1997).
[86] Rees, C. W. and Yue, T.-Y., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2247.

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CHAPTER 9

Carbocations

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Introduction

A book containing authoritative reviews of many aspects of carbocation chemistry has been published.[1] These reviews are up-to-date to the end of 1991, as the book is the result of a symposium held in honour of George Olah in 1992; it features many of the world's leading carbocation chemists. At least one book review of it has also appeared.[2] Olah has an introductory chapter concerning his decades-long search for stable long-lived carbocations in superacid media,[3] and other review chapters include ones on carbocations at surfaces and interfaces,[4] on the X-ray structural analyses that have been performed on many carbocation salts and related compounds in recent years,[5] and on natural product chemistry in superacids.[6] Other review chapters will be referred to below, as appropriate.

Long-lived cyclopropylcarbinyl cation chemistry, including spiro cations and dications, has been reviewed,[7] and some of the more interesting newer carbocations, such as (**1**), are the subject of a short survey.[8] The use of secondary deuterium isotope effects in the study of carbocation-forming reactions has been revisited,[9] and the

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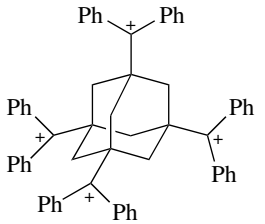
analysis of normal and special salt effects with respect to the formation of contact, space-separated and solvent-separated ion pairs is discussed.[10]



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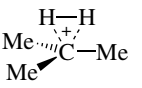

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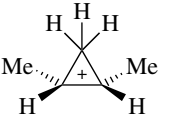


(**3**)

The application of molecular mechanics calculations to organic reactions, including carbocation intermediates in addition to reactants and transition states, is the subject of a review.[11] A large set of new cation parameters for MM3 calculations, based on heats of formation and molecular geometries, gives good agreement with experiment except for cations with strong hyperconjugative interactions.[12] However, a reported new empirical force field method for localized and delocalized carbocations includes hyperconjugative effects, and gives very good agreement between calculated, experimental and *ab initio* structures and heats of formation.[13]

Simple Carbocations

Hypervalent carbocations have received some attention this year.[14] The concept of three-centre, two-electron bonding in these entities is supported by a topological bifurcation analysis of the electronic structure of CH_5^+;[15] this and the related species CH_6^{2+} and CH_7^{3+} are also the subject of a review.[16] The $CH_3^+ + H_2$ reaction has been studied theoretically.[17]

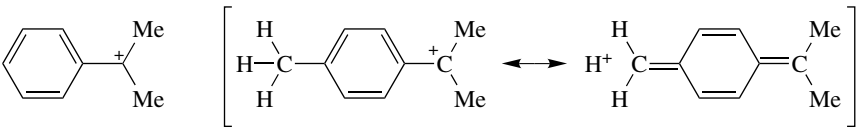
An *ab initio* study of protonated isobutane reveals that (**2**) has the lowest energy of the several possible structures studied,[18] and it has been shown experimentally that fast reversible protonation of all of the C—H bonds occurs before ionization when isobutane is treated with DF–SbF_5 superacid at 0 °C.[19] The branching rearrangement of linear $C_4H_9^+$ involves a protonated methylcyclopropane, according to a theoretical study,[20] and $C_5H_{11}^+$ rearranges via a protonated 1,2-dimethylcyclopropane.[20] The most stable structure for this is given as (**3**), a corner-protonated cyclopropane, according to a different analysis.[21] An unusual out–in hydrogen transfer process undergone by perhydro[2.2]paracyclophane in CF_3SO_3H–CH_2Cl_2 appears to require proton migration from one hypervalent species to another.[22]

Estimates of the kinetics of methyl loss from energy-selected $C_4H_6^+$ species have been made by calculation.[23] The hydride transfer from alkanes to carbenium ions in the gas phase is calculated to involve a species with a symmetric potential well, which is different from the situation in superacid or zeolite media.[24] A correlation between the charge on a carbon and the in-plane tensor component of its ^{13}C chemical shift has been observed for a number of simple cationic and anionic species.[25] High-level calculations

have been used to investigate the relevant factors at work in the reaction between 2-methyl-2-propyl cation and 2-methylpropene, as a model for some of the carbenium ion reactions important in sterol biosynthesis.[26]

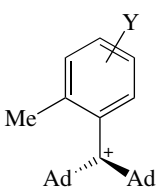
The solvolysis mechanisms of 2,2-dimethyl-3-pentyl- and 1-(1-adamantyl)-propyl sulfonates appear to involve partial reversible ionization to the intimate ion pair followed by competing elimination and solvent separation, substitution products being formed from the separated ions.[27] The lifetimes of simple tertiary carbocations may be some 100 times shorter than previously thought; several 3-(4-methoxyphenyl)-1,1-dimethylpropyl species hydrolyse in 50% aqueous TFE with rate constants estimated at some 3.5×10^{12} s^{-1}.[28] Much elimination was also observed.[28] Two studies concerning proposed carbocation intermediates in enzymatic processes are reported.[29,30]

Benzyl Cations

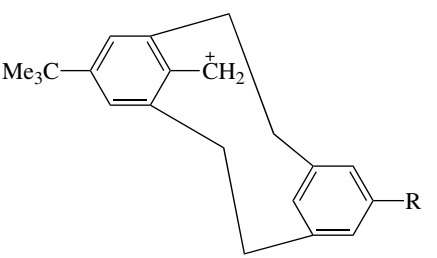


(**4**) (**5**) (**6**)

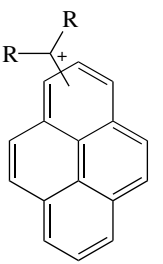
The cumyl cation (**4**) has been the subject of an X-ray crystallographic study, as its hexafluoroantimonate salt at −124 °C.[31] It is nearly planar (8 ° twist), with a short bond between the C^+ and the ring (1.41 Å), consistent with benzylic delocalization. The Me−C^+ bonds are also shortened, indicative of hyperconjugative interaction.[31] However, calculations are taken to show that hyperconjugation is not important in isolated benzyl cations; e.g. structures such as (**6**) are not important contributors to the overall structure of (**5**).[32] The stabilization provided by alkyl groups would thus be because of their polarizability, and the Baker–Nathan effect would be due to steric hindrance to solvation.[32] The heats of formation of some α-methylbenzyl cations indicate that the primary stabilization in these species comes from the α-substituents, and that the stabilization provided by the aromatic ring is secondary.[33]



(**7**)



(**8**)
R = H, Me_3C, Br, CN

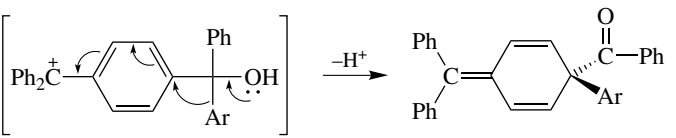


(**9**)
R = Me, Ph, CF_3

Solvolysis studies involving crowded benzyl cations, with neopentyl, *t*-butyl and isopropyl groups in both α-positions, give Yukawa–Tsuno *r* values of <1, indicative of reduced coplanarity in the benzyl cation and the transition state leading to it.[34] Calculation gave twist angles in agreement with the values obtained experimentally, using $r/r_{max} = \cos^2 \theta$.[34] ^{13}C NMR studies on the crowded adamantyl-substituted cation (**7**) indicate the presence of some resonance stabilization, with the dihedral angle being about 60 °.[35] Solvolytic studies on the corresponding bromides in 83% aqueous dioxane have been used to investigate through-space electronic interactions in the cyclophane benzyl cation species (**8**).[36] Various pyrenylmethylcarbenium ions (**9**) have been generated from the corresponding alcohols, in order to study their charge delocalization.[37] If one of the R groups is CF_3, increased electron demand at the carbocation centre greatly increases the arenium ion character of the system.[38]

Benzhydryl, Trityl, and Fluorenyl Cations

A new *Y* solvolysis scale has been developed for benzylic species with extensive charge delocalization, based upon the solvolyses of some benzhydryl bromides and *t*-butyl(2-naphthyl)methyl bromides.[39] Chlorides have negative salt effects on the ionization of benzhydryl bromide in γ-butyrolactone.[40] The X-ray structure of the dimerization product of 1,8-bis(dimethylammonio)-4-naphthyl(phenyl)methyl carbocation has been determined; it appears to be formed via a $4\pi + 2\pi$-cycloaddition mechanism.[41]

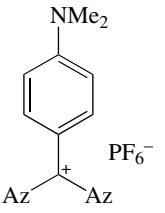


(**10**)

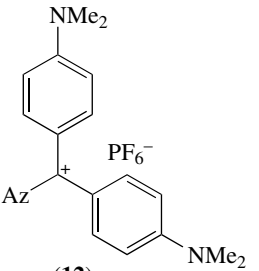
Ph = 2,6-$(MeO)_2C_6H_3$; Ar = Ph, 4-MeC_6H_4, 4-$MeOC_6H_4$

Compound (**10**) undergoes an interesting aryl group migration, giving a cyclohexadienyl species.[42] The thermodynamic stabilities of eleven *para*-substituted trityl cations and seven 9-phenylxanthenyl cations in sulfolane are reported.[43] These are compared with and correlated with many other species properties, e.g. pK_{R^+} values in aqueous H_2SO_4, ^{13}C NMR chemical shift values, and free energies of methoxy group exchange.[43] The very stable cation species (**11**) and (**12**) have pK_{R^+} values of around 13;[44] base treatment of cation (**13**) gives the stable neutral quinone methide (**14**).[45] This is stabilized because the charge-separated resonance forms with a phenoxide plus tropylium cation structure are important contributors.[45]

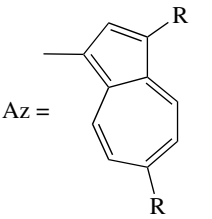
The transient zwitterion (**15**), obtained from the β-hydroxy acid precursor by laser flash photolysis, has been characterized;[46] it reacts with nucleophiles more slowly than does the 9-fluorenyl cation itself. The parent acid was also characterized.[46] Evidence has been presented that (**16**) undergoes substantial *E*1 elimination via a primary carbocation.[47] An analysis of solvolysis results for (**17**) is indicative of extensive charge delocalization throughout the fluorenyl ring at the transition state; apparently



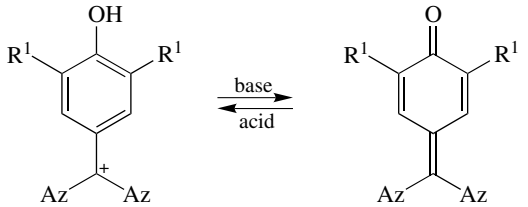
(**11**)



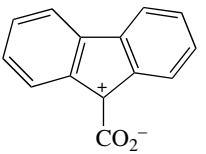
(**12**)



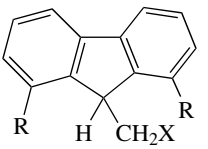
R = H, Me, CMe_3



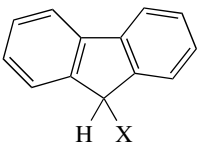
(**13**) (**14**)



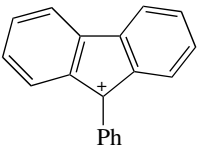
(**15**)



(**16**)
R = H, Br; X = I, Br, OBs



(**17**)
X = Br, OTs



(**18**)

antiaromaticity is insignificant.[48] A similar conclusion was reached for the 9-phenylfluorenyl system (**18**); calculations suggested that the phenyl and fluorenyl rings are not coplanar, and that the 9-fluorenyl and 9-phenyl-9-fluorenyl cations are equivalent to the diphenylmethyl and triphenylmethyl cations, respectively.[49]

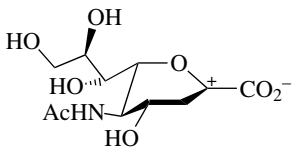
Acylium Ions

The formyl cation, $H-\overset{+}{C}=O$, has been observed and characterized spectroscopically for the first time; it is stable in $HF–SbF_5$ at room temperature if 200 atm pressure of CO is maintained over it.[50] A commentary on this work appeared in the same journal issue.[51]

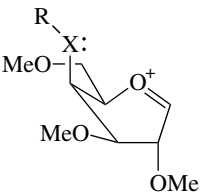
A calculational study of the formyl cation to isoformyl cation ($H-\overset{+}{O}=C$) rearrangement reveals that the latter is much the less stable of the two.[52]

The acid-catalysed acylation of carbonyl compounds by acylium ions is the subject of a review.[53] It has been pointed out that the acylating agent in many reactions is actually $R-\overset{+}{C}=\overset{+}{O}-H$, particularly for the reactions of benzene and deactivated aromatic systems.[54] A detailed study of a number of acylium ions, making use of solid-state NMR and *ab initio* calculations, is reported.[55] Some hyperconjugative stabilization of aliphatic acylium ions is suggested, although not much, and quantitative estimates of the amount of positive charge delocalized into the ring are reported for some aromatic ones.[55] Some novel gas-phase ketalization reactions of diols and related species by acylium ions have been observed,[56] as have some reactions of acylium and thioacylium ions with 1,3-dioxane.[57]

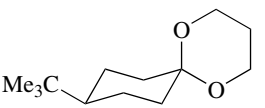
Oxonium Ions



(**19**)



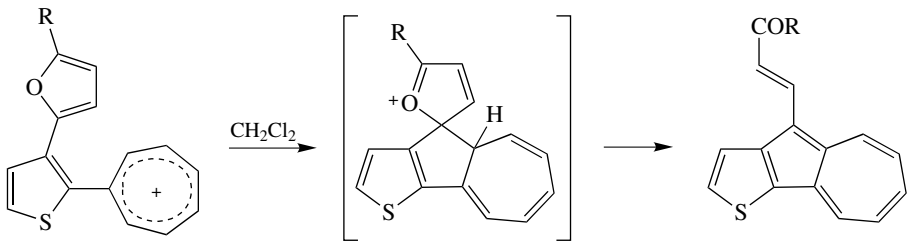
(**20**)



(**21**)

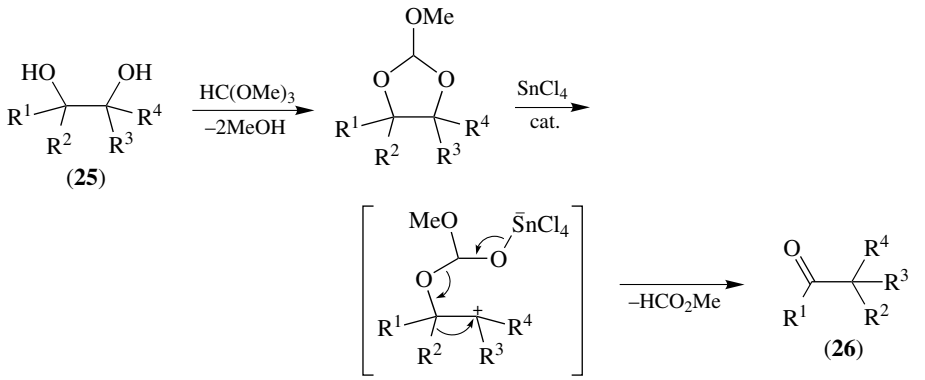
Quantum mechanical calculations show that the silyl cation (**19**) has a twisted structure, and that the α-CO_2^- group provides substantial electrostatic stabilization.[58] Isotope effects for its formation reaction are also reported.[58] Evidence is provided for the stabilization of incipient oxocarbenium ions by axial electronegative substituents, as in (**20**); the presence of the most electronegative substituent results in the fastest reaction.[59] Lewis acid-promoted cleavage of spirocyclic dioxanes such as (**21**) involves oxonium ions, and high axial vs equatorial product selectivities are possible with the correct choice of Lewis acid and nucleophile.[60] Reactions which lead to 1,3-dioxenium salts have been reviewed.[61]

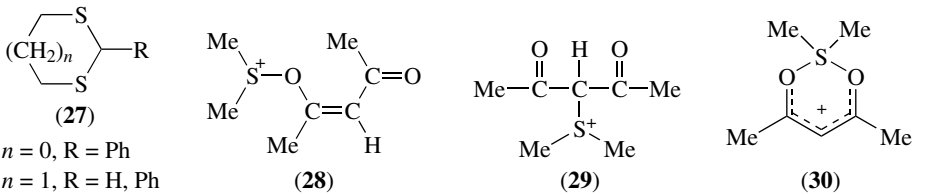
The facile synthesis of (**24**) from (**22**) has the oxonium cation (**23**) as an intermediate.[62] Vinyl oxocarbenium ions are reported to take part in intermolecular



(**22**) (**23**) (**24**)

4 + 3-cycloaddition reactions.[63] The reduction of several xanthylium and triphenylmethylium cations by some NAD(P)H analogues has been studied.[64] The methoxymethyl cation is reported to be able to cleave peptide bonds in the gas phase.[65] The pinacol rearrangement, (**25**)→(**26**), can be achieved using trimethyl orthoformate and a Lewis acid catalyst as shown.[66]



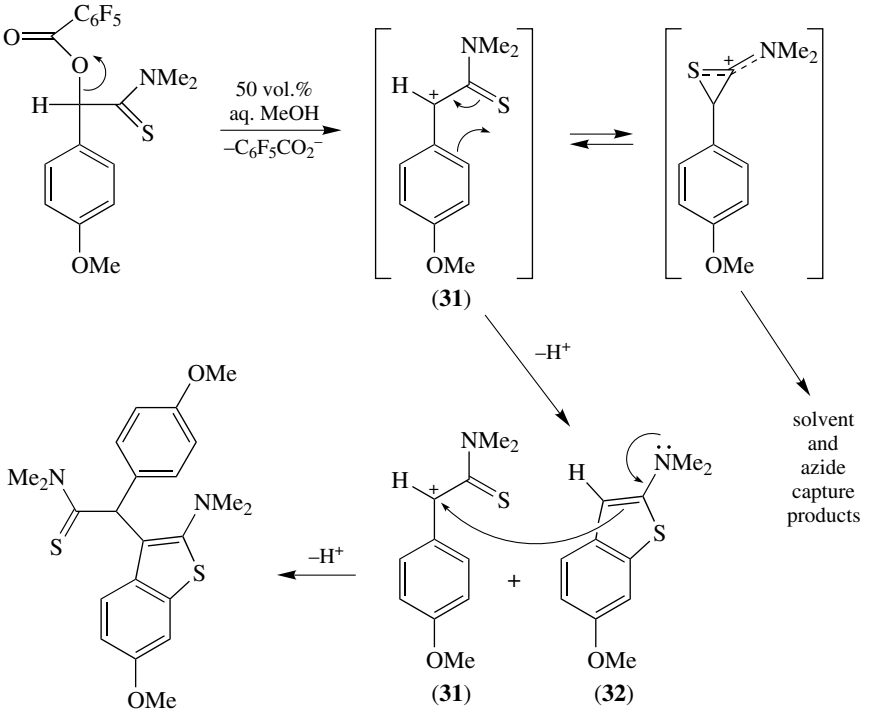


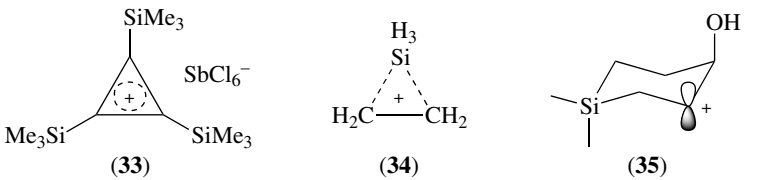
Carbocations Containing Sulfur

The $^{+}C(SH)_3$ cation and the radical dication derived from it have been the subject of high-level calculations.[67] The ability of two adjacent sulfur atoms to stabilize cations, anions, and radicals makes these species useful for relating bond-breaking and electron-transfer energies.[68,69] Electrophilicity parameters for the dithiocarbenium ions (**27**) have been worked out,[70] and the stabilities of the cations (**28**), (**29**) and (**30**) have been estimated using PM3 calculations.[71] Cation (**31**) can be captured by solvent or azide ion, or it may ring close to (**32**), which subsequently alkylates another (**31**) cation as shown.[72]

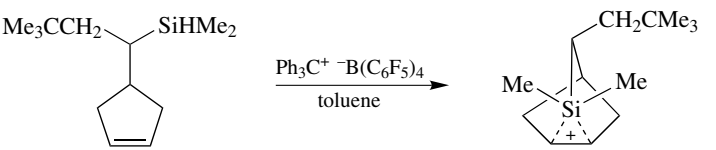
Carbocations Containing Silicon

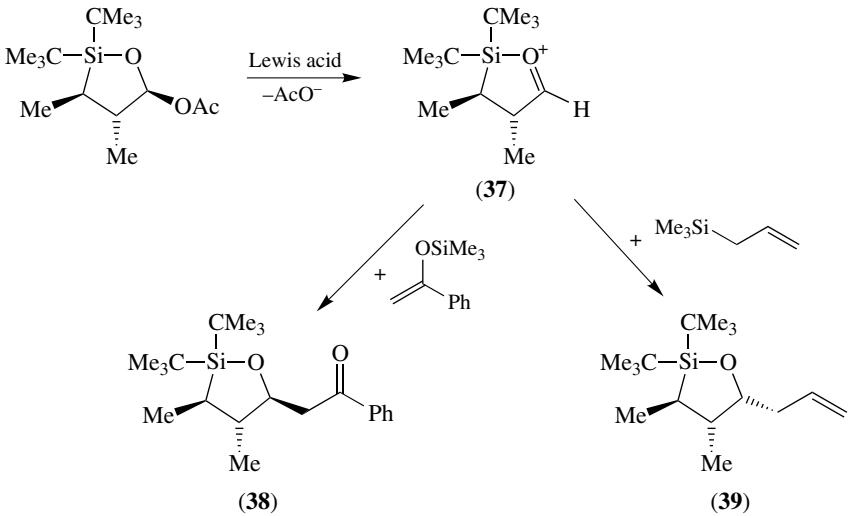
The first X-ray structure of an α-silyl-substituted carbocation (**33**) is reported; its pK_{R^+} value is predicted to be 4.[73] The trimesitylsilylium cation is proposed to be a nearly free, tricoordinate species.[74] The dimethylsilylium cation undergoes isomer interconversion via (**34**), according to high-level calculations; the most stable structure is





Me_2SiH^+, followed by $C_2H_5SiH_2^+$.[75] The $C_6SiH_7^+$ species formed from $PhSiH_3$ in the gas phase abstracts hydride ion readily.[76] It does not have a silacycloheptatrienyl cation structure, but is apparently a $C_6H_6 \cdot SiH^+$ bridged species.[76] In chloroform β,γ-epoxysilanes give (**35**).[77] Capture by *p*-nitrobenzoic acid results in products which have an equatorial *p*-nitrobenzoate group and a hydroxy group, with the axial to equatorial ratio for the latter being 4 : 1. In acetone, however, attack at silicon leading to ring-opened products is preferred.[77]

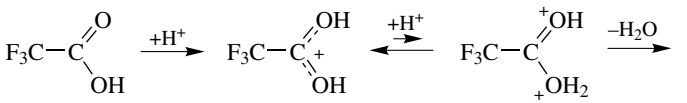




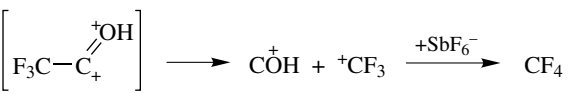
The internally stabilized silyl cation (**36**), formed by hydride transfer as shown, has a 2-silanorbornyl cation structure, and is not coordinated to the solvent or the counterion.[78] NMR chemical shifts calculated on the basis of the bridged structure shown are in agreement with the experimental values. The authors describe it as 'free but internally π-stabilized'.[78] The silicon-stabilized oxonium ion (**37**) shows considerable stereoselectivity in its reactions; (**38**) is the preferred product isomer by a 92 : 8 ratio, and (**39**) by 98 : 2.[79]

The low-temperature solution reactions of silylenes with arenes, which involve silyl cation intermediates, have been reviewed,[80] and another pertinent review is available.[81]

Fluorinated Carbocations



(**40**)

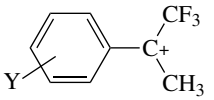


The chemistry of highly fluorinated carbocations, preparations, and reactions is the subject of an extensive review.[82] Also available is a discussion on the use of intrinsic ^{19}F NMR isotope shifts for the determination of carbocation structures.[83]

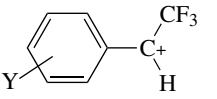
A large number of simple fluorinated carbocations have been the subject of theoretical calculation, and the resulting calculated ^{19}F and ^{13}C chemical shifts correlate

well with the experimental ones.[84] In 1 : 1 FSO_3H–SbF_5 (but not in more weakly acidic media) trifluoroacetic acid diprotonates to the gitonic dication (**40**), which then decomposes as shown; this process is another possible source of $H-\overset{+}{C}=O$ (or $H-\overset{+}{O}=C$).[84] In FSO_3H–SbF_5 at −78 °C, *t*-butyl fluoroformate protonates and decomposes to Me_3C^+ and $F\overset{+}{C}(OH)_2$; some evidence for the presence of $F-\overset{+}{C}=O$ was also obtained.[85]

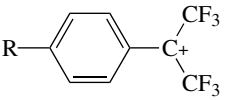
The stabilities of the trifluoro-substituted cations (**41**) and (**42**) in the gas phase have been determined by examining the exchange reaction between the parent cation (Y = H) and the appropriate precursor molecules, styrenes for (**41**)[86] and α-chloro compounds for (**42**).[87] For (**41**) the Yukawa–Tsuno r^+ value was 1.41, and for (**42**) it



(**41**)

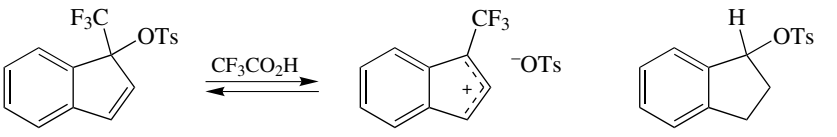


(**42**)

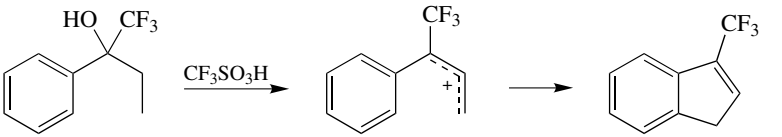


(**43**)

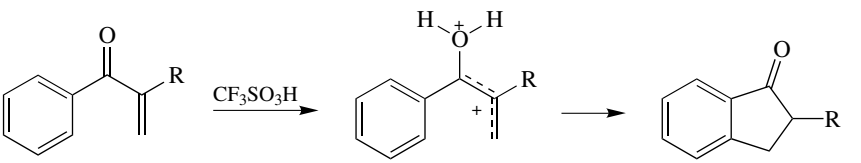
was 1.53, indicating a very high demand for resonance stabilization in these highly destabilized cations, compared with a normal value of 1.14 for the $-CH_3$ species. For both the ρ value was about −10, much the same as for $-CH_3$.[86,87] Cation (**43**) is a postulated intermediate in the reaction of azide ion with the triflate precursor.[88]



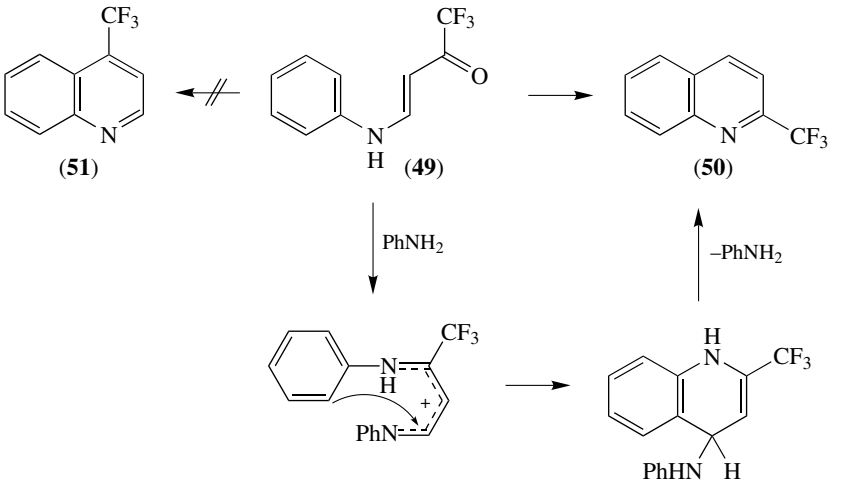
(**44**) (**45**) (**46**)



(**47**)

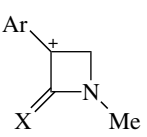


(**48**)

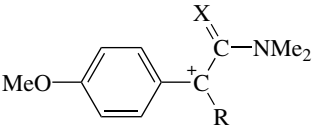


Solvolysis of (**44**) gives the doubly destabilized cation (**45**), which shows a preference for internal return.[89] Compound (**44**) is 10^9 times less reactive than is (**46**), of which 10^6 is attributed to the antiaromaticity of (**45**) and 10^3 to the presence of the electron-withdrawing CF_3.[89] The similarity of the destabilized cation (**47**) and the doubly protonated species (**48**) is demonstrated by the similar electrophilic cyclizations that these species undergo.[90] Double-bond protonation was not observed.[90] Compound (**49**) undergoes aniline-catalysed ring closure as shown to give (**50**), rather than the expected isomer (**51**).[91]

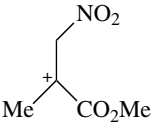
Other Destabilized Carbocations



(**52**)
X = O, S



(**53**)
X = O, S; R = H, Me

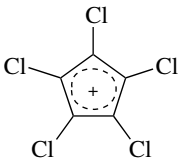


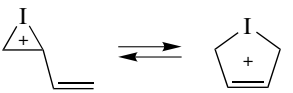
(**54**)

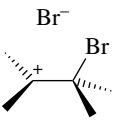
Destabilized carbocations are those with electron-withdrawing groups α to the C^+ centre, such as the α-CF_3 species discussed above. Carbocations in the β-lactam and β-thiolactam series (**52**), formed during solvolysis of the mesylate precursors, show only minimal or non-existent stabilization by the C=O and C=S groups.[92] Good nucleophiles such as N_3^- react directly with the mesylates in an S_N2 displacement.[92] Also, it has been shown that 2-oxo bridgehead carbocations solvolyse 10^8–10^{10} times more slowly than do the equivalent methylene compounds, showing that any π-conjugative stabilization provided by the C=O must be negligibly small.[93] For (**53**; R = H) the solvolysis rates are decreased with respect to the parent, 80-fold for X = O

and 30 000-fold for X = S.[94] Ions (**53**; R = Me) also undergo deprotonation by solvent, but the differences in the elimination rates are much smaller.[94] Nitration of α,β-unsaturated esters with nitronium tetrafluoroborate involves species such as (**54**), according to trapping experiments.[95]

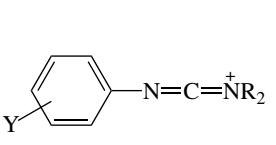
Carbocations Containing Other Heteroatoms

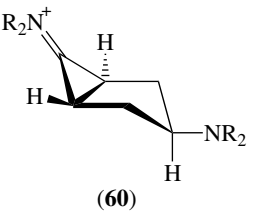

(**55**)

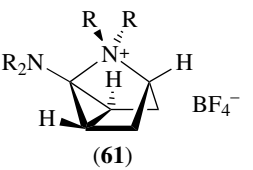

(**56**) (**57**)

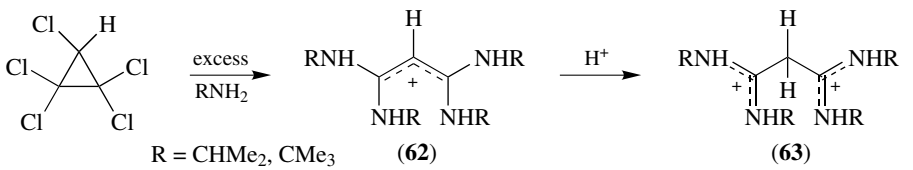

(**58**)

The π-donor ability of halogens in the species $^{+}AX_3$ and $^{+}AH_2X$ (A = C, Si, Ge, Sn and Pb) increases in the order F < Cl < Br < I for all cations, according to a new theoretical study,[96] contradicting an earlier one.[97] The IR spectrum of (**55**) in a cryogenic SbF_5 matrix shows no evidence for any stabilizing effect of the chlorine lone pairs, in contrast to that observed in $^{+}CCl_3$ and $^{+}C_3Cl_3$.[98] Treatment of buta-1,3-diene with I^{+} gives (**56**), but calculations indicate that (**57**) is the global minimum of the $C_4H_6I^{+}$ surface, so it may also be capable of existence.[99] Highly reactive alkenes such as methoxystilbene may form bromocarbenium bromide ion pairs such as (**58**) when treated with tribromide ion in chlorinated aprotic solvents.[100] The gas-phase reactions of cysteine with the dimethylchloronium ion and the methoxymethyl cation have been investigated.[101]


(**59**)


(**60**)

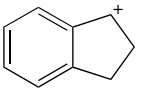

(**61**)


R = $CHMe_2$, CMe_3 (**62**) (**63**)

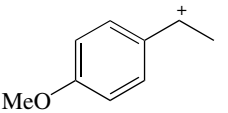
Imidinium ions such as (**59**), formed from formamidine precursors by C−X bond cleavage, are more reactive than carbocations, being trapped by solvent or nucleophile at not quite diffusion-controlled rates, in general.[102] The reaction rates are not

correlated by the N_+ scale.[102] Species such as (**60**) have been studied by calculation, and (**61**) can be prepared as a stable salt.[103] Allylic cations (**62**) and the dications (**63**) formed from them have been studied spectroscopically.[104]

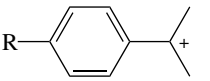
Carbocations in Zeolites



(**64**)



(**65**)



(**66**)

Several types of carbocation have proved to be stable when entrapped in a zeolite cage. For instance, (**64**) and related dimeric cations can be prepared from indene,[105] and (**65**) and several other cations can be prepared from 4-vinylanisole, some of the latter being stable for several weeks.[106] Absolute lifetimes of cumyl cations (**66**) have been measured in non-acidic zeolites, and their reactivities with co-absorbed alcohols have been studied.[107] Triarylmethyl cations can be prepared by 'ship-in-a-bottle' syntheses in large-pore zeolites.[108]

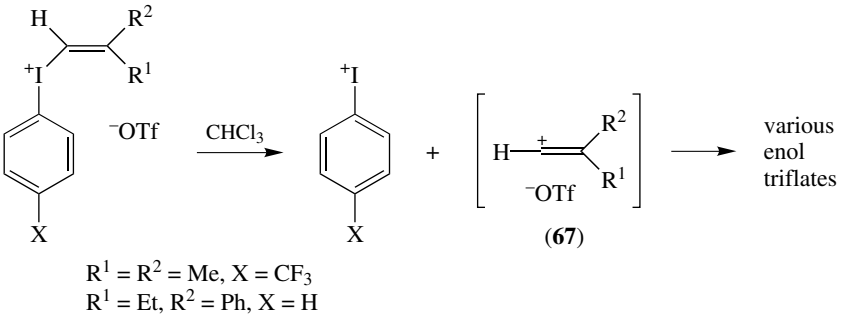
Allylic Systems

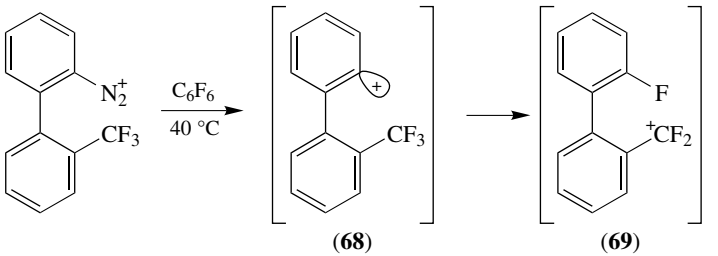
The intramolecular 4 + 3-, 3 + 3-, 4 + 2-, and 3 + 2-cycloaddition reactions of cyclic and acyclic allylic cations have been reviewed, together with methods for their generation by thermal and photochemical routes.[109] The synthetic uses of cycloaddition reactions of oxyallyl cations, generated from polybromo and some other substrates, have also been summarized; seven-membered rings result from 4 + 3-cycloadditions of these with dienes.[110] The use of heteroatom-stabilized allylic cations in 4 + 3-cycloaddition reactions is also the subject of a new experimental study.[111] The one-bond nucleophilicities (*N* values) of some monomethyl- and dimethyl-substituted buta-1,3-dienes have been estimated from the kinetics of their reactions with benzhydryl cations to form allylic species.[112] Calculations on allyl cations have been used in a comparison of empirical force field and *ab initio* calculational methods.[113]

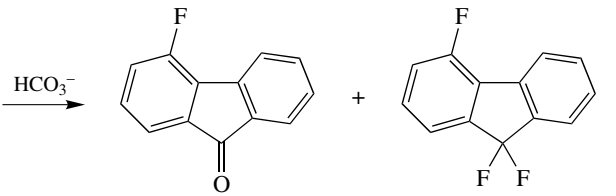
Vinyl and Aryl Cations

Long-lived vinyl cations have been reviewed.[114] Vinyl cations (**67**) can be prepared by the fragmentation of alkenyl(aryl)iodonium triflates, giving triflate capture products, some of which may be rearranged.[115] Otherwise vinyl cation research has been quiet this year.

The phenyl cation has been the subject of high-level *ab initio* calculations.[116] The ground state was shown to be a singlet, and the singlet–triplet gap was estimated.[116] The gas-phase transfers of H^+, H^-, and H_2O to Ph^+ have been studied.[117] Arenium



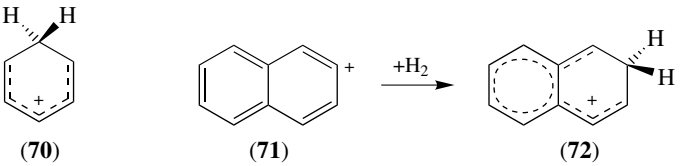




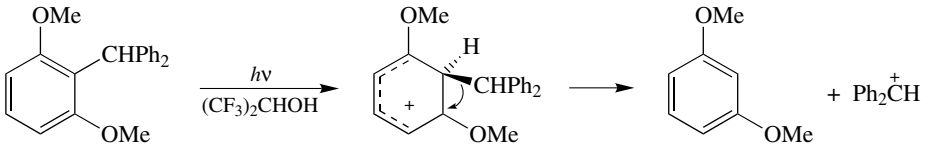
ions and (*R*)-(−)-2-chlorobutane form complexes in the gas phase, and the complete racemization observed in the alkylated aromatic products which result is taken to mean that the components of the complex have undergone mutual charge transfer, and that the product-forming reaction is one between the 2-butyl cation and the neutral arene.[118] Intramolecular fluoride ion abstractions have been observed, such as (**68**)→(**69**); similar intermolecular fluoride abstractions by arenium ions from suitable highly fluorinated substrates are also possible.[119]

Arenium and Nitrenium ions

On the surface of the solid metal halide superacid HBr–$AlBr_3$, benzene gives the benzenium cation (**70**), which was characterized *in situ* by ^{13}C MAS NMR.[120] All the methyl derivatives and one ethyl derivative were also studied.[120] The aromatic substitution reactions occurring in the complexes between gaseous arenium ions and



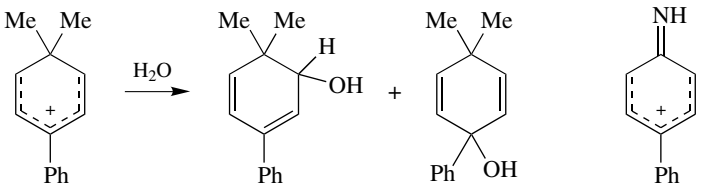
(**70**) (**71**) (**72**)



(**73**) (**74**)

proelectrophiles such as RX, ROH, epoxides, esters, and diazoalkanes in the gas phase represent an alternative electrophilic aromatic substitution mechanism, according to a new review.[121] The process (**71**)→(**72**) has been studied in a flowing afterglow experiment, as part of an investigation into the chemical constraints existing on organic cations in the interstellar medium.[122] Protonation of (**73**) by hexafluoropropan-2-ol gives (**74**), which then loses diphenylmethyl cation in a photochemical retro-Friedel–Crafts reaction.[123] The resulting diphenylmethyl cation can be captured as its hexafluoroisopropyl ether, or it may alkylate the ring in a different position, giving rearranged (**73**). Rearrangement of the cyclohexadienyl cation (**74**) may also occur without prior separation of the diphenylmethyl cation.[123]

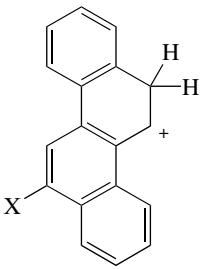
In aqueous solution, the benzenium ion (**75**) gives the hydrated products (**76**) (90%) and (**77**) (8%) almost exclusively, with only 2% of the methyl-migrated aromatic product being observed;[124] (**76**) is both the kinetically and the thermodynamically preferred product. The lifetime of (**75**) is 150 ns, similar to the 300 ns observed for (**78**), but (**78**) gives the unconjugated *para* product equivalent to (**77**) preferentially, perhaps



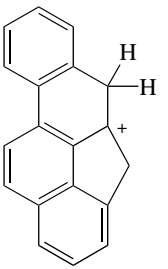
(**75**) (**76**) (**77**) (**78**)

indicating the presence of a larger amount of positive charge at the *para* position in the latter case.[124] NMR and calculational studies of some stable protonated ions of the chrysene skeleton, (**79**) and (**80**), have been made; (**79**; X = Ac) protonates on the C=O group.[125] Some diarylnitrenium ions have been studied by examining the products formed by trapping them with electron-rich alkenes.[126] Calculations predict

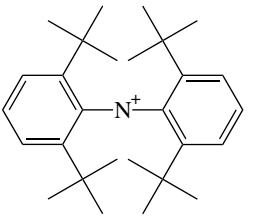
that (**81**) has a triplet ground state, the steric bulk of the substituent groups destabilizing the singlet state.[127]



(**79**)
X = H, F, Cl, Br



(**80**)

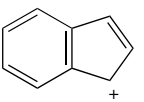


(**81**)

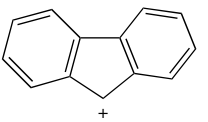
Aromatic Systems

High-level calculations on the 'remarkably' stabilized trilithiocyclopropenium cation $C_3Li_3^+$, and the related species $C_3HLi_2^+$, $C_3H_2Li^+$, and $C_3H_3^+$, are reported.[128] The cyclopentadienyl cation (**82**) and the indenyl cation (**83**) are reported to be 'as antiaromatic as cyclobutadiene and benzocyclobutadiene', according to magnetic evidence, but the fluorenyl cation (**84**) is non-aromatic, owing to the presence of compensating diamagnetic and paramagnetic character;[129] (**82**) has a triplet ground state, but the ground states of (**83**) and (**84**) are singlets.[129] The antiaromatic species (**86**) can be generated from (**85**) solvolytically, the end-products being those of solvent capture, with some elimination and rearrangement.[130] A strong dependence of reaction rate upon solvent ionizing power was observed. In TFE at 25 °C, (**85**) is less reactive than the indenyl and fluorenyl derivatives by factors of 500 and 30 000, respectively, and its antiaromaticity causes it to react a huge 10^{14} times more slowly than does

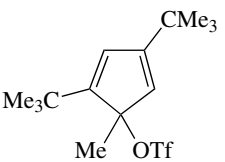
(**82**)



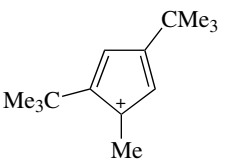
(**83**)



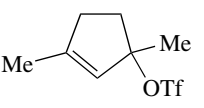
(**84**)



(**85**)



(**86**)



(**87**)

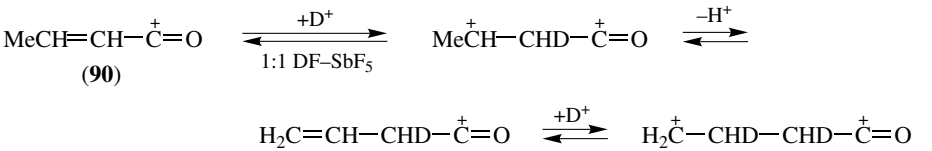
(**88**)
X = H, Br, NO_2

(**89**)

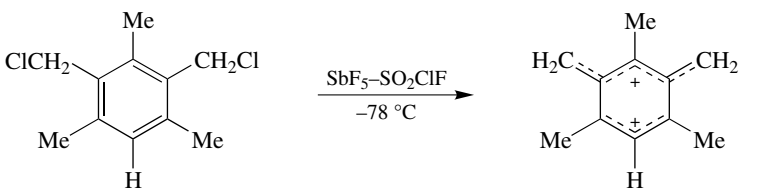
(**87**).[130] Protonation of the diatropic Hückel [14]annulenes (**88**) gives the first examples of persistent dimethyldihydropyrenium cations (**89**), which are paratropic $4n\pi$[12]annulenium ions.[131] The ring currents are reversed; the chemical shift of the methyl groups in (**88**; R = H) is −4.23, whereas in (**89**; R = H) values of 1.70 and 1.32 are found.[131] A fullerene carbocation, C_{76}^{+}, has been synthesized using the 'electron hole' oxidant $[Ar_3N^{+\cdot}][CB_{11}H_6Br_6^{-}]$,[132] and fullerene dications and trications have been used in the gas phase to initiate the 'ball-and-chain' polymerizations of allene and propyne.[133]

Dications

The structures of many interesting dications have been reviewed.[81] The hydrogen isotope exchange processes taking place in the crotonyl cation (**90**) in superacid media involve two dications; rate constants and isotope effects for all the reactions shown could be obtained by computer modelling.[134] 1,2-Bis(trialkylsilyl)ethanes are possible vicinyl dication synthons, giving products that can be thought of as deriving from $ArCHCHAr$.[135] Superacid treatment of (**91**) gives the unique dienylallyl dication (**92**), but the parent bisallylic benzene dication, i.e. (**92**) with all Hs, could not be prepared.[136]

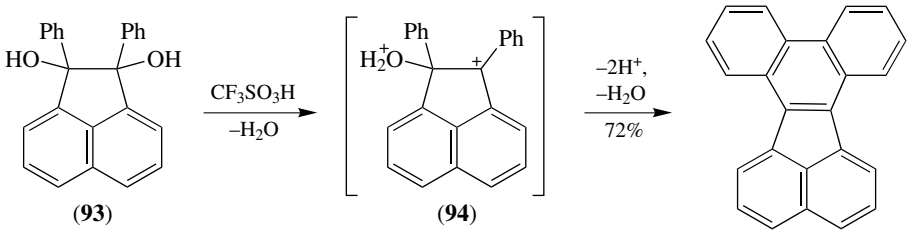


(**90**)



(**91**)

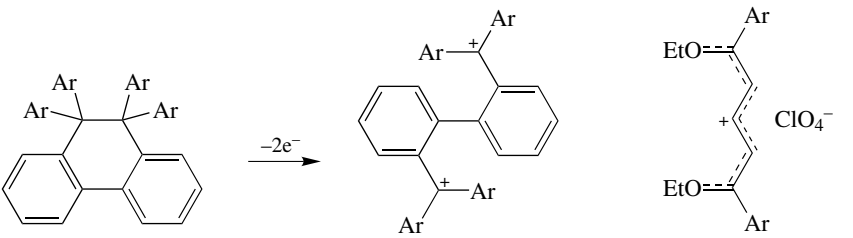
(**92**)



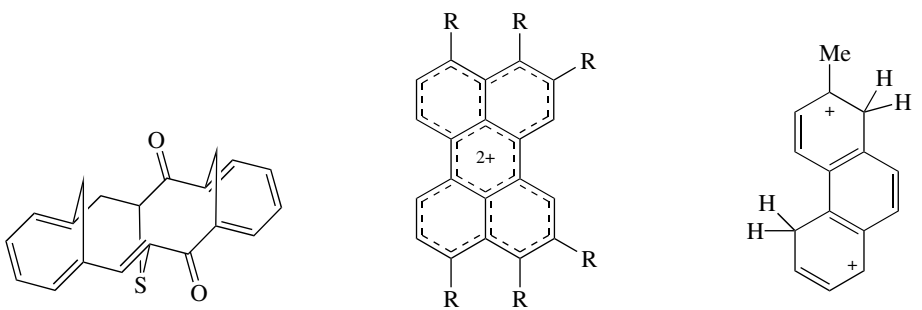
(**93**) (**94**)

Superacid dehydrative cyclization of pinacols such as (**93**) gives condensed aromatic compounds as shown, presumably via dicationic species like (**94**).[137]

Dications such as (**95**) can be prepared electrochemically as shown, and can be isolated as their di-BF_4^- salts following treatment with HBF_4.[138] Reaction of species such as (**96**) with 1,4-diaminobenzene leads to new bis(pentadienylium) dications with a phenylene-1,4-diamine spacer, which are dyes with interesting optical properties.[139]



Ar = 4-$Me_2NC_6H_4$, 4-$MeOC_6H_4$ (**95**) (**96**)



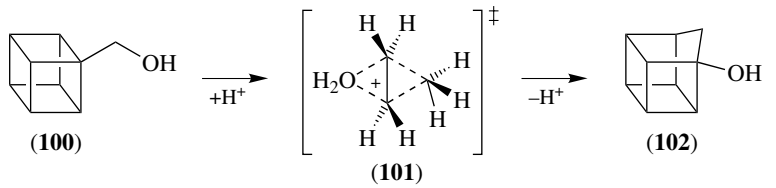
(**97**) (**98**) (**99**)

R = H, Me

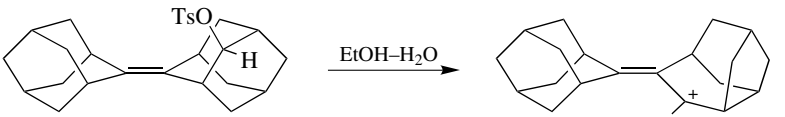
Diprotonation of (**97**) with H_2SO_4 gives a species which is protonated at both carbonyl groups, not the delocalized annulene dication, presumably for steric reasons.[140] Oxidation dications of perylenes, e.g. (**98**), are [$4n + 2$] species with diamagnetic ring currents, whereas the dibenzo[*cd*, *lm*] derivative [two more benzene rings at the top and

the bottom of (**98**)] is a $4n$ paramagnetic species.[141] Several persistent mono- and dications of various phenanthrenes, e.g. (**99**), have also been described.[142]

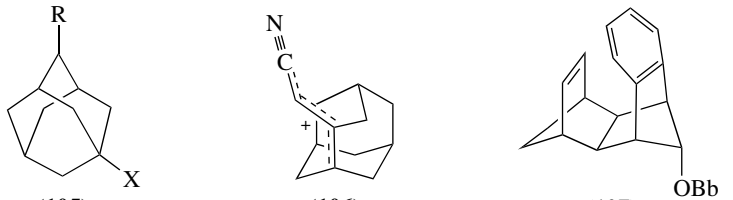
Polycyclic Systems



(**100**) (**101**) (**102**)



(**103**) (**104**)



(**105**) (**106**) (**107**)

R = Me, OMe

Several carbocation rearrangements, including some that take place in cyclic and polycyclic systems, have been reviewed.[143] A semiempirical study has been made of the effect of the geometry, and of the presence or absence of methyl substituents, on the stabilities of protonated cyclopropylcarbinyl ketones, in an attempt to resolve the 7-nortricyclane anomaly.[144] The cubylcarbinyl cation is highly unlikely to exist, according to calculations based on the protonation of (**100**).[145] This undergoes a ring enlargement via a transition state that looks like (**101**), drawn for the equivalent process in the 1-propyl cation, giving (**102**) without losing the oxygen first.[145] The unstrained homoallylic system (**103**) undergoes ethanolysis concerted with σ-bond migration, giving products resulting from the rearranged allylic cation (**104**) to the extent of at least 95%.[146]

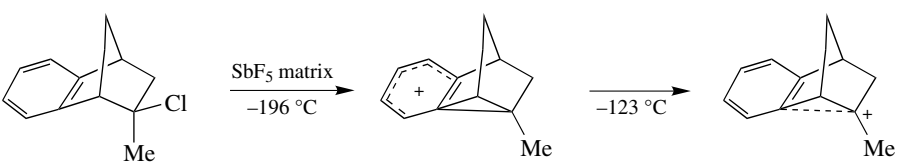
Rearrangements which take place in carbocation sulfinate ion pairs, $C^+ \cdot ArSO_2^-$, may involve re-bonding to the same sulfinate oxygen or bonding to the other one, according to labelling studies.[147] The processes studied included the norbornyl→norbornyl and

protoadamantyl→adamantyl rearrangements; the more stable carbocations were the more selective.[147] The stereoselectivity observed in 5-substituted adamant-2-yl cations (**105**) was found to depend on the electron demand of the substituent X.[148] Addition of benzenesulfonyl chloride to 1-phenyltricyclo[4.1.0.$0^{2,7}$]heptane opens one of the cyclopropane rings with high *endo*, *anti* stereoselectivity.[149] A γ-cyano substituent can participate in allylic bridgehead solvolyses via species such as (**106**), mesomeric stabilization partially counteracting the inductive destabilization; the allylic system solvolyses 2×10^5 times faster than the non-allylic system, and adding the CN group does not change this.[150] The assistance to solvolysis provided by benzene rings and double bonds in laticyclic systems such as (**107**) has been studied (Bb = *p*-bromobenzoate).[151]

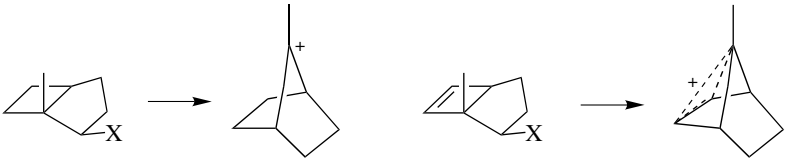
Bridged Systems

Not surprisingly, many of the review chapters in reference 1 are concerned with bridged, or rapidly equilibrating, systems. These include verification of computed structures by NMR and IR spectroscopy,[152] and by X-ray structure determination,[5,152] and the use of isotope effects[83] and the isotopic perturbation method[153] for determining structural details. Also reviewed are the use of IR spectroscopy[154] and CP/MAS NMR spectroscopy[155] for determining carbocation structures in cryogenic matrices. More specific reviews of transannular participation in bridged carbocations in superacids,[156] carbocation rearrangements,[143] and the $C_9H_9^+$ system[157] are also available. The gas-phase stabilities of bridgehead carbocations correlate with their solvolytic reactivities over 23 log units, and also correlate well with the stabilities as given by *ab initio* calculations.[158]

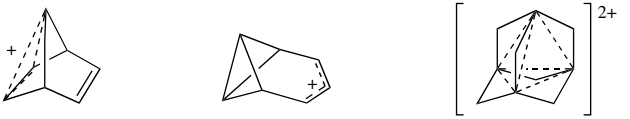
The problem of norbornyl cation stabilities vs. solvolysis rate discrepancies in the norbornyl system has been addressed in an important paper.[159] The classical and non-classical norbornyl cations do not resemble the 2-*endo*- and 2-*exo* -norbornyl solvolysis transition states very closely. The authors conclude that Brown was wrong, but that Winstein was not entirely right either.[159] A substituent in the benzene ring has little effect upon the kinetics of the acid-catalysed hydrolysis of 2-*exo*-norbornyl phenyl ether.[160] The FTIR spectra of matrix-isolated 2-methylbenzonorbornen-2-yl cations have been examined; at −196 °C the structure can best be represented as (**108**), rather like a phenonium cation, but at higher temperatures a transition takes place to a structure that is more nearly represented as (**109**), with some π-bridging.[161] The stereoselectivities of some 7-methyl-7-norborn(en)yl cations have been investigated; (**110**) has a classical structure and reacts in a stereo-random manner, whereas (**111**) is



(**108**) (**109**)



(**110**) (**111**)



(**112**) (**113**) (**114**)

fairly stereoselective.[162] The presence or absence of the methyl group in (**111**) makes no difference to its stereoselectivity.[162] There is only an 8 kcal mol^{-1} difference in enthalpy between the two isomeric $C_7H_7^+$ cations (**112**) and (**113**), as determined from solvolysis studies of the mesylate precursors.[163] A theoretical study of the three-dimensionally homoaromatic species (**114**) has been performed.[164]

References

[1] Surya Prakash, G. K. and Schleyer, P. von R. (Eds), *Stable Carbocation Chemistry*, Wiley, New York, 1996.
[2] Mayr, H., *J. Am. Chem. Soc.*, **119**, 12027 (1997).
[3] Olah, G. O., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 1.
[4] Clark, D. T., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 13.
[5] Laube, T., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 14.
[6] Jacquesy, J.-C., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 17.
[7] Olah, G. A., Reddy, P. V., and Surya Prakash, G. K., in *Chemistry of the Cyclopropyl Group* (Ed. Z. Rappoport), Wiley, Chichester, 1995, Vol. 2, p. 813; *Chem. Abs.*, **125**, 246909 (1996).
[8] Laube, T., *Angew. Chem., Int. Ed. Engl.*, **35**, 2765 (1996).
[9] Sunko, D. E., *Croat. Chem. Acta*, **69**, 1275 (1996); *Chem. Abs.*, **126**, 185638 (1997).
[10] Dvorko, G. F., *Dopov. Nats. Akad. Nauk Ukr.*, **1996**, 109; *Chem. Abs.*, **126**, 199173 (1997).
[11] Fukazawa, Y., *Kagaku Kogyo*, **47**, 700 (1996); *Chem. Abs.*, **125**, 300229 (1996).
[12] Strobl, D., Weiser, J., and Fitjer, L., *Tetrahedron*, **53**, 2767 (1997).
[13] Reindl, B., Clark, T., and Schleyer, P. von R., *J. Comput. Chem.*, **17**, 1406 (1996); *Chem. Abs.*, **125**, 246922 (1996).
[14] Sommer, J., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 15.
[15] Marx, D. and Savin, A., *Angew. Chem., Int. Ed. Engl.*, **36**, 2077 (1997).
[16] Olah, G. A. and Rasul, G., *Acc. Chem. Res.*, **30**, 245 (1997).
[17] Tapia, O., Moliner, V., and Andres, J., *Int. J. Quantum Chem.*, **63**, 373 (1997); *Chem. Abs.*, **127**, 33763 (1997).
[18] Mota, C. J. A., Esteves, P. M., Ramírez-Solís, A., and Hernández-Lamoneda, R., *J. Am. Chem. Soc.*, **119**, 5193 (1997).
[19] Sommer, J., Bukala, J., Hachoumy, M., and Jost, R., *J. Am. Chem. Soc.*, **119**, 3274 (1997).
[20] Boronat, M., Viruela, P., and Corma, A., *Appl. Catal., A*, **146**, 207 (1996); *Chem. Abs.*, **125**, 327877 (1996).

[21] Fărcaşiu, D. and Norton, S. H., *J. Org. Chem.*, **62**, 5374 (1997).
[22] Ernst, L., Hopf, H., and Savinsky, R., *Liebigs Ann./Recl.*, **1997**, 1915.
[23] Keister, J. W., Baer, T., Evans, M., Ng, C. Y., and Hsu, C.-W., *J. Phys. Chem. A*, **101**, 1866 (1997).
[24] Frash, M. V., Solkan, V. N., and Kazansky, V. B., *J. Chem. Soc., Faraday Trans.*, **1997**, 515.
[25] Wiberg, K. B., Hammer, J. D., Keith, T. A., and Zilm, K., *Tetrahedron Lett.*, **38**, 323 (1997).
[26] Jenson, C. and Jorgensen, W. L., *J. Am. Chem. Soc.*, **119**, 10846 (1997).
[27] Shiner, V. J., Neumann, T. E., and Basinger, B. B., *Croat. Chem. Acta*, **69**, 1405 (1996); *Chem. Abs.*, **126**, 185681 (1997).
[28] Toteva, M. M. and Richard, J. P., *J. Am. Chem. Soc.*, **118**, 11434 (1996).
[29] George, P., Glusker, J. P., and Bock, C. W., *J. Am. Chem. Soc.*, **119**, 7065 (1997).
[30] Barak, D., Ordentlich, A., Segall, Y., Velan, B., Benschop, H. P., De Jong, L. P. A., and Shafferman, A., *J. Am. Chem. Soc.*, **119**, 3157 (1997).
[31] Laube, T., Olah, G. A., and Bau, R., *J. Am. Chem. Soc.*, **119**, 3087 (1997).
[32] Exner, O. and Böhm, S., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1235.
[33] Ponomarev, D. A. and D'yachenko, L. G., *Zh. Prikl. Khim. (S.-Petersburg)*, **69**, 1215 (1996); *Chem. Abs.*, **126**, 7592 (1997).
[34] Fujio, M., Ohe, M., Nakata, K., Tsuji, Y., Mishima, M., and Tsuno, Y., *Bull. Chem. Soc. Jpn*, **70**, 929 (1997).
[35] Lomas, J. S., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2601.
[36] Yamato, T., Fujita, K., Shinoda, N., Noda, K., Nagano, Y., Arimura, T., and Tashiro, M., *Res. Chem. Intermed.*, **22**, 871 (1996); *Chem. Abs.*, **125**, 327818 (1996).
[37] Laali, K. K. and Hansen, P. E., *J. Org. Chem.*, **62**, 5804 (1997).
[38] Laali, K. K., Tanaka, M., Hollenstein, S., and Cheng, M., *J. Org. Chem.*, **62**, 7752 (1997).
[39] Liu, K.-T., Chin, C.-P., Lin, Y.-S., and Tsao, M.-L., *J. Chem. Res. (S)*, **1997**, 18.
[40] Dvorko, G. F., Golovko, N. N., and Ponomareva, E. K., *Zh. Obshch. Khim.*, **66**, 1334 (1996); *Chem. Abs.*, **126**, 74388 (1997).
[41] Pozharskii, A. F., Aleksandrov, G. G., and Vistorobskii, N. V., *Zh. Org. Khim.*, **32**, 1049 (1996); *Chem. Abs.*, **126**, 238011 (1997).
[42] Wada, M., Wei, W., Kirishima, K., Natsume, S., and Erabi, T., *Bull. Chem. Soc. Jpn*, **70**, 1413 (1997).
[43] Arnett, E. M., Flowers, R. A., Ludwig, R. T., Meekhof, A. E., and Walek, S. A., *J. Phys. Org. Chem.*, **10**, 499 (1997).
[44] Ito, S., Kobayashi, H., Kikuchi, S., Morita, N., and Asao, T., *Bull. Chem. Soc. Jpn*, **69**, 3225 (1996).
[45] Ito, S., Kikuchi, S., Kobayashi, H., Morita, N., and Asao, T., *J. Org. Chem.*, **62**, 2423 (1997).
[46] Lew, C. S. Q., Wagner, B. D., Angelini, M. P., Lee-Ruff, E., Lusztyk, J., and Johnston, L. J., *J. Am. Chem. Soc.*, **118**, 12066 (1996).
[47] Meng, Q. and Thibblin, A., *J. Am. Chem. Soc.*, **119**, 4834 (1997).
[48] Liu, K.-T. and Lin, Y.-S., *Tetrahedron Lett.*, **38**, 1419 (1997).
[49] Liu, K.-T., Lin, Y.-S., and Tsao, M.-L., *Org. React. (Tartu)*, **31**, 59 (1997).
[50] de Rege, P. J. F., Gladysz, J. A., and Horváth, I. T., *Science (Washington, D.C.)*, **276**, 776 (1997).
[51] Surya Prakash, G. K., *Science (Washington, D.C.)*, **276**, 756 (1997); *Chem. Abs.*, **127**, 4824 (1997).
[52] Chalk, A. J. and Radom, L., *J. Am. Chem. Soc.*, **119**, 7573 (1997).
[53] Luk'yanov, S. M. and Koblik, A. V., *Usp. Khim.*, **65**, 3 (1996); *Russ. Chem. Rev.*, **65**, 1 (1966).
[54] Shudo, K. and Ohwada, T., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 16.
[55] Xu, T., Barich, D. H., Torres, P. D., Nicholas, J. B., and Haw, J. F., *J. Am. Chem. Soc.*, **119**, 396 (1997).
[56] Moraes, L. A. B., Pimpim, R. S., and Eberlin, M. N., *J. Org. Chem.*, **61**, 8726 (1996).
[57] Moraes, L. A. B. and Eberlin, M. N., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2105.
[58] Horenstein, B. A., *J. Am. Chem. Soc.*, **119**, 1101 (1997).
[59] Miljković;, M., Yeagley, D., Deslongchamps, P., and Dory, Y. L., *J. Org. Chem.*, **62**, 7597 (1997).
[60] Newitt, L. A. and Steel, P. G., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2033.
[61] Olekhnovich, E. P., Arsenyev, V. G., Olekhnovich, L. P., and Minkin, V. I., *Khim. Geterotsikl. Soedin.*, **1996**, 1445; *Chem. Abs.*, **126**, 186001 (1997).
[62] Kusuhara, N., Sugano, Y., Takagi, H., Miyake, H., and Yamamura, K., *J. Chem. Soc., Chem. Commun.*, **1997**, 1951.
[63] Harmata, M. and Jones, D. E., *J. Org. Chem.*, **62**, 1578 (1997).
[64] Cheng, J.-P. and Lu, Y., *J. Phys. Org. Chem.*, **10**, 577 (1997).
[65] Freitas, M. A., O'Hair, R. A. J., Dua, S., and Bowie, J. H., *J. Chem. Soc., Chem. Commun.*, **1996**, 1409.
[66] Kita, Y., Yoshida, Y., Mihara, S., Fang, D.-F., Higuchi, K., Furukawa, A., and Fujioka, H., *Tetrahedron Lett.*, **38**, 8315 (1997).

[67] Glaser, R., Chen, G. S., and Grutzmacher, H., *J. Comput. Chem.*, **18**, 1023 (1997); *Chem. Abs.*, **127**, 50157 (1997).
[68] Stoelting, D. T., Ludwig, R. T., and Arnett, E. M., *Heteroat. Chem.*, **7**, 481 (1996); *Chem. Abs.*, **126**, 74461 (1997).
[69] Arnett, E. M. and Flowers, R. A., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 8.
[70] Mayr, H., Henninger, J., and Siegmund, T., *Res. Chem. Intermed.*, **22**, 821 (1996); *Chem. Abs.*, **125**, 327817 (1996).
[71] Kletskii, M. E., Olekhnovich, E. P., Arsen'ev, V. G., Kolpikov, A. N., Olekhnovich, L. P., and Minkin, V. I., *Zh. Obshch. Khim.*, **66**, 293 (1996); *Chem. Abs.*, **125**, 300297 (1996).
[72] Richard, J. P., Lin, S.-S., and Williams, K. B., *J. Org. Chem.*, **61**, 9033 (1996).
[73] de Meijere, A., Faber, D., Noltemeyer, M., Boese, R., Haumann, T., Müller, T., Bendikov, M., Matzner, E., and Apeloig, Y., *J. Org. Chem.*, **61**, 8564 (1996).
[74] Lambert, J. B. and Zhao, Y., *Angew. Chem., Int. Ed. Engl.*, **36**, 400 (1997).
[75] Ignatyev, I. S. and Sundius, T., *Organometallics*, **15**, 5674 (1996); *Chem. Abs.*, **126**, 31403 (1997).
[76] Jarek, R. L. and Shin, S. K., *J. Am. Chem. Soc.*, **119**, 6376 (1997).
[77] Badali, F., Karalis, A., Tham, W. Y., and White, J. M., *Aust. J. Chem.*, **49**, 1293 (1996).
[78] Steinberger, H.-U., Müller, T., Auner, N., Maerker, C., and Schleyer, P. von R., *Angew. Chem., Int. Ed. Engl.*, **36**, 626 (1997).
[79] Shaw, J. T. and Woerpel, K. A., *J. Org. Chem.*, **62**, 6706 (1997).
[80] Lumen, R., Mournier, P. A., Powell, J. M., Saint, G. N., and Timms, P. L., *Int. Conf. Low Temp. Chem., 2nd*, **1996**, 69; *Chem. Abs.*, **127**, 262716 (1997).
[81] Surya Prakash, G. K., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 4.
[82] Krespan, C. G. and Petrov, F. A., *Chem. Rev.*, **96**, 3269 (1996).
[83] Forsyth, D. A., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 10.
[84] Surya Prakash, G. K., Rasul, G., Burrichter, A., Laali, K. K., and Olah, G. A., *J. Org. Chem.*, **61**, 9253 (1996).
[85] Olah, G. A., Burrichter, A., Mathew, T., Vankar, Y. D., Rasul, G., and Surya Prakash, G. K., *Angew. Chem., Int. Ed. Engl.*, **36**, 1875 (1997).
[86] Mishima, M., Inoue, H., Itai, S., Fujio, M., and Tsuno, Y., *Bull. Chem. Soc. Jpn*, **69**, 3273 (1996).
[87] Mishima, M., Inoue, H., Fujio, M., and Tsuno, Y., *Bull. Chem. Soc. Jpn*, **70**, 1163 (1997).
[88] Nesi, M., Brasca, M. G., Longo, A., Moretti, W., and Panzeri, A., *Tetrahedron Lett.*, **38**, 4881 (1997).
[89] Allen, A. D., Fujio, M., Mohammed, N., Tidwell, T. T., and Tsuji, Y., *J. Org. Chem.*, **62**, 246 (1997).
[90] Suzuki, T., Ohwada, T., and Shudo, K., *J. Am. Chem. Soc.*, **119**, 6774 (1997).
[91] Schlosser, M., Keller, H., Sumida, S., and Yang, J., *Tetrahedron Lett.*, **38**, 8523 (1997).
[92] Creary, X., Zhu, C., and Jiang, Z., *J. Am. Chem. Soc.*, **118**, 12331 (1996).
[93] Takeuchi, K., Ohga, Y., Yoshida, M., Ikai, K., Shibata, T., Kato, M., and Tsugeno, A., *J. Org. Chem.*, **62**, 5696 (1997).
[94] Richard, J. P., Lin, S.-S., Buccigross, and Amyes, T. L., *J. Am. Chem. Soc.*, **118**, 12603 (1996).
[95] Hewlins, S. A., Murphy, J. A., Lin, J., Hibbs, D. E., and Hursthouse, M. B., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1559.
[96] Frenking, G., Fau, S., Marchand, C. M., and Grützmacher, H., *J. Am. Chem. Soc.*, **119**, 6648 (1997).
[97] Olah, G. A., Rasul, G., Heiliger, L., and Surya Prakash, G. K., *J. Am. Chem. Soc.*, **118**, 3580 (1996).
[98] Vančik, H., Novak, I., and Kidemet, D., *J. Phys. Chem. A*, **101**, 1523 (1997).
[99] Campos, P. J. and Rodríguez, M. A., *J. Org. Chem.*, **61**, 8664 (1996).
[100] Bellucci, G., Chiappe, C., and Lo Moro, G., *J. Org. Chem.*, **62**, 3176 (1997).
[101] Freitas, M. A., O'Hair, R. A. J., and Williams, T. D., *J. Org. Chem.*, **62**, 6112 (1997).
[102] Dalby, K. N. and Jencks, W. P., *J. Am. Chem. Soc.*, **119**, 7271 (1997).
[103] Dotzauer, M., Eisfeld, W., Vilsmaier, E., Fröhlich, K., Bergsträsser, U., and Tetzlaff, C., *J. Org. Chem.*, **61**, 8526 (1996).
[104] Clark, G. R., Rickard, C. E. F., Surman, P. W. J., and Taylor, M. J., *J. Chem. Soc., Faraday Trans.*, **1997**, 2503.
[105] Pitchumani, K. and Ramamurthy, V., *J. Chem. Soc., Chem. Commun.*, **1996**, 2763.
[106] Rao, V. J., Prevost, N., Ramamurthy, V., Kojima, M., and Johnston, L. J., *J. Chem. Soc., Chem. Commun.*, **1997**, 2209.
[107] Cozens, F. L., O'Neill, M., and Schepp, N. P., *J. Am. Chem. Soc.*, **119**, 7583 (1997).
[108] Cano, M. L., Corma, A., Fornés, V., García, H., Miranda, M. A., Baerlocher, C., and Lengauer, C., *J. Am. Chem. Soc.*, **118**, 11006 (1996).

[109] Harmata, M., *Tetrahedron*, **53**, 6235 (1997).
[110] Demuner, A. J., Barbosa, L. C. A., and Pil-Veleso, D., *Quim. Nova*, **20**, 18 (1997); *Chem. Abs.*, **126**, 330220 (1997).
[111] Harmata, M. and Jones, D. E., *Tetrahedron Lett.*, **38**, 3861 (1997).
[112] Mayr, H. and Hartnagel, M., *Liebigs Ann.*, **1996**, 2015.
[113] Reindl, B., Clark, T., and Schleyer, P. von R., *J. Comput. Chem.*, **18**, 533 (1997); *Chem. Abs.*, **126**, 277012 (1997).
[114] Siehl, H.-U., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 5.
[115] Hinkle, R. J. and Thomas, D. B., *J. Org. Chem.*, **62**, 7534 (1997).
[116] Nicolaides, A., Smith, D. M., Jensen, F., and Radom, L., *J. Am. Chem. Soc.*, **119**, 8083 (1997).
[117] Matyuk, V. M., Pobezhimova, I. N., and Potapov, V. K., *High Energy Chem. (Transl. of Khim. Vys. Energ.)*, **31**, 98 (1997); *Chem. Abs.*, **126**, 292971 (1997).
[118] Aschi, M., Cacace, F., and Troiani, A., *Angew. Chem., Int. Ed. Engl.*, **36**, 83 (1997).
[119] Ferraris, D., Cox, C., Anand, R., and Lectka, T., *J. Am. Chem. Soc.*, **119**, 4319 (1997).
[120] Xu, T., Barich, D. H., Torres, P. D., and Haw, J. F., *J. Am. Chem. Soc.*, **119**, 406 (1997).
[121] Aschi, M., Attina, M., and Cacace, F., *Res. Chem. Intermed.*, **22**, 645 (1996); *Chem. Abs.*, **125**, 275023 (1996).
[122] Le Page, V., Keheyan, Y., Bierbaum, V. M., and Snow, T. P., *J. Am. Chem. Soc.*, **119**, 8373 (1997).
[123] MacKnight, E. and McClelland, R. A., *Can. J. Chem.*, **74**, 2518 (1996).
[124] McClelland, R. A., Ren, D., Ghobrial, D., and Gadosy, T. A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 451.
[125] Laali, K. K., Hollenstein, S., Harvey, R. G., and Hansen, P. E., *J. Org. Chem.*, **62**, 4023 (1997).
[126] Moran, R. J., Cramer, C., and Falvey, D. E., *J. Org. Chem.*, **62**, 2742 (1997).
[127] Cramer, C. J. and Falvey, D. E., *Tetrahedron Lett.*, **38**, 1515 (1997).
[128] Jemmis, E. D., Subramanian, G., Kos, A. J., and Schleyer, P. von R., *J. Am. Chem. Soc.*, **119**, 9504 (1997).
[129] Jiao, H., Schleyer, P. von R., Mo, Y., McAllister, M. A., and Tidwell, T. T., *J. Am. Chem. Soc.*, **119**, 7075 (1997).
[130] Allen, A. D., Sumonja, M., and Tidwell, T. T., *J. Am. Chem. Soc.*, **119**, 2371 (1997).
[131] Laali, K. K., Bolvig, S., Raeker, T. J., and Mitchell, R. H., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2635.
[132] Bolskar, R. D., Maathur, R. S., and Reed, C. A., *J. Am. Chem. Soc.*, **118**, 13093 (1996).
[133] Baranov, V., Wang, J., Javahery, G., Petrie, S., Hopkinson, A. C., and Bohme, D. K., *J. Am. Chem. Soc.*, **119**, 2040 (1997).
[134] Fărcaşiu, D. and Bologa, U. L., *J. Org. Chem.*, **61**, 8860 (1996).
[135] Porter, J. M., Xuan, X., Blackman, B., Hsu, D., and Fry, A. J., *Tetrahedron Lett.*, **38**, 7147 (1997).
[136] Olah, G. A., Shamma, T., Burrichter, A., Rasul, G., and Surya Prakash, G. K., *J. Am. Chem. Soc.*, **119**, 3407 (1997).
[137] Klumpp, D. A., Baek, D. N., Surya Prakash, G. K., and Olah, G. A., *J. Org. Chem.*, **62**, 6666 (1997).
[138] Suzuki, T., Nishida, J., and Tsuji, T., *Angew. Chem., Int. Ed. Engl.*, **36**, 1329 (1997).
[139] Saggio, G., Mazières, M.-R., Fialon, M.-P., Sanchez, M., and Wolf, J.-G., *Bull. Soc. Chim. Fr.*, **96**, 1071 (1996).
[140] Kuroda, S., Oda, M., Kuramoto, S., Fukuta, A., Mizukami, Y., Nozawa, Y., Miyatake, R., Izawa, M., and Shimao, I., *Tetrahedron Lett.*, **38**, 8291 (1997).
[141] Laali, K. K., Tanaka, M., and Fetzer, J. C., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1315.
[142] Laali, K. K., Hollenstein, S., and Hansen, P. E., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2207.
[143] Shubin, V. G. and Borodkin, G. I., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 7.
[144] Buckley, N., *J. Org. Chem.*, **62**, 2205 (1997).
[145] Smith, B. J. and Tsanaktsidis, J., *J. Org. Chem.*, **62**, 5709 (1997).
[146] Huang, X. and Bennet, A. J., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1027.
[147] Herpers, E. and Kirmse, W., *Liebigs Ann./Recl.*, **1997**, 2031.
[148] Adcock, W., Head, N. J., Lokan, N. R., and Trout, N. A., *J. Org. Chem.*, **62**, 6177 (1997).
[149] Vasin, V. A., Kostryukov, S. G., and Razin, V. V., *Zh. Org. Khim.*, **32**, 59 (1996); *Chem. Abs.*, **125**, 300256 (1996).
[150] Takeuchi, K., Kitagawa, T., Ohga, Y., Nakakimura, A., and Munakata, M., *Tetrahedron*, **53**, 8155 (1997).
[151] Chow, T. J., *Bull. Inst. Chem., Acad. Sin.*, **44**, 25 (1997); *Chem. Abs.*, **27**, 205211 (1997).
[152] Schleyer, P. von R., Maerker, C., Buzek, P., and Sieber, S., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 2.
[153] Saunders, M., Jiménez-Vázques, H. A., and Kronja, O., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 9.

[154] Sunko, D. E., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 11.
[155] Myhre, P. C. and Yannoni, C. S., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 12.
[156] Sorensen, T. S., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 3.
[157] Ahlberg, P., in *Stable Carbocation Chemistry* (Eds Surya Prakash, G. K. and Schleyer, P. von R.), Wiley, New York, 1996, Chapter 6.
[158] Abboud, J.-L., Castaño, O., Della, E. W., Herreros, P. M., Notario, R., and Rossier, J.-C., *J. Am. Chem. Soc.*, **119**, 2262 (1997).
[159] Schreiner, P. R., Schleyer, P. von R., and Schaefer, H. F., *J. Org. Chem.*, **62**, 4216 (1997).
[160] Lajunen, M., Himottu, M., and Tanskanen-Lehti, K., *Acta Chem. Scand.*, **51**, 515 (1997).
[161] Vančik, H., Genaev, A. M., and Shubin, V. G., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 667.
[162] Herrmann, R. and Kirmse, W., *Liebigs Ann./Recl.*, **1997**, 337.
[163] Bentley, T. W., Llewellyn, G., Norman, S. J., Kemmer, R., Kunz, U., and Christl, M., *Liebigs Ann./Recl.*, **1997**, 229.
[164] Chan, M. S. W. and Arnold, D. R., *Can. J. Chem.*, **75**, 192 (1997)

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CHAPTER 10

Nucleophilic Aliphatic Substitution

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Vinylic Systems

Rappoport and colleagues' work has continued.[1,2] In an attempt to develop the k_{OTf}/k_{OMs} ratio as a mechanistic tool for the addition–elimination route in nucleophilic vinylic substitution, the reactions of several pairs of vinyl triflates (**1a**) and mesylates (**1b**) were examined.[1] When Ar = p-$O_2NC_6H_4$ or Ph and Y = Y′ = CO_2Et, reactions with piperidine or morpholine in MeCN or THF gave the normal substitution product, with k_{OTf}/k_{OMs} ratios of 3.7–10.6. However, reactions of these substrates (**1b**) (and of others involving Y, Y′ variously as CN and/or Me) with thiolate nucleophiles led to ketonic products via S−O bond cleavage. These findings indicate that k_{OTf}/k_{OMs} ratios cannot be used as a general mechanistic tool. Attempts to delineate the scope of the addition–elimination route have continued in a study of the reaction of methyl β-chloro-(3-bromo-2,4,6-trimethyl)cinnamate (**2**) with MeS^- in MeCN.[2] The main products are

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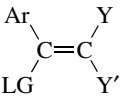
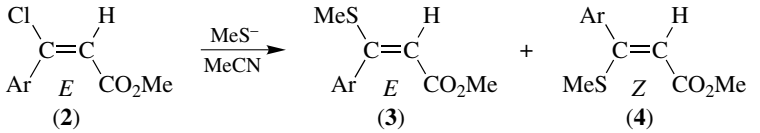
the isomers (**3**) and (**4**), in the ratio of 2.3 : 1, with a small amount of the arylacetylene (**5**). The formation of both isomers suggests an elimination–addition mechanism via (**6**) and this was confirmed by deuterium incorporation experiments.

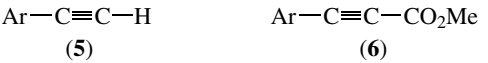


(**1**)

a; LG = OTf
b; LG = OMs



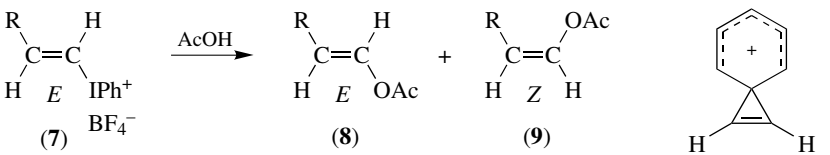
(**2**) (**3**) (**4**)



(**5**) (**6**)

In (**2**) to (**6**): Ar = 3-Br-2,4,6-Me_3C_6H

The styryl iodonium salt (**7a**) reacts slowly with acetic acid to give the *E* and *Z* isomeric products (**8a**) and (**9a**) in the ratio 85 : 15.[3] The decenyl system (**7b**) is much more reactive and gives only the inversion product, the *Z* isomer (**9b**). It was suggested that the styryl system reacts in a two-step mechanism via the vinylene phenonium ion (**10**), whereas the decenyl system follows a one-step vinylic S_N2 mechanism. In contrast, 2-bromo-1-decenyliodonium salt reacts with bromide ion in MeCN with complete retention.[4] The observed rate constants show an unexpected dependence on [Br^-], in accordance with a mechanism involving ligand coupling within a bromoiodane intermediate.



(**7**) (**8**) (**9**) (**10**)

a; R = C_6H_5
b; R = *n*-C_8H_{17}

Reactions of α, β, β-trifluorostyrene and (*Z*)-β-chloro-α, β-difluorostyrene with 9-methylfluoren-9-yl anion (potassium salt) are accelerated by ion-pair solvating agents (18-crown-6, [2.2.2]-cryptand) and retarded by $KBPh_4$ as a common-ion reagent.[5] This was interpreted as indicating that solvent-separated ion pairs are more reactive than contact ion pairs in these reactions.

The kinetics and mechanism of the reactions of trialkyl phosphites with mucochloric acid (dichloroaldehydoacrylic acid) have been studied.[6] Cine-substitution products are formed in reactions of 2,5- and 2,6-dichloro-1,4-benzoquinone with pyrrolidine.[7]

The reaction of vinyl fluoride with CN^- has been studied by the DFT B3YLP/6–31+G(d) method.[8] This nucleophilic substitution is mainly a π attack with a barrier height of 14.8 kcal mol^{-1}, which is 17.91 kcal mol^{-1} more favourable than the σ attack.

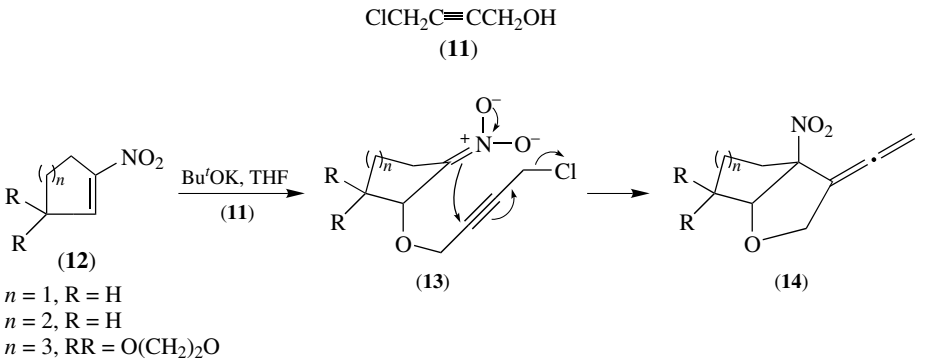
Allylic and Other Unsaturated Systems

γ-Trifluoromethylated allylic acetates give S_N2'-type reactions with various Grignard reagents in the presence of catalytic amounts of copper(I) cyanide and trimethylsilyl chloride, without any trace of the corresponding S_N2 products.[9] This high selectivity was ascribed to the strong electron-attracting effect of CF_3. In related work a new route for the asymmetric construction of quaternary carbon centres containing a CF_3 group has been devised by using highly regio- and stereo-selective S_N2' reactions of organocopper and organocuprate reagents with certain allylic mesylates.[10]

Copper-mediated S_N2' displacement of enantiomerically pure allylic mesyloxy vinyl sulfoxides occurs with high yields and stereoselectivities.[11] The S_N2' reactions of structurally related mesyloxy sulfides and sulfones with organocuprates have also been examined.

The Bu^{t}OK-promoted reaction of 4-chlorobut-2-yn-1-ol (**11**) with nitroalkenes (**12**) gives 3-vinylidenetetrahydrofurans (**14**) in good yields with complete diastereoselectivity.[12] It is supposed that oxa-Michael addition to form the intermediate (**13**) is followed by intramolecular S_N2' substitution.

S_N2' ring-opening reactions of various 11-oxatricyclo[6.2.1.0^{1,6}]undec-9-en-5-ones by organometallic reagents have been reported.[13] Primary, secondary, and tertiary organolithium reagents were effective, but organocuprates and Grignard reagents were generally ineffective. There was competitive attack on the carbonyl group.

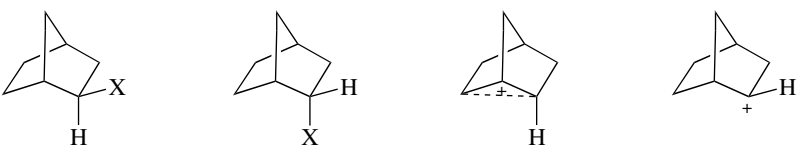


Nucleophilic reaction of Et_3N with diallyl disulfide has been found to differ from that with diallyl sulfide in being very much more exothermic and also autocatalytic.[14] Possible mechanisms were discussed. EHMO calculations have been performed for

1-halo-3-phenylpropa-1,2-dienes and kinetics of hydrolysis have been studied.[15] At pH<8 the hydrolysis appears to proceed by a solvent-assisted S_N1 mechanism involving the intermediate formation of $[PhCHCCH]^+$, but at pH > 9.5 an S_N2' mechanism, with concerted bond breaking and making, is involved.

Norbornyl System

In order to analyse the solvolysis behaviour of epimeric norbornyl derivatives, the dissociation mechanisms of protonated 2-*exo*-norbornanol (**15**) and 2-*endo*-norbornanol (**16**) have been studied by *ab initio* calculations at the B3LYP/6–311+G*//B3LYP/6–31G* level.[16] In agreement with experimental solvolysis data, the activation energy (including the 1.2 kcal mol^{-1} ground state energy difference) for dissociation of *exo*-(**15**) is 3.7 kcal mol^{-1} lower than that of *endo*-(**16**). This is much smaller than the 14 kcal mol^{-1} energy difference favouring the isolated non-classical norbornyl cation (**17**) over the classical ion (**18**). Changes in geometry and charge distribution reduce the energy difference between the classical and non-classical cation moieties in the *endo* and *exo* solvolysis transition structures to 7.5 kcal mol^{-1}. This is reduced further by the stronger leaving-group interaction in the 2-*endo* transition structure compared with the 2-*exo* structure.



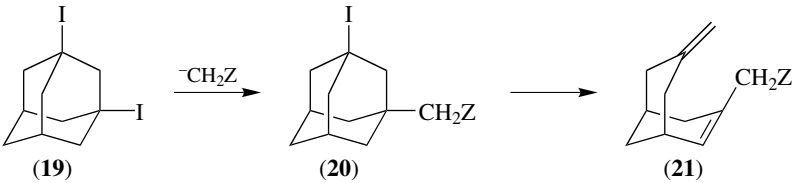
(**15**) (**16**) (**17**) (**18**)

X = H_2O^+

Rate constants for the hydrolysis of 2-*exo*-norbornyl phenyl ether and several *meta*- or *para*-substituted derivatives have been measured in concentrated perchloric acid solutions.[17] The effect of substituents on the rate constant and activation parameters is small. The mechanism appears to be of the *A*-1 type.

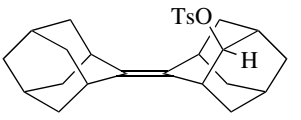
Miscellaneous Polycyclic Systems

The reactions of 1,3-dihaloadamantanes with various carbanions in DMSO have been studied.[18] For example, potassium enolates of acetophenone and pinacolone and the anion of nitromethane react with 1,3-diiodoadamantane (**19**) under photo-stimulation; a free-radical chain process forms a 1-iodo monosubstitution product (**20**) as an intermediate, which undergoes concerted fragmentation to yield derivatives of 7-methylidenebicyclo[3.3.1]nonene (**21**). These and other results were interpreted in terms of the $S_{RN}1$ mechanism. The work has been extended to the reactions of 1- and 2-halo- and 1,2-dichloro-adamantanes, examples of the $S_{RN}1$ mechanism again being found.[19]

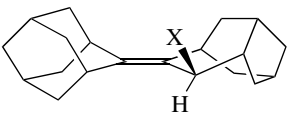


(**19**) (**20**) (**21**)

Z = COPh, $COCMe_3$, or NO_2



(**22**)

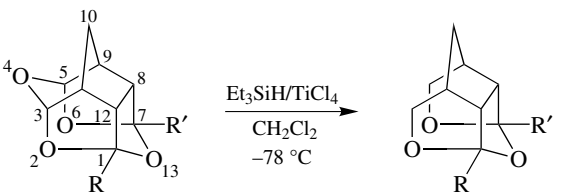


(**23**)

X = OH or OEt

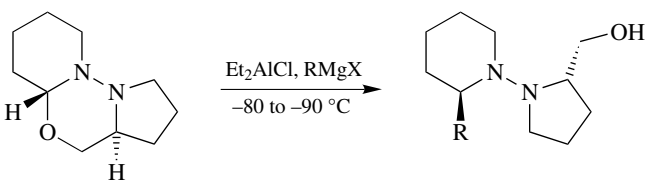
Rate constants for the aqueous ethanolysis of 4-adamantylidene-2_{ax}-adamantyl tosylate (**22**) give an *m* value of 0.86 in correlation with Y_{OTs}.[20] This substrate is about five times more reactive than 2-adamantyl tosylate, and the products arise from the rearrangement of the substituted adamantyl ring into a protoadamantyl ring (**23**). These and other results are consistent with a transition state involving concerted σ-bond participation and departure of the tosylate leaving group.

A remarkable regioselective and stereoselective double nucleophilic substitution of the acetal group of tetraacetal tetraoxa-cages (**24a**) with silicon-containing nucleophiles



(**24a**) (**24b**)

i; R = R′ = CH_3
ii; R = CH_3, R′ = CH_2Ph
iii; R = R′ = H



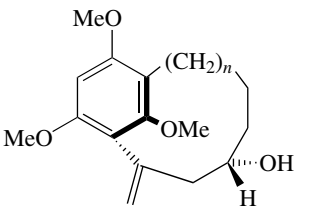
(**25**) (**26**)

mediated by Lewis acids has been found.[21] A critical role was attributed to the C−O−C bond angle strain of the unusually large bond angle C(3)−O(4)−C(5) of (**24a**).

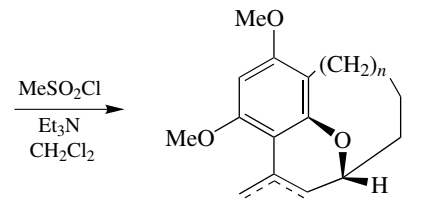
Nucleophilic alkylation with Grignard reagents (mediated by Et_2AlCl) on chiral perhydropyrido(2.1-*b*]pyrrolo[1,2-*d*][1,3,4]oxadiazine (**25**) proceeds via an S_N2 mechanism below −80 °C, forming the inversion product (**26**) with high stereoselectivity.[22] At higher temperatures the stereoselectivity shifts in favour of retention.

The reactions of the [6]- and [7]-metacyclophanols (**27**) with $MeSO_2Cl$ in the presence of Et_3N in CH_2Cl_2 proceed rapidly to give the corresponding strained tricyclic ethers (**28**).[23] A mesylate is formed first by attack of RSO_2Cl on OH, and the mesylate group is then expelled by attack of the neighbouring OMe, an intramolecular version of the S_N2 mechanism.

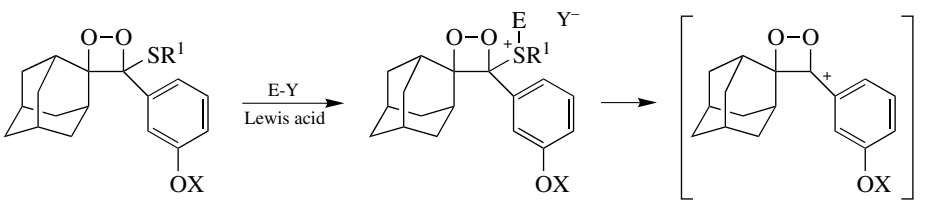
Alkylthio- or arylthio-substituted 1,2-dioxetanes derived from an adamantylidene vinyl system (**29**) undergo attack by appropriate oxygen nucleophiles in the presence of Lewis acid to form alkoxy-, aryloxy-, or acyloxy-substituted 1,2-dioxetanes (**32**).[24] A novel S_N1 reaction mechanism was suggested, involving species (**30**) and (**31**).



(**27**)
n = 1,2



(**28**)

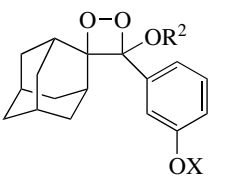


(**29**) (**30**) (**31**)

R^1 = CH_2CH_3 X = H, Piv
CH_2CF_3
C_6H_4F

R^2 = alkyl, aryl, acyl

R^2OH
Lewis acid



(**32**)

The kinetics of the reaction of 3-azabicyclo[3.3.0]octane with chloramine have been studied in the pH range 8–13.[25] Two competitive bimolecular reactions lead to the formation of *N*-amino and *N*-chloro derivatives, by reaction between neutral species in the former case and by reaction between chloramine and protonated aza compound in the latter case.

Epoxide Reactions

The chemoselectivity, regioselectivity, diastereoselectivity, and enantioselectivity of heteroatom oxidations, epoxidations and CH insertions by dioxiranes have been reviewed.[26] The selective ring-opening reactions of epoxides at high pressures have been reviewed (in Japanese).[27]

The base-catalysed hydrolysis of ethylene oxide has been studied by the MNDO method.[28] The structures of the reactant, product, and transition state were optimized and a reaction mechanism was proposed.

The kinetics of the reaction between acetic acid and epichlorohydrin in the presence of chromium acetate and chromic anhydride have been studied.[29] Rate constants for the reaction of epichlorohydrin with *p*-cresol in the presence of basic catalysts have been measured in the temperature range 71–100 °C.[30] Several simultaneous reactions occur, depending on the catalyst, and an appropriate kinetic model was developed.

The aromatic substituent effect on the stereoselectivity has been studied for the condensed-phase and gas-phase acid-induced methanolysis of 2-aryloxiranes derived from 3,4-dihydronaphthalene and *trans*-1,2,3,4,4a,10a-hexahydrophenanthrene bearing a tertiary benzylic oxirane centre.[31] Linear free energy relationships were applied successfully.

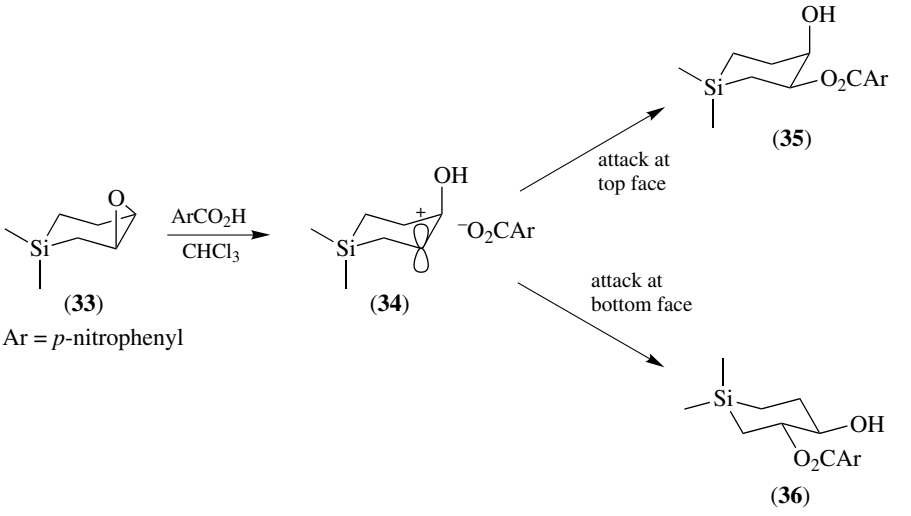
The ring opening of several oxiranes by various thiosilanes (promoted by tetrabutylammonium fluoride as catalyst) occurs regioselectively under mild conditions.[32] With the amphiphilic reagents isothiocyanatotrimethylsilane and *O*-trimethylsilyl thioacetate the sulfur centre exclusively attacks the oxiranes. A plausible reaction mechanism was suggested to explain the role of F^- as promoter.

The ring opening of the β,γ-epoxysilane (**33**) with *p*-nitrobenzoic acid in chloroform is regiospecific and gives the two esters (**35**) and (**36**).[33] The mechanism involves the β-silicon-stabilized carbenium ion (**34**), which is captured by the *p*-nitrobenzoate counter-ion.

The reactions of monoepoxy derivatives, (**37**) and (**38**), of *cis*-1,2-dihydrocatechols with various *O*-, *N*-, *C*-, and *Hal*-centred nucleophiles have been studied.[34] In both direct and acid-catalysed processes, these epoxides undergo exclusively nucleophilic attack at C(5a).

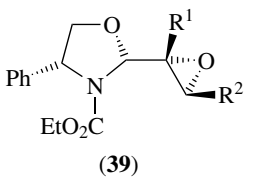
Chiral epoxyoxazolidines (**39**) undergo regioselective ring opening by sodium azide to products (**40**).[35] Further appropriate manipulations of functional groups lead to chiral β-amino alcohols, which are intermediates for the enantioselective synthesis of bioactive products related to taxol.

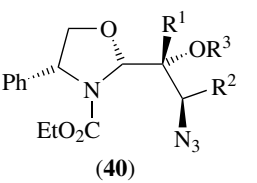
The stereochemistry of the cobalt(II) chloride-catalysed opening of cinnamoyl epoxides with *N*-substituted anilines is controlled by the *para* substituent of the aromatic ring.[36] Thus *p*-OMe promotes cleavage giving the *anti* amino alcohol as the

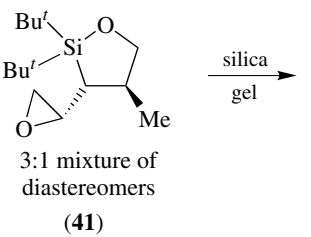


major product, whereas amines containing *p*-Cl, *p*-Br, or *p*-Me and also the parent unsubstituted amine afford the *syn* amino alcohols as major product.

A ring-expansion reaction based on epoxide ring opening and control of stereochemistry by σ-participation of a silyl group has been devised.[37] An example







is shown in (**41**)–(**43**). The ring-expansion product (**42**) was obtained in diastereomerically pure form. A mechanism for the ring-expansion reaction was proposed.

The Lewis acid trimethylsilyl triflate brings about the rearrangement of 2,3-epoxyamines to the corresponding 2-trimethylsilyloxymethylaziridinium ions.[38] Such intermediates react regiospecifically with nitrogen nucleophiles to form 1-substituted 2,3-amino alcohols with full stereochemical control.

The kinetics of the alkylation of tertiary amines with 1,3-dichloropropan-2-ol have been studied.[39] The mechanism is thought to involve a chlorohydrin–epoxide equilibrium.

Other Small Rings

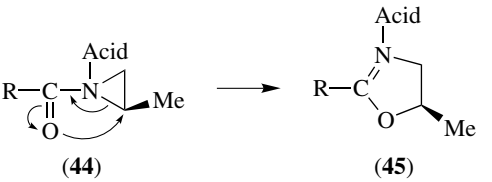
The three-electron S_N2 reactions of arylcyclopropane cation radicals have been studied in detail.[40,41] Stereochemical experiments with methanol, water, or cyanide as nucleophile showed that the reactions occur stereospecifically with complete inversion of configuration at the carbon atom undergoing substitution.[40] Various kinetic studies were carried out. The reaction of phenylcyclopropane cation radical with a series of alcohols as nucleophiles showed small steric effects. In further studies, steric and electronic effects of substituents in the cyclopropyl or phenyl ring were investigated.[41] Substitution takes place at the most highly substituted carbon atom with a high degree of regioselectivity, but steric effects measured for alkyl groups attached to the carbon atom undergoing substitution are very small. The electronic effects on the rate constants for the reactions of *para*-substituted phenylcyclopropane cation radicals with methanol or pyridine in 1,2-dichloroethane at 23 °C are, however, substantial. Hammett-type treatments are reasonably successful, ρ values being about 2.

When *gem*-dibromocyclopropanes are heated with alcoholic potash, cyclopropanone acetals and propargylic ethers are obtained.[42] The mechanism was discussed.

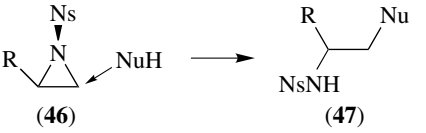
A theoretical and an experimental study of the acid-catalysed isomerization of 1-acylaziridines to the oxazolines has been carried out.[43] Such isomerization may conceivably proceed by various paths, but the S_Ni mechanism, as in (**44**) and (**45**), has often been assumed to operate. The re-examination in this paper finds experimental and theoretical support for this in certain cases.

The diesters of *N*-phosphorylated aziridine are unreactive towards alkylating agents, but after conversion into the ionic monoesters they undergo ready *N*-methylation with MeI, followed by fast opening of the aziridinium ion by the iodide ion.[44] A novel ring-opening reaction of various 2-alkyl- and 2,2-dimethyl-*N*-(diethoxyphosphoryl)aziridines with copper-modified Grignard reagents proceeds regiospecifically at the least hindered carbon.[45] Aziridines substituted at the N by nosyl (4-nitrobenzenesulfonyl) are highly reactive electrophiles towards various nucleophiles, e.g. amines, thiols, alkoxides, cyanide.[46] The corresponding S_N2 adducts are formed without competing attack on the nosyl functionality, (**46**) and (**47**). The nosyl group can then be split off under mild conditions to give primary amines.

A new method has been developed for the preparation of enantiomerically pure monosubstituted aziridines via the reaction of an *N*-tosyl-*O*-tosylaziridine (**48**) with a primary organocuprate reagent.[47] Attack occurs at the least substituted carbon atom of



(**44**) (**45**)



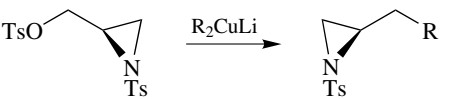
(**46**) (**47**)

R = Me, Ph
Ns = *p*-nitrobenzenesulfonyl

the aziridine ring, resulting in ring-opened intermediates, which then undergo ring closure to the desired product (**49**) by displacement of *O*-Ts.

An anomalous reaction of 2-benzenesulfonyl-3-aryloxaziridines (Davis reagents) with indoles has been reported.[48] In this it appears that a π-bond in the indole acts nucleophilically to attack the *O* of the oxaziridine ring and thereby cleave the O—N bond.

3-Phenyloxetane reacts with nitric acid in dichloromethane under anhydrous



(**48**) (**49**)

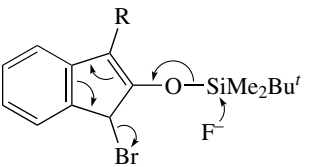
conditions by a mixture of *ortho* and *para* aromatic nitration and oxetane ring opening.[49] The latter affords 1,3-diol dinitrates. Kinetic studies of these reactions, and analogous reactions of related substrates, were carried out, the results being rather complex. The ring opening involves S_N2 reaction of nitrate ion with an oxetane–nitric acid complex.

5-Azidoisothiazoles may be thermolysed in *p*-xylene solution to yield bicyclic products.[50] In the case of several 4-substituted derivatives, unimolecular loss of N_2 from the azide moiety is followed by ring closure involving the 4-substituent and the remaining N atom of the azide. Stereoisomeric cyclic sulfites of 1,1,2-triphenylethane-1,2-diol undergo an unexpected S_N1-type ring cleavage when treated with alcohols, thereby yielding enantiomerically pure ethers.[51]

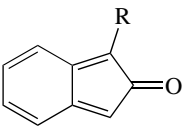
Substitution at Elements Other than Carbon

1-Bromo-2-*t*-butyldimethylsilyloxyindenes (**50**) react with caesium fluoride to form inden-2-ones (**51**), which may then be efficiently trapped in both intra- and intermolecular additions.[52]

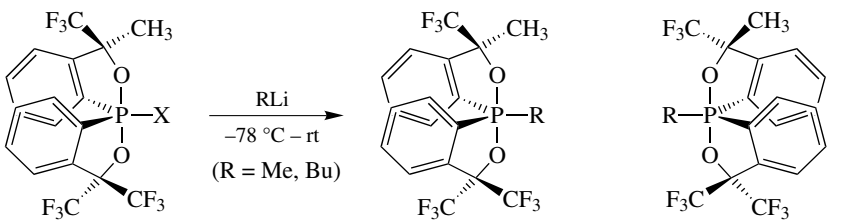
Ab initio MO calculations have been carried out for the base-catalysed methanolysis of a substituted 1,3,2-oxathiaphospholane.[53] The results suggest that ring opening with retention of configuration at phosphorus is energetically the most favourable. This provides a rational interpretation for the chemo- and stereo-selectivity ascertained experimentally. The stereochemistry of nucleophilic substitution reactions of sterically rigid phosphoranes has been investigated.[54] The stereochemistry of reaction at pentacoordinate phosphorus was found to depend on the leaving group, stereochemistry of phosphorane, and solvent; see (**52**)–(**54**). Thus, for example, SMe compounds with alkyllithium reagents led to inversion, whereas OMe compounds gave various ratios of inversion and retention depending on the other factors mentioned above.



(**50**)



(**51**)



(**52**)

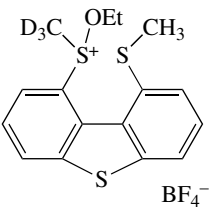
X = SMe, OMe, $OCH_2CH_2NMe_2$

retention

(**53**)

inversion

(**54**)



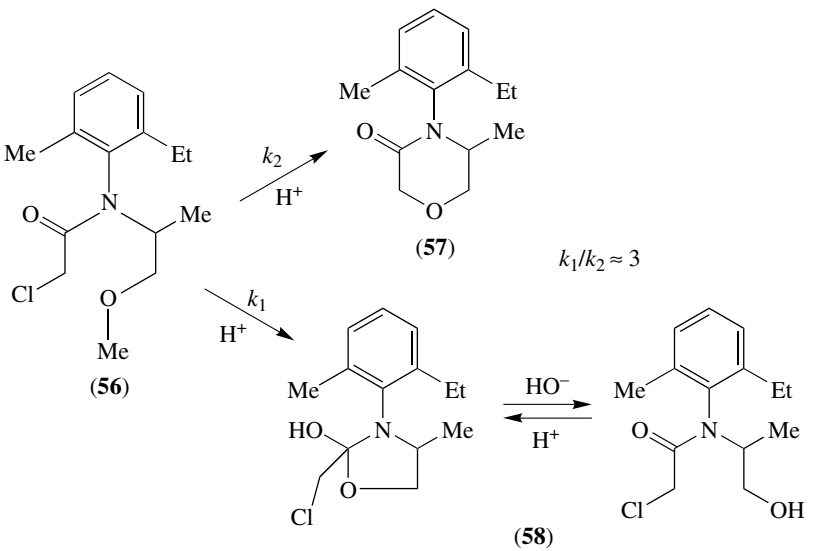
(**55**)

Scrambling of ethoxy groups between sulfur atoms in close proximity has been observed for 1-(d_3-methylethoxysulfonio)-9-(methylthio)dibenzothiophene (**55**) and some analogous compounds.[55]

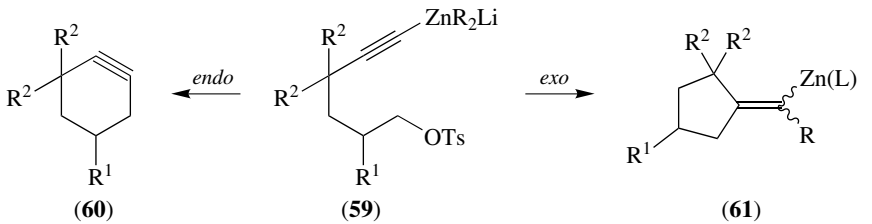
Intramolecular Substitution

The substrate (**56**) undergoes acid hydrolysis to give (**57**) and (**58**) in parallel first-order reactions.[56] The hydrolytic cleavage of the ether linkage [giving (**58**)] is about three times faster than the intramolecular cyclization [giving (**57**)].

2,4,6-Trimethoxydiazoacetophenone undergoes acid-catalysed cyclization to give 4,6-dimethoxy-3(2*H*)-benzofuranone.[57] Under the same conditions diazoacetophenone gives the intermolecular product 2-hydroxyacetophenone. The difference in reaction mechanism was attributed to the interaction of *o*-OMe with the diazomethyl group.



Alkynyl zincates (**59**), derived from 5-hexynyl tosylates, undergo a π-type *endo* cyclization to form cyclohexynes (**60**).[58] This reaction takes place in competition with *exo* cyclization, leading to the formation of 1-(cyclopentylidene)alkylzincs (**61**).



A 'facilitated transition' hypothesis has been suggested to replace the 'reactive rotamer' hypothesis as an explanation for the *gem*-dialkyl effect in intramolecular cyclization reactions.[59]

Anchimeric Assistance

Rate measurements for thermolysis of 4-azidothiazoles in *p*-xylene solution have found neighbouring-group effects from nitro (19-fold rate increase), phenyliminomethyl (16-fold), formyl (4.5-fold) and acetyl (2.2-fold) substituents in the 5-position.[60] See also under Other Small Rings above.[50]

Secondary deuterium isotope effects are important in the study of neighbouring-group participation in solvolytic reactions.[61] This subject has now been reviewed at considerable length. Other evidence bearing on participation is also discussed.

Further relevant studies have been made regarding the possible intervention of a neighbouring methoxy group effect in the solvolysis reactions of *trans*-2-methoxycyclopentyl and *trans*-2-methoxycyclohexyl tosylate.[62] Three probes were used: effect on rate of varying solvent ionizing power, effect of added azide ion, and identity of solvolysis products in 97% aqueous 2,2,2-trifluoroethanol. The results appear to confirm the occurrence of neighbouring-group participation in the solvolysis of the above substrates, but strong electrophilic solvation exerts a dominant effect on the reactivity.

Ambident Nucleophiles

The methylation of *N*-phenylhydroxylamine with methyl arenesulfonates in DMSO occurs on the O atom, in contrast to methylation in methanol, where *N*-alkylation occurs.[63] Rate data were obtained for various systems pertinent to the problem of alternative sites of alkylation and Hammett treatments were applied.

Further work by the same research group is on the kinetics of the reactions of substituted *N*-methylbenzohydroxamates with substituted phenyldimethylsulfonium salts.[64] As the substituents in the hydroxamate nucleophile are changed from electron-releasing to electron-attracting, the α-effect is diminished. The reactivity of the hydroxamates correlates with their oxidation potentials, indicating the inclusion of some single electron transfer (SET) character in the transition state for these reactions. The matter is further pursued in a later paper.[65]

The regioselectivities of *myo*-inositol derivatives towards electrophiles have been studied by using various levels of quantum mechanical calculation.[66] The calculations appear to favour the O(6) position, but experimentally the O(3) position is the major site for electrophilic attack. Such experiments usually involve rather polar solvents and repetition of some of the calculations for molecules embedded in a medium of dielectric constant of 40 found O(3) to be preferred as reaction site.

Isotope Effects

The $^{14}N/^{15}N$ and secondary α-$^{1}H/^{2}H$ kinetic isotope effects (KIEs) for the S_N2 reaction between PhS^- and benzyldimethylphenylammonium ion at different ionic strengths in DMF at 0 °C indicate that the structure of the transition state changes markedly with the ionic strength of the medium.[67] A more reactant-like, more ionic, transition state is found at the higher ionic strength. A further contribution from the same research group

employs secondary α-^{1}H/^{2}H and heavy atom KIEs to determine the symmetry of S_N2 transition states.[68] The results for two different S_N2 reactions suggest that the magnitude of secondary α-^{1}H/^{2}H KIEs 'can be determined by the length of only the shorter (stronger) reacting bond in an unsymmetrical S_N2 transition state rather than by the usual nucleophile-leaving group distance'.

The relationship between secondary α-^{1}H/^{2}H KIEs and transition state looseness has been investigated by MP2/6–31 + +G(d,p) calculations on three identity $X^- + CH_3X$ S_N2 reactions.[69] The secondary KIE increases with increasing transition structure looseness. It was shown that looseness is best defined as a Δ-elongation of the C−X bond lengths, where the reference state can be either the isolated reactants or the ion–dipole complex.

Solvent KIEs for $MeCl + Cl^-$ in the presence of 1–4 molecules of water were examined by *ab initio* calculations.[70] The ratio k_H/k_D was <1 for the monohydrated system and >1 for the dihydrated system; it increased with the number of microsolvating water molecules, owing to breakage of hydrogen bonds in attaining the transition state.

Gas-phase Reactions

Guided beam tandem mass spectrometry techniques have been used to examine the promotion of the S_N2 reaction

$$^{37}Cl^- + CH_3^{35}Cl \rightarrow {}^{35}Cl^- + CH_3^{37}Cl$$

by translational energy.[71] The translational energy threshold is 45 ± 15 kJ mol^{-1}, well above the previously reported potential energy barrier height of 10–13 kJ mol^{-1} for the S_N2 transition state. Much further experimental and theoretical information is provided in this paper.

Rate constants have been measured for the reaction of Cl^- with CH_3Br over buffer gas pressures from 300–1100 Torr at 125 °C by ion mobility spectrometry (IMS).[72] The experiments indicate that this reaction is not moved onto its high-pressure limit of kinetic behaviour by the use of buffer gas pressures near 1 atm. The same authors have carried out a similar study of the reaction of Cl^- with isopropyl bromide at 640 Torr and 20–175 °C.[73] It was concluded that under these conditions the reaction occurs primarily by a distinctly two-step mechanism:

$$Cl^- + i\text{-PrBr} \underset{}{\overset{K_1}{\rightleftharpoons}} Cl^-(i\text{-PrBr}) \xrightarrow{k_1} Br^- + i\text{-PrCl}$$

in which a thermal energy ion complex, $Cl^-(i\text{-PrBr})$, is maintained in a state of chemical equilibrium with the reactants. Values of K_1 and k_1 were obtained. The S_N2 transition state is 1.6 kcal mol^{-1} above the energy of the reactants.

Translational energy dependence has been studied for a series of chloride exchange reactions in the gas phase.[74] This varies with the changes in the potential-energy surfaces across the series of reactions in a manner that is consistent with the predictions

of statistical reaction rate theory. The same authors have also studied the role of translational energy in the system[75]

$$^{35}Cl^- + {}^{37}ClCH_2CN \rightleftharpoons {}^{37}Cl^- + {}^{35}ClCH_2CN$$

The observed energy dependence is indistinguishable from that predicted by RRKM theory, suggesting that increased translational energy is redistributed statistically in the collision complex.

Rate constants and products for the reactions of $Cl^-(D_2O)_n + CH_3Br$ ($n = 1$–3) have been measured over various temperature ranges.[76] For example, the $n = 1$ reaction was studied from 238 to 478 K and the rate constant is well described by the equation $k = (6.0 \times 10^{-10}) \exp(-1270/T)$ cm^3 s^{-1}. The reaction mechanism was determined as ligand switching to produce $Cl^-(CH_3Br)$, followed by thermal decomposition of the complex. RRKM theory was used to model the decomposition of $Cl^-(CH_3Br)$. The same research group has also studied the effects of solvation, isotopic substitution, and temperature on the reactions of $F^-(H_2O)_n$ with CH_3Br ($n = 0$–5).[77] The characteristics of the reactions vary greatly with the value of n.

A quantum dynamical study of the $Cl^- + CH_3Br$ S_N2 reaction has been made.[78] The calculations are described in detail and the resulting value of the rate constant is in much better agreement with experiment than is that derived from statistical theory. In related work on the same reaction, a reaction path Hamiltonian analysis of the dynamics is presented.[79] The same research group has used statistical theory to calculate the rate constant for the S_N2 reaction

$$F^- + CH_3Cl \rightarrow FCH_3 + Cl^-$$

in its dependence on relative translational energy E_{rel} and CH_3Cl temperature T.[80] At best, statistical theory only qualitatively reproduces the dependence of the experimental rate constant on translational energy and temperature.

The integrated MO + MO (IMOMO) method, recently proposed for geometry optimization, has been tested for accurate single-point calculations.[81] Test examples included the activation barrier of the S_N2 reaction of Cl^- + alkyl chloride. The conclusion was that IMOMO single-point calculation provides a method for obtaining reliable local energetics such as bond energies and activation barriers for a large molecular system.

The performance of the B3-LYP variant of density functional theory, when used in conjunction with the 6–31G(d) and 6–311 + G(3df,2p) basis sets in describing the S_N2 reactions of $Cl^- + CH_3Cl$ and $Cl^- + CH_3Br$, has been examined in detail.[82] The results appear to be patchy. The same research group has carried out high-level *ab initio* molecular orbital calculations at the G2(+) level of theory on the identity front-side nucleophilic substitution reactions with retention of configuration, $X^- + CH_3X$ for X = F, Cl, Br, and I, and has compared the findings with those for back-side attack.[83] For chloride exchange in CH_3Cl, which has been found in gas-phase experiments at high energies, the results suggest that this may be the first example of a front-side S_N2 reaction with retention of configuration at saturated carbon.

Stationary points of the potential surface for the S_N2 reaction

$$F^- + CH_3Cl \rightarrow FCH_3 + Cl^-$$

have been investigated by large-scale coupled cluster [CCSD(T)] calculations.[84] The ion–dipole complexes in the reactant and product channels have well depths of 15.8 and 9.6 kcal mol^{-1}, respectively, and are separated by a small barrier of 3.3 ± 0.3 kcal mol^{-1}.

Quantum scattering calculations have been reported for the S_N2 reaction of Cl^- with CH_3Cl.[85] In the method used, the rotating bond approximation (RBA) has been adapted so that three degrees of freedom, including the C−Cl stretching vibrations and the CH_3 umbrella mode, are treated explicitly. Initial excitation of the C−Cl vibration was found to have a large effect on the reaction probabilities, while excitation of the CH_3 umbrella vibration is less significant. In related work, the temperature dependence of the rate constant for the $Cl^- + CH_3Br$ reaction has been studied down to 23 K.[86] The rate constant is increased by over two orders of magnitude when the temperature is reduced from 300 to 23 K.

Identity S_N2 reactions of $MeF + F^-$ and $MeCl + Cl^-$ have been compared computationally with the reactions of $MeF + LiF$ or NaF and of $MeCl + LiCl$.[87] Calculations by new methods essentially confirm results obtained previously by other methods. Extension of the calculations to the corresponding ethyl systems gave lower barriers than for methyl systems in the reactions involving ion pairs as nucleophiles.

Theoretical studies have been carried out for the gas-phase nucleophilic ring-opening of 3,4-epimino-, 3,4-epoxy-, and 3,4-epithio-but-1-ene.[88] Attack by HO^- on α-C, γ-C, and δ-C was examined by using MP2/6–31+G*//MP2/6–31+G* *ab initio* molecular orbital methods.

The question, 'Does nucleophilic substitution reaction occur in electron-excited condition?' has been addressed in a short review article in Japanese.[89]

The reaction between ammonia and methyl halides has been studied by using *ab initio* quantum-chemical methods.[90] An examination of the stationary points in the reaction potential surface leads to a possible new interpretation of the detailed mechanism of this reaction in different media. In the gas phase, the product is predicted to be a strongly hydrogen-bonded complex of alkylammonium and halide ions, in contrast to the observed formation of the free ions from reaction in a polar solvent. Another research group has also studied the reaction between ammonia and methyl chloride.[91] A quantitative analysis was made of the changes induced on the potential-energy surface by solvation and static uniform electric fields, with the help of different indexes. The indexes reveal that external perturbations yield transition states which are both electronically and structurally advanced as compared to the transition state in the gas phase.

S_N2 displacements of Cl^- ion from MeCl, EtCl, and $ClCH_2CH_2Cl$ by AcO^- and by HO^- have been studied in *ab initio* molecular orbital calculations at the HF/6–31+G(d), MP2/6–31+G(d), and MP4/6–31+G(d) levels.[92] The gas-phase reactions of HO^- have no overall barrier, but there is a small overall barrier for the reactions with AcO^-. A self-consistent reaction-field solvation model was used to examine the S_N2 reactions between MeCl and HO^- and between $ClCH_2CH_2Cl$ and AcO^- in solution. A

PM3 and SM3–PM3 semiempirical MO study of the conventional S_N2 hydrolysis and neighbouring-group hydrolysis reaction mechanisms in the gas phase and in aqueous solution for 2,2′-dichlorodiethyl sulfide has been described.[93] The calculations predict substantially faster reactions in aqueous solution, with the neighbouring-group mechanism always being preferred. Various other details of the mechanisms were elucidated.

A series of molecular dynamics experiments has been presented for the reaction of Cl^- with CH_3Cl taking place in liquid simple point-charge water nanoclusters containing 6, 16, or 32 solvent molecules at temperatures close to 200 K.[94] It was found that solvation effects lead to significant enhancement of the computed free-energy barriers, even in aggregates containing only six water molecules. Numerous other interesting findings are presented. The semiempirical MO AM1 method has been employed to investigate the mechanism of the alkaline S_N2 hydrolysis of methyl nitrate and the influence of the solvent thereon.[95] The activation energy for hydrolysis in the gas phase was calculated as 50.61 kJ mol^{-1}, but this is increased to 89.65 kJ mol^{-1} by the solvent effect. The latter value was considered to be in essential agreement with the experimental value of 82.42 kJ mol^{-1}. A microscopic description of non-adiabatic, non-equilibrium, and equilibrium solvations has been presented for the solvated cluster S_N2 reactions

$$(H_2O)_nCl^- + CH_3Cl \rightarrow ClCH_3 + Cl^-(H_2O)_n$$

with $n = 0$–4.[96] The treatment involved *ab initio* MO calculations, and the ratio of non-adiabatic solvation to equilibrium solvation rate constants was evaluated.

As part of a theoretical examination of the factors controlling the catalytic efficiency of a transmethylation enzyme (catechol *O*-methyltransferase), the reaction mechanism of the non-enzymic transmethylation of catechol by *S*-adenosylmethionine (AdoMet, as modelled by sulfonium ion) has been elucidated by using *ab initio* and semiempirical quantum mechanical methods.[97] The gas-phase reaction between catecholate and sulfonium is extremely fast, involving no overall barrier, and the reaction profile to some extent resembles that of a typical gas-phase S_N2 reaction. However, in aqueous solution, this reaction is very slow, with a predicted barrier of 37.3 kcal mol^{-1}. Good agreement between calculated KIEs for the model reaction and measured KIEs for the enzymic reaction suggests that the transition states are similar.

Radical Processes

The evidence for single-electron transfer (SET) in the reactions of lithium aluminium hydride (LAH) with *hindered* primary alkyl iodides is overwhelming. A study has now shown for the first time that SET may also be involved in reactions of LAH with *unhindered*, unsubstituted primary alkyl iodides, the particular substrate studied being 1-iodoctane.[98] A theory of the rates of S_N2 reactions and their relation to those of outer-sphere bond-rupture electron transfers has been presented in detail.[99] A unified approach is introduced in which there can be a flux density for crossing the transition state, which is either bimodal, one part leading to S_N2 and the other to ET products, or

unimodal with a less marked energy-dependent separation of the rates of formation of these products.

9-Mesitylfluorenyl anion (9MsF$^-$) is unreactive towards MeI at temperatures below −78 °C.[100] Above −60 °C the absorption spectrum of 9MsF$^-$ in the presence of MeI is replaced by that of the corresponding 9-mesitylfluorenyl radical (9MsF$^\cdot$), and 9-methyl-9-mesitylfluorene is formed in low yield. In a study of the electron-transfer photochemistry of chrysanthemol, an intramolecular S_N2' reaction of a vinylcyclopropane radical cation has been observed.[101] In a long series of studies of the reactivity of the acids of trivalent phosphorus and their derivatives, the behaviour of $>P-O^-$ nucleophiles towards arylmethyl bromide systems has been examined.[102] Further evidence for an X-philic substitution/SET tandem mechanism has been obtained.

Stereochemical results for the alkylation of two anions by optically active α-chloro-*p*-nitrophenylethane have been interpreted in terms of competition between $S_{RN}1$ and S_N2 mechanisms.[103] The ambident anion of 2-nitropropane gives *C*-alkylation with complete racemization by $S_{RN}1$ and *O*-alkylation by S_N2. The other anion studied was diethyldithiocarbamate.

The kinetics and mechanism of the reactions of *p*-nitrocumyl bromide with azide ions in DMSO have been studied.[104] In contrast to the reactions of the corresponding chloride in dipolar aprotic solvents, no evidence for an $S_{RN}1$ mechanism was found. A similar situation obtained in a related study of the reactions of nitrite ions with *p*-nitrocumyl bromide.[105]

Medium Effects

It is widely held that protic ('acidic') solvents favour monoalkylation of diethyl malonate carbanion, whereas aprotic ('inert') solvents favour dialkylation. Exactly opposite results have now been obtained in the reactions of the alkali metal salts of diethyl malonate with 1,2-bis-, 1,2,4,5-tetrakis-, and 1,2,3,4,5,6-hexakis-(bromomethyl)benzenes in ethanol and in DMSO, the former solvent preferring dialkylation (cyclization) and the latter monoalkylation.[106] Other interesting related observations were made.

The kinetics of the reaction between bromopropionate and thiosulfate ions have been studied at 10–40 °C in various ethanol–water mixtures.[107] Activation parameters were evaluated as a function of ionic strength and dielectric constant of the medium. The medium effect of mixed solvents on the rate constants of the Menshutkin reaction of triethylamine with ethyl iodide has been studied for binary mixtures of cyclohexane with benzene or ethyl acetate,[108] and with chlorobenzene or dimethoxyethane.[109] Rates were measured over the temperature range 293.1–353.1 K, and activation parameters were determined.

The application of correlation analysis of solvent effects to mechanistic studies of solvolysis has been reviewed by Takeuchi in Japanese.[110] The article mainly covers the behaviour of tertiary chloro compounds. This author's research group has continued experimental studies in this area.[111–113] Rates of solvolysis of 2-chloro-2,4-trimethylpentane have been measured in 17 solvents and analysed through the extended Grunwald–Winstein equation, which includes a term for nucleophilic participation.[111]

The contribution of this term in the correlation is, however, very small, indicating that the neopentyl group in the substrate shields the rear side of the reaction centre very effectively. The application of the Grunwald–Winstein equation in the solvolysis of highly congested, simple secondary and tertiary alkyl systems has also been examined.[112] The solvolyses of 4-chloro-2,2,4,6,6-pentamethylheptane and 3,3-dimethyl-1-neopentyl-butyl mesylate show upward dispersion of points for fluorinated solvents in Grunwald–Winstein plots using the Y_{OTs} or Y_{Cl} scales. It is suggested that this indicates stronger Brønsted base-type solvation (solvation by hydrogen bonding) towards the cationic moiety of the standard adamantane systems than in the highly congested substrates mentioned above. Structural effects in Grunwald–Winstein correlations (both original and extended types) have been examined for the solvolysis of five tertiary alkyl chlorides.[113]

Solvent effects have been studied for the solvolyses of 1-(4-methoxyphenyl)-1-phenyl-2,2,2-trifluoroethyl chloride and 1-(4-methoxyphenyl)-1-phenylethyl chloride in a wide range of binary solvent systems, in order to elucidate the influence of an electron-withdrawing α-substituent.[114] The former substrate failed to give a single linear correlation by using the ordinary Y or Y_{Cl} scale, but better behaviour was found in correlation with Y_{BnCl} and in extended dual-parameter treatment. These results suggest that the incipient cationic charge in the solvolysis of the trifluoro-substituted substrate is delocalized strongly into the aryl rings in the transition state. Rate constants for solvolysis of cyclopentyl *para*-substituted benzenesulfonates in aqueous binary mixtures with acetone, ethanol, or methanol have been reported.[115] The results have been interpreted by applying the original and the extended Grunwald–Winstein relationship, the Hammett equation, potential energy surface model, and quantum mechanical model. The Grunwald–Winstein plots involving Y_{OTs} show dispersion, but the extended treatment gives good correlations. Various inferences are drawn regarding transition-state structures.

The aromatic ring parameter I, proposed by Kevill, has been applied by him to solvolyses of β-arylalkyl toluene-*p*-sulfonates.[116] These reactions proceed with anchimeric assistance (k_Δ pathway) and are very well correlated by a Grunwald–Winstein treatment involving Y_{OTs} and I. Alternative treatments, and their interrelationship, are discussed. Liu continues to contest the necessity for introducing an aromatic ring parameter I.[117,118] His research group has studied the solvolysis of *t*-butyl(2-naphthyl)methyl bromide in a range of solvents and a (new) Y_{xBnBr} scale was based on these results[117] (xBnBr signifies benzylic bromides with extended charge delocalization). The utility of the new scale was demonstrated by applying it to the solvolytic reactivities of benzhydryl bromide and 4-nitrobenzhydryl bromide. Rates of solvolysis of 9-fluorenyl bromide and tosylate have been measured.[118] In the case of the bromide, significant nucleophilic solvent intervention was detected. The much lower reactivity of 9-fluorenyl bromide than benzhydryl bromide (factor 10^4) is said to be due to the larger amount of energy needed in the ionization step of the former and not to its antiaromaticity.

Rate constants for the alkaline hydrolysis of methyl iodide have been measured in dilute aqueous solutions of *t*-BuOH and 1,4-dioxane, containing 0–10 mol% of organic solvent, the temperature range being 283–323 K.[119] The kinetics were discussed in

relation to solvent structure and it was shown that the destabilization of HO^- was the major kinetic factor. The S_N2 reaction of CH_3Cl with Cl^- in supercritical water has been treated in an *ab initio* study involving the polarizable continuum model (PCM).[120] Literature data concerning the solvent effect on the alkylation kinetics of amines with *N*-[(methylthio)chloromethylene]arenesulfonamides have been interpreted with a multiparameter LFER of the Koppel–Palm type.[121]

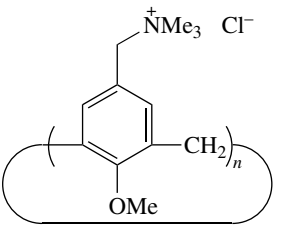
A long series on the kinetics and mechanism of the unimolecular heterolysis of commercial haloorganic compounds has continued in a study of the effect of bromide salts and lithium perchlorate on the ionization rate of benzhydryl bromide in γ-butyrolactone and acetone.[122] The verdazyl indicator method was applied. The nature of special and normal salt effects has also been discussed.[123]

Phase-transfer Catalysis and Other Intermolecular Effects

The effects of small amounts of anionic α-amino acids and several small peptides on the kinetics of S_N1 hydrolysis of 2-(4-nitrophenoxy)tetrahydropyran have been investigated at pH of 11 and 40 °C.[124] The retarding effect of 1 molal co-solute was plotted as $\ln(k_{m=1}/k_{m=0})$ versus the number of CH groups in the amino acid side-chain. Various linear correlations were observed and the results were interpreted in terms of the hydrophobicity of CH. The effects of alcohols as co-solute were also studied.

The kinetics of alkylation by benzyl bromide of the Schiff base esters of amino acids ($Ph_2C{=}NCH_2CO_2CMe_3$) in the presence of cinchona salts show features similar to those of enzyme-promoted reactions: variable orders, substrate saturation, catalyst inhibition, and non-linear Arrhenius-type plots.[125] A tight coordination of the Schiff base substrate by electrostatic interaction with the quaternary N of the cinchona salt provides a favourable chiral environment for asymmetric alkylation.

Water-soluble calix[*n*]arenes (**62**; $n = 4$, 6, and 8) containing trimethylammoniomethyl groups act as efficient inverse phase-transfer catalysts in the nucleophilic substitution reactions of alkyl and arylalkyl halides with nucleophiles in water.[126] (Inverse phase-transfer catalysts facilitate reactions between two immiscible reactants via the transport of an organic substrate into an aqueous solution of a second substrate, in which reactions take place.)



(**62**)
n = 4, 6, or 8

Structural Effects

The effect of Ba^{2+} or Sr^{2+} on the substitution of the crown ether derivatives 2′, 5′, 8′, 11′, 14′-pentaoxacyclopentadecyl-3,6-dioxoheptyl tosylate or 2,5,8,11,14-pentaoxacyclopentadecylmethyl tosylate with MeO^-, in the form of Me_4NOMe, showed that Ba^{2+} was the better catalyst.[127] The kinetics, formation constant, and the interaction of the lariat with the metal cation are discussed.

The effects of α-$Me_2NC(O)$ and α-$Me_2NC(S)$ on the rate constants for partitioning of α-substituted 1-(4-methoxyphenyl)ethyl carbocations between nucleophilic addition of 50 : 50 (v/v) MeOH–H_2O (k_s, s^{-1}) and deprotonation by this solvent (k_e, s^{-1}) have been examined.[128] These substituents lead to 80-fold and ≥ 30 000-fold decreases, respectively, in k_s, but to much smaller changes in k_e. *Ab initio* calculations suggest that the partitioning is strongly controlled by the relative thermodynamic stabilities of the neutral products of the reactions.

The kinetics of the reactions of six amines with phenacyl bromide in acetonitrile have been studied conductimetrically at several temperatures and activation parameters were calculated.[129] The relative reactivities of the amines were explained in terms of inductive and steric effects. Relative reactivities have been determined conductimetrically for the 2-propanolysis of a series of chlorides and they lie in the order $PhSCl > PhCOCl > PhSO_2Cl > PhCH_2Cl \gg PhCl$, with rate coefficient ratios $9.5 \times 10^4 : 1 : 7.14 \times 10^{-2} : 4.7 \times 10^{-3} : \sim 10^{-26}$.[130] (The value for chlorobenzene was estimated.)

The solvolysis of 1,3-di-*t*-butyl-5-methyl-5-cyclopenta-1,3-dienyl trifluoroacetate shows a strong dependence on solvent ionizing power ($m = 0.97$ in Grunwald–Winstein correlation) and gives products of substitution, allylic and skeletal rearrangement with substitution, and elimination.[131] These results provide the first measurements of the kinetics of formation of a cyclopentadienyl cation, the prototype of a 4π-electron carbocation, destabilized by antiaromaticity. The reactivity of the above substrate in TFE at 25 °C is calculated to be lower than that of analogous fluorenyl and indenyl derivatives by factors of 3×10^4 and 4×10^2, respectively, and is exceeded by that calculated for 1,3-dimethyl-3-cyclopentenyl trifluoroacetate by a factor of 10^{14}, showing the large carbocation destabilizing effects of antiaromaticity.

The reaction of sodium borohydride with benzhydryl halides under solvolytic conditions has been reinvestigated.[132] Contrary to the literature, $NaBH_4$ was not found to be a convenient trap for benzhydryl carbocations.

Correlation Analysis by the Hammett Equation and Other LFERs

In a review article entitled ‘How to get wrong results from good experimental data: a survey of incorrect applications of regression’, Exner offered some trenchant warnings which should be heeded by all those who engage in correlation analysis.[133] Numerous examples are given from the literature, in which experimental data were processed in an incorrect way from the point of view of statistics. The results were more or less biased and sometimes completely wrong.

Systemization and analysis of literature data bearing on the quantitative estimation of inductive interaction of functional groups in organic and organometallic compounds

have been presented in an extensive review.[134] The authors' own work devoted to elaborating a new model of the inductive effect, which permits theoretical calculation of the inductive constants of various substituents at any reaction centre, is generalized. Important theoretical matters, such as the inductive effects of alkyl groups, are also discussed.

The Yukawa–Tsuno equation continues to find considerable application.[135–138] 1-Arylethyl bromides react with pyridine in acetonitrile by unimolecular and bimolecular processes.[135] These processes are distinct; there is no intermediate mechanism. The S_N1 rate constants, k_1, for *meta* or *para*-substituted 1-arylethyl bromides conform well to the Yukawa–Tsuno equation, with $\rho = -5.0$ and $r = 1.15$, but the correlation analysis of the S_N2 rate constants k_2 is more complicated. This is attributed to a change in the balance between bond formation and cleavage in the S_N2 transition state as the substituent is varied. The rate constants of solvolysis in 1 : 1 (v/v) aqueous ethanol of α-*t*-butyl-α-neopentylbenzyl and α-*t*-butyl-α-isopropylbenzyl *p*-nitrobenzoates at 75 °C follow the Yukawa–Tsuno equation well, with $\rho = -3.37$, $r = 0.78$ and $\rho = -3.09$, $r = 0.68$, respectively.[136] The considerable reduction in r from the value of 1.00 in the defining system for the σ^+ scale is ascribed to steric inhibition of coplanarity in the transition state. Rates of solvolysis (80% aqueous ethanol, 25 °C) have been measured for 1-(substituted phenyl)-1-phenyl-2,2,2-trifluoroethyl and 1,1-bis(substituted phenyl)-2,2,2-trifluoroethyl tosylates.[137] The former substrate shows a bilinear Yukawa–Tsuno plot; the latter shows excellent conformity to the Yukawa–Tsuno equation over the whole range of substituents, with $\rho = -8.3/2$ and $r = 1.19$. Substituent effects on solvolysis of 2-aryl-2-(trifluoromethyl)ethyl *m*-nitrobenzenesulfonates in acetic acid or in 80% aqueous TFE have been analyzed by the Yukawa–Tsuno equation to give $\rho = -3.12$, $r = 0.77$ (130 °C) and $\rho = -4.22$, $r = 0.63$ (100 °C), respectively.[138] The r values are considered to indicate an enhanced resonance effect, compared with the standard aryl-assisted solvolysis, and this is attributed to the destabilization of the transition state by the electron-withdrawing CF_3 group.

Nucleophilic substitution reactions of 1-phenylethyl chlorides $YC_6H_4CH(CH_3)Cl$ with phenoxides $XC_6H_4O^-$ and thiophenoxides $XC_6H_4S^-$ have been investigated theoretically by using the PM3 method.[139] The Brønsted α and β values are greater for the phenoxides, indicating more advanced reaction in the transition state than for the thiophenoxides. This is supported by a greater magnitude of ρ_X and ρ_{XY} for the phenoxides than for the thiophenoxides. Other details of the reactions, both in the gas phase and in water, were investigated.

Nucleophilic substitutions of cycloalkylmethyl arenesulfonates $C_nH_{2n-1}CH_2OSO_2C_6H_4Z$ with anilines $XC_6H_4NH_2$ in methanol at 65 °C have been studied.[140] The reactivity order (given Z and X) $n = 4>6>7>5$ largely reflects the influence on steric effects of ring size, but the behaviour for $n = 5$ is anomalous. Application of the Taft equation in a form involving both polar and steric terms suggests that the retardation for $n = 5$ may be due to an enhanced polar ($\rho^*\sigma^*$) term.

Nucleophilicity and Leaving-group Effects

Second-order rate constants for the reactions of phenacyl bromide with a number of anionic or neutral nucleophiles in 3 : 2 (v/v) acetone–water have been measured at several temperatures.[141] Correlation analysis with the Brønsted equation or Swain–Scott equation is not satisfactory. Better results were obtained with the two-parameter Edwards equation.

Solvolysis of the *R*,*R* and *R*,*S* isomers of 2-bromo-9-(1-X-ethyl)fluorenes, X = Cl, Br, I, or OBs, in 25% (v/v) acetonitrile in water has been studied with respect to rates of formation of elimination products and of substitution products (X = OH or NHCOMe).[142] The parent 9-(1-X-ethyl)fluorenes and the 2,2′-dibromo-9-(1-X-ethyl)-fluorenes were also studied. Various effects of leaving group and of the presence of nucleophiles on the competition between the reactions were observed and the Brønsted equation was applied to the results for the elimination reactions. A related study of solvolysis of 9-(X-methyl)fluorenes, X = I, Br, or Bs, was also carried out, in which the Swain–Scott equation was applied to nucleophilic selectivities in the S_N2 reactions.[143]

Correlation of nucleophilic rate data for phenyldimethylsulfonium ions with common nucleophiles, with pK_{lg}^{Me} values shows that the slopes of the lines, β_{lg}^{Me}, correlate qualitatively with the Edwards hardness parameter for the nucleophile and not with the Swain–Scott *n* parameter.[144] *cis*,*cis*-2,4,6-Trimethyl-1,3,5-triaminocyclohexane is weakly basic in aqueous solution, because of steric inhibition to solvation of the conjugate acid.[145] The three NH_2 groups are axial and the steric effect also results in reduced reactivity as a nucleophile in S_N2 reactions. Highly stereoselective syntheses of *β*-*C*-, *N*-, and *O*-glycosides have been carried out by addition of anionic nucleophiles to glycosyl iodides.[146] S_N2 reactions are involved, but some substrates are susceptible to *E*2 elimination when treated with highly basic anions.

Enthalpies of reaction for nucleophilic substitution of ethyl iodide by a series of 27 nucleophiles in acetonitrile have been determined.[147] Various empirical correlations were developed. Partial desolvation accompanying activation has been identified as the major contributor to activation thermodynamic parameters, while the 'propensity' of the reacting central atom in the nucleophilic anion plays a crucial role in determining reaction thermodynamic parameters.

The decomposition of aliphatic *N*-nitroamines in aqueous sulfuric acid involves an acid-catalysed S_N2 displacement from the protonated *aci*-nitro tautomer, the nucleophile being a water molecule at acidities below 82–85% H_2SO_4 and a bisulfate ion at higher acidities.[148] Bisulfate is the poorer nucleophile by a factor of about 1000. For a series of substrates, $RNHNO_2$, correlation analysis of the rate constants through Taft's σ^* is effective, the ρ^* values being negative, with a more negative value for the bisulfate reaction.

An unusually large kinetic Br/Cl leaving-group effect has been observed for solvolysis of 1-halospiro(adamantane-2,2′-adamantane) in slightly ethanolic or aqueous acetone.[149] This is consistent with the occurrence of F-strain.

In a series of studies of the reactions of charged substrates, the nucleophilic substitution reactions of (4-methoxybenzyl)dimethylsulfonium chloride have been

examined.[150] Such reactions occur only for nucleophiles of intermediate hardness and display a range of mechanisms, as revealed by kinetic and product studies. Pyridine-d_5 reacts by a mixed S_N1/S_N2 mechanism. In non-ionic superbase-catalysed silylation of alcohols, there is an augmented nucleophilicity of P in the catalyst $P(MeNCH_2CH_2)_3N$.[151]

Miscellaneous Studies (Mainly Kinetic)

The excess acidity method has been applied to the acid-catalysed hydrolysis of isopropyl phenyl ether at different temperatures.[152]

Rate constants and products of the nucleophilic substitution and elimination reactions of 1-(4-methoxyphenyl)-3-methyl-3-butyl derivatives 4-$MeOC_6H_4CH_2CMe_2X$ (X = Cl, OH, $O_2CC_6F_5$) have been determined in 'mostly aqueous' solvents.[153] The absolute rate constant for reaction of the corresponding tertiary carbocation in 50 : 50 (v/v) TFE–water was estimated as 3.5×10^{12} s^{-1}.

The kinetics of the hydrolysis of *N*-(2,4-dinitrophenyl)benzhydrazonyl bromide and its derivatives have been studied over a wide range of pH.[154] Roles for both S_N1 and S_N2 mechanisms were inferred.

The kinetics of the basic hydrolysis of 2-chloroethanol have been studied by using a chloride ion-selective electrode.[155] The reaction attains equilibrium at about 92% conversion.

Product studies of the stereoselective cycloaddition and epoxidation of enol ethers by α-peroxylactone were interpreted in terms of S_N2 processes.[156] Steric and stereoelectronic effects are important.

New experimental data on the hydrolysis of dilute solutions of carbon tetrachloride indicate clearly that the reaction is first order in CCl_4.[157] This is contrary to the classical work of Fells and Moelwyn-Hughes, whose data have been reanalysed and shown to be consistent with first-order kinetics. The same research group has carried out extensive work on the kinetics of hydrolysis (neutral or alkaline) of many halogenated hydrocarbons in relation to studies in environmental and toxicological chemistry.[158]

Kinetics of the transformations of the N–F class of fluorinating agents in water, acetonitrile, alcohols, and aqueous solutions of alkali metal hydroxides have been studied.[159] Other kinetic studies include the reactions of triphenylphosphine with 3-methoxy- or 3-acetoxy-4,4,5,5-tetrasubstituted-1,2-dioxolanes,[160] the reactions of 2-amino-5-chlorobenzophenone with HCl in MeOH–H_2O (the aspect of nucleophilic aliphatic substitution lies in certain products arising from attack of NH_2 on CH_3OH; there are six products in all, and rate constants are evaluated for the formation of each of them),[161] and the hydrolysis of derivatives of diazidophenylmethane.[162]

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References

[1] Schottland, E. Z. and Rappoport, Z., *J. Org. Chem.*, **61**, 8536 (1996).
[2] Yannai, M. B. and Rappoport, Z., *J. Org. Chem.*, **62**, 5634 (1997).
[3] Okuyama, T. and Ochiai, M., *J. Am. Chem. Soc.*, **119**, 4785 (1997).
[4] Okuyama, T., Takino, T., Sato, K., and Ochiai, M., *Chem. Lett.*, **1997**, 955.
[5] Artamkina, G. A., Shtern, M. M., Sazonov, P. K., and Beletskaya, I. P., *Zh. Org. Khim.*, **32**, 1329 (1996); *Chem. Abs.*, **126**, 305330 (1997).
[6] Polezhaeva, N. A., Loginova, I. V., Galkin, V. I., Ovechkina, E. V., Sakhibullina, V. G., and Cherkasov, R. A., *Zh. Obshch. Khim.*, **66**, 798 (1996); *Chem. Abs.*, **125**, 328923 (1997).
[7] Chapyshev, S. V. and Ibata, T., *Izv. Akad. Nauk, Ser. Khim.*, **1996**, 2702; *Chem. Abs.*, **126**, 131345 (1997).
[8] Tang, T. H. and Fu, X.-Y., *THEOCHEM*, **392**, 153 (1997); *Chem. Abs.*, **127**, 81034 (1997).
[9] Yamazaki, T., Umetani, H., and Kitazume, T., *Tetrahedron Lett.*, **38**, 6705 (1997).
[10] Hiraoka, S., Yamazaki, T., and Kitazume, T., *J. Chem. Soc., Chem. Commun.*, **1997**, 1497.
[11] Marino, J. P., Viso, A., Lee, J.-D., de la Pradilla, R. F., Fernández, P., and Rubio, M. B., *J. Org. Chem.*, **62**, 645 (1997).
[12] Dulcère, J.-P. and Dumez, E., *J. Chem. Soc., Chem. Commun.*, **1997**, 971.
[13] Woo, S., Parvez, M., and Keay, B. A., *Can. J. Chem.*, **75**, 665 (1997).
[14] Chepel, L. M., Vladimirov, L. V., and Zelenetskii, A. N., *Khim. Fiz.*, **15**, 48 (1996); *Chem. Abs.*, **126**, 211714 (1997).
[15] Lee, K.-R., Ra Y. H., Jung, I.-C., and Huh, T. S., *J. Korean Chem. Soc.*, **41**, 351 (1997); *Chem. Abs.*, **127**, 277851 (1997).
[16] Schreiner, P. R., Schleyer, P. von R., and Schaefer, H. F., *J. Org. Chem.*, **62**, 4216 (1997).
[17] Lajunen, M., Himottu, M., and Tanskanen-Lehti, K., *Acta Chem. Scand.*, **51**, 515 (1997).
[18] Lukach, A. E., Santiago, A. N., and Rossi, R., *J. Org. Chem.*, **62**, 4260 (1997).
[19] Santiago, A. N., Stahl, A. E., Rodriguez, G. L., and Rossi, R. A., *J. Org. Chem.*, **62**, 4406 (1997).
[20] Huang, X. and Bennet, A. J., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1027.
[21] Wu, H.-J. and Chern, J.-H., *J. Org. Chem.*, **62**, 3208 (1997).
[22] Yamazaki, N. and Kibayashi, C., *Tetrahedron Lett.*, **38**, 4623 (1997).
[23] Lee, W. S. and Nagao, Y., *Tetrahedron Lett.*, **38**, 3267 (1997).
[24] Akhavan-Tafti, H., Eickholt, R. A., Arghavani, Z., and Schaap, A. P., *J. Am. Chem. Soc.*, **119**, 245 (1997).
[25] Elkhatib, M., Marchand, A., Peyrot, L., Counioux, J. J., and Delalu, H., *Int. J. Chem. Kinet.*, **29**, 89 (1997).
[26] Adam, W. and Smerz, A. K., *Bull. Soc. Chim. Belg.*, **105**, 581 (1996).
[27] Kotsuki, H., *Kagaku Kogyo*, **47**, 845 (1996); *Chem. Abs.*, **125**, 274941 (1996).
[28] Li, L., Tang, Z., and Sun, Z., *Yuanzi Yu Fenzi Wuli Xuebao*, **13**, 348 (1996); *Chem. Abs.*, **126**, 343192 (1997).
[29] Bukowska, A. and Bukowski, W., *J. Chem. Technol. Biotechnol.*, **67**, 176 (1996); *Chem. Abs.*, **125**, 327834 (1997).
[30] Chlebicki, J., Shiman, L. Yu., Guskov, A. K., Makarov, M. G., and Shvets, V. F., *Int. J. Chem. Kinet.*, **29**, 73 (1997).
[31] Crotti, P., Di Bussolo, V., Favero, L., Pineschi, M., Sergiamepietri, D., Renzi, G., Ricciutelli, M., and Rozelli, G., *Tetrahedron*, **53**, 5515 (1997).
[32] Tanabe, Y., Mori, K., and Yoshida, Y., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 671.
[33] Badali, F., Karalis, A., Tham, W. Y., and White, J. M., *Aust. J. Chem.*, **49**, 1293 (1996).
[34] Banwell, M. G., Haddad, N., Hudlicky, T., Nugent, T. C., Mackay, M. F., and Richards, S. L., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1779.
[35] Agami, C., Couty, F., Hamon, L., and Venier, O., *J. Org. Chem.*, **62**, 2106 (1997).
[36] De, A., Ghosh, S., and Iqbal, J., *Tetrahedron Lett.*, **38**, 8379 (1997).
[37] Tanino, K., Yoshitani, N., Moriyama, F., and Kuwajima, I., *J. Org. Chem.*, **62**, 4206 (1997).
[38] Liu, Q., Marchington, A. P., Boden, N., and Rayner, C. M., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 511.
[39] Timoshenko, D. O. and Kravtsov, O. V., *Dopov. Nats. Akad. Nauk Ukr.*, **1996**, 121; *Chem. Abs.*, **126**, 224887 (1997).
[40] Dinnocenzo, J. P., Simpson, T. R., Zuilhof, H., Todd, W. P., and Heinrich, T., *J. Am. Chem. Soc.*, **119**, 987 (1997).
[41] Dinnocenzo, J. P., Zuilhof, H., Lieberman, D. R., Simpson, T. R., and McKechney, M. W., *J. Am. Chem. Soc.*, **119**, 994 (1997).
[42] Kostikov, R. R., Varakin, G. S., Molchanov, A. P., and Oglobin, K. A., *Zh. Org. Khim.*, **32**, 39 (1996); *Chem. Abs.*, **125**, 300480 (1996).

[43] Hori, K., Nishiguchi, T., and Nabeya, A., *J. Org. Chem.*, **62**, 3081 (1997).
[44] Le Roux, C., Modro, A. M., and Modro, T. A., *J. Chem. Res. (S)*, **1997**, 100.
[45] Gajda, T., Napieraj, A., Osowska-Pacewicka, K., Zawadzki, S., and Zwierzak, A., *Tetrahedron*, **53**, 4935 (1997).
[46] Maligres, P. E., See, M. M., Askin, D., and Reider, P. J., *Tetrahedron Lett.*, **38**, 5253 (1997).
[47] Bergmeier, S. C. and Seth, P. P., *J. Org. Chem.*, **62**, 2671 (1997).
[48] Mithani, S., Drew, D. M., Rydberg, E. H., Taylor, N. J., Mooibroek, S., and Dmitrienko, G. I., *J. Am. Chem. Soc.*, **119**, 1159 (1997).
[49] Hylands, K. A. and Moodie, R. B., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 709.
[50] L'abbé, G., Dyall, L. K., Meersman, K., and Dehaen, W., *J. Chem. Res. (S)*, **1997**, 226; (*M*), **1997**, 1631.
[51] Fleischer, R., Galle, D., and Braun, M., *Liebigs Ann./Recl.*, **1997**, 1189.
[52] Jones, D. W. and Ryder, T. C. L. M., *J. Chem. Soc., Chem. Commun.*, **1997**, 1169.
[53] Uchimaru, T., Stec, W. J., Tsuzuki, S., Hirose, T., Tanabe, K., and Taira, K., *Chem. Phys. Lett.*, **263**, 691 (1996); *Chem. Abs.*, **126**, 74918 (1997).
[54] Kojima, S., Nakamoto, M., Yamazaki, K., and Akiba, K., *Tetrahedron Lett.*, **38**, 4107 (1997).
[55] Kimura, T., Nakayama, H., Obinata, T., and Furukawa, N., *Chem. Lett.*, **1997**, 301.
[56] Arcelli, A., Papa, M., Porzi, G., and Sandri, S., *Tetrahedron*, **53**, 10513 (1997).
[57] Kresge, A. J. and Popik, V. V., *Electron. Conf. Heterocycl. Chem., [Proc.]*, [computer optical disk] 1996 (Pub. 1997); *Chem. Abs.*, **127**, 205213 (1997).
[58] Harada, T., Otani, T., and Oku, A., *Tetrahedron Lett.*, **38**, 2855 (1997).
[59] Parrill, A. L. and Dolata, D. P., *THEOCHEM*, **370**, 187 (1996); *Chem. Abs.*, **26**, 211695 (1997).
[60] Ceulemans, E., Vercauteren, K., Dyall, L. K., Buelens, D., and Dehaen, W., *Tetrahedron*, **53**, 9657 (1997).
[61] Sunko, D. E., *Croat. Chem. Acta*, **69**, 1275 (1996); *Chem. Abs.*, **26**, 185638 (1997).
[62] Roberts, D. D., *J. Org. Chem.*, **62**, 1857 (1997).
[63] Fountain, K. R., White, R. D., Patel, K. D., New, D. G., Xu, Y. B., and Cassely, A. J., *J. Org. Chem.*, **61**, 9434 (1996).
[64] Fountain, K. R., Dunkin, T. W., and Patel, K. D., *J. Org. Chem.*, **62**, 2738 (1997).
[65] Fountain, K. R. and Patel, K. D., *J. Org. Chem.*, **62**, 4795 (1997).
[66] Kim, K. S., Cho, S. J., Oh, K. S., Son, J. S., Kim, J., Lee, J. Y., Lee, S. J., Lee, S., Chang, Y.-T., Chung, S.-K., Ha, T.-K., Lee, B.-S., and Lee, I., *J. Phys. Chem. A*, **101**, 3776 (1997).
[67] Pham, T. V. and Westaway, K. C., *Can. J. Chem.*, **74**, 2528 (1996).
[68] Westaway, K. C., Pham, T. V., and Fang, Y., *J. Am. Chem. Soc.*, **119**, 3670 (1997).
[69] Glad, S. S. and Jensen, F., *J. Am. Chem. Soc.*, **119**, 227 (1997).
[70] Okuno, Y., *Chem. Phys. Lett.*, **264**, 120 (1997); *Chem. Abs.*, **126**, 117632 (1997).
[71] DeTuri, V. F., Hintz, P. A., and Ervin, K. M., *J. Phys. Chem. A*, **101**, 5969 (1997).
[72] Sahlstrom, K. E., Knighton, W. B., and Grimsrud, E. P., *J. Phys. Chem. A*, **101**, 5543 (1997).
[73] Sahlstrom, K. E., Knighton, W. B., and Grimsrud, E. P., *J. Phys. Chem. A*, **101**, 1501 (1997).
[74] Craig, S. L. and Brauman, J. I., *Ber. Bunsenges. Phys. Chem.*, **101**, 510 (1997); *Chem. Abs.*, **126**, 343217 (1997).
[75] Craig, S. L. and Brauman, J. I., *Science (Washington, D.C.)*, **276** (5318), 1536 (1997); *Chem. Abs.*, **127**, 81039 (1997).
[76] Seeley, J. V., Morris, R. A., Viggiano, A. A., Wang, H., and Hase, W. L., *J. Am. Chem. Soc.*, **119**, 577 (1997).
[77] Seeley, J. V., Morris, R. A., and Viggiano, A. A., *J. Phys. Chem. A*, **101**, 4598 (1997).
[78] Wang, H., Goldfield, E. M., and Hase, W. L., *J. Chem. Soc., Faraday Trans.*, **93**, 737 (1997).
[79] Wang, H. and Hase, W. L., *Chem. Phys.*, **212**, 247 (1996); *Chem. Abs.*, **126**, 30966 (1997).
[80] Wang, H. and Hase, W. L., *J. Am. Chem. Soc.*, **119**, 3093 (1997).
[81] Svensson, M., Humbel, S., and Morokuma, K., *J. Chem. Phys.*, **105**, 3654 (1996); *Chem. Abs.*, **125**, 300231 (1996).
[82] Glukhovtsev, M. N., Bach, R. D., Pross, A., and Radom, L., *Chem. Phys. Lett.*, **260**, 558 (1996); *Chem. Abs.*, **125**, 327759 (1997).
[83] Glukhovtsev, M. N., Pross, A., Schlegel, H. B., Bach, R. D., and Radom, L., *J. Am. Chem. Soc.*, **118**, 11258 (1996).
[84] Botschwina, P., Horn, M., Seeger, S., and Oswald, R., *Ber. Bunsenges. Phys. Chem.*, **101**, 387 (1997); *Chem. Abs.*, **126**, 343187 (1997).
[85] Clary, D. C. and Palma, J., *J. Chem. Phys.*, **106**, 575 (1997); *Chem. Abs.*, **126**, 131087 (1997).
[86] Le Garrec, J.-L., Rowe, B. R., Queffelec, J. L., Mitchell, J. B. A., and Clary, D. C., *J. Chem. Phys.*, **107**, 1021 (1997); *Chem. Abs.*, **127**, 161374 (1997).
[87] Streitwieser, A., Choy, G. S.-C., and Abu-Hasanayn, F., *J. Am. Chem. Soc.*, **119**, 5013 (1997).

[88] Lee, J. K., Kim, C. K., Lee, B.-S., and Lee, I., *J. Phys. Chem. A*, **101**, 2893 (1997).
[89] Saigusa, H., *Kagaku (Kyoto)*, **52**, 67 (1997); *Chem. Abs.*, **127**, 220283 (1997).
[90] Maran, U., Karelson, M., and Pakkanen, T. A., *THEOCHEM*, **397**, 263 (1997); *Chem. Abs.*, **127**, 148809 (1997).
[91] Fradera, X., Amat, L., Torrent, M., Mestres, J., Constans, P., Besalu, E., Marti, J., Simon, S., Lobato, M., Oliva, J. M., Luis, J. M., Andres, J. L., Sola, M., Carbo, R., and Duran, M., *THEOCHEM*, **371**, 171 (1996); *Chem. Abs.*, **126**, 185677 (1997).
[92] Maulitz, A. H., Lightstone, F. C., Zheng, Y.-J., and Bruice, T. C., *Proc. Natl. Acad. Sci. USA*, **94**, 6591 (1997); *Chem. Abs.*, **127**, 121387 (1997).
[93] Donovan, W. H. and White, W. E., *THEOCHEM*, **370**, 209 (1996); *Chem. Abs.*, **126**, 199168 (1997).
[94] Re, M. and Laria, D., *J. Chem. Phys.*, **105**, 4584 (1996); *Chem. Abs.*, **125**, 274968 (1996).
[95] Gong, X., Ling, Y., and Xiao, H., *J. Energ. Mater.*, **15**, 35 (1997); *Chem. Abs.*, **126**, 185654 (1997).
[96] Okuno, Y., *J. Chem. Phys.*, **105**, 5817 (1996); *Chem. Abs.*, **125**, 274979 (1996).
[97] Zheng, Y.-J. and Bruice, T. C., *J. Am. Chem. Soc.*, **119**, 8137 (1997).
[98] Welder, C. O. and Ashby, E. C., *J. Org. Chem.*, **62**, 4829 (1997).
[99] Marcus, R. A., *J. Phys. Chem. A*, **101**, 4072 (1997).
[100] Tolbert, L. M., Bedlek, J., Terapane, M., and Kowalik, J., *J. Am. Chem. Soc.*, **119**, 2291 (1997).
[101] Herbertz, T. and Roth, H. D., *J. Am. Chem. Soc.*, **118**, 10954 (1996).
[102] Witt, D. and Rachon, J., *Phosphorus Sulfur Silicon Relat. Elem.*, **117**, 149 (1996); *Chem. Abs.*, **127**, 81503 (1997).
[103] El Badraoui, K., Chanon, M., Merlet, D., Chajara, K., and Courtieu, J., *Tetrahedron Lett.*, **38**, 831 (1997).
[104] Paine, S. W. and Ridd, J. H., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2571.
[105] Paine, S. W. and Ridd, J. H., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2577.
[106] Holý, P., Havránek, M., Pánková, M., Ridvan, L., and Závada, J., *Tetrahedron*, **53**, 8195 (1997).
[107] Khalid, Z., Uddin, F., and Kausar, T., *J. Nat. Sci. Math.*, **36**, 69 (1996); *Chem. Abs.*, **125**, 300283 (1996).
[108] Nevecna, T., Vyhlidalova, J., and Bekarek, V., *Acta Univ. Palacki. Olomuc., Fac. Rerum Nat., Chem.*, **34**, 21 (1995); *Chem. Abs.*, **127**, 108627 (1997).
[109] Nevecna, T., Lukesova, M., and Bekarek, V., *Acta Univ. Palacki. Olomuc., Fac. Rerum Nat., Chem.*, **34**, 23 (1995); *Chem. Abs.*, **127**, 108628 (1997).
[110] Takeuchi, K., *Yuki Gosei Kagaku Kenkyusho Koenshu*, **11**, 30 (1997); *Chem. Abs.*, **126**, 292911 (1997).
[111] Takeuchi, K., Ohga, Y., Ushino, T., and Takasuka, M., *J. Phys. Org. Chem.*, **9**, 777 (1996).
[112] Takeuchi, K., Ohga, Y., Ushino, T., and Takasuka, M., *J. Org. Chem.*, **62**, 4904 (1997).
[113] Takeuchi, K., Ohga, Y., Ushino, T., and Takasuka, M., *J. Phys. Org. Chem.*, **10**, 717 (1997).
[114] Kweon, J.-M., Kim, S.-H., and Yoh, S.-D., *Bull. Korean Chem. Soc.*, **17**, 1056 (1996); *Chem. Abs.*, **126**, 103737 (1997).
[115] Koo, I. S., Yang, K., Kang, K., Park, J. K., Oh, H. K., and Lee, I., *Bull. Korean Chem. Soc.*, **18**, 179 (1997); *Chem. Abs.*, **126**, 317095 (1997).
[116] Kevill, D. N. and D'Souza, M. J., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 257.
[117] Liu, K.-T., Chin, C.-P., Lin, Y.-S., and Tsao, M.-L., *J. Chem. Res. (S)*, **1997**, 18.
[118] Liu, K.-T. and Lin, Y.-S., *Tetrahedron Lett.*, **38**, 1419 (1997).
[119] Panov, M. Yu., Sokolova, O. B., and Eremenko, I. E., *Zh. Obshch. Khim.*, **66**, 1156 (1996); *Chem. Abs.*, **126**, 18483 (1997).
[120] Pomelli, C. S. and Tomasi, J., *J. Phys. Chem. A*, **101**, 3561 (1997).
[121] Makitra, R. G., Vasyutyn, Ya. M., and Pirigin, Ya. N., *Zh. Org. Khim.*, **32**, 861 (1996); *Chem. Abs.*, **126**, 211713 (1996).
[122] Dvorko, G. F., Golovko, N. N., and Ponomareva, E. A., *Zh. Obshch. Khim.*, **66**, 1506 (1996); *Chem. Abs.*, **126**, 171168 (1997).
[123] Dvorko, G. F., *Dopov. Nats. Akad. Nauk Ukr.*, **1996**, 109; *Chem. Abs.*, **126**, 199173 (1997).
[124] Streefland, L., Blandamer, M. J., and Engberts, J. B. F. N., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 769.
[125] Esikova, I. A., Nahreini, T. S., and O'Donnell, M. J., *ACS Symp. Ser.*, **1997**, 659 (Phase-Transfer Catalysis), 89; *Chem. Abs.*, **127**, 65345 (1997).
[126] Shimizu, S., Kito, K., Sasaki, Y., and Hirai, C., *J. Chem. Soc., Chem. Commun.*, **1997**, 1629.
[127] Casadio, C., Doddi, G., and Mencarelli, P., *Electron. Conf. Heterocycl. Chem., [Proc.]*, [computer optical disk] 1996 (Pub. 1997); *Chem. Abs.*, **127**, 205204 (1997).
[128] Richard, J. P., Lin, S.-S., Buccigross, J. M., and Amyes, T. L., *J. Am. Chem. Soc.*, **118**, 12603 (1996).
[129] Awwal, A., Miah, A. S., Kabir, M., and Al-Mamun, M. R., *J. Bangladesh Acad. Sci.*, **20**, 137 (1996); *Chem. Abs.*, **126**, 157065 (1997).
[130] Hirata, A., Kiyan, N. Z., and Miller, J., *Quim. Nova*, **20**, 238 (1997); *Chem. Abs.*, **127**, 65344 (1997).
[131] Allen, A. D., Sumonja, M., and Tidwell, T. T., *J. Am. Chem. Soc.*, **119**, 2371 (1997).

[132] Liu, K.-T. and Huang, H.-C., *J. Chin. Chem. Soc. (Taipei)*, **44**, 249 (1997); *Chem. Abs.*, **127**, 205203 (1997).
[133] Exner, O., *J. Phys. Org. Chem.*, **10**, 797 (1997).
[134] Cherkosov, A., Galkin, V. I., and Cherkasov, R. A., *Usp. Khim.*, **65**, 695 (1996); *Russ. Chem. Rev.*, **65**, 641 (1996); *Chem. Abs.*, **126**, 185636 (1997).
[135] Lim, C., Kim, S.-H., Yoh, S.-D., Fujio, M., and Tsuno, Y., *Tetrahedron Lett.*, **38**, 3243 (1997).
[136] Fujio, M., Ohe, M., Nakata, K., Tsuji, Y., Mishima, M., and Tsuno, Y., *Bull. Chem. Soc. Jpn*, **70**, 929 (1997).
[137] Fujio, M., Morimoto, H., Kim, H.-J., and Tsuno, Y., *Bull. Chem. Soc. Jpn*, **70**, 1403 (1997).
[138] Okamura, M., Hazama, K., Ohta, M., Kato, K., Horaguchi, T., and Ohno, A., *Chem. Lett.*, **1997**, 973.
[139] Kim, W. K., Ryu, W. S., Park, H. Y., Han, I.-S., Kim, C. K., and Lee, I., *Bull. Korean Chem. Soc.*, **18**, 868 (1997); *Chem. Abs.*, **127**, 277858 (1997).
[140] Oh, H. K., Song, S. J., Jo, D.-S., and Lee, I., *J. Phys. Org. Chem.*, **10**, 91 (1997).
[141] Winston, S. J. and Rao, P. J., *Indian J. Chem.*, **35A**, 979 (1996); *Chem. Abs.*, **125**, 275040 (1996).
[142] Meng, Q., Gogoll, A., and Thibblin, A., *J. Am. Chem. Soc.*, **119**, 1217 (1997).
[143] Meng, Q. and Thibblin, A., *J. Am. Chem. Soc.*, **119**, 4834 (1997).
[144] Fountain, K. R., Dunkin, T. W., and Patel, K. D., *J. Org. Chem.*, **62**, 3711 (1997).
[145] Parker, D., Senanayake, D., Vepsailainen, J., Williams, S., Batsanov, A. S., and Howard, J. A. K., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1445.
[146] Gervay, J. and Hadd, M. J., *J. Org. Chem.*, **62**, 6961 (1997).
[147] Kondo, Y., Tsukamoto, T., and Kimura, N., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1765.
[148] Cox, R. A., *Can. J. Chem.*, **74**, 1774 (1996).
[149] Kevill, D. N., D'Souza, M. J., and Lomas, J. S., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 131.
[150] Buckley, N. and Oppenheimer, N. J., *J. Org. Chem.*, **62**, 540 (1997).
[151] D'Sa, B. A., McLeod, D., and Verkade, J. G., *J. Org. Chem.*, **62**, 5057 (1997).
[152] Lajunen, M. and Setälä, J., *Acta Chem. Scand.*, **51**, 334 (1997).
[153] Toteva, M. M. and Richard, J. P., *J. Am. Chem. Soc.*, **118**, 11434 (1996).
[154] Park, C.-I., Cha, K.-W., Lee, I., and Chang, B.-D., *J. Korean Chem. Soc.*, **41**, 198 (1997); *Chem. Abs.*, **127**, 81024 (1997).
[155] Ziao, N., Trokourey, A., and Kotchi, K. P., *J. Soc., Ouest-Afr. Chim.*, **1**, 63 (1996); *Chem. Abs.*, **127**, 277861 (1996).
[156] Adam, W. and Blancafort, L., *J. Org. Chem.*, **61**, 8432 (1996).
[157] Jeffers, P. M., Brenner, C., and Wolfe, N. L., *Environ. Toxicol. Chem.*, **15**, 1064 (1996); *Chem. Abs.*, **125**, 246978 (1996).
[158] Jeffers, P. M. and Wolfe, N. L., *Environ. Toxicol. Chem.*, **15**, 1066 (1996); *Chem. Abs.*, **125**, 246979 (1996).
[159] Zupan, M., Papez, M., and Stavber, S., *J. Fluorine Chem.*, **78**, 137 (1996); *Chem. Abs.*, **125**, 247059 (1996).
[160] Baumstark, A. L., Vasquez, P. C., and Chen, Y.-X., *Heterocycl. Commun.*, **2**, 35 (1996); *Chem. Abs.*, **125**, 246995 (1996).
[161] Nudelman, N. S. and De Waisbaum, R. G., *J. Phys. Org. Chem.*, **10**, 97 (1997).
[162] Kwon, K.-S., Seo, J.-H., and Lee, Y.-G., *J. Korean Chem. Soc.*, **41**, 313 (1997); *Chem. Abs.*, **127**, 161371 (1997).

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CHAPTER 11

Carbanions and Electrophilic Aliphatic Substitution

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Carbanion Structure and Stability

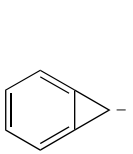
The ion $(C_2CHC_2)^-$ has been formed in the gas phase, by the process $^-C{\equiv}C{-}CH(OCOR){-}C{\equiv}CD \rightarrow (C_2CHC_2)^- + (\text{'}RDCO_2\text{'})$ (R = H, Me or Et); *ab initio* calculations have established that the ground-state triplet is much less stable than the singlet which approximates to trigonal planar with C(2)—C(3)—C(4) angle close to 130° and significant triple and double bond character between C(1)—C(2) and C(2)—C(3), respectively.[1]

Advantage has been taken of the ready accessibility of eleven *para*-substituted trityl and 9-phenylxanthyl cations, radicals, and carbanions in a study of the quantitative relationship between their stabilities under similar conditions.[2] Hammett-type correlations have also been demonstrated for each series. Heats and free energies of deprotonation and the first and second oxidation potentials of the resulting carbanions were compared. The first and second reduction potentials and the $pK_R{}^+$ values of the cations in aqueous sulfuric acid were compared, as were calorimetric heats of hydride transfer from cyanoborohydride ion. For radicals, consistent results were obtained for bond dissociation energies derived, alternatively, from the carbocation and its reduction potential or from the carbanion and its oxidation potential.

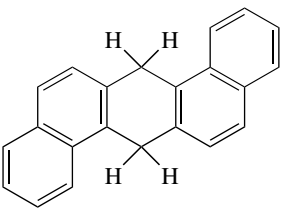
Electron photodetachment spectra for indenyl and fluorenyl anions have been measured and the electron affinities of the corresponding radical and bond dissociation energies of the corresponding neutrals determined. Comparison has been made with solution-phase data in an attempt to determine the dependence of gas and solution properties on ionic size and extent of charge distribution.[3] Benzocyclopropenyl anion

Organic Reaction Mechanisms 1997. Edited by A. C. Knipe and W. E. Watts

(**1**) has been generated in the gas phase and found to be surprisingly stable.[4] Consequently, benzocyclopropene is 34.5 kcal mol^{-1} more acidic than the allylic position of cyclopropene and only 4 ± 3 kcal mol^{-1} less acidic than toluene. *Ab initio* calculations have reproduced the measured acidity of benzocyclopropene, $\Delta H^{\circ}_{\text{acid}} = 386 \pm 3$ kcal mol^{-1}, and the electron affinity of benzocyclopropenyl radical (0.51 eV $< EA <$ 1.11 eV). The unusual stability of the anion has been attributed to the propensity of the aromatic ring to alleviate an unfavourable 4π-electron interaction within the three-membered ring, combined with pyramidalization of the anionic centre, which minimizes interaction of the lone pair with the aromatic sextet.



(**1**)



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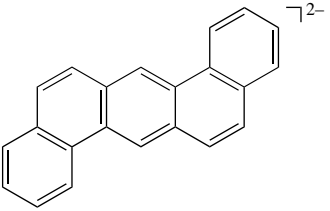
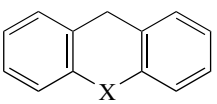


(**3**)

The second equilibrium ion-pair acidity constant (pK_2) of 9,10-dihydrodibenz[*a*,*h*]-anthracene (DBDHA) (**2**) in THF at 298 K has been found to be considerably lower than for other 9,10-dihydroanthracene (DHA) derivatives and the dependence on the counter ions sodium (pK_2 28.5) and potassium (pK_2 30.4) is less marked as a consequence of extended *p*,π-conjugation of the dianion (**3**) with the outer benzene rings.[5] The disodium, dipotassium, and dirubidium salts exist as contact ion triplets and the dilithium salt as a solvent-separated triplet.



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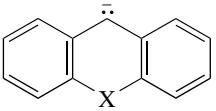

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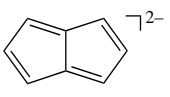


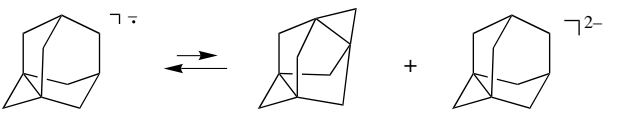
(**6**)

a; X = CH_2
b; X = O
c; X = NMe
d; X = S

An *ab initio* MO study at the Hartree–Fock SCF level using the 6–31G(d) basis set has defined structural parameters and charge distributions for DHA (**4a**), xanthane (**4b**), *N*-methylacridene (**4c**), and thioxanthene (**4d**) and their monoanions (**5a**–**d**).[6] The charge distributions of the significantly flattened anions correlate well with the observed ^{13}C NMR chemical shifts. The heteroanthracenide anions (**5b**–**d**) are rare examples of extensively delocalized 16π-electron systems, for which the extent of overall delocalization of benzylic negative charge increases in the order O < N < S, but the extent of delocalization into the benzenoid rings increases in the order S < N < O.

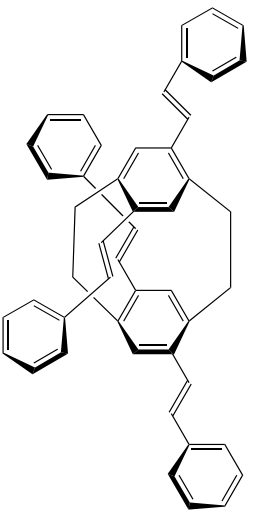
The tendency for the planar pentalene dianion (**6**) to become folded as a complex ligand has been highlighted in a discussion of the chemistry of non-alternant highly unsaturated hydrocarbons.[7]

The structure and energy of a series of ions generated from pentacyclo[3.3.1.1^{3,7}.0^{1,3}.0^{5,7}]decane (**7**) has been explored by using HF, MP2 and DFT methods to estimate enthalpy changes of isodesmic disproportionation reactions and by considering the reorganization of frontier orbitals as a consequence of addition or removal of electrons from the neutral molecule.[8] The dication (**7**$^{2+}$), which is considered to be 'three-dimensionally homoaromatic', is stable relative to a localized structure with similar features but is highly unstable compared to the radical cation (**7**$^{+\cdot}$). In contrast, the dianion (**7**$^{2-}$) is unstable relative to the radical anion (**7**$^{\cdot-}$) and shows no evidence of electron delocalization.



(**7**$^{\cdot-}$) (**7**) (**7**$^{2-}$)

A tetraanion salt (**8**$^{4-}$)/4M^{+} has been formed by stepwise four-electron transfer from 4,7,12,15-tetrastyryl[2.2]paracyclophane (**8**) to lithium, sodium, and potassium metals in [^{2}H$_{8}$]THF at 220 K; a strong effect of the cyclophane hub on the charge distribution has been demonstrated and the influence of o^1, o^2, o^3, o^4-tetramethyl and p^1, p^2, p^3, p^4-tetramethoxy substituents on the ease of reduction has been tested.[9]



(**8**)

The UV–visible and NMR spectra have revealed that the charge on the disilanylene 1,2-dianion derived from dimetallation of 1,2-chloro-1,2-disilaacenaphthene is much less delocalized than the corresponding carbon dianion, but more delocalized than for phenylsilyl anions.[10] Persilylated dimethylenecyclobutene has been reduced by lithium metal in 1,2-dimethoxyethene to give the first reported 6C–8π allyl anion system, persilylated dimethylenecyclobutene dianion dilithium;[11] the six carbon atoms of the π-

skeleton are nearly coplanar and the C—Si bond lengths are considerably shortened by $p\pi$–σ^* conjugation.

A rare species of salts consisting of a heteroatom-stabilized carbocation and a heteroatom-stabilized carbanion has been formed by deprotonating methyl (*Z*)- or (*E*)-3-hydroxy-2,3-dimesitylpropenoate with tetrakis(dimethylamino)methane; the resonance stabilization of the cation $[(CH_3)_2N]_3C^+$ and enolate anion, which is of *E*-configuration exclusively, since the guanadinium ion is incapable of forming a chelate, prevents a spontaneous *O*- or *C*-alkylation.[12]

A hybrid HF–DFT approach has been used to determine gas-phase acidities (ΔH values) for a range of aliphatic, cyclic, and polycyclic carbon acids and reference compounds. The results obtained have been discussed in terms of strain in three- and four-membered rings, carbon hybridization aromaticity and topological analysis of electron density.[13]

Calculations using GIAO and IGAIM methods have enabled the chemical shifts of methyl cation and anion to be determined by gauging the shielding of the nucleus by neighbouring electrons; the experimental data for cyclopentadienide ion, benzene, tropylium ion, and cyclooctatetraene dianion have also been reproduced and the data have been correlated by a simple model that also accounts for the large downfield shifts found for carbenes.[14]

An unsuccessful attempt has been made to determine the separate electronic and steric effects of alkyl groups on the acidities of hydrocarbons, acetophenone derivatives, and acetone derivatives $CH_3COCHR^1R^2$ (at either site) by multivariational analyses of experimental and theoretical acidities for each set.[15] A thermodynamic cycle has been used to estimate the aqueous phase $pK_a = 22.7 \pm 1.0$ for the methyl group of acetic acid and $pK_a = 3.3 \pm 1.0$ for the corresponding enol.[16] Equilibrium acidities have been determined for several nitroaryl substituted nitroalkanes and cyanomethanes, 2,4,6-TNT, and 9-cyanofluorene[17] in acetonitrile; the influence of common cation BH^+ on the electronic spectra of the anions obtained in the presence of strong guanidine bases (B) has been attributed to formation of two types of ion pair.[18]

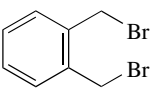
Equilibrium contact ion-pair acidities have been reported for monomeric lithium and caesium salts of several sulfones and a sulfoxide in THF.[19]

A study of biomimetic oxygenations of phenol and indol derivatives has featured theoretical investigation of the charge-transfer complexes formed between carbanions and molecular oxygen (organodioxide anions).[20]

Carbanion Reactions

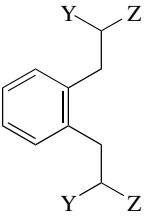
Enolates and Related Species

A study of the mono- vs di-alkylation reactions of dibromide (**9**) with carbanions (**10c**–**g**), covering a range of >15 pK units in DMSO, has revealed that the carbanions (**10d**–**g**) derived from the less acidic carbon acids give exclusively the bis(monoalkylated) product (**11**); however, carbanions (**10a**–**c**) give the cyclic product (**12**) of dialkylation.[21] This dichotomy is apparently a consequence of the relative rates of formation (by proton transfer, k_d) and cyclization (k_c) of the conjugate base of the monoalkylated intermediate.

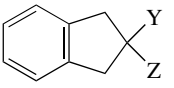


(**9**)

(**10**)



(**11**)



(**12**)

a; YZ = —$(CO_2Me_2O_2C)$—
b; Y = Z = CN
c; Y = Z = COMe
d; Y = Z = CO_2Et
e; Y = (N═CPh_2), Z = CO_2Me
f; Y = (N═CH(*p*-ClC_6H_4), Z = CO_2Et
g; Y = Ph, Z = CN

A new method of kinetically controlled generation of the more substituted enolate from an unsymmetrical ketone involves precomplexation of the ketone with aluminium tris(2,6-diphenylphenoxide) (ATPH) at −78°C in toluene, followed by deprotonation with diisopropylamide (LDA); highly regioselective alkylations can then be performed.[22] ATPH has also been used, through complexation, as a carbonyl protector of α,β-unsaturated carbonyl substrates during regioselective Michael addition of lithium enolates (including dianions of β-dicarbonyl compounds).[23]

It has been shown that selective α-vinylation of enolate anions derived from 1,3-dicarbonyl compounds can be achieved by reaction with 4-*t*-butyl-1-cyclohexenyl-(aryl)iodonium and 1-cyclopentenyl(aryl)iodonium tetrafluoroborates without competing α-arylation, provided that the alkenyliodonium salt used bears a *p*-methoxyphenyl, rather than phenyl, group.[24]

Photostimulated $S_{RN}1$ reactions of carbanion nucleophiles in DMSO have been used to advantage in C—C bond formation (Scheme 1).[25–27] Thus, good yields of substitution products have been obtained from neopentyl iodide on reaction with enolates of acetophenone and anthrone, but not with the conjugate base of acetone or nitromethane (unless used in conjunction, whereby the former acts as an entrainment agent).[25] 1,3-Diiodoadamantane forms an intermediate 1-iodo monosubstitution product on reaction with potassium enolates of acetophenone and pinacolone and with the anion of nitromethane; subsequent fragmentation of the intermediate gives derivatives of 7-methylidenebicyclo[3.3.1]nonene. Reactions of 1,3-dibromo- and 1-bromo-3-chloro-adamantane are less effective.[26]

$$RX + Nu^- \xrightarrow{ET} R^{\cdot} + X^- + Nu^{\cdot}$$

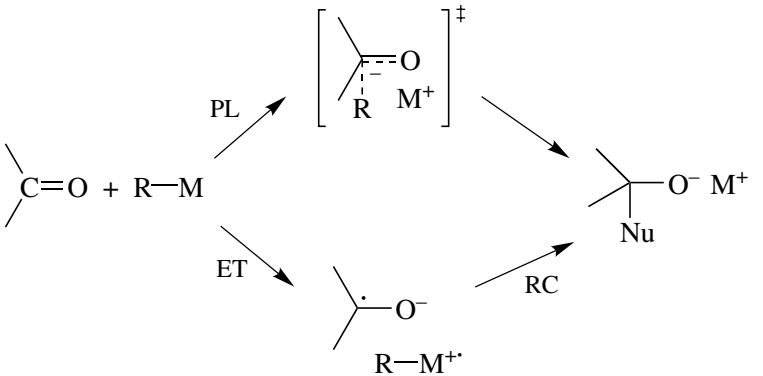
$$R^{\cdot} + Nu^- \longrightarrow (RNu)^{\cdot -}$$

$$(RNu)^{\cdot -} + RX \longrightarrow RNu + R^{\cdot} + X^-$$

SCHEME 1

Photoassisted heteroaromatic nucleophilic substitution reactions of various carbanion nucleophiles with 2-bromopyridine, iodobenzene, bromobenzene, bromomesitylene, and 2-chloroquinoline in KNH_2–liquid NH_3 have also been compared.[27]

Aldol reactions have continued to attract attention.[28–39] In order to determine the mechanism of addition of lithium pinacolone enolate [CH_2=C(OLi)C$(Me)_3$] to benzaldehyde the carbonyl-carbon KIE ($^{12}k/^{13}k = 1.019$) and the substituent effects ($\rho = 1.16 \pm 0.31$) have been compared with those for other lithium reagents.[28,29] The small positive KIE, which is larger than the equilibrium IE ($^{12}K/^{13}K = 1.006$) determined by *ab initio* MO calculations (HF/6–31 + G*), is in contrast with $^{12}k/^{14}k = 1.000$ for MeLi addition which proceeds by the rate-determining ET mechanism, characterized by a much smaller ρ value. Since probe experiments showed no evidence of single electron transfer, it has been concluded that the significant isotope effect for reaction of lithium pinacolone enolate is indicative of rate-determining polar attack (PL) rather than radical coupling (RC) (Scheme 2).

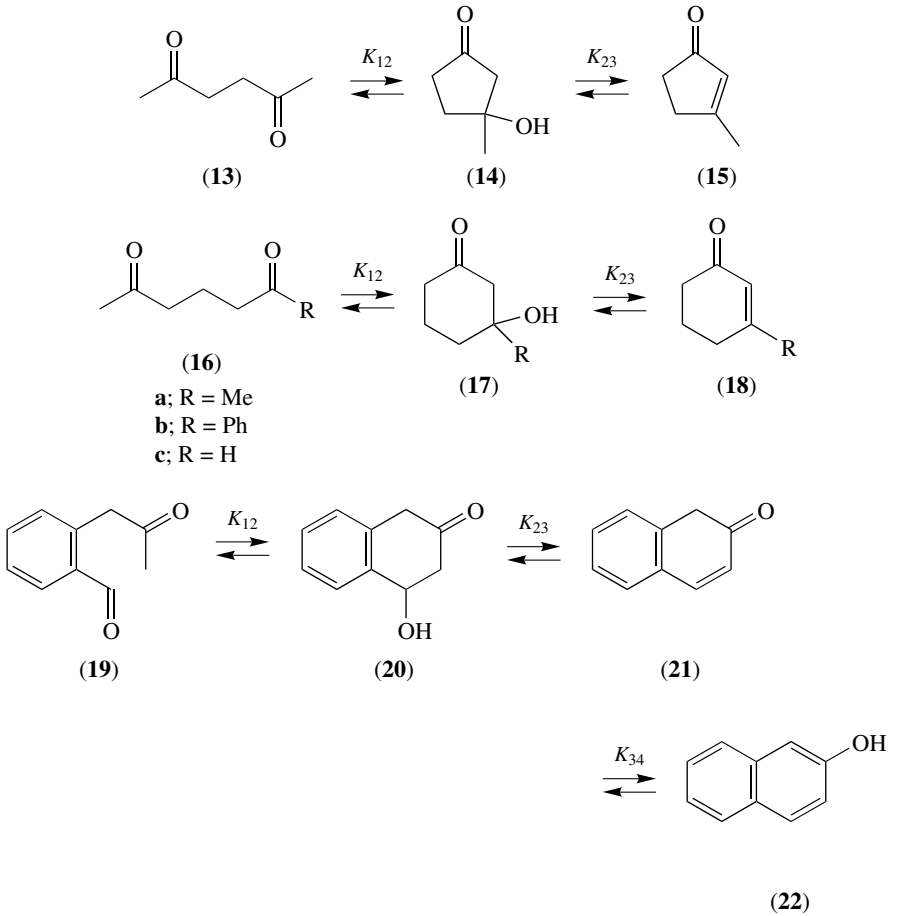


SCHEME 2

Methyl ketone enolates bearing a β-heteroatom substituent have been designed to effect highly 1,5-diastereoselective additions to aldehyde electrophiles and used to achieve double-stereodifferentiating aldol reactions.[30]

Detailed analysis of the rate and equilibrium constants determined for both phases of intramolecular aldol condensation reactions (**13** → **15**, **16** → **18**, and **19** → **21**) in terms of Marcus theory, has established that the intrinsic barriers for the intramolecular reactions are the same as those determined previously for the intermolecular counterparts.[31] Consequently, rate constants for intramolecular aldol reactions are predictable from the energetics of the reactions and the effective molarity can be calculated. An associated discussion of Baldwin's rules suggests that they are a consequence of the need to achieve a conformation from which reaction can take place

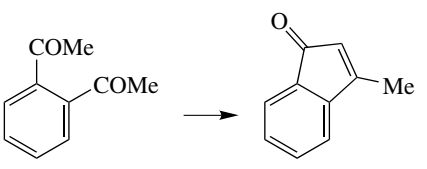
by a simple rotation and bond reorganization, rather than a consequence of strain implicit in following an obligatory Dunitz–Burgi trajectory.



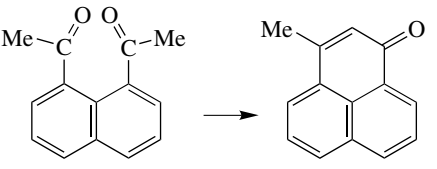
Studies of relative rates, activation parameters, kinetic isotope, and solvent isotope effects, and correlation of rates with an acidity function, have elucidated the mechanisms of cyclization of diacetyl aromatics (**23**–**26**) promoted by tetramethylammonium hydroxide in DMSO.[32] Rate-determining base-catalysed enolate anion formation from (**24**–**26**) is followed by relatively rigid intramolecular nucleophilic attack and dehydration whereas the cyclization step is rate determining for (**23**).

By systematic screening of the effects of Lewis acids on the competitive reactions of benzaldehyde and *N*-benzylideneaniline with propiophenone enolate in CH_2Cl_2 or CH_3CN, it has been found that addition of a small amount of the lanthanide salt

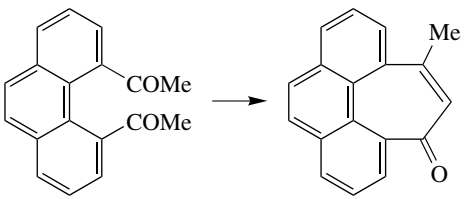
$Yb(OTf)_3$ (0.2 mole equiv.) can promote an unprecedented preferential reaction (>99%) of the aldimine over the aldehyde if the trimethylsilyl enolate is used.[33]



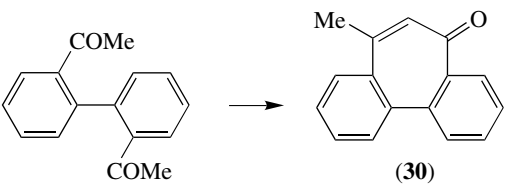
(**23**) (**27**)



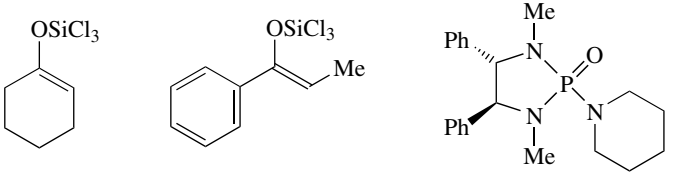
(**24**) (**28**)



(**25**) (**29**)



(**26**) (**30**)



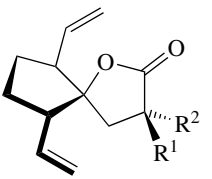
(**31**) (**32**) (**33**)

Boron enolates bearing menthol-derived chiral ligands have been found to exhibit excellent diastereo- and enantio-control on reaction with aldehydes[34] and imines.[35] Highly diastereo- and enantio-selective aldol additions of geometrically defined trichlorosilyl ketone enolates (**31**) and (**32**) have been achieved by promoting the reactions with chiral Lewis bases, of which (*S*,*S*)-(**33**) proved to be the most effective.[36] Moderate enantiomeric excesses have been achieved by using chiral amino alcohols as catalysts for the Baylis–Hillman condensation of aldehydes with methyl vinyl ketone; the unexpected pressure effect on the reaction has been rationalized.[37]

Results of semiempirical calculations and deuterium exchange experiments indicate that the succinyl transfer from aryl enol succinates to the enolates of aryl ketones occurs by an addition–elimination mechanism and does not involve a retro-ene process.[38]

Further evidence for the intermediacy of 4-hydroxycyclopent-2-en-1-ones (1 : 1 adducts) in the Weiss reaction of 1,2-dicarbonyl compounds R^1COCOR^2 with dimethyl 3-oxoglutarate $(MeO_2CCH_2)_2CO$, to give *cis*-bicyclo[3.3.0]octane tetraesters, has been reported and steric effects on the condensation have been explored.[39]

The high diastereoselectivity found on base-promoted cyclization of ethyl 7-bromo-2-methylheptenoates (bearing 3-, 4- or 6-methyl substituents) has been attributed to folding strain control of incipient cyclohexane formation.[40] The selectivity is only moderate for the 5-methyl substrate but increases with the bulk of the substituent: Ph < Me ≈ Et < *i*-Pr < *t*-Bu.

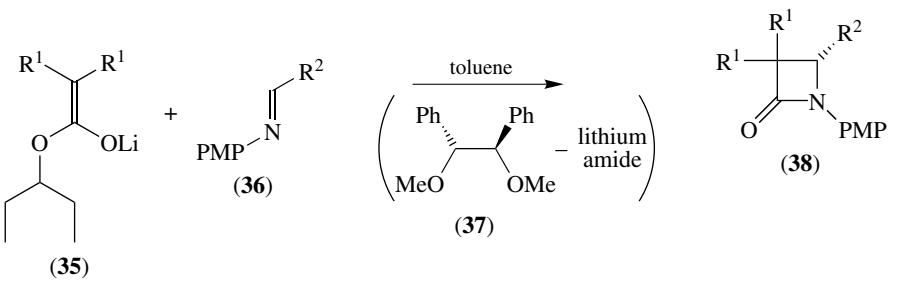


(**34**)

a; $R^1 = R^2 = H$
b; $R^1 = H$, $R^2 = CO_2Me$

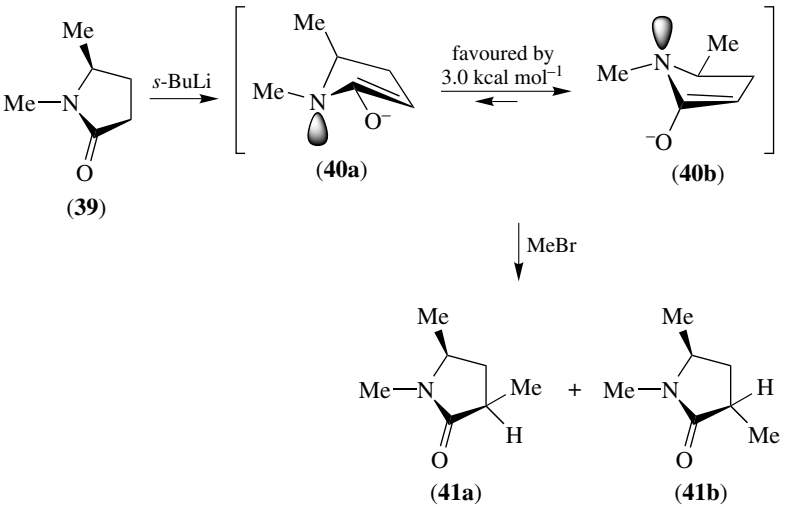
The alkylation of (±)-spirolactones (**34a**) and (**34b**) with higher diastereoface selectivity has been modelled by geometry-optimized *ab initio* 4–31G calculations which suggest that approach of the electrophile occurs at an angle of ca 80° to the plane of the enolate and with some displacement away from the oxygen linked to the metal ion.[41] Asymmetric α-methylation of phenylalanine derivatives has been achieved with 82% *ee* and retention of configuration in the absence of any external chiral source.[42]

Highly stereoselective aldol reactions of lithium ester enolates ($LiCR^1R^2CO_2R^3$) with (R_s)-2-(*p*-tolylsulfinyl)cyclohexanone have been attributed to intermediacy of tricoordinate lithium species which involve the enolate and the sulfinyl and carbonyl oxygens of the substrates.[43] The *O*-metallated *β*-hydroxyalkanoates formed by aldol-type reaction of carbonyl compounds with enolates derived from esters of alkanoic acids undergo spontaneous intramolecular cyclization to *β*-lactones if phenyl rather than alkyl esters are used; the reaction has also been found to occur with other activated derivatives of carboxylic acids.[44]

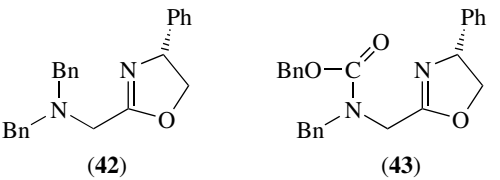


(**35**) (**36**) (**37**) (**38**)

Asymmetric formation of β-lactams (**38**) in high *ee* has been achieved by reaction of achiral imines (**36**) with a ternary complex of achiral lithium ester enolate (**35**), achiral lithium amide, and a chiral ether ligand (**37**) (in either stoichiometric or catalytic amount);[45] the size and nature of the lithium amide have a considerable effect on the enantioselectivity of the ternary complex.



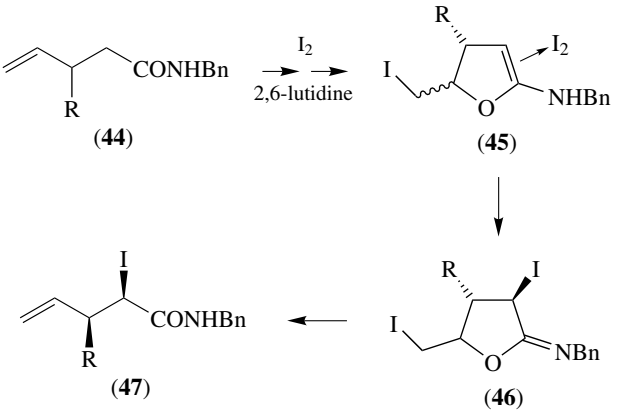
The nitrogen lone pair has been shown by both experiment and theoretical calculation to bias facially the alkylation reactions of nitrogen-containing pseudo-planar enolates (**40**) derived from pyrrolidinone (**39**). The preferred approach *anti* to the lone pair has been attributed to a heretofore unappreciated electronic effect.[46]



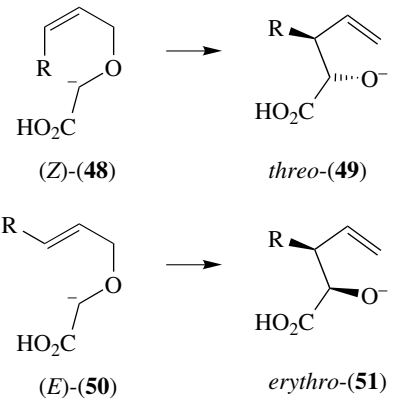
On alkylation of 2-(aminomethyl)oxazolines (**42**) and (**43**), stereochemical induction is evident for the tertiary carbamates (**43**), but not the tertiary amines (**42**); this is apparently a consequence of prior complexation of the carbamate carbonyl group to the base and kinetic preference for (*E*)-enolate formation on deprotonation.[47]

4-Alkenylamides (**44**) having a β-chiral centre have been found to undergo *syn*-selective α-iodination with iodine to give *syn*-α-iodoalkenamides, via an intermediate

ketene *N,O*-acetal (**45**) which undergoes α-iodination from the opposite side to the *β*-substituent to give (**47**).[48]

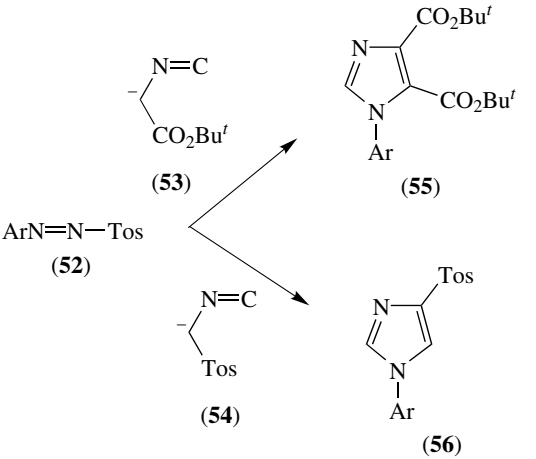


Several alternative transition structures for the [2.3]-Wittig rearrangements (*Z*)-(**48**) → *threo*-(**49**), and (*E*)-(**50**) → *erythro*-(**51**), have been explored by *ab initio* molecular orbital calculations at the 6–31G* level in an attempt to explain why the observed stereoselection is opposite to that for alkenes which do not bear a 1-carboxylic group.[49] It has been concluded that coordination of lithium cation to two oxygen atoms and the C(4) carbon plays a significant role in reactions of (**48**) and (**50**), thereby making it easier to break the O(2)—C(3) bond.

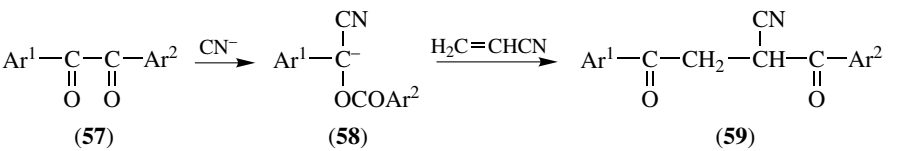


Reactions of arylazosulfones (**52**) with conjugate bases (**53**) and (**54**) of active-methylene isonitriles in DMSO give 1-arylimidazoles (**55**) and (**56**), respectively.[50]

Distinctly different mechanisms are believed to apply following initial addition of the nucleophile.



The AM1 MO method has been applied in a theoretical study of the addition of malononitrile anion to carbonyl compounds; substituent effects on the energetics of the reaction and the nucleophilic attack reactivity were investigated and the influence of hydrogen bonding a single water molecule to formaldehyde oxygen and/or the carbanion was estimated.[51] The endothermic addition of $R\bar{C}HCN$ (R = CN, $CSNH_2$) to MeCHO has been shown by AM1 calculations to proceed via a late product-like transition state; the same applies to the competing 1,2- and 1,4-additions to α,β-unsaturated nitriles.[52] Structural limitations of the nitrile aldol reaction have been probed; lithiated phenylacetonitrile has been found to exhibit higher diastereoselectivity (in favour of *anti*-aldol) than for other metallated phenylacetonitriles towards benzaldehyde, but the diastereoselectivity is markedly reduced by increase in electron-withdrawing power of *para*-substituents on the aldehyde.[53] Diastereoselectivities exhibited by aliphatic nitriles are lower and not uniformly *anti*-selective. Reaction of the zwitterion *i*-$Pr_3P^+CH_2\bar{C}(CN)CO_2Et$ with ArN=C=O proceeds via the adduct *i*−$Pr_3P^+CH_2C(CN)(CO_2Et)C(O)\bar{N}Ar$ to the rearranged zwitterion *i*-$Pr_3P^+CH_2\bar{C}(CN)C(O)N(Ar)CO_2Et$; thio analogues are obtained from PhN=C=S.[54]

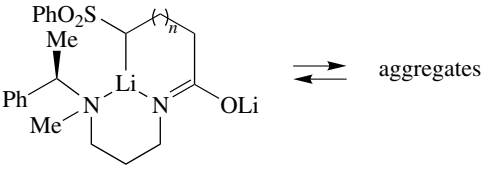


SCHEME 3

Alkene insertion between the carbonyls of benzils (**57**) has been achieved by Michael addition catalysed by cyanide ion, as depicted in Scheme 3.[55] α-Cyanocarbanions, from R^1R^2CHCN–BuLi in THF, have also been used to effect regiospecific ring opening of 3,3,3-trifluoropropene oxide to form $CF_3CHOHCH_2CCNR^1R^2$ diastereoisomers;[56]

carbanions from diethyl malonate and nitromethane fail to react under these conditions. The dimer $(Ph_2CCN)_2$ is formed by a SET pathway on reaction of α-cyanodiphenylmethide carbanion with polyhalomethanes $CHBr_3$, CCl_4, or $CHCl_3$.[57]

Long-range asymmetric induction controlled by supramolecular interaction of intermediate dilithio species (**60**) has been shown to account for the selective formation of two (out of four) *β*-hydroxy sulfone diastereoisomers on reaction of α-sulfonyl carbanions with benzaldehyde in THF at −100°C.[58]



(**60**)

Reactions of *trans*-*β*-styryl sulfone carbanion (*E*)-$Cl\bar{C}HSO_2CH{=}CHPh$, with PhCHO, CH_3CN, and $ArNO_2$ under phase-transfer conditions have been explored.[59]

The anionic Michael adducts of highly diastereoselective kinetically controlled reactions between lithiated sulfoximines and acyclic enones undergo S_Ni displacement of the sulfonimidoyl group to give cyclopropanes (in high enantiomeric purity if sulfoximine enantiomers are used).[60] The *t*-butylsulfinyl group has been shown to be the most effective choice of chiral auxiliary for asymmetric aziridination of *N*-sulfinylimines with sulfur ylides.[61] The induction depends on the nature of the methylene transfer agent and on the chirality of the *t*-butylsulfinyl sulfur. α-Sulfonyl carbanion intermediates have been implicated in substitution and ring-opening reactions of episulfones.[62]

Chiral crown ether phosphine–palladium complexes have been used to catalyse the alkylation of carbanions derived from α-nitro ketones and α-nitro esters,[63] and proline rubidium salts have been used to catalyse asymmetric Michael addition of nitroalkanes to prochiral acceptors;[64] 80% enantioselectivity can be achieved in each case.

pH and secondary deuterium kinetic isotope effects on the reaction of D-amino acid oxidase with nitroalkane anions have provided evidence for direct carbanion attack on the flavin.[65]

Heteroatom-stabilized Species

Reviews have featured epoxidation, cyclopropanation, aziridination, olefination, and rearrangement reactions of asymmetric ylides;[66] non-phosphorus stabilized carbanions in alkene synthesis;[67] phosphorus ylides and related compounds;[68] the Wittig reaction;[69,70] and [2,3]-Wittig rearrangement of α-phosphonylated sulfonium and ammonium ylides.[71] Reactions of carbanions with electrophilic reagents, including alkylation and Wittig–Horner olefination reactions, have been discussed with reference to Hammett $\rho\sigma$ correlations.[72]

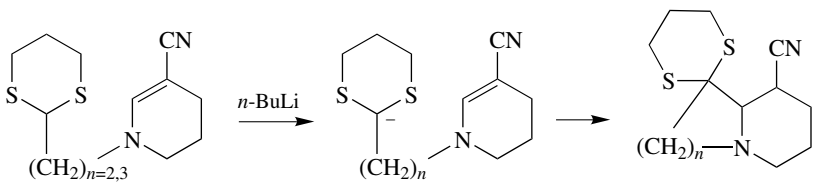
Mechanisms of competing reactions of Wittig reagents with substituted 2-amino-1,4-naphthoquinones have been discussed[73] and a study of the stereoselectivity of the indirect Wittig reaction of a 1,2-hydroxyphosphonium salt has led to the conclusion

that, for reaction of an aliphatic aldehyde with an unstable ylide, Wittig reaction stereochemistry is controlled at an initial 2 + 2-cycloaddition step.[74] Mechanisms of reaction of Wittig–Horner reagents with 1,3-dioxo-$\Delta^{2,\alpha}$-indanmalononitrile[75] and with aromatic and α,β-unsaturated aldehydes,[76] to give (*Z*)-1-chlorovinyl sulfides with high stereoselectivity (>98%), have been discussed. Highly functionalized 2-cyclohexenone-dicarboxylates have been synthesized by novel Michael–Wittig condensation reactions of methyl 3-oxo-4-(triphenylarsoranylidene)butenonate and substituted 2,2-dimethyl-2*H*-pyran-5-carboxylates.[77]

Ab initio study of the potential energy surface for P—C bond rotation in the 2-oxo- and 2-thioxo-2-methyl-1,3,2-diazaphosphorinane and -1,3,2-diazaphosphosolidine anions has established that in each case the lowest energy six-membered ring structure features a near planar carbanion with its substituent parallel to the P=X axis (X = O, S).[78]

The scope and limitations of the metal anions of 2-halo-1,3-dithiane *trans*-1,3-dioxide as diastereoselective carbonyl anion equivalents has been explored with regard to reaction with aldehydes.[79] Reactions of metallated *trans*-1,3-dithiolane 1,3-dioxide (five-membered ring) with aldehydes under kinetic and thermodynamic control have also been studied and contrasted with those of the metallated monooxide, parent sulfide, and 1,3-dithiane 1,3-dioxide (six-membered ring).[80]

Stereoselective intramolecular conjugate addition reactions (Scheme 4) of dithiane anions tethered to an α,β-unsaturated nitrile have been developed to advantage for the synthesis of axially substituted indolizidines and quinolizidines.[81] The control of axial nitrile orientation by a 'peg-in-a-pocket' template effect has been discussed.



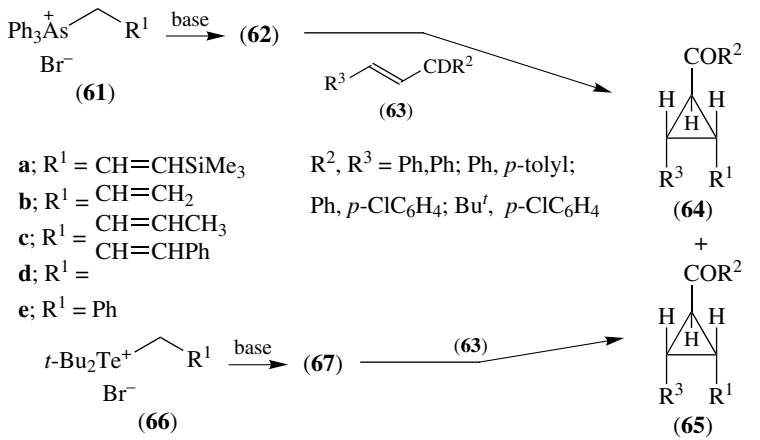
SCHEME 4

It has now been shown that *anti*-betaines derived from RCHO and ArCHO form exclusively *trans*-epoxides without evidence of crossover in the presence of a more reactive aldehyde;[82] in contrast, the *trans*-epoxide formed exclusively by *syn*-betaines derived from ArCHO are found to incorporate only a more reactive aldehyde if present. *syn*-Betaines from RCHO form mixtures of *cis*- and *trans*-epoxides, with and without incorporation of a more reactive aldehyde if present. It has therefore been concluded that the high *trans* selectivity observed in epoxidation with aromatic aldehydes is a result of irreversible formation of *anti*-betaines and reversible formation of *syn*-betaine. The lower selectivity in the case of aliphatic aldehydes is a consequence of only partial reversibility in the formation of *syn*-betaine.

Diastereoselectivity in the addition of electrophiles to the carbanions of 2-(alkylthio)thiolane-1-oxides has been explored and a six-membered cyclic transition

state involving the sulfoxide moiety and metal cation has been proposed for reaction with carbonyl compounds.[83]

Stereoselective cyclopropanation reactions of cyclic and acyclic enones have been performed using dimethylsulfonium acetate bromide in the presence of DBU.[84] Highly selective synthesis of two alternative geometric isomers, (**64**) and (**65**), of vinyl-substituted cyclopropane derivatives has been achieved by stereocontrolled cyclopropanation reactions of α,β-unsaturated ketones (**63**) with semistabilized telluronium and arsonium ylides, respectively.[85] Thus telluronium ylides (**67a**–**e**) react with (**63**) to give *cis*-2-vinyl-*trans*-3-substituted cyclopropyl ketones (**65a**–**i**) whereas arsonium ylides (**62a**–**e**) give *trans* counterparts (**64a**–**i**). It has been argued that telluronium displacement is rate determining following a reversible addition of (**67a**–**e**) but that the addition of (**62a**–**e**) is irreversible.



New aspects of acylation reactions of aza-allyl carbanions derived from ethyl *N*-[bis(methylthio)methylene]glycinate and *N*-[bis(methylthio)methylene]benzylamine have been reported.[86]

Gas-phase reactions of anions derived from CH_3SCD_2CN have been studied by Fourier transform ion cyclotron resonance techniques.[87]

3-(4-Halophenyl)pyridazinium ylides have been found to act as strong carbon nucleophiles towards diazoaromatic compounds to yield stable carbanion disubstituted ylides for which the intense colour has been attributed to intramolecular charge transfers.[88]

Indium-mediated coupling of aldehydes with 3-bromo-3,3-difluoropropene occurs selectively at the *gem*-difluorocarbon which exhibits α,α-difluoroallyl carbanion behaviour.[89]

Organometallic Species

Review articles have featured new organometallic reagents using highly reactive metals[90] and the synthetic potential of remarkably stable chiral, non-racemic 2-lithiopiperidines and 2-lithiopyrrolidines.[91]

A concerted electron transfer mechanism, with formation of an alkyl radical and quinone radical anion, has been proposed to account for the products of reaction of benzophenone with alkyllithium or Grignard reagents;[92] the ratio of addition to reduction products is dependent on the alkyl group and not on the metal.

The regioselectivity of the diisopropyl squarate ester–octa-1,3,5,7-tetraene–polyquinane cascade has been controlled by positioning a nucleofuge within one of the alkenyllithium reactants and thereby promoting exclusive formation of either linear or angular products.[93] Chirality transfer has also been advanced during such reaction cascades by using strategically placed substituents on the cycloalkenyl anion nucleophile to establish a favoured position of equilibration of helical diastereoisomers prior to cyclooctatriene formation by conrotatory ring closure.[94]

Solvent and temperature effects on the diastereoselective addition of *n*-BuLi to 2-phenylpropanal have been reassessed[95] and the stereochemistry of addition of organolithium reagents to carbohydrate enones has been studied.[96] No compelling evidence has been found to support the suggestion that addition of *n*-BuLi to benzoic acid might compete with formation of the lithium salt and thereby provide an alternative to the sequential route to $PhCOBu^n$.[97]

Organolithiums have been shown to add to a variety of trithiocarbonate oxides exclusively in a thiophilic manner, as a consequence of the electrophilic character of the sulfine sulfur, to give an intermediate carbanion stabilized by three sulfur atoms; the soft carbanion, which forms trithioorthoester oxide on quenching with water, acts as the equivalent of the (alkylthio)carbonyl anion in Michael addition.[98]

Chiral disubstituted cyclopropanes have been formed by enantioselective carbolithiation of cinnamyl acetals.[99]

Perfluoro-1,2-dichlorocyclobutene undergoes replacement of one chlorine by lithium on reaction with Bu^tLi in ether;[100] an intermediate perfluorocyclobutyne may be formed from 1-chloro-2,2,3,3-tetrafluorocyclobutene with PhLi.

Carbocyclization of ω-alkenyl-α-methoxybenzyllithiums to form five- or six-membered rings has been studied;[101] the five-membered ring is formed with a *cis*-stereochemical relationship between the methoxy substituent and the adjacent methyl group. Intramolecular carbolithiation of vinyl sulfides at $-105°C$ in THF has been found to occur non-stereospecifically with regard to the newly formed C—Li centre.[102]. The stereochemistry of selective tandem Michael addition alkylation reactions of vinylphosphonates has been explored.[103]

Ab initio calculations on the competing metallo-dehydrogenation and nucleophilic addition reactions of organomethides with crotonaldehyde dimethylacetal reveal that addition to the double bond predominates in the case of lithium whereas this is only slightly preferred in the case of potassium methide; the effect of R′OK on deaggregation of RLi oligomers and on weakening C^-—Li^+ interaction has been discussed.[104]

Asymmetric synthesis of primary amines by nucleophilic 1,2-addition of alkyllithiums to aldehyde SAMP/RAMP hydrazones has been reported in detail.[105] On reaction with a range of lithium alkyls, 1,3,5-triazine has been found to form 1,4-adducts which yield 1,4-dihydrotriazines on hydrolysis;[106] in contrast $LiNR_2$ or $LiCR_3(thf)_2$ promote 1,3,5-triazine ring-opening reactions.

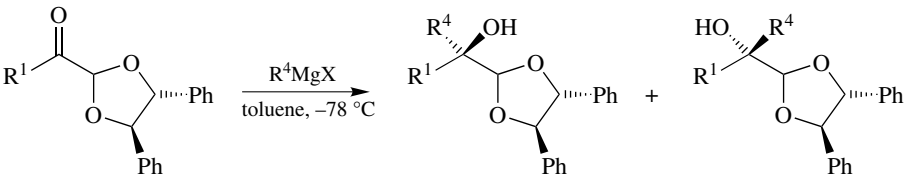
Regio- and stereo-selective ring-opening reactions of unsymmetrical oxatricycloundecenones have been promoted by S_N2' reactions with primary, secondary, and tertiary organolithium reagents whereas hydride reagents, organocuprates, and Grignard reagents were ineffective.[107]

(*E*)-2-ethoxyvinyllithium, formed from (*E*)-1-bromo-2-ethoxyethylene by halogen–metal exchange at −75°C, has been found to decompose rapidly at −50°C, apparently by antiperiplanar elimination of LiOEt, which is impossible for the more stable *Z*-isomer;[108] 2,2-diethoxyvinyllithium and (*Z*)-1,2-diethoxyvinyllithium are stable at 0°C and (*E*)-1,2-diethoxyvinyllithium will tolerate reflux conditions at 75°C. Half-lives of organolithium reagents in common ethereal solvents have been compiled for the benefit of synthetic organic chemists.[109]

Although an α-CF_3 group is known to retard S_N2 reactions of carbon nucleophiles with alkyl sulfonates, it has now been found that γ-trifluoromethylated allylic acetals undergo S_N2'-type reactions with Grignard reagents in presence of catalytic amounts of CuCN and TMS-Cl without formation of S_N2 products.[110] This provides an alternative means of introducing a carbon nucleophile adjacent to a CF_3 group.

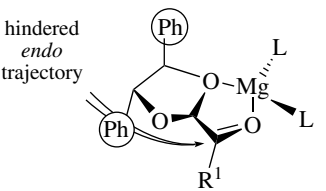
Lewis acid-mediated S_N2-type displacement reactions of RMgX have been used for asymmetric synthesis of 2-substituted piperidines,[111] and $BeCl_2$ has been found to promote addition of RLi and RMgX to cyclohex-2-enone.[112]

The diastereoselectivity of addition of PhMgBr to *N*-benzylimines derived from (*R*)-glyceraldehyde can be reversed by changing the *O*-protection from 2,3-di-*O*-benzyl to 2,3-di-*O*-isopropylidene.[113] The high diastereoselectivity and sense of asymmetric induction achieved on addition of alkylmagnesium halides to chiral α-ketoacetals (**68**) is consistent with a hypothesis that the magnesium ion forms a chelate (**69**) through complexation with the carbonyl oxygen and one of the oxygens of the acetal; the nucleophile adds preferentially to the *exo* face, since the trajectory for approach to the *endo* face of the bicyclic system is sterically hindered.[114]



(**68**)

R^1 = Me or C_5H_{11}; R^4 = phenyl, allyl, vinyl, Pr^i, Et



(**69**)

Regioselective endocyclic cleavage of the ortho ester *cis*-2-methoxy-4-methyl-1,3-dioxane by Grignard reagents, involving rupture of the less congested C(2)—O(1) bond remote from the 4-methyl substituent, has been discussed.[115]

High enantioselectivity has been achieved on addition of diethylzinc to benzaldehyde catalysed by a chiral diamine, (*S*)-2-(*N*,*N*-disubstituted aminomethyl)pyrrolidine,[116] and by chiral helical titanate complexes of tetradentate ligands.[117] Enantioselective additions of dialkylzinc reagents to *N*-(diphenylphosphinoyl)imines, promoted by aziridino alcohols,[118] and to the carbon–nitrogen double bond of the nitrone 3,4-dihydroisoquinoline *N*-oxide, promoted by dicyclopentyl(*R*,*R*)-tartrate,[119] have also been reported.

A complete set of ^{13}C kinetic isotope effects determined (by a natural abundance CMR method) for addition of lithium dibutylcuprate to cyclohexenone, in THF at $-78^{\circ}C$, have been shown to be consistent with those calculated theoretically for rate-determining reductive elimination from an intermediate square-planar copper complex.[120] Thus, the KIE $(^{12}k/^{13}k) = 1.020$–1.026 at C(3) is indicative of substantial bonding change, and partial alkyl transfer can explain the significant low KIE = 1.011–1.016 for C_a of the butyl group.

Stereospecific generation and reactions of allylic alkali and alkaline earth metals have been reviewed[121] and solvent-mediated allylation of carbonyl compounds with allylstannanes has been explored.[122] Chiral phosphoramides derived from (*S*)-proline have been used to catalyse asymmetric allylation of aromatic aldehydes by allylic trichlorosilanes.[123]

Proton-transfer Reactions

It has been reported that rates of proton transfer from carbon acids to water or hydroxide ion can be predicted by application of multi-dimensional Marcus theory to a model whereby diffusion of the base to the carbon acid is followed by simple proton transfer to give a pyramidal anion, planarization of the carbon, and adjustment of the bond lengths to those found in the final anion.[124] The intrinsic barriers can be estimated without input of kinetic information. The method has been illustrated by application to a range of carbon acids having considerable variation in apparent intrinsic barrier.

The kinetics and equilibrium of protium–deuterium exchange between pentafluoroethane and aqueous hydroxide ion have been studied.[125]

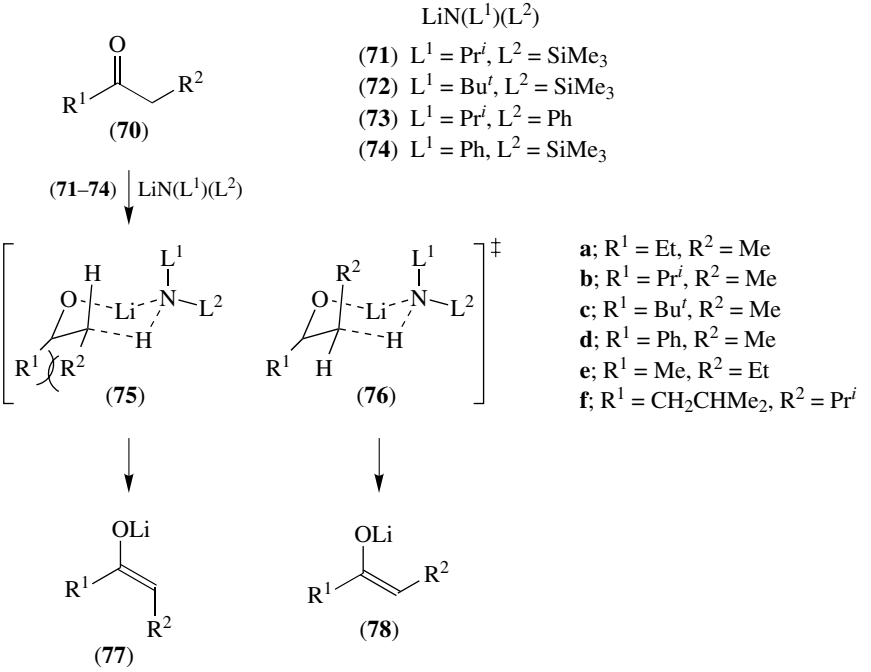
Cubyl anion has been prepared by reacting (trimethylsilyl)cubane with fluoride ion in a Fourier transform mass spectrometer and its reactions with acids such as H_2O, Me_2NH, $EtNH_2$, $MeNH_2$, and NH_3 have been monitored. The results suggest that cubane is thermodynamically more acidic than cyclopropane. The electron affinity of the cubyl radical and the C—H BDE for cubane have also been estimated.[126]

A comparative study of gas-phase and liquid-phase CH acidity of α-substituted cyclopropanes has verified the correctness of an electrostatic model for the effect of solvation on equilibrium acidity;[127] among variants of the LCAO MO method, only the semiempirical AM1 method accurately predicted the proton affinity of the conjugate carbanions; effects of solvation on protonation rates have been desegregated.

Results of *ab initio* study, at the MP2/6–31+G*//MP2/6–31 + G* level, of proton transfers from ZCH_3 to ZCH_2^- (Z = F, Cl, Br, OH, SH, SeH) suggest that the polarizability of Z is the dominant effect on both the order of CH acidity and the barriers to proton transfers; however, it is improbable that the reactions could be observed experimentally since Z may be either displaced by S_N2 reaction (Z = halogen) or deprotonated (Z = YH).[128]

Determination of the acidities of eight enols $R^1R^2C{=}C(OH)R^3$ in DMSO and the oxidation potentials of their conjugate bases have permitted the estimation of the corresponding H—O bond dissociation enthalpies since $BDE_{HA} = 1.37pK_{WA} + 23.1E_{ox}(A^-) + 73.3$ kcal mol^{-1}.[129] The results have been discussed in terms of steric and electronic effects. For $MeS_2C{=}C(OH)R$, pK_{HA} increases, $E_{ox}(A^-)$ becomes more negative, and BDE decreases with the bulk of R.

A study of acid-catalysed enolization and carbon-acid ionization of isobutyrophenone has combined the solvent isotope effect $k_{-1}^H/k_{-1}^D = 0.56$ and substrate isotope effect $k^H/k^D = 6.2$ determined for the enolization in H_2O and D_2O with literature information in order to estimate the solvent isotope effect on the enolization equilibrium, $K_E(H_2O)/K_E(D_2O) = 0.92$, and on the CH ionization of butyrophenone, $k_a^K(H_2O)/k^K(D_2O) = 5.4$.[130] This is the first report of an isotope effect on K_E for keto–enol equilibrium of a simple aldehyde or ketone.

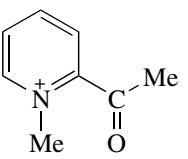


The effect of the steric and electronic nature of lithium amide bases (**71**–**74**) on highly stereoselective kinetic enolate formation from six ketones (**70a**–**f**) in THF has been investigated. The results in general can be rationalized with respect to the cyclic

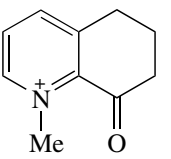
chair-like transition state for concerted proton transfer to the base and the lithium cation coordinated to the oxygen; the *E*/*Z* ratio is dependent on the energy difference between transition states (**75**) and (**76**). Excellent *E* or *Z* stereoselectivity can be achieved using sterically hindered (**72**) or electronically dominated (**74**), respectively.[131]

An eight-membered cyclic transition has been proposed to account for the enantioselectivity observed on deprotonation of 4-substituted cyclohexanones by chiral bidentate lithium amides in THF, in presence of excess Me_3SiCl.[132]

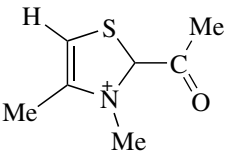
Reviews have featured asymmetric protonations of enol derivatives[133] and of enolates and enols.[134] Highly enantiofacial protonation of prochiral lithium enolates has been achieved using chiral β-hydroxy sulfoxides.[135]



(**79**)

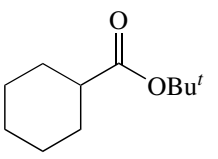


(**80**)

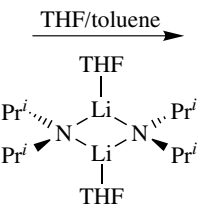


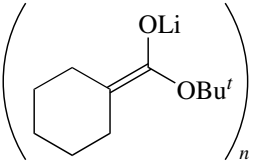
(**81**)

Results of a study of electrostatic acceleration of enolization in cationic ketones have implications for enzymatic catalysis of enolization.[136] Rate constants determined for water-, acetate- and hydroxide ion-catalysed enolizations of cationic ketones (**79**) (pK_a 11.13) and (**80**) (pK_a 11.90) have been compared with those for (**81**). It has been estimated that the inductive effects of the charged rings lower the pK_as of (**81**) and (**79**) by 4.2 and 1.2 log units, respectively, whereas for (**79**) the electrostatic effect lowers the pK_a by 6.3 log units, and enhances k_{OH} by 330-fold relative to a typical methyl ketone. The rate of enolization of (**81**) is enhanced 2.3×10^4-fold by the through-space electrostatic effect.



(**82**)

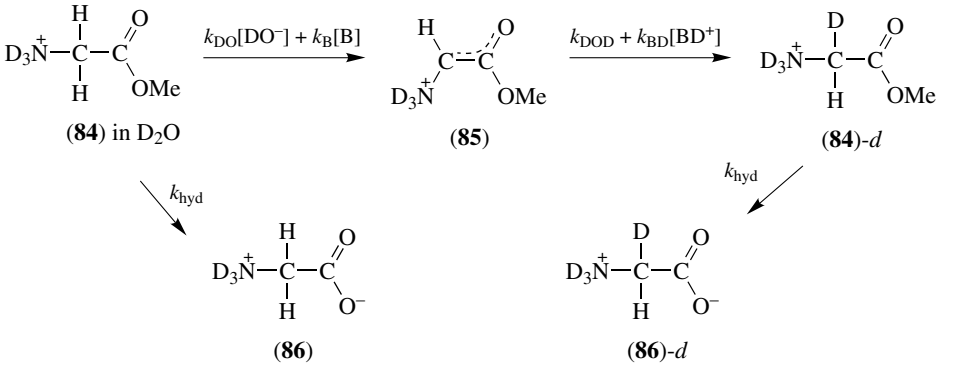




(**83**)

A study[137] of the disappearance of ester (**82**) and appearance of enolate (**83**), promoted by lithium diisopropylamide in THF–toluene, has implicated disolvated LDA

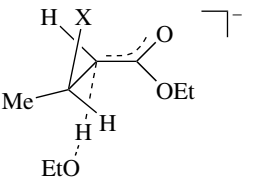
monomers in the rate-determining proton transfer, for which $k_H/k_D = 22 \pm 1$ and $k_{obs} \propto [LDA]^{0.53\pm0.03}$.



(**84**) in D_2O (**85**) (**84**)-*d*

(**86**) (**86**)-*d*

It has been found that deprotonation of (**84**) ($pK_a \approx 21$) in D_2O can be monitored by NMR at 25°C and neutral pD but that the rate of hydrolysis of (**84**) to form glycine is 10 times faster than exchange of the first α-hydrogen for deuterium.[138] The value of $k_{DO} = 6.0\ l\ mol^{-1}\ s^{-1}$ for (**84**) is 20 times larger than for acetone and suggests that the large polar stabilization of (**85**) by the α-NH_3^+ group is well developed in the transition state.



(**87**)

Results of a study of base-catalysed deuteration of *β*-substituted ethyl butanoates in ethanol-*d* under conditions which exclude effects of ion pairing and aggregation establish that stereoelectronic effects generally produce higher stereoselection than do steric effects.[139] Electronegative substituents at C(3) adopt an antiperiplanar position to the forming C—D bond in the preferred transition state (**87**) for electrophilic attack. It is assumed that the geometry of the enolate is *trans* in each case. The diastereoselection achieved with *β*-OR is independent of R and much greater for $OCMe_3$ than for the larger CH_2CMe_3 substituent. The same pattern is apparent on protonation of acyclic *β*-ethoxy aldehyde and ketone enolates but less pronounced for protonation of the cyanocarbanion from a *β*-ethoxy nitrile. The results also have implications for the stereoselectivity of 1,4-conjugate addition of ethanol-*d* to α,*β*-unsaturated esters.

The H–D exchange reaction of 3-ethoxybutanoate in ethanol-*d* (which occurs with a diastereomeric excess of 82%) has been modelled by performing *ab initio* calculations on protonation of the enolate of 3-fluorobutanoic acid by HCN; the predicted diastereomeric excess (84–91%) is dependent on the level of theory used but similar for both *cis* and *trans* enolates.[140] For each diastereomeric pathway the C—F bond is

orientated *anti* to the incipient C—H bond; this may be a consequence of a stabilizing interaction between the electron rich σ-orbital of the enolate—HCN bond and the low-lying σ*-orbital of the C—F bond or, alternatively, minimization of electrostatic repulsion.

The similar catalytic behaviour of oximate and phenoxide bases found for deprotonation of bis(2,4-dinitrophenyl)methane in 50% H_2O–50% Me_2SO ($\beta = 0.45$) implies that comparable solvation changes are involved; this is also apparent from the similar variations of acidity of oximes and phenols on transfer from H_2O to DMSO–H_2O mixtures.[141] Rates of reprotonation of the carbanion by conjugate oxime acids have also been reported. In contrast, the α-effect causes oximates to be much better nucleophiles, than phenoxides of comparable basicity, in addition or substitution reactions. The rapid levelling off of this advantage with increasing basicity ($pK_a > 8$) is now believed to reflect especially large solvational imbalances in the transition state for the nucleophilic reactions; it has been argued that the need for desolvation of the oximate develops much further ahead of bond formation than is the case for deprotonation reactions.

A kinetic study of the deprotonation–reprotonation behaviour of (4-nitrophenyl)-nitromethane in 50% H_2O–50% Me_2SO mixtures promoted by bases (phenoxide and carboxylate ions, primary amines) has revealed a one-step equilibration at pH $\geq$ 4.2; the equilibration in acidic media is complicated by protonation of the exocyclic nitro group.[142] The results suggest that the substrate acts essentially as a nitroalkane rather than a *p*-nitrotoluene. A further study of kinetics of deprotonation of (4-nitrophenyl)nitromethane has provided evidence of a steric effect on proton tunnelling on reaction with *N′*-propyl-*N*,*N*-dipropylbenzimidamide.[143]

Results of an *ab initio* study of the identity proton transfer reaction for the system $CH_3NO_2/CH_2{=}NO_2^-$, and previous findings for other $CH_3Y/CH_2{=}Y^-$ systems, indicate that the evident transition state imbalance in these gas-phase reactions increases with π-acceptor strength of Y, in the order $CN \ll CH{=}O \leq CH{=}CH_2 \leq NO_2$; in contrast to solution reactions there is not a concomitant significant increase in the intrinsic barriers.[144] However, it is not clear from results for gas-phase proton transfer from protonated nitromethane to *aci*-nitromethane ($CH_3N^+O_2H$–$CH_2{=}NOH$) whether the stronger π-acceptor (N^+O_2H) creates greater imbalance than NO_2. It is concluded that the dependence of the barriers on the π-acceptor is a result of a complex interplay between resonance/imbalance effects, inductive/field effects and electrostatic/hydrogen bonding effects; the dominant influence is solvent dependent.

Solvent and substituent effects on intrinsic rate constants k_0 for proton transfer from 2-nitro-4-X-phenyl acetonitriles (X = NO_2, SO_2Me, CN, CF_3, Br, and Cl) to piperidine and morpholine in aqueous Me_2SO have been explored.[145] The expectation that the solvent effect on k_0 should be intermediate between those reported for deprotonation of acetylacetone and 9-cyanofluorene (based on consideration of delocalization of charge and hydrogen bonding to the nitro group) was not realized, apparently because Me_2SO is a better solvator than water for nitro groups that carry only a small fraction of charge rather than a full negative charge. Brønsted β_B values ($d\log k_1^B/dpK_a^{BH}$), Brønsted α_{CH} values ($d\log k_1^B/d\log K_a^{CH}$) and intrinsic rate constants

have been calculated from the kinetic results for reactions in 10, 50, and 100% ($X = NO_2$, SO_2Me, CN, only) water. The intrinsic rate constants are insensitive to the Me_2SO content of the solvent. However, they decrease with increasing electron-withdrawing strength of X as a consequence of the transition state imbalance, whereby delocalization of the negative charge lags behind proton transfer, revealed by $\alpha_{CH} < \beta_B$.

A Brønsted β_B value of 0.5 and α_{CH} value of 1.31 have been calculated for deprotonation reactions of (3,5-dinitrophenyl)nitromethane promoted by substituted benzoate ions and of substituted (3-nitro-, 4-nitro- and 3,5-dinitro-)phenylnitromethanes promoted by benzoate ion, respectively, in methanol.[146] The intrinsic rate constants are $(2.0–6.3)\times10^4$ times lower than for the same reactions in acetonitrile solution, and this has been attributed to commensurate reduction of strength of the hydrogen bond between the carbon acid and benzoate ion in the imbalanced transition state. The transfer activity coefficient ($\log^M\gamma^{AN}$) from methanol to acetonitrile solution have been calculated for (*m*-nitrophenyl)nitromethyl anion (3.6) and (*m*-nitrophenyl)-nitromethane (−1.0).

The kinetics of proton transfer from ethyl bis(4-nitrophenyl)acetate to *N*-bases with guanidine-like character, in acetonitrile, are determined by basicity and steric hindrance in the vicinity of the reacting site of the *N*-base and also by different distributions of positive charge in protonated *N*-bases.[147]

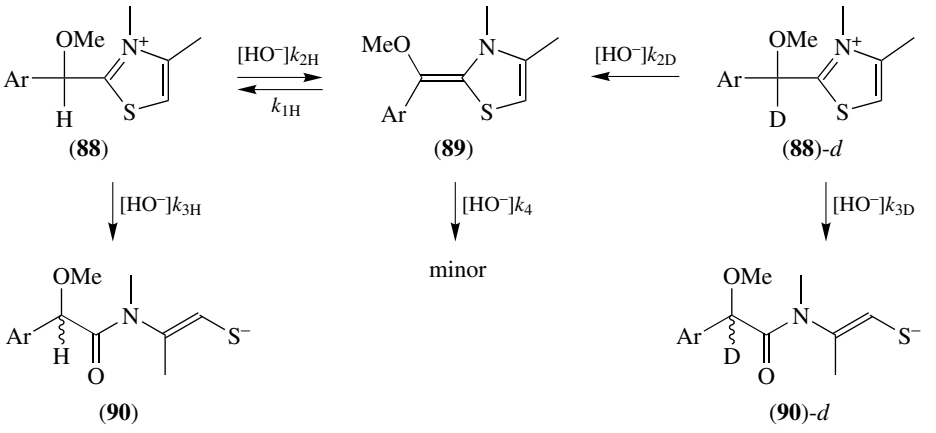
The stabilizing effects of the 1,3-sulfur atoms on the carbocations, radicals, and carbanions generated from 2-aryl-1,3-dithianes and -dithiolanes has permitted the measurement of a variety of bond-making and bond-breaking energies (in DMSO and sulfolane) and their correlation with electron-transfer energies.[148]

AM1 molecular orbital studies of gas-phase deprotonations of *N*-methyl-4-(Y-phenylsulfonylmethyl)pyridinium cations and *N*-(Y-benzyl)-4-(phenylsulfonylmethyl)-pyridinium cations promoted by NH_3 reveal negative transition state imbalances, $I\ (= \alpha - \beta) < 0$ (where $\alpha = 0.17–0.18$ and $\beta = 0.53$), which are a consequence of the difference in distance between the substituents and the anionic charge centre in the transition state and products.[149]

A study of gas-phase negative-ion chemistry of Lewis acid–base complexes of BH_3 with Me_2S, Me_3N, Me_3P, and Et_3N has shown that the α-CH acidities in the complexes (to form dipole-stabilized carbanions) are up to 20 kcal mol^{-1} higher than in the uncomplexed molecules.[150]

Results of a kinetic study of enamine formation by C(2α)-proton abstraction from 2-benzylthiazolium salts (**88**) have implications for mechanistic studies of the thiamin diphosphate-dependent enzymes which feature protonation of the enamine/C(2α)-carbanion.[151] The primary isotope effect for deprotonation of (**88a**) is $k_{2H}/k_{2D} = 4–6$ and the values estimated for C(2α)—H pK_a are 15.0–15.5 and 15.7 for (**88a**) and (**88b**), respectively. A minimum effective molarity of 4500 M has been estimated for reprotonation of the enamine (**89b**) derived from (**88b**) by benzoylformate decarboxylase. Directed aromatic metallation reactions have been reviewed.[152]

Deprotonation of *o*- and *p*-bromochlorobenzene by lithium diisopropylamide at the two halogen adjacent positions is unselective whereas lithium 2,2,6,6-tetramethylpiperidine favours deprotonation α- to the smaller halogen atom.[153] Studies of benzene and



a; Ar = *p*-$(Me_3)\overset{+}{N}C_6H_4$ ($k_4 = 0$)
b; Ar = C_6H_5 ($k_4 \neq 0$)

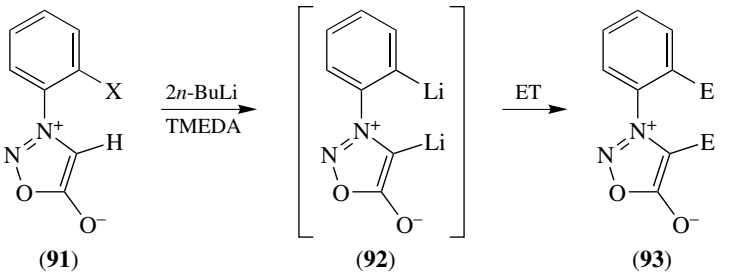
all of its mono-, di-, tri-, tetra-, and penta-fluoro-substituted derivatives, equilibrating with the corresponding anions in the gas phase, have revealed perfect additivity of the substituent effects on the thermodynamic acidity but a tendency for the rates of metallation to level off with the number of halogens.[154] Gas-phase equilibrium measurements have also shown that chlorobenzene is more acidic than fluorobenzene by 0.55 ± 0.15 kcal mol^{-1} (ΔG° at 330 K).[155]

Lithiation of 3-(*t*-butoxycarbonyl)amino-4-carbomethoxythiophene by LDA has been found to occur adjacent to the NHBoc group and next to the methyl ester under conditions of kinetic and thermodynamic control, respectively; the *N*-methylated derivative is lithiated only next to the ester.[156]

A method of metallation of fluoronitro aromatics has been developed in which the metallated intermediate generated by hindered base is trapped by *in situ* Me_3SiCl or Me_3SnCl; it has been possible to use sodium and potassium salts (e.g. NaHMDS) since the directing effect apparently relies on induction rather than metal coordination.[157] The possible mechanism of *ortho*-directed metallation of anisole by *n*-BuLi has been discussed in the light of significant *ortho*-deuterium kinetic isotope effects (2.3–3.2) determined for the reaction promoted with and without TMEDA added.[158] The regioselectivity of lithiation of certain 1,3-disubstituted methoxyarenes has been studied,[159] and the mesoionic ring has been used to direct *ortho*-lithiation of 3-phenyl sydnone (**91**)[160] (Scheme 5).

Asymmetric deprotonation of *N*-(*t*-butoxycarbonyl)indolines at the 2-position with *s*-butyllithium–(−)-sparteine has been reported.[161] Results of an *ab initio* MO study of deprotonated 2,3-dihydrooxepin suggest that the allylic anion is 15 kcal mol^{-1} more stable than the vinylic anion, which is, in turn, 8 kcal mol^{-1} more stable than the vinyl anion of cyclohepta-1,3,5-triene.[162]

Base-catalysed epimerization at the benzylic pyrrolidine C(2) position of a new carbapenem is induced by a remote cationic centre,[163] and irreversible photodeprotona-

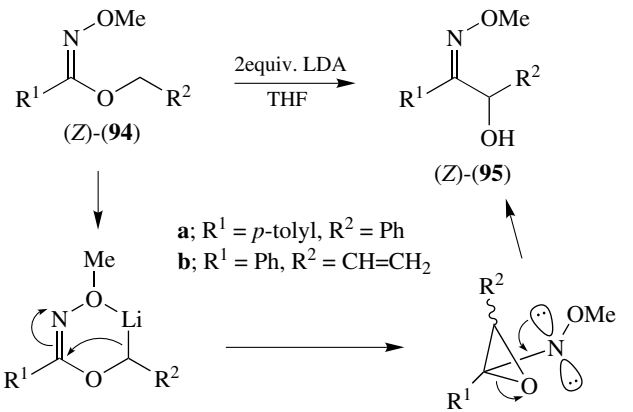


SCHEME 5

tion of the benzylic protons of 10-methyl- and 10-phenyl-thioxanthenium salts to give the corresponding sulfonium ylide has been achieved.[164]

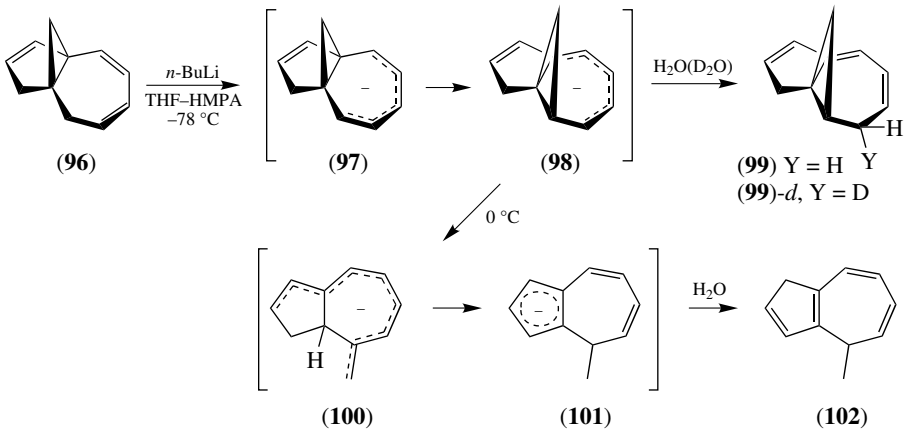
Miscellaneous

Review articles have addressed advances in photochemical generation and reactions of carbanions,[165] the [1,2]-Wittig rearrangement stereochemistry and synthetic application,[167] and the aza-Wittig rearrangement.[168]



SCHEME 6

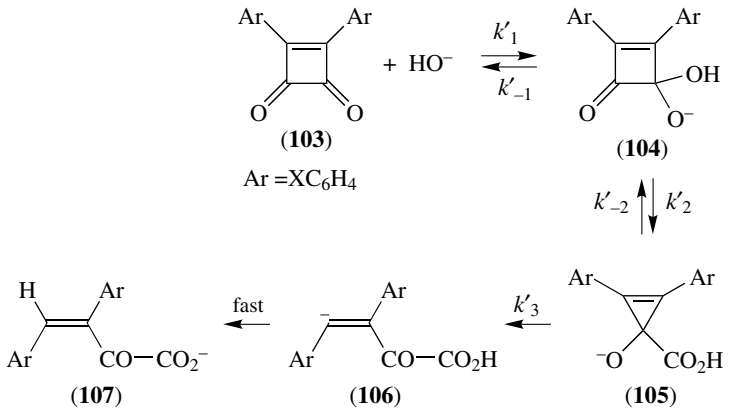
The discovery that a mixture of (*Z*)-(**94a**) and (*Z*)-(**94b**), on treatment with LDA, forms only (*Z*)-(**95a**) and (*Z*)-(**95b**) is consistent with an intramolecular mechanism (e.g. Scheme 6) for this new imino-Wittig rearrangement of hydroximates; alternative radical pathways have also been discussed for reactions of *Z*- and *E*-isomers.[169]



SCHEME 7

The tricyclo[5.3.1.0]undecatrienyl anion (**97**) undergoes circumambulatory rearrangement at −78°C to form anion (**98**) which is trapped by D_2O at the least hindered *anti* face to give (**99**)-d_1.[170] At higher temperature (**98**) is converted to (**102**), as indicated in Scheme 7.

Methanol-*O*-*d*, methyl nitrite, and dimethyl disulfide have been examined as potential chemical probes for distinguishing between alkoxides and enolates in the gas phase.[171] Methanol-*O*-*d* proved to be unsuitable and methyl nitrite reacts too slowly; in contrast, the reactive ambident behaviour of dimethyl disulfide results in elimination across the C—S bond on reaction with alkoxides ('hard bases') and attack at sulfur by enolates ('soft bases'). This probe has been applied to investigation of the anionic oxy-Cope rearrangement. The dianionic oxy-Cope rearrangement is a key step in a squarate ester cascade involving stereoinduced introduction of two alkenyllithium reagents *cis* to each other.[172]

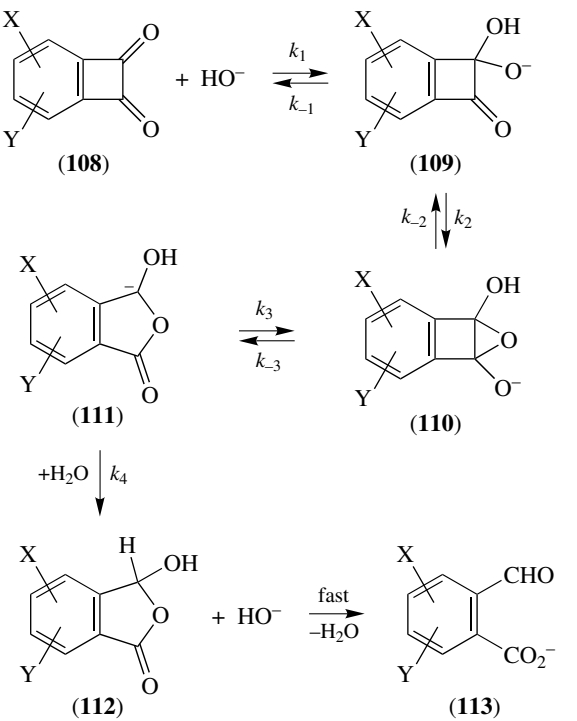


SCHEME 8

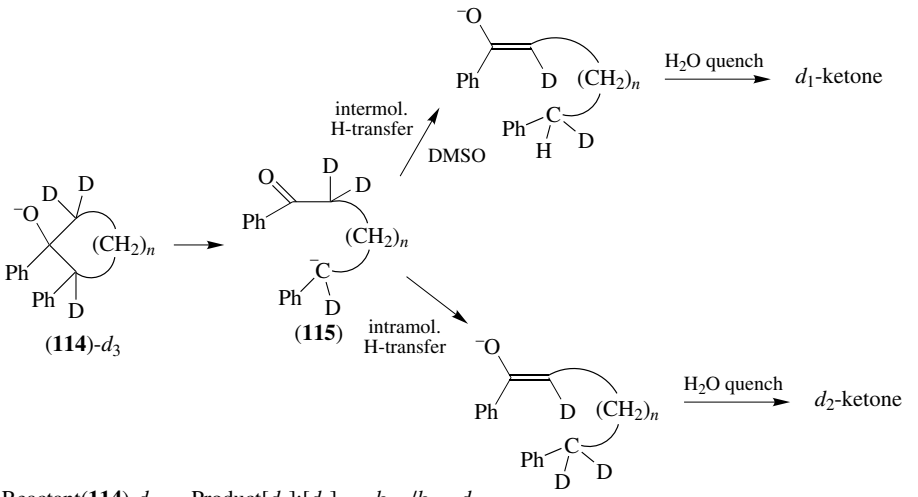
Base-catalysed ring fission of 3,4-diphenylcyclobut-3-ene-1,2-diones (**103**) in 50% (v/v) aqueous DMSO proceeds by rapid reversible addition of hydroxide ion followed by rate-determining benzilic acid-type rearrangement to form an intermediate 1-hydroxycyclopropane-1-carboxylic acid which ring opens to the corresponding (*Z*)-2-oxo-3,4-diphenylbut-3-enoic acid (Scheme 8).[173] This is supported by the value of Hammett $\rho = 1.3$ (for variation of substituents on one or both rings), the kinetic solvent effects, and the three-oxygen enrichment of (**107**) from reaction of (**103**) in 50% $H_2{}^{18}O$–DMSO.

In contrast, for reaction of benzocyclobutene-1,2-diones (**108**) to give 2-sulfonylbenzoic acids (**113**) in water–DMSO, $\rho = 3.6$, $k_2^{D_2O}/k_2^{H_2O} = 1.7$, and reaction is believed to proceed as shown in Scheme 9, with rate-determining conversion of (**110**) to (**111**) or (**109**) to (**110**).[174]

Rates of ring openings of 1,2-diphenylcycloalkanols in dimesyl sodium–DMSO increase in the ring-size order $6 < 5 \ll 7 < 9 < 8$ with a spread in reactivities of ca 10^6; correlation with estimates of strain release is poor but improved on consideration of entropic factors.[175] Results of isotopic labelling experiments (Scheme 10) suggest that for (**114d**) the intermediate benzylic carbanion is formed by rate-determining C—C bond cleavage and protonated intermolecularly by DMSO. In the case of (**114a**) proton transfer is rate limiting and occurs by both inter- and intra-molecular routes.



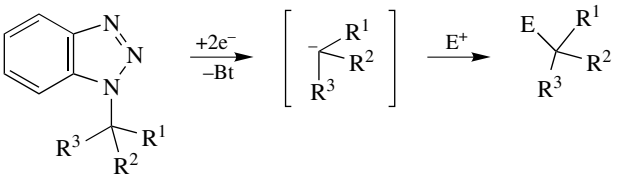
SCHEME 9



Reactant(**114**)-d_3	Product[d_1]:[d_2]	k_{114}/k_{114}-d_3
a; (n = 2)	65:35	2.47
b; (n = 3)	–	–
c; (n = 4)	42:58	1.37
d; (n = 5)	95:5	1.43

SCHEME 10

The first report of direct carbanion formation by acyclic C—N bond cleavage has exploited the benzotriazolyl leaving group in a novel transformation promoted by lithium in THF (Scheme 11).[176]



(**116**)

a; R^1, R^2 = Ph, R^3 = H
b; R^1 = Ph, R^2, R^3 = H
c; R^1 = CH═CH_2, R^2, R^3 = H

SCHEME 11

The synthetic application of vicarious nucleophilic substitution, whereby hydrogen of an electrophilic arene is replaced by an α-functionalized alkyl substituent, has been reviewed;[177] the sequence usually involves attack on a nitroalkene by a carbanion containing a leaving group X at the carbanionic centre, β-elimination of HX from the σ-adduct, and rearomatization on subsequent protonation.

Direct and nearly quantitative spectral observation of radical intermediates has provided evidence of single electron transfer on reaction of the sterically hindered 9-mesitylfluorenyl anion with methyl iodide.[178] Comparisons with earlier results for 9-

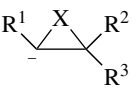
phenylfluorenyl anion, which is more reactive towards MeI yet unreactive towards hindered iodides, suggest that the donor carbanion reacts by an 'inner-sphere' electron transfer which requires close approach to the alkyl iodide. Hexakis(trifluoromethyl)-cyclopentadiene has been formed from pentabis(trifluoromethyl)cyclopentadienide ion on reaction with one electron transfer agent.[179] Novel nucleophilic addition of fluorenide ion to fullerene C_{60} in THF has been reported.[180]

Gas-phase acidities for the different ring positions of phenyl radical and the corresponding C—H bond strengths for the phenide ion have been derived from a study of *o*-, *m*-, and *p*-benzyne negative ions generated in the gas phase.[181] Results of theoretical studies of *o*-, *m*-, and *p*-benzyne negative ions are in good agreement with experimental observations.[182]

The acidity of 1,3,5,7-tetranitrocubane, which features nitro groups on alternate corners of cubane, has been measured ($pK_a \approx 21$) and reactions of the corresponding *o*-nitro anion have been explored.[183]

A study of gas-phase reactions of benzyl and methoxide anions with alkyl formate and other esters has revealed some differences in behaviour of these anions of comparable basicity.[184] The delocalized benzyl anion and localized methoxide ion engage in exclusive transacylation and proton transfer, respectively, on reaction with alkyl formates. However, proton transfer is sufficiently exothermic to dominate when benzyl anion reacts with methyl acetate. Both anions react with methyl benzoate, methyl trifluoroacetate, and methyl cyanoformate by competing transacylation and S_N2 reactions.

A complex sequence of cyclization and ring-opening reactions (which achieves equivalence of the central carbons of $CH_2{=}C{=}CH^-$ and that of S=C=S) has been proposed to account for formation of thioketenyl anion on reaction of allenylanion with CS_2 and COS in the gas phase.[185]



(**117**) X = O
(**118**) X = NR_4

The chemistry of oxiranyl anions (**117**) and aziridinyl anions (**118**) has been reviewed[186] and tris-1,2,3-*p*-nitrophenylcyclopropene has been found to resist conversion to the corresponding anti-aromatic cyclopropenyl anion by deprotonation even though it has been estimated to have a pK_a of 32.[187]

Examples of highly enantio- and regio-selective aldol condensation reactions have featured in a review of organic synthesis and catalytic antibodies.[188]

Electrophilic Aliphatic Substitution

A kinetic study of structural effects on the *N*-nitrosation of amino acids by nitrite in aqueous solution has established that the dominant term in the rate equation corresponds to nitrosation by dinitrogen trioxide.[189] Nitrosation by intramolecular migration of the nitroso group from an initially nitrosated carboxylate group can compete when the transition state has a five- or six-membered ring structure. Nitrosation of *N*-methyl-4-tolylsulfonylguanidine involves rapid nitrosation of the *N*-

methyl nitrogen atom followed by slow, general-base-catalysed proton transfer;[190] proton transfer, from protonated nitrosourea to the solvent, has likewise been shown to occur in nitrosation of five ureas $RNHCONH_2$.[191] The mechanism of conversion of nitroalkenes RCH_2NO_2 to corresponding carboxylic acids RCO_2H on reaction with $NaNO_2$–AcOH in DMSO has been discussed.[192] The stereochemistry of the S_E2'' reaction of dienylmethylsilanes has been reviewed.[193]

References

[1] Blanksby, S. J., Dua, S., Bowie, J. H., and Sheldon, J. C., *J. Chem. Soc., Chem. Commun.*, **1997**, 1833.
[2] Arnett, E. M., Flowers, R. A., Ludwig, R. T., Meekhof, A. E., and Walek, S. A., *J. Phys. Org. Chem.*, **10**, 499 (1997).
[3] Römer, B., Janaway, G. A., and Brauman, J. I., *J. Am. Chem. Soc.*, **119**, 2249 (1997).
[4] Moore, L., Lubinski, R., Baschky, M. C., Dahlke, G. D., Hare, M., Arrowood, T., Glasovac, Z., Eckert-Maksic, M., and Kass, S. R., *J. Org. Chem.*, **62**, 7390 (1997).
[5] Nir, M., Shapiro, I. O., and Rabinovitz, M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 329.
[6] Kasmai, H. S. and Liu, R., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1605.
[7] Butenschön, H., *Angew. Chem., Int. Ed. Engl.*, **36**, 1695 (1997).
[8] Chan, M. S. W. and Arnold, D. R., *Can. J. Chem.*, **75**, 192 (1997).
[9] Shabtai, E., Rabinovitz, M., König, B., Knieriem, B., and de Meijere, A., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2589.
[10] Wakahara, T., Kodama, R., Akasaka, T., and Ando, W., *Bull. Chem. Soc. Jpn*, **70**, 665 (1997).
[11] Sekiguchi, A., Matsuo, T., Ebata, K., and Sakurai, H., *Chem. Lett.*, **1996**, 1133.
[12] Meier, H., Bub, M., and Adam, M., *Liebigs Ann.*, **1996**, 2131.
[13] Alkorta, I. and Elguero, J., *Tetrahedron*, **53**, 9741 (1997).
[14] Wiberg, K. B., Hammer, J. D., Todd, A. K., and Zilm, K., *Tetrahedron Lett.*, **38**, 323 (1997).
[15] Balcioglu, N., Sevin, F., Evin, O., and Peynircioglu, B., *Ber. Bunsen-Ges. Phys. Chem.*, **100**, 1723 (1996); *Chem. Abs.*, **126**, 103816 (1997).
[16] Grabowski, J. J., *J. Chem. Soc., Chem. Commun.*, **1997**, 255.
[17] Galęzowski, W., Stańczyk, M., and Jarczewski, A., *Can. J. Chem.*, **75**, 285 (1997).
[18] Galęzowski, W., Stańczyk, M., Grześkowiak, I., and Jarczewski, A., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2647.
[19] Streitwieser, A., Wang, G. P., and Bors, D. A., *Tetrahedron*, **53**, 10103 (1997).
[20] Yoshioka, Y., Yamanaka, S., Yamada, S., Kawakami, T., Nishino, M., Yamaguchi, K., and Nishinaga, A., *Bull. Chem. Soc. Jpn*, **69**, 2701 (1996).
[21] Ridvan, L. and Závada, J., *Tetrahedron*, **53**, 14793 (1997).
[22] Saito, S., Ito, M., and Yamamoto, H., *J. Am. Chem. Soc.*, **119**, 611 (1997).
[23] Saito, S., Shimada, I., Takamori, Y., Tanaka, M., Maruoka, K., and Yamamoto, H., *Bull. Chem. Soc. Jpn*, **70**, 1671 (1997).
[24] Ochiai, M., Shu, T., Nagaoka, T., and Kitagawa, Y., *J. Org. Chem.*, **62**, 2130 (1997).
[25] Penenory, A. B. and Rossi, R. A., *Gazz. Chim. Ital.*, **125**, 605 (1995); *Chem. Abs.*, **125**, 275013 (1996).
[26] Lukach, A. E., Santiago, A. N., and Rossi, R. A., *J. Org. Chem.*, **62**, 4260 (1997).
[27] Wong, J.-W., Natalie, K. J., Nwokogu, G. C., Pisipati, J. S., Flaherty, P. T., Greenwood, T. D., and Wolfe, J. F., *J. Org. Chem.*, **62**, 6152 (1997).
[28] Yamataka, H., Sasaki, D., Kuwatani, Y., Mishima, M., and Tsuno, Y., *Chem. Lett.*, **1997**, 271.
[29] Yamataka, H., Sasaki, D., Kuwatani, Y., Mishima, M., and Tsuno, Y., *J. Am. Chem. Soc.*, **119**, 9975 (1997).
[30] Evans, D. A., Coleman, P. J., and Côté, B., *J. Org. Chem.*, **62**, 788 (1997).
[31] Guthrie, J. P. and Guo, J., *J. Am. Chem. Soc.*, **118**, 11472 (1996).
[32] Bowden, K. and Brownhill, A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 997.
[33] Kobayashi, S. and Nagayama, S., *J. Org. Chem.*, **62**, 232 (1997).
[34] Gennari, C., Moresca, D., Vulpetti, A., and Pain, G., *Tetrahedron*, **53**, 5593 (1997).
[35] Gennari, C., Vulpetti, A., and Pain, G., *Tetrahedron*, **53**, 5909 (1997).
[36] Denmark, S. E., Wong, K.-T., and Stavenger, R. A., *J. Am. Chem. Soc.*, **119**, 2333 (1997).
[37] Markó, I. E., Giles, P. R., and Hindley, N. J., *Tetrahedron*, **53**, 1015 (1997).
[38] Murray, W. V., Turchi, I. J., and Bussolari, J. C., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2715.
[39] Ornum, S. G. V., Li, J., Kubiak, G. G., and Cook, J. M., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 3471.

[40] Tokoroyama, T. and Kusaka, H., *Can. J. Chem.*, **74**, 2487 (1996).
[41] Pellissier, H., Michellys, P.-V., and Santelli, M., *J. Org. Chem.*, **62**, 5588 (1997).
[42] Kawabata, T., Wirth, T., Yahiro, K., Hideo, S., and Fuji, K., *ICR Annu. Rep.*, **3**, 36 (1996); *Chem. Abs.*, **127**, 12981 (1997).
[43] Ruano, J. L. G., Barros, D., Maestro, M. C., Araya-Maturana, R., and Fischer, J., *J. Org. Chem.*, **61**, 9462 (1996).
[44] Wedler, C., Ludwig, R., and Schick, H., *Pure Appl. Chem.*, **69**, 605 (1997).
[45] Fujieda, H., Kanai, M., Kambara, T., Iida, A., and Tomioka, K., *J. Am. Chem. Soc.*, **119**, 2060 (1997).
[46] Meyers, A. I., Seefeld, M. A., Lefker, B. A., and Blake, J. F., *J. Am. Chem. Soc.*, **119**, 4565 (1997).
[47] Le Bail, M., Aitken, D. J., Vergne, F., and Husson, H.-P., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1681.
[48] Okada, M., Kitagawa, O., Hanano, T., and Taguchi, T., *Tetrahedron*, **53**, 6825 (1997).
[49] Okajima, T. and Fukazawa, Y., *Chem. Lett.*, **1997**, 81.
[50] Dell'Erba, C., Novi, M., Petrillo, G., and Tavani, C., *Tetrahedron*, **53**, 2125 (1997).
[51] El-Taher, S., *Int. J. Quantum Chem.*, **62**, 419 (1997); *Chem. Abs.*, **126**, 317074 (1997).
[52] El-Taher, S. and Elnagdi, M. H., *Heteroat. Chem.*, **8**, 299 (1997); *Chem. Abs.*, **127**, 220289 (1997).
[53] Carlier, P. R., Lo, K. M., Lo, M. M.-C., Lo, P. C.-K., and Lo, C. W.-S., *J. Org. Chem.*, **62**, 6316 (1997).
[54] Gololobov, Y. G., Kardanov, N. A., Khroustalyov, V. N., and Petrovskii, P. V., *Tetrahedron Lett.*, **38**, 7437 (1997).
[55] Miyashita, A., Numata, A., Suzuki, Y., Iwamoto, K.-i., and Higashino, T., *Chem. Lett.*, **1997**, 697.
[56] Katagiri, T., Akizuki, M., Kuriyama, T., Shinke, S., and Uneyama, K., *Chem. Lett.*, **1997**, 549.
[57] Zheng, Z. and Cheng, J., *Chin. Sci. Bull.*, **42**, 292 (1997); *Chem. Abs.*, **127**, 135444 (1997).
[58] Magnus, N. and Magnus, P., *Tetrahedron Lett.*, **38**, 3491 (1997).
[59] Makosza, M. and Krylova, I., *Liebigs Ann./Recl.*, **1997**, 2337.
[60] Pyne, S. G., Dong, Z., Skelton, B. W., and White, A. H., *J. Org. Chem.*, **62**, 2337 (1997).
[61] Ruano, J. L. G., Fernández, I., del Prado Catalina, M., and Cruz, A. A., *Tetrahedron: Asymmetry*, **7**, 3407 (1996).
[62] Dishington, A. P., Douthwaite, R. E., Mortlock, A., Muccioli, A. B., and Simpkins, N. S., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 323.
[63] Sawamura, M., Nakayama, Y., Tang, W.-M., and Ito, Y., *J. Org. Chem.*, **61**, 9090 (1996).
[64] Yamaguchi, M., Igarashi, Y., Reddy, R. S., Shiraishi, T., and Hirama, M., *Tetrahedron*, **53**, 11223 (1997).
[65] Kurtz, K. A. and Fitzpatrick, P. F., *J. Am. Chem. Soc.*, **119**, 1155 (1997).
[66] Li, A.-H., Dai, L.-X., and Aggarwal, V. K., *Chem. Rev.*, **97**, 2341 (1997).
[67] Armstrong, A., *Prep. Alkenes*, **1996**, 59; *Chem. Abs.*, **126**, 276964 (1997).
[68] Walker, B. J., *Organophosphorus Chem.*, **27**, 264 (1996); *Chem. Abs.*, **126**, 89422 (1997).
[69] Vedejs, E. and Peterson, M. J., *Adv. Carbanion Chem.*, **2**, 1 (1996); *Chem. Abs.*, **126**, 171626 (1997).
[70] Nicolau, K. C., Härter, M. W., Gunzner, J. L., and Nadin, A., *Liebigs Ann./Recl.*, **1997**, 1283.
[71] Makomo, H., Saquet, M., Simeon, F., Masson, S., About-Jaudet, E., Collignon, N., and Gulea Purcarescu, M., *Phosphorus Sulfur Silicon Relat. Elem.*, **1996**, 109; *Chem. Abs.*, **125**, 328787 (1997).
[72] Kabachnic, M. I. and Mastryukova, T. A., *Izv. Akad. Nauk, Ser. Khim.*, **1996**, 634; *Chem. Abs.*, **125**, 246913 (1996).
[73] Boulos, L. S. and Arsanious, M. H. N., *Tetrahedron*, **53**, 3649 (1997).
[74] Nishizawa, M., Komatsu, Y., Garćia, D. M., Noguchi, Y., Imagawa, H., and Yamada, H., *Tetrahedron Lett.*, **38**, 1215 (1997).
[75] Boulos, L. S. and Yakout, E.-S. M. A., *Heteroat. Chem.*, **8**, 253; *Chem. Abs.*, **127**, 34293 (1997).
[76] Otten, P. A., Davies, H. M., van Steenis, J. H., Gorter, S., and van der Gen, A., *Tetrahedron*, **53**, 10527 (1997).
[77] Moorhoff, C. M., *Tetrahedron*, **53**, 2241 (1997).
[78] Kranz, M., Denmark, S. E., Swiss, K. A., and Wilson, S. R., *J. Org. Chem.*, **61**, 8551 (1996).
[79] Aggarwal, V. K., Boccardo, G., Worrall, J. M., Adams, H., and Alexander, R., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 11.
[80] Aggarwal, V. K., Schade, S., and Adams, H., *J. Org. Chem.*, **62**, 1139 (1997).
[81] Fleming, F. F., Hussain, Z., Weaver, D., and Norman, R. E., *J. Org. Chem.*, **62**, 1305 (1997).
[82] Aggarwal, V. K., Calamai, S., and Ford, J. G., *J. Chem. Soc., Perkin Trans. 21*, **1997**, 593.
[83] Brunck, J.-S., Deicke, B., and Voss, J., *Tetrahedron*, **53**, 2459 (1997).
[84] Collado, I., Domínguez, C., Ezquerra, J., and Pedregal, C., *Tetrahedron Lett.*, **38**, 2133 (1997).
[85] Tang, Y., Huang, Y.-Z., Dai, L.-X., Sun, J., and Xia, W., *J. Org. Chem.*, **62**, 954 (1997).
[86] Alvarez-Ibarra, C., Csákÿ, A. G., Martinez-Santos, E., and Quiroga, M. L., *Tetrahedron*, **53**, 3679 (1997).
[87] Kauw, J., Born, M., Ingemann, S., and Nibbering, N. M. M., *Rapid Commun. Mass Spectrom.*, **10**, 1400 (1996); *Chem. Abs.*, **125**, 300328 (1996).
[88] Mangalagiu, I. I. and Petrovanu, M. G., *Tetrahedron*, **53**, 4411 (1997).

[89] Kirihara, M., Takuwa, T., Takizawa, S., and Momose, T., *Tetrahedron Lett.*, **38**, 2853 (1997).
[90] Ricke, R. D. and Hanson, M. V., *Tetrahedron*, **53**, 1925 (1997).
[91] Gawley, R. E., *Curr. Org. Chem.*, **1**, 71 (1997); *Chem. Abs.*, **127**, 121763 (1997).
[92] McKinley, J., Aponick, A., Raber, J. C., Fritz, C., Montgomery, D., and Wigal, C. T., *J. Org. Chem.*, **62**, 4874 (1997).
[93] Paquette, L. A. and Doyon, J., *J. Org. Chem.*, **62**, 1723 (1997).
[94] Paquette, L. A., Kuo, L. H., Hamme, A. T., Kreuzholz, R., and Doyon, J., *J. Org. Chem.*, **62**, 1730 (1997).
[95] Cainelli, G., Giacomini, D., Galletti, P., and Marini, A., *Angew. Chem., Int. Ed. Engl.*, **35**, 2849 (1996).
[96] Achmatowicz, O., Szechner, B., and Maurin, J. K., *Tetrahedron*, **53**, 6035 (1997).
[97] Beak, P. and Pfeifer, L. A., *J. Phys. Org. Chem.*, **10**, 537 (1997).
[98] Leriverend, C., Metzner, P., Capperucci, A., and Degl'Innocenti, A., *Tetrahedron*, **53**, 1323 (1997).
[99] Norsikian, S., Marek, I., Poisson, J.-F., and Normant, J. F., *J. Org. Chem.*, **62**, 4898 (1997).
[100] Wiberg, K. B. and Marquez, M., *Tetrahedron Lett.*, **38**, 1685 (1997).
[101] Krief, A. and Bousbaa, J., *Tetrahedron Lett.*, **38**, 6291 (1997).
[102] Hoffmann, R. W., Koberstein, R., Remacle, B., and Krief, A., *J. Chem. Soc., Chem. Commun.*, **1997**, 2189.
[103] Vieth, S., Costisella, B., and Schneider, M., *Tetrahedron*, **53**, 9623 (1997).
[104] Fossey, J., Ghigo, G., Tonachini, G., and Venturello, P., *Tetrahedron*, **53**, 7937 (1997).
[105] Enders, D., Nübling, C., and Schubert, H., *Liebigs Ann./Recl.*, **1997**, 1089.
[106] Boesveld, W. M., Hitchcock, P. B., and Lappert, M. F., *J. Chem. Soc., Chem. Commun.*, **1997**, 2091.
[107] Woo, S., Parvez, M., and Keay, B. A., *Can. J. Chem.*, **75**, 665 (1997).
[108] Schlosser, M. and Wei, H.-x., *Tetrahedron*, **53**, 1735 (1997).
[109] Stanetty, P. and Mihovilovic, M. D., *J. Org. Chem.*, **62**, 1514 (1997).
[110] Yamazaki, T., Umetani, H., and Kitazume, T., *Tetrahedron Lett.*, **38**, 6705 (1997).
[111] Yamazaki, N. and Kibayashi, C., *Tetrahedron Lett.*, **38**, 4623 (1997).
[112] Krief, A., de Vos, M. J., De Lombart, S., Bosret, J., and Couty, F., *Tetrahedron Lett.*, **38**, 6295 (1997).
[113] Badorrey, R., Cativiela, C., Díaz-de-Villegas, M. D., and Gálvez, J. A., *Tetrahedron*, **53**, 1411 (1997).
[114] Akhoon, K. M. and Myles, D. C., *J. Org. Chem.*, **62**, 6041 (1997).
[115] Bailey, W. F., Croteau, A. A., and Rivera, A. D., *Tetrahedron Lett.*, **38**, 4047 (1997).
[116] Asami, M. and Inoue, S., *Bull. Chem. Soc. Jpn*, **70**, 1687 (1997).
[117] Guo, C., Qiu, J., Zhang, X., Verdugo, D., Larter, M. L., Christie, R., Kenney, P., and Walsh, P. J., *Tetrahedron*, **53**, 4145 (1997).
[118] Andersson, P. G., Guijarro, D., and Tanner, D., *J. Org. Chem.*, **62**, 7364 (1997).
[119] Ukaji, Y., Simizu, Y., Kenmoku, Y., Ahmed, A., and Inomata, K., *Chem. Lett.*, **1997**, 59.
[120] Frantz, D. E., Singleton, D. A., and Snyder, J. P., *J. Am. Chem. Soc.*, **119**, 3383 (1997).
[121] Yanagisawa, A. and Yamamoto, H., *Adv. Carbanion Chem.*, **2**, 87 (1996); *Chem. Abs.*, **126**, 171627 (1997).
[122] Cokley, T. M., Harvey, P. J., Marshall, R. L., McCluskey, A., and Young, D. J., *J. Org. Chem.*, **62**, 1961 (1997).
[123] Iseki, K., Kuroki, Y., Takahashi, M., Kishimoto, S., and Kobayashi, Y., *Tetrahedron*, **53**, 3513 (1997).
[124] Guthrie, J. P., *J. Am. Chem. Soc.*, **119**, 1151 (1997).
[125] Nayak, A. K. and Sarkar, S. K., *Int. J. Chem. Kinet.*, **29**, 767 (1997).
[126] Hare M., Emrick, T., Eaton, P. E., and Kass, S. R., *J. Am. Chem. Soc.*, **119**, 237 (1997).
[127] Tupitsyn, I. F., Zatsepina, N. N., and Popov, A. S., *Zh. Obshch. Khim.*, **66**, 1308 (1996); *Chem. Abs.*, **126**, 117706 (1997).
[128] Verth, J. E. V. and Saunders, W. H., *J. Org. Chem.*, **62**, 5743 (1997).
[129] Bordwell, F. G., Zhang, S., Eventova, I., and Rappoport, Z., *J. Org. Chem.*, **62**, 5371 (1997).
[130] Keeffe, J. R. and Kresge, A. J., *Can. J. Chem.*, **74**, 2481 (1996).
[131] Xie, L., Isenberger, K. M., Held, G., and Dahl, L. M., *J. Org. Chem.*, **62**, 7516 (1997).
[132] Toriyama, M., Sugasawa, K., Shindo, M., Tokutake, N., and Koga, K., *Tetrahedron Lett.*, **38**, 567 (1997).
[133] Yanagisawa, A., Ishihara, K., and Yamamoto, H., *Synlett*, **1997**, 411; *Chem. Abs.*, **127**, 50086 (1997).
[134] Fehr, C., *Angew. Chem., Int. Ed. Engl.*, **35**, 2567 (1996).
[135] Kosugi, H., Hoshino, K., and Uda , H., *Tetrahedron Lett.*, **38**, 6861 (1997).
[136] Tobin, J. B. and Frey, P. A., *J. Am. Chem. Soc.*, **118**, 12253 (1996).
[137] Sun, X., Kenkre, S. L., Remenar, J. F., Gilchrist, J. H., and Collum, D. B., *J. Am. Chem. Soc.*, **119**, 4765 (1997).
[138] Rios, A. and Richard, J. P., *J. Am. Chem. Soc.*, **119**, 8375 (1997).

[139] Mohrig, J. R., Rosenberg, R. E., Apostol, J. W., Bastienaansen, M., Evans, J. W., Franklin, S. J., Frisbie, C. D., Fu, S. S., Hamm, M. L., Hirose, C. B., Hunstad, D. A., James, T. L., King, R. W., Larson, C. J., Latham, H. A., Owen, D. A., Stein, K. A., and Warnet, R., *J. Am. Chem. Soc.*, **119**, 479 (1997).
[140] Rosenberg, R. E. and Mohrig, J. R., *J. Am. Chem. Soc.*, **119**, 487 (1997).
[141] Moutiers, G., Le Guével, E., Villien, L., and Terrier, F., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 7.
[142] Moutiers, G., Thuet, V., and Terrier, F., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1479.
[143] Ellis, N. A. and Hubbard, C. D., *J. Solution Chem.*, **26**, 369 (1997); *Chem. Abs.*, **127**, 161457 (1997).
[144] Bernasconi, C. F., Wenzel, P. J., Keeffe, J. R., and Gronert, S., *J. Am. Chem. Soc.*, **119**, 4008 (1997).
[145] Bernasconi, C. F. and Wenzel, P. J., *J. Am. Chem. Soc.*, **118**, 11446 (1996).
[146] Gandler, J. R., Saunders, O. L., and Barbosa, R., *J. Org. Chem.*, **62**, 4677 (1997).
[147] Schroeder, G., Brzezinski, B., Leska, B., Gierczyk, B., and Jarczewski, A., *Bull. Pol. Acad. Sci., Chem.*, **44**, 45 (1996); *Chem. Abs.*, **125**, 300380 (1996).
[148] Stoelting, D. T., Ludwig, R. T., and Arnett, E. M., *Heteroat. Chem.*, **7**, 481 (1996); *Chem. Abs.*, **126**, 74461 (1997).
[149] Kim, W. K., Ryu, W. S., Sohn, C. K., Lee, B.-S., Kim, C. K., and Lee, I., *Bull. Korean Chem. Soc.*, **18**, 208 (1997); *Chem. Abs.*, **126**, 27737 (1997).
[150] Ren, J., Workman, D. B., and Squires, R. R., *Angew. Chem., Int. Ed. Engl.*, **36**, 2230 (1997).
[151] Barletta, G. L., Zou, Y., Huskey, W. P., and Jordan, F., *J. Am. Chem. Soc.*, **119**, 2356 (1997).
[152] Snieckus, V., *NATO ASI Ser., Ser. E*, **320**, 191 (1996); *Chem. Abs.*, **125**, 300154 (1996).
[153] Mongin, F. and Schlosser, M., *Tetrahedron Lett.*, **38**, 1559 (1997).
[154] Bücker, H. H., Nibbering, N. M. M., Espinos, D., Mongin, F., and Schlosser, M., *Tetrahedron Lett.*, **38**, 8519 (1997).
[155] Andrade, P. B. M. and Riveros, J. M., *J. Mass Spectrom.*, **31**, 767 (1996); *Chem. Abs.*, **125**, 247111 (1996).
[156] Carroll, W. A. and Zhang, X., *Tetrahedron Lett.*, **38**, 2637 (1997).
[157] Black, W. C., Guay, B., and Scheuermeyer, F., *J. Org. Chem.*, **62**, 758 (1997).
[158] Stratakis, M., *J. Org. Chem.*, **62**, 3024 (1997).
[159] Baker, R. W., Liu, S., Sargent, M. V., Skelton, B. W., and White, A. H., *Aust. J. Chem.*, **50**, 831 (1997).
[160] Turnbull, K. and Krein, D. M., *Tetrahedron Lett.*, **38**, 1165 (1997).
[161] Gross, K. M. B., Jun, Y. M., and Beak, P., *J. Org. Chem.*, **62**, 7679 (1997).
[162] Power, T. D. and Sebastian, J. F., *Tetrahedron Lett.*, **37**, 9127 (1996).
[163] Azami, H., Barrett, D., Chiba, T., Fujikawa, A., Sakane, K., and Shirai, F., *Chem. Pharm. Bull.*, **45**, 209 (1997); *Chem. Abs.*, **126**, 144010 (1997).
[164] Brousmiche, D., Shukla, D., and Wan, P., *J. Chem. Soc., Chem. Commun.*, **1997**, 709.
[165] Budac, D. and Wan, P., *Adv. Carbanion Chem.*, **2**, 147 (1996); *Chem. Abs.*, **126**, 171107 (1997).
[166] Tomooka, K., Yamamoto, H., and Nakai, T., *Liebigs Ann./Recl.*, **1997**, 1275.
[167] Tomooka, K., *Kagaku to Kogyo (Tokyo)*, **50**, 159 (1997); *Chem. Abs.*, **126**, 156951 (1997).
[168] Vogel, C., *Synthesis*, **1997**, 497; *Chem. Abs.*, **127**, 34068 (1997).
[169] Miyata, O., Koizumi, T., Ninomiya, I., and Naito, T., *J. Org. Chem.*, **61**, 9078 (1996).
[170] Oda, M., Masaki, Y., Okazaki, Y., Kajioka, T., Izawa, M., Miyatake, R., Kuroda, S., and Scott, L. T., *Chem. Lett.*, **1997**, 595.
[171] Lee, J. K. and Grabowski, J. J., *J. Org. Chem.*, **61**, 9422 (1996).
[172] Paquette, L. A., Kuo, L. H., and Doyon, J., *J. Am. Chem. Soc.*, **119**, 3038 (1997).
[173] Al-Najjar, A., Bowden, K., and Horri, M. V., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 993.
[174] Bowden, K. and Horri, M. V., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 989.
[175] Moosavi, S. M., Beddoes, R. S., and Watt, C. I. F., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1585.
[176] Katritzky, A. R. and Qi, M., *J. Org. Chem.*, **62**, 4116 (1997).
[177] Makosza, M. and Wojciechowski, K., *Liebigs Ann./Recl.*, **1997**, 1805.
[178] Tolbert, L. M., Bedlek, J., Terapane, M., and Kowalik, J., *J. Am. Chem. Soc.*, **119**, 2291 (1997).
[179] Chambers, R. D., Gray, W. K., Vaughan, J. F. S., Korn, S. R., Médebielle, M., Batsanov, A. S., Lehmann, C. W., and Howard, J. A. K., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 135.
[180] Komatsu, K., Murata, Y., Wang, G.-W., and Wan, T. S. M., *Proc. Electrochem. Soc.*, **1996**, 96; *Chem. Abs.*, **125**, 300591 (1996).
[181] Wenthold, P. G., Hu, J., and Squires, R. R., *J. Am. Chem. Soc.*, **118**, 11865 (1996).
[182] Nash, J. J. and Squires, R. R., *J. Am. Chem. Soc.*, **118**, 11872 (1996).
[183] Lukin, K. A., Li, J., Eaton, P. E., Kanomata, N., Hain, J., Punzalan, E., and Gilardi, R., *J. Am. Chem. Soc.*, **119**, 9591 (1997).
[184] Gatev, G. G., Zhong, M., and Brauman, J. I., *J. Phys. Org. Chem.*, **10**, 531 (1997).
[185] DePuy, C. H., Bierbaum, V. M., Robinson, M. S., Davico, G. E., and Gareyev, R., *Tetrahedron*, **53**, 9847 (1997).

[186] Satoh, T., *Chem. Rev.*, **96**, 3303 (1996).
[187] Klicic J., Rubin, Y., and Breslow, R., *Tetrahedron*, **53**, 4129 (1997).
[188] Hiratake, J. and Oda, J., *Yuki Gosei Kagaku Kyokaishi*, **55**, 452 (1997); *Chem. Abs.*, **127**, 17218 (1997).
[189] Gil, R., Casado, J., and Izquierdo, C., *Int. J. Chem. Kinet.*, **29**, 495 (1997).
[190] Leis, J. R., Norberto, F., Moreira, J. A., and Iley, J., *J. Chem. Res. (S)*, **1997**, 88.
[191] Gonzalez Alatorre, G. and Linarejos, J. C., *Av. Ing. Quim.*, **5**, 228 (1995); *Chem. Abs.*, **127**, 65364 (1997).
[192] Matt, C., Wagner, A., and Mioskowski, C., *J. Org. Chem.*, **62**, 234 (1997).
[193] Fleming, I., Jones, G. R., Landais, Y., Leslie, C. P., Morgan, I. T., and Peukert, S., *Prog. Organosilicon Chem., [Jubilee Int. Symp. Organosilicon Chem.], 10th*, **1993**, 223; *Chem. Abs.*, **126**, 18911 (1997).

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CHAPTER 12

Elimination Reactions

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_E_1_cB_ Mechanisms

The degree to which fluorine-substituted ethyl carbanions (**1**–**3**) are stabilized by negative hyperconjugation has been examined at the MP2/6–31 + G*//MP2/6–31 + G* level.[1] The expected sensitivity to conformation and consequent weakening of the C—F bond *anti* to the unshared electron pair in the carbanion is revealed for that bond by the increase in length, the corresponding increase in charge on fluorine, and the ^{18}F–^{19}F equilibrium isotope effect on ionization of the conjugate acid. In order to determine whether the incipient carbanion of an *E*1*cB* reaction may also be stabilized by negative hyperconjugation, stationary points (**4**–**7**) for the reaction of hydroxide ion with 1,1,1-trifluoroethane were determined. Isotope effects for the ion–dipole complex (**5**) reveal little bonding change whereas KIEs for the proton transfer transition state (**6**) are substantial; the deuterium KIE suggests that the *anti* proton is about half transferred in the transition state and the isotope effect for *anti* fluorine is only 55–60% of its value in the product (**7**) (which requires relocation of H_2O before elimination can be completed). Consequently, the transition structure resembles that for a concerted *E*2 process rather than the proton transfer step of an *E*1*cB* reaction. Further calculations

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revealed that the corresponding KIEs for *E*2 reaction of HO^- with ethyl fluoride indeed differed little from those for the *E*1*cB* reaction of 1,1,1-trifluoroethane. Thus, the deprotonation step of the *E*1*cB* reaction involves concerted changes at both the α- and *β*-carbon atoms; if the intermediate carbanion is well stabilized by induction, resonance, or solvation there will be little weakening of the bond to the leaving group in the transition state for its formation, and vice versa. Consequently, the transition state for an *E*1*cB* reaction proceeding via a relatively unstable carbanion can resemble that for a concerted *E*2 reaction well before actual change of mechanism is dictated by further destabilization of the carbanion. This spectrum of behaviour is in keeping with suggestions of Gander and Jencks, who reasoned that the transformation from *E*1*cB* to *E*2 mechanism occurs with very little change in transition state structure.

$CF_2HCH_2^-$ (**1**) $CF_2CH_2^-$ (**2**) CF_3CFH^- (**3**)

$HO^- + CH_3CF_3 \longrightarrow HO\text{--}CH_3CF_3^-$
0 kcal (**4**) –19.0 kcal (**5**)

$[HO\text{--}H\text{--}CH_2CF_3]^-$ (**6**) –18.5 kcal $HOH\text{--}CH_3CF_3^-$ (**7**) –19.5 kcal

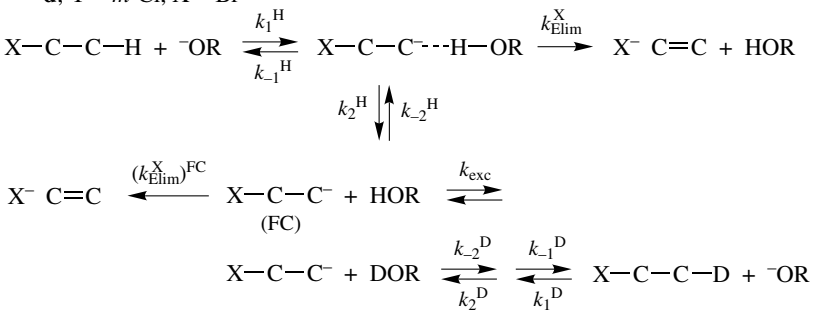
Mechanistic studies of alkoxide-promoted dehydrohalogenations of $C_6H_5CH_2CH_2X$ and various derivatives $YC_6H_4CHX'CH_2X$ and $YC_6H_4CHX'CHF_2X$ (where X = Br, Cl, or F and X′ = Br or Cl) have been extended to include MeO^-/MeOH-promoted dehydrohalogenations of (**8a**–**c**) and interpreted with reference to Scheme 1.[2] The Arrhenius behaviour of the primary KIEs, $(k^H/k^D)_{obs} = 3.40$, 3.49, 2.19 and $(k^H/k^T)_{obs} = 6.20$, 6.55, 3.56 for (**8a**), (**8b**), and (**8c**), respectively, has been used to calculate the internal return parameters, $a = k_1/k^X_{Elim}$. For (**8a**) and (**8b**), $a^H = 0.59$, $a^D = 0.13$–0.14, and $a^T = 0.07$, whereas for (**8c**) the values $a^H = 1.9$, $a^D = 0.50$, and $a^T = 0.28$ are indicative of greater internal return which resulted in the relatively low KIEs observed. Since $k_1 = k_{obs}(a + 1)$, it has been possible to estimate the respective values $k_1^H/k_1^D = 4.74$, 4.91, and 4.75 and $k_1^H/k_1^T = 9.20$, 9.75, and 9.17 for (**8a**), (**8b**) and (**8c**), respectively. Hence differences in the observed isotope effects are a consequence of variations in the amount of internal return and not variations in the degree of hydron transfer in the transition state. Likewise, the element effect $(k^{HBr}/k^{HCl}) = 29$, found on comparison of (**8d**) with (**8a**), has been shown to depend mainly on $k^{HBr}/k^{HCl} = 19$ for the hydron transfer step and not on the C—X bond breaking reflected in k^X_{Elim}. The kinetic isotope effect $k^{MeOD}/k^{MeOH} \approx 2.5$ is believed to be consistent with the loss of three methanols of solvation prior to the hydron transfer step.

The effects of reactant structures on the ketene-forming elimination reactions of aryl esters of substituted phenylacetic acids (**9**) and (**10**) with secondary amines in acetonitrile (Scheme 2) have been studied in anticipation that the transition state might have *E*1*cB*-like *E*2 character.[3] The reactions are second order for R_2NH–MeCN and

$YC_6H_4C^iHClCH_2X$

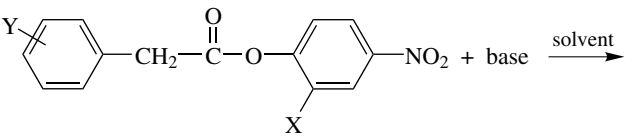
(**8**)

a; Y = *m*-Cl, X = Cl
b; Y = *m*-CF_3, X = Cl
c; Y = *p*-CF_3, X = F
d; Y = *m*-Cl, X = Br

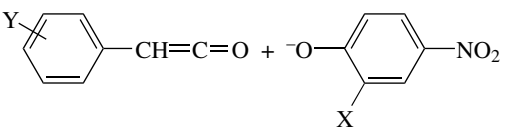


SCHEME 1

values of Brønsted $\beta = 0.44$–0.84 and $|\beta_{1g}| = 0.41$–0.50 decrease with the electron-withdrawing ability of Y; as the base strength becomes weaker the value of $\rho_H = 2.0$–3.6 (the Hammett slope at Y = H) changes little but $|\beta_{1g}|$ increases. Both ρ_H and β decrease with change of X from H to NO_2. The results are as expected, there being evidence that the reaction coordinate has a large horizontal component corresponding to proton transfer. The values of β, ρ_H and $|\beta_{1g}|$ are lower for the aqueous solvent system in which (**9e**) was found to react by concurrent *E*2 and *E*1*cB* mechanisms (as evidenced by corresponding dissection of the curvilinear dependence of k_{obs} vs free buffer concentration).



(**9**) X = H
(**10**) X = NO_2
Y = **a**; H, **b**; *p*-MeO, **c**; *m*-Cl
d; *m*-NO_2, **e**; *p*-NO_2

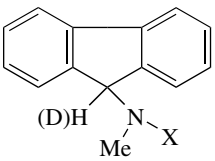


(**11**) (**12**)

Base–solvent = R_2N–MeCN,
$R_2N/R_2NH_2^+$–70% MeCN (aq.)
R_2NH = Bz(Pr^i)NH, Bu_2^iNH, Pr_2^iNH, 2,6-DMP

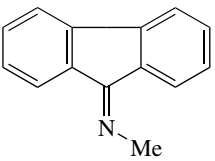
SCHEME 2

It has been concluded[4] that solvent- and hydroxide ion-promoted eliminative formation of imine (**14**) from (**13a**) in 25 vol.% acetonitrile in water occurs by the *E*2 mechanism for which $k^H/k^D = 4.8 \pm 0.2$ and 6.7 ± 0.2, respectively. Base-promoted reactions of the corresponding substrates (**16a**–**c**), which feature a much poorer leaving group, occurs by the reversible $E1cB_R$ mechanism as evidenced by complete incorporation of ^1H at the 9-position of the deuterated substrate (*d*-**16b**) after one half-life with MeO^-/MeOH; the apparent second-order dependence on base has been tentatively ascribed to a medium effect. In contrast, the strongly activated substrate (**16d**) undergoes desulfonative rearrangement to give (**17**) by intramolecular nucleophilic aromatic substitution involving rate-limiting general base catalysed hydron transfer for which $k_H/k_D = 5.8 \pm 0.3$ in MeO^-/MeOH; alternative mechanisms have been suggested.

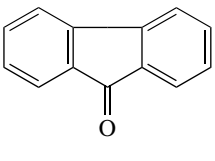


(**13**)

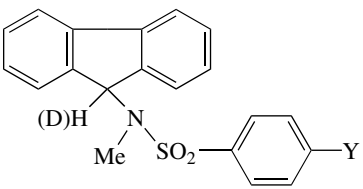
X = **a**; Cl, **b**; OCOPh



(**14**)

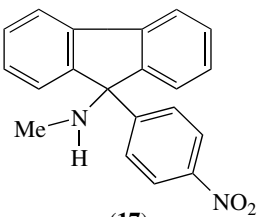


(**15**)



(**16**)

Y = **a**; OMe, **b**; Me, **c**; Br, **d**; NO_2

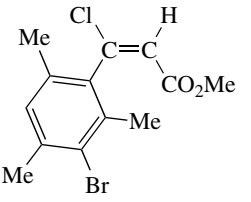


(**17**)

The pH–rate profile for unbuffered hydrolysis of glyceraldehyde-3-phosphate (6-3-P) has been attributed to hydrolysis of the monoanion of the phosphate monoester at pH < 4, spontaneous formation of glyceraldehyde from the phosphate dianion at pH 7–8, and, at higher pH, hydroxide-catalysed methylglyoxal formation. Reaction of the dianion is not subject to a solvent isotope effect and is believed to occur by the irreversible $E1cB_1$ mechanism whereby an enediolate intermediate, formed on rate-determining C(2) deprotonation, subsequently expels phosphate trianion by C—O bond breaking. The diethylacetal and 2-methyl-G-3-P do not hydrolyse under the same conditions.[5]

The kinetics of reaction of *O*-(*N*-arylcarbamoyl)benzophenone oximes in NaOMe–MeOH to give benzophenone oxime sodium salt and the corresponding methyl *N*-arylcarbamates have been studied.[6] The Hammett constants $\rho_{obs} = 0.68$ and $\rho_{k_2} = -1.32$ have been estimated for the $E1cB_R$ process for which k_2 governs conversion of the intermediate $ArN^-CO_2N{=}CPh_2$ to $ArN{=}C{=}O$ and $Ph_2C{=}NO^-$.

An attempt to study resolved ((*E*)-**18**) as a probe for the detailed mechanism of the Ad_N–*E* vinylic substitution reaction has been complicated by intervention of a competing reaction route; this is believed to involve a competing $(E1cB)_I$ elimination–addition, for which antiperiplanar orientation of H and Cl is not a requirement.[7] α-Deuterated (ca 50%) *E*- and *Z*-substitution products (which do not themselves exchange deuterium) are obtained on reaction with MeS^- in 9 : 1 CD_3CN–D_2O but no incorporation of deuterium in unreacted ((*E*)-**18**) occurs and neither does isomerism to ((*Z*)-**18**) precede elimination.



(**18**)

*E*2 Mechanisms

It has been argued that the accepted electromeric interpretation of Saytzeff orientation and its exceptions is unsound. A Unified Rule for Elimination (URE) has now been proposed to account for regioselectivity of eliminations of a wide range of substrates and reaction conditions.[8]

The interpretation is based on the balance of competition between 'nucleophile-led' reactions (via contact ion pairs or concerted and tending towards *E*1*cB*) and 'electrophile-led' reactions (the *E*1 extreme, via solvated ion pairs). The solvated ion pairs are favoured with better nucleofuges, and/or greater solvating power, and collapse via loss of the more hydride-like β-hydrogen; collapse of the contact ion pairs involves preferential loss of the most acidic β-hydrogen, and demands interaction with the nucleophile.

Ab initio calculations at the MP2/6–31+ G* level have been performed for gas-phase *E*2 elimination reactions of CH_3CH_2X (X = NH_3^+, Br, Cl, F, SH) promoted by NH_2^-, OH^-, F^-, PH_2^-, SH^-, and Cl^- in order to determine how changes in transition-state geometry, from reactant-like to product-like, influence kinetic isotope effects.[9] Secondary isotope effects (α-H) on leaving group departure are correlated with the hybridization at C_α in the transition state, whereas there is no such correlation between secondary (β-H) isotope effects and the transition state hybridization at C_β. The primary deuterium isotope effect is influenced markedly by the nucleophilic atom concerned but approach to a broad maximum for a symmetric transition structure can be discerned when due allowance is made for the element effect.

Computational results from a study of the gas-phase reaction of NH_2^- with $CH_3CH_2SCH_3$ are consistent with a mechanism proposed by Nibbering in 1987 and reveal that ethene is formed by α-deprotonation followed by an intramolecular *syn*-elimination.[10] Although the barrier for the *syn*-elimination is greater than for a

conventional *E*2 mechanism, there is energetic advantage for deprotonation which is effectively irreversible.

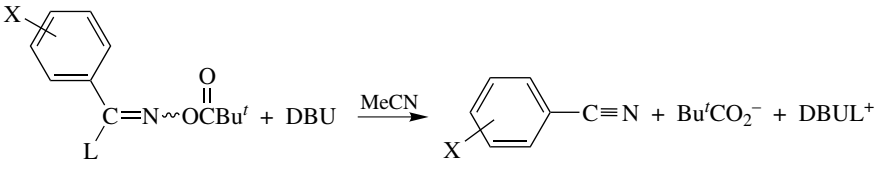
Density functional theory and a high-level *ab initio* procedure (G2+) have been used to explore the potential energy surface for the base-induced elimination reaction of fluoride ion with ethyl fluoride.[11] The DFT barriers are smaller and looser than those predicted by the *ab initio* method but the nature of the transition state cannot be defined with confidence since the predictions are unusually sensitive to the choice of functional and basis set. The results suggest that improvement in density functional methods will require fundamental change in the functionals themselves.

A study of the competitive reactivity of two good leaving groups within the same molecule has revealed that for gas-phase anionic elimination reactions, $X^- + YCH_2CH_2CH_2Z$, the kinetic regiochemistry is very sensitive to small differences in leaving group thermochemistry.[12] The 1,3-disubstituted framework enables intrinsic leaving group abilities to be compared without interference from other structural effects. For Y = Br, Z = Cl, Br^- is favoured as a leaving group over Cl^- by 8.4 kcal mol^{-1} in enthalpy. The observed elimination ratios (Br^-/Cl^-) for near-collision controlled reactions promoted by AcO^- (200 : 1), HO^- (6 : 1), MeO^- (91 : 1), *i*-AmO^- (95 : 1), and F^- (105 : 1) reveal that selectivity increases with the energy difference between attacking base and departing leaving group. For mixed diesters $RCO_2CH_2CH_2O_2CR'$ a difference in leaving group energetics of only 1.1 kcal mol^{-1} results in a propionate : acetate ratio of 2.5 : 1 when F^- is the base, and only 1.6 : 1 when MeO^- is used. Interpretation of results for halo esters (Y = halogen, Z = O_2CMe) has led to the conclusion that bromide is an inherently worse leaving group than chloride by a factor of five, should thermochemistry be factored out.

Formation of the sterically unfavourable (*Z*)-alkadienes on dehydrosulfonylation of α,α-dialkylated (*E*)-allylic sulfones promoted by Bu^tOK/Bu^tOH has been attributed to a '*syn*-effect' which, by definition, stabilizes the *syn*-conformation required on approach to the transition state.[13] The *syn*-effect of substituents at the δ-position of the (*E*)-allylic sulfones decreases in the order $RO- \gg CH_3- > RS- > -CH_2- > (CH_3)_2CH- > (CH_3)_3C- > C_6H_5-$ and in accord with previous observations of isomerization of (*E*)-vinylic to allylic sulfones.

Dehydrochlorination of β,β'-dichlorodiethyl sulfide promoted by $PhCH_2NR_3^+$ and KOH or NaOH in aqueous heptane mixtures has been found to give $(CH_2{=}CH)_2S$ via $CH_2{=}CHSCH_2CH_2Cl$ under phase-transfer and single-phase conditions.[14]

Elimination reactions of (*E*)- and (*Z*)-benzaldehyde *O*-pivaloyloximes (**19a**) and (**19b**) with DBU in MeCN have been found to occur by a nitrile-forming *E*2 mechanism which is ca 2000-fold faster for the latter isomer in each case.[15] The corresponding Hammett substituent constants, activation parameters, and primary deuterium isotope effects, suggest that the *anti* elimination from (**19b**) (for which $\rho = 2.4 \pm 0.1$, $k_H/k_D = 2.7 \pm 0.3$, $\Delta H^{\neq} = 12.5 \pm 0.2$ kcal mol^{-1}, and $\Delta S^{\neq} = -31.0 \pm 0.6$ eu) proceeds to (**20**) via a more symmetrical transition state with a smaller degree of proton transfer, less charge development at the β-carbon and greater extent of triple bond formation than for *syn* elimination from (**19a**) (for which $\rho = 1.4 \pm 0.1$, $k_H/k_D = 7.8 \pm 0.3$, $\Delta H^{\neq} = 8.8 \pm 0.1$ kcal mol^{-1} and $\Delta S^{\neq} = -23.6 \pm 0.4$ eu).

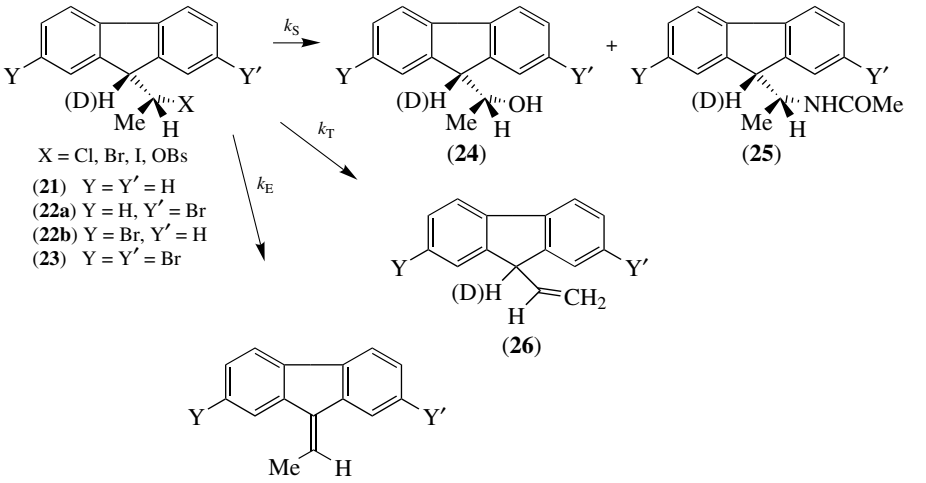


(**19a**) (*E*)-isomer
(**19b**) (*Z*)-isomer

(**20**)
X = *p*-MeO, *m*-Br, *p*-NO_2; L = H
X = H; L = H or D

Solvolytic Reactions

Solvolysis of *R*,*R* and *R*,*S* isomers (**22a-X**) and (**22b-X**), respectively, (X = I, Br, OBs) in 25 vol.% acetonitrile in water has been found to give elimination products (**26**), (**27a**), and (**27b**) and substitution products (**22a-OH**), (**22b-OH**), (**22a-NHCOMe**), and (**22b-NHCOMe**) (Scheme 3).[16] Previous results for (**21-X**) have suggested that concerted solvent-promoted *E*2 reactions become significant when the β-hydrogen is of high acidity, otherwise competing stepwise elimination and substitution reactions predominate. Brønsted parameters, $\alpha = 0.08$, 0.07 and -0.10, have been obtained from the elimination rate constants k_E for iodides, bromides, and brosylates, respectively, on variation of Y and Y′. These are believed to indicate that the iodides and bromides react by the concerted *E*2 reaction, with a high degree of proton transfer in the transition state, but that the brosylates (which give much smaller fractions of the stable alkenes) may react primarily through intermediate carbocation formation.



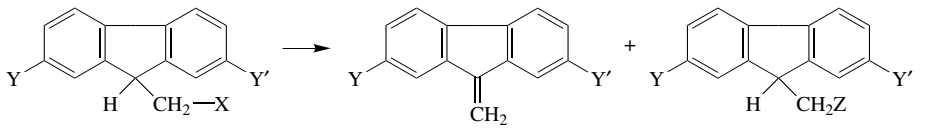
X = Cl, Br, I, OBs
(**21**) Y = Y′ = H
(**22a**) Y = H, Y′ = Br
(**22b**) Y = Br, Y′ = H
(**23**) Y = Y′ = Br

(**24**)
(**25**)
(**26**)

(**27a**) Y = H, Y′ = Br
(**27b**) Y = Br, Y′ = H
(**28**) Y = Y′ = Br

SCHEME 3

Solvolysis of (**29-X**, X = I, Br, OBs) in 25 vol.% acetonitrile in water gives elimination product (**32**) and substitution products (**33a**) and (**33b**).[17] The rate of elimination increases with increasing acidity of the substrate (Brønsted $\alpha > 0$) as evidenced by results for ring-substituted substrates (**30-X**) and (**31-X**). However, for elimination reactions of the brosylates (**29-OBs**) and (**31-OBs**), the small kinetic deuterium isotope effect ($k_H/k_D = 2.0 \pm 0.1$ and 2.8 ± 0.1, respectively) is believed to be a consequence of competing $E1$ reaction via a primary ion pair.



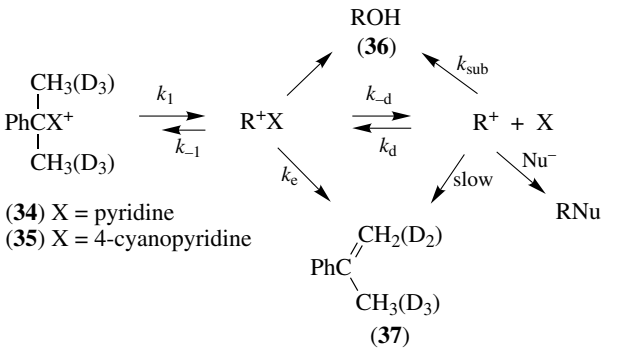
X = **a**; I, **b**; Br, **c**; OBs

(**29**) Y = Y′ = H
(**30**) Y = H, Y′ = Br
(**31**) Y = Y′ = Br

(**32**)

(**33a**), Z = OH
(**33b**), Z = NHCOMe

Full details of a study of leaving group-promoted solvolytic elimination reactions of 1-(1-methyl-1-arylethyl)pyridinium cations in 25 vol.% acetonitrile (aqueous) have been reported.[18] Reactions of (**34**) and (**35**) are found to proceed via a common carbocation intermediate of ion–molecule pair type to give the substitution product (**36**) and elimination product (**37**) (Scheme 4). The total rate of reaction of (**35**) exceeds that for (**34**) by 1100-fold, corresponding to a Brønsted parameter of $\beta_{lg} = -0.93$, and the fraction of (**37**) obtained is governed by $\beta = 0.12$ for the dehydronation (k_e) of the ion–molecule pair by the leaving group; the product ratio is hardly affected by the presence of substituted pyridines. For (**34**) and (**35**), $k_{obs}^{H}/k_{obs}^{D6} = 1.85 \pm 0.10$ (60 °C) and 1.53 ± 0.06 (40 °C), respectively, and corresponding values of $k_e^{H}/k_e^{D6} = 2.7 \pm 0.20$ and 3.4 ± 0.2 have been estimated.

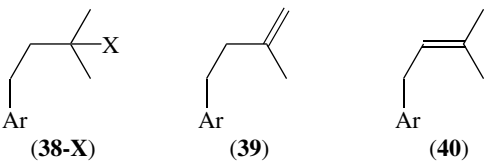


(**34**) X = pyridine
(**35**) X = 4-cyanopyridine

SCHEME 4

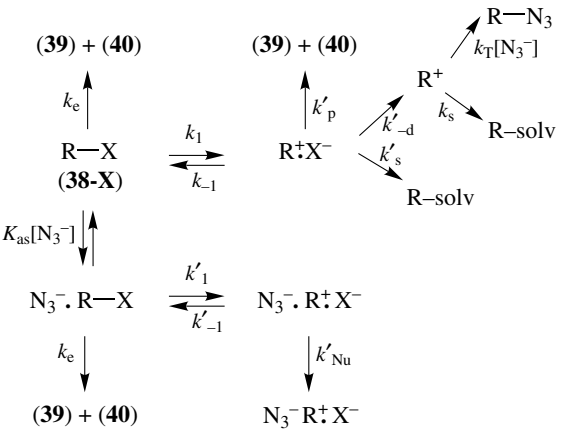
A concerted unimolecular mechanism has been proposed to account for the formation of elimination products on solvolysis of the tertiary 1-(4-methoxyphenyl)-3-methyl-3-butyl derivatives (**38-X**) in aqueous solvents.[19] Thus, in 50 : 50 (v/v) CF_3CH_2OH–H_2O, (**38a**) and (**38b**) give 39% and 56%, respectively, of the alkene

products of elimination and the constant total alkene yields are unaffected by the addition of the nucleophile N_3^- (0.5 M). The small amount of adduct (**38-N_3**) obtained in presence of azide ion is believed to form via a preassociation complex N_3^-.(**38-X**) only at the expense of formation of (**38-solv**) since the alkenes (**39**) and (**40**) can form by concerted elimination of free (**38-X**) or the association complex. Ion-pair or ion–molecule intermediates of the reactions of simple tertiary derivatives are believed to undergo direct reaction with a molecule of solvent within the solvent shell that is present at the time of their formation, with $k_s' \approx k_s = k_{reorg}$. The distribution of products obtained from acid-catalysed reactions of (**38c**) and 4-(4-methoxyphenyl)-2-methylbut-1-ene (**39**) is also inconsistent with reaction exclusively via a common carbocation intermediate, presumably as a consequence of differences in its solvent shell and the possibility that solvent attack may in part be concerted with protonation of (**39**). It is concluded that the ion pair intermediates ($\mathbf{R}^+.\mathbf{X}^-$) of the reactions of (**38-X**) are so reactive that they undergo little or no diffusional separation to the free carbocation ($k_s' > k_{-d}'$, Scheme 5).



(**38-X**) (**39**) (**40**)

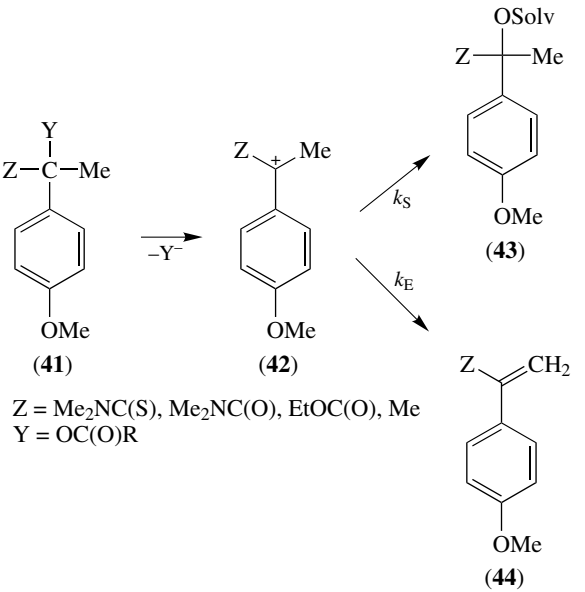
Ar = 4-MeO.C_6H_4
a; X = Cl
b; X = $O_2CC_6F_5$
c; X = OH



SCHEME 5

The partitioning of α-substituted 1-(4-methoxyphenyl)ethyl carbocations (**42**) between nucleophilic capture (k_S) and deprotonation (k_E) in 50 : 50 (v/v) MeOH–H_2O has been studied (Scheme 6).[20] The effect of α-(*N*,*N*-dimethylcarbamoyl) and α-

(*N*,*N*-dimethylthiocarbamoyl) substituents (Z) is to reduce the rate of solvent trapping by 80-fold and $\geq$ 30 000-fold, respectively. This, combined with the much smaller effect on k_E, accounts for the unusually large proportion of elimination product obtained from the α-amido- and α-thioamido-benzyl derivatives. Computational studies have established that the relative magnitude of the rate constants k_S and k_E is strongly controlled by the relative thermodynamic stabilities of the respective neutral products.

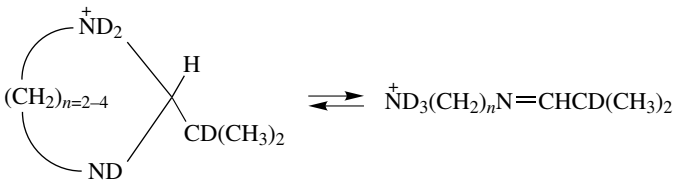


SCHEME 6

Results of a study of the mechanism and temperature-dependent kinetics of the dehydration of hot compressed liquid water do not corroborate an earlier claim that isobutene formation is catalysed by dissociation of Bu^{t}OH at 250 °C.[21]

Rate and equilibrium constants have been measured for the acid-catalysed dehydration of heterocyclic ring hydrates of benzofuran, benzothiophene, chromene, and thiochromene.[22] The reactions are believed to proceed via intermediate carbocations despite the surprisingly small accelerating effects of heterocyclic oxygen and sulfur atoms in the five-membered ring series and the deceleration observed for dehydration of corresponding six-membered rings. Alcohol dehydration by polyphosphoric acid has also been studied.[23]

Rate constants and activation parameters have been determined from results of an NMR study of the acid-catalysed ring–chain tautomeric equilibria established for five-, six-, and seven-membered 1,3-dinitrogen heterocycles (**45**) (imidazolidine, hexahydropyrimidine and -diazepine ring systems, respectively) in 4 : 1 DMSO–D_2O.[24] For $n = 2$ and 3 the equilibrium is found to favour the ring tautomer whereas for $n = 4$ the monoimine predominates. The much higher free energy/enthalpy of activation for the six-membered ring opening has been attributed to the lower ground-state energy of this ring.



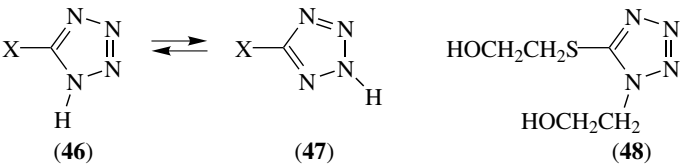
(**45**)

Pyrolytic Reactions

Cycloreversion with Nitrogen Extrusion

Results of an *ab initio* MO study of the thermal decomposition of several α-azido five-membered heterocycles suggest that the ring is almost intact in the transition state, there being a concerted but asynchronous process between N_2 departure and ring cleavage.[25] It is not clear whether an open-shell singlet nitrene intermediate is formed or whether the transition state leads directly to the ring-opened product. The activation barriers decrease in the order thiophenes > furans > pyroles and are much less than for phenyl azide decomposition, which is believed to proceed with smaller charge transfer between the azido group and the ring; larger internal electrostatic force may also favour the transition state for heterocycle cleavage and partly account for the high rate constants observed.

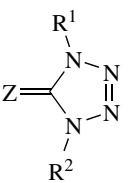
Evidence in support of a stepwise thermal fragmentation of oxadiazolines in benzene at 110 °C has implicated carbonyl ylide intermediates and oxiranes as unstable precursors of the elimination product, ketene acetals, rather than concerted fragmentation to N_2, acetone and carbene.[26]



(**46**) (**47**) (**48**)

a; X = OMe
b; X = SMe
c; X = H

R^1 =	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**
	H	H	H	H	Me	Me	H	Me
R^2 =	H	Me	Et	Ph	Me	Ph	C_2H_4OH	CH_2OH



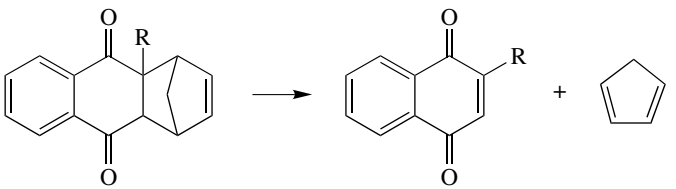
(**49**) Z = O
(**50**) Z = S

Gas-phase thermolysis of substituted tetrazoles (**46a**,**b** and **48**), the 1,4-disubstituted 1,4-dihydro-5*H*-tetrazol-5-ones (**49a**–**f**) and the 1,4-disubstituted 1,4-dihydro-5*H*-tetrazol-5-thiones (**50b**,**c**,**e**–**h**) have been monitored by photoelectron spectroscopy.[27]

Compounds (**46a**) and (**46b**) lose formaldehyde and thioformaldehyde, respectively, before nitrogen extrusion from intermediate unsubstituted tetrazole (**46c**); the tetrazole then extrudes N_2 to form cyanamide. For (**49a**,**b**) and (**50b**,**c**,**e**–**h**) the predominant reaction is 3 + 2-cycloreversion to azides and isocyanates or isothiocyanates, respectively.

Other Cycloreversions

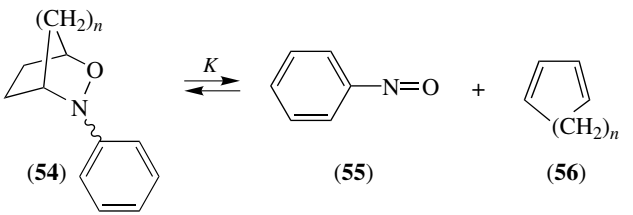
A review of direct observation of the transition state has traced the development of the femtosecond reaction dynamic technique, which has been used to demonstrate that the retro-Diels–Alder reaction can proceed by a stepwise mechanism as well as the usual concerted process.[28] The oxide anion accelerated retro-Diels–Alder reaction has also been reviewed[29] and the promise of this mild reaction for synthetic application has been emphasized.



(**51**) (**52**) (**53**)

a; R = Me
b; R = H

Retro-Diels–Alder reactions of anthracenedione (**51a**) have been shown to proceed faster in aqueous solution than in organic solvents, apparently as a consequence of enhanced hydrogen bonding of water to the activated complex,[30] since hydrophobic interactions with (**51a**) are of negligible importance. The results have been compared with previous kinetic data for bimolecular and intramolecular Diels–Alder reactions and the corresponding hydrogen bond and hydrophobic interactions have been discussed.



(**54**) (**55**) (**56**)

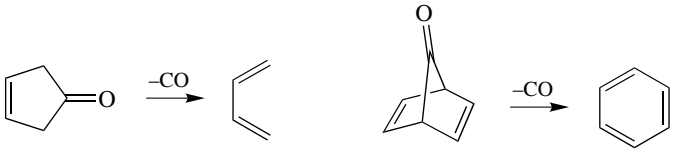
a; n = 1, **b**; n =2

Reaction between nitrosobenzene (**55**) and cyclopentadiene (**56a**) gives an unstable cycloadduct (**54a**); however, in a highly aqueous medium the adduct is stabilized by hydrogen bonding and the hetero retro-Diels–Alder reaction is retarded, thereby enabling a study of the equilibrium dynamics with both reactants and products present in solution.[31] Comparison with the corresponding reaction of cyclohexa-1,3-diene has been made in an attempt to separate the effects of the aqueous medium on the rate constants for the forward and reverse reaction.

It has been suggested previously that the thermal cycloreversion of cyclohexene to ethylene plus buta-1,3-diene proceeds via a vinylcyclobutane intermediate and that, as a consequence, the stereochemistry of deuterium labels on the cyclohexene is not reflected in the deuterated ethenes obtained. This conclusion is supported by results of a study of the stereochemistry of thermal conversion of 1-vinyl-2,3-*cis*-dideuteriocyclobutane to butadiene and 1,2-dideuterioethylenes; equal amounts of (*E*)-CHD=CHD and (*Z*)-CHD=CHD were formed.[32]

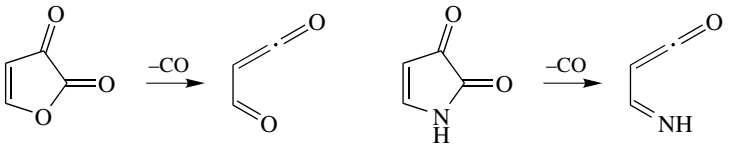
A detailed quantum mechanical study of the mechanism of thermal decomposition of isoxazole has been conducted since previous theoretical predictions appeared to be inconsistent with the experimental results.[33] It has been concluded that the main unimolecular decomposition is through the sequence isoxazole $\rightarrow NCCH_2CHO \rightarrow CH_3CN + CO$ and that the minor products, HCN and H_2CCO, probably arise via a cyclic carbene as proposed in the experimental study.

Pericyclic reactions—cyclic orbital overlap



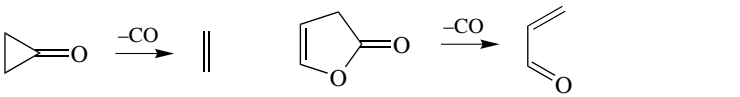
(**57**) (**58**) (**59**) (**60**)

Pseudopericyclic reactions—two orbital disconnections

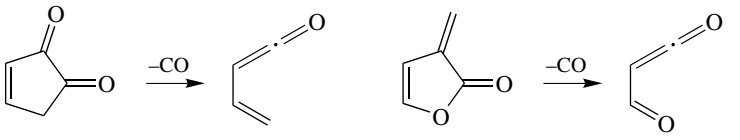


(**61**) (**62**) (**63**) (**64**)

One orbital disconnection



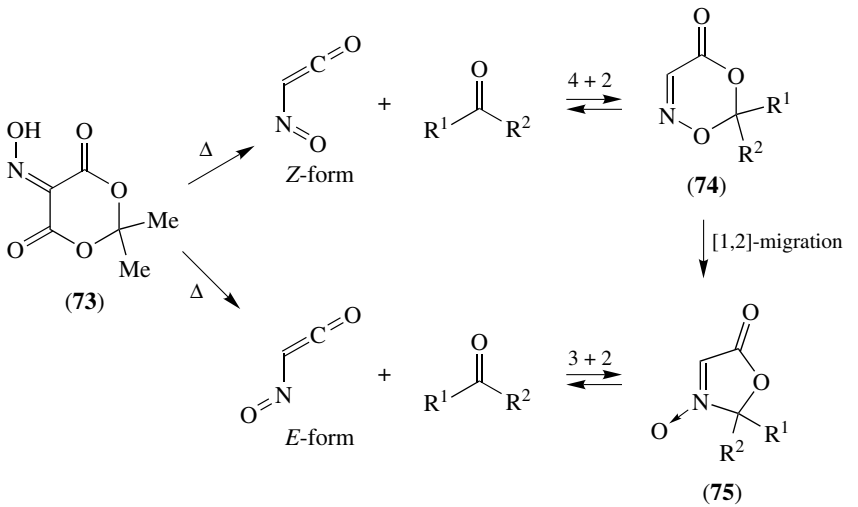
(**65**) (**66**) (**67**) (**68**)



(**69**) (**70**) (**71**) (**72**)

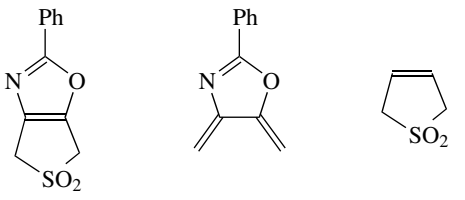
SCHEME 7

A systematic *ab initio* study of thermal chelotropic decarbonylations (Scheme 7) has been conducted in order to explore the effects of zero, one, and two orbital disconnections and to resolve an ambiguity in the Woodward–Hoffman rules which envisaged two orbital symmetry-allowed decarbonylation pathways.[34] The transition structures were located at the MP2/6–31G* level and single point energies were obtained at the MP4-(SDTQ)/D95** + ZPE level. The out-of-plane 'linear' pericyclic transition states for reactions of (**57**) and (**59**) are in contrast with the two-orbital disconnection planar transition states found for decarbonylation of furandione (**61**) and pyrroledione (**63**). In contrast, fragmentations of (**67**), (**69**) and (**71**) each involve a single disconnection. Although decarbonylation of (**65**) is symmetry allowed it becomes 'effectively forbidden' since the energy barrier of this 'non-linear' process is unusually high.



SCHEME 8

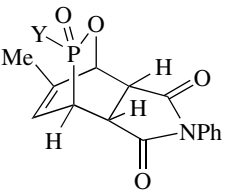
Cyclic nitrones, which are commonly formed by cycloaddition of ketones to nitrosoketene, can also be obtained by pyrolysis of 5-isonitroso-2,2-dimethyl-1,3-dioxane-4,6-dione (**73**) (isonitroso Meldrum's acid) in the presence of various ketones. Two possible reaction pathways (Scheme 8) have been proposed previously to account for formation of cyclic nitrones from (**73**), but the proposed nitrosoketene intermediate could not be observed. Spectroscopic evidence for generation of the nitrosoketene in the gas phase at $\geq 80\ ^{\circ}C$ has now been found and *ab initio* calculations in support of the vibrational frequencies observed have been reported.[35]



Heteroaromatic-fused 3-sulfolenes generally undergo extrusion of SO_2 at 160–180 °C to form the corresponding *o*-quinodimethanes; 2-phenyloxazolo-3-sulfolene (**76**), however, loses SO_2 at room temperature to give (**77**). It has now been shown by theoretical calculations of homodesmic reactions of oxazolo-3-sulfolene relative to 3-sulfolene (**78**) that oxazolo ring fusion induces strain in the 3-sulfolene ring; this is greater than that induced by other five-membered aromatic heterocycles and can therefore account for the unusual reactivity of oxazolo-3-sulfolene or its 2-phenyl derivative.[36] The effect of change of electron delocalization during SO_2 extrusion does not differ to a great extent for oxazolo-, furano-, and thiozolo-3-sulfolenes.

Novel 1,3-selenazabuta-1,3-dienes have been generated by thermal cycloreversion of 2,4,6-trisubstituted 6*H*-1,3,5-oxaselenazines and trapped with dienophiles or nucleophiles with formation of 4 + 2-cycloadducts or 1,4-adducts, respectively.[37]

The potential surface for the gradient path addition of ethylene to silene and the possible existence and stability of intermediates in the thermal decomposition reaction of silacyclobutane has been explored.[38] The energy maximum of the multi-step process corresponds to a cyclic transition state leading on one side to a planar silacyclobutane transition state which falls to ground-state puckered silacyclobutane and on the other side to a *trans* diradical which fragments to ethylene and silene.



(**79**)

a; Y = OEt
b; Y = Et_2N

Retro-cycloaddition extrusion of the metaphosphate moiety from 2,3-oxaphosphabicyclo[2.2.2]octene derivatives (**79**), in 1,2-dichloroethane at 100 °C in the presence of PrOH, has been shown to proceed via an unsymmetrical transition state in which C—P bond breakage and P=O bond formation are more advanced than C—O breakage.[39] The secondary deuterium isotope effect on H adjacent to the P—C bond is 1.060 ± 0.008 for (**79a**) and 1.081 ± 0.009 for (**79b**) and the oxygen kinetic isotope effect on the P—O—C bridge is 0.9901 ± 0.0016 for (**79a**).

Results of a kinetic and theoretical study of the unimolecular decomposition of cyclobutanol behind incident and reflected shock waves at 950–1450 K show that vinyl alcohol is produced through a biradical before isomerizing to acetaldehyde.[40]

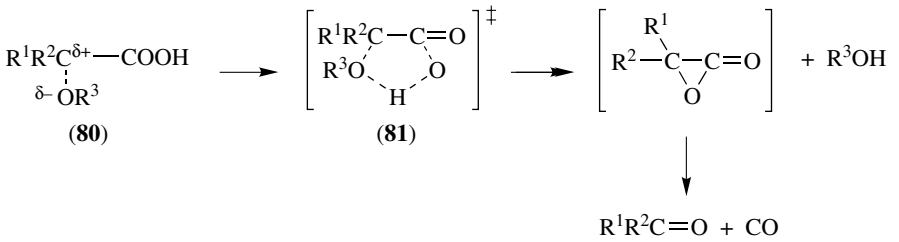
Acid Derivatives

A theoretical study of the thermal isomerization and decomposition of oxalic acid has attempted to account for the predominant formation of CO_2 and HCOOH from the vapour at 400–430 K.[41] Transition-state theory calculations indicate that a bimolecular hydrogen migration from oxygen to carbon of intermediate dihydroxycarbene (formed along with CO_2) achieved through a hydrogen exchange with a second oxalic acid

molecule may account for HCOOH formation. A unimolecular channel to produce CO_2, CO and H_2O may become significant at higher temperatures.

Gas-phase decarboxylation of β-ketocarboxylic acids $XCOCH_2COOH$ (X = H, OH, and CH_3) has also been the subject of theoretical studies.[42] *Ab initio* calculations reveal that decarboxylation via a six-membered (rather than four-membered) ring transition state is favoured. Activation barriers of 23.8, 23.3 and 28.5 kcal mol^{-1} have been calculated for decarboxylation of 3-oxopropanoic acid, acetoacetic acid, and malonic acid, respectively. Only marginal effects of solvent on the energy barriers and on the geometries of the reactants and transition structures are predicted. The activation energy predicted for reaction of malonic acid agrees well with the experimental value and rate constants have been predicted for decarboxylation of 3-oxopropanoic acid and acetoacetic acid in the gas phase.

Rates of decarbonylation (promoted by oxygen at room temperature) and decarboxylation (at 190 °C) of 1,3- and 1,4-benzeneketodicarboxylic acids have been reported.[43]



SCHEME 9

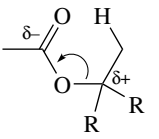
A unimolecular elimination involving a semi-polar five-membered cyclic transition state (**81**) (Scheme 9, R^1 = Ph, $R^2 = R^3 = H$) appears to account for the formation of benzaldehyde, CO, and H_2O on eliminative fragmentation of mandelic acid in the gas phase.[44] The same type of transition state has been proposed for gas-phase pyrolysis of $ROCH_2COOH$ (R = MeO, EtO, and Ph^iO) with corresponding formation of ROH, CO, and formaldehyde; the rate of reaction is little dependent on R.[45]

The limited knowledge of thermal behaviour of halogenated acids has been extended significantly by a pyrolysis (infrared laser-powered) and semiempirical study which has established that mono-, di- and tri-chloroacetic, trifluoroacetic, and bromoacetic acid eliminate HX and that both bromo- and iodo-acetic acid undergo C—X bond homolysis; acetic acid undergoes decarboxylation and dehydration under the same conditions.[46] The semiempirical calculations of corresponding activation energies are consistent with these conclusions.

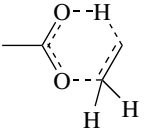
Semiempirical and *ab initio* techniques have been applied to the unimolecular decomposition of 2-chloropropanoic acid, which is known to form HCl, CO, and CH_3CHO. In keeping with the experimental data, the results suggest that reaction proceeds by a two-step mechanism involving rate-determining formation of intermediate α-propiolactone, which then fragments to form CO and CH_3CHO.[47]

The lactone formation occurs via a distorted five-membered transition state with participation of leaving chloride and carboxylic hydrogen.

A systematic study of the impact of geminal α-fluorine substitution upon the rate of decarboxylation of β-lactones has included investigation of the thermolysis of α,α-difluoro β-lactones, to give CO_2 and 1,1-difluoroalkenes, in the gas phase and in solution.[48] The gas-phase results have been interpreted, with reference to *ab initio* calculations on the fluoro- and non-fluorinated β-lactone systems, in terms of a probable concerted, asynchronous, non-polar mechanism. However, a polar mechanism which probably involves formation of an intermediate zwitterion has been invoked to explain the solvent dependence observed.

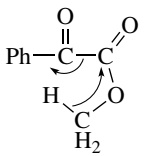


(**82**)

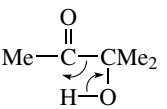


(**83**)

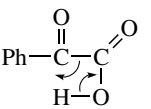
The kinetics of concerted thermal elimination reactions of a series of ethyl (hetero) arylcarboxylate esters (2-thienyl-, 3-thienyl-, 2-furyl, 3-furyl, 4-pyridyl-, 3-pyridyl-, and 2-pyridylcarboxylate) in the gas phase seem to indicate that there is little charge separation in the transition state (**83**); this is in contrast with the behaviour of the corresponding *t*-butyl and isopropyl esters for which a semi-concerted transition state (**82**) was proposed previously.[49] Results of a kinetic study of the gas-phase elimination reactions of methylbenzoyl formate (**84**) and 3-hydroxy-3-methylbutan-2-one (**85**) have been compared with those for pyruvic acid (**87**) and benzoylformic acid (**86**).[50] The relative rates of reaction [(**86**)/(**87**) ≈ 46, (**87**)/(**85**) = 1.1×10^5 and (**86**)/(**82**) = 1×10^6] reveal that the acidity of the hydrogen atom involved in the elimination process, rather than the initial polarization of the C—C bond which undergoes cleavage, is the important rate-controlling factor.



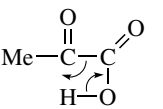
(**84**)



(**85**)



(**86**)



(**87**)

Results of a kinetic study of the formation of phthalide by dehydrobromination of α-bromo-*o*-toluic acid are believed to provide support for an intimate ion-pair mechanism for the pyrolysis of some types of halo acids in the gas phase.[51]

The thermal decomposition of 2-azidoacetic acid ($N_3CH_2CO_2H$) in the vapour phase has been shown, by photoelectron and matrix isolation infrared spectroscopy, to involve simultaneous formation of CO_2 and methanimine (CH_2NH) with concerted ejection of N_2.[52] No evidence was found for formation of intermediate nitrene (NCH_2CO_2H) or the imine ($HNCHCO_2H$) to which it could be converted by 1,2-hydrogen shift.

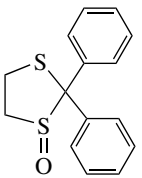
Benzo[*c*]phenanthrene-5,6-dicarboxylic anhydride and 6*H*-benzo[*cd*]pyrene-6-one have been found to form combustion effluents benzo[*ghi*]fluoranthene and cyclopenta[*cd*]pyrene on thermolysis.[53]

The kinetics of formation of ketene and acetic acid on thermal unimolecular decomposition of acetic anhydride at 750–980 K have been reported and used to re-evaluate the Arrhenius equation as $k = 10^{12.2}\exp(-145\ \text{kJ mol}^{-1}/RT)\ \text{s}^{-1}$ for the temperature range 470–980 K.[54] Results of *ab initio* MO calculations suggest that the reaction proceeds by concerted elimination through a six-centre transition state, with potential barrier height 156 kJ mol^{-1}.

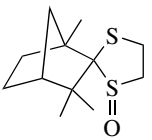
Reactivities and activation parameters for pyrolytic unimolecular first-order elimination reactions of *N*-acetylurea, *N*-acetylthiourea, *N*,*N*′-diacetylthiourea and *N*-acetylthiobenzamide have been interpreted with reference to those for other amide derivatives.[55] The first-order rate constants for pyrolysis of $RCONHCSNHC_6H_4R'$ (R = Me, R′ = H; R = Ph, R′ = H, 4-NO_2, 3-Cl, 4-Cl, 4-Me) have also been measured at 423–500 K and correlated with Hammett σ° values to give $\rho = 1.99$ at 450 K.[56]

Sulfur Compounds

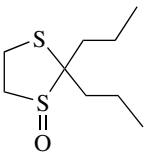
Flash vacuum pyrolysis (FVP) of 1,3-dithiolane 1-oxides (**88**–**90**), as a possible route to thiocarbonyl compounds, has been studied.[57] Thiobenzophenone and thiofenchone are obtained from (**88**) and (**89**), respectively, but there was no evidence of heptane-4-thione formation from (**90**). A stepwise homolytic cleavage has been proposed.



(**88**)



(**89**)



(**90**)

FVP has also been used to induce fragmentation of 1,6,6aλ^4-trithiapentalene and its methyl-substituted derivatives with formation of thiophene-3-thiones (or the thiol tautomers) by loss of CS and/or $CH_2{=}C{=}S$ and subsequent rearrangement.[58]

Alkyl Halides

The reaction dynamics of multi-bond breakage during elimination of iodine from 1,2-diiodo-1,1,2,2-tetrafluoroethane has been the subject of femtosecond clocking in a supersonic molecular beam;[59] the process proceeds via $C_2F_4I^+$ and involves sequential C—I bond breakages taking 200 fs and 25 ps, respectively.

Pyrolysis of 2-chloro-1,1,1-trifluoroethane at 973–1148 K has been shown to form primarily $CF_2{=}CHF$ (formed by α,α-HCl elimination followed by 1,2-F migration), along with $CH{=}CHCF_3$ and $CF_2{=}CHCl$, at low temperature; pentafluoropropene products predominate at high temperature.[60] Competing HX elimination and C—X fission have been found to occur in high-temperature thermal decompositions of C_2H_5I[61] and chloromethylacetylene.[62]

Pyrolyses of chloroacetaldehyde and 1-chloropropionaldehyde have been found to form ketene by elimination of HCl and MeCl, respectively; 2-chloropropionaldehyde eliminates HCl to form *s-trans*-acrolein under the same conditions.[63]

Nitrogen Compounds

Ab initio density functional calculations have been applied to dimethylnitramine decomposition in order to calculate the primary deuterium kinetic isotope effect ($k^{H}/k^{D6} = 4.21$) for HONO elimination $Me_2NNO_2 \rightarrow [TS] \rightarrow CH_2NMe + NO_2H$ and the secondary isotope effect ($k^{H}/k^{D6} = 1.4$) for N—N bond homolysis, each at 240 °C.[64] Since the experimentally observed isotope effect is 1.57, it has been concluded that the latter process may be rate determining.

5-Nitro-2,4-dihydro-3*H*-1,2,4-triazol-3-ones (NTO) isotopically labelled with ^{15}N at N(1,2), N(4) and N(6) positions have been used to elucidate the origins of nitrogen atoms in its decomposition gases N_2, NO, NO_2, and HCN.[65] Three competing reactions involving homolysis of the nitro group from the NTO ring have been proposed to occur.

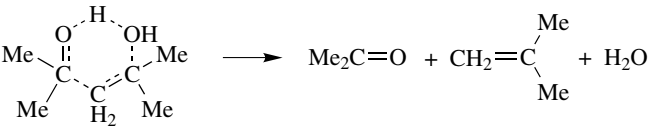
Semiempirical AM1 calculations on the transition state for the retroene-type elimination of propene from allylamines reveal that the most favoured geometry resembles a half-chair or a flattened boat.[66] In keeping with experimental observations, it is predicted that electron-donor substituents on nitrogen should promote the reaction since the negative charge on this atom decreases in the polar transition state.

The mechanisms of stepwise monomolecular thermal decomposition of 1,5- and 2,5-disubstituted tetrazoles feature nitrogen evolution by rate-limiting breakdown of intermediate azidoazomethines and azodiazo compounds, respectively;[67] the activation parameters have been reported.

Transition states for rate-limiting elimination of nitrogen on unimolecular thermal decomposition of methyl and ethyl azide have been defined by application of Pulay's SQMFF method.[68]

Alcohols

The gas-phase unimolecular pyrolysis of 2,4-dimethylpentane-2,4-diol has been found to occur by eliminative formation of acetone, isobutene, and H_2O via a concerted six-membered cyclic transition state (Scheme 10).[69] Single-pulse shock tube studies of the eliminative decomposition of ethoxy compounds have also been reported.[70]



SCHEME 10

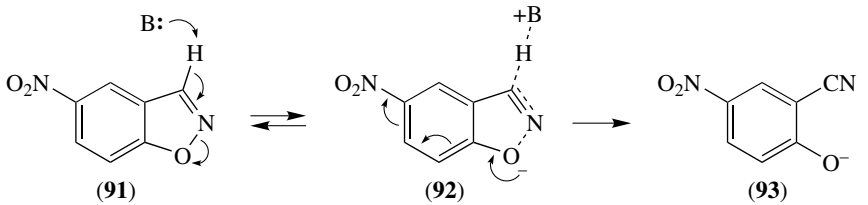
Other Pyrolytic Reactions

Ab initio and density functional calculations of the thermal *syn* elimination transition states for E_i reaction of organic amine oxide, sulfoxide, and phosphoxide have confirmed the expected planar geometry and known order of reactivity.[71]

AM1 calculations on an expected retroene-type propene elimination from allylphosphines have revealed that the rigid phosphaalkene character of the transition state causes it to be easily distorted and destabilized by substituents on the phosphorus atom; this can favour competing P—C bond homolysis.[72]

Reactions Catalysed by Biomolecules

The medium-sensitive Kemp elimination reaction (**91**) →(**93**) has been used as a probe in an attempt to mimic the microenvironment of enzyme action and the consequent effects on ground-state and transition-state stabilities.[73] It has been shown that the reaction is catalysed, with rate accelerations as high as 10^6 and at least 1000 turnovers per basic site, by a subset of several hundred water-soluble polymers prepared by alkylating polyethyleneimine with different combinations of three contrasting alkyl groups. The proton transfer from carbon is apparently catalysed by polymer amine groups of pK_a down to 5.7 and exhibiting effective molarities of ca 1000 M in these enzyme-like catalysts (synzymes). It has been pointed out that proton transfer by uncharged amines is relatively insensitive to the solvation or precise positioning of the catalytic base; consequently, high catalytic activity can be attributed to creation of a hydrophobic cavity which enables the substrate to bind in close proximity to a catalytic base embedded in a positively charged framework capable of stabilizing the delocalized negatively charged transition state (**92**). The most promising synzyme fractions displayed saturation behaviour and Michaelis–Menten kinetics; the effective molarities are exceptionally high for an enzyme model involving general base catalysis.



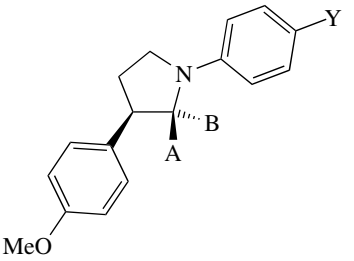
(**91**) (**92**) (**93**)

The stereochemistry of β-elimination reactions catalysed by D-galactonate dehydratase (GalD) and D-glucarate dehydratase (GlucD) enzymes is apparently not dictated by the pK_as of the α-protons of the carboxylate anion substrates.[74] It had been observed previously that enzyme-catalysed dehydration initiated by abstraction of the α-proton (p$K_a > 29$) from a carboxylate anion substrate usually proceeds via *anti* elimination, whereas *syn* elimination occurs when the proton is α- to an aldehyde, ketone, or thioester and correspondingly more acidic (p$K_a < 25$).

Alternative mechanisms for the OH transfer process in enzyme–coenzyme B_{12}-catalysed dehydration of 1,2-dihydroxyethane, to give acetaldehyde and water, have been explored using *ab initio* MO calculations.[75] Transfer within an $(HOCH-CH_2OH)^{\cdot}$ radical was ruled out because the activation energy is too high, and no intermediate bridge structure could be found to facilitate conversion of 1,2-dihydroxyethyl cation (if it could be formed from the radical) to 2,2-dihydroxyethyl cation. The radical cation $(HOCH-CH_2OH_2)^{+\cdot}$ transformed rapidly to a stable

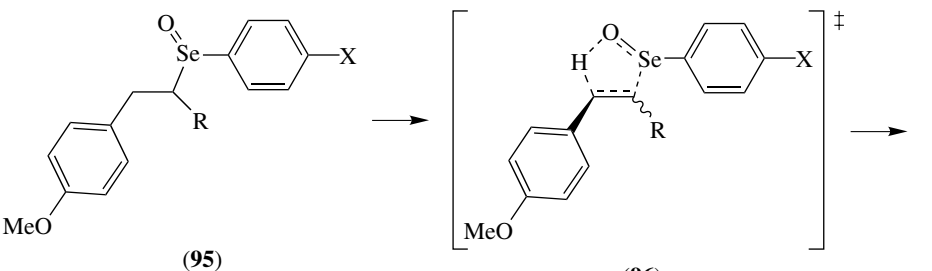
hydrogen-bonded hydrate of the *anti*-vinyl alcohol radical cation $(H_2O\cdots HOCH{-}CH_2)^{\cdot+}$, which is an acetaldehyde precursor.

β-Elimination catalysed by the *N*-terminal domain of DNA polymerase β, whereby doxyribose 5-phosphate is excised from DNA, has been the subject of a modelling study.[76] Intermediate Schiff's bases formed through Lys-68 or Lys-72 may be deprotonated at C(2)′ by His-34 or water, respectively, with stabilization of the phosphomonoester leaving group by Lys-35 in either case.



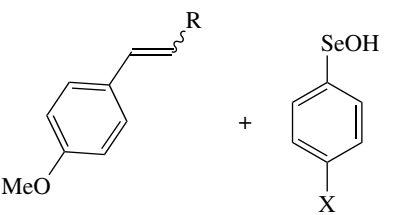
(**94**)

a; A = CO_2H, B = H, Y = $NHC(O)CH_2Br$
b; B = CO_2H, A = H, Y = $NHC(O)CH_2Br$



(**95**) (**96**)

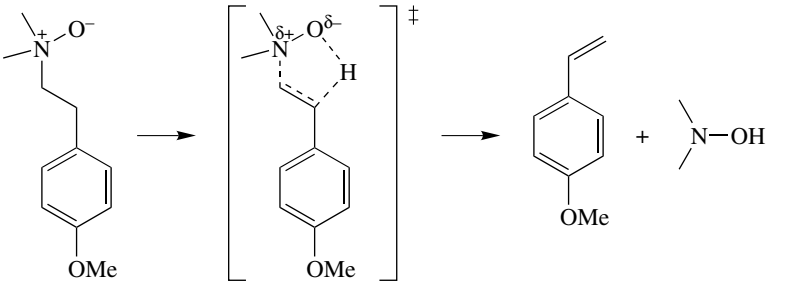
a; R = CO_2H, X = NO_2
b; R = CH_2OH, X = NO_2
c; R = CH_3, X = NO_2
d; R = H, X = NO_2
e; R = H, X = H



(**97**) (**98**)

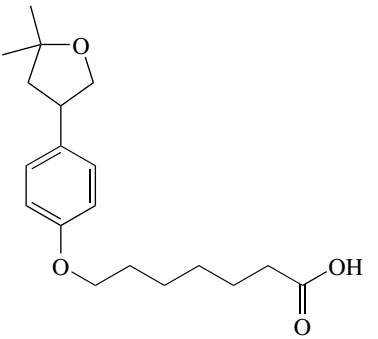
Monoclonal antibodies raised against proline derivatives (**94a**) and (**94b**) have been used to catalyse the selenoxide *syn*-elimination reaction (**95**) → (**97**). It was reasoned that the flexible selenoxide (**95**) would be constrained within the low dielectric

environment in a conformation conducive to formation of the planar five-membered pericyclic transition state (**96**) which is less polar than the initial state.[77] The catalytic activity of the antibodies generally increases with decreasing use of the substituent α- to the selenoxide moiety ($R = CO_2H < CH_2OH < CH_3 < H$).



(**99**) (**100**) (**101**)

A further report of an antibody-catalysed [2,3]-sigmatropic reaction has featured the Cope elimination of *N*-oxide (**99**) to dimethylhydroxyamine and 4-methoxystyrene (**101**).[78]



(**102**)

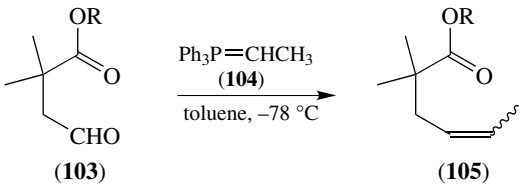
Monoclonal antibodies generated against hapten (**102**) have effected rate enhancement of ca 10^3 over the uncatalysed reaction, largely through reduction of activation enthalpy, and displayed the expected Michaelis–Menten kinetics and inhibition by (**102**). For reaction of the deuterated substrate (**99**)-2,2-d_2 the kinetic isotope effect $k_{catH}/k_{catD} = 2.78$. Change of reaction medium from water to organic solvents, DMF and 1,4-dioxane, also accelerates the uncatalysed reaction, mainly by lowering the enthalpy of activation. A crude enzymic preparation from microorganisms has also been used to induce Cope elimination reaction of *N*-oxides derived from quaternary ammonium surfactants.[79]

The enzyme-catalysed cyclization of (*R*)-[9-$^2H_1$,$^3H_1$]geranyl diphosphate to (4*S*)-limonene has been found to terminate predominately by *re*-facial, *anti* proton elimination at the *cis* methyl group of the intermediate (3*S*)-linalyl diphosphate.[80]

Elimination Reactions in Synthesis

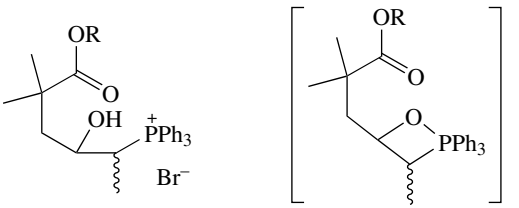
Review articles of synthetic importance have featured: eliminations involving carbon–halogen bonds and leading to highly strained rings,[81] elimination and addition–elimination reactions,[82] enol ether formation from unsaturated acetals,[83] and the Wittig reaction and related methods.[84]

The mechanism of the indirect Wittig reaction has been explored[85] by investigating the stereochemistry of base promoted reaction of 1,2-hydroxyphosphonium salts (**106a**,**b**). The stereoisomeric salts, which were obtained in a 92 : 8 ratio by hydrolysis of stereoisomeric 1,2-oxaphosphetane intermediates (**107a**,**b**) formed on reaction of salt free ylide (**104**) and aldehyde (**103**), react smoothly with DBU to form stereoisomeric alkenes (**105**) and in the same proportions ($Z/E = 93:7$) as for the direct Wittig reaction. In the absence of any evidence of fragmentation–recombination it has been calculated that the salts (**106**) re-form (**107**) via the corresponding betaines and that the stereochemistry of the indirect Wittig reaction is controlled at the initial 2 + 2-cycloaddition stage.



(**103**) (**105**)

R = $CH_2OC_6H_4Br$-*p*

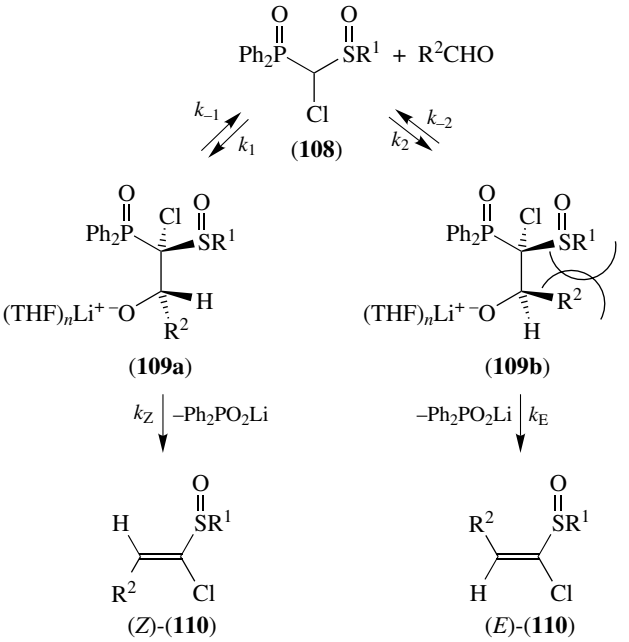


(**106**) (**107**)

The Curtin–Hammett principle has been invoked[86] to explain the high *Z*-selectivity observed on synthesis of 1-chlorovinyl sulfoxides (**110**) by Horner–Wittig reaction between aldehydes and lithiated anions (**108**) of [(α-chloro)sulfinylmethyl]diphenylphosphine oxides. It is argued that there is fast equilibrium between Horner–Wittig adducts (**109a**) and (**109b**) and that $k_Z \gg k_E$ applies because of the build-up of steric repulsion in (**109b**) between the sulfinyl substituent [$S(O)R^1$] and R^2 as the eclipsed conformation is approached.

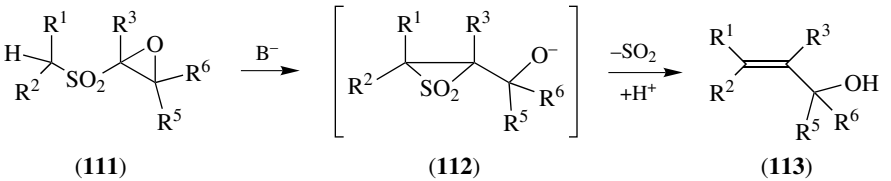
A kinetic study of the reaction of trialkylphosphites with mucochloric acid has established that this unusual variant of the Arbuzov reaction proceeds with elimination of both alkyl halide and HCl at the second stage.[87]

α,β-Epoxysulfones (**111**), on treatment with base, have been found to undergo a new variant of the Ramberg–Bäcklund reaction and thereby form allylic alcohols (**113**).[88]



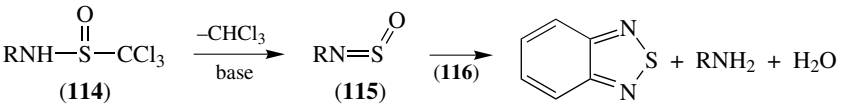
SCHEME 11

The reaction (Scheme 12), which is believed to proceed by 3-*exo-tet* ring opening via a strained 1-hetero-4-thiaspiro[2.2]pentane transition state, has been applied to form a range of mono-, di- and tri-substituted allylic alcohols.



SCHEME 12

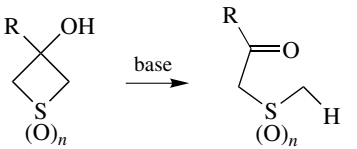
Readily available allylic and benzylic trichloromethyl sulfoxides undergo an unusual base-induced β-elimination of chloroform, with formation of the corresponding α,β-unsaturated sulfine, under mild conditions at room temperature; the procedure has been applied to form vinylthioaldehyde *S*-oxides and vinylthioketone *S*-oxides.[89] *N*-Sulfinylamines (**115**) have likewise been prepared by β-elimination of chloroform from trichloromethanesulfinamides (**114**).[90] The reaction is promoted rapidly at room temperature by pyrrolidine and Et_3N and the sulfinylamines (**115**) can be trapped by *o*-phenylenediamine (**116**), to give benzothiadiazole, before desulfonative hydrolysis occurs.



Preliminary results on the enantioselective formation of sulfur and nitrogen medium-sized heterocycles by base-induced ring opening of hetero-oxabicyclic [3.2.1] and [3.3.1] systems have been reported.[91] The reaction involves a deprotonation–C—O bond elimination sequence. The kinetics and mechanism of gas-phase unimolecular elimination reactions of some substituted aminoazoles have been studied as an aid to heterocycle synthesis.[92]

Other Reactions

3-Hydroxythietane derivatives (**117b**–**g**) have been shown to undergo eliminative ring cleavage in aqueous sodium hydroxide at a rate which is dependent on the substituent (H or Ph) at the 3-position and the oxidation state of the ring sulfur.[93] This retro-aldol reaction occurs 4×10^4–5×10^5 times faster than for open-chain analogues; and it has been estimated that the corresponding relief of strain energy (between 41 and 33%) is much greater than the 26% for alkene-forming eliminations of cyclobutanes. It has been argued that the degree of ring cleavage is greater in the transition state for thietane than for cyclobutane ring opening. Consistent with this view are the relative sensitivities to α-phenyl substitution and the uniformly positive values of $\Delta S^{\ddagger}$ found for the 3-hydroxythietanes. The deuterium isotope effect (1.7) found for reaction of (**117e**) in NaOD–D_2O suggests that protonation of the carbon leaving group is concerted with ring cleavage.



(**117**) (**118**)

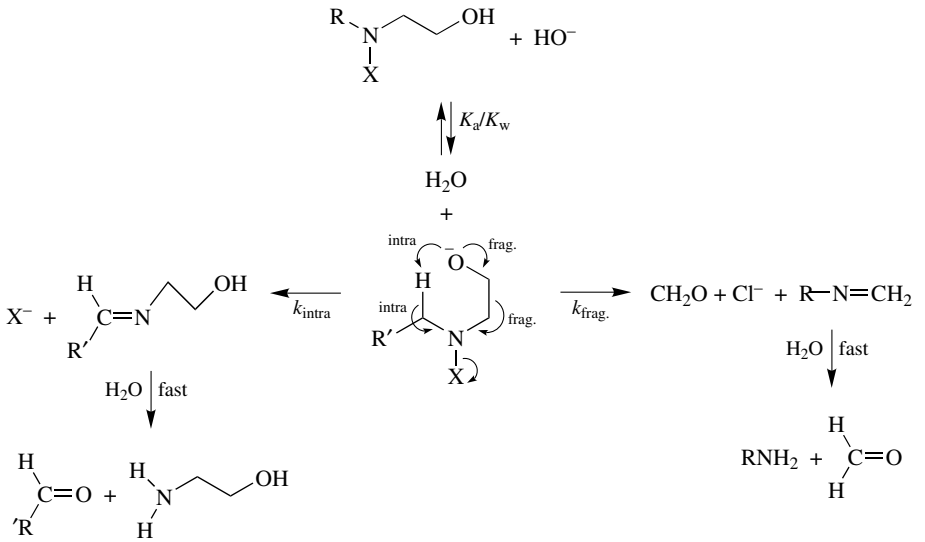
$n = 0$ **a**; R = H, **b**; R = Ph
$n = 1$ **c**; R = H (*cis*), **d**; R = H (*trans*), **e**; R = Ph
$n = 2$ **f**; R = H, **g**; R = Ph

The predictive capabilities of results of theoretical calculations of isotope effects have again been questioned,[94] following an experimental and theoretical study of the decarboxylation of 3-carboxybenzisoxazole at room temperature (Kemp's reaction). The experimentally determined ^{15}N isotope effect in acetone is 1.0312 ± 0.0006 and the ^{13}C isotope effect (1.0448, 1.0445, 1.0472, and 1.0418 in 1,4-dioxane, acetonitrile, DMF, and water, respectively) is independent of solvent polarity even though the reaction rate is markedly solvent dependent. Theoretical models at the semiempirical (AM1, PM3, SAM1) and *ab initio* (up to B3LYP/6–31+ + G**) levels were all unable to predict the experimental results quantitatively.

Results of a PM3 semiempirical study of the quaternary benzenesulfonamide salt of *trans*-3-(hydroxymethyl)-2-phenyl-1-methylpyrrolidine indicate that it fragments in a stepwise manner via an intermediate benzylic cation. The unexpected formation of a ring-opened sulfonamide rather than the expected tosylate ester on reaction of the 2-aryl-3-hydroxymethylpyrrolidine with $R''SO_2Cl$ is thereby explained.[95]

Thermal cleavage of 4-azido-2-pyrrolinones has been modelled at the MP2/6–31G* and MP4SDQ/6–31G*//MP2/6–31G* levels with allowance for electrostatic effect of the solvent.[96] The favoured route is rate determining expulsion of N_2 from the *trans* conformer of the reactant, to give an azirine intermediate from which a zwitterion forms in a concerted manner. Electron donor groups at C(3) and C(5) and alkyl groups at N(1) in the pyrrolidine ring favour electrocyclic closure of the zwitterion to a *β*-lactone, through cooperative torquoelectronic and steric hindrance effects. Stabilization of the zwitterion by solvent increases the energy barrier for competing fragmentation.

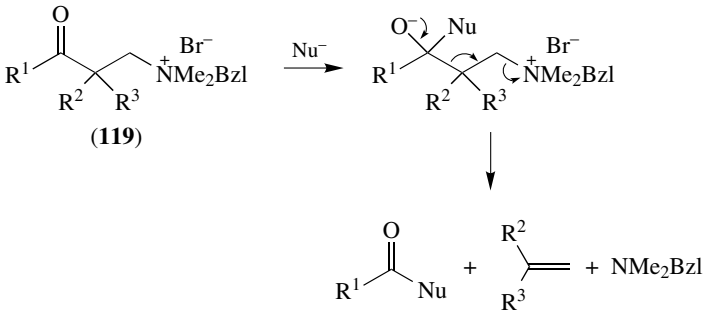
It has been established that competitive charge-remote and anion-induced fragmentation pathways occur during the collision induced loss of C_3H_6, C_4H_8, and C_6H_{12} from non-8-enoate anion.[97]



SCHEME 13

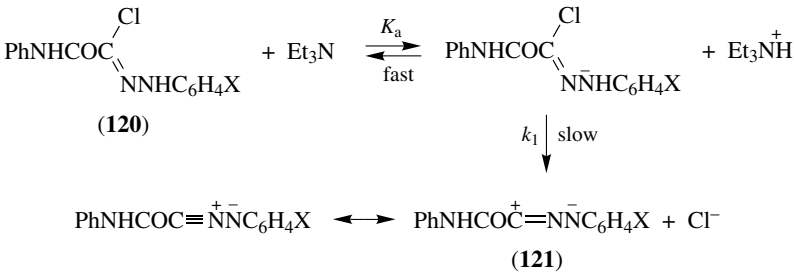
A study of the decomposition of *β*-hydroxy-*N*-chloroamines in aqueous medium has established that pre-equilibrium formation of the conjugate alcoholate is a prerequisite feature of the competing fragmentation and intramolecular elimination paths (Scheme 13).[98] A very high effective molarity ($EM = 2 \times 10^5$ M) has been estimated for the intramolecular process, which cannot occur in the case of (*N*-chloro)butylethanolamine. For reaction of (*N*-chloro)ethylethanolamine $k_{intra}/k_{frag} = 6.1$ and the solvent isotope effect $(k_{OH^-}/k_{OD^-})_{obs} = 0.68$ is consistent with pre-equilibrium deprotonation followed by a unimolecular reaction in which there is no participation by solvent.

Grob-type fragmentations induced by nucleophilic attack of NH_2^- on the carboxyl group of quaternary β-aminoaldehydes and β-aminoketones (**119**) have been reported (Scheme 14).[99] *N*-(2-Imino-1-oxopropyl)glycine is formed as an intermediate in the base-catalysed decomposition of (*N*-X)-Ala-Gly.[100]



SCHEME 14

The oxanilic hydrazide and tetrazine formed when *N*-aryl-2-oxo-2-phenylamino-ethanehydrazonyl chloride (**120**) is treated with Et_3N in 1,4-dioxane–water (4 : 1, v/v) at 25 °C arise from the intermediate nitrilium amide (**121**).[101] A kinetic study has now established that (**121**) is formed from (**120**) according to Scheme 15. The second-order rate constant $k_{obs} = 0.37\sigma_X^- - 0.77$, where $\rho_{obs} = 0.37 = \rho_a + \rho_1$; since $\rho_a \approx 1.18$ [cf. that determined for acid dissociation of PhNHCON(CN)=NNHC$_6$H$_4$X], it has been possible to evaluate $\rho_1 = -0.81$, which compares favourably with the value $\rho = -0.63$ for C—Br heterolysis of PhC(Br)=NNHC$_6$H$_4$X in the same solvent.



SCHEME 15

Results of an *ab initio* study of H_2 elimination from protonated formaldehyde and formaldimine suggest that the process is concerted, whereas a two-step elimination mechanism applies in the case of protonated thioformaldehyde.[102]

Ring opening–ring closure sequences have been proposed to account for formation of 4-(trifluoromethyl)imidazoles on base-promoted trifluoromethyl elimination from 4,4-bis(trifluoromethyl)-5-hydroxyimidazoline.[103]

Kinetics of oxidative deamination and decarboxylation of D,L-leucine by acidic permanganate in presence of silver ion have been interpreted[104] and the formation of

monoaminovinyl derivatives via aminolysis of activated vicinal dihalovinyl compounds has been studied.[105]

References

[1] Saunders, W. H., *J. Org. Chem.*, **62**, 244 (1997).
[2] Koch, H. F., Lodder, G., Koch, J. G., Bogdan, D. J., Brown, G. H., Carlson, C. A., Dean, A. B., Hage, R., Han, P., Hopman, J. C. P., James, L. A., Knape, P. M., Roos, E. C., Sardina, M. L., Sawyer, R. A., Scott, B. O., Testa, C. A., and Wickham, S. D., *J. Am. Chem. Soc.*, **119**, 9965 (1997).
[3] Cho, B. R., Kim, Y. K., and Yoon, C.-O. M., *J. Am. Chem. Soc.*, **119**, 691 (1997).
[4] Meng, Q. and Thibblin, A., *J. Am. Chem. Soc.*, **119**, 1224 (1997).
[5] Humeres, E., *Gazz. Chim. Ital.*, **126**, 449 (1996); *Chem. Abs.*, **125**, 248233 (1996).
[6] Kozeny, V., Mindl, J., and Sterba, V., *Chem. Pap.*, **51**, 29 (1997); *Chem. Abs.*, **126**, 343213 (1997).
[7] Yannai, M. B. and Rappoport, Z., *J. Org. Chem.*, **62**, 5634 (1997).
[8] Gevorkyan, A. A., Arakelyan, A. S., and Cockerill, A. F., *Tetrahedron*, **53**, 7947 (1997).
[9] Glad, S. S. and Jensen, F., *J. Org. Chem.*, **62**, 253 (1997).
[10] Gronert, S. and Freed, P., *J. Org. Chem.*, **61**, 9430 (1996).
[11] Merrill, G. N., Gronert, S., and Kass, S. R., *J. Phys. Chem. A*, **101**, 208 (1997).
[12] Holman, R. W., Sumpter, T. L., Farrar, J., Weigel, K., and Bartmess, J. E., *J. Phys. Org. Chem.*, **10**, 585 (1997).
[13] Shibayama, A., Nakamura, T., Asada, T., Shintani, T., Ukaji, Y., Kinoshita, H., and Inomata, K., *Bull. Chem. Soc. Jpn*, **70**, 381 (1997).
[14] Kuntsevich, A. D., Shantrokha, A. V., Golovkov, V. F., Shcherbakova, L. F., Kuznetsov, P. E., and Shcherbakov, A. A., *Dokl. Akad. Nauk*, **345**, 68 (1995); *Chem. Abs.*, **127**, 65354 (1997).
[15] Cho, B. R., Cho, N. S., and Lee, S. K., *J. Org. Chem.*, **62**, 2230 (1997).
[16] Meng, Q., Gogoll, A., and Thibblin, A., *J. Am. Chem. Soc.*, **119**, 1217 (1997).
[17] Meng, Q. and Thibblin, A., *J. Am. Chem. Soc.*, **119**, 4834 (1997).
[18] Thibblin, A. and Saeki, Y., *J. Org. Chem.*, **62**, 1079 (1997).
[19] Toteva, M. M. and Richard, J. P., *J. Am. Chem. Soc.*, **118**, 11434 (1996).
[20] Richard, J. P., Lin, S.-S., Buccigross, J. M., and Amyes, T. L., *J. Am. Chem. Soc.*, **118**, 12603 (1996).
[21] Xu, X., Antal, M. J., and Anderson, D. G. M., *Ind. Eng. Chem. Res.*, **36**, 23 (1997); *Chem. Abs.*, **127**, 81045 (1997).
[22] Kelly, S. C., McDonnell, C. A., O'Ferrall, R. A., Rao, S. N., Boyd, D. R., Brannigan, I. N., and Sharma, N. D., *Gazz. Chim. Ital.*, **126**, 747 (1996); *Chem. Abs.*, **126**, 74381 (1997).
[23] Vereshchagin, S. N., Kirik, N. P., Shishkina, N. N., and Anshits, A. G., *Kinet. Catal.* (transl. of *Kinet. Katal.*, **37**, 780 (1996); *Chem. Abs.*, **126**, 103745 (1997).
[24] Moodie, R. B., Moustras, M. Z., Read, G., and Sandall, J. P. B., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 169.
[25] Sengupta, D. and Nguyen, M. T., *Tetrahedron*, **53**, 9647 (1997).
[26] Couture, P., El-Saidi, M., and Warkentin, J., *Can. J. Chem.*, **75**, 326 (1997).
[27] Awadallah, A., Kowski, K., and Rademacher, P., *J. Heterocycl. Chem.*, **34**, 113 (1997).
[28] Asperger, S., *Kem. Ind.*, **46**, 227 (1997); *Chem. Abs.*, **127**, 56328 (1997).
[29] Bunnage, M. E. and Nicolaou, K. C., *Chem. Eur. J.*, **3**, 187 (1997); *Kinet. Catal.* (transl. of *Kinet. Katal.*, **37**, 780 (1996); *Chem. Abs.*, **126**, 292906 (1997).
[30] Wijnen, J. W. and Engberts, J. B. F. N., *J. Org. Chem.*, **62**, 2039 (1997).
[31] Wijnen, J. W. and Engberts, J. B. F. N., *Liebigs Ann./Recl.*, **1997**, 1085.
[32] Lewis, D. K., Hutchinson, A., Lever, S. J., Spaulding, E. L., Bonacorsi, S. J., and Baldwin, J. E., *Isr. J. Chem.*, **36**, 233 (1996); *Chem. Abs.*, **126**, 330285 (1997).
[33] Higgins, J., Zhou, X., and Liu, R., *J. Phys. Chem. A*, **101**, 7231 (1997).
[34] Birney, D. M., Ham, S., and Unruh, G. R., *J. Am. Chem. Soc.*, **119**, 4509 (1997).
[35] Matsui, H., Zückerman, E. J., Katagiri, N., Kaneko, C., Ham, S., and Birney, D. M., *J. Phys. Chem. A*, **101**, 3936 (1997).
[36] Chao, I., Lu, H.-f., and Chou, T.-s., *J. Org. Chem.*, **62**, 7882 (1997).
[37] Shimada, K., Aikawa, K., Fujita, T., Aoyagi, S., Takikawa, Y., and Kabuto, C., *Chem. Lett.*, **1997**, 701.
[38] Schaad, L. J. and Skancke, P. N., *J. Phys. Chem. A*, **101**, 7408 (1997).
[39] Jankowski, S. and Rudzinski, J., *Heteroat. Chem.*, **7**, 369 (1996); *Chem. Abs.*, **125**, 275987 (1996).
[40] Tanaka, S., Tomariguchi, S., Saito, K., Takahashi, O., and Tabayashi, K., *Isr. J. Chem.*, **36**, 249 (1996); *Chem. Abs.*, **126**, 305360 (1997).
[41] Higgins, J., Zhou, X., Liu, R., and Huang, T. T.-S., *J. Phys. Chem. A*, **101**, 2702 (1997).

[42] Huang, C.-L., Wu, C.-C., and Lien, M.-H., *J. Phys. Chem. A*, **101**, 7867 (1997).
[43] Ismatov, D. N., Azizov, U. M., and Iskandarov, S., *Ukr. Khim. Zh.*, **1996**, 101; *Chem. Abs.*, **126**, 31012 (1997).
[44] Chuchani, G. and Martin, I., *J. Phys. Org. Chem.*, **10**, 121 (1997).
[45] Chuchani, G., Rotinov, A., and Dominguez, R. M., *J. Phys. Org. Chem.*, **9**, 787 (1996).
[46] Hettema, H., Hore, N. R., Renner, N. D., and Russell, D. K., *Aust. J. Chem.*, **50**, 363 (1997).
[47] Safont, V. S., Moliner, V., Andrés J., and Domingo, L. R., *J. Phys. Chem. A*, **101**, 1859 (1997).
[48] Ocampo, R., Dolbier, W. R., Bartberger, M. D., and Paredes, R., *J. Org. Chem.*, **62**, 109 (1997).
[49] Al-Awadi, N. A., El-Dusouqui, O. M. E., and Mathew, T., *Int. J. Chem. Kinet.*, **29**, 289 (1997).
[50] Al-Awadi, N. A. and El-Dusouqui, O. M. E., *Int. J. Chem. Kinet.*, **29**, 295 (1997).
[51] Chuchani, G. and Dominguez, R. M., *React. Kinet. Catal. Lett.*, **59**, 53 (1996); *Chem. Abs.*, **126**, 211729 (1997).
[52] Dyke, J. M., Groves, A. P., Morris, A., Ogden, J. S., Dias, A. A., Oliveira, A. M. S., Costa, M. L., Barros, M. T., Cabral, M. H., and Moutinho, A. M. C., *J. Am. Chem. Soc.*, **119**, 6883 (1997).
[53] Sarobe, M., Jenneskens, L. W., and Wiersum, U. E., *Tetrahedron Lett.*, **38**, 4689 (1997).
[54] Akao, M., Saito, K., Okada, K., Takahashi, O., and Tabayashi, K., *Ber. Bunsen-Ges. Phys. Chem.*, **100**, 1237 (1996); *Chem. Abs.*, **125**, 247064 (1996).
[55] Al-Awadi, N., Elnagdi, M. H., Mathew, T., and El Gamry, I., *Heteroat. Chem.*, **7**, 417 (1996); *Chem. Abs.*, **126**, 31015 (1997).
[56] Al-Awadi, N., Elnagdi, M. H., Mathew, T., and El Gamry, I., *Heteroat. Chem.*, **8**, 63 (1997); *Chem. Abs.*, **126**, 131128 (1997).
[57] Christensen, J. B. and Holm, A., *Acta Chem. Scand.*, **51**, 527 (1997).
[58] Flammang, R., Barbieux-Flammang, M., Gerbaux, P., and Pedersen, C. T., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1261.
[59] Zhong, D., Ahmad, S., and Zewail, A. H., *J. Am. Chem. Soc.*, **119**, 5978 (1997).
[60] Salmon, R. P. and Ritter, E. R., *Chem. Phys. Processes Combust.*, **1996**, 507; *Chem. Abs.*, **126**, 131133 (1997).
[61] Kumaran, S. S., Su, M.-C., Lim, K. P., and Michael, J. V., *Symp. (Int.) Combust.*, *[Proc.]*, **1996**, 605; *Chem. Abs.*, **126**, 277113 (1997).
[62] Kumaran, S. S., Lim, K. P., Michael, J. V., Tilson, J. L., Suslensky, A., and Lifshitz, A., *Isr. J. Chem.*, **36**, 223 (1996); *Chem. Abs.*, **126**, 293013 (1997).
[63] Sakaizumi, T., Haga, J., and Ohashi, O., *J. Anal. Appl. Pyrolysis*, **37**, 27 (1996); *Chem. Abs.*, **125**, 247065 (1996).
[64] Harris, N. J. and Lammertsma, K., *J. Phys. Chem. A*, **101**, 1370 (1997).
[65] Oxley, J. C., Smith, J. L., Rogers, E., and Dong, X. X., *J. Phys. Chem. A*, **101**, 3531 (1997).
[66] Rodriguez, L., Munoz, W., Martin, G., and Ocando-Mavarez, E., *Heteroat. Chem.*, **8**, 85 (1997); *Chem. Abs.*, **126**, 185673 (1997).
[67] Prokudin, V. G., Poplacskii, V. S., and Ostrovskii, V. A., *Izv. Akad. Nauk, Ser. Khim.*, **1996**, 2209; *Chem. Abs.*, **126**, 185730 (1997).
[68] Arenas, J. F., Otero, J. C., Sanchez-Galvez, A., and Soto, J., *J. Mol. Struct.*, **410–411**, 451 (1997); *Chem. Abs.*, **127**, 176037 (1997).
[69] Chuchani, G., Dominguez, R. M., Rotinov, A., and Martin, I., *Int. J. Chem. Kinet.*, **29**, 851 (1997).
[70] Herzler, J., Manion, J. A., and Tsang, W., *J. Phys. Chem. A*, **101**, 5494 (1997).
[71] Jursic, B. S., *THEOCHEM*, **389**, 257 (1997); *Chem. Abs.*, **126**, 305296 (1997).
[72] Ocando-Mavarez, E., Martin, G., Rodriguez, L., and Munoz, W., *Heteroat. Chem.*, **8**, 97 (1997); *Chem. Abs.*, **126**, 293383 (1997).
[73] Hollfelder, F., Kirby, A. J., and Tawfik, D. S., *J. Am. Chem. Soc.*, **119**, 9578 (1997).
[74] Palmer, D. R. J., Wieczorek, S. J., Hubbard, B. K., Mrachko, G. T., and Gerlt, J. A., *J. Am. Chem. Soc.*, **119**, 9580 (1997).
[75] George, P., Glusker, J. P., and Bock, C. W., *J. Am. Chem. Soc.*, **119**, 7065 (1997).
[76] Mullen, G. P., Antuch, W., Maciejewski, M. W., Prasad, R., and Wilson, S. H., *Tetrahedron*, **53**, 12057 (1997).
[77] Zhou, Z. S., Jiang, N., and Hilvert, D., *J. Am. Chem. Soc.*, **119**, 3623 (1997).
[78] Yoon, S. S., Oei, Y., Sweet, E., and Schultz, P. G., *J. Am. Chem. Soc.*, **118**, 11686 (1996).
[79] Clancy, S. F., Thies, M., and Paradies, H., *J. Chem. Soc., Chem. Commun.*, **1997**, 2035.
[80] Coates, R. M., Elmore, C. S., Croteau, R. B., Williams, D. C., Morimoto, H., and Williams, P. G., *J. Chem. Soc., Chem. Commun.*, **1997**, 2079.
[81] Baird, M. S. and Bolesov, I. G., *Chem. Halides Pseudo-Halides Azides*, **1995**, 1351; *Chem. Abs.*, **125**, 247232 (1996).
[82] Westwell, A. D. and Williams, J. M. J., *Prep. Alkenes*, **1996**, 95; *Chem. Abs.*, **126**, 276966 (1997).

[83] Deagostino, A., Prandi, C., Tonachini, G., and Venturello, P., *Trends Org. Chem.*, **5**, 103 (1995); *Chem. Abs.*, **126**, 305273 (1997).
[84] Lawrence, N. J., *Prep. Alkenes*, **1996**, 19; *Chem. Abs.*, **126**, 330217 (1997).
[85] Nishizawa, M., Komatsu, Y., García, D. M., Noguchi, Y., Imagawa, H., and Yamada, H., *Tetrahedron Lett.*, **38**, 1215 (1997).
[86] Otten, P. A., Davies, H. M., van Steenis, J. H., Gorter, S., and van der Gen, A., *Tetrahedron*, **53**, 10527 (1997).
[87] Polezhaeva, N. A., Loginova, I. V., Galkin, V. I., Ovechkina, E. V., Sakhibullina, V. G., and Cherkasov, R. A., *Zh. Obshch. Khim.*, **66**, 798 (1996); *Chem. Abs.*, 125, 328923 (1997).
[88] Evans, P. and Taylor, R. J. K., *Tetrahedron Lett.*, **38**, 3055 (1997).
[89] Braverman, S., Grinstein, D., and Gottlieb, H. E., *Tetrahedron*, **53**, 13933 (1997).
[90] Braverman, S. and Cherkinsky, M., *Tetrahedron Lett.*, **38**, 487 (1997).
[91] Lautens, M., Fillion, E., and Sampat, M., *J. Org. Chem.*, **62**, 7080 (1997).
[92] Al-Awadi, N. A. and Elnagdi, M. H., *Heteroat. Chem.*, **8**, 293 (1997); *Chem. Abs.*, **127**, 220346 (1997).
[93] Young, D. J. and Stirling, C. J. M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 425.
[94] Czyryca, P. and Paneth, P., *J. Org. Chem.*, **62**, 7305 (1997).
[95] Rosende, E. G., Domingo, L. R., Sepúlveda-Arques, J., Mármol, D. P., García, E. Z., Acero-Alarcón, A., and Solesio, B. Y., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 643.
[96] Suárez, D. and Sordo, T. L., *J. Am. Chem. Soc.*, **119**, 10291 (1997).
[97] Dua, S., Bowie, J. H., Cerda, B. A., Wesdemiotis, C., Raftery, M. J., Kelly, J. F., Taylor, M. S., Blanksby, S. J., and Buntine, M. A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 695.
[98] Armesto, X. L., Canle, M., Carretero, P., García, M. V., and Santaballa, J. A., *Tetrahedron*, **53**, 2565 (1997).
[99] Mölm, D. and Risch, N., *Liebigs Ann./Recl.*, **1997**, 1765.
[100] Armesto, X. L., Canle, M., García, M. V., and Santaballa, J. A., *Tetrahedron*, **53**, 12615 (1997).
[101] Shawali, A. S., Elwan, N. M., and Awad, A. M., *J. Chem. Res. (S)*, **1997**, 268.
[102] Suárez, D. and Sordo, T. L., *J. Phys. Chem. A*, **101**, 1561 (1997).
[103] Li, H.-Y., DeLucca, I., Drummond, S., and Boswell, G. A., *J. Org. Chem.*, **62**, 2550 (1997).
[104] Chourey, V. R., Pande, S., Shastry, L. V., and Shastry, V. R., *Asian J. Chem.*, **9**, 435 (1997); *Chem. Abs.*, **127**, 117929 (1997).
[105] Kravchenko, V. V., Popov, A. F., Dontsova, N. E., Litvinov, V. P., and Lutsyuk, A. F., *Ukr. Khim. Zh. (Russ. Ed.)*, **62**, 104 (1996); *Chem. Abs.*, **126**, 343214 (1997).

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CHAPTER 13

Addition Reactions: Polar Addition

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Reviews

During the coverage period of this chapter, reviews have appeared on the following topics: investigation of the early steps in electrophilic bromination through the study of the reaction with sterically encumbered alkenes;[1] new findings in bromination of alkenes;[2] addition of hydrogen halides to vinylic compounds;[3] reactions of alkynes with organometallic reagents (carbometallation and hydrometallation);[4] asymmetric addition of amines to α,β-unsaturated esters and nitriles in the enantioselective synthesis of β-amino acids;[5] asymmetric synthesis of β-amino acids via Michael addition of chiral metal amides (namely Li amides);[6] double Michael additions and other domino reactions and their application to natural product synthesis;[7] asymmetric ylide reactions (epoxidation, cyclopropanation, aziridination, olefination and rearrangements);[8] nucleophilic addition–oxidation reactions of σ^3, λ^3-dialkyl(silylamino)phosphines with mono- and di-substituted alkynes;[9] and antibody-catalysed cationic reactions—re-routing of chemical transformations.[10]

Electrophilic Additions

Carbon 1*s* ionization energies of $CH_2{=}CH_2$, $MeCH{=}CH_2$, and $Me_2C{=}CH_2$ have been measured in the gas phase at high resolution using synchrotron radiation and analysed

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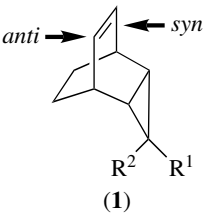
by means of *ab initio* calculations. For the first time, the resolution was high enough to assign energies to the non-equivalent cations in propene and methylpropene. A linear correlation was found between the ionization energies and activation energies for addition of electrophiles HF, HCl, HBr and HI to these molecules. The correlation revealed that both reactivity and regioselectivity are quantitatively related to core-ionization energies. Theoretical analysis of the core-ionization energies showed that the difference between ionization energies for the doubly bonded carbons originate from the charge distribution in the non-ionized molecule. Theoretical analysis of the transition state for addition of HCl to propene and 2-methylpropene indicated that a significant portion of the difference between Markovnikov and anti-Markovnikov addition is also due to the charge distribution in the initial state rather than to different ability of the molecule to delocalize the added charge in the transition state. The increase in reactivity with the number of methyl groups also appears to be strongly influenced by the initial-state charge distribution.[11]

The distinction between electrophilic and electron-transfer mechanisms of addition reactions to vinyl double bonds of $ArX-CH=CH_2$ (X = S, O, Se) has been achieved by studying substituent effects. Specifically, the effects of *meta* and *para* substituents on the rates of electrophilic additions correlated with Hammett σ values, while ionization of the substrates to the corresponding radical cations correlates with σ^+. The significance of the respective correlations were confirmed by statistical tests. The σ(electrophilic)/σ^+(ET) dichotomy is in accord with the conventional paradigm for σ/σ^+ correlations and further support has been found by *ab initio* calculations. Interestingly, the application of this criterion to the reactions of aryl vinyl sulfides and ethers with tetracyanoethylene indicates that cyclobutanes are formed via direct electrophilic addition to the electron-rich alkene rather than via an electron-transfer mechanism.[12]

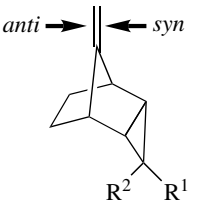
The cyclopropyl group embedded in the bicyclo[2.2.2]octene system (**1**) has been reported to affect the *syn*/*anti* selectivity of electrophilic additions to the C=C bond in the same way as do electron-withdrawing groups (Table 1).[13,14] This behaviour is in sharp contrast to the conventional viewing of the cyclopropane ring as a strongly electron-donating functionality. On the other hand, the *exo*-methylene analogue (**2**) suggests electron-donating behaviour for the cyclopropane ring. For comparison, the authors have also studied the corresponding cyclobutane derivative (**3**), which proved to exhibit little stereo-differentiation. The previously observed *anti*-facial selectivity for (**2**)[15–18] was attributed to the out-of-phase interaction of the π and Walsh orbitals; apparently, the corresponding interaction is irrelevant in the case of (**1**). Electronic factors governing stereofacial selectivity in Michael-type additions[19] will be discussed in the section on nucleophilic additions.

The order of redox potentials for oxidation of (**4**) (F>Cl $\approx$ Br) has been reported and found most consistent with a detectable resonance contribution through the σ-framework. The most difficult oxidation of (**5**) (despite the fluoro substituent being one carbon atom more removed from the double bond) is consistent with the Whiffer effect (σ-hyperconjugative destabilization proceeding through two pathways is more than double the same effect through one pathway), in consonance with the AM1 prediction. The facial selectivity of epoxidation and diazetidine formation from (**4**) proved to be in

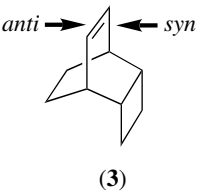
Table 1. *syn*/*anti* selectivity of the electrophilic attack on (**1**) (**3**)



(**1**)



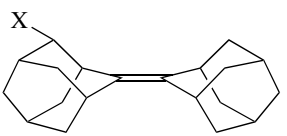
(**2**)



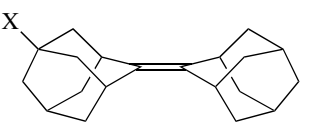
(**3**)

Alkene	R^1	R^2	*Reagent*	*syn : anti*	*Ref.*
(**1**)	H	H	OsO_4	95 : 5	13
(**1**)	H	H	MCPBA	92 : 8	13
(**1**)	H	H	B_2HO_6	74 : 26	14
(**1**)	CN	H	OsO_4	98 : 2	13
(**1**)	CN	H	MCPBA	82 : 12	13
(**1**)	H	CN	OsO_4	> 99 : 1	13
(**1**)	H	CN	MCPBA	94 : 6	13
(**2**)	H	H	OsO_4	12 : 88	13
(**2**)	H	H	CCl_2	44 : 56	15, 16
(**2**)	H	H	9-BBN	11 : 89	15, 16
(**2**)	Me	Me	CCl_2	34 : 66	15, 16
(**2**)	Me	Me	9-BBN	5 : 95	15, 16
(**3**)	–	–	OsO_4	40 : 60	15, 16
(**3**)	–	–	MCPBA	42 : 78	15, 16

the order Cl>F>Br; (**5**) was found to be less selective for these reactions, which is not consistent with the Ciepłak effect. The authors argue that both steric and electronic factors contribute to these results.[20]



(**4**)



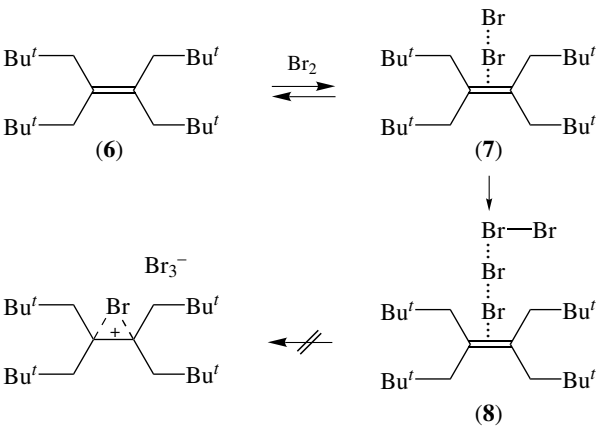
(**5**)

Halogenation and Related Reactions

The kinetics and the products of bromination of several substituted stilbenes with $Bu_4N^+Br_3^-$ have been investigated in aprotic solvents at different temperatures and concentrations. Stilbenes bearing electron-withdrawing or moderately electron-donating substituents gave stereospecifically the *anti* addition products; the reaction followed a second-order rate law and inverse kinetic isotope effect $k_H/k_D = 0.85\ (\pm 0.05)$ was

found for the bromination of *cis*-stilbene. By contrast, the reactions of *cis*- and *trans*-4,4′-dimethoxystilbenes yielded mixtures of *meso*- and *d,l*-dibromides in both $CHCl_3$ and 1,2-dichloroethane. The rate constants ($k_{Br_3^-}$) measured for the latter alkenes deviate considerably from the Hammett correlations and added Br^- had a significant effect on the rates. The reactions of these activated stilbenes with molecular Br_2, carried out at low $[Br_2]$, followed a mixed second-order–third-order rate law. The kinetics and product distribution from the bromination of stilbenes bearing electron-withdrawing or moderately electron-donating substituents were interpreted on the basis of the known mechanism involving a product- and rate-determining nucleophilic attack by Br^- on the alkene–Br_2 π-complex. The data related to the bromination of more activated methoxystilbenes were rationalized via the ionization of the initially generated 1 : 1 π-complex to a bromocarbenium–bromide ion pair competing with the formation of a bromonium–tribromide ion pair and with the nucleophilic attack by Br^- (even in aprotic solvents).[21]

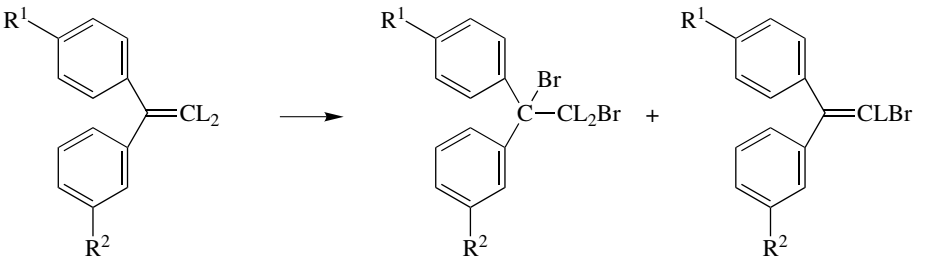
An L-shaped arrangement of bromine atoms has been identified by spectroscopy and theoretical studies on the 2 : 1 π-complex (**8**) generated by electrophilic bromination of tetraneopentylethylene (**6**). The reaction stops at the stage (**8**) which, for the first time, allowed its detection and determination of its thermodynamic parameters by UV spectroscopy (Scheme 1). Theoretical calculations predict an alkene–$Br_2 \cdot Br_2$ rather than the Br_2–alkene–Br_2 structure.[22]



SCHEME 1

Discrete and continuum models for the solvent involvement have been employed to steady equilibrium and non-equilibrium solvation effects on bromination of ethylene. Two mechanisms were identified that lead to transition states of different symmetry. One mechanism operates in the gas phase and non-polar solvents. The second one, that leads to the typical C_{2v} transition state, holds in medium-to-very polar solvents. In water, the solvent molecules participate actively and non-equilibration solvations effects proved to be substantial and larger than those previously reported for the S_N2 reaction.[23]

The kinetics of bromination of (**9a–c**; L = H or D) in CH_2Cl_2 (Scheme 2) have demonstrated that the reaction is always second order in Br_2 and first order in alkenes with the following constants k_3: (**9a**), 1.7×10^7; (**9b**), 8.0×10^4; (**9c**), 52 $dm^6\ mol^{-2}\ s^{-1}$ (L = H). Alkene (**9a**; L = H) gave a mixture of dibromide (**10a**) and vinyl bromide (**11a**) in a ratio changing from 99 : 1 at 10^{-2} mol dm^{-3} to 5 : 95 at 10^{-4} mol dm^{-3} Br_2 and alkene. The k_3 value proved to be independent of the reagent concentrations and of the extent of proton loss from the intermediate, showing that the last step was not rate limiting and the formation of the intermediate was completely rate determining.[24]



(**9a**) $R^1 = R^2 = H$
(**9b**) $R^1 = CF_3$, $R^2 = H$
(**9c**) $R^1 = R^2 = CF_3$

(**10**) (**11**)

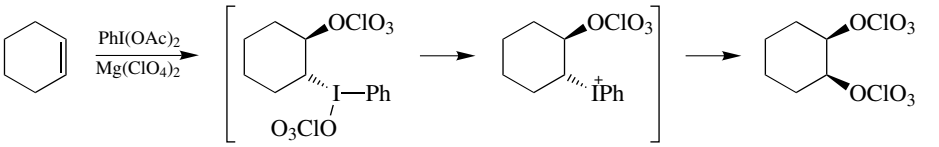
SCHEME 2

Bromine complexes of ethylene and cyclopropene have been isolated in argon matrices and studied by IR spectroscopy and *ab initio* methods. Two methods, namely MP2 and BLYP, were compared and found suitable for the calculation of IR spectra as they exhibited only minor differences.[25]

Bromination of tetrafluorobenzobarrelene with Br_2 has been reported to produce stereoisomers of the annulated tricyclic dibromide. However, when pyridine, 15-crown-5, or Me_2S were present, the *trans*-dibromide was obtained as the main product. MNDO calculations suggested that different cationic intermediates are responsible for the two pathways: cyclic bromonium ions lead to the former, whereas open cations give rise to the latter product.[26]

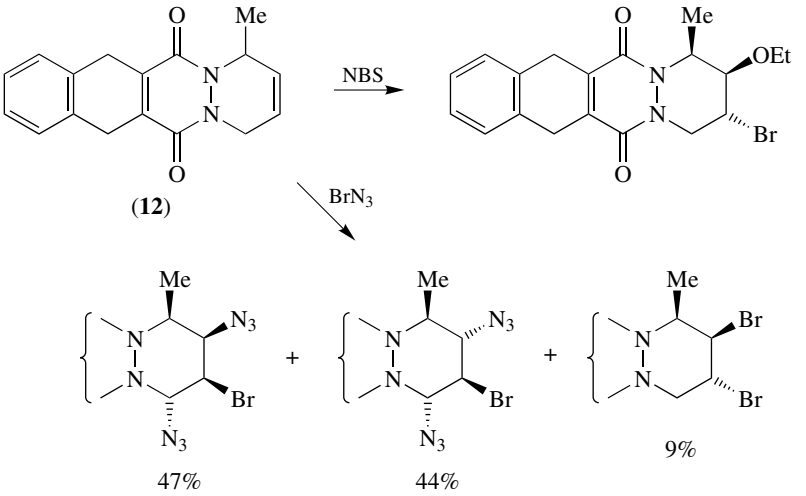
The course of addition reactions of ROH–XeF_2 to alkenes has been elucidated using norbornene, 2-methylpent-2-ene and hex-1-ene as model substrates. It turned out that the alkoxyxenon fluoride intermediates (ROXeF) can react either as oxygen electrophiles (initially adding alkoxy substituent) or as apparent fluorine electrophiles (initially adding fluorine), depending on the reaction conditions. Simple addition of poorly nucleophilic alcohols to norbornene was also observed in certain instances. Selectivity between the various reaction pathways (simple fluorination, alkoxyfluorination, or alcohol addition) proved to be sensitive to various reactions conditions, especially solvent, temperature, and catalyst.[27]

A formal equivalent of Woodward reaction has been developed, which is based on the addition of hypervalent iodine species (Scheme 3).[28]



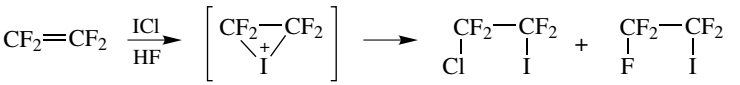
SCHEME 3

The course of electrophilic additions (NBS, BrN_3 or IN_3) to the tetrahydropyridazine moiety of (**12**) has been elucidated and shown to be controlled by conformational factors (Scheme 4).[29]



SCHEME 4

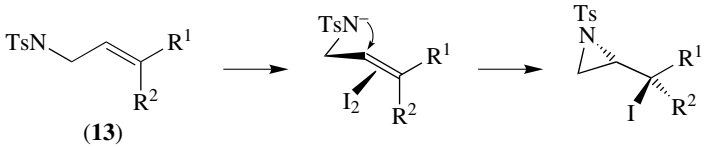
Electrophilic iodofluorination of fluoroalkenes (Scheme 5) has been reported to be the preferential pathway when carried out with ICl–HF in the presence of BF_3. By contrast, if BF_3 is absent, the reaction turns into iodochlorination as the main pathway.[30]



with BF_3 :	1%	78–91%
without BF_3 :	48%	19%

SCHEME 5

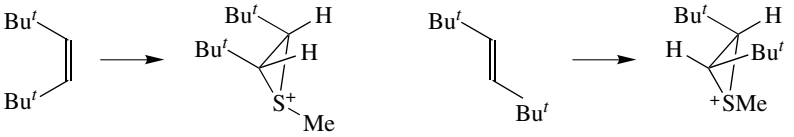
NaH-mediated iodoaziridination reaction of *N*-allylic tosylamides (**13**) has been developed and shown to exhibit excellent *anti* stereospecificity (Scheme 6).[31]



SCHEME 6

Additions of ArSX, ArSeX, and Related Reactions

Cis- and *trans*-di-*t*-butylthiiranium tetrafluoroborates (**14**) and (**15**) were generated from *cis*- and *trans*-di-*t*-butylethylene, respectively (Scheme 7), on reaction with methylbis(methylthio)sulfonium tetrafluoroborate in liquid SO_2 at −78 °C. Their reaction with water was studied and different reaction modes were found.[32]



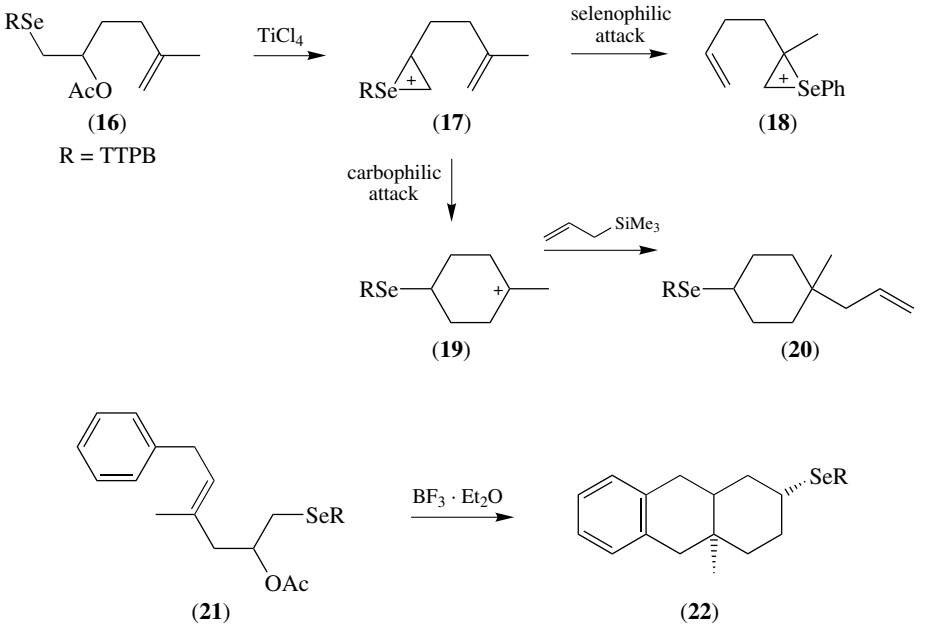
Steric protection by the bulky 2,4,6-tri-*t*-butylphenyl (TTBP) group of the selenium atom in the episelenonium ion intermediate (**17**), generated *in situ* from (**16**), has been utilized in the selective formation of carbocyclic compounds (**17**)→(**19**)→(**20**) and (**21**)→(**22**). The selenophilic attack (**17**)→(**18**), leading to isomerization, can thus be avoided (Scheme 8).[33]

Additions of Hydrogen Halides and Other Acids

A linear correlation has been found between the ionization energies and activation energies for addition of HF, HCl, HBr, and HI to $CH_2{=}CH_2$, $MeCH{=}CH_2$, and $Me_2C{=}CH_2$;[11] for a more detailed discussion, see the introduction to this section.

The bimolecular reaction mechanism for adding HCl to $CH_2{=}CH_2$ has been studied by a number of advanced quantum chemistry methods. The transition-state structures and energy were examined in detail; high-level calculations support the existence of an intimate association of chloride anion and a bridged ethyl cation, with some covalent bonding retained between chloride and hydrogen. A tunnelling correction of 1 kcal mol^{-1} in the reaction barrier was obtained by the Bell equation.[34] Another theoretical study of the gas-phase addition of HF and HCl to $CH_2{=}CH_2$, using the *ab initio* MP2(full)/6–31G* method, has also been reported.[35]

A selected ion flow tube has been used to study the reaction of $C_2H_7O^+$, generated by the collision of H_3O^+ with C_2H_4. Reactions of the latter species with EtOCHO, Pr^{i}OH, AcOH, toluene, $CH_3CH{=}O$, allene, MeOH, cyclopropane, H_2O and C_2H_6 were studied to obtain information on the isomeric forms of the $C_2H_7O^+$ ions and the data were



SCHEME 8

compared with those previously reported on the reactivity of other isomeric forms, namely $(Me_2OH)^+$ and $(EtOH_2)^+$, with the same neutral reactants. The rate coefficient data turned out to show a very strong correlation between the reactivities of $(EtOH_2)^+$ and $H_3O^+ - C_2H_4$, indicating that the associated ions are similar in form to these strongly bonded species,[36] and is consistent with conclusions based on calculated potential energy surfaces (see below[37]). The agreement with the product distribution is less conclusive.[36] Generally, where proton transfer is exothermic for the strongly bonded species, it occurs rapidly for the associated ions. Where this transfer is very endothermic, association occurs for the associated ions, as it does for the strongly bonded species. In intermediate cases, the associated ions exhibit some additional transformations that are either endothermic for the strongly bonded species in their ground vibrational state or can be considered as ligand switching, indicating that the associated ions have access to the weak ligand-bonded form. These findings suggest that the associated ions are higher energy forms of protonated EtOH with access to the weak ligand-bonded form. The data further imply that the reaction is controlled by an early barrier giving a set of rate coefficients that are independent of whether the isomer is the strongly bonded form or produced in the association reaction, but that the products are controlled by the energy in the isomer and by the dominant conformation of that isomer.[36]

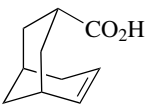
Another group[37] has explored the potential surface of $C_2H_7O^+$ using the G2 procedure, which led to the identification of four stable structures: protonated species $(C_2H_5OH_2)^+$ and $(Me_2OH)^+$, and the electrostatic complexes $(C_2H_4 \cdots H \cdots O^+H_2)$

and ($CH_3^+ \cdots HOCH_3$). Experiments conducted using a selected ion flow tube identified the product of the ion-molecule association reaction $H_3O^+ + C_2H_4$ as $(C_2H_5OH_2)^+$ (protonated ethanol).[37]

The ^{13}C NMR study of the polymerization of pent-1-ene with 95% H_2SO_4 points to the carbenium-ion mechanism, which involves the formation of sulfuric acid esters and their further heterolytic dissociation to generate aliphatic carbenium ions, whose steady-state concentration is low. By contrast, polymerization in 60–70% H_2SO_4 proved to occur via oxonium (rather than carbenium) ions.[38]

The acid-catalysed addition of AcOH and MeOH to the vinylcyclopropane moiety of the homotropylidene system of tetracyclo[5.3.2.$0^{2,10}$.$0^{3,6}$]dodeca-4,8,11-triene (**23**) afforded a kinetic mixture of 9-AcO and 9-MeO-tricyclo[4.3.3.$0^{2,5}$]dodeca-3,7,10-trienes, respectively, in which the β-derivatives greatly predominated over their less sterically congested α-counterparts.[39] Studies with AcOD excluded a relationship between the stereochemistry of D^+ (and H^+) attack and the nucleophilic trapping of the intermediate carbocation, indicating a stepwise process that involves (1) proton attack on (**23**) generating a cyclopropyl carbocation and (2) cleavage of the latter species with tight assistance by the nucleophilic solvent to give the final product with high β-diastereoselectivity. By contrast, addition of $Cl_2C{=}C{=}O$ turned out to occur at the cyclobutene moiety.[39]

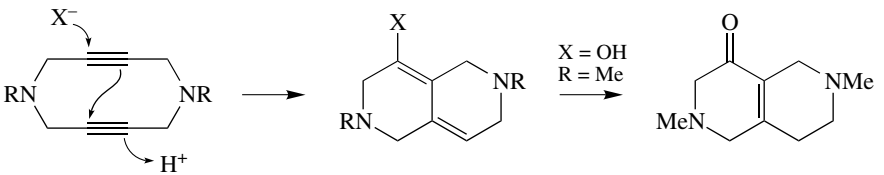
(**23**)



(**24**)

The solvent and temperature effect on the π-route cyclization of *endo*-bicyclo[3.3.1]-non-6-ene-3-carboxylic acid (**24**) has been studied.[40]

The reaction of (**25**; R = Pr^i) with HCl has been found to give (**26**; X = Cl) in quantitative yield as a result of transannular cyclization (Scheme 9); similar reactions occurred with H^+–MeOH or H_3O^+. Activation parameters, obtained by investigating the cyclization of (**25**) at different temperatures, are $\Delta H^* = 21 \pm 1$ kcal mol^{-1} and $\Delta S^* = -9 \pm 2$ cal mol^{-1} K^{-1}. These results are compatible with an Ad_E2 mechanism.[41]

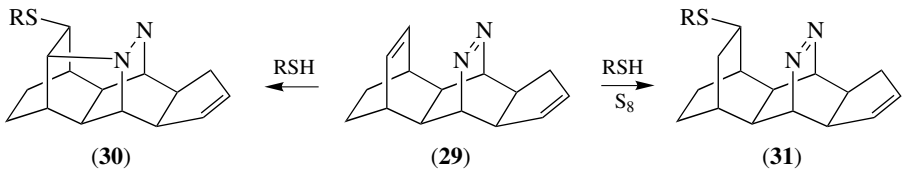


(**25**) (**26**) (**27**)

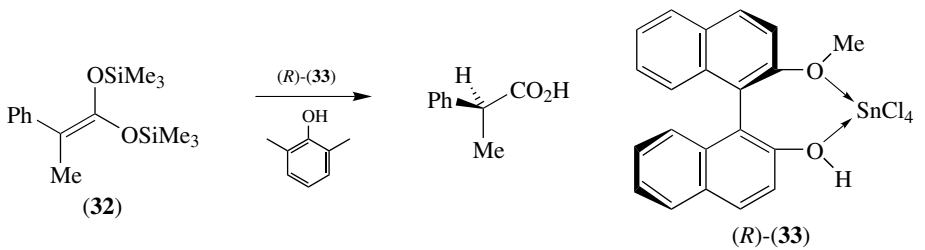
R = Pr^i, Me; X = Cl, MeO, OH

SCHEME 9

Whereas (**29**) reacts with sulfides RSH via a radical mechanism to afford the cyclic product (**30**), in the presence of elemental sulfur the reaction takes an ionic course, giving the expected 1,2 adduct (**31**).[42]



The first examples of the highly enantioselective protonation of silyl enol ethers, such as (**32**), have been reported (68–94% *ee*), using a complex of $SnCl_4$ and the monomethyl ether of BINOL (*R*)-(**33**). In this catalytic cycle, the active catalyst is reprotonated by a bulky phenol (Scheme 10).[43]



SCHEME 10

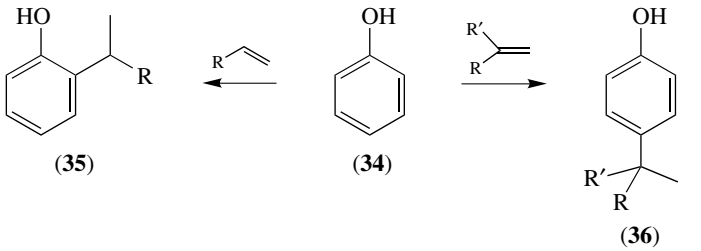
Additions of Electrophilic Carbon

The addition of Me_3C^+ to $Me_2C{=}CH_2$ has been investigated in the gas phase and in solution with *ab initio* calculations and Monte Carlo statistical mechanics simulations. The reaction is exothermic by ~ 20 kcal mol^{-1} and proceeds without activation energy in the gas phase. By contrast, solvation introduces a 3–4 kcal mol^{-1} barrier at a $C \cdots C$ separation near 5 Å in CH_2Cl_2, THF, and MeOH. An intermediate with a shallow energy well was found at near 3 Å separation. Implications for sterol biosynthesis were also discussed in this paper.[44]

Kinetics data suggest that the mechanism for the formation of hydrogenated furan from α-alkenes and formaldehyde involves the reversible addition of protonated formaldehyde to the alkene.[45]

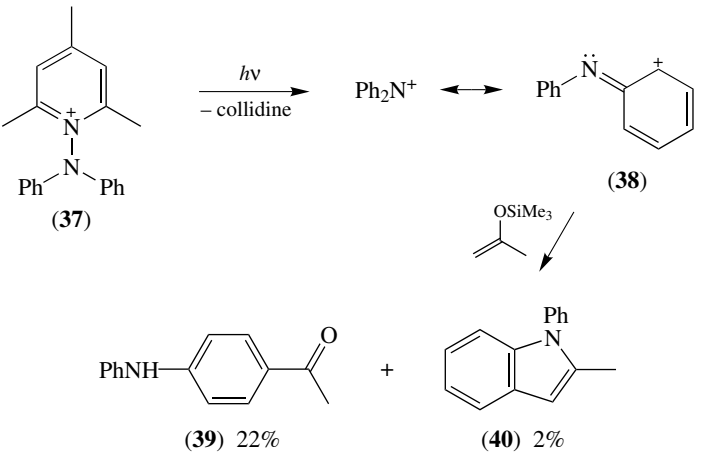
The reaction of a 1 : 1 mixture of PhOH (**34**) and linear alkenes with a Lewis acid ($AlCl_3$) in $CHCl_3$ at room temperature has been reported to be *ortho*-regioselective, producing *s*-alkylphenols (**35**) in 48–60% yield. By contrast, branched alkenes give exclusively the corresponding *p*-*t*-alkylphenols (**36**) (80–85%). Addition of increasing amounts of PhOK to the reacting system reduced the protic acidity and promoted *ortho*-

regioselective alkylation in the latter case. These results were tentatively interpreted in terms of H-bonded templates vs a charge-controlled mechanism.[46]



(**35**) (**34**) (**36**)

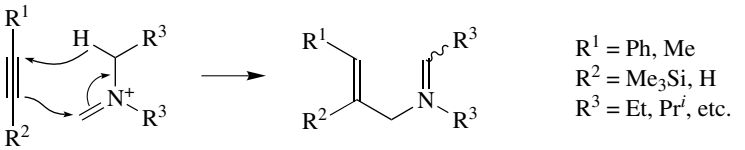
Photolysis of *N*-(diphenylamino)-2,4,6-trimethylpyridinium tetrafluoroborate (**37**) generates diarylnitrenium ion (**38**) as revealed by its reaction with electron-rich alkenes (silyl enol ethers and allylsilanes) to give products of substitution at *para*- and *ortho*-positions (**39**) and (**40**) (Scheme 11).[47]



(**37**) (**38**) (**39**) 22% (**40**) 2%

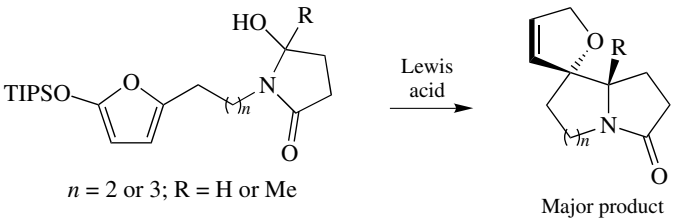
SCHEME 11

A previously unknown ene reaction of iminium ions with alkynes has been reported (Scheme 12); the parent amines must be of low nucleophilicity for the reaction to occur.[48]



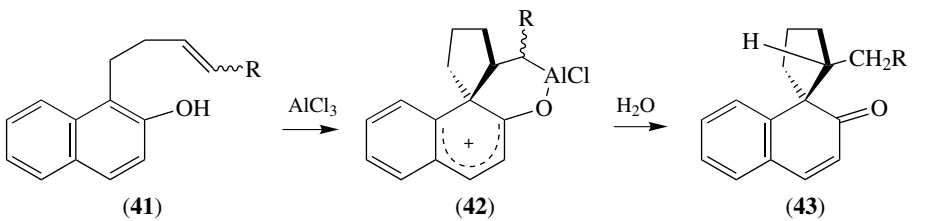
SCHEME 12

Substituted furans have been found to undergo vinylogous Mannich-type cyclization to give the *threo*-adducts as the major products (Scheme 13). The effect of solvent (CH_2Cl_2, MeCN, THF, and Et_2O), Lewis acid ($ZnCl_2$, $BF_3 \cdot Et_2O$, Et_2AlCl, and 3.0 M $LiClO_4$), and temperature (−20 to 40 °C) were examined.[49]



SCHEME 13

A stereoselective, Lewis acid-mediated cyclization of 1-substituted-2-naphthols (**41**) has been reported to produce spirocyclic ketones (**43**). Evidence has been presented for the involvement of the cyclic aluminium intermediate (**42**).[50]



(**41**) (**42**) (**43**)

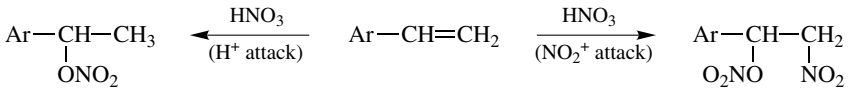
Carbocyclization of a monoepiselenonium intermediate derived from a diene has been discussed earlier in this chapter (Scheme 8),[33] as was the acid-catalysed transannular cyclisation of a bisalkyne (Scheme 9).[41]

Additions of Electrophilic Nitrogen and Oxygen

The addition of NO_2^+ to $CH_2{=}CH_2$ has been studied in the gas phase by TF-ISR, MIKE and CAD mass spectrometry, complemented by *ab initio* calculations at the MP2/6–31+G* level. The results are believed to provide a clear answer to the principal mechanistic question addressed, demonstrating that the reaction yields an *O*-nitroso product (presumably CH_3CHONO^+) rather than a *C*-product.[51]

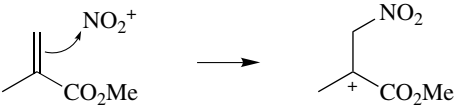
Kinetics studies and product analysis of the reaction of 4-R-styrenes (**44**; R = Me, H, Cl, CF_3, NO_2) with HNO_3 in CH_2Cl_2 showed preferential attack at the C=C bond, while aromatic nitration was negligible. With increasingly electron-withdrawing substituents, the reaction changes from one that is third order in HNO_3 [and gives rise to the 1-arylethyl nitrate (**45**)] to one which is of higher order in HNO_3 [and affords 2-nitro-1-arylethylnitrate (**46**)]. Both reactions proceed through transition states with

carbocationic character, by initial β-addition of H^+ and NO_2^+, respectively. The β-nitro-nitrate (**46**) is believed to be formed, in part, via a radical pathway.[52]



(**45**) (**44**) (**46**)

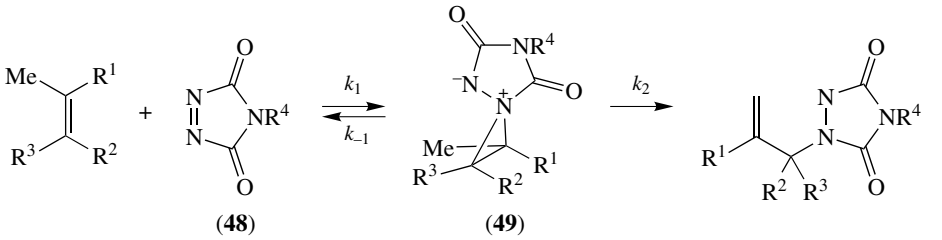
Reaction intermediates formed in the nitration of a series of α,β-unsaturated esters, such as (**47**), with NO_2BF_4 have been reported to exhibit the expected behaviour of α-carbonyl cations. Three diagnostic reaction types were observed: (1) Ritter reaction; (2) cyclopropane formation from propyl cations; (3) Wagner–Meerwein migration of alkyl groups. Semi-empirical calculations of the relative gas-phase stabilities of the proposed intermediate cations have also been performed.[53]



(**47**)

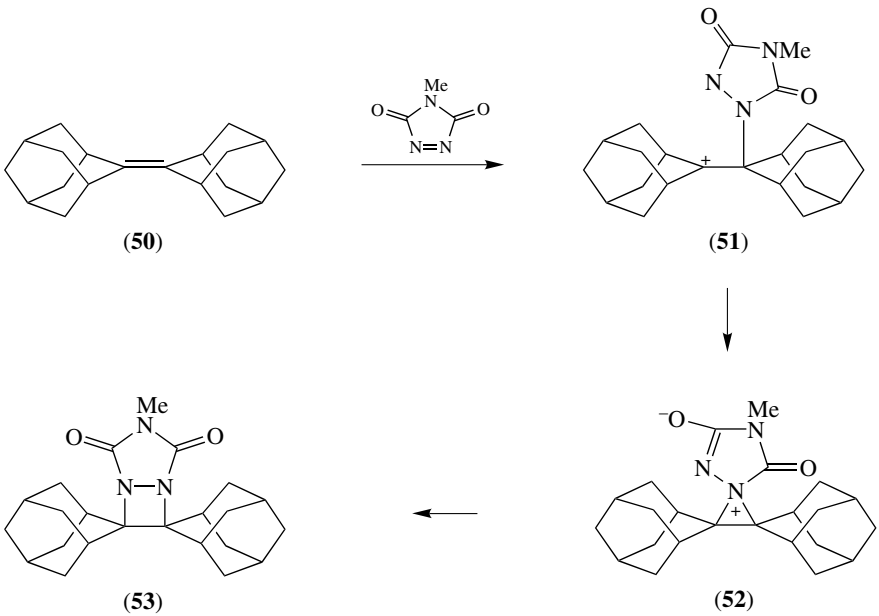
The ene reaction of *N*-alkyltriazolinediones (**48**) with propene, *trans*- and *cis*-butene, and tetramethylethylene has been investigated theoretically with *ab initio* MO calculations. All geometries were fully optimized at the RHF/6–31G* level, followed by MP2/6–31G* and Beckel3LYP/6–31G* single-point energy calculations. A stepwise mechanism, involving an aziridinium imide intermediate (**49**), has been identified as the lowest energy pathway. The most stable transition structure for the first, rate-limiting step involves a decidedly non-least-motion attack of (**48**) on the alkene, with methyl group rotation to bring hydrogen in close proximity with the nitrogen of (**48**) for favourable electrostatic and secondary orbital interactions. Some isomerization of the intermediate (**49**) appears feasible, while reversion to reactants is less favourable than the product-forming hydrogen transfer. The activation energies decrease in the series from propene to butenes to tetramethylethylene, as the alkenes become more substituted and electron-rich. Kinetics isotope effects (KIE) were computed with the RHF/6–31G* geometries and frequencies, using the Bigeleisen–Mayer equation and the QUIVER programme. The calculated KIE were in reasonable accord with the experimental measurements. The unique stabilizing N···H interaction in the first transition structure, involving both electrostatic and secondary orbital interactions, was proposed as significantly stabilizing the first transition state and contributing to the observed KIE.[54]

The addition of *N*-methyltriazolinedione to bisadamantylidene (**50**), that gives the [2 + 2] adduct (**53**), clearly does not proceed in one step, since aminoaziridinium intermediate (**52**) was observed to build up during the reaction and its amount correlates



(**48**) (**49**)

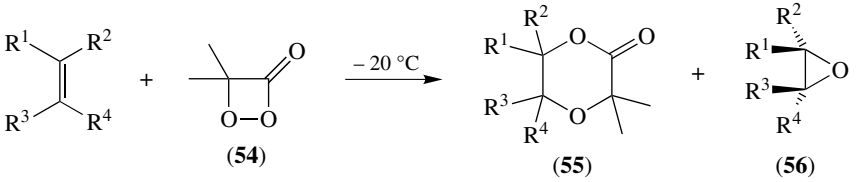
with the overall reaction rate of (**53**) formation. However, no correlation of the overall reaction rate and any solvent polarity parameters could be found despite the fact that charge-separated intermediates are involved. It was proposed that the zwitterion species (**51**) is the likely intermediate between (**50**) and (**52**), although it could not be directly detected owing to its apparently low concentration. C−H bonding stabilization of both (**51**) and (**52**) in $CHCl_3$ has been suggested as a possible rationalisation for the correlation between the overall rate of (**53**) formation and the stability of (**52**) relative to the starting materials.[55]



(**50**) (**51**) (**52**) (**53**)

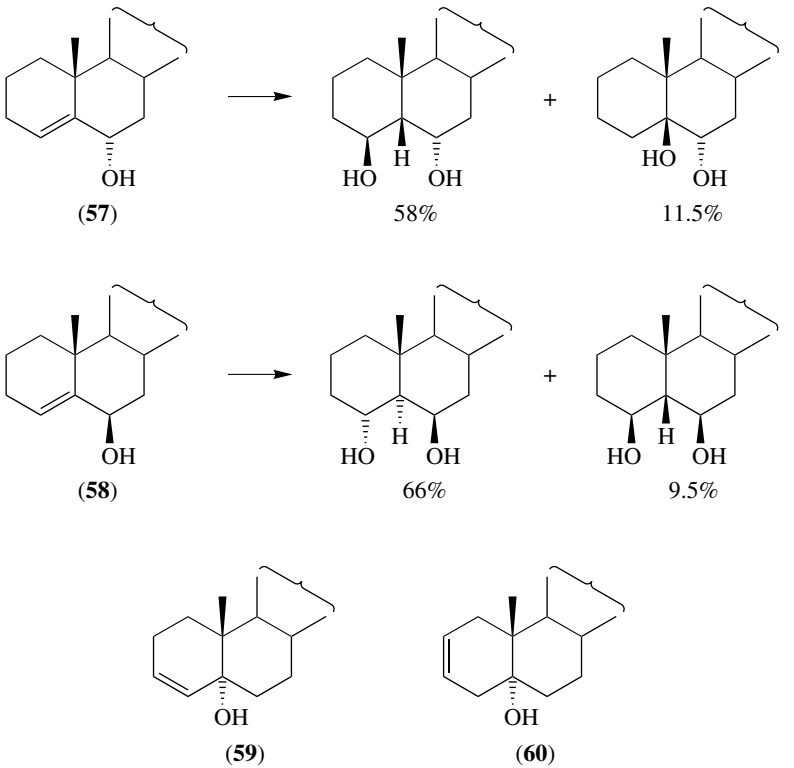
A full report has now been published on the asymmetric version of Atkinson's aziridination of activated alkenes.[56]

Vinyl ethers, such as EtOCH=CH_2, EtOCH=CHMe, EtOCH=CHOEt, etc. (with or without an additional oxygen function), have been shown to react with α-peroxy lactones (**54**) to give mainly the products of stereoselective cycloaddition (**55**) contaminated by epoxides (**56**).[57]



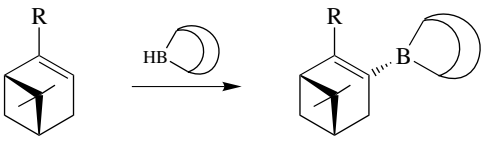
Additions Initiated by Metals and Metal Ions as Electrophiles

The hydroboration of 6α- and 6β-hydroxyandrost-4-ene-17-one (**57**) and (**58**) has been shown to take place predominantly on the face of the alkene opposite to the allylic OH group (Scheme 14).[58] The same stereochemistry has been observed for 5α-hydroxy-2-enes (**59**),[59] 5α-hydroxy-2-enes (**60**), and 1α-hydroxy-2-enes.[60]



SCHEME 14

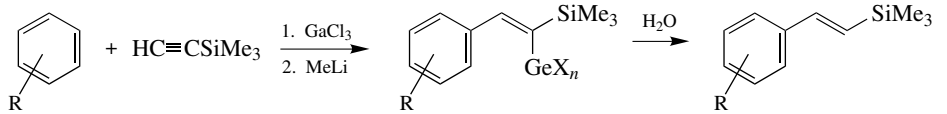
Rates of hydroboration of (**61**; R = Me, Et, Pr, Bu^i, and Ph) with 9-borabicyclo-[3.3.1]nonane have been elucidated and found to decrease with increasing steric bulk of R; no reaction was observed for R = Pr^i. The products (**62**) are potentially valuable for the asymmetric reduction of prochiral ketones.[61]



(**61**) (**62**)

Hydrosilylation of hex-1-ene and ethylene with SiH_4 occurs in the presence of $LiAlH_4$ as a catalyst. A reaction mechanism involving SiH_4 and the alkyl anion, generated by the initial interaction of the olefin with $LiAlH_4$, has been proposed.[62]

By the action of $GaCl_3$, trimethylsilylacetylene is converted into a strongly electrophilic species that reacts with aromatic hydrocarbons in the Friedel–Crafts fashion (Scheme 15) to generate (**63**) that can be further reacted with MeLi to afford, after aqueous workup (**65**).[63]



(**63**) X = Cl
(**64**) X = Me

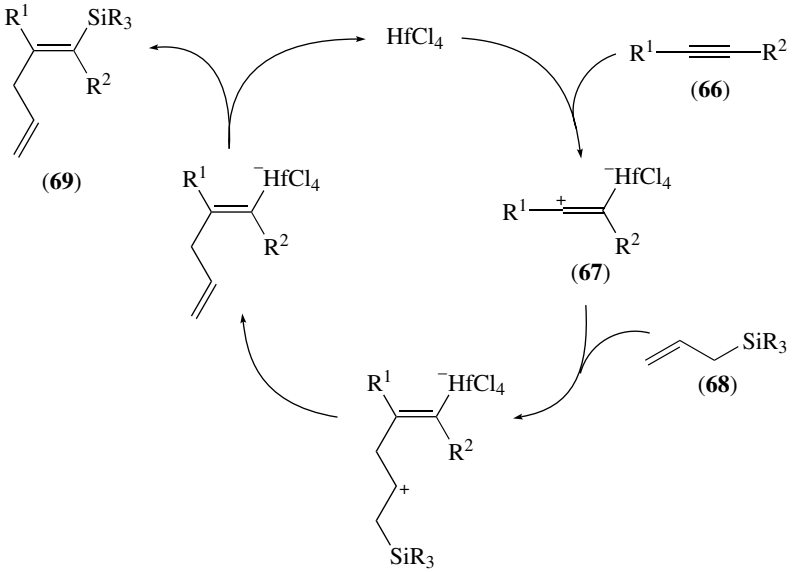
(**65**)

SCHEME 15

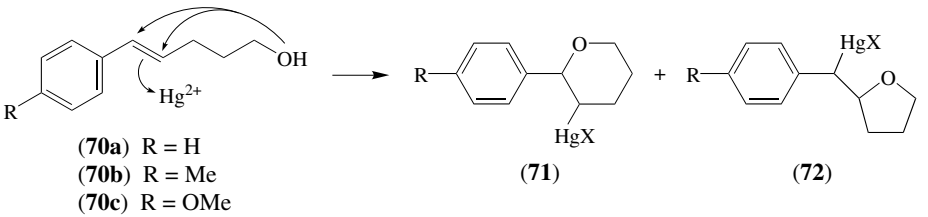
The addition of substituted allylsilanes (**68**) to alkynes (**66**) in the presence of $HfCl_4$ or $EtAlCl_2$–Me_3SiCl as Lewis acid catalysts produced the silylated 1,4-dienes (**69**) regio- and stereo-selectively in high yields in an exclusive *trans*-fashion (Scheme 16). The relative reactivities within the series are consistent with the involvement of cationic species (**67**) as intermediates.[64]

A study of the intramolecular alkoxymercuration of (*E*)-5-arylpent-4-en-1-ols (**70**) has indicated that the regioselectivity is closely related to the Hammett constants of the *para*-substituents on the benzene ring. Large solvent effects on the regioselectivity were also observed (Scheme 17 and Tables 2 and 3). By contrast, the related oxymercuration of β-methylstyrene is 100% α-selective. This comparison shows that the regioselectivity of the intermolecular reaction is controlled by electronic factors, whereas the cyclization is governed by a delicate balance of steric and electronic effects.[65]

The C−H bond of terminal alkynes (the donor alkynes) (**73**) can be added to either terminal alkynes (self-coupling) or activated internal alkynes (acceptor alkynes) (**74**) in the presence of $(AcO)_2Pd$ as catalyst and an electron-rich encumbered ligand, tris(2,6-dimethoxyphenyl)phosphine to afford enynes (**76**) (Scheme 18). The activated internal alkynes (**74**) for the cross-coupling include those bearing an ester, sulfone, or ketone group. In these cases, the self-coupling is completely suppressed (even at 1 : 1 ratios of donor to acceptor alkynes, although the recommended ratio is 2 : 1 in favour of the acceptor alkyne). This technology was applied to the synthesis of conformationally rigid retinoid analogues.[66]



SCHEME 16



SCHEME 17

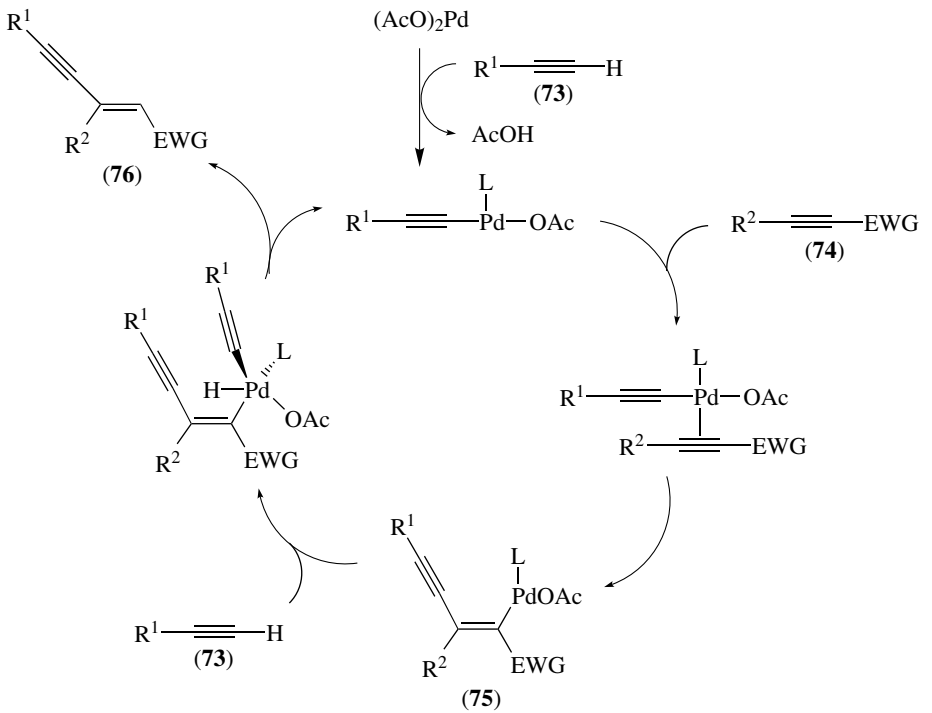
Table 2. Regioselectivity of the ring closure of (70a–c) in MeOH

R	(**71**)	:	(**72**)
H	52	:	48
Me	82	:	18
OMe	≈100	:	0

Regio- and stereo-selective dimerization of alk-1-ynes catalysed by classical and non-classical hydride complexes of Ru(II) and Os(II) stabilized by the tripodal polydentate ligand $(Ph_2PCH_2CH_2)_3P$ has been reported to produce the corresponding (*Z*)-1,4-disubstituted butenynes. Irrespective of the nature of the hydride ligand (classical or non-classical), vinylidene complexes appear to be the immediate precursors to the C−C bond-forming step.[67]

Table 3. Solvent effect on the cyclization of (70a)

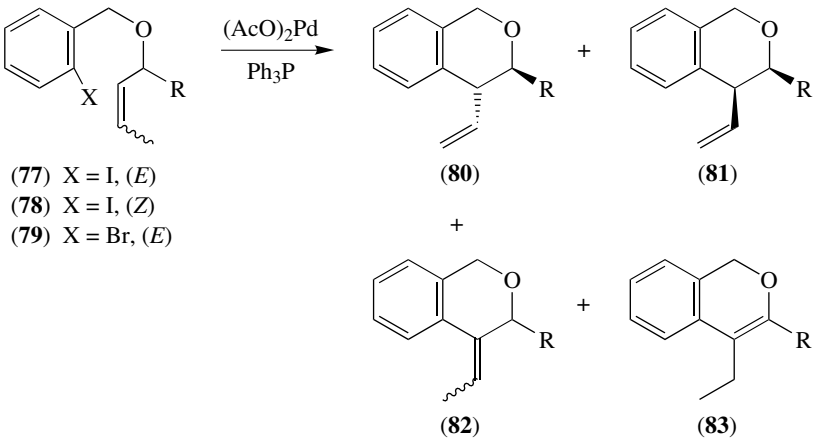
Solvent	*Yield of* (**71**) (%)
THF–H_2O (1 : 1)	65
MeOH	52
EtOH	56
PrOH	46
BuOH	33
Pr^{i}OH	22
Bu^{t}OH	19



SCHEME 18

Iodoarenes (**77**) and (**78**) have been reported to undergo intramolecular Heck reaction producing the isochromanes (**80**)–(**83**). The selectivity of the reaction depends on the size of the substituent R: increasing bulk of R leads to a decrease in diastereoselectivity and an increase in regioselectivity (Table 4). High-pressure experiments confirmed the proposed mechanism and showed that bromoarenes, such as (**79**), which tend to be unreactive, give good results when the cyclization is carried out under high pressure.[68]

In the [3 + 2] vs [2 + 2] controversy for the osmylation reaction,[69,70] the pendulum has now swung in favour of the [3 + 2] mechanism. The main arguments are derived from kinetics and Hammett correlation, kinetic isotope effect (KIE),[69,70] and quantum



(**77**) X = I, (*E*)
(**78**) X = I, (*Z*)
(**79**) X = Br, (*E*)

(**80**) (**81**)

(**82**) (**83**)

Table 4. Heck-type cyclization of (**77**) (**79**)

X	R	Configuration	(**80**) : (**81**)	[(**80**)+(**81**)] : [(**82**) : (**83**)]
I	Me	*E* (99:1)	15 : 1	1.6 : 1
I	Me	*E* (17:1)	7.5 : 1	1.5 : 1
I	Et	*E* (27:1)	3.7 : 1	2.7 : 1
I	Et	*E* (17:1)	3.0 : 1	2.0 : 1
I	Pr^i	*E* (4.0:1)	1 : 1	6.0 : 1
Br	Me	*E* (99:1)	2.8 : 1	1 : 1

chemistry calculations.[71] Interestingly, high-level calculations of various models, such as pure OsO_4, and OsO_4 with one or two coordinated NH_3 molecule(s) (as model for basic ligands), have clearly demonstrated a much higher activation energy for the [2 + 2] pathway as opposed to very low energy for the [3 + 2] cycloaddition.[71] Even Sharpless, the main supporter of the [2 + 2] mechanism, has recently shown the KIE to be consistent with a [3 + 2] cycloaddition as the rate-limiting step.[72] However, in view of the complexity of the problem, namely the apparent variation in the mechanism as a function of ligands present and the non-linear Hammett relationship,[70] this may not yet be the final word. Note, for instance, that for the analogous rhenium-mediated reaction, a stepwise mechanism has been clearly demonstrated.[73]

Miscellaneous Electrophilic Additions

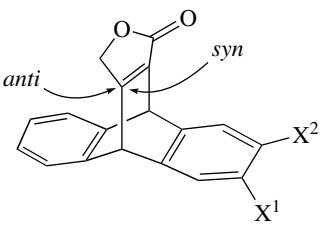
The reaction of alkenyl alkyl ethers and ketene acetals with PX_3 (X = Cl or Br) has been reported to occur readily in the presence of an organic base and to result in the electrophilic substitution of a vinyl hydrogen atom with the PX_2 group. Thus, (2-alkoxyalkenyl)-, (1-bromo-2-alkoxyalkenyl)- and (2,2-dialkoxyalkenyl)-phosphorus dichlorides and dibromides were obtained in 70–98% yield. The reaction proceeds regio- and stereo-selectively and is believed to involve formation of a cyclic phosphirenium ion.[74]

Nucleophilic Additions

The effect of a remote substituent on the facial selectivities in a nucleophilic conjugate addition has been investigated for the reaction of EtSH with a series of dibenzobicyclo[2.2.2]octatrienes (**84**). *Syn*-addition proved to be favoured for nitro substituent and polar solvents increased the selectivity (Table 5).[19]

Table 5. *syn*/*anti* selectivity in the reaction of (**84**) with EtSH

X^1	X^2	Solvent	*syn : anti*
H	NO_2	Neat	63 : 37
H	NO_2	C_6H_6	62 : 38
H	NO_2	Et_2O	69 : 31
H	NO_2	DMF	79 : 21
H	NO_2	DMSO	77 : 23
NO_2	NO_2	Neat	54 : 46
NO_2	NO_2	DMF	75 : 25
NO_2	NO_2	DMSO	73 : 27



(**84**)

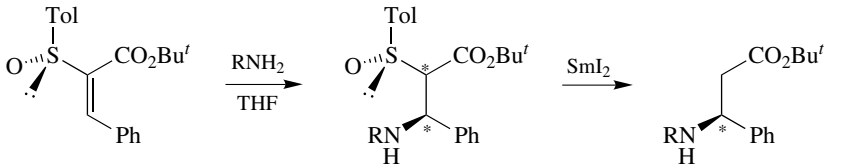
Additions to Multiple Bonds Conjugated with C=O

In the reaction of hydrazine with 2-(1-alkoxyalkylidene)-1,3-dicarbonyl compounds, the ^{13}C NMR spectral evidence indicates that the only point of initial hydrazine attack is the carbon atom in the ethylene bond and the only observed intermediate is the corresponding enehydrazine. MNDO calculations of the electronic characteristics showed that the reaction obeys orbital control.[75]

Parameters useful to predict and control the reaction outcome of conjugate addition of HN_3 to quinones have been assessed and the optimum conditions for the efficient synthesis of aminonaphthoquinones and azidobenzohydroquinones were found. This strategy was applied to the formal synthesis dephostatine.[76]

Michael addition of a series of primary amines RNH_2 [R = H, $PhCH_2$, $H_2N(CH_2)_3NH_2$] to *t*-butyl (*S*,*E*)-2-(*p*-tolylsulfinyl)cinnamate (**85**), followed by Sm(II) reduction, has been reported to produce (*S*)-*β*-amino esters (**86**) with 49–98% *ee*.[77]

Addition of morpholine, H_2N–GlyGlyOH or N_2H_4 to HC≡CCOMe gives the expected oxo enamines via a second-order process (first order in each reactant). The product of the hydrazine addition, $H_2NNHCH{=}CHCOMe$, reacted with additional

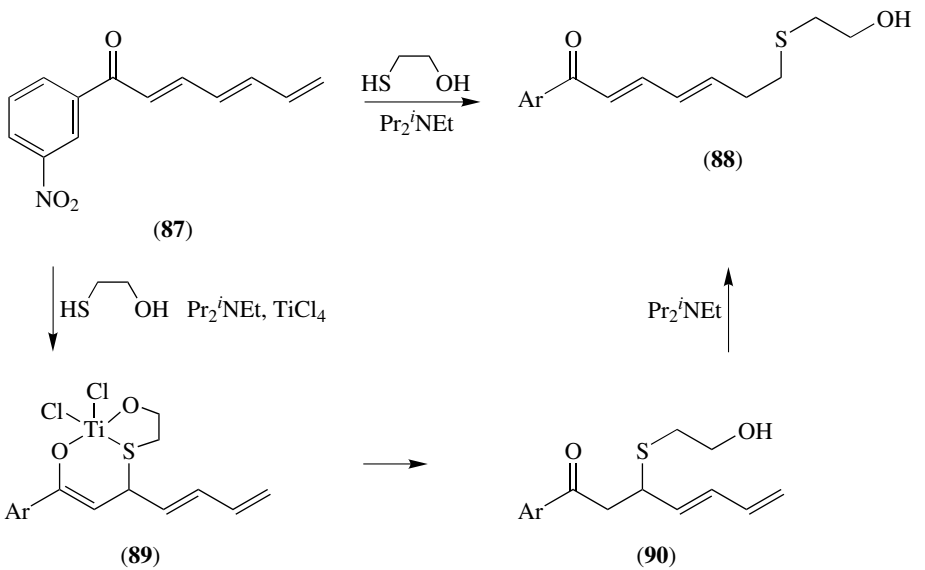


(**85**) (**86**)

N_2H_4 to afford 3-methylpyrazole via an intramolecular nucleophilic attack followed by dehydration.[78]

Thiophenoxide ion reacts with $PhC{\equiv}CCO_2Me$ in DMF containing ~ 0.5% MeOH to give a mixture of (*E*)- and (*Z*)-products $PhC(SPh){=}CHCO_2Me$. The rate constant depends on the MeOH concentration, indicating a third-order reaction. The plot of $\log k_3$ vs Hammett σ constants varies from 0.42 to 0.77, depending on the temperature. The activation parameters and ρ values are consistent with a concerted mechanism.[79]

While Michael addition of mercaptoethanol to dienones and trienones, e.g. (**87**), occurs at ω-carbon (**88**), β-attack can be enforced by the presence of $TiCl_4$ (Scheme 19). The latter outcome has been rationalized by Ti chelation (**89**). The resulting β-isomer (**90**) can be equilibrated to the ω-isomer (**88**).[80]

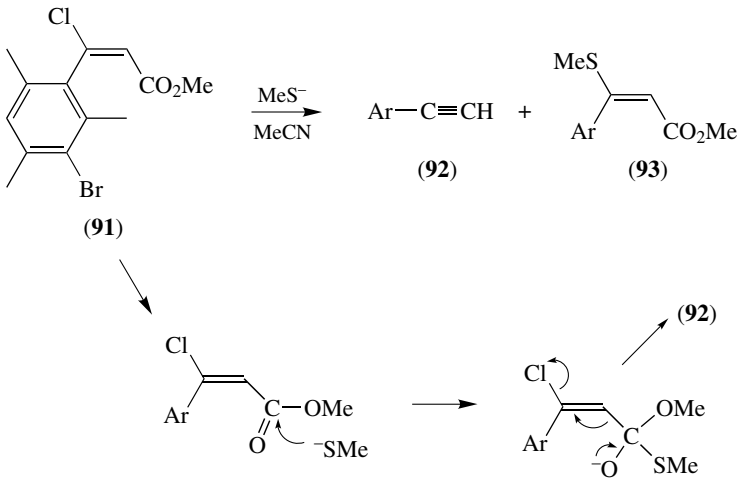


(**87**) (**88**) (**89**) (**90**)

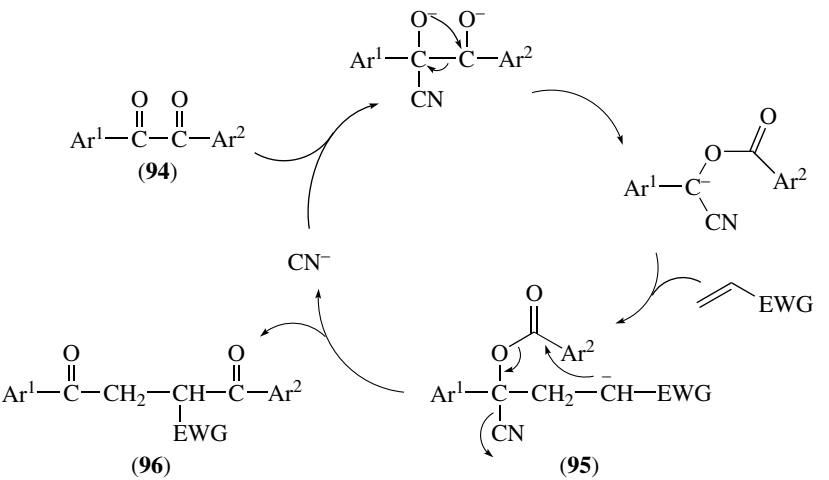
SCHEME 19

Reaction of methyl β-chloro-(3-bromo-2,4,6-trimethyl)cinnamate (**91**) with MeS^- has been shown to give mixtures of elimination (**92**) and substitution (**93**) products (Scheme 20).[81]

Benzils (**94**) react with typical Michael acceptors in the presence of a catalytic amount of CN^- to give 1,4-diketones (**95**), which arise by insertion of ethylene group between the carbonyls of the benzil units (Scheme 21).[82]



SCHEME 20

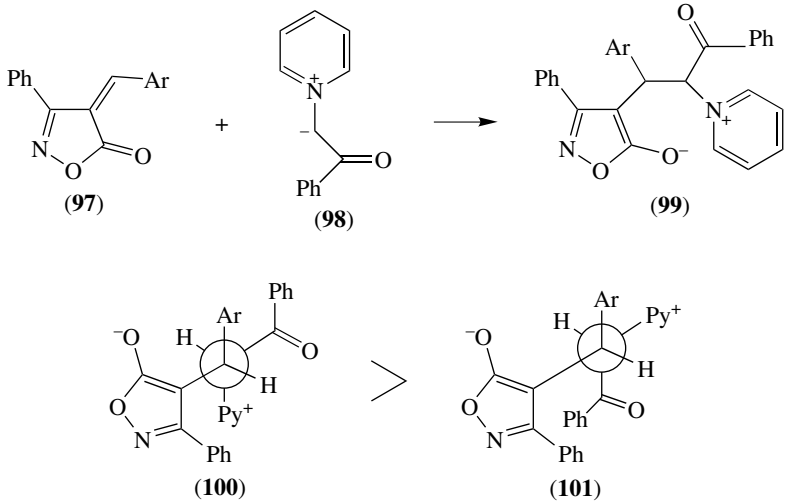


SCHEME 21

The Michael addition of (−)-dimenthyl malonate to a series of α,β-unsaturated ketones, including ferrocenyl derivatives, has been reported to occur with 10–50% *de*; pure diastereoisomers were obtained by recrystallization.[83]

In addition to an earlier report by another group,[84] $FeCl_3$ has now been found to catalyse Michael addition of β-dicarbonyl compounds to highly reactive enones (CH_2=CHCOMe, PhCH=CHCOMe, PhCH=COPh).[85]

The reactions of (arylmethylene)isoxazol-5-ones (**97**) with pyridinium ylides (**98**) leads to the diastereoselective formation of olates (**99**) as a result of preferential Michael addition rather than 1,3-cycloaddition (Scheme 22). The stereoselectivity of the reaction has been rationalized by the involvement of the preferential transition state [(**100**) over (**101**)].[86]

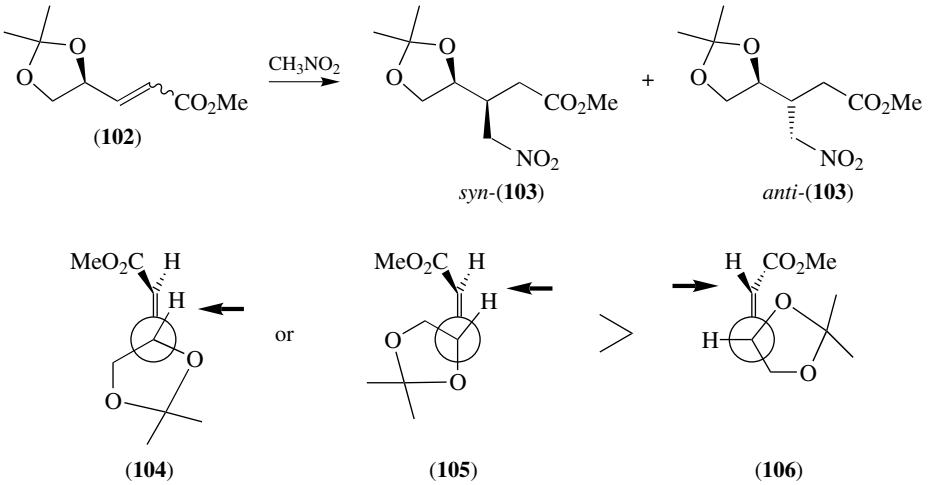


SCHEME 22

Regioselectivity in the Michael addition of nitromethane to α,β-unsaturated esters in the presence of Triton B has been studied both theoretically and experimentally.[87]

A rubidium salt of proline (5–10 mol%) has been reported to catalyse the asymmetric Michael addition of nitroalkanes to prochiral acceptors. When L-proline was used, acyclic (*E*)-enones produced (*S*)-adducts, whereas cyclic (*Z*)-enones gave (*R*)-adducts.[88]

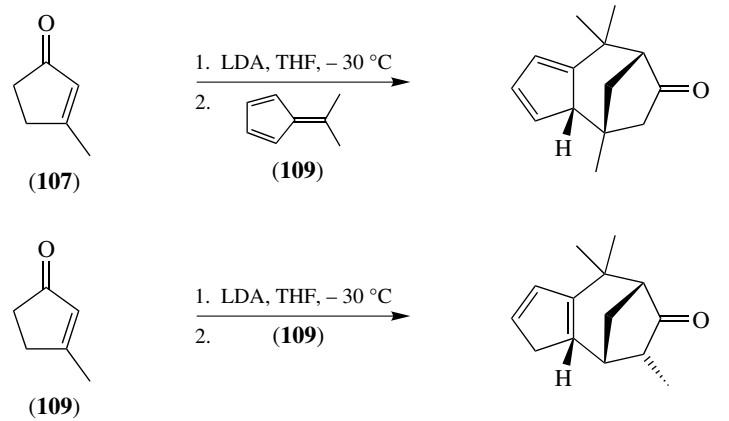
Syn-selective Michael addition of nitromethane and its homologues to enoates derived from (*R*)-(+)-glyceraldehyde acetonide (*Z*)-(**102**) in the presence of $Bu_4N^+F^- \cdot 3H_2O$ or DBU has been reported to produce mainly *syn*-(**103**) with 80–100% *de* (Scheme 23).



SCHEME 23

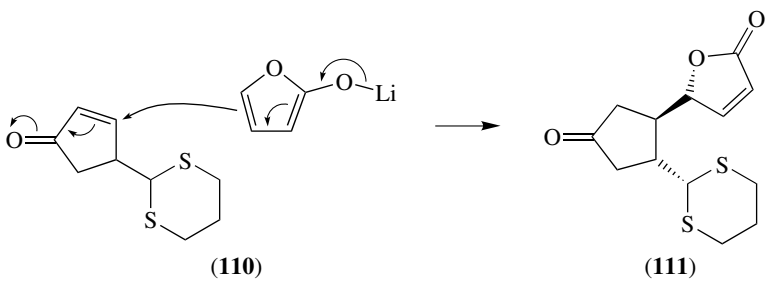
The addition to (*E*)-(**102**) exhibited slightly lower diastereoselectivity for CH_3NO_2 and, in particular, for its primary homologues (34–80% *de*), while secondary homologues were non-selective. The observed stereochemical outcome has been rationalized by the preferential transition states (**104**) and (**105**), respectively.[89]

Sequential 'double Michael' addition of cyclic dienolates, generated from (**107**) or (**108**), to fulvene (**109**) has been developed as a method for rapid access to the tricyclo[5.3.0.$n^{2,5}$]alkane system (Scheme 24).[90]



SCHEME 24

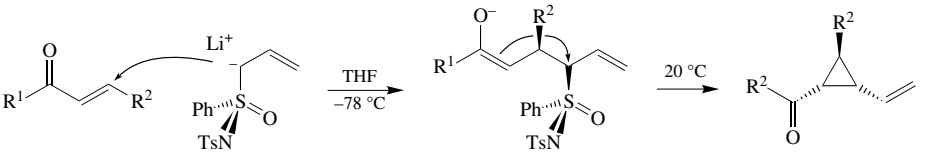
Highly diastereoselective conjugate addition of lithiated γ-crotonolactone (**110**) to cyclic enones has been reported to give adduct (**111**) (Scheme 25). This methodology has been applied to the synthesis of brefeldine.[91]



SCHEME 25

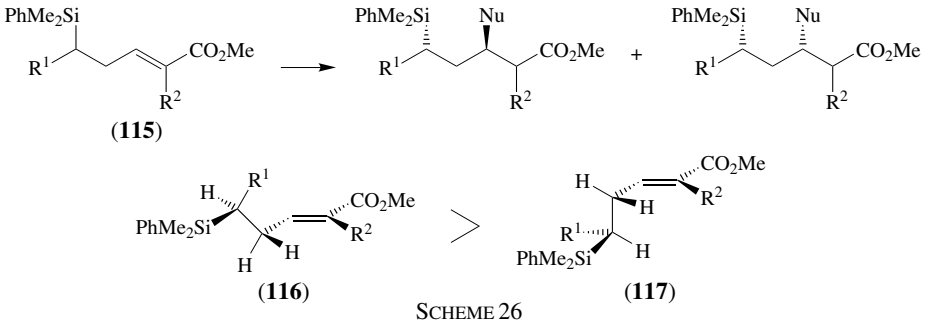
Stabilized lithiated sulfoximines (**112**) undergo highly diastereoselective Michael additions to cyclic enones at −78 °C under kinetically controlled conditions. At room temperature, the initially formed adducts (**113**) undergo intramolecular substitution of the sulfonimidoyl group, with inversion of configuration to afford the corresponding cyclopropanes (**114**).[92]

In a search for open-chain 1,3-stereo-control, addition of organometallic nucleophiles [MeLi, MeMgBr, Me_3ZnLi, $Me_2CuCNLi_2$, $(PhMe_2Si)_2CuLi$, etc.] to a series of δ-



(**112**) (**113**) (**114**)

substituted Michael acceptors (**115**) has been studied (Scheme 26). In an attempt to identify a rule based purely on steric effects by which it might be possible to predict which diastereoisomer would be the major product in each of these reactions, lowest energy conformations were calculated for the substrates (**115**). The rule that emerged (with a number of anomalies, however), predicts structure (**116**) to be somewhat preferred over (**117**).[93]

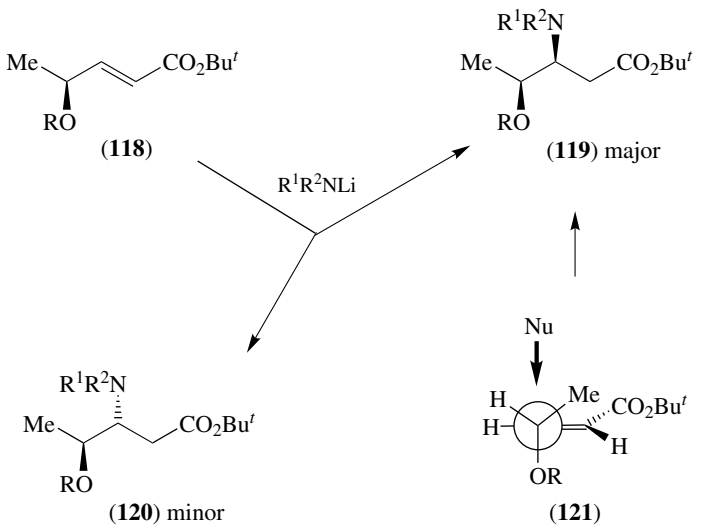


(**115**)

(**116**) (**117**)

SCHEME 26

The conjugate addition of R^1R^2NLi ($R^1 = R^2 = PhCH_2$ or $R^1 = Me_3Si$, $R^2 = PhCH_2$) to *t*-butyl 4-(RO)-substituted pent-2-enoates (**118**) has been reported to produce mixtures of the *syn*- and *anti*-amino esters (**119**) and (**120**).

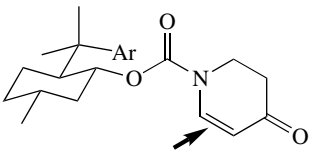


(**118**) (**119**) major

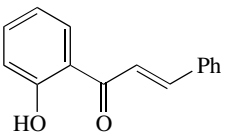
(**120**) minor (**121**)

Sterically bulky OR groups (trityloxy or Bu^tPh_2SiO) gave the *syn*-diastereoisomer (**119**) either exclusively or predominantly. The *syn*-selectivity was rationalized by a modified Felkin–Ahn model (**121**).[94]

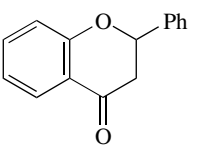
Lewis acid-promoted asymmetric conjugate addition of an allylsilane to a series of 8-arylmenthol-derived *N*-acyl-2,3-dihydro-4-pyridones (**122**) has been reported to lead to 2-allyl-4-piperidones with moderate to high levels of asymmetric induction; the highest levels were attained with Ar = 2-naphthyl. The stereochemical course of the reaction was attributed to π-stacking and the method was applied to the asymmetric synthesis of (−)-*N*-methylconiine.[95]



(**122**)



(**123**)

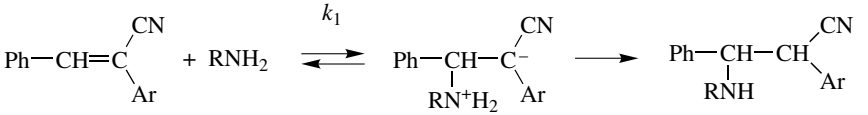


(**124**)

Theoretical studies of cyclization of 2′-hydroxychalcone (**123**) using AM1 with totally optimized molecular geometries suggest a six-step mechanism including several equilibration states and led to the following conclusions: (1) at the conformational equilibration of (**123**), there could be 43.9% of *s-cis*-conformer; (2) the acid dissociation of *trans-s-trans*-(**123**) is considerable; (3) the E_E, ΔH_f and net charges show that the rotation of ring A of (**123**) and the formation of the ring of (**124**) occur without great difficulty; (4) although the keto structure of (**124**) is the most stable one, the enolate is also present in the reaction medium; (5) the conversion of the enol of (**124**) into the keto form is the rate-limiting step of the reaction.[96]

Additions to Multiple Bonds Activated by Other Electron-withdrawing Groups

The addition of substituted benzylamines to α-cyano-4-nitrostilbene (**125**) has been found to involve the formation of the zwitterionic species (**126**) in an equilibrium, and its subsequent decomposition to (**127**) catalysed by a second molecule of the amine.[97]



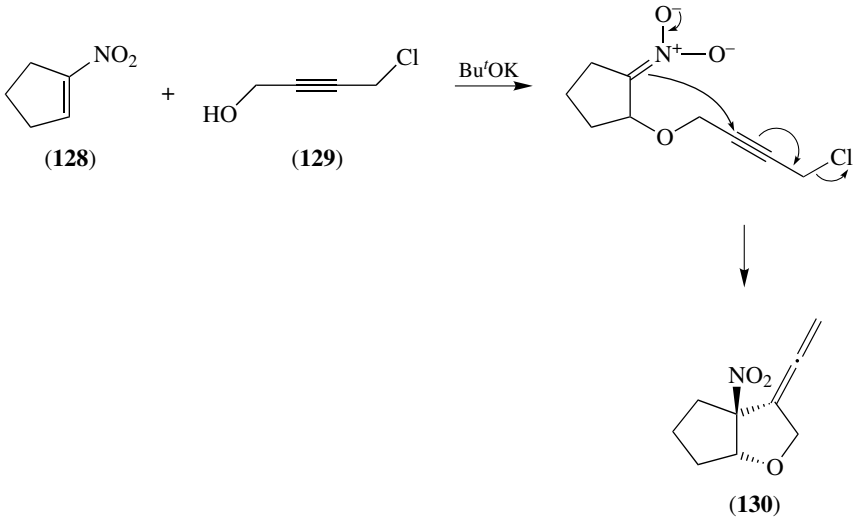
(**125**) (**126**) (**127**)

R = $PhCH_2$
Ar = *p*-O_2N-C_6H_4

Addition of sodium alkoxides, thiolates, and Na salts of stabilized carbanions across the double bond of 6-vinylpurines has been described.[98]

Bu^tOK has been reported to promote the reaction of 4-chlorobut-2-yn-1-ol (**129**) with nitroalkanes (**128**) affording 3-vinylidenetetrahydrofurans (**130**) as a result of tandem

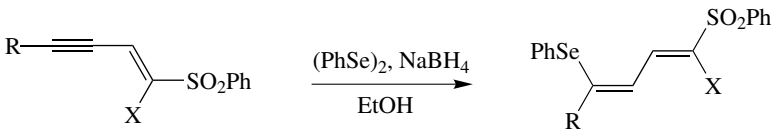
oxo-Michael addition–S_N2 substitution. The reaction occurs with excellent diastereoselectivity originating in the 1,3-strain-control.[99]



(**128**) (**129**) (**130**)

Michael addition of 1,3-dicarbonyl compounds to conjugated prochiral nitroalkenes catalysed by $(acac)_2Ni$ and $(acac)_2Co$ has been reported to give up to 30% *ee* when carried out in the presence of cinchonidine.[100]

Addition of PhSeNa to the conjugated system of enyne sulfones (**131**; X = H, Cl, Br) occurs at the δ-position with preferential formation of the (1*E*,1*Z*)-isomer (**132**).[101]

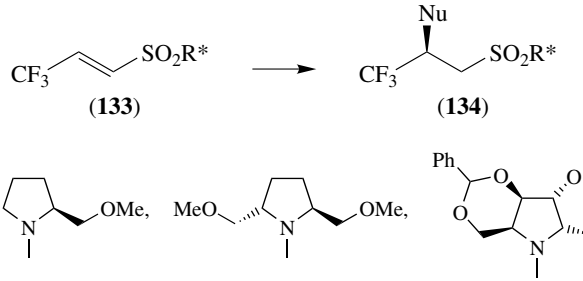


(**131**) (**132**)

Conformational analysis of α,β-unsaturated sulfonamides based on *ab initio* calculations predicts a hinge-like molecular shape for the ground-state conformation. Following this lead, three chiral trifluoromethylated sulfonamides (**133**) were reacted with PhCOMe–LDA and $CH_2(CO_2Me)_2$–NaH, respectively, to give the addition products (**134**) of up to 98% *ee* (Scheme 27).[102]

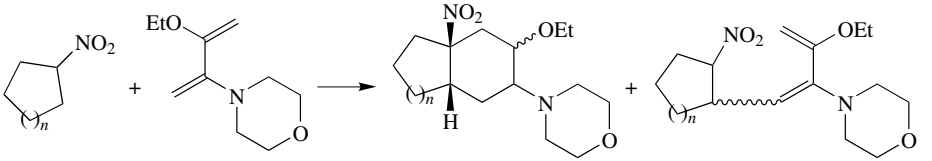
Reformatsky reagents have been shown to react with various styrenes activated by electron-withdrawing groups in the 1,1-positions (**135**). The reaction is further improved when carried out in the presence of Cp_2TiCl_2. Strong evidence has been accumulated for the involvement of an SET process.[103]

Cycloaddition vs conjugative Michael-type addition of 2-ethoxy-3-morpholinobuta-1,3-diene (**137**) to nitroalkenes (**136**) has been thoroughly investigated. With 1-nitrocyclopentene (**136a**), carbocyclic products (**138**) largely predominated, whereas



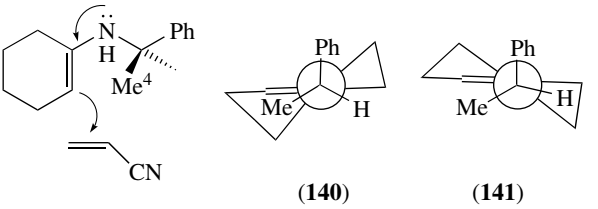
SCHEME 27

with 1-nitrocyclohexene (**136b**), only Michael-type products were formed (**139**). The products from β-nitrostyrene proved to be dependent on the reaction conditions.[104]



(**136**a) $n = 1$ (**137**) (**138**) (**139**)
(**136**b) $n = 2$

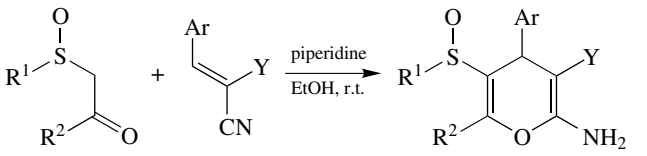
The origin of the observed 1,4-asymmetric induction in Michael reactions of chiral imines (Scheme 28) has been rationalized by conformational transmission of chirality. Thus, the phenethylamine auxiliary forces the cyclohexene part of the intermediate enamine into a half-chair conformation (**140**) that is 0.8 kcal mol^{-1} lower in energy than (**141**). Axial attack as shown then leads to the major product; the energy difference between (**140**) and (**141**) roughly correlates with the observed diastereoselectivity ($\sim 9:1$).[105]



(**140**) (**141**)

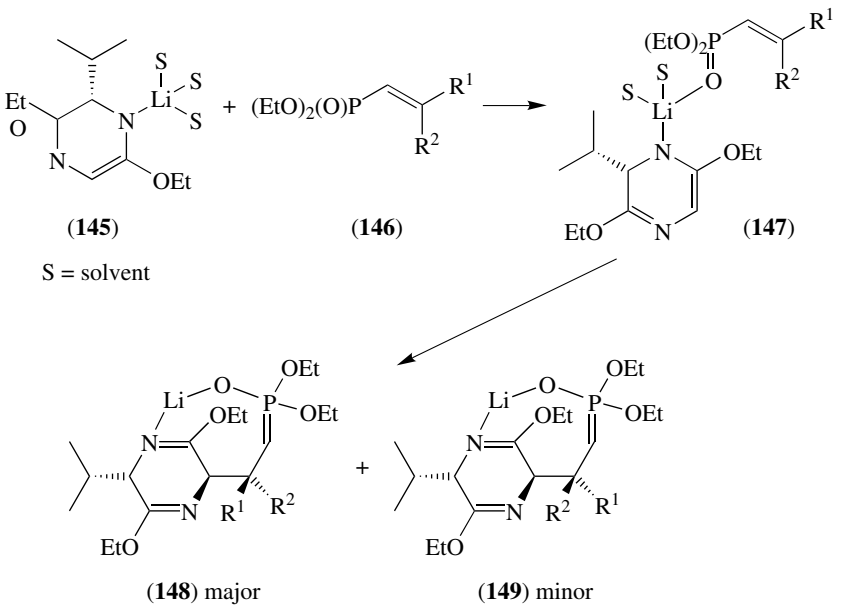
SCHEME 28

Michael additions of β-keto sulfoxides (**142**) and β-keto sulfones to highly activated acceptors (**143**) has been shown to produce 2-amino-4*H*-pyran adducts (**144**) under mild conditions.[106]



(**142**) (**143**) (**144**)

According to a semiempirical study, the stereoselectivity of conjugate addition of lithiated bislactim ethers (**145**) to alkenylphosphonates (**146**) in the gas phase originates from an initial lithium–phosphoryl coordination to generate a disolvated chelate (**147**), followed by a rate-determining reorganization through competitive eight-membered cyclic transition structures (**148**) and (**149**).[107]



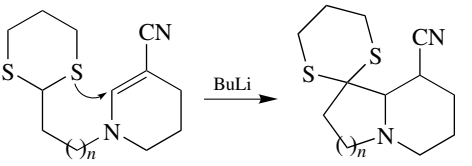
(**145**) (**146**) (**147**)

S = solvent

(**148**) major (**149**) minor

SCHEME 29

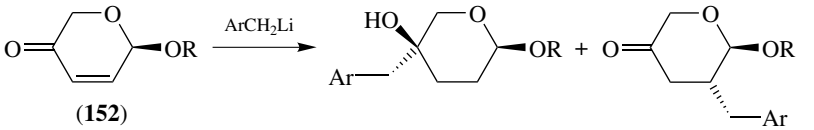
Dithiane anions undergo intramolecular conjugate addition to the α,β-unsaturated nitrile moiety in (**150**) to produce indolizidine and quinolizidine (**151**), in which the nitrile group exhibits a strong, thermodynamic preference for the axial orientation.[108]



(**150**) (**151**)

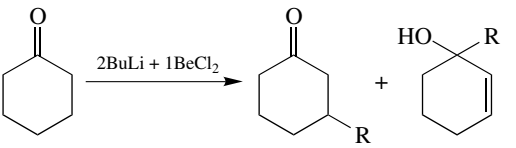
Additions of Organometallics to Activated Double Bonds

In a study of the reactivity of organolithium reagents with selected carbohydrate enones, such as 2,3,6-trideoxy-α-L-hex-2-enopyranosid-4-ulose (**152**) and 2,3-dideoxy-α-D-hex-2-enopyranosid-4-ulose, addition to the carbonyl group has been found to occur with increasing stereoselectivity in the order butyl, benzyl, and 2,5-dimethoxy-4-methylphenyllithium. By contrast, 2,5-dimethoxybenzyllithium underwent preferential and completely stereoselective 1,4-addition (the 1,4- to 1,2-addition ratio was 1.7 : 1 in this instance).[109]



(**152**)

Organoberyllium compounds, generated by transmetallation from Grignard and organolithium reagents with $BeCl_2$, have been found to add to 2-cyclohexen-1-one via 1,4-addition in THF (Scheme 30), whereas 1,2-addition is favoured in Et_2O. Generally, the selectivity varies with the conditions and the nature of the R group.[110]

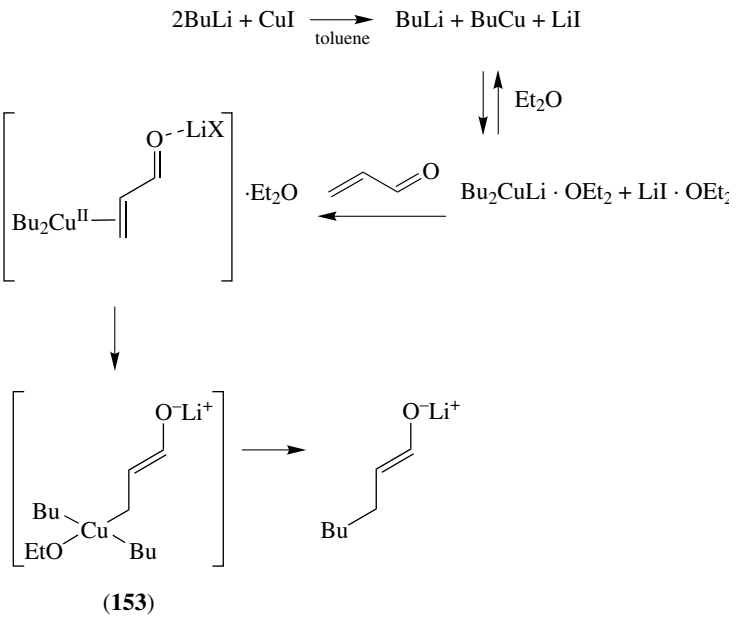


THF >100 : 1

Et_2O <1 : 100

SCHEME 30

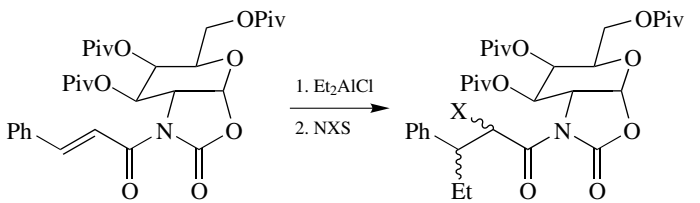
Mixtures of BuLi and CuI prepared in toluene have been shown to react with α,β-unsaturated ketones predominantly in a 1,2-fashion. Addition of two equivalents of Et_2O to the mixture resulted in a dramatic preference for the usual 1,4-product. These results have been interpreted as evidence for stabilization of the intermediate Cu(III) species (**153**) on the 1,4-pathway by coordination to the ethereal solvent (Scheme 31).[111]



(**153**)

SCHEME 31

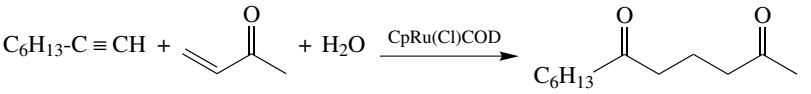
The stereoselective synthesis of *β*-branched α-halocarboxylic acids containing two newly formed chiral centres (**155**) has been accomplished by a reaction consisting of 1,4-addition of dialkylaluminium chlorides to α,*β*-unsaturated *N*-acyloxazolidinones (**154**) followed by quenching the intermediate aluminium enolate with *N*-halosuccinimides. The most efficient stereo-control was achieved with oxazolidines derived from glucosamine (**154**). Although *β*-branched aliphatic α-halo carboxylic acids were synthesized stereoselectively, the highest stereoselectivity was observed for *β*-aryl substrates.[112]



(**154**) (**155**) *de* = 91:6:3

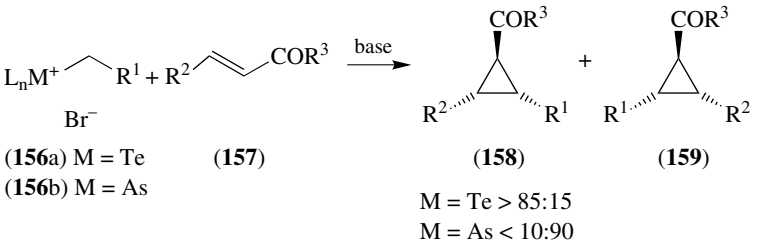
A ruthenium-catalysed, three-component addition of alkyne to α,*β*-unsaturated ketones to produce 1,5-diketones has been developed (Scheme 32).[113]

The semi-stabilized telluronium ylides, generated *in situ* from the corresponding telluronium salts (**156**; R^1 = CH=CHSiMe$_3$, CH=CH$_2$, CH=CHMe, CH=CHPh, Ph), have been reported to react with α,*β*-unsaturated carbonyl compounds (**157**: R^2 = Ph, OR′, NR′$_2$) to afford 2-vinylcyclopropyl derivatives (**158**) with high



SCHEME 32

selectivity. On the other hand, arsonium ylides gave mainly their diastereoisomers (**159**); mechanistic differences were extensively discussed.[114]

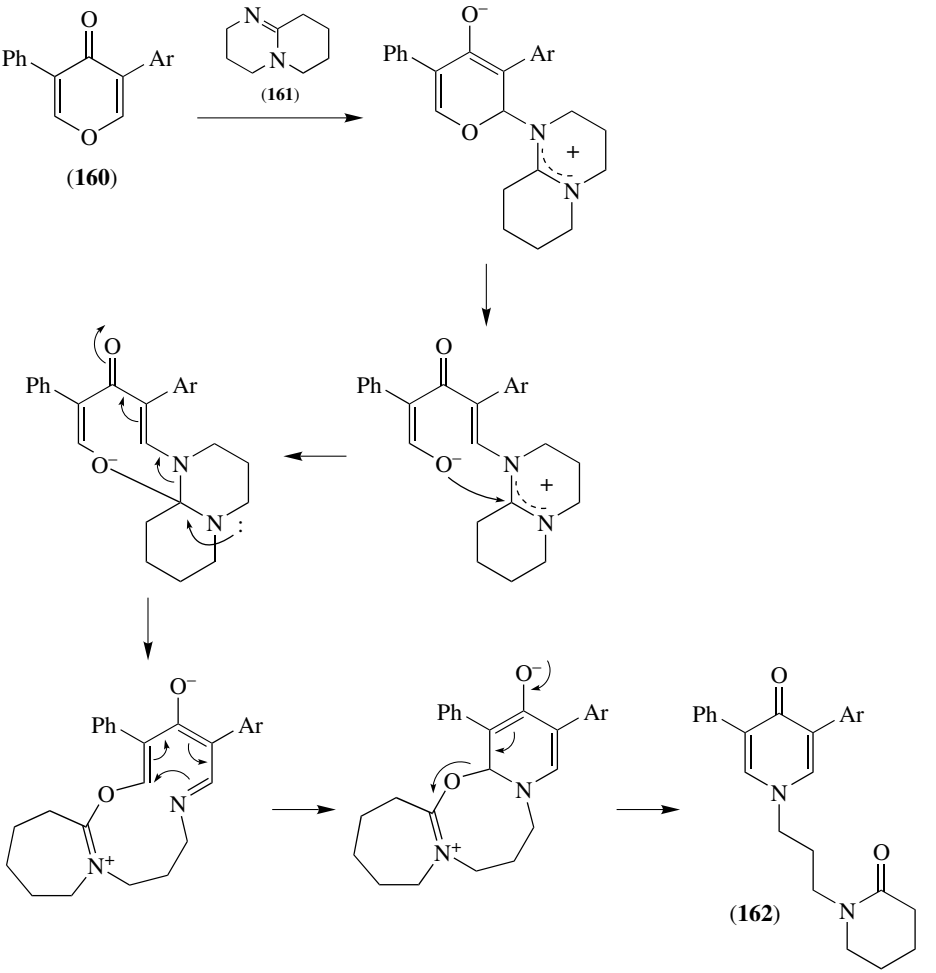


Miscellaneous Nucleophilic Additions

Ab initio calculations of hydroxide attack on acetylene at the SCF/6–31+G** and MP2/aug-cc-pvdz level resulted in the identification of several $C_2H_3O^-$ species. MP2 geometry optimizations were performed with augmented, correlation-consistent, polarized valence, double-ζ basis sets. The total energies of the most crucial structures were also recalculated at the QCISD(T) level with MP2-optimized geometries. Nine structures corresponding to local minima have been found at the MP2 level, their stability decreasing in the following order: acetaldehyde>enolate anion>acetyl anion≈ethynide anion–H_2O complex>ethenyloxy anion≈vinyloxy anion. The ethynide–water complex is either the most stable product of the reaction of HO^- with acetylene or at least an initial stable intermediate.[115] These results agree well with gas-phase data on the reaction, where ethynide has been observed as the only product.[116] This investigation provides the basis for a different view of nucleophilic addition to acetylene: both thermodynamic and kinetic factors seem to favour the formation of an ethynide–water complex rather than ethynyloxy anions.[115]

DBU (**161**) has been reported to react with diarylpyrone (**160**) in a 1,4-fashion, followed by a fragmentation cascade, to afford the aminopropyl caprolactam derivative (**162**) (Scheme 33).[117]

Reactions of PhO^- with the super-electrophilic substrate (**163**) have been examined by 400 MHz ^{1}H NMR spectroscopy in MeCN–DME (1 : 1) as a function of temperature (−40 to 23 °C) and in DMSO at room temperature (Scheme 34). The *O*-bonded σ-adduct (**164**), resulting from the attack at C(7) of (**163**), has been observed and characterized for the first time; no C(5) adduct was detected at −40 °C or in subsequent monitoring the reaction. Apparently, the C(7) attack is favoured by both kinetics and thermodynamics. Upon warming the reaction mixture to ambient temperature, (**164**)

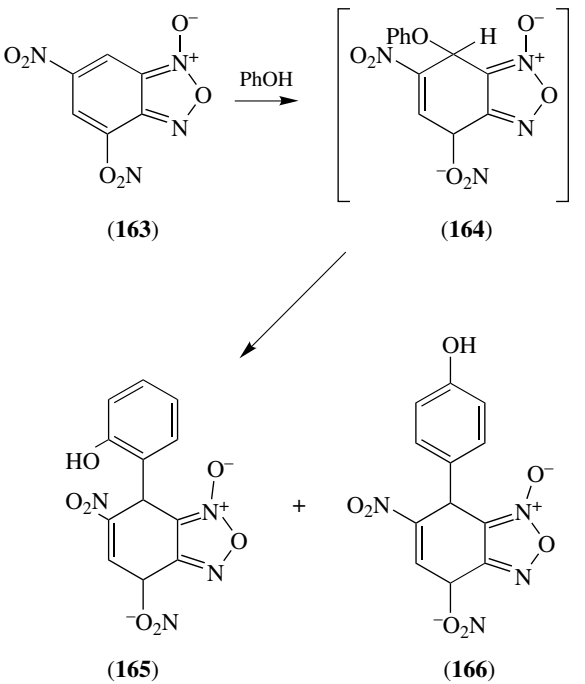


SCHEME 33

gave way to the more stable C(7) *C*-bonded σ-adducts (**165**) and (**166**) ($\sim 1:6$). With 3,5-di-*t*-butylphenoxide (in place of PhO^-), the C(7) attachment is precluded by steric hindrance and the *O*-attached product [analogous to (**164**)] was observed at room temperature. The results of the kinetics and thermodynamics were discussed with regard to stereoelectronic stabilization in the adducts.[118]

β-Dicarbonyl compounds (ethyl acetoacetate and diethyl malonate) have been added to indene in a cerium(IV) ammonium nitrate-mediated addition.[119] Similar additions have been observed for ring-substituted styrenes.[120]

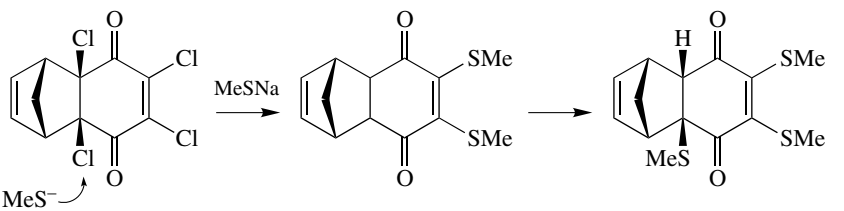
Tetrachlorobenzoquinone derivative (**167**) has been reported to react with MeSNa to give triply-substituted product (**168**); other *N*-, *O*-, and *C*-nucleophiles behave in a similar way.[121]



(**163**) (**164**)

(**165**) (**166**)

SCHEME 34



(**167**) (**168**)

References

[1] Brown, R. S., *Acc. Chem. Res.*, **30**, 131 (1997).
[2] Lenoir, D., *Chem. Unserer Zeit*, **31**, 94 (1977); *Chem. Abs.*, **127**, 17248 (1997).
[3] Le Goaller, R. and Loumouamoum, A., *Actual. Chim.*, **1997**, 12; *Chem. Abs.*, **127**, 50124 (1997).
[4] Negishi, E. and Choueiry, D., *Prep. Alkenes*, **1996**, 137; *Chem. Abs.*, **126**, 276968 (1997).
[5] Juaristi, E. and Garcia-Barradas, O., in *Enantioselective Synthesis of β-Amino Acids* (Ed. Juaristi, E.), Wiley-VCH, New York, 1997, p. 139; *Chem. Abs.*, **127**, 191005 (1997).
[6] Davies, S. G. and Ichihara, O., *Yuki Gosei Kagaku Kyokaishi*, **55**, 42 (1997); *Chem. Abs.*, **126**, 199800 (1997).
[7] Fukumoto, K., *Yakugaku Zasshi*, **116**, 671 (1996); *Chem. Abs.*, **125**, 275521 (1996).
[8] Li, A.-H., Dai, L.-X., and Aggarwal, V. K., *Chem. Rev.*, **97**, 2341 (1997).
[9] Angelov, C. M., Mazzuca, D. A., and Cavell, R. G., *Phosphorus Sulfur Silicon Relat. Elem.*, **1996**, 109; *Chem. Abs.*, **125**, 328800 (1996).
[10] Li, T., Lerner, R. A., and Janda, K. D., *Acc. Chem. Res.*, **30**, 115 (1997).
[11] Sæthre, L. J., Thomas, T. D., and Svensson, S., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 749.

[12] Aplin, J. T. and Bauld, N. L., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 853.
[13] Tsuji, M., Ohwada, T., and Shudo, K., *Tetrahedron Lett.*, **38**, 6693 (1997).
[14] Schueler, P. E. and Rhodes, Y. E., *J. Org. Chem.*, **39**, 2063 (1974).
[15] Hoffmann, R. W., Hauel, N., and Landmann, B., *Chem. Ber.*, **116**, 389 (1983).
[16] Hoffmann, R. W. and Hauel, N., *Tetrahedron Lett.*, **1979**, 4959.
[17] Becherer, J. and Hoffmann, R. W., *Tetrahedron*, **34**, 1193 (1978).
[18] Hoffmann, R. W., Kurz, H. R., Becherer, J., and Reetz, M. T., *Chem. Ber.*, **111**, 1264 (1264).
[19] Okamoto, I., Ohwada, T., and Shudo, K., *Tetrahedron Lett.*, **38**, 425 (1997).
[20] Nelsen, S. F., Klein, S. J., Trieber, D. A., Ismagilov, R. F., and Powell, D. R., *J. Org. Chem.*, **62**, 6539 (1997).
[21] Bellucci, G., Chiappe, C., and Lo Moro, G., *J. Org. Chem.*, **62**, 3176 (1997).
[22] Bianchini, R., Chiappe, C., Lenoir, D., Lemmen, P., Herges, R., and Grunenberg, J., *Angew. Chem., Int. Ed. Engl.*, **36**, 1228 (1997).
[23] Assfeld, X., Garapon, J., Rinaldi, D., Riuz-Lopez, M. F., and Rivail, J. L., *THEOCHEM*, **371**, 107 (1996).
[24] Bellucci, G. and Chiappe, C., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 581.
[25] Maier, G. and Senger, S., *Liebigs Ann./Recueil*, **1997**, 317.
[26] Bodrikov, I. V., Subbotin, A. Yu., Borisov, A. V., Shebelova, I. Yu., and Filipushchenko, M. V., *Zh. Org. Khim.*, **32**, 83 (1996); *Chem. Abs.*, **125**, 300271 (1996).
[27] Druelinger, M. L., Shellhamer, D. F., Chapman, R. D., Shackleford, S. A., Riner, M. E., Carter, S. L., Callhan, R. P., and Youngstrom, C. R., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 787.
[28] De Mico, A., Margarita, R., Parlanti, L., Piancatelli, G., and Vescovi, A., *Tetrahedron*, **53**, 16877 (1997).
[29] Cano, M. C., Gómez-Contreras, F., Sabz, A. M., and Yunta, M. J. R., *Can. J. Chem.*, **75**, 348 (1997).
[30] Petrov, V. A. and Krespan, C. G., *J. Org. Chem.*, **61**, 9605 (1996).
[31] Kitagawa, O., Suzuki, T., and Taguchi, T., *Tetrahedron Lett.*, **38**, 8371 (1997).
[32] Lucchini, V., Modena, G., Pasi, M., and Pasquato, L., *J. Org. Chem.*, **62**, 7018 (1997).
[33] Toshimitsu, A., Terada, M., and Tamao, K., *Chem. Lett.*, **1997**, 733.
[34] Boerve, K. J. and Jensen, V., *J. Chem. Phys.*, **105**, 6910 (1996); *Chem. Abs.*, **125**, 300277 (1996).
[35] Mendez, M. I., Sordo, J. A., and Sordo, T. L., *THEOCHEM*, **371**, 91 (1996); *Chem. Abs.*, **126**, 171127 (1997).
[36] Matthews, K. K., Adams, N. G., and Fisher, N. D., *J. Phys. Chem.*, **101**, 2841 (1997).
[37] Fairley, D. A., Scott, G. B. I., Freeman, C. G., Maclagan, R. G. A. R., and McEwan, M. J., *J. Phys. Chem.*, **1010**, 2848 (1997).
[38] Kazansky, V. B., *Kinet. Catal.*, **37**, 627 (1996); *Chem. Abs.*, **125**, 300282 (1996).
[39] Freccero, M., Gamba, A., Gandolfi, R., and Amade, M. S., *Tetrahedron*, **53**, 4869 (1997).
[40] Mlinaric-Majerski, K., Kazazic, S., Vinkovic, M., and Kragol, G., *Croat. Chem. Acta*, **69**, 1339 (1996); *Chem. Abs.*, **126**, 185696 (1997).
[41] Ritter, J. and Gleiter, R., *Liebigs Ann./Recueil*, **1997**, 1179.
[42] Hünig, S., Brand, U., Peters, K., Prokschy, F., and von Schnering, H. G., *Liebigs Ann./Recueil*, **1997**, 785.
[43] Ishihara, K., Nakamura, S., Kaneeda, M., and Yamamoto, H., *J. Am. Chem. Soc.*, **118**, 12854 (1996).
[44] Jensen, C. and Jorgensen, W. L., *Synlett*, **1997**, 518.
[45] Talipov, R. F., Safarov, I. M., Talipova, G. R., and Safarov, M. G., *React. Kinet. Catal. Lett.*, **61**, 63 (1997); *Chem. Abs.*, **127**, 234000 (1997).
[46] Sartori, G., Bigi, F., Maggi, R., and Arienti, A., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 257.
[47] Moran, R. J., Cramer, C., and Falvey, D. E., *J. Org. Chem.*, **62**, 2742 (1997).
[48] Ofial, A. R. and Mayr, H., *Angew. Chem., Int. Ed. Engl.*, **36**, 143 (1977).
[49] Martin, S. F. and Bur, S. K., *Tetrahedron Lett.*, **38**, 7641 (1997).
[50] Bodajla, M., Jones, G. R., and Ramsden, C. A., *Tetrahedron Lett.*, **38**, 2573 (1997).
[51] Cacace, F., de Petris, G., Pepi, F., Rossi, I., and Venturini, A., *J. Am. Chem. Soc.*, **118**, 12719 (1996).
[52] Lewis, R. J. and Moodie, R. B., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 563.
[53] Hewlins, S. A., Murphy, J. A., Lin, J., Hibbs, D. E., and Hursthouse, M. B., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1559.
[54] Chen, J. S., Houk, K. N., and Foote, C. S., *J. Am. Chem. Soc.*, **119**, 9852 (1996).
[55] Nelsen, S. F. and Klein, S. J., *J. Phys. Org. Chem.*, **10**, 456 (1997).
[56] Atkinson, R. S., Coogan, M. P., and Lochrie, I. S. T., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 897.
[57] Adam, W. and Blancafort, L., *J. Org. Chem.*, **61**, 8432 (1996).
[58] Hanson, J. R., Hitchcock, P. B., and Liman, M. D., *Aust. J. Chem.*, **50**, 249 (1997).
[59] Alam, M., Hanson, J. R., Liman, M., and Nagaratham, S., *J. Chem. Res. (C)*, **1996**, 56.
[60] Hanson, J. R., Liman, M. D., and Nagaratham, S., *J. Chem. Res. (C)*, **1997**, 282.
[61] Dhokte, U. P. and Brown, H. C., *J. Org. Chem.*, **62**, 865 (1997).
[62] Kobayashi, M. and Itoh, M., *Chem. Lett.*, **1996**, 1013; *Chem. Abs.*, **126**, 74900 (1997).
[63] Yamaguchi, M., Kido, Y., Hayashi, A., and Hirama, M., *Angew. Chem., Int. Ed. Engl.*, **36**, 1313 (1997).

[64] Yoshikawa, E., Gevorgyan, V., Asao, N., and Yamamoto, Y., *J. Am. Chem. Soc.*, **119**, 6781 (1997).
[65] Senda, Y., Kanto, H., and Itoh, H., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1143.
[66] Trost, B. M., Sorum, M. T., Chan, C., Harms, A. E., and Rühter, G., *J. Am. Chem. Soc.*, **119**, 698 (1997).
[67] Bianchini, C. and Peruzzini, M., *Phosphorus Res. Bull.*, **6**, 151 (1996); *Chem. Abs.*, **127**, 161380 (1997).
[68] Tieze, L. F., Burkhardt, O., and Henrich, M., *Liebigs Ann./Recueil*, **1997**, 887.
[69] Corey, E. J. and Noe, M. C., *J. Am. Chem. Soc.*, **118**, 11038 (1996).
[70] Nelson, D. W., Gypser, A., Ho, P. T., Kolb, H. C., Kondo, T., Kwong, H.-L., McGrath, D. V., Rubin, A. E., Norrby, P.-O., Gable, K. P., and Sharpless, K. B., *J. Am. Chem. Soc.*, **119**, 1840 (1997).
[71] Dapprich, S., Ujaque, G., Maseras, F., Lledós, A., Musaev, D. G., and Morokuma, K., *J. Am. Chem. Soc.*, **118**, 11660 (1996).
[72] DelMonte, A. J., Haller, J., Houk, K. N., Sharpless, K. B., Singleton, D. A., Strassner, T., K Thomas, A. A., *J. Am. Chem. Soc.*, **119**, 9907 (1997).
[73] Gable, K. P. and Juliette, J. J. J., *J. Am. Chem. Soc.*, **118**, 2625 (1996).
[74] Kazankova, M. A., Trostyanskaya, I. G., Efimova, I. V., and Beletskaya, I. P., *Zh. Org. Khim.*, **32**, 1657 (1996); *Chem. Abs.*, **126**, 330655 (1997).
[75] Emelina, E. E., Iz'yurov, A. L., Ermakov, N. V., and Ershov, B. A., *Zh. Org. Khim.*, **32**, 449 (1996); *Chem. Abs.*, **125**, 300287 (1996).
[76] Couladouros, E. A., Plyta, Z. F., Haroutounian, S. A., and Papageorgiu, V. P., *J. Org. Chem.*, **62**, 6 (1997).
[77] Matsuyama, H., Itoh, N., Yoshida, M., Kamigata, N., Sasaki, S., and Iyoda, M., *Chem. Lett.*, **1997**, 375.
[78] Um, I.-H., Lee, J.-S., and Kwon, D.-S., *Bull. Korean Chem. Soc.*, **18**, 268 (1997); *Chem. Abs.*, **126**, 330320 (1997).
[79] Hamed, E. A., *Indian J. Chem.*, **36A**, 102 (1997); *Chem. Abs.*, **126**, 292937 (1997).
[80] Brocchini, S. J. and Lawton, R.-G., *Tetrahedron Lett.*, **38**, 6319 (1997).
[81] Yannai, M. B. and Rapoport, Z., *J. Org. Chem.*, **62**, 5634 (1997).
[82] Miyashita, A., Numata, A., Suzuki, Y., Iwamoto, K., and Higashino, T., *Chem. Lett.*, **1997**, 697.
[83] Sebo, L., Alfoldi, J., Rihs, G., and Toma, Š., *Collect. Czech. Chem. Commun.*, **61**, 1805 (1996).
[84] Kočovský, P. and Dvořák, D., *Tetrahedron Lett.*, **27**, 5015 (1986).
[85] Christofers, J., *J. Chem. Soc., Chem. Commun.*, **1997**, 943.
[86] Risitano, F., Grassi, G., Bruno, G., and Nicol, F., *Liebigs Ann./Recueil*, **1997**, 441.
[87] Floch, L., Kuban, J., Gogová, A., Záluský, P., Jakubík, T., and Pronyová, N., *Molecules*, **1**, 175 (1996); *Chem. Abs.*, **127**, 50168 (1997).
[88] Yamaguchi, M., Igarashi, Y., Reddy, R. S., Shiraishi, T., and Hirama, M., *Tetrahedron*, **53**, 11223 (1997).
[89] Costa, J. S., Dias, A.-Q., Anholeto, A. L., Monteiro, M. D., Patrocinio, V. L., and Costa, P. R. R., *J. Org. Chem.*, **62**, 4002 (1997).
[90] Hong, B.-C. and Hong, J.-H., *Tetrahedron Lett.*, **38**, 255 (1997).
[91] Haynes, R. K., Lam, W.-L., Yeung, L.-L., Williams, I. D., Ridley, A. C., Starling, S. M., Vonwiller, S. C., Hambley, T. W., and Lelandais, P., *J. Org. Chem.*, **62**, 4552 (1997).
[92] Pyne, S. G., Dong, Z., Skelton, B. W., and White, A. H., *J. Org. Chem.*, **62**, 2337 (1997).
[93] Barbero, A., Blakemore, D. C., Fleming, I., and Wesley, R. N., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1329.
[94] Asa, N., Shimada, T., Sudo, T., Tsukada, N., Yazawa, K., Gyoung, Y. S., Uyehara, T., and Yamamoto, Y., *J. Org. Chem.*, **62**, 6274 (1997).
[95] Sato, M., Aoyagi, S., Yago, S., and Kibayashi, C., *Tetrahedron Lett.*, **37**, 9063 (1996).
[96] Yamin, L. J., Blanco, S. E., Luco, J. M., and Ferretti, F. H., *THEOCHEM*, **390**, 209 (1997); *Chem. Abs.*, **126**, 317103 (1977).
[97] Varghese, B., Suri, D., Kothari, S., and Banerji, K. K., *J. Chem. Res. (S)*, **1997**, 388.
[98] Øverås, A. T., Bakkestuen, A. K., Gundersen, L.-L., and Rise, F., *Acta Chem. Scand.*, **51**, 1116 (1997).
[99] Dulcère, J.-P. and Dumez, E., *J. Chem. Soc., Chem. Commun.*, **1997**, 971.
[100] Brunner, H. and Kimel, B., *Monatsh. Chem.*, **127**, 1063 (1996).
[101] Yoshimatsu, M. and Hasegawa, J., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 211.
[102] Tsuge, H., Takumi, K., Nagai, T., Okano, T., Eguchi, S., and Kimoto, H., *Tetrahedron Lett.*, **53**, 823 (1997).
[103] Ding, Y., Zhao, Z., and Zhoo, C., *Tetrahedron*, **53**, 2899 (1997).
[104] Marc, G., Nitti, P., Pitacco, G., Pizzioli, A., and Valentin, E., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 223.
[105] Lucero, M. J. and Houk, K. N., *J. Am. Chem. Soc.*, **119**, 826 (1997).
[106] Marco, J. L., *J. Org. Chem.*, **62**, 6575 (1997).
[107] Ojea, V., Riuz, M., Vilar, J., and Quintela, J. M., *Tetrahedron*, **7**, 3335 (1996).
[108] Fleming, F. F., Hussain, Z., Weaver, D., and Norman, R. E., *J. Org. Chem.*, **62**, 1305 (1997).
[109] Achmatowicz, O., Szechner, B., and Maurin, J. K., *Tetrahedron*, **53**, 6035 (1997).
[110] Krief, A., de Vos, M. J., De Lomabart, S., Bosret, J., and Couty, F., *Tetrahedron Lett.*, **38**, 6295 (1997).
[111] Kingsbury, C. L. and Smith, R. A. J., *J. Org. Chem.*, **62**, 4629 (1997).
[112] Rück-Braun, K., Stamm, A., Engel, S., and Kunz, H., *J. Org. Chem.*, **62**, 967 (1997).

[113] Trost, B. M., Portnoy, M., and Kurihara, H., *J. Am. Chem. Soc.*, **119**, 836 (1997).
[114] Tang, Y., Huang, Y.-Z., Dai, L.-X., and Xia, W., *J. Org. Chem.*, **62**, 954 (1997).
[115] Dolgounitcheva, O., Zakrzewski, V. G., and Oretiz, J. V., *J. Phys. Chem.*, **101**, 1758 (1997).
[116] Bohme, D. K., McKay, G. I., Schiff, H. I., and Hemsworth, R. S., *J. Chem. Phys.*, **61**, 2175 (1974).
[117] Johnson, M., and Foglesong, R. J., *Tetrahedron Lett.*, **38**, 7003 (1997).
[118] Buncel, E., Manderville, R. A., and Dust, J. M., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1019.
[119] Nair, V., Mathew, J., and Mathew, J., *Indian J. Chem.*, **36B**, 366 (1997).
[120] Nair, V., Mathew, J., and Nair, L. G., *Synth. Commun.*, **27**, 3053 (1997).
[121] Wladislaw, B., Di Vitta, C., Marzorati, L., de Arruda Campos, I. P., and Lucchini, V., *Tetrahedron Lett.*, **38**, 2625 (1997).

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CHAPTER 14

Addition Reactions: Cycloaddition

N. DENNIS

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Miscellaneous Cycloadditions 461
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Reviews have appeared on the use of cycloaddition reactions in organic synthesis[1] and on asymmetric cycloaddition reactions and their application in asymmetric synthesis of natural products.[2]

An extensive review of the use of density functional theory calculations on electrocyclic reactions, cycloadditions, and sigmatropic shifts has been published.[3] A cycloaddition model for the transformation of graphite into the carbon cages of fullerenes is described.[4]

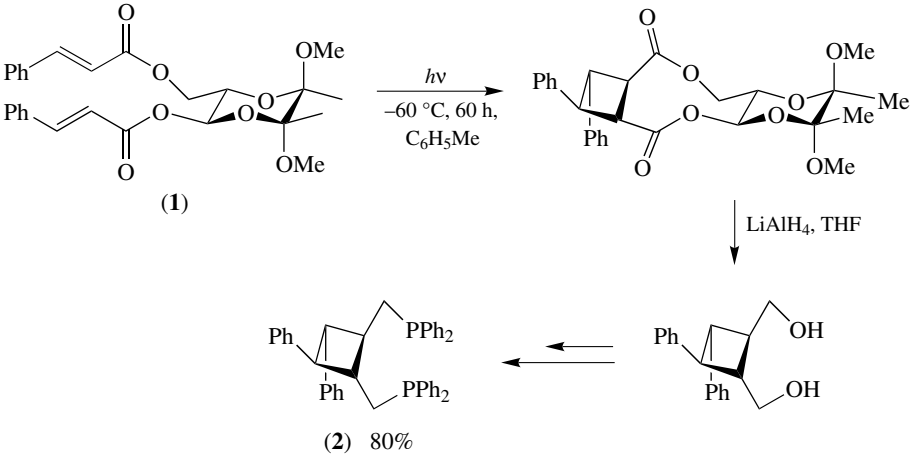
A book describing the numerous 2 + 2-, 2 + 3-, 2 + 4- and 2 + 1-cycloadditions of silenes has been published.[5] Silylated bisketenes [O=C=C(SiMe$_3$)CR=C=O] undergo 2 + 2-, 4 + 1- and 4 + 2-cycloaddition reactions.[6]

The 2 + 1-, 2 + 2-, 3 + 2-, 4 + 2- and 5 + 2-cycloaddition reactions of pyrylium salts and pyrenes have been reviewed.[7]

2 + 2-Cycloaddition

The effect of temperature on the disappearance rate of the starting material and the effect of temperature on the product selectivity in 2 + 2-intramolecular cycloadditions have been investigated.[8]

An *ab initio* CASSCF study of the dimerization of cyclobutadiene showed that *syn*-dimerization is highly favoured over *trans*-dimerization, and no synchronous concerted pathway was detected.[9] Photo-ionization and photo-sensitized electron transfer have been used to generate radical cations of arylalkene probe molecules that undergo intramolecular cyclobutanation or Diels–Alder reactions.[10] The intramolecular 2 + 2-photo-cycloaddition of dicinnamates (**1**) is a key step in the synthesis of C_2-symmetric chelating bisphosphanes (**2**) incorporating a cyclobutane backbone (Scheme 1).[11] Esters of α-(4-ethoxyphenyl)acrylic acid with chiral auxiliaries undergo thermal 2 + 2-cycloaddition with tetrafluoroethylene at 130 °C, to afford tetrafluorocyclobutanecarb-

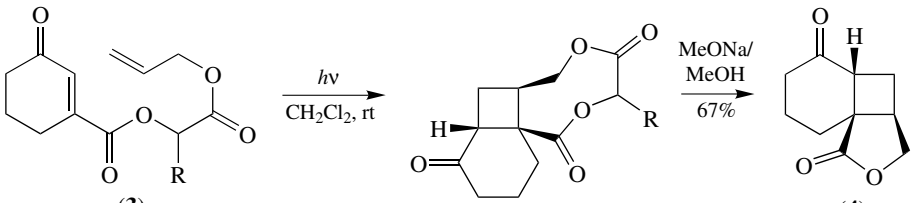


(**1**)

(**2**) 80%

SCHEME 1

oxylic esters with high diastereoselectivity.[12] The photo-reaction of the captodative alkene, 2-morpholinoacrylonitrile with 2- and 4-substituted 1-acetonaphthones yields both 2 + 2- and 2 + 4-cycloadducts.[13] L-Lactic acid and (*R*)-3-hydroxybutyric acids (**3**) prove to be effective chiral spacers for asymmetric intramolecular 2 + 2-photo-cycloaddition reactions leading to cyclobutanes (**4**) (Scheme 2).[14]



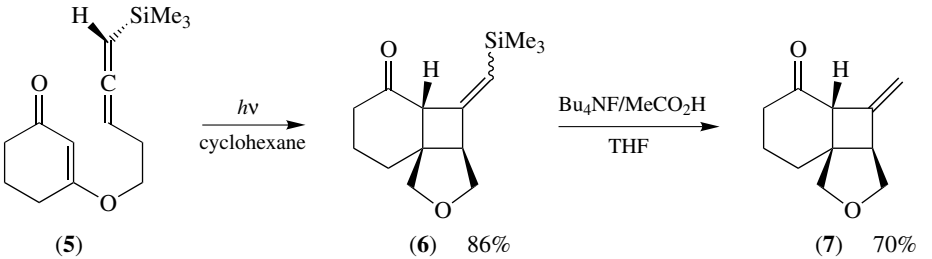
(**3**)
R = H, Me

(**4**)

SCHEME 2

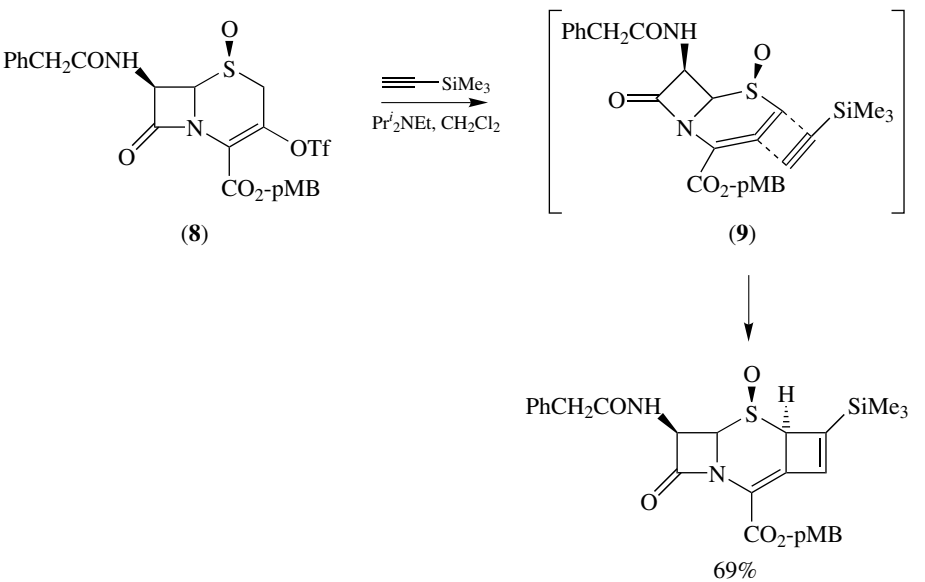
Fullerene, C_{60}, undergoes photochemical 2 + 2-cycloaddition with *N*,*N*-diethyl-4-methylpent-3-en-1-yn-1-amine to produce the stable C_{60}-fused cyclobutenamine that is photo-oxidized to the dihydrofullerenone amide in high yield.[15] The photochemical 2 + 2-cycloaddition of arylalkenes with C_{60} has been shown to occur by a two-step mechanism involving the formation of a dipolar or diradical intermediate in the rate-determining step.[16] The 2 + 2-photo-cycloaddition of *cis*- and *trans*-1-(*p*-methoxyphenyl)-1-propene to C_{60} produces only *trans*-2 + 2-adduct. This is consistent with a two-step mechanism.[17] The 2 + 2-photo-cycloaddition of cyclic 1,3-diones to C_{60} results in the formation of two furanylfullerenes, one chiral and the other achiral. None of the expected De Mayo cyclooctane-1,3-dione addition products were formed.[18]

The intramolecular 2 + 2-photo-cycloadditions of optically active allenesilanes (**5**) with enones and enoates produce silyl-substituted *exo*-methylenecyclobutanes (**6**) in high enantiometric excess. Photo-desilation leads to the parent unsaturated *exo*-methylenecyclobutanes (**7**) (Scheme 3).[19] The cycloaddition of naphthoquinone to allyltrimethylsilane in the presence of Me_2AlCl yields the expected 2 + 2-cycloadduct that slowly rearranges to the 2 + 3-adduct.[20] In the presence of bases, Cephalosporin triflates (**8**) undergo 2 + 2- and 4 + 2-cycloaddition with alkenes, alkynes, and dienes via an intermediate six-membered cyclic allene (**9**) (Scheme 4).[21]



(**5**) (**6**) 86% (**7**) 70%

SCHEME 3



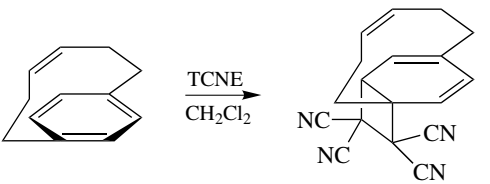
(**8**) (**9**)

SCHEME 4

RHF methodology, used to investigate the cycloaddition reaction of isocyanic acid with methylenimine, confirmed a two-step mechanism via a *cis* intermediate for the equimolar reaction.[22] The 2 + 2-cycloaddition of chlorosulfonyl and trichloroacetyl

isocyanates to sugar vinyl ethers yields the corresponding azetidin-2-ones, intermediates in the synthesis of β-lactam antibiotics.[23]

Ab initio self-consistent reaction field and Monte Carlo statistical mechanics calculations were used to study the solvent effects on the polar 2 + 2-cycloaddition of 1,1-dicycanoethylene with methyl vinyl ether.[24] The cycloaddition of (*Z*)-[6]paracycloph-3-ene (**10**) with TCNE is regioselective, yielding a single 2 + 2-cycloadduct (**11**) (Scheme 5).[25] The addition of LiCl in Et_2O shows a strong salt effect in the 2 + 2-cycloaddition of TCNE with $EtOCH{=}CH_2$ and $PhCMe{=}CH_2$.[26] The reaction of cyanoacetylene with [2.2](2,5)furanoparacyclophane (**12**), at 160 °C and 1 bar, produces a mixture of 'ring-enlarged' ketones (**13**)–(**18**) (Scheme 6).[27] The 2 + 2-photo-cycloaddition of cyanoethylenes to 1,4,5,6-tetrahydro- and 1,4-dihydro-pyridines proceeds with retention of alkene geometry, suggesting a concerted process.[28] A study of the irradiation of photo-substrates containing 2-carboalkoxycyclopentenone chromophores has shown that hydrogen bonding and solvent effects can control the diastereoselectivity in intramolecular 2 + 2-photo-cycloadditions.[29]

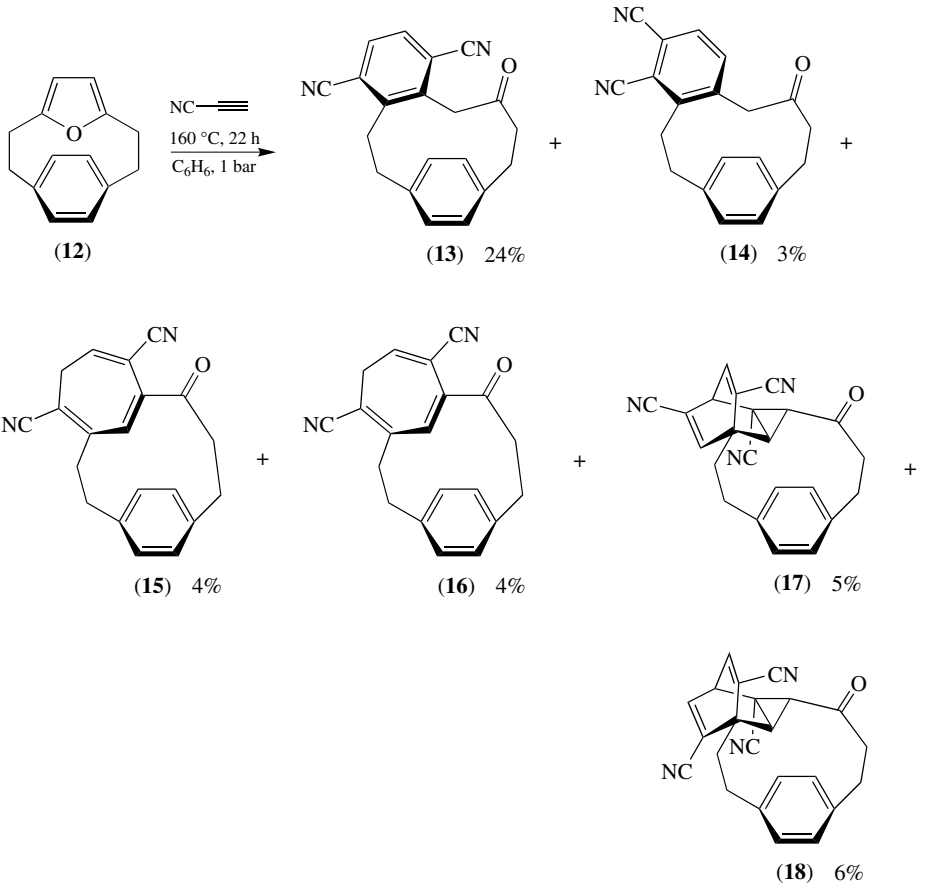


(**10**) (**11**)

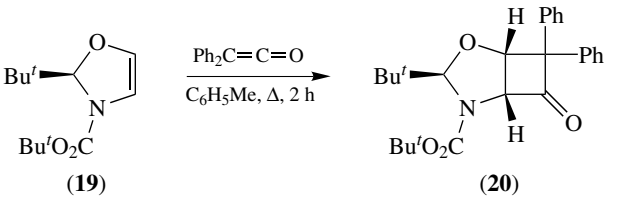
SCHEME 5

The semi-empirical AM1 method was used to investigate the cycloaddition of ketenes with 2-amino-β-D-arabino[1′, 2′ : 4, 5]oxazoline to β-lactams.[30] The rates of 2 + 2-ring closure of the bisketenes, $O{=}C{=}C(C_6H_4X)C(SiMe_3){=}C{=}O$, to cyclobutanediones correlate well with σ_p^+ constants of the aryl substituents at 70 °C.[31] Ketenes derived photochemically from diazoketones cycloadd stereospecifically with *N*-benzylbenzaldimine to form *trans*-substituted β-lactams, being intermediates in the synthesis of β-lactam antibiotics such as thienamycin.[32]

The 2 + 2-cycloaddition reaction of α-alkoxyketene-derived imines yields β-lactams with quaternary stereogenic centres at C(4).[33] The 2 + 2-cycloaddition of chiral aminoketenes with chiral imines yields *cis*-β-lactams with the absolute stereochemistry of the C(3) and C(4) positions being controlled by the ketene partner only.[34] The 2 + 2-cycloaddition of ketenes with (*R*)-2-*t*-butyldihydrooxazole (**19**) yields predominately the regioisomer (**20**) from steric control rather than the expected electronic control (Scheme 7).[35] The double 2 + 2-cycloaddition reaction between ketenylidenetriphenylphosphorane (**21**) and carbon suboxide (**22**) produces the bis(ylidic) spirocyclobutanedione (**23**) (Scheme 8).[36] Semiempirical and *ab initio* calculations have been used to investigate the Lewis acid-promoted 2 + 2-cycloaddition leading to the formation of β-lactones.[37]

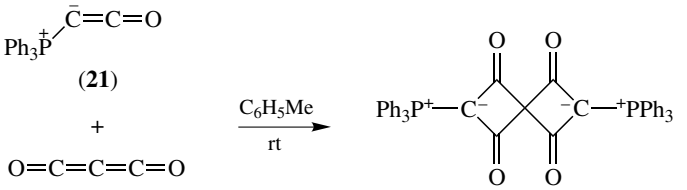


SCHEME 6

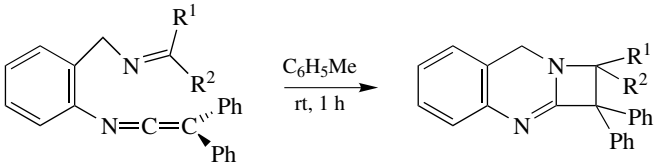


SCHEME 7

Ab initio calculations indicate that in the gas phase the reaction of ketene imine and formaldehyde is concerted but asynchronous whereas in dichloromethane it is a two-step zwitterionic reaction.[38] The 2 + 2-cycloadditions of keteniminium triflates with imines yields 2-azetidiniminium salts with *cis* stereoselectivity.[39] The intramolecular 2 + 2-cycloaddition of ketenimines with imines (**24**) provides a novel synthesis of azeto[2,1-*b*]quinazolines (**25**) (Scheme 9).[40]



SCHEME 8



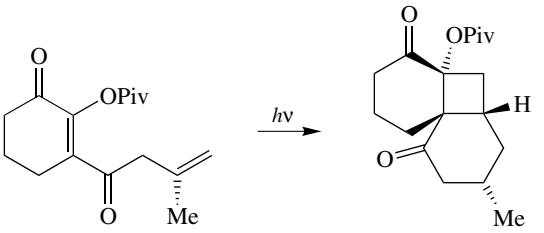
R^1	R^2
H	$CH(Me)_2$
H	(*E*)-CH═CHPh
H	3-furyl
H	4-$MeOC_6H_4$
H	4-$O_2NC_6H_4$
Me	4-$O_2NC_6H_4$

SCHEME 9

A review of photo-cycloadditions of dienones and quinones has been published.[41] The first example of a Lewis acid-catalysed 2 + 2-cycloaddition of styrene with naphthoquinone has been reported.[42] FMO methods have been used to investigate the effect of substituents on the regiochemistry of the 2 + 2-photo-cycloaddition of α,β-unsaturated carbonyl compounds with substituted alkenes.[43] Evidence has been presented for the presence of a triplet exciplex intermediate in the photo-cycloaddition of 4,4-dimethylcyclohexenone to 1,1-diphenylethylene.[44] The intramolecular 2 + 2-photo-cycloaddition of 2-acyloxy-3-hexenoylcyclohexenones (**26**) is highly diastereoselective yielding the tricyclic adduct (**27**) (Scheme 10).[45]

FMO calculations using PM3-Cl were used to investigate the regioselectivities obtained by the photochemical reactions between 2-pyridone and penta-2,4-dienoate.[46] The hard and soft acid–base principle has been successfully used to predict product formation in Paterno-Büchi reactions.[47] The 2 + 2-photo-cycloaddition of homobenzvalene with methyl phenylglyoxylate, benzyl, benzophenone, and 1,4-benzoquinone produced the corresponding Paterno-Büchi products.[48] The photo-cycloaddition of acrylonitrile to 5-substituted adamantan-2-ones produces *anti*- and *syn*-oxetanes in similar ratios irrespective of the nature of the 5-substituent.[49]

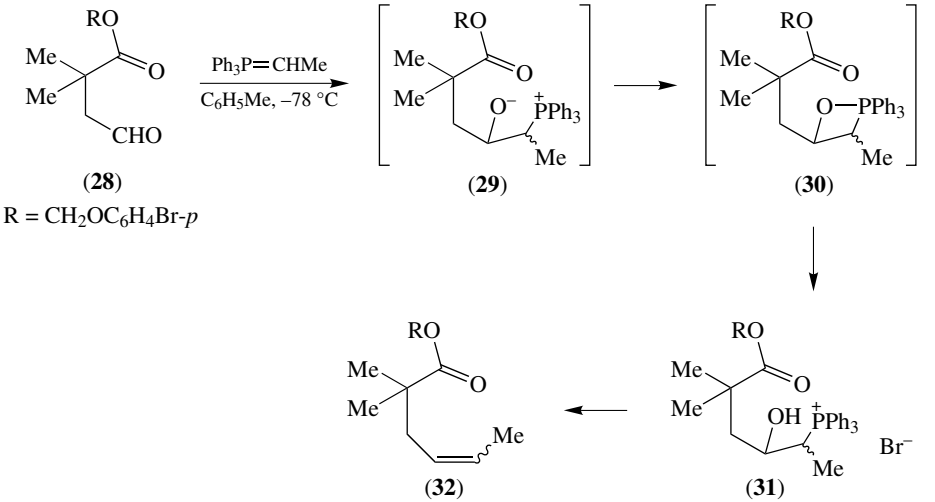
Theoretical calculations rule out a 2 + 2-cycloaddition step of osmium tetraoxide to alkenes as the initial step of the dihydroxylation reaction.[50] A synchronous 2 + 2-



(**26**) (**27**) 70%

SCHEME 10

cycloaddition step, (**29**) to (**30**), has been proposed for the indirect Wittig reaction of aldehyde (**28**) leading to the alkenes (**32**) via the isolated 1,2-hydroxyphosphonium salt (**31**) (Scheme 11).[51]



(**28**)
R = $CH_2OC_6H_4Br$-*p*

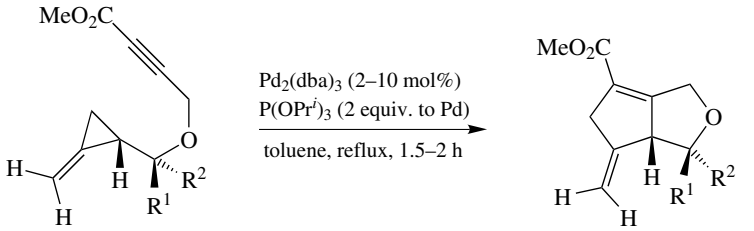
(**29**) (**30**) (**31**) (**32**)

SCHEME 11

2 + 3-Cycloaddition

Tandem intramolecular 1,3-dipolar cycloadditions and cycloreversion, phosphinimine alkylidenemalonate cyclization, and retro-malonate additions have been reviewed.[52] The origins of the stereoselection in the 1,3-dipolar cycloadditions to chiral alkenes[53] and the 3 + 2-cycloadditions of fullerene, C_{60}, have been reviewed.[54] The selectivity of the double 3 + 2-cycloaddition of tethered double vinyl carbene species in the presence of C_{60} varies with the nature of the tether.[55]

The 1,3-dipolar cycloaddition of allenes with 1,3-dipoles has been reviewed.[56] The scope and limitations of palladium-catalysed intramolecular 3 + 2-cycloaddition of diastereomerically pure methylenecyclopropanes (**33**) yielding methylenecyclopentenes (**34**) has been investigated (Scheme 12).[57] Chiral 2,5-dialkyl-7-phenyl-7-phosphabicy-



(**33**) (**34**)

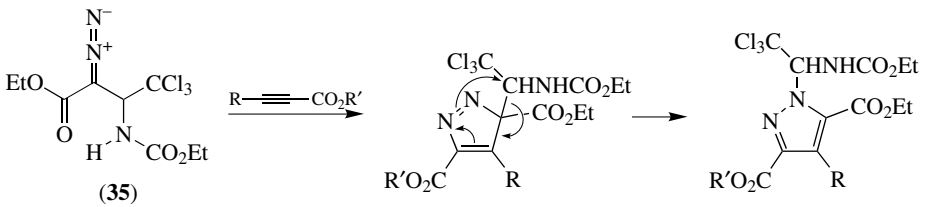
R^1	R^2
C_6H_{11}	H
H	C_6H_{11}
C_7H_{15}	H
H	C_7H_{15}
—$(CH_2)_5$—	

SCHEME 12

clo[2.2.1]heptanes catalyse the asymmetric 3 + 2-cycloaddition of buta-2,3-dienoates with electron-deficient alkenes to yield cyclopentenes with high regio- and stereoselectivity.[58]

Ab initio MO calculations (MP2/6–31G*) of the reactions of nitrosoketene with formaldehyde, acetone and prop-2-enal indicate a 3 + 2-pathway via a concerted, planar, and pseudo-pericyclic transition state.[59]

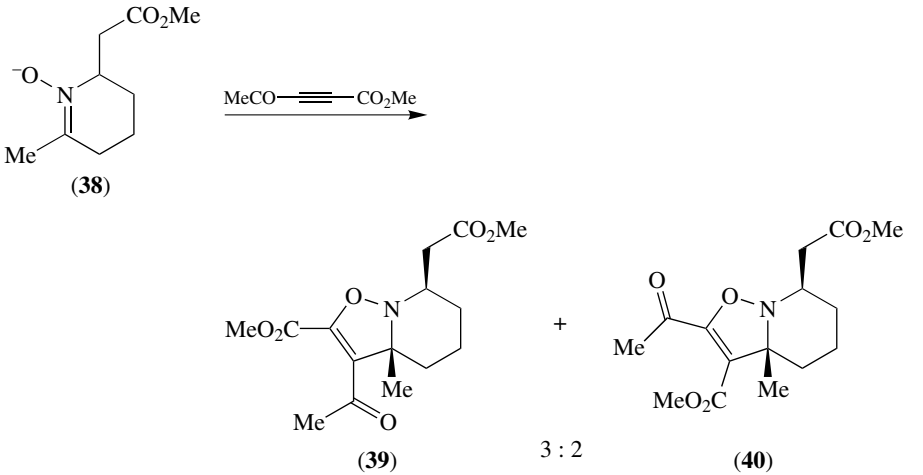
The 3 + 2-cycloaddition of commercially available Me_3SiCHN_2 with camphor sultam-derived dipolarophiles produces 3-trimethylsilyl-substituted-Δ^1-pyrazolines which on acid treatment convert into optically active Δ^2-pyrazolines.[60] The nucleophilic addition of ethyl diazoacetate with *N*-ethoxycarbonyl-*N*-(2,2,2-trichloroethylidene)amine produces a new diazo intermediate (**35**), which by 1,3-dipolar cycloaddition followed by a sigmatropic rearrangement of the cycloadduct (**36**) furnishes a substituted pyrazole (**37**) (Scheme 13).[61].



(**35**) (**36**) (**37**)

R	R′
CO_2Me	Me
H	Me
CO_2Et	Et
H	Et

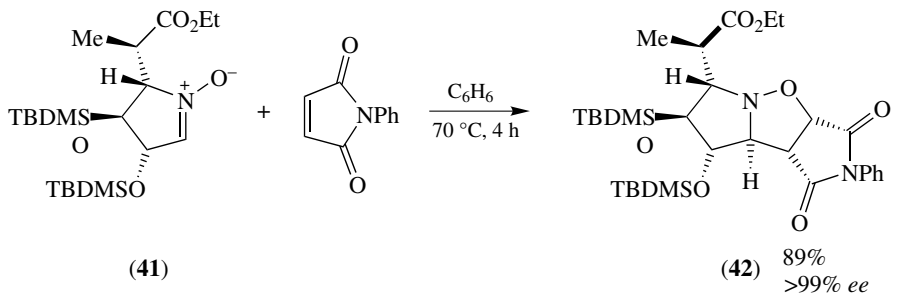
SCHEME 13



SCHEME 14

The use of $TiCl_2$–TADDOLate and Mg(II)-phenanthroline catalysts in asymmetric 1,3-dipolar cycloadditions of alkenes with nitrones has been reviewed.[62] The 1,3-dipolar cycloaddition of 3-acryloyloxazolidin-2-one with nitrones catalysed by [TiX_2(TADDOLato)] complex shows high regio-, diastereo-, and enantio-selectivity.[63]

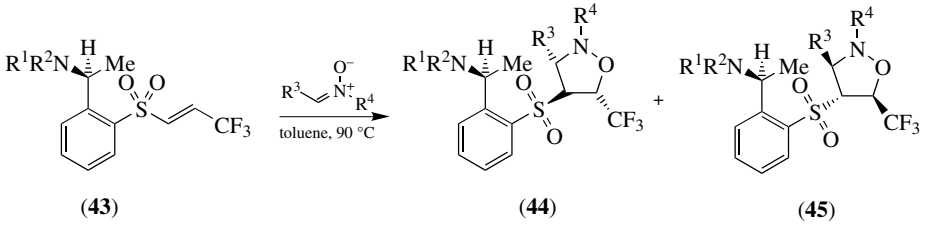
Cyclic nitrones with substituents α to the nitrogen atom (**38**) undergo 1,3-dipolar cycloaddition with methyl propiolate to form isoxazolo[2,3-*a*]pyridines (**39**) and (**40**) with high regio- and stereo-specificity (Scheme 14).[64] The chiral cyclic nitrones (**41**) undergo asymmetric $3+2$-cycloaddition reaction with α,β-unsaturated carbonyl compounds to form cycloadducts (**42**) with very high diastereomeric excess (>99%) (Scheme 15).[65]



SCHEME 15

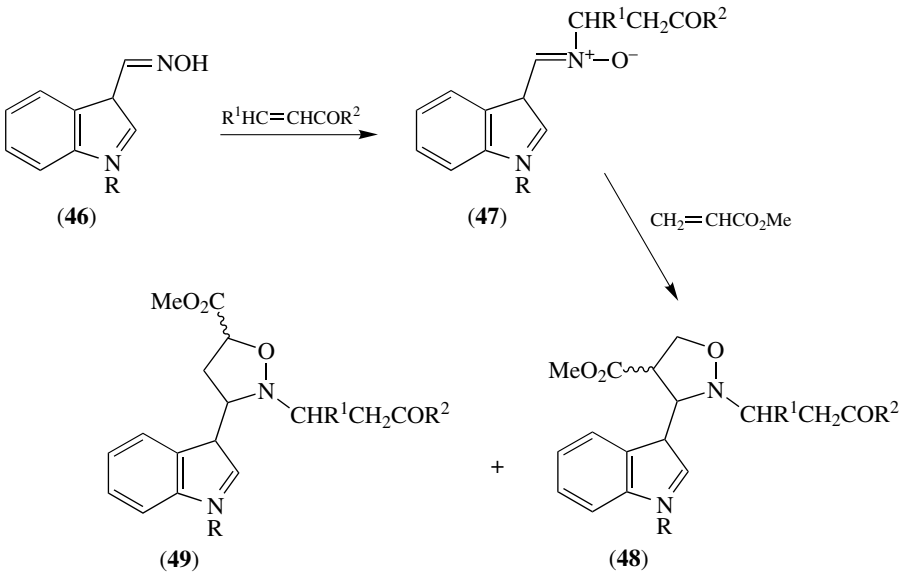
Chiral crotonates derived from *S*-citronellol, 1-(−)-menthol, and *S*-solketol undergo 1,3-dipolar cycloaddition with cyclic and acyclic nitrones.[66] Asymmetric 1,3-dipolar cycloaddition of optically active trifluoromethylated α, β-unsaturated aryl sulfones (**43**) with nitrones yield the corresponding isoxazolidines (**44**) and (**45**) with high regio- and

diastereo-selectivity (Scheme 16).[67] Nitrones (**47**) generated from indol-3-yl-carbaldehyde oximes (**46**) undergo 1,3-dipolar cycloaddition with electron-deficient dipolarophiles to produce isoxazolidines (**48**) and (**49**) (Scheme 17).[68]



(**43**) (**44**) (**45**)

SCHEME 16

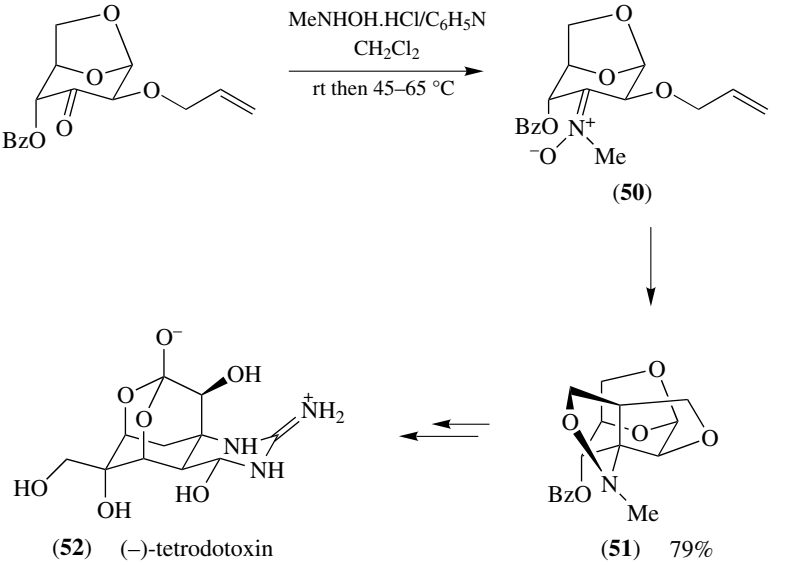


(**46**) (**47**) (**49**) (**48**)

SCHEME 17

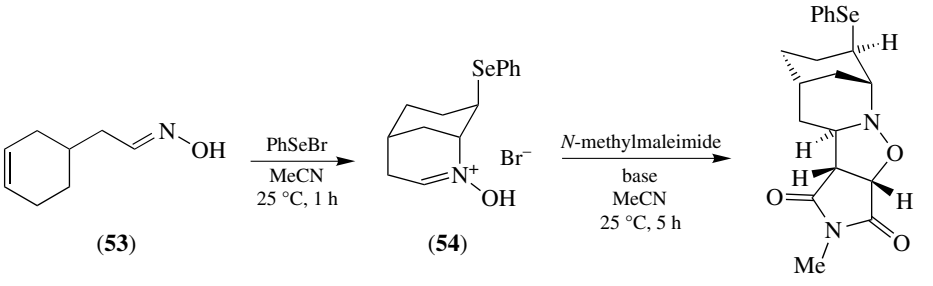
The 1,3-dipolar cycloaddition of *N*-benzyl-*C*-ethoxycarbonylnitrone with (*S*)-5-hydroxymethyl-(5*H*)-furan-2-one is regio- and stereo-selective.[69] The intramolecular 1,3-dipolar cycloaddition of sugar ketonitrones (**50**) provides a convenient method for the stereoselective formation of carbohydrate derivatives (**51**) possessing nitrogenated quaternary centres. This methodology has been successfully used to prepare synthetic precursors of (−)-tetrodotoxin (**52**) (Scheme 18).[70] The hydrophobic effect has been shown to influence the rate and selectivity of 1,3-dipolar cycloaddition reactions of *C*,*N*-diphenylnitrone with electron-deficient dipolarophiles.[71]

The diastereoselectivity in the intramolecular 1,3-dipolar cycloaddition of 2-fluoronitrones with ethyl vinyl ether was the reverse of that exhibited by the

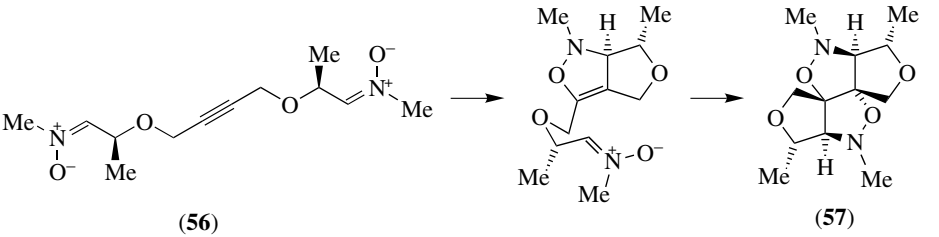


SCHEME 18

corresponding 2-hydronitrones.[72] The initial PhSeBr cyclization of oximes (**53**) produces the bicyclic nitrone salt (**54**) that undergoes 1,3-dipolar cycloaddition with *N*-methylmaleimide to yield the tetracyclic cycloadduct (**55**) in 67% overall yield from the oxime (Scheme 19).[73] The diastereofacial selectivity in the 3 + 2-cycloaddition of cyclic nitrones to (*E*-γ-oxygenated α, β-unsaturated esters leading to *endo* adducts may be rationalized through the Houk transition state model.[74] The dinitrone (**56**) undergoes two consecutive intramolecular 1,3-dipolar cycloadditions to form the chiral non-racemic compound (**57**) (Scheme 20).[75] The 1,3-dipolar cycloaddition of *C*-2(thiazolyl)nitrones with chiral acrylates substituted with Oppolzer's camphor sultam produces isoxazolidines with high regio- and diastereo-selectivities and good asymmetric induction.[76] The use of 9-anthrylcarbinol as a chiral auxiliary in the 1,3-dipolar cycloaddition of acrylates to cyclic nitrones has been described.[77] The



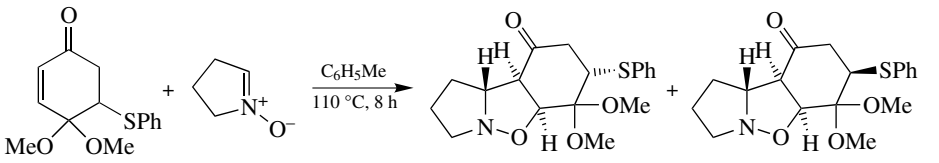
SCHEME 19



(**56**) (**57**)

SCHEME 20

phenylthio derivative (**58**) is an efficient masked chiral synthetic equivalent of *p*-benzoquinone in the 1,3-dipolar cycloaddition with cyclic nitrones (**59**), which forms the tricyclic cycloadducts (**60**) and (**61**) (Scheme 21).[78]

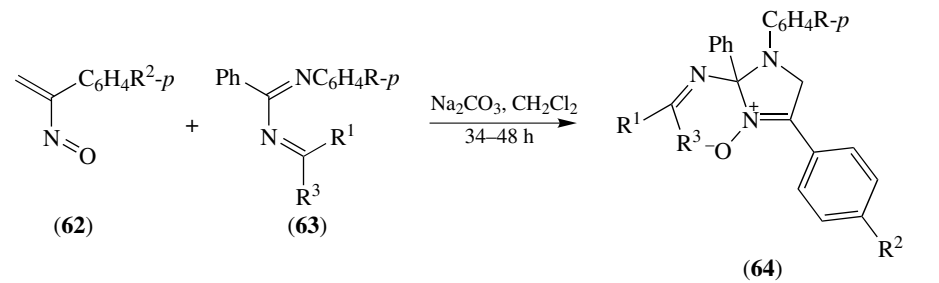


(**58**) (**59**) (**60**) (**61**)

SCHEME 21

The addition of $ZnBr_2$ to the tandem 1,3-azaprotio cyclotransfer–cycloaddition of a ketoxime with divinyl ketone results in rate enhancement and the exclusive formation of 1-aza-7-oxabicyclo[3.2.1]octan-3-ones.[79] The 1,3-dipolar cycloaddition of 1-aza-1-cyclooctene 1-oxide with alkenes produces the corresponding isoxazolidines in high yields with a minimum of polymeric material.[80] The cycloaddition of thiophene-2-carbaldehyde oxime with acetonitrile and methyl acrylate produces the 1,3-dipolar adduct, substituted isoxazolidines, and not the previously reported 4 + 2-adducts.[81] Density functional theory and semi-empirical methods have been used to investigate the 3 + 2-cycloaddition of azoxides with alkenes to produce 1,2,3-oxadiazolidines.[82] The 3 + 2-cycloaddition of α-nitrosostyrenes (**62**) with 1,3-diazabuta-1,3-dienes (**63**) and imines produces functionalized cyclic nitrones (**64**) regioselectively (Scheme 22).[83]

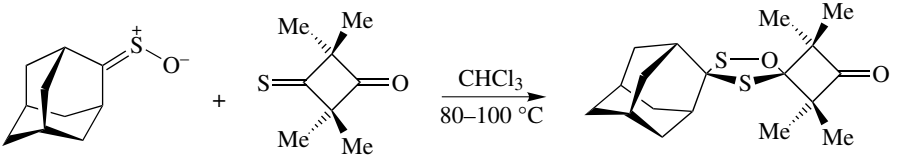
The first unequivocal 1,3-dipolar cycloaddition of sulfines involves the reaction of 2,2,4,4-tetramethyl-3-thioxocyclobutanone *S*-oxide with diaryl thioketones to produce



(**62**) (**63**) (**64**)

SCHEME 22

spiro-1,2,4-oxadithiolanes at room temperature.[84] The reaction of adamantanethione *S*-oxide (**65**) with thioketones (**66**) produces the mixed bis-spirane (**67**) by 1,3-dipolar cycloaddition (Scheme 23).[85] However, the reaction of thiobenzophenone *S*-oxide with the thioketone afforded the spiro-1,2,4-trithiolane rather than the expected spiro-1,2,4-oxadithiolane.[86]

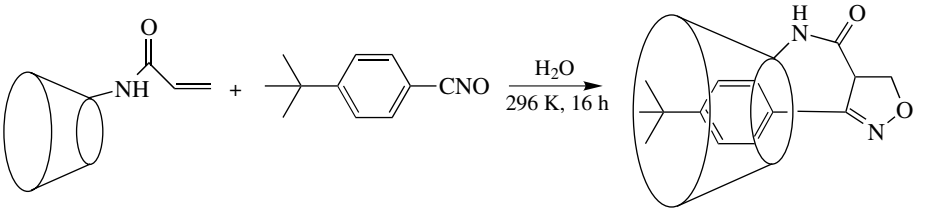


(**65**) (**66**) (**67**) 83%

SCHEME 23

Nitrile oxides react with the methyl enol ethers of (*R*s)-1-fluoro-alkyl-2-(*p*-tolylsulfinyl)ethanones to produce (4*S*,5*R*,*R*s)-4,5-dihydroisoxazoles with high regio- and diastereo-selectivity.[87] In the 1,3-dipolar cycloaddition of benzonitrile oxide with adamantane-2-thiones and 2-methyleneadamantanes, the favoured approach is *syn*, as predicted by the Cieplak's transition-state hyperconjugation model.[88] The 1,3-dipolar cycloaddition reaction of acetonitrile oxide with bicyclo[2.2.1]hepta-2,5-diene yields two 1 : 1 adducts and four of six possible 2 : 1 adducts.[89] Moderate catalytic efficiency, ligand acceleration effect, and concentration effect have been observed in the magnesium ion-mediated 1,3-dipolar cycloadditions of stable mesitonitrile oxide to allylic alcohols.[90] The cycloaddition reactions of acryloyl derivatives of the Rebek imide benzoxazole with nitrile oxides are very stereoselective but show reaction rates and regioselectivities comparable to simple achiral models.[91].

The 3 + 2-cycloaddition of nitrile oxides to 2-crotyl-1,3-dithiane 1-oxides produces exclusively 5-acyldihydroisoxazoles.[92] Lewis acid addition to 1,3-dipole cycloaddition reactions of mesityl nitrile oxide with α, β-unsaturated 2-acyl-1,3-dithiane 1-oxides can reverse the sense of induced stereoselectivity.[93] The 1,3-dipolar cycloaddition of 4-*t*-butylbenzonitrile oxide with 6^A-acrylamido-6^A-deoxy-β-cyclodextrin (**68**) in aqueous solution favours the formation of the 4-substituted isoxazoline (**69**) rather than the 5-substituted regioisomer (Scheme 24).[94] Tandem intramolecular cycloadditions of silyl nitronate, synthons of nitrile oxides, yield functionalized hydrofurans.[95]



(**68**) (**69**)

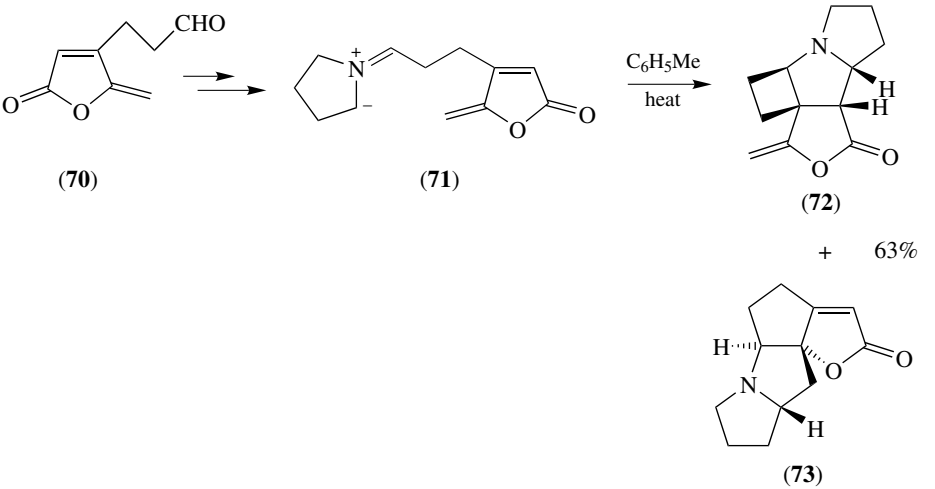
SCHEME 24

AM1 calculations have been used to explain the regioselectivities of the intermolecular asymmetric 1,3-dipolar cycloadditions of 2,2-dimethyl-3,4-dihydro-2*H*-pyrrole *N*-oxides with chiral α, β-unsaturated esters.[96] MO calculations have shown that only in-plane aromaticity is operating in transition structures associated with the 1,3-dipolar cycloaddition of acetylene and ethylene with $H_2C{=}\overset{+}{N}{-}O^-$ and fulminic acid.[97] Steric factors control the face selectivity of the regiospecific reactions of diazomethane, 3,4-dihydroquinoline *N*-oxide, and nitrile oxides with *trans*-3,4-dimethyl-1-methoxycarbonylcyclobutene. In the case of *cis*-3,4-dimethyl-1-methoxycarbonylcyclobutene, the expected increase in diastereoselectivity is only observed with 3,4-dihydroquinoline *N*-oxide.[98] The 1,3-dipolar cycloaddition reactions of heterocyclic *N*-oxides with alkenes, alkynes, isocyanates, thioisocyanates, and heterodienes have been reviewed.[99] The 3 + 2-cycloaddition of *C*-(dialkoxyphosphoryl)nitrile oxides to alkenes provides a route to functionalized heterocycles bearing a phosphonate moiety.[100]

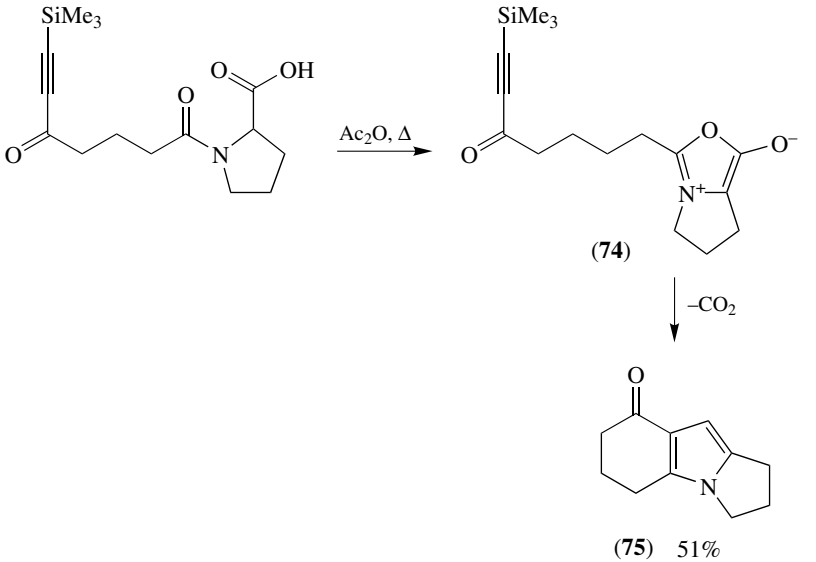
Stable *N*-phosphino- and *N*-phosphonio-nitrilimines undergo 3 + 2-cycloaddition with electron-poor and electron-rich dipolarophiles, respectively, to produce substituted pyrazolines.[101] The first diastereoselective 3 + 2-cycloaddition between bis(trityl)nitrilimine and an acrylate, (*R*)-α-(acryloxy)-β, β-dimethyl-γ-butyrolactone, has been reported.[102] The 1,3-dipolar cycloaddition of *N*, *N*′-diarylbisnitrile imides with cinnamonitriles produces exclusively 5, 5′-dicyano-4, 4′, 5, 5′-tetrahydro[3, 3′-di-1*H*-pyrazoles] which yield the corresponding 3, 3′-di-1*H*-pyrazoles on thermal aromatization.[103]

The $Rh_2(OAc)_4$-catalysed reactions of ethyl diazoacetate with substituted benzaldehydes yielded 1,3-dioxolanes via an initially formed carbonyl ylide. Catalyst-dependent diastereo-control was observed only when *p*-nitrobenzaldehyde was used as catalyst.[104] The intramolecular cycloaddition of carbonyl ylide dipoles with tethered alkenyl π-bonds is greatly enhanced by placing an sp^2 centre on the tethered side-chain.[105] The thermal reaction of 3-phenyloxirane-2,2-carbonitrile and 2-phenyl-3-thia-1-azaspiro-[4,4]non-1-ene-4-thione yields *cis*- and *trans*-cycloadducts via a regioselective 1,3-dipolar cycloaddition of an intermediate carbonyl ylide.[106]

Non-stabilized azomethine ylides (**71**), produced from 4-substituted protoanemonin (**70**), undergo intramolecular cycloaddition to produce polycyclic cycloadducts (**72**) and (**73**) in good yield (Scheme 25).[107] The dihalogen-substituted azomethine ylides, iminodifluoromethanides, prepared by the reaction of difluorocarbene with *N*-benzylidine amines, undergo 1,3-dipolar cycloaddition with electron-deficient alkenes to produce substituted pyrrolidines.[108] A general synthesis of tri- and tetra-substituted oxotetrahydroindoles (**75**) via the intramolecular 1,3-dipolar cycloaddition of azomethine ylides (**74**) with tethered alkynes has been described (Scheme 26).[109] Silicon-based tethers have been used to control the diastereofacial selectivity in azomethine ylide cycloadditions. Thus, azomethine ylides incorporating longer tethers [$OSiPh_2O(CH_2)_2OCOCH{=}CH_2$] (**76**) favour *endo-si* attack (**77**) whereas shorter tethers [$OSiR_2CH_2CH{=}CH_2$] (**78**) favour the *endo-re* product (**79**) (Scheme 27).[110] UV–VIS spectroscopy has been used to investigate the kinetics of 1,3-dipolar cycloaddition reactions between *N*-*p*-methoxybenzylidene-α-phenylglycine methyl ester and nitrosobenzene.[111]

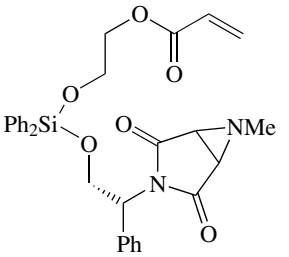


SCHEME 25



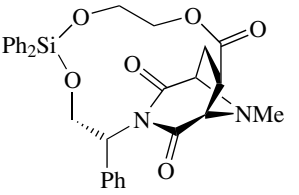
SCHEME 26

The 3 + 2-cycloaddition of ring-fused isomunchnones with various dipolarophiles produces predominantly the *exo*-dipolar adduct; *exo* selectivity could be enhanced by the inclusion of substituents on any position of the fused five-membered ring.[112] Dihydropyrimidine-fused isothiomunchnones and isomunchnones (**80**) undergo intramolecular 1,3-dipolar cycloadditions to form cycloadducts (**81**) with high regio- and stereo-selectivity (Scheme 28).[113] The tandem 1,3-dipolar cycloadditions of 1,3-

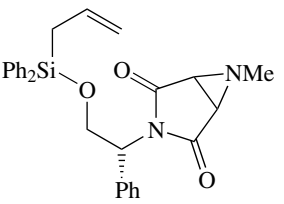


(**76**)

*h*ν (3000 Å)
MeCN, isoprene

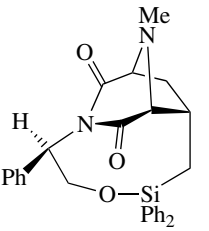


(**77**) 73%, *ds* = 12 : 1



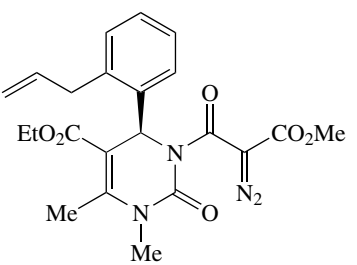
(**78**)

*h*ν (2537 Å)
quartz, MeCN

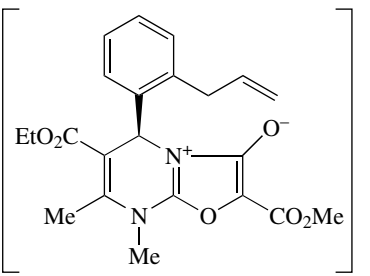


(**79**) 71%, *ds* = 10 : 1

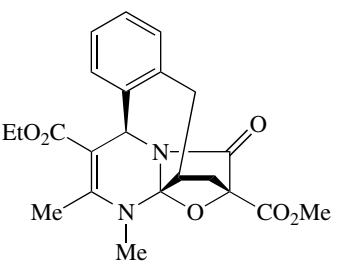
SCHEME 27



$Rh_2(OAc)_4$
heat



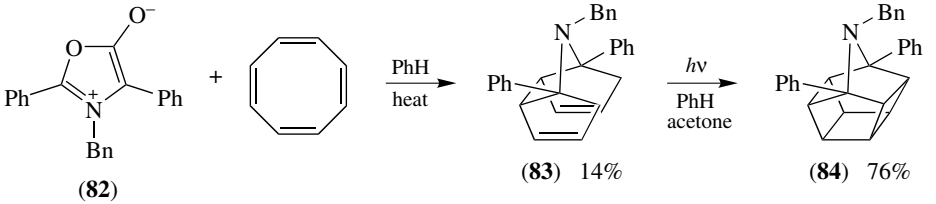
(**80**)



(**81**) 88%

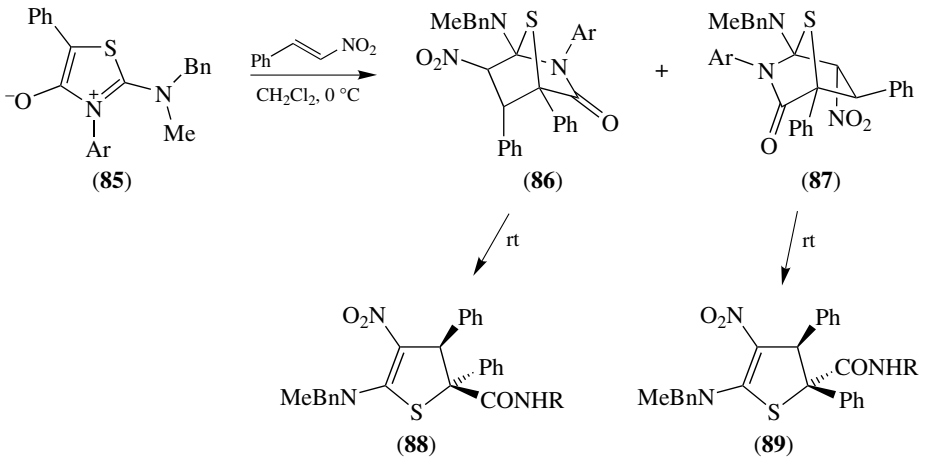
SCHEME 28

oxazolium-5-olates (**82**) with cycloocta-1,3,5,7-tetraene yields 10-benzyl-9,11-diphenyl-10-azatetracyclo[6.3.0.0^{4,11}.0^{5,9}]undeca-2,6-diene (**83**), which can be photolysed to give azahomopentaprismane (**84**) (Scheme 29).[114] The 1,3-dipolar addition of 3-methyl-2-(4-nitromethyl)-4-phenyl-1,3-oxazolium-5-olate with chiral nitroalkenes derived from D-galacto- and D-manno-hept-1-enitols produced acyclic pyrrole *C*-nucleosides with high regiospecificity.[115] The 1,3-dipolar cycloaddition of 1,3-thiazolium-4-olates (**85**) with *trans*-*β*-nitrostyrene produces the transient cycloadducts (**86**) and (**87**), which rearrange to the diastereoisomeric racemic 4,5-dihydrothiophenes (**88**) and (**89**), respectively (Scheme 30).[116]



(**82**) (**83**) 14% (**84**) 76%

SCHEME 29



(**85**) (**86**) (**87**) (**88**) (**89**)

SCHEME 30

A review on the inter- and intra-molecular cycloaddition of oxidopyridiniums and pyridinium ylides has appeared.[117] The known 1,3-dipolar cycloaddition of 1-methyl-4-phenyl-3-oxidopyridinium with electron-deficient dipolarophiles has been used to produce tropenones which can be transformed into 6- and 7-substituted 3-phenyltropanes, analogues of cocaine.[118]

(2-*t*-Butylseleno)propenenitrile reacts with DMAD to yield the expected 3 + 2-cycloadduct which spontaneously converts into dimethyl 5-cyano-4,5-dihydroselenophene-2,3-dicarboxylate.[119]

Calculated and experimental kinetic isotope effects for the asymmetric OsO_4 dihydroxylation support a 3 + 2-cycloaddition as the rate-determining step.[120]

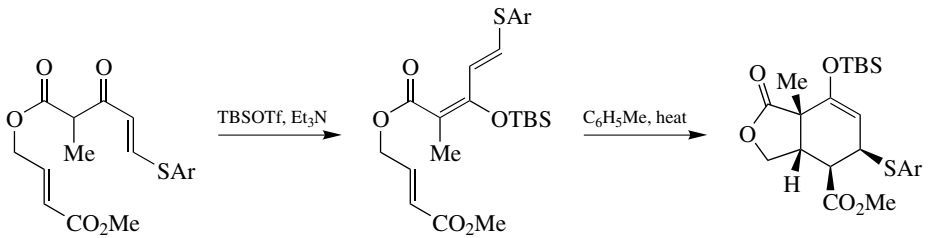
2 + 4-Cycloaddition

Activation energy has been estimated for the Diels–Alder reaction.[121] AM1 MO calculations of the thermal Diels–Alder reactions of cyclohexadiene with CH_2=CHR (R = Me, CN, CHO) indicate that these reactions may occur through a concerted pathway and also two radical pathways.[122,123] The Diels–Alder reactions between cyclopentadiene and conformationally flexible dienophiles have been studied by the PMO method.[124] A density functional study of the Diels–Alder reactions of cyclopentadiene with ethylene, acrylonitrile, and acrylaldehyde has been published.[125] *Ab initio* MO calculations on the Diels–Alder reaction between 2-phenylcyclopentadiene and α-(methylthio)acrylonitrile correctly describe the observed *endo*/*exo* stereoselectivity and the *para*/*meta* regioselectivity observed experimentally.[126] Conformational and *endo*/*exo* preferences of acrylates in Diels–Alder reactions have been investigated at several *ab initio* levels.[127] Semiempirical PM3 methods have been used to investigate the Diels–Alder reaction between methyl propenoate and thebaine and its analogues.[128] The Diels–Alder additions of hexachlorocyclopentadiene with chiral alkenes show excellent *anti* selectivity that follows the 'inside-alkoxy' model.[129] The dibromoboryl group is a powerful neutral activity group for the Diels–Alder reaction of cyclopentenyl and cyclohexenyl dienophiles at room temperature.[130] The diene moiety of 5-bromopyrone reacts with unactivated or poorly activated alkenes to yield cycloadducts with high regio- and stereo-selectivity.[131]

Diels–Alder reactions in aqueous solutions have been reviewed.[132] The stereoselectivities and rates of Diels–Alder reactions in different solvents have been correlated with a solvent parameter, defined on the basis of internal pressure and polarity of the reaction medium.[133] An investigation of the solvent effects on Diels–Alder reactions indicates that hydrogen bonding is a major factor in aqueous accelerations.[134] Monte Carlo simulations have been performed to investigate further the hydrophobic and hydrogen-bonding effects on Diels–Alder reactions in aqueous solution.[135] The retro-Diels–Alder reaction between cyclopentadiene and nitrosobenzene can be retarded by using water as solvent.[136] Semiempirical methods using SCRF approach and a combined quantum (transition state) and molecular mechanics (solvent molecules) method (QC/MM) have been used to investigate the *endo*/*exo* selectivity of Diels–Alder reactions in water and methanol.[137] $Cu(NO_3)_2$ in water catalyses the Diels–Alder reaction of 3-phenyl-1-(2-pyridyl)prop-2-en-1-ones with cyclopentadiene by a factor of 79 300 relative to the non-catalysed reaction in CH_3CN.[138] The Diels–Alder reactions of cyclopentadiene with acrylonitrile and diethyl fumarate have been performed in supercritical water.[139] An investigation of solvent effects on Diels–Alder reactions of acrylonitrile in fluorinated alcohol–water mixtures showed that reaction rate depends on solvophobic, hydrogen-bond-donating, and dipolarity interactions, while *endo*/*exo* selectivity is influenced by solvophobic and dipolarity interactions.[140] By changing the reaction solvent from CH_2Cl_2 to THF, it is possible to reverse the enantiofacial selectivity of the Diels–Alder reactions of 3-crotonyl-2-oxazolidinone

with cyclopentadiene catalysed by an aluminium complex of a chiral menthol derivative.[141] In carbo- and hetero-Diels–Alder reactions, the use of CH_3NO_2 as the solvent enhances the reactivity of $Cu(OTf)_2$-bisdihydrooxazole catalyst compared with the reactivity of CuX_2–bisdihydrooxazole in CH_2Cl_2.[142] The rate of 4 + 2-cycloadditions of furan with methyl acrylate in solid C_6H_6 was found to fluctuate rapidly with time.[143] The regiochemical course of the Diels–Alder reaction has been examined in supercritical CO_2. The previously reported reversal of the normal regiochemical course of the reaction was not confirmed.[144] The π-facial selectivity of the Lewis acid-catalysed 4 + 2-cycloaddition of 2,4-diphenyl-1-thiabuta-1,3-diene with (*S*)-*N*-acryloyl-4-benzyl-1,3-oxazolidin-2-one can be controlled by solvents or additives without altering the auxiliary chirality for the asymmetric induction.[145]

cis-Hydroisobenzofuranone (**91**), a potential precursor of the taxol C-ring, can be prepared by the intramolecular Diels–Alder reaction of triene (**90**) (Scheme 31).[146] The unactivated intramolecular Diels–Alder reaction of trienes, (**92**) and (**93**), will lead to the *trans*- and *cis*-cycloadducts, respectively, through a choice of the proper substituents (Scheme 32).[147] The thermal conversion of nona-1,3,8-triene to indan and indene by flash thermal pyrolysis involves an intramolecular 2 + 4-cyclo-aromatization to a benzyne intermediate.[148] Experimental activation parameters for the intramolecular Diels–Alder reactions of nona-1,3,8-triene, deca-1,3,9-triene, and undeca-1,3,10-triene were measured and their stereoselectivities were predicted using the Monte Carlo jumping between wells/molecular dynamics method.[149] The key step in the asymmetric synthesis of the marine toxin (−)-isopulo'upone (**96**) is the intramolecular Diels–Alder reaction of the trienimide (**94**), in the presence of a chiral cationic Cu(II) bis(oxazoline) complex, to produce the bicyclic cycloadduct (**95**) with high diastereo- and enantioselectivity (Scheme 33).[150] The reaction of 2-(methylthio)acylonitrile with cyclooctatetraene provides a further example of an all-carbon Diels–Alder cycloaddition to COT.[151]

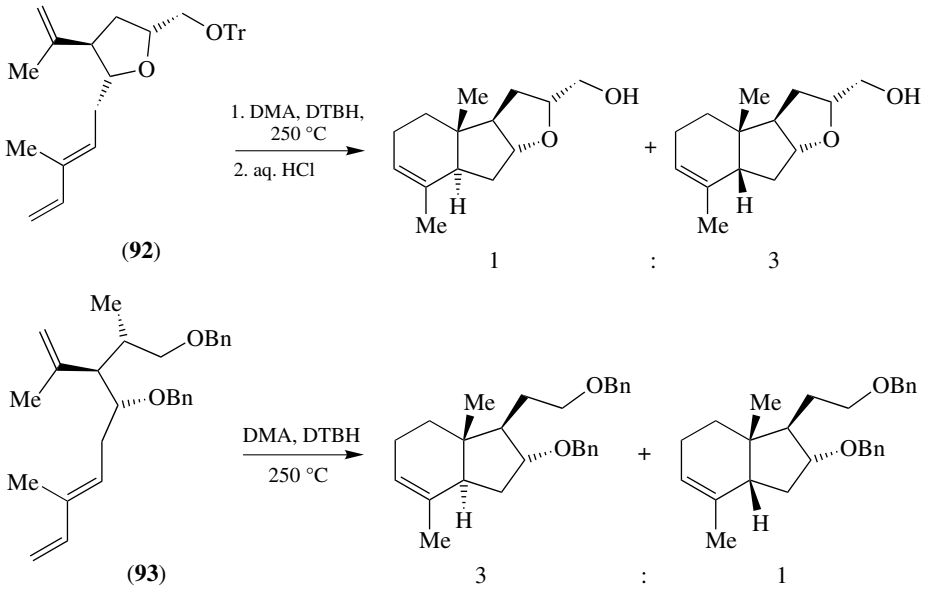


(**90**) 46% (**91**) >95% *cis*

SCHEME 31

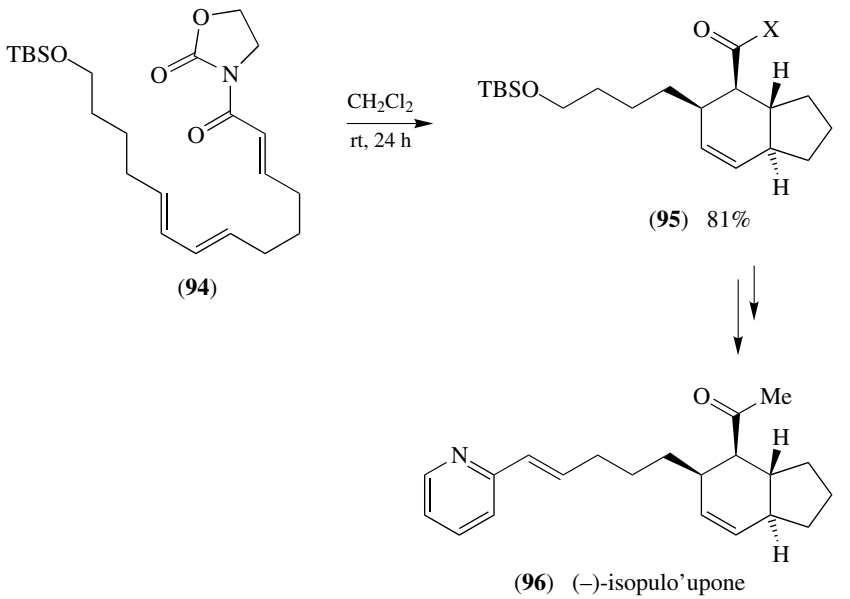
Acenaphthylene, indene, and styrene undergo periselective 4 + 2-cycloaddition with 3-ethoxycarbonyl-2*H*-cyclohepta[*b*]furan-2-one in high yield.[152]

Ab initio and DFT calculations of the Diels–Alder reactions of vinylallene and diallene with dipolarophiles show that these reactions are concerted processes and that cumulated dienes are less reactive than non-cumulated dienes.[153] Electron-rich

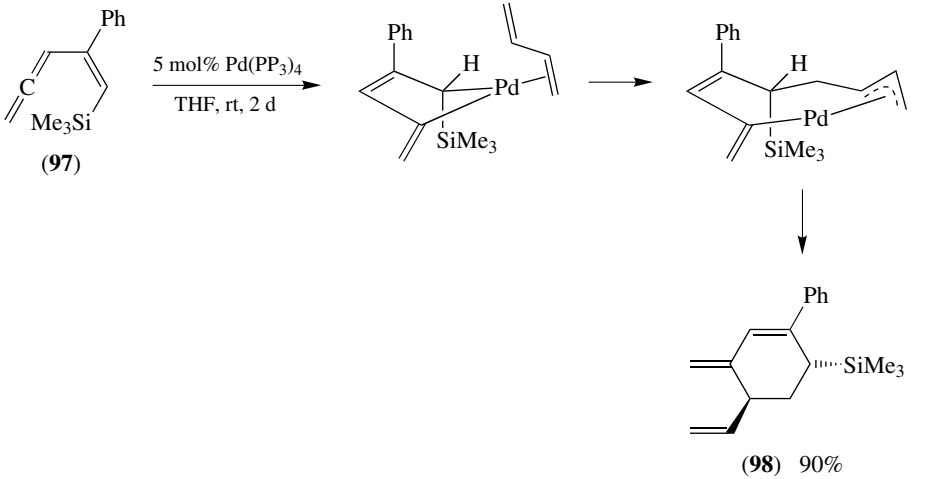


SCHEME 32

arylallenes react with 1,2,3,4,5-pentamethylcyclopentadiene to yield Diels–Alder products via a cation radical-catalysed cycloaddition.[154] The palladium(0)-catalysed intermolecular 4 + 2-cycloaddition of unactivated dienes with vinylallenes (**97**) readily produces substituted cyclohexenes (**98**) in high yields (Scheme 34).[155]



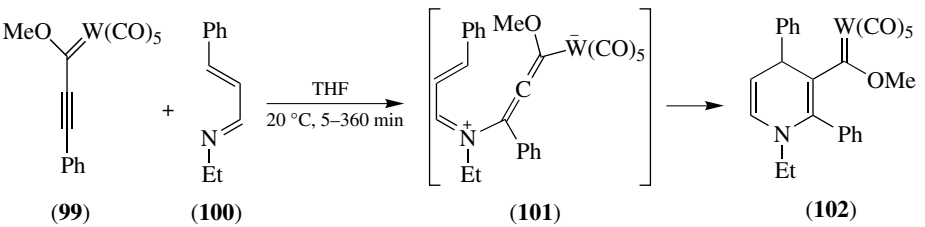
SCHEME 33



SCHEME 34

An AM1 semiempirical method was used to investigate the Diels–Alder cycloaddition reactions of vinyl sulfenes with buta-1,3-dienes.[156] The reactivity and stereoselectivity of vinyl boranes have been reviewed.[157] Aromatic methyleneamines undergo reverse-electron-demand Diels–Alder reactions with cyclopentadiene, norbornene, and vinyl sulfides.[158]

Tungsten Fischer alkynyl carbene complexes (**99**) react with neutral 1-azadienes (**100**) to produce regioselectively substituted 1,4-dihydropyridines (**102**) in high yields. An initial Michael addition yields an allenic intermediate (**101**) (Scheme 35).[159] Alkynyldihydroboranes undergo Diels–Alder reaction with isoprene in hexanes to produce the corresponding hexa-1,4-dienes in high yield and high regioselectivity.[160] Substituent effects on the Fe^+-mediated 4 + 2-cycloadditions of dienes with alkynes have been examined by four-section ion-beam and ion cyclotron resonance mass spectrometry.[161] The Diels–Alder addition of β-functionalized alkynyliodonium salts to unsymmetrical diones proceeds with excellent regioselectivity to produce substituted cyclohexadiene iodonium compounds.[162]

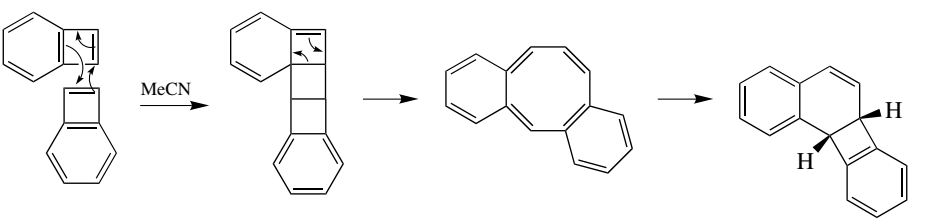


SCHEME 35

AM1 semiempirical calculations show that, in the gas phase, the reactivity of C_{70} fullerene with butadiene is only slightly greater than that of C_{60}. However, in toluene,

the reactivity of C_{60} is much greater than that of C_{70} with butadiene.[163] The Diels–Alder reaction of 4-hydroxytropones with fullerene (C_{60}) under pressure (300 MPa) yields two bicyclo[3.2.2]non-3-ene-2,6-dione adducts.[164] *o*-Quinodimethanes derived from sultines undergo 4 + 2-cycloaddition with C_{60} to yield cycloadduct which can be oxidized to the corresponding *p*-benzoquinone-containing fullerenes.[165]

A variety of quantum chemical procedures for assessing Diels–Alder reactions of butadiene with C_2H_4, HCHO, and HCHS have been investigated.[166] A density functional theory study of the Diels–Alder reaction of cyclopropene with butadiene supports the hypothesis that transition state structures are stabilized through interactions between the hydrogen of cyclopropene and the π-bond of butadiene.[167,168] An *ab initio* MO study of the cycloaddition of perfluorobuta-1,3-diene to perfluorobutene confirms the experimentally observed reversal of relative stabilities on perfluorination of buta-1,3-diene and cyclobutene.[169] The dimerization of benzocyclobutadiene was investigated by flow NMR spectroscopy and the results indicate an initial formation of a 4 + 2-dimer (**103**) which rearranges to the isolated dimer (**105**) via a dibenzo[*a*,*d*]-cyclooctatetraene (**104**) (Scheme 36).[170] Investigations of the aminium salt-catalysed Diels–Alder reactions of 2,2-dimethylbuta-1,3-diene with β-methylstyrenes indicated rate-determining one-electron oxidation of the styrenes to their cation radicals via an outer-sphere electron transfer.[171] *Ab initio* G2MS and IMDMO(G2MS : MP2) methods have been used to calculate the activation barriers of Diels–Alder reactions of acetylene with butadiene and cyclopentadiene.[172] AM1 calculations were used to determine the role of secondary orbital interactions in the regioselectivity of the catalysed and non-catalysed Diels–Alder reactions of juglone with aliphatic dienes.[173] The Diels–Alder reaction of 1-(2-butadienyl)pyridinium bromide with cyclopentadiene proceeds stereospecifically and regioselectively.[174]



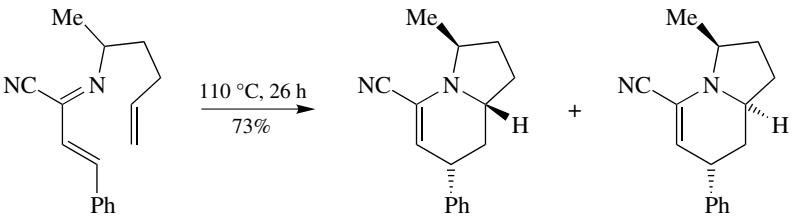
(**103**) (**104**) (**105**)

SCHEME 36

Density functional theory computational studies have been used to determine the importance of secondary orbital interactions for the stability of transition-state structures for the 4 + 2-cycloaddition of furan with cyclopropene.[175] Kinetic studies of the 2 + 4-cycloaddition of 2-cyclopropylidene acetates with furan and dimethylfulvene suggest a mechanism involving diradicals or zwitterions as intermediates.[176] Cyclopropene, produced by the reaction of allyl chloride with sodium bis(trimethylsilyl)amide, reacts with 1,3-diphenylisobenzofuran to produce both *endo*- and *exo*-Diels–Alder cycloadducts isolated for the first time.[177]

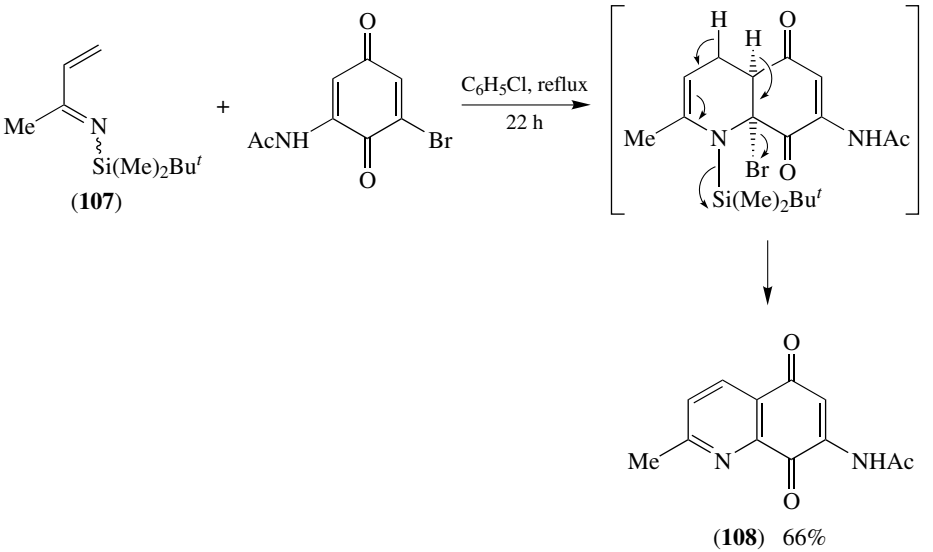
Ab initio calculations at the MP2(FC)/6–31G*//RHF/6–31G* level show that the chelotropic reactions of 1,3-dienes with SO_2 cannot be two-step as recently reported.[178] On investigation, the Diels–Alder reactions of 1-(phenylthio)-4-alkoxy-1,3-dienes have been shown to produce exclusively the *endo* adducts. The regio competition between sulfur and oxygen favours the oxygen substituent.[179] Molecular mechanics calculations have been used to quantify the geometric and strain effects controlling homo-Diels–Alder reactivity of 1,3-dienes.[180] Unexpectedly, the 4 + 2-cycloaddition of nitroalkenes with Danishefsky's diene exhibits *exo* selectivity as a result of electrostatic repulsion between the nitro group and the silyloxy group on the diene.[181] A biradical mechanism has been shown to operate in the Diels–Alder reaction of 5-methylene-2(5*H*)-furanones with 1,3-dienes.[182] The geometry of dienes obtained from 2,3-disubstituted sulfolenes bearing a 3-carbonyl derivative is dependent on the nature of the 3-carboxy group and on the functionality of the 2-substituent.[183]

Ab initio and density functional theoretical studies of the 4 + 2-cycloaddition of 2-azabutadiene with formaldehyde predict a concerted reaction that agrees well with experimental evidence.[184] The azadiene *N*-phenyl-1-aza-2-cyanobuta-1,3-diene reacts with electron-rich, electron-poor, and neutral dipolarophiles under mild thermal conditions.[185] 5,6-Dihydro-4*H*-1,2-oxazines have been shown to be useful as synthon equivalents of 2-cyano-1-azabuta-1,3-dienes.[186] The intramolecular Diels–Alder reaction of 1-aza-1,3-butadienes (**106**) can be activated by a 2-cyano substituent (Scheme 37).[187] Stereoselectivity in the hetero-Diels–Alder reactions of heterobutadienes, nitrosoalkenes, and heterodienophiles has been extensively reviewed.[188] The azadiene 1-(*t*-butyldimethylsilyloxy)-1-azabuta-1,3-diene (**107**) reacts with halobenzoquinones, naphthoquinones, and *N*-phenylmaleimide to yield low to good yields of various pyridine heterocycles (**108**) (Scheme 38).[189] The 4 + 2-cycloaddition of homophthalic anhydride with *N*-(cinnamylidene)tritylamine produces the 3,4-adduct whereas with *N*-(cinnamylidene)benzylidine the 1,2-adduct is produced.[190]



SCHEME 37

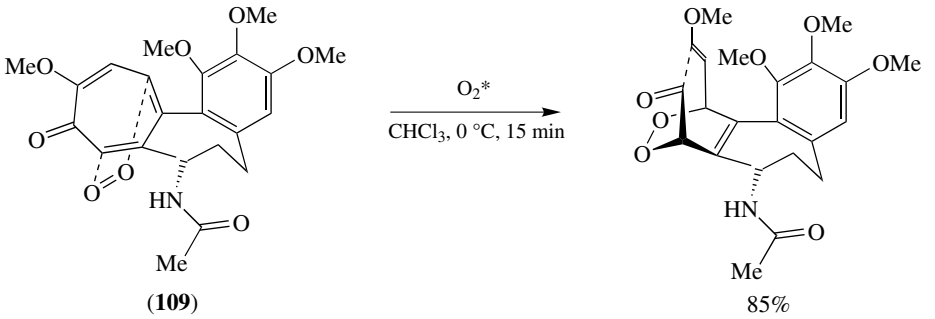
In hetero-Diels–Alder reactions, the effect of ligand structure and acidity on the catalytic activity of lanthanide catalysts has been reviewed.[191] The effect of different C(2)-symmetric bisoxazolines on the zinc(II)-catalysed hetero-Diels–Alder reaction of ethyl glyoxylate with conjugated 1,3-dienes has been investigated.[192] The hetero-Diels–Alder reaction 4-dimethylamino-2-phenyl-1-thiabuta-1,3-diene with methyl acrylate and *N*-enoyloxazolidinone produces *cis*-3,4-disubstituted 3,4-dihydro-2*H*-



SCHEME 38

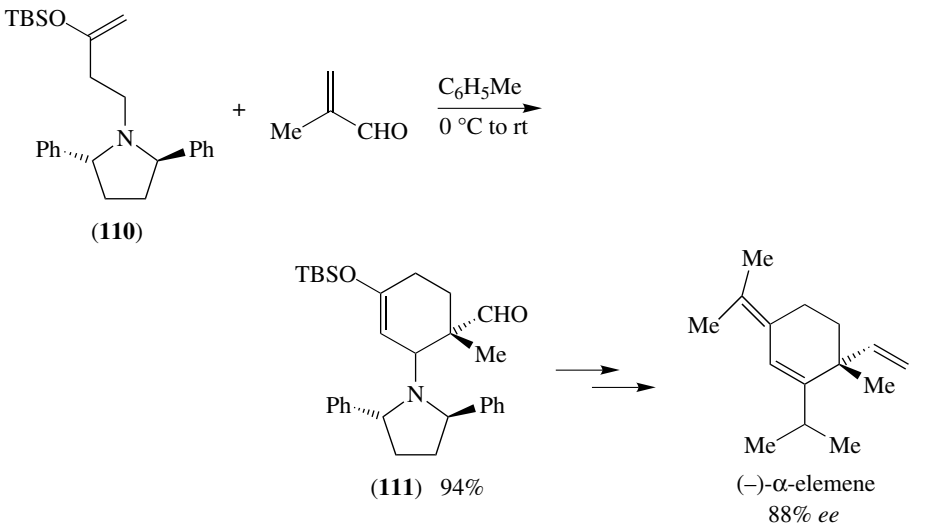
thiopyrans.[193] The use of hetero-Diels–Alder reactions of *N*-arylimines and *N*-benzylimines in the synthesis of nitrogen heterocycles has been reviewed.[194] Hetero-Diels–Alder addition of DMAD to α-thioxothioamides produces unstable 1,4-dithianes that extrude sulfur to yield substituted thiophenes.[195] The hetero-Diels–Alder reaction of *trans*-1-methoxy-3-(trimethylsilyloxy)buta-1,3-diene with aliphatic and aromatic ketones in the presence of chiral Cu(II) complexes of bidentate bisoxazoline yields cycloadducts with enantiometric excess up to 99%.[196] The asymmetric hetero-Diels–Alder reaction of a thiabutadiene with acrylamides in the presence of chiral $Cu(OTf)_2$–bis(benzylideneamino)cyclohexane complex is highly enantioselective.[197] The Diels–Alder reaction of thiobenzophenone and its 4, 4′-dichloro derivative with DMAD furnishes 1*H*-2-benzothiopyrans.[198] Monoclonal antibodies have been shown to catalyse the hetero-Diels–Alder addition of *cis*-piperylene to nitroso dienophiles.[199] A semiempirical AM1 method has been used to investigate the hetero-Diels–Alder dimerization of methyl 4,6-*O*-benzylidine-3-deoxy-3-*C*-methylene-α-D-hexopyranoside-2-ulose.[200] AM1 semiempirical calculations have been used to investigate the reactivity of 4 + 2-cycloaddition of silylketenes with acyl isocyanates followed by hetero-Diels–Alder reaction with acetylene derivatives.[201] Tetraethoxyethylene reacts with *C*-acylimines to produce only 4 + 2-cycloadducts.[202] The Diels–Alder reactions of 7-(methoxyimino)-4-methylchromene-2,8-dione with electron-rich dienophiles yields oxazines with high regio- and site selectivity.[203] The retro-Diels–Alder dissociation of cyclopentadiene–acyl nitroso compound cycloadducts provide a good source of nitroxyl.[204]

An extensive review of recent advances in the area of asymmetric Diels–Alder reactions has been published.[205] Sterically constrained tricyclic 2-oxazolidinones serve as excellent chiral auxiliaries for asymmetric Diels–Alder reactions.[206] The Diels–Alder reactions of (−)-(a*S*, 7*S*)-colchicine (**109**) with hetero- and carbo-dienophiles show



SCHEME 39

high positional selectivity at the 8,12-positions of the alkaloid and high π-facial diastereoselectivity (Scheme 39).[207] Electrostatic and steric interactions are considered to control the π-facial diastereoselectivity of the Diels–Alder reactions between anthraceno[3.3.3]*ortho*-benzophane and -naphthophane with dienophiles.[208] The π-facial reactivity of hetero-Diels–Alder reaction 2-(2′, 3′, 4′, 6′-tetra-*O*-acetyl-*β*-D-glucopyranosyloxy)buta-1,3-diene in the presence of lanthanide–$(fod)_3$ complexes can be correlated with the ionic radius of the lanthanide metal.[209] In the reaction of chiral 1,3-dienes with maleic anhydride, π-facial selectivity is increased when the homoallylic hydroxyl group is substituted with larger protecting groups.[210] An investigation of the Diels–Alder reactions of cyclopenta-1,3-dienes substituted at C(5) by simple alkyl groups has shown that the facial selectivity can be explained by steric hindrance.[211,212] The asymmetric Diels–Alder reaction of chiral 1-amino-3-siloxybuta-1,3-diene (**110**) with a variety of dienophiles proceeds with excellent facial selectivity to yield substituted cyclohexenones (**111**) with high enantiomeric excess (Scheme 40).[213]

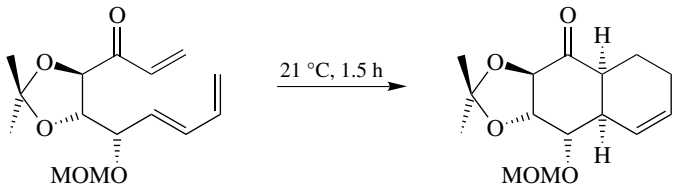


SCHEME 40

The Diels–Alder reaction between cyclopentadiene and acryloyloxazolidinone is enantioselectively catalysed by the bis(oxazoline)–magnesium perchlorate complex.[214]

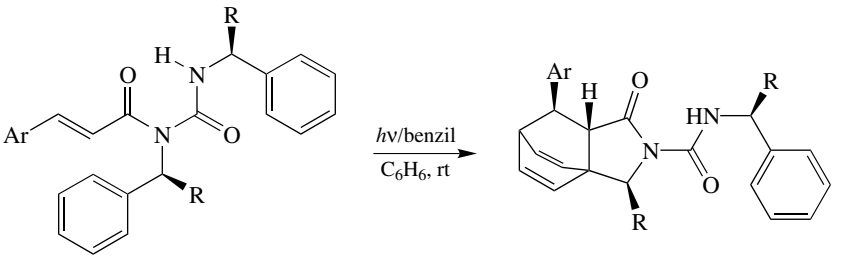
Ab initio calculations of the ionic Diels–Alder reactions of triazoloisoquinolinium and tetramethoxycarbonylquinolizinium ions with electron-rich dienophiles have been reported.[215] The $2^+ + 4$-cycloadditions of arenediazonium ions with (*E*)-penta-1,3-diene, 2,3-dimethylbutadiene, and (*E*)-2-methylpenta-1,3-diene produce dihydropyridazines and pyridazinium salts.[216] The similarity approach has been applied to predict successfully the preferred regiochemistry of various types of pericyclic reaction including polar and semi-polar Diels–Alder and $2 + 2$-cycloadditions.[217]

The use of isopropylidine acetals (**112**) as tethers in the intramolecular Diels–Alder reactions of dienes with alkenes facilitates the formation of *cis*-fused cycloadducts (**113**) from an *endo* transition state (Scheme 41).[218] The intramolecular Diels–Alder reaction of 4-[tris-(2-methylethyl)silyl]oxy-2*H*-thiopyran derivatives with potential dienophiles tethered at C(2), C(3), C(5), and C(6) positions yielded cycloadducts when the dienophiles were activated with a carbomethoxy group.[219] By the substitution of a phenylsulfonyl group on the dienophile of 2-benzopyran-3-ones, it is possible to enhance *exo* addition during intramolecular Diels–Alder cyclizations to yield a predominance of *trans*-fused hexaphenanthrenes related to natural products.[220] The intramolecular Diels–Alder reaction of 2-furfuryl fumarates has been investigated by molecular mechanics (SIBFA)/continuum reaction field computations.[221] The intramolecular $4 + 2$-photo-cycloaddition of *N*-benzylcinnamamides (**114**) in the presence of C_6H_6 gives 3-azatricyclo[5.2.2.0^{1,5}]undeca-8,10-dien-4-ones (**115**) with high stereoselectivity (Scheme 42).[222]



(**112**) (**113**) 79%

SCHEME 41



(**114**) (**115**)

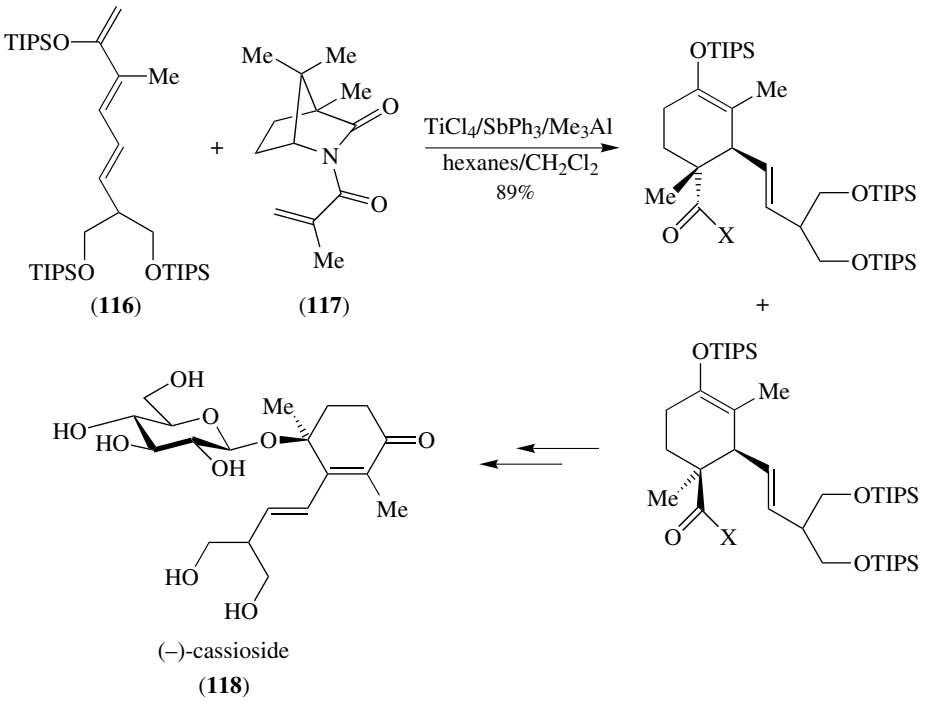
R = H, Me Ar = 4-XC_6H_4

SCHEME 42

cis-2-Amino-3,3-dimethyl-1-indanol is a highly efficient chiral auxiliary in the Diels–Alder addition of *N*-acryloyloxazolidinones to dienes in the presence of Lewis acids.[223] The chiral boron Lewis acid catalysts CAB1, BLA2, and BLA3 catalyse the Diels–Alder addition of cyclopentadiene with acetylenic aldehydes with good enantioselectivity.[224] The formyl C−H···O hydrogen bond has been proposed as the key to transition-state organization in enantioselective Diels–Alder reactions catalysed by chiral Lewis acids.[225] The Lewis acid-catalysed Diels–Alder cycloaddition of *exo*-2-oxazolidinone dienes with methyl vinyl ketone and methyl propiolate proceeds with high regio- and stereo-selectivity.[226] For the first time, the Lewis acid-catalysed Diels–Alder addition of activated cyclooctenes to various 1,3-dienes has been observed.[227] The first enantioselective Diels–Alder reactions of cyclopentadiene with α, β-acetylenic aldehydes catalysed by a chiral super Lewis acid has been described.[228] Scandium(III) perfluorooctanesulfonate is a Lewis acid catalyst for intramolecular Diels–Alder reactions of aldehydes with non-activated dienes under mild conditions.[229] Lewis acid-catalysed Diels–Alder reactions of (*Z*)-1,3-dienes with a variety of α-substituted acrolein have been shown to proceed with excellent regio- and high *endo* selectivity.[230] The tin(IV) chloride-catalysed hetero-Diels–Alder reaction of methyl 2-oxo-4-phenylbut-3-enoate with styrene produces dihydropyrans via an ionic stepwise mechanism.[231] The Lewis-acid catalysed 4 + 2-cycloaddition of chiral α-silyloxyaldimines with 2-silyloxybuta-1,3-dienes yielded only two 2,6-*trans*-isomeric adducts which were transformed into *trans*-2,6-disubstituted-4-piperidones.[232] The asymmetric Diels–Alder reaction of TIPS-protected trienolsilyl ethers (**116**) with chiral dienophile (**117**) catalysed by $TiCl_4$–$SbPH_3$ coupled with glycosidation with *p*-methoxybenzyl (MPM)-protected carbohydrate sulfoxides is a key step in the synthesis of the antiulcerogenic terpene glycoside (−)-cassioside (**118**) (Scheme 43).[233]

The facially perturbed enantiopure (*S*,*S*)-2-(*p*-tolylsulfinyl)norborneno-*p*-benzoquinones (**119**), undergo asymmetric Diels–Alder additions with cyclopentadiene to yield the four possible adducts (**120**) and (**121**). The *endo-syn* cycloadducts (**121**) can be used in the synthesis of the cage compound garudane (**122**) (Scheme 44).[234] The antiaromatic compound 1,4-biphenylenequinone (**123**) has been synthesized and trapped by Diels–Alder reaction with cyclopentadiene (Scheme 45).[235] The 4 + 2-cycloadditions of 4-methylene-5-(bromomethylene)-4,5-dihydrothiazole with 2- and 3-bromonaphthaquinones are highly regiospecific.[236]

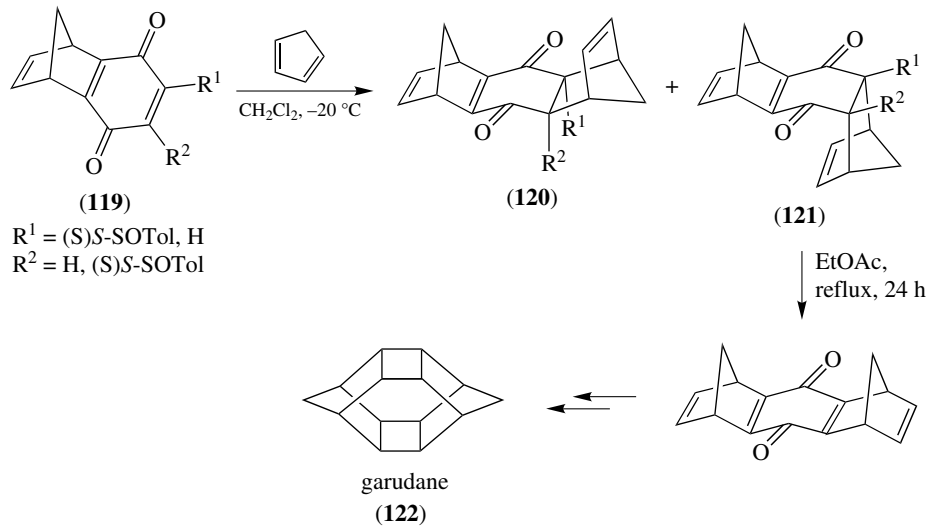
The Lewis acid-promoted tandem inter[4 + 2]/intra[3 + 2]-cycloaddition of the (fumaroyloxy)nitroalkene (**124**) with the chiral β-silylvinyl ether (**125**) is the key step in the total synthesis of (+)-crotanecine (**126**), the necine base of a number of pyrrolizidine alkaloids (Scheme 46).[237] The tandem inter[4 + 2]/intra[3 + 2]-cycloadditions of nitroalkenes (**127**) with dipolarophiles attached to the β-carbon of a vinyl ether (**128**) provides a method of asymmetric synthesis of highly functionalized aminocyclopentanes (**129**) (Scheme 47).[238] *trans*-2-(1-Methyl-phenylethyl)cyclohexanol has been developed as a new auxiliary in tandem 4 + 2/3 + 2-cycloadditions of nitroalkenes.[239] The scope and limitations of the bridged mode tandem inter-[4 + 2]/intra[3 + 2]-cycloadditions involving simple penta-1,4-dienes are described in detail.[240] A tandem intermolecular/intramolecular Diels–Alder cycloaddition was successfully used to synthesize a B/C *cis*-fused taxane nucleus (**130**) in 50% overall



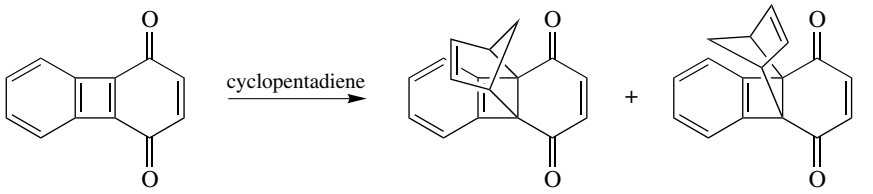
SCHEME 43

yield (Scheme 48).[241] Tandem cyclopropyl iminium ion/4 + 2-cycloaddition reactions provide a route to bicyclic and tricyclic heterocycles (Scheme 49).[242]

The Diels–Alder reaction of pyrrole-3-carboxylic esters with *N*-methyl- and *N*-phenyl-maleimides yield exclusively *endo* adducts.[243] The Diels–Alder reaction of

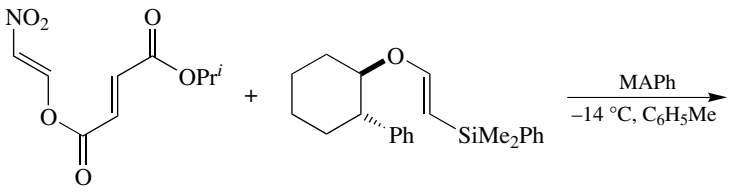


SCHEME 44

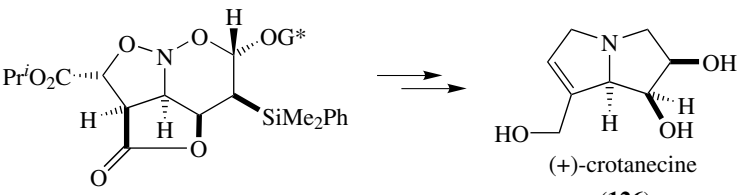


(**123**)

SCHEME 45



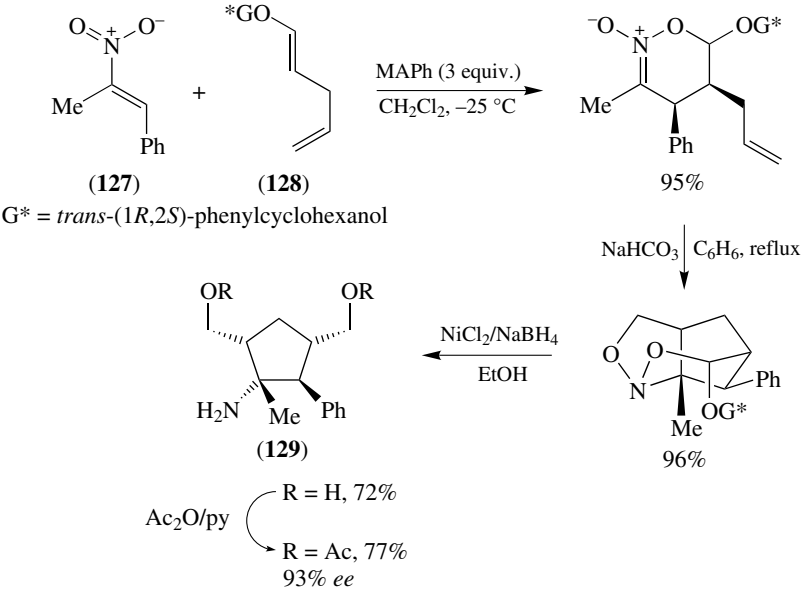
(**124**) (**125**)



(**126**)

SCHEME 46

cyclopentadiene with chiral cinnamoyl- and crotonyl-(2-*p*-tolylsulfinyl)pyrrole in the presence of $AlCl_3$ or $Yb(OTf)_3$ proceeds readily to yield the corresponding *endo* adducts with high diastereoselectivity.[244] Radical cation-initiated cycloaddition reactions between 2-vinylpyrrole and *β*-substituted enaminonitriles lead to different cycloadducts depending on the substituents.[245] The 4 + 2-cycloadditions of *N*-acylindole-2,3-quinodimethanes and substituted 3-vinylindoles (**131**) with bismaleimides (**132**) provide a new route to biscarbazoles (**133**) with potential as DNA minor groove binding ligands (Scheme 50).[246] An investigation of the second-order rate constants for the Diels–Alder addition of dimethyl fumarate to isobenzofuran, 5*H*-cycloprop[*f*]isobenzofuran, and substituted derivatives suggests that *π*-bond fixation (Mills–Nixon effect) does not control the reactivity of 5*H*-cycloprop[*f*]isobenzofuran.[247] A Pummerer reaction of an *o*-amido-substituted sulfoxide (**134**) produces a 2-amino-substituted isobenzofuran (**135**), which in the presence of an electron-deficient dienophile undergoes a Diels–Alder cycloaddition followed by a ring opening to produce vinylogous *C*-acyliminium ions (**136**), which readily aromatize (Scheme 51).[248]

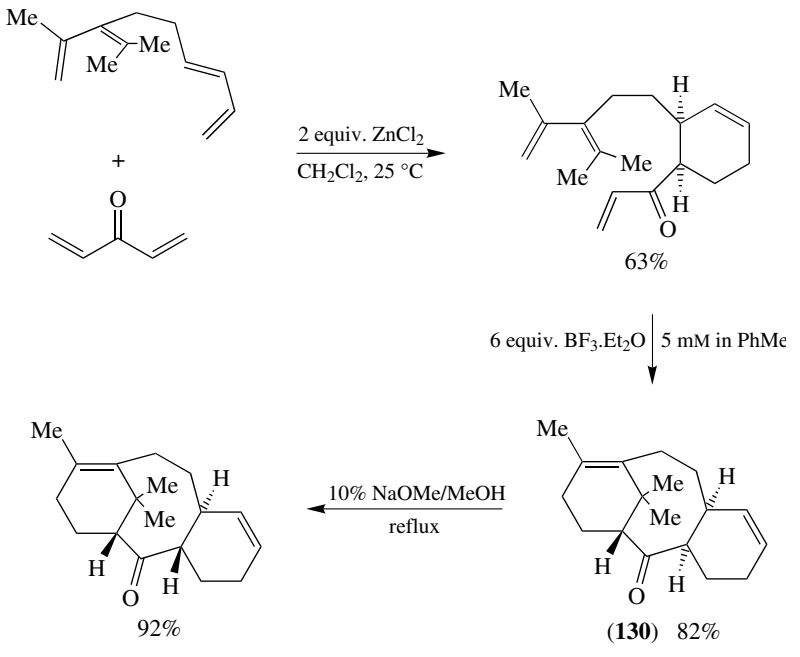


(**127**) (**128**)

G* = *trans*-(1*R*,2*S*)-phenylcyclohexanol

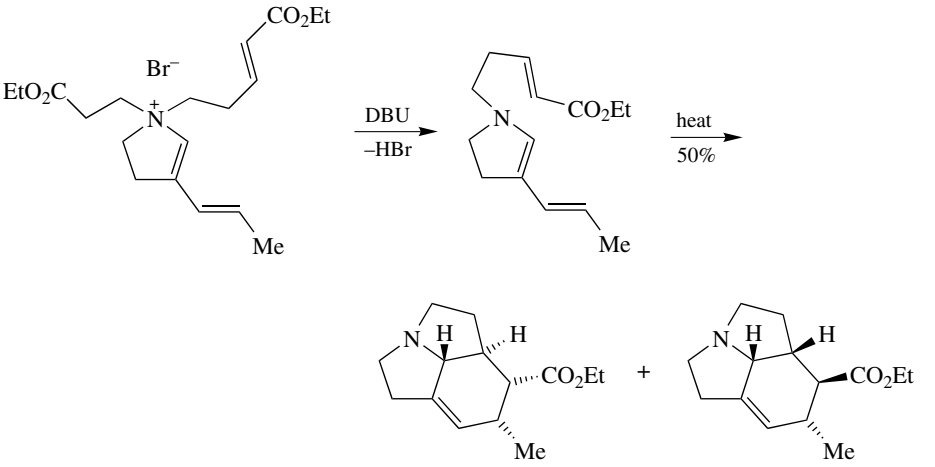
(**129**)

SCHEME 47

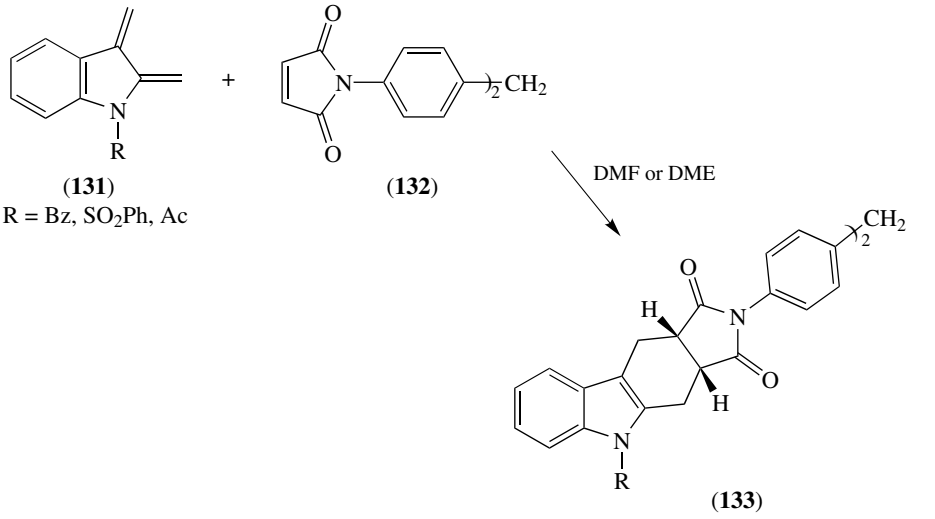


(**130**) 82%

SCHEME 48

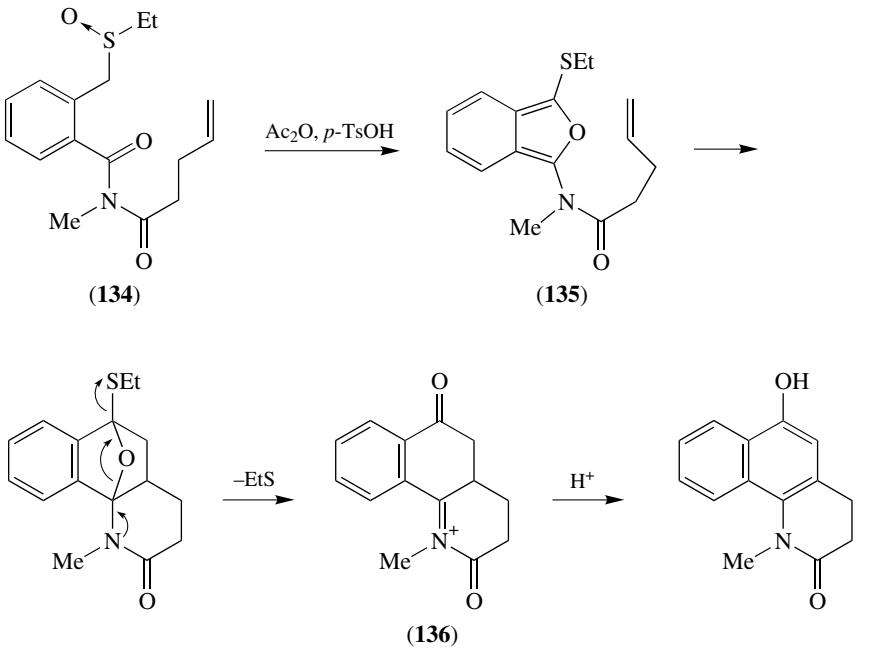


SCHEME 49



SCHEME 50

MO calculations at the MP4SDTP/6–311G**//MP2/6–311G** level on the Diels–Alder reaction of ethylene with 1-phosphabut-3-en-1-yne show that the reaction is endothermic compared with the all-carbon case, which is exothermic.[249] *Ab initio* studies have been presented for hetero-Diels–Alder reactions between phosphorus-containing dienes and dienophiles.[250] *Ab initio* calculations on the Diels–Alder reaction between 2*H*-phosphole and phosphaethene indicate that the reaction is concerted and synchronous.[251] The Diels–Alder reaction between 1,3,5-triphosphabenzene and phosphaacetylene to form tetraphosphabarrelene was studied at the MP4SDQ/6–

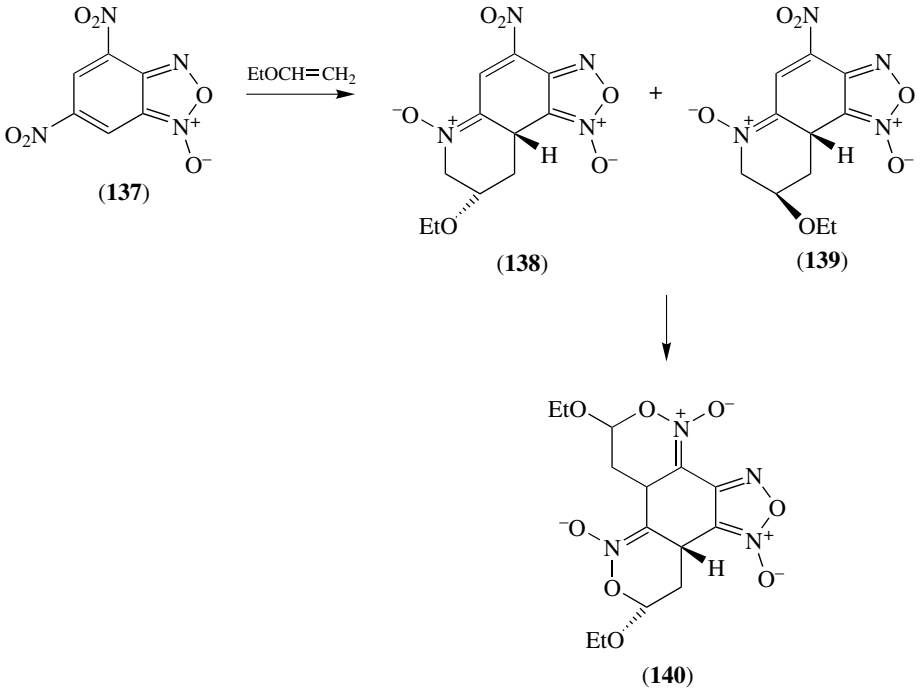


SCHEME 51

31G*/M2/6–31G* level.[252] Trialkyl 2-phosphonoacrylates undergo 4 + 2-cycloaddition with *N*-buta-1,3-dienylsuccinimide to produce the *ortho* adduct.[253]

The kinetics of high-pressure cycloaddition reactions of tropone with dienophiles and enophiles have been reviewed.[254] The Diels–Alder reaction of 9,10-dimethylanthracene with acrylonitrile has been investigated at high pressure in acetonitrile and in ethereal solutions of lithium perchlorate.[255] The combination of high pressure and a solution of lithium perchlorate in diethyl ether is an excellent reaction rate accelerator in 4 + 2-cycloaddition reactions.[256]

The presence or absence of the dioxolane protecting group in dienes dictates whether they participate in normal or inverse-electron-demand Diels–Alder reactions.[257] The intramolecular inverse-electron-demand Diels–Alder cycloaddition of 1,2,4-triazines tethered with imidazoles produce tetrahydro-1,5-naphthyridines following the loss of N_2 and CH_3CN.[258] The inverse-electron-demand Diels–Alder reaction of 4,6-dinitrobenzofuroxan (**137**) with ethyl vinyl ether yields two diastereoisomeric dihydrooxazine *N*-oxide adducts (**138**) and (**139**) together with a bis(dihydrooxazine *N*-oxide) product (**140**) in the presence of excess ethyl vinyl ether (Scheme 52).[259] The inverse-electron-demand Diels–Alder reaction of 2,4,6-tris(ethoxycarbonyl)-1,3,5-triazine with 5-aminopyrazoles provides a one-step synthesis of pyrazolo[3,4-d]pyrimidines.[260] The intermolecular inverse-electron-demand Diels–Alder reactions of trialkyl 1,2,4-triazine-4,5,6-tricarboxylates with protected 2-aminoimidazole produced 1*H*-imidazo[4,5-*c*]pyridines and the rearranged 3*H*-pyrido[3,2-*d*]pyrimidin-4-



SCHEME 52

ones.[261] The unsymmetrical 3-methoxy-6-methylthio-1,2,4,5-tetrazine reacts with neutral and electron-rich dienophiles to yield 4 + 2-cycloadducts.[262]

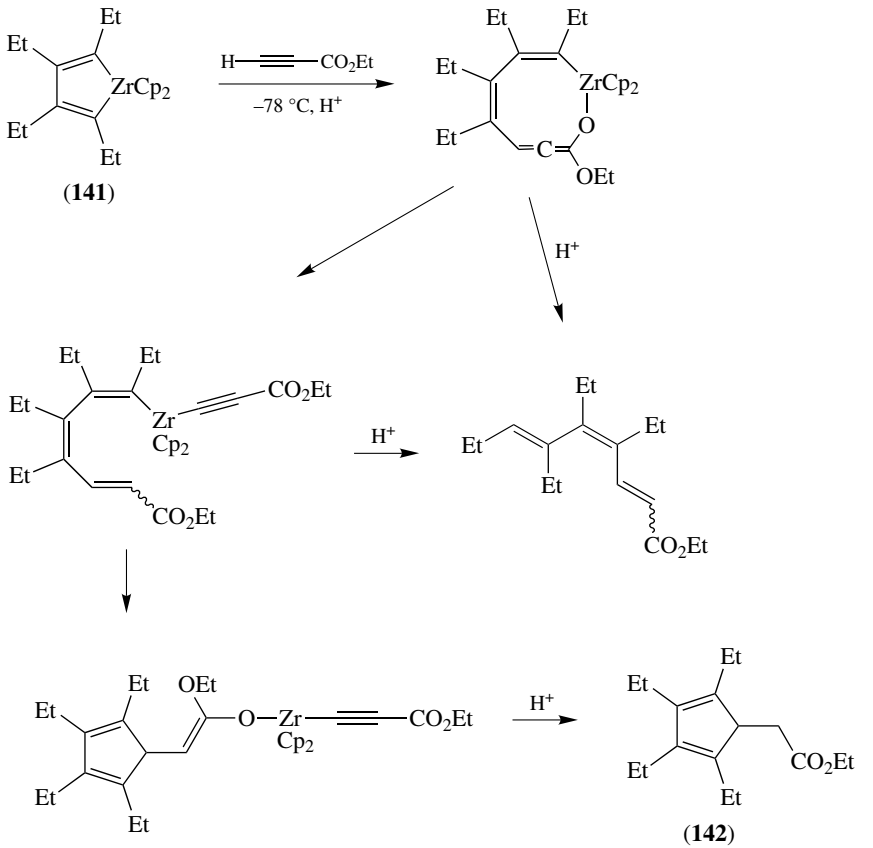
Tetradehydrodianthracene undergoes 4 + 2-cycloaddition with electron-deficient dienes such as 1,2,4,5-tetrazines.[263] The Diels–Alder reactions of [3.3]*ortho*-anthracenophanes with *N*-(*p*-nitro, chloro, or methoxy-substituted phenyl)maleimides yield approximately equal quantities of *inside* and *outside* adducts.[264] The photo-oxidation of bulky water-soluble 1,4-disubstituted naphthalenes with singlet oxygen yields both the expected 1,4- and the unexpected 5,8-endoperoxides.[265]

The reaction of aryl and methyl isothiocyanates with α-thioxothioamides produces 2,3-dihydro-2-thioxothiazole and 2-iminothiazole via 4 + 2- and 2 + 2-cycloadditions, respectively.[266] The Diels–Alder reaction of 2-(*p*-tolylthio)naphthazarin with 1-methoxycyclohexa-1,3-diene yields a tricyclic cycloadduct which, after oxidation to the corresponding *p*-tolylsulfinyl derivative, reacts with a second molecule of the diene to form tetracyclic tetrahydropolyhydroxyquinones.[267] *N*-Arylmonothiomaleimides readily undergo 4 + 2-cycloaddition at both the C=S and C=C groups with both electron-withdrawing and electron-donating groups.[268]

Miscellaneous Cycloadditions

Ab initio MO calculations have been used to determine the transition structures for the ene reactions of cyclopropene with ethylene, propene, and cyclopropene.[269]

Zinconacyclopentadienes (**141**), substituted with alkyl groups, undergo 1,1-cycloaddition with propynoates to yield cyclopentadienes (**142**) as outlined in Scheme 53.[270]

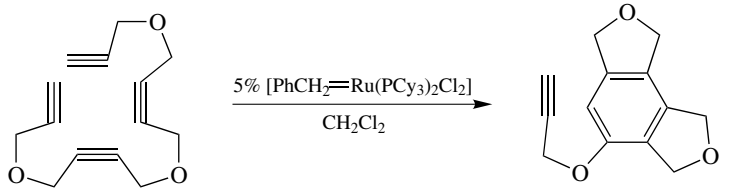


SCHEME 53

The $SnCl_4$-promoted 2 + 1-cycloaddition of 1-seleno-2-silylethene with 2-phosphonoacrylates yields highly functionalized cyclopropanephosphonic acid ester products.[271] The Lewis acid-promoted 2 + 1-cycloadditions of 1-(phenylseleno)-2-(trimethylsilyl)ethene with tris(alkoxycarbonyl)olefins yields *cis*-substituted cyclopropanes exclusively.[272]

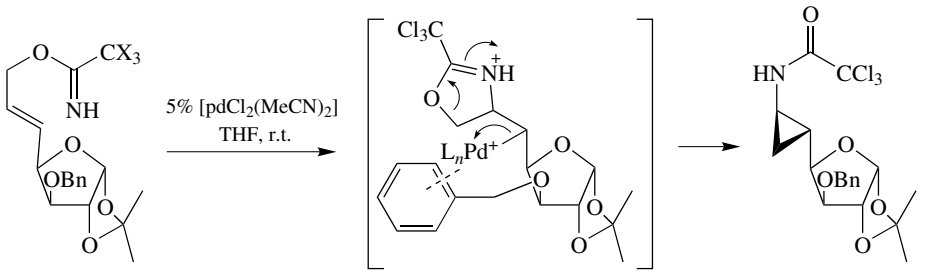
$PhCH_2{=}Ru(PCy_3)_2Cl_2$ catalyses the cyclooligomerization of trienes (**143**) to benzene derivatives (**144**) via a cascade of four metathesis reactions (Scheme 54).[273] Isocyanate cyclotrimerization catalysed by dimethylbenzylamine–phenyl glycidyl ether–phenol has been studied by IR and PMR spectroscopy.[274]

The attempted Pd(II)-catalysed aza-Claisen rearrangement of the trichloroacetimidate (**145**) yielded the diastereoisomerically pure cyclopropane derivative (**146**) (Scheme 55).[275]



(**143**) (**144**) 68%

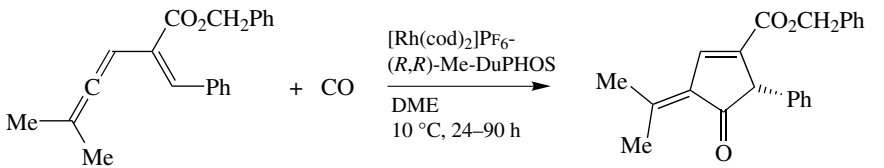
SCHEME 54



(**145**) (**146**) 58%

SCHEME 55

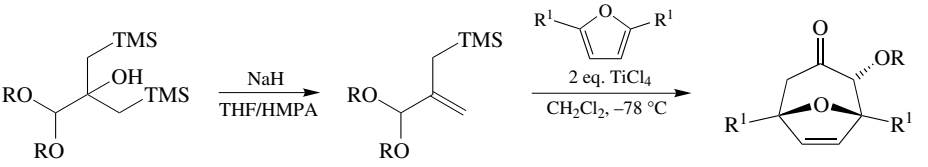
The rhodium-catalysed asymmetric 4 + 1-cycloaddition of vinylallenes (**147**) with CO furnishes 5-substituted 2-alkylidenecyclopent-3-enones (**148**) with up to 95% enantioselectivities (Scheme 56).[276]



(**147**) (**148**) 94%
95.0% *ee*

SCHEME 56

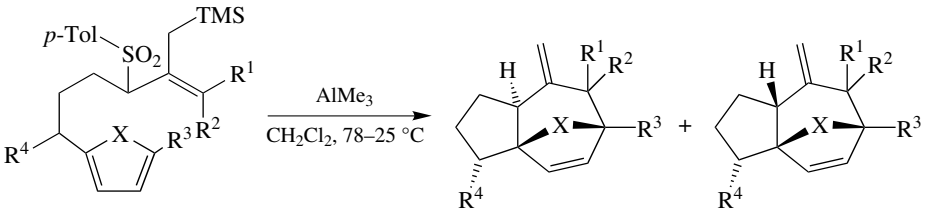
A review of intramolecular 4 + 3-cycloadditions of allyl cations has been presented.[277] The 4 + 3-cycloaddition reaction of C(2)-substituted furans with 1,3-dimethyloxyallyl cations show high *endo* diastereoselectivity and a *cis* diastereospecificity.[278] The tandem Peterson olefination/[4 + 3]-cycloaddition of tertiary alcohols (**149**) in the presence of furan and Lewis acids ($TiCl_4$) furnishes cycloheptanes (**150**) in modest yields (Scheme 57).[279] (Trimethylsilyl)methyl allylic sulfones (**151**) were used to investigate the scope and limitations of intramolecular 4 + 3-cycloadditions of allylic sulfones (Scheme 58).[280] Lewis acid-catalysed 4 + 3-



(**149**)

(**150**)
R = Et, Me, Pr^i
R^1 = Me, H

SCHEME 57



(**151**)
X = CH_2, O

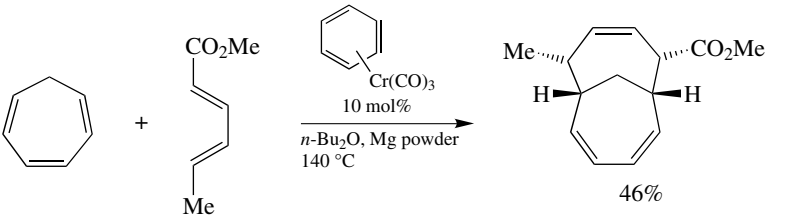
SCHEME 58

intermolecular cycloaddition of (trimethylsilyl)methyl allylic acetals with furan proceed with high diastereoselectivity.[281] Chiral α-chloroimines are efficient precursors of chiral 2-aminoallyl cations which undergo facial and *endo*-selective 4 + 3-cycloadditions with furan or pyrrole to produce iminium salts of chiral bicyclo[3.2.1]octanone.[282]

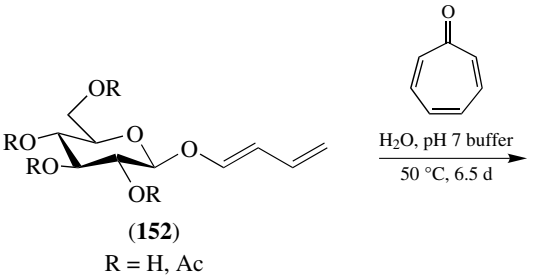
Conical intersections of the 4 + 4-photo-cycloaddition of butadiene with butadiene has been located at the CASSCF/4–31G level.[283] The intramolecular 4 + 4-photo-cycloaddition of two pyridones linked by a three-atom chain yields a nearly quantitative yield of head-to-head cycloadducts.[284] The photo-irradiation of 2-furan in the presence of 1-naphthalenecarbonitrile through a Pyrex filter produced both the major 4 + 4-cycloadduct and the minor 2 + 2-adduct.[285]

Trimethylsilyl triflate in 3.0 M lithium perchlorate–ethyl acetate is an effective promoter of 5 + 2-cycloaddition reactions between quinone monoacetal and 2,3-dimethylbut-2-ene.[286]

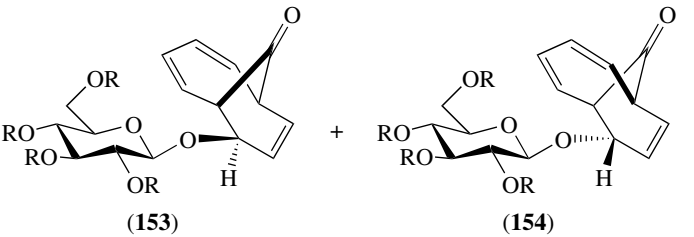
An extensive review of 6 + 4-cycloaddition reactions has been published.[287] The use of a 'precatalyst' in the chromium(0)-promoted 6 + 4-cycloaddition reaction of cyclohepta-1,3,5-triene with acyclic dienes ensures that only stoichiometric quantities of the metal are involved in the cycloaddition (Scheme 59).[288] The first example of an aqueous 6 + 4-cycloaddition of tropone with the water-soluble diene 1-(β-D-glucopyranosyloxy)buta-1,3-diene (**152**) yields 2-(glucopyranosyloxy)bicyclo-[4.4.1]undecanones (**153**) and (**154**) with *exo* selectivity (Scheme 60).[289] A new benzannulation sequence is based on chromium(0)-promoted 6π + 4π-photo-cycloaddition of (η^6-thiepin-1,1-dioxide)tricarbonylchromium(0) in the presence of a diene followed by a Ramberg–Bäcklund rearrangement of the cycloadduct.[290]



SCHEME 59



(**152**)
R = H, Ac

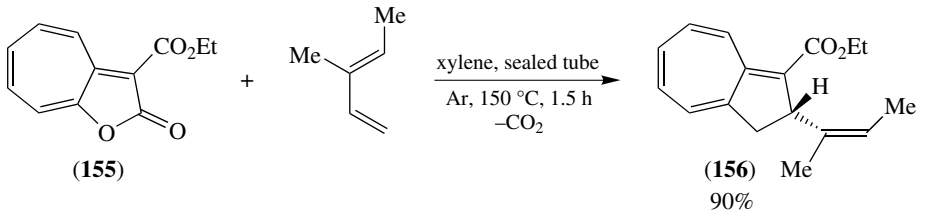


(**153**) (**154**)

54%

SCHEME 60

The 8 + 2-cycloaddition of 2*H*-cyclohepta[*b*]furan-2-one (**155**) with acyclic 1,3-dienes provides a facile route to bicyclo[5.3.0] ring systems (**156**) (Scheme 61).[291] 2*H*-Benzo[*b*]thiete in the *o*-quinoid form undergoes 8 + 2-cycloaddition with 1,3-dithiolane-2-thione, 1,3-dithiole-2-thiones, and adamantanethione to produce 4*H*-1,3-benzodithianes.[292]



(**155**) (**156**)
90%

SCHEME 61

References

[1] Dell, C. P., *Contemp. Org. Synth.*, **4**, 87 (1997); *Chem. Abs.*, **126**, 343131 (1997).
[2] Huang, P.-Q., *Huaxue*, **54**, 133 (1996); *Chem. Abs.*, **126**, 225118 (1997).
[3] Wiest, O. and Houk, K. N., *Top. Curr. Chem.*, **183**, 1 (1996); *Chem. Abs.*, **126**, 49491 (1997).
[4] Strout, D. L. and Scuseria, G. E., *J. Phys. Chem.*, **100**, 6492 (1996).
[5] Brook, A. G. and Brook, M. A., *Adv. Organomet. Chem.*, **39**, 71 (1996).
[6] Colomvakos, J. D., Egle, I., Ma, J., Pole, D. L., Tidwell, T. T., and Warkentin, J., *J. Org. Chem.*, **61**, 9522 (1996).
[7] Ohkata, K. and Akiba, K.-Y., *Adv. Heterocycl. Chem.*, **65**, 283 (1996); *Chem. Abs.*, **125**, 300697 (1996).
[8] Becker, D. and Cohen-Arazi, Y., *J. Am. Chem. Soc.*, **118**, 8278 (1996).
[9] Li, Y. and Houk K. N., *J. Am. Chem. Soc.*, **118**, 880 (1996).
[10] Schepp, N. P., Shukla, D., Sarker, H., Bauld, N. L., and Johnston, L. J., *J. Am. Chem. Soc.*, **119**, 10325 (1997).
[11] Haag, D. and Scharf, H.-D., *J. Org. Chem.*, **61**, 6127 (1996).
[12] Serelis, A. K. and Simpson, G. W., *Tetrahedron Lett.*, **38**, 4277 (1997).
[13] Memarian, H. R., Nasr-Esfahani, M., Boese, R., and Dopp, D., *Liebigs Ann./Recl.*, **1997**, 1023.
[14] Faure, S., Piva-Le Blanc, S., Piva, O., and Pete, J.-P., *Tetrahedron Lett.*, **38**, 1045 (1997).
[15] Zhang, X., Fan, A., and Foote, C. S., *J. Org. Chem.*, **61**, 5456 (1996).
[16] Vassilikogiannakis, G. and Orfanopoulos, M., *J. Am. Chem. Soc.*, **119**, 7394 (1997).
[17] Vassilikogiannakis, G. and Orfanopoulos, M., *Tetrahedron Lett.*, **38**, 4323 (1997).
[18] Jensen, A. W., Khong, A., Saunders, M., Wilson, S. R., and Schuster, D. I., *J. Am. Chem. Soc.*, **119**, 7303 (1997).
[19] Shephard, M. S. and Carreira, E. M., *J. Am. Chem. Soc.*, **119**, 2597 (1997).
[20] Murphy, W. S. and Neville, D., *Tetrahedron Lett.*, **38**, 7933 (1997).
[21] Elliott, R. L., Nicholson, N. H., Peaker, F. E., Takle, A. K., Richardson, C. M., Tyler, J. W., White, J., Pearson, M. J., Eggleston, D. S., and Haltiwanger, R. C., *J. Org. Chem.*, **62**, 4998 (1997).
[22] Fang, D.-C. and Fu, X.-Y., *THEOCHEM*, **365**, 219 (1996); *Chem. Abs.*, **125**, 220888 (1996).
[23] Chmielewski, M., Kaluza, Z., and Furman, B., *J. Chem. Soc., Chem. Commun.*, **1996**, 2689.
[24] Lim, D. and Jorgensen, W. L., *J. Phys. Chem.*, **100**, 17490 (1996).
[25] Tobe, Y., Sorori, T., Kobiro, K., Kakiuchi, K., and Odaira, Y., *J. Phys. Org. Chem.*, **9**, 1 (1996).
[26] Kiselev, V. D., Shtyrlin, Y. G., Murzin, D. G., and Konovalov, A. I., *Dokl. Akad. Nauk*, **345**, 64 (1995); *Chem. Abs.*, **127**, 65370 (1997).
[27] Breitkopf, V., Bubenitschek, P., Hopf, H., Jones, P. G., Klarner, F.-G., Schomburg, D., Witulski, B., and Zimny, B., *Liebigs Ann./Recl.*, **1997**, 127.
[28] Donati, D., Fusi, S., and Ponticelli, F., *J. Chem. Res. (S)*, **1997**, 34.
[29] Crimmins, M. T. and Choy, A. L., *J. Am. Chem. Soc.*, **119**, 10237 (1997).
[30] Barcza, M. V., de M. Carneiro, J. W., Serra, A. A., and Barboza, J. C. S., *THEOCHEM*, **394**, 281 (1997); *Chem. Abs.*, **127**, 149322 (1997).
[31] Liu, R. and Tidwell, T. T., *J. Chem. Soc., Perkin Trans. 2*, **1996**, 2757.
[32] Podlech, J. and Linder, M. R., *J. Org. Chem.*, **62**, 5873 (1997).
[33] Palomo, C., Aizpurua, J. M., Garcia, J. M., Galarza, R., Legido, M., Urchegui, R., Roman, P., Luque, A., Server-Carrio, J., and Linden, A., *J. Org. Chem.*, **62**, 2070 (1997).
[34] Palomo, C., Aizpurua, J. M., Mielgo, A., and Linden, A., *J. Org. Chem.*, **61**, 9186 (1996).
[35] Cagnon, J. R., Le Bideau, F., Marchand-Brynaert, J., and Ghosez, L., *Tetrahedron Lett.*, **38**, 2291 (1997).
[36] Pandolfo, L., Facchin, G., Bertani, R., Ganis, P., and Valle, G., *Angew. Chem., Int. Ed. Engl.*, **35**, 83 (1996).
[37] Pons, J.-M., Oblin, M., Pommier, A., Rajzmann, M., and Liotard, D., *J. Am. Chem. Soc.*, **119**, 3333 (1997).
[38] Fang, D.-C. and Fu, X.-Y., *Chem. Phys. Lett.*, **259**, 265 (1996); *Chem. Abs.*, **125**, 246929 (1996).
[39] Barbaro, G., Battaglia, A., Bruno, C., Giorgianni, P., and Guerrini, A., *J. Org. Chem.*, **61**, 8480 (1996).
[40] Alajarin, M., Molina, P., and Vidal, A., *Tetrahedron Lett.*, **37**, 8945 (1996).
[41] Horspool, W. M., *Photochemistry*, **27**, 80 (1996); *Chem. Abs.*, **126**, 88897 (1997).
[42] Murphy, W. S. and Neville, D., *Tetrahedron Lett.*, **37**, 9397 (1996).
[43] Suishu, T., Shimo, T., and Somekawa, K., *Tetrahedron*, **53**, 3545 (1997).
[44] Caldwell, R. A., Hrncir, D. C., Munoz, T., and Unett, D. J., *J. Am. Chem. Soc.*, **118**, 8741 (1996).
[45] Crimmins, M. T., King, B. W., Watson, P. S., and Guise, L. A., *Tetrahedron*, **53**, 8963 (1997).
[46] Suishu, T., Tsuru, S., Shimo, T., and Somekawa, K., *J. Heterocycl. Chem.*, **34**, 1005 (1997).

[47] Sengupta, D., Chandra, A. K., and Nguyen, M. T., *J. Org. Chem.*, **62**, 6404 (1997).
[48] Christl, M. and Braun, M., *Liebigs Ann./Recl.*, **1997**, 1135.
[49] Chung, W.-S. and Ho, C.-C., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 553.
[50] Pidun, U., Boehme, C., and Frenking, G., *Angew. Chem., Int. Ed. Engl.*, **35**, 2817 (1996).
[51] Nishizawa, M., Komatsu, Y., Garcia, D. M., Noguchi, Y., Imagawa, H., and Yamada, H., *Tetrahedron Lett.*, **38**, 1215 (1997).
[52] Sha, C.-K., *Adv. Nitrogen Heterocycl.*, **2**, 147 (1996); *Chem. Abs.*, **126**, 301274 (1997).
[53] Raimondi, L., *Gazz. Chim. Ital.*, **127**, 167 (1997); *Chem. Abs.*, **127**, 220588 (1997).
[54] Zheng, D., Li, Y., and Zhu, D., *Huaxue Tongbao*, **1996**, 10 (1996); *Chem. Abs.*, **126**, 89290 (1997).
[55] Isobe, H., Tokuyama, H., Sawamura, M., and Nakamura, E., *J. Org. Chem.*, **62**, 5034 (1997).
[56] Broggini, G. and Zecchi, G., *Gazz. Chim. Ital.*, **126**, 479 (1996); *Chem. Abs.*, **125**, 328532 (1997).
[57] Lautens, M. and Ren, Y., *J. Am. Chem. Soc.*, **118**, 9597 (1996).
[58] Zhu, G., Chen, Z., Jiang, Q., Xiao, D., Cao, P., and Zhang, X., *J. Am. Chem. Soc.*, **119**, 3836 (1997).
[59] Ham, S. and Birney, D. M., *Tetrahedron Lett.*, **38**, 5925 (1997).
[60] Mish, M. R., Guerra, F. M., and Carriera, E. M., *J. Am. Chem. Soc.*, **119**, 8379 (1997).
[61] Belaissaoui, A., Jacquot, S., Morpain, C., Schmitt, G., Vebrel, J., and Laude, B., *Can. J. Chem.*, **75**, 523 (1997).
[62] Gothelf, K. V. and Jorgensen, K. A., *Acta Chem. Scand.*, **50**, 652 (1996).
[63] Jensen, K. B., Gothelf, K. V., and Jorgensen, K. A., *Helv. Chim. Acta*, **80**, 2039 (1997).
[64] Bowman, W. R., Davies, R. V., Slawin, A. M. Z., Sohal, G. S., Titman, R. B., and Wilkins, D. J., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 155.
[65] Ishikawa, T., Tajima, Y., Fukui, M., and Saito, S., *Angew. Chem., Int. Ed. Engl.*, **35**, 1863 (1996).
[66] Baskaran, S. and Trivedi, G. K., *J. Chem. Res. (S)*, **1996**, 542.
[67] Tsuge, H., Okana, T., Eguchi, S., and Kimoto, H., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1581.
[68] Malamidou-Xenikaki, E., Stampelos, X. N., Charalambis, T. A., and Karapostolou, C. C., *Tetrahedron*, **53**, 747 (1997).
[69] Ondrus, V., Orsag, M., Fisera, L., and Pronayova, N., *Chem. Pap.*, **51**, 161 (1997); *Chem. Abs.*, **127**, 161736 (1997).
[70] Torrente, S., Noya, B., Paredes, M. D., and Alonso, R., *J. Org. Chem.*, **62**, 6710 (1997).
[71] Pandey, P. S. and Pandey, I. K., *Tetrahedron Lett.*, **38**, 7237 (1997).
[72] Ihara, M., Tanaka, Y., Takahashi, N., Tokunaga, Y., and Fukumoto, K., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 3043.
[73] Dondas, H. A., Grigg, R., and Frampton, C. S., *Tetrahedron Lett.*, **38**, 5719 (1997).
[74] Busque, F., de March, P., Figueredo, M., Font, J., Monsalvatje, M., Virgili, A., Alvarez-Larena, A., and Piniella, J. F., *J. Org. Chem.*, **61**, 8578 (1996).
[75] Aurich, H. G., Biesemeier, F., and Harms, K., *Liebigs Ann./Recl.*, **1997**, 469.
[76] Tejero, T., Dondoni, A., Rojo, I., Merchan, F. L., and Merino, P., *Tetrahedron*, **53**, 3301 (1997).
[77] Carriere, A., Virgili, A., and Figueredo, M., *Tetrahedron: Asymmetry*, **7**, 2793 (1996).
[78] de March, P., Escoda, M., Figueredo, M., Font, J., Alverez-Larena, A., and Piniella, J. F., *J. Org. Chem.*, **62**, 7781 (1997).
[79] Saba, I. S., Frederickson, M., Grigg, R., Dunn, P. J., and Levett, P. C., *Tetrahedron Lett.*, **38**, 6099 (1997).
[80] Al-Jaroudi, S. S., Perzanowski, H. P., Wazeer, M. I. M., and Ali, Sk. A., *Tetrahedron*, **53**, 5581 (1997).
[81] Kusurkar, R. S., Wadia, M. S., Bhosale, D. K., Tavale, S. S., and Puranik, V. G., *J. Chem. Res. (S)*, **1996**, 478.
[82] Jursic, B. S., *J. Heterocycl. Chem.*, **34**, 1383 (1997).
[83] Sharma, A. K., Mazumdar, S. N., and Mahajan, M. P., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 3065.
[84] Huisgen, R., Mloston, G., and Polborn, K., *J. Org. Chem.*, **61**, 6570 (1996).
[85] Huisgen, R., Mloston, G., Polborn, K., Sustmann, R., and Sicking, W., *Liebigs Ann./Recl.*, **1997**, 179.
[86] Huisgen, R., Mloston, G., Polborn, K., and Palacios-Gambra, F., *Liebigs Ann./Recl.*, **1997**, 187.
[87] Bravo, P., Bruche, L., Crucianelli, M., Farina, A., Meille, S. V., Merli, A., and Seresini, P., *J. Chem. Res. (S)*, **1996**, 348.
[88] Chung, W.-S., Tsai, T.-L., Ho, C.-C., Chiang, M. Y. N., and le Noble, W. J., *J. Org. Chem.*, **62**, 4672 (1997).
[89] Krawczyk, H. and Gryff-Keller, A., *J. Chem. Res. (S)*, **1996**, 452.
[90] Kanemasa, S., Okuda, K., Yamamoto, H., and Kaga, S., *Tetrahedron Lett.*, **38**, 4095 (1997).
[91] Curran, D. P. and Yoon, M.-W., *Tetrahedron, 53*, 1971 (1997).
[92] Page, P. C. B., Purdie, M., and Lathbury, D., *Tetrahedron*, **53**, 1061 (1997).
[93] Page, P. C. B., Purdie, M., and Lathbury, D., *Tetrahedron*, **53**, 7365 (1997).
[94] Meyer, A. G., Easton, C. J., Lincoln, S. F., and Simpson, G. W., *J. Chem. Soc., Chem. Commun.*, **1997**, 1517.

[95] Hassner, A., Friedmann, O., and Dehaen, W., *Liebigs Ann./Recl.*, **1997**, 587.
[96] Baskaran, S., Baskaran, C., Nadkarni, P. J., Trivedi, G. K., and Chandrasekhar, J., *Tetrahedron*, **53**, 7057 (1997).
[97] Morao, I., Lecea, B., and Cossio, F. P., *J. Org. Chem.*, **62**, 7033 (1997).
[98] Cinquini, E., Freccero, M., Gandolfi, R., Amade, M. S., and Rastelli, A., *Tetrahedron*, **53**, 9279 (1997).
[99] Weglinski, Z. and Puszko, A., *Pr. Nauk. Akad. Ekon. im. Osakara Langego Wroclawiu*, **728**, 111 (1996); *Chem. Abs.*, **127**, 34161 (1997).
[100] Pavlov, V. A., Kurdjukov, A. I., Moskva, V. V., and Baird, M. S., *Phosphorus Sulfur Silicon Relat. Elem.*, **1996**, 109; *Chem. Abs.*, **125**, 328797 (1996).
[101] Palacios, F., Pagalday, J., Piquet, V., Dahan, F., Barceiredo, A., and Bertrand, G., *J. Org. Chem.*, **62**, 292 (1997).
[102] Faure, J.-L., Reau, R., Wong, M. W., Koch, R., Wentrup, C., and Bertrand, G., *J. Am. Chem. Soc.*, **119**, 2819 (1997).
[103] Farag, A. M., Kheder, N. A., and Budesinsky, M., *Tetrahedron*, **53**, 9293 (1997).
[104] Doyle, M. P., Forbes, D. C., Protopopova, M. N., Stanley, S. A., Vasbinder, M. M., and Xavier, K. R., *J. Org. Chem.*, **62**, 7210 (1997).
[105] Weingarten, M. D., Prein, M., Price, A. T., and Padwa, A., *J. Org. Chem.*, **62**, 2001 (1997).
[106] Meier, K.-R., Linden, A., Mloston, G., and Heimgartner, H., *Helv. Chim. Acta*, **80**, 1190 (1997).
[107] Grigg, R., Savic, V., and Thornton-Pett, M., *Tetrahedron*, **53**, 10633 (1997).
[108] Novikov, M. S., Khlebnikov, A. F., Masalev, A. E., and Kostikov, R. R., *Tetrahedron Lett.*, **38**, 4187 (1997).
[109] Nayyar, N. K., Hutchison, D. R., and Martinelli, M. J., *J. Org. Chem.*, **62**, 982 (1997).
[110] Garner, P., Cox, P. B., Anderson, J. T., Protasiewicz, J., and Zaniewski, R., *J. Org. Chem.*, **62**, 493 (1997).
[111] Zanocco, A. L., Marquet, V. A., and Rodriguez, C. H., *Bol. Soc. Chil. Quim.*, **42**, 167 (1997); *Chem. Abs.*, **127**, 149357 (1997).
[112] Padwa, A. and Prein, M., *J. Org. Chem.*, **62**, 6842 (1997).
[113] Kappe, C. O., Peters K., and Perters, E.-M., *J. Org. Chem.*, **62**, 3109 (1997).
[114] Gribble, G. W., Sponholtz, W. R., Switzer, F. L., D'Amato, F. J., and Byrn, M. P., *J. Chem. Soc., Chem. Commun.*, **1997**, 993.
[115] Avalos, M., Babiano, R., Cabanillas, A., Cintas, P., Jimenez, J. L., Palacios, J. C., Aguilar, M. A., Corchado, J. C., and Espinosa-Garcia, J., *J. Org. Chem.*, **61**, 7291 (1996).
[116] Avalos, M., Babiano, R., Cabanillas, A., Cintas, P., Higes, F. J., Jimenez, J. L., and Palacios, J. C., *J. Org. Chem.*, **61**, 3738 (1996).
[117] Sliwa, W., *Heterocycles*, **43**, 2005 (1996); *Chem. Abs.*, **125**, 275681 (1996).
[118] Kozikowski, A. P., Araldi, G. L., and Ball, R. G., *J. Org. Chem.*, **62**, 503 (1997).
[119] Dopp, D. and Sturm, T., *Liebigs Ann./Recl.*, **1997**, 541.
[120] DelMonte, A. J., Haller, J., Houk, K. N., Sharpless, K. B., Singleton, D. A., Strassner, T., and Thomas, A. A., *J. Am. Chem. Soc.*, **119**, 9907 (1997).
[121] He, G., *Huaxue Yanjiu Yu Yingyong*, **8**, 430 (1996); *Chem. Abs.*, **126**, 327773 (1997).
[122] Li, Y.-H., Hong, S.-G., Wang, S., and Peng, Y.-Y., *Chin. J. Chem.*, **15**, 21 (1997); *Chem. Abs.*, **126**, 277057 (1997).
[123] Li, Y., Peng, Y., Wang, S., and Hong, S., *Wuli Huaxue Xuebao*, **13**, 532 (1997); *Chem. Abs.*, **127**, 161381 (1997).
[124] Kim, C. K., Lee, I. Y., Lee, B.-S., Lee, I., and Kim, K., *J. Korean Chem. Soc.*, **40**, 483 (1996); *Chem. Abs.*, **125**, 220951 (1996).
[125] Branchadell, V., *Int. J. Quantum Chem.*, **61**, 381 (1997); *Chem. Abs.*, **126**, 171113 (1997).
[126] Domingo, L. R., Picher, M. T., Andres, J., and Safont, V. S., *J. Org. Chem.*, **62**, 1775 (1997).
[127] Garcia, J. I., Mayoral, J. A., and Salvatelli, L., *Tetrahedron*, **53**, 6057 (1997).
[128] Baas, J. M. A., Woudenberg, R. H., and Maat, L., *Liebigs Ann./Recl.*, **1997**, 13.
[129] Haller, J., Niwayama, S., Duh, H.-Y., and Houk, K. N., *J. Org. Chem.*, **62**, 5728 (1997).
[130] Lee, Y.-K. and Singleton, D. A., *J. Org. Chem.*, **62**, 2255 (1997).
[131] Afarinkia, K., Daly, N. T., Gomez-Farnos, S., and Joshi, S., *Tetrahedron Lett.*, **38**, 2369 (1997).
[132] Zhou, J., *Daxue Huaxue*, **11**, 28 (1996); *Chem. Abs.*, **126**, 88866 (1997).
[133] Kumar, A., *J. Phys. Org. Chem.*, **9**, 287 (1996).
[134] van der Wel, G. K., Wijnen, J. W., and Engberts, J. B. F. N., *J. Org. Chem.*, **61**, 9001 (1996).
[135] Furlani, T. R. and Gao, J., *J. Org. Chem.*, **61**, 5492 (1996).
[136] Wijnen, J. W. and Engberts, J. B. F. N., *Liebigs Ann./Recl.*, **1997**, 1085.
[137] Schlachter, I., Mattay, J., Suer, J., Howeler, U., Wurthwein, G., and Wurthwein, E.-U., *Tetrahedron*, **53**, 119 (1997).
[138] Otto, S., Bertoncin, F., and Engberts, J. B. F. N., *J. Am. Chem. Soc.*, **118**, 7702 (1996).

[139] Korzenski, M. B. and Kolis, J. W., *Tetrahedron Lett.*, **38**, 5611 (1997).
[140] Cativiela, C., Garcia, J. I., Gil, J., Martinez, R. M., Mayoral, J. A., Salvatella, L., Urieta, J. S., Mainar, A. M., and Abraham, M. H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 653.
[141] Naraku, G., Hori, K., Ito, Y. N., and Katsuki, T., *Tetrahedron Lett.*, **38**, 8231 (1997).
[142] Johannsen, M. and Jorgensen, K. A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1183.
[143] Zhulin, M. B., Koreshkov, Y. D., Bogdanov, V. S., and Kel'tseva, M. V., *Izv. Akad. Nauk, Ser. Khim.*, **1996**, 2450; *Chem. Abs.*, **126**, 185694 (1997).
[144] Renslo, A. R., Weinsrein, R. D., Tester, J. W., and Danheiser, R. L., *J. Org. Chem.*, **62**, 4530 (1997).
[145] Saito, T., Kawamura, M., and Nishimura, J., *Tetrahedron Lett.*, **38**, 3231 (1997).
[146] Grimaud, L., Ferezou, J.-P., Prunet, J., and Lallemand, J.-Y., *Tetrahedron*, **53**, 9253 (1997).
[147] Taber, D. F. and Song, Y., *J. Org. Chem.*, **61**, 7508 (1996).
[148] Bradley, A. Z. and Johnson, R. P., *J. Am. Chem. Soc.*, **119**, 9917 (1997).
[149] Deidrich, M. K., Klarner, F.-G., Beno, B. R., Houk, K. N., Senderowitz, H., and Still, W. C., *J. Am. Chem. Soc.*, **119**, 10255 (1997).
[150] Evans, D. A. and Johnson, J. S., *J. Org. Chem.*, **62**, 786 (1997).
[151] Boucher, J.-L., De Riggi, I., and Stella, L., *J. Org. Chem.*, **62**, 6077 (1997).
[152] Nair, V., Nair, A. G., Rath, N. P., and Eigendorf, G. K., *Chem. Lett.*, **1997**, 505.
[153] Manoharan, M. and Venuvanalingam, P., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1799.
[154] Schmittel, M. and Wohrle, C., *J. Org. Chem.*, **60**, 8223 (1995).
[155] Murakami, M., Itami, K., and Ito, Y., *J. Am. Chem. Soc.*, **119**, 7163 (1997).
[156] Jursic, B. S., *J. Heterocycl. Chem.*, **34**, 77 (1997).
[157] Singleton, D. A., *Adv. Cycloaddit.*, **4**, 121 (1997); *Chem. Abs.*, **127**, 149167 (1997).
[158] Campos, P. J., Lamaza, I., Rodriguez, M. A., and Canal, G., *Tetrahedron Lett.*, **38**, 6741 (1997).
[159] Barluenga, J., Tomas, M., Lopez-Pelegrin, J. A., and Rubio, E., *Tetrahedron Lett.*, **38**, 3981 (1997).
[160] Leung, S.-W. and Singleton, D. A., *J. Org. Chem.*, **62**, 1955 (1997).
[161] Schroeter, K., Schalley, C. A., Schroder, D., and Schwarz, H., *Helv. Chim. Acta*, **80**, 1205 (1997).
[162] Murch, P., Arif, A. M., and Stang, P. J., *J. Org. Chem.*, **62**, 5059 (1997).
[163] Mestres, J., Duran, M., and Sola, M., *J. Phys. Chem.*, **100**, 7449 (1996).
[164] Moti, A., Takamori, Y., and Takeshita, H., *Chem. Lett.*, **1997**, 395.
[165] Illescas, B. M., Martin, N., Seoane, C., Orti, E., Viruela, P. M., Viruela, R., and de la Hoz, A., *J. Org. Chem.*, **62**, 7585 (1997).
[166] Barone, V. and Arnaud, R., *J. Chem. Phys.*, **106**, 8727 (1997); *Chem. Abs.*, **127**, 33713 (1997).
[167] Jursic, B. S., *J. Org. Chem.*, **62**, 3046 (1997).
[168] Sodupe, M., Rios, R., Branchadell, V., Nicholas, T., Oliva, A., and Dannenberg, J. J., *J. Am. Chem. Soc.*, **119**, 4232 (1997).
[169] Giju, K. T. and Jemmis, E. D., *THEOCHEM*, **388**, 201 (1996); *Chem. Abs.*, **126**, 211689 (1997).
[170] Trahanovsky, W. S. and Arvidson, K. B., *J. Org. Chem.*, **61**, 9528 (1996).
[171] Yueh, W. and Bauld, N. L., *J. Phys. Org. Chem.*, **9**, 529 (1996).
[172] Froese, R. D. J., Coxon, J. M., West, S. C., and Morokuma, K., *J. Org. Chem.*, **62**, 6991 (1997).
[173] Motoyoshiya, J., Kameda, T., Asari, M., Miyamoto, M., Narita, S., Aoyama, H., and Hayashi, S., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1845.
[174] Lee, S.-J., Tzeng, C.-B., Lin, S.-C., Chao, I., Lu, H.-F., and Chou, T.-S., *J. Org. Chem.*, **61**, 9293 (1996).
[175] Jursic, B. S., *Tetrahedron Lett.*, **38**, 1305 (1997).
[176] de Meijere, A., Teichmann, S., Seyed-Mahdavi, F., and Kohlstruk, S., *Liebigs Ann./Recl.*, **1996**, 1989.
[177] Binger, P., Wedemann, P., Goddard, R., and Brinker, U. H., *J. Org. Chem.*, **61**, 6462 (1996).
[178] Suarez, D., Inglesias, E., Sordo, T. L., and Sordo, J. A., *J. Phys. Org. Chem.*, **9**, 17 (1996).
[179] Maddaluano, J., Gaonac'h, O., Marcual, A., Toupet, L., and Giessner-Prettre, C., *J. Org. Chem.*, **61**, 5290 (1996).
[180] Pramanik, A. and Chandrasekhar, J., *Indian Acad. Sci., Chem. Sci.*, **108**, 459 (1996); *Chem. Abs.*, **126**, 157011 (1997).
[181] Node, M., Nishide, K., Imazato, H., Kurosaki, R., Inoue, T., and Ikariya, T., *J. Chem. Soc., Chem. Commun.*, **1996**, 2559.
[182] Branchadell, V., Font, J., Moglioni, A. G., de Echaguen, C. O., Oliva, A., Ortuno, R. M., Vecianna, J., and Vidal-Gancedo, J., *J. Am. Chem. Soc.*, **119**, 9992 (1997).
[183] Leonard, J., Fearnley, S. P., Hague, A. B., Wong, G., and Jones, M. F., *Tetrahedron Lett.*, **38**, 3067 (1997).
[184] Venturini, A., Joglar, J., Fustero, S., and Gonzalez, J., *J. Org. Chem.*, **62**, 3919 (1997).
[185] Sisti, N. J., Motorina, I. A., Dau, M.-E. T. H., Riche, C., Fowler, F. W., and Grierson, D. S., *J. Org. Chem.*, **61**, 3715 (1996).
[186] Motorina, I. A., Fowler, F. W., and Grierson, D. S., *J. Org. Chem.*, **62**, 2098 (1997).
[187] Sisti, N. J., Zeller, E., Grierson, D. S., and Fowler, F. W., *J. Org. Chem.*, **62**, 2093 (1997).

[188] Tietze, L. F. and Kettschau, G., *Top. Curr. Chem.*, **189**, 1 (1997); *Chem. Abs.*, **127**, 161285 (1997).
[189] Behforouz, M., Gu, Z., Stelzer, L. S., Ahmadian, M., Haddad, J., and Scherschel, J. A., *Tetrahedron Lett.*, **38**, 2211 (1997).
[190] Georgieva, A., Spassov, S., Stanoeva, E., Topalova, I., and Tchanev, C., *J. Chem. Res. (S)*, **1997**, 148.
[191] Spino, C., Clouston, L. L., and Berg, D. J., *Can. J. Chem.*, **75**, 1047 (1997).
[192] Yao, S., Johannsen, M., and Jorgensen, K. A., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2345.
[193] Marchand, A., Pradere, J.-P., and Guingant, A., *Tetrahedron Lett.*, **38**, 1033 (1997).
[194] Laschat, S., *Liebigs Ann./Recl.*, **1997**, 1.
[195] Marchand, E. and Morel, G., *Bull. Soc. Chim. Fr.*, **133**, 903 (1996).
[196] Johannsen, M., Yao, S., and Jorgensen, K. A., *J. Chem. Soc., Chem. Commun.*, **1997**, 2169.
[197] Saito, T., Takekawa, K., Nishimura, J., and Kawamura, M., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2957.
[198] Rapp, J. and Huisgen, R., *Tetrahedron*, **53**, 961 (1997).
[199] Meekel, A. A. P., Resmihni, M., and Pandit, U. K., *Bioorg. Med. Chem.*, **4**, 1051 (1996); *Chem. Abs.*, **125**, 3246990 (1996).
[200] Fan, B. T., Barbu, A., and Doucet, J.-P., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1937.
[201] Matsumoto, T., Takaoka, K., Aoyama, T., and Shioiri, T., *Tetrahedron*, **53**, 225 (1997).
[202] Felderhoff, M. and Sustmann, R., *Monatsh. Chem.*, **127**, 967 (1996).
[203] Nicolaides, D. N., Bezergiannidou-Balouctsi, C., Awad, R. W., Litinas, K. E., and Malamidou-Xenikaki, *J. Org. Chem., **62***, 499 (1997).
[204] Atkinson, R. N., Storey, B. M., and King, S. B., *Tetrahedron Lett.*, **37**, 9287 (1996).
[205] Whiting, A., *Adv. Asymm. Synth.*, **1996**, 126; *Chem. Abs.*, **125**, 246823 (1996).
[206] Nakamura, T., Hashimoto, N., Ishizuka, T., and Kunieda, T., *Tetrahedron Lett.*, **38**, 559 (1997).
[207] Brecht, R., Haenel, F., Seitz, G., Frenzen, G., Pilz, A., Massa, W., and Wocadlo, S., *Liebigs Ann./Recl.*, **1997**, 851.
[208] Mataka, S., Ma, J., Thiemann, T., Rudzinski, J. M., Tsuzuki, H., Sawada, T., and Tashiro, M., *Tetrahedron*, **53**, 885 (1997).
[209] Cousins, R. P. C., Ding, W. C., Pritchard, R. G., and Stoodley, R. J., *J. Chem. Soc., Chem. Commun.*, **1997**, 2171.
[210] Crisp, G. and Gebauer, M. G., *J. Org. Chem.*, **61**, 8425 (1996).
[211] Letourneau, J. E., Wellman, M. A., and Burnell, D. J., *J. Org. Chem.*, **62**, 7272 (1997).
[212] Wellman, M. A., Burry, L. C., Letourneau, J. E., Bridson, J. N., and Miller, D. O., and Burnell, D. J., *J. Org. Chem.*, **62**, 939 (1997).
[213] Kozmin, S. A. and Rawal, V. H., *J. Am. Chem. Soc.*, **119**, 7165 (1997).
[214] Desimoni, G., Faita, G., Invernizzi, A. G., and Righetti, P. P., *Tetrahedron*, **53**, 7671 (1997).
[215] Ritzberger-Baumgartner, W. and Schantl, J. G., *Molecules*, **1**, 119 (1996); *Chem. Abs.*, **127**, 50146 (1997).
[216] Harrnagel, M., Grimm, K., and Mayr, H., *Liebigs Ann./Recl.*, **1997**, 71.
[217] Ponec, R., *J. Chem. Inf. Comput. Sci.*, **37**, 745 (1997); *Chem. Abs.*, **127**, 50189 (1997).
[218] Wong, T., Wilson, P. D., Woo, S., and Fallis, A. G., *Tetrahedron Lett.*, **38**, 7045 (1997).
[219] Ward, D. E., Nixey, T. E., Gai, Y., Hrapchak, M. J., and Abaee, M. S., *Can. J. Chem.*, **74**, 1418 (1996).
[220] Bush, E. J., Jones, D. W., and Ryder, T. C. L. M., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1929.
[221] Giessner-Prettre, C., Huckel, S., Maddaluno, J., and Jung, M. E., *J. Org. Chem.*, **62**, 1439 (1997).
[222] Kishikawa, K., Akimoto, S., Kohmoto, S., Yamamoto, M., and Yamada, K., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 77.
[223] Sudo, A. and Saigo, K., *Chem. Lett.*, **1997**, 97.
[224] Ishihara, K., Kondo, S., Kurihara, H., and Yamamoto, H., *J. Org. Chem.*, **62**, 3026 (1997).
[225] Corey, E. J., Barnes-Seeman, D., and Lee, T. W., *Tetrahedron Lett.*, **38**, 1699 (1997).
[226] Mandal, A. H., Gomez, A., Trujillo, G., Mendez, F., Jimenez, H. A., de Jesus Rosales, M., Martinez, R., Delgado, F., and Tamariz, J., *J. Org. Chem.*, **62**, 4105 (1997).
[227] Liu, H.-J., Wang, D.-X., Kim, J. B., Browne, E. N. C., and Wang, Y., *Com. J. Chem.*, **75**, 899 (1997).
[228] Corey, E. J. and Lee, T. W., *Tetrahedron Lett.*, **38**, 5755 (1997).
[229] Hanamoto, T., Sugimoto, Y., Jin, Y. Z., and Inanaga, J., *Bull. Chem. Soc. Jpn*, **70**, 1421 (1997).
[230] Roush, W. R. and Barda, A. D., *J. Am. Chem. Soc.*, **119**, 7402 (1997).
[231] Sera, A., Ueda, N., Itoh, K., and Yamada, H., *Heterocycles*, **43**, 2205 (1996); *Chem. Abs.*, **126**, 31248 (1997).
[232] Ishimaru, K., Yamamoto, Y., and Akiba, K., *Tetrahedron*, **53**, 5423 (1997).
[233] Boeckman, R. K. and Liu, Y., *J. Org. Chem.*, **61**, 7984 (1996).
[234] Carreno, M. C., Ruano, J. L. G., Urbano, A., and Lopez-Solera, M. I., *J. Org. Chem.*, **62**, 976 (1997).
[235] Kilic, H. and Balci, M., *J. Org. Chem.*, **62**, 3434 (1997).

[236] Hariri, M. A., Jouve, K., Pautet, F., Domard, M., Fenet, B., and Fillion, H., *J. Org. Chem.*, **62**, 405 (1997).
[237] Denmark, S. E. and Thorarensen, A., *J. Am. Chem. Soc.*, **119**, 125 (1997).
[238] Denmark, S. E. and Dixon, J. A., *J. Org. Chem.*, **62**, 7086 (1997).
[239] Denmark, S. E. and Thorarensen, A., *J. Org. Chem.*, **61**, 6727 (1996).
[240] Denmark, S. E., Guagnano, V., Dixon, J. A., and Stolle, A., *J. Org. Chem.*, **62**, 4610 (1997).
[241] Winkler, J. D., Kim, H. S., Kim, S., Ando, K., and Houk, K. N., *J. Org. Chem.*, **62**, 2957 (1997).
[242] Boeckman, R. K., Breining, S. R., and Arvanitis, A., *Tetrahedron*, **53**, 8941 (1997).
[243] Perrin, S., Monnier, K., and Laude, B., *J. Chem. Res. (S)*, **1997**, 104.
[244] Arai, Y., Masuda, T., and Masaki, Y., *Chem. Lett.*, **1997**, 145.
[245] Gurtler, C. F., Blechert, S., and Steckhan, E., *Chem. Eur. J.*, **3**, 447 (1997); *Chem. Abs.*, **127**, 4982 (1997).
[246] Pindur, U., Gonzalez, E., and Mehrabani, F., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1861.
[247] Anthony, I. J. and Wege, D., *Aust. J. Chem.*, **49**, 1263 (1996).
[248] Padwa, A., Kappe, C. O., Cochran, J. E., and Snyder, J. P., *J. Org. Chem.*, **62**, 2786 (1997).
[249] Bachrach, S. M., *J. Org. Chem.*, **62**, 5081 (1997).
[250] Lee, B.-S., Kim, C. K., Choi, J. W., and Lee, I., *Bull. Korean Chem. Soc.*, **17**, 849 (1996); *Chem. Abs.*, **126**, 327857 (1997).
[251] Salzner, U., Bachrach, S. M., and Mulhearn, D. C., *J. Comput. Chem.*, **18**, 198 (1997); *Chem. Abs.*, **126**, 104160 (1997).
[252] Bachrach, S. M. and Magdalinos, P., *THEOCHEM*, **368**, 1 (1996); *Chem. Abs.*, **126**, 89485 (1997).
[253] Defacqz, N., Touillaux, R., Tinant, B., Declercq, J.-P., Petters, D., and Marchand-Byrnaert, J., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1965.
[254] Sugiyama, S., Mori, A., and Takeshita, H., *Kagaku Kogyo*, **47**, 867 (1996); *Chem. Abs.*, **125**, 274943 (1996).
[255] Shtyrlin, Y. G., Fedorenko, V. Y., Iskhakova, G. G., Kiselev, V. D., and Konovalov, A. I., *Zh. Obshch. Khim.*, **66**, 499 (1996); *Chem. Abs.*, **126**, 7553 (1997).
[256] Jenner, G. and Salem, R. B., *Tetrahedron*, **53**, 4637 (1997).
[257] Bodwell, G. J. and Pi, Z., *Tetrahedron Lett.*, **38**, 309 (1997).
[258] Neipp, C. E., Ranslow, P. B., Wan, Z., and Snyder, J. K., *Tetrahedron Lett.*, **38**, 7499 (1997).
[259] Halle, J.-C., Vichard, D., Pouet, M.-J., and Terrier, F., *J. Org. Chem.*, **62**, 7178 (1997).
[260] Dang, Q., Brown, B. S., and Erion, M. D., *J. Org. Chem.*, **61**, 5204 (1996).
[261] Wan, Z. and Snyder, J. K., *Tetrahedron Lett.*, **38**, 7495 (1997).
[262] Sakya, S. M., Groskopf, K. K., and Boger, D. L., *Tetrahedron Lett.*, **38**, 3805 (1997).
[263] Sauer, J., Breu, J., Holland, U., Herges, R., Neumann, H., and Kammermeier, S., *Liebigs Ann./Recl.*, **1997**, 1473.
[264] Mataka, S., Ma, J., Thiemann, T., Mimura, T., Sawada, T., and Tashiro, M., *Tetrahedron*, **53**, 6817 (1997).
[265] Pierlot, C. and Aubry, J.-M., *J. Chem. Soc., Chem. Commun.*, **1997**, 2289.
[266] Marchand, E. and Morel, G., *Bull. Soc. Chim. Fr.*, **134**, 623 (1977).
[267] Carreno, M. C., Ruano, J. L. G., and Urbano, A., *J. Org. Chem.*, **61**, 6136 (1996).
[268] Tamaru, Y., Harayama, H., Sakata, H., Konishi, H., Fugami, K., Kimura, M., Tanaka, S., Okajima, T., and Fukazawa, Y., *Liebigs Ann./Recl.*, **1997**, 907.
[269] Deng, Q., Thomas, B. E., Houk, K. N., and Dowd, P., *J. Am. Chem. Soc.*, **119**, 6902 (1997).
[270] Takahashi, T., Sun, W.-H., Xi, C., and Kotora, M., *J. Chem. Soc., Chem. Commun.*, **1997**, 2069.
[271] Yamazaki, S., Imanishi, T., Moriguchi, Y., and Takada, T., *Tetrahedron Lett.*, **38**, 6397 (1997).
[272] Yamazaki, S., Kumagai, H., Takada, T., and Yamabe, S., *J. Org. Chem.*, **62**, 2968 (1997).
[273] Peters, J.-U. and Blechert, S., *J. Chem. Soc., Chem. Commun.*, **1997**, 1983.
[274] Komarova, L. I., Frenkel, Ts. M., Shvorak, A. E., Pankratov, V. A., and Lokshin, B. V., *Izv. Akad. Nauk, Ser. Khim.*, **1996**, 1662; *Chem. Abs.*, **125**, 327862 (1997).
[275] Ammenn, J., Altmann, K.-H., and Bellus, D., *Helv. Chim. Acta*, **80**, 1589 (1997).
[276] Murakami, M., Itami, K., and Ito, Y., *J. Am. Chem. Soc.*, **119**, 2950 (1997).
[277] Harmata, M., *Adv. Cycloaddit.*, **4**, 41 (1997); *Chem. Abs.*, **127**, 135350 (1997).
[278] Montana, A. M., Ribes, S., Grima, P. M., and Garcia, F., *Chem. Lett.*, **1997**, 847.
[279] Harmata, M. and Jones, D. E., *Tetrahedron Lett.*, **38**, 3861 (1997).
[280] Harmata, M., Herron, B. F., Kahraman, M., and Barnes, C. L., *J. Org. Chem.*, **62**, 6051 (1997).
[281] Harmata, M. and Jones, D. E., *J. Org. Chem.*, **62**, 1578 (1997).
[282] Kende, A. W. and Huang, H., *Tetrahedron Lett.*, **38**, 3353 (1997).
[283] Bearpark, M. J., Deumal, M., Robb, M. A., Vreven, T., Yamamoto, N., Olivucci, M., and Bernardi, F., *J. Am. Chem. Soc.*, **119**, 709 (1997).
[284] Sieburth, S. McN. and Siegel, B., *J. Chem. Soc., Chem. Commun.*, **1996**, 2449.

[285] Noh, T. and Kim, D., *Tetrahedron Lett.*, **37**, 9329 (1996).
[286] Collins, J. L., Grieco, P. A., and WAlker, J. K., *Tetrahedron Lett.*, **38**, 1321 (1997).
[287] Rigby, J. H., *Org. React. (N. Y.)*, **49**, 331 (1997); *Chem. Abs.*, **126**, 88863 (1997).
[288] Rigby, J. H. and Fiedler, C., *J. Org. Chem.*, **62**, 6106 (1997).
[289] Lubineau, A., Bouchain, G., and Queneau, Y., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2863.
[290] Rigby, J. H. and Warshakoon, N. C., *J. Org. Chem.*, **61**, 7644 (1996).
[291] Nair, V., Anilkumar, G., Nandakumar, M. V., Mathew, B., and Rath, N. P., *Tetrahedron Lett.*, **38**, 6441 (1997).
[292] Meier, H., Groschl, D., Beckert, R., and Weiss, D., *Liebigs Ann./Recl.*, **1997**, 1603.

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CHAPTER 15

Molecular Rearrangements

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Aromatic Rearrangements

Benzene Derivatives

A simple example of a Fries rearrangement accelerated by microwave irradiation has been presented.[1] A study has been made[2] of solvent effects on the liquid-phase Fries rearrangement of phenyl acetate over zeolites, and a selective Fries rearrangement of that ester into hydroxyacetophenones has been catalysed by high-silica zeolites.[3] It has been shown[4] that, in the Fries rearrangement of phenyl and naphthyl esters over K10-montmorillonite, framework aluminium acts as a Lewis acid, catalysing the rearrangement. An increase in the size of the migrating group and/or substrate was found to increase the proportion of *ortho*-isomer. Group 3 and 4 metal triflates have also been found to act as efficient catalysts in the Fries rearrangement of phenyl and naphthyl acylates.[5] A new LDA-mediated O → C carbamoyl migration in *O*-(2-

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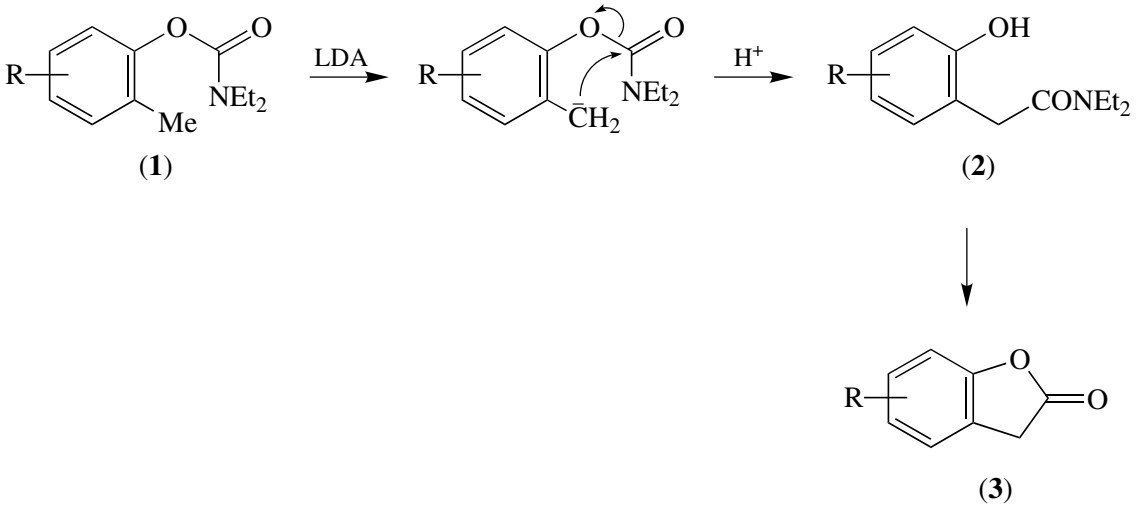
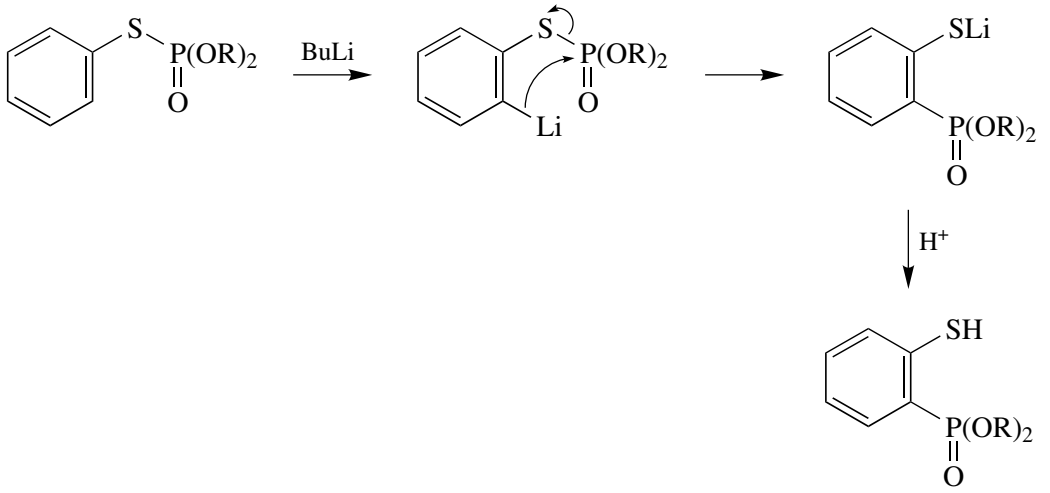


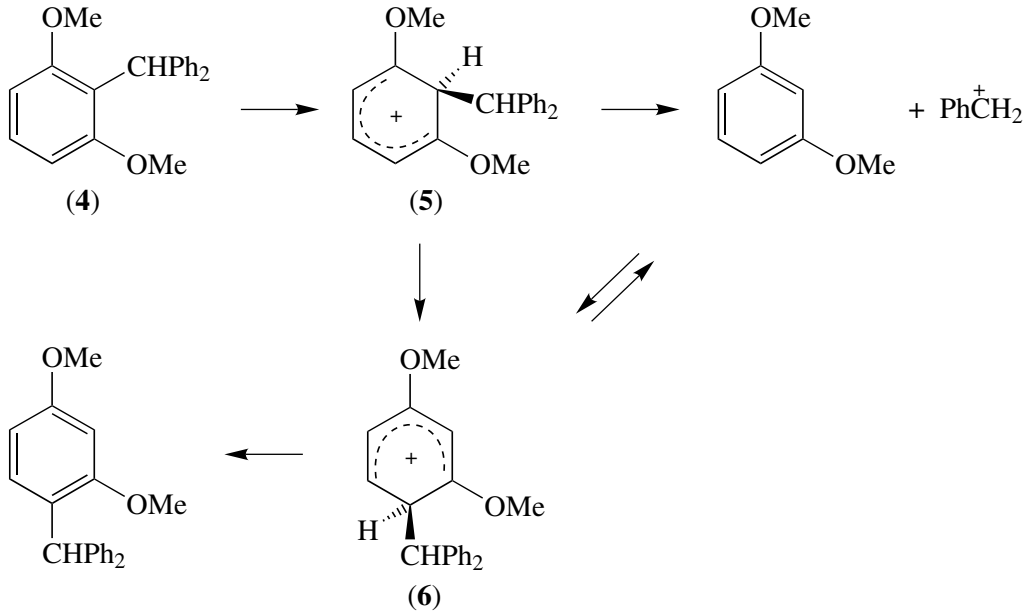
SCHEME 1

methylaryl)carbamates (**1**) has provided[6] an efficient route to aryl acetamides (**2**), precursors to benzo- and naphtho-furanones (**3**) (see Scheme 1). New *O*-mercaptoaryl phosphonates and their derivatives have been prepared[7] via an *ortho*-lithiation of *O,O*-diisopropyl *S*-aryl phosphorothioates followed by a phosphoryl group S → C migration (see Scheme 2). Dimeric ketenes, presumably generated from transient cyclohexa-2,4-dienones, have been observed[8] on laser flash photolysis of phenyl acetate (and benzyl phenyl ether), thus providing additional proof for the involvement of cyclohexadienones in the photo-Fries (and photo-Claisen) rearrangements.

It has been demonstrated[9] that photo-protonation of 2-diphenylmethyl-1,3-dimethoxybenzene (**4**) to the cyclohexadienyl cation (**5**) not only results in dissociative cleavage of the diphenylmethyl cation (the reverse of the step in a Friedel–Crafts alkylation that produces the cyclohexadienyl cation), but is accompanied by a surprising rearrangement to the isomeric 2,4-dimethoxybenzenium ion (**6**). This (see Scheme 3) represents the first example of a system where rearrangement involving two isomeric

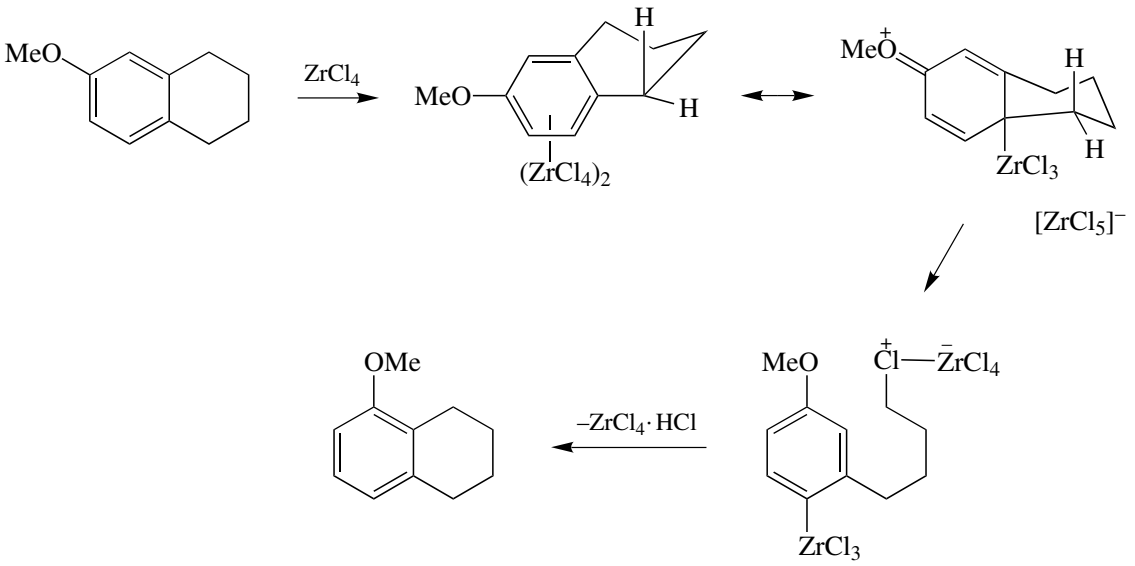


SCHEME 2

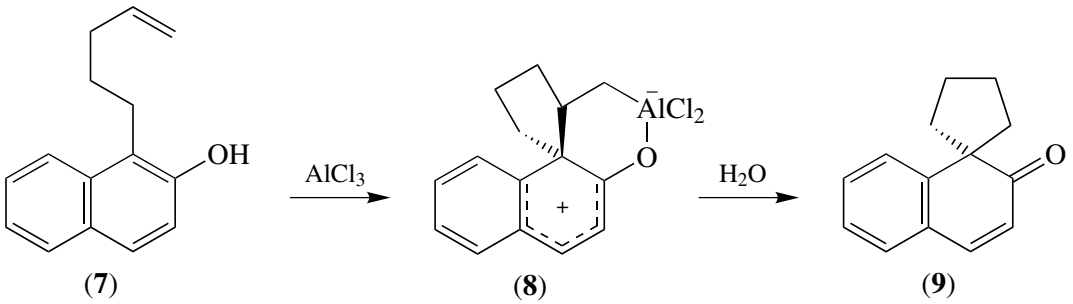


SCHEME 3

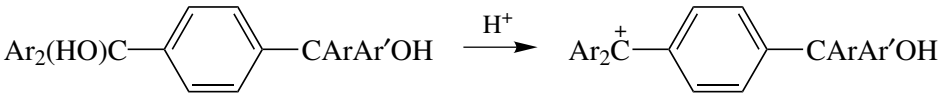
cyclohexadienyl cations has been observed with laser flash photolysis, and shows that cyclohexadienyl cations of the Friedel–Crafts reaction of 1,3-dimethoxybenzene and the diphenylmethyl cation rearrange on the nanosecond time-scale, without separating the aromatic substrate and the electrophile. 6-Methoxytetralins have been transformed into 8-methoxytetralins through the action of zirconium tetrachloride. The authors[10] proposed that the transformation proceeds via scission of the C(1)−C(8a) bond, followed by an intramolecular Friedel–Crafts cyclization (see Scheme 4). The formation of spiroketone (**9**) from treatment of 5-(2-naphthalenol)pent-1-ene (**7**) with aluminium chloride has been explained[11] by invoking the involvement of a cyclic aluminium



SCHEME 4

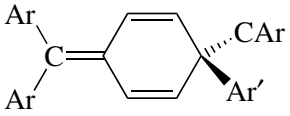


(**7**) (**8**) (**9**)



(**10**) (**11**)

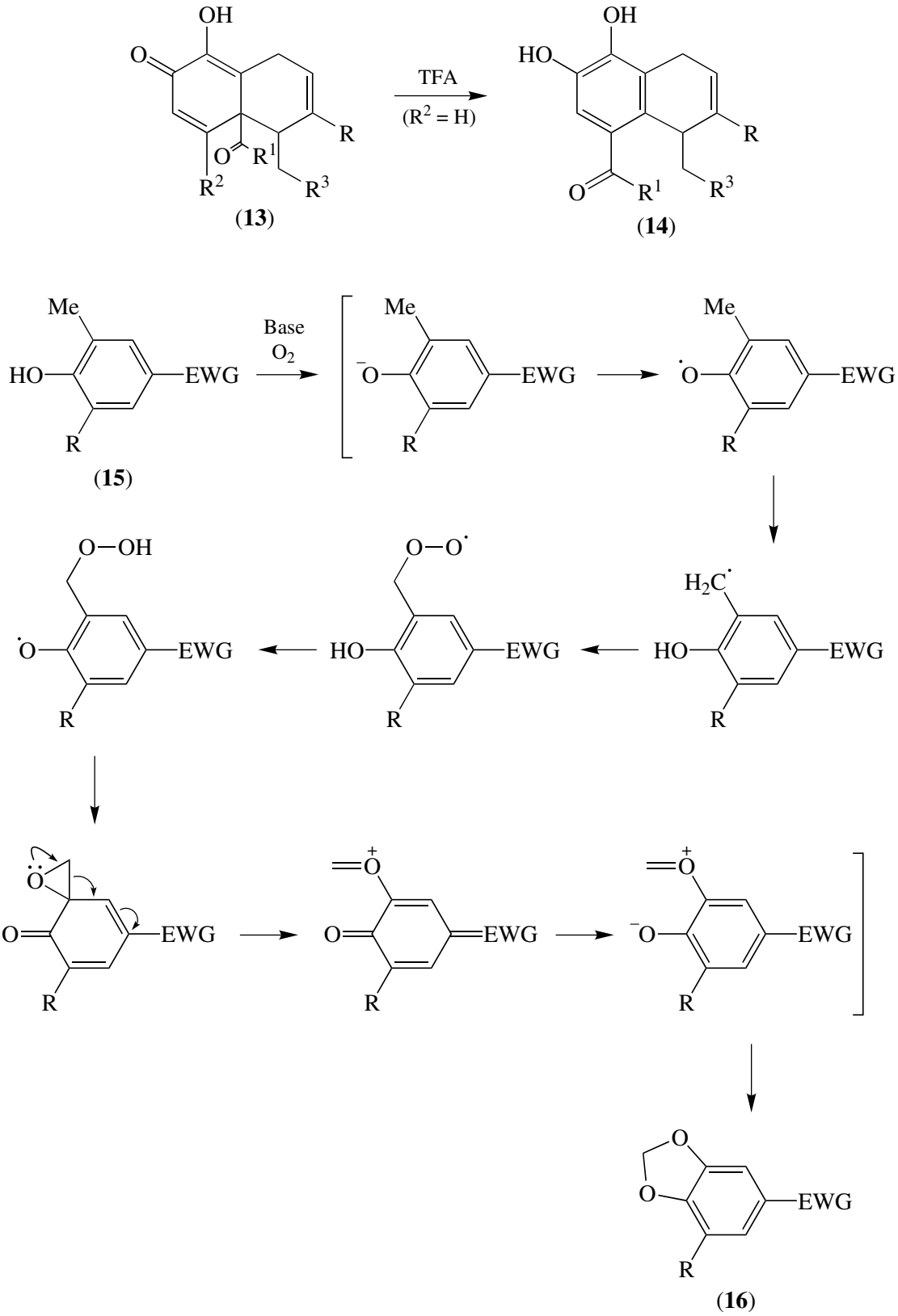
Ar = 2,6-$(MeO)_2C_6H_3$



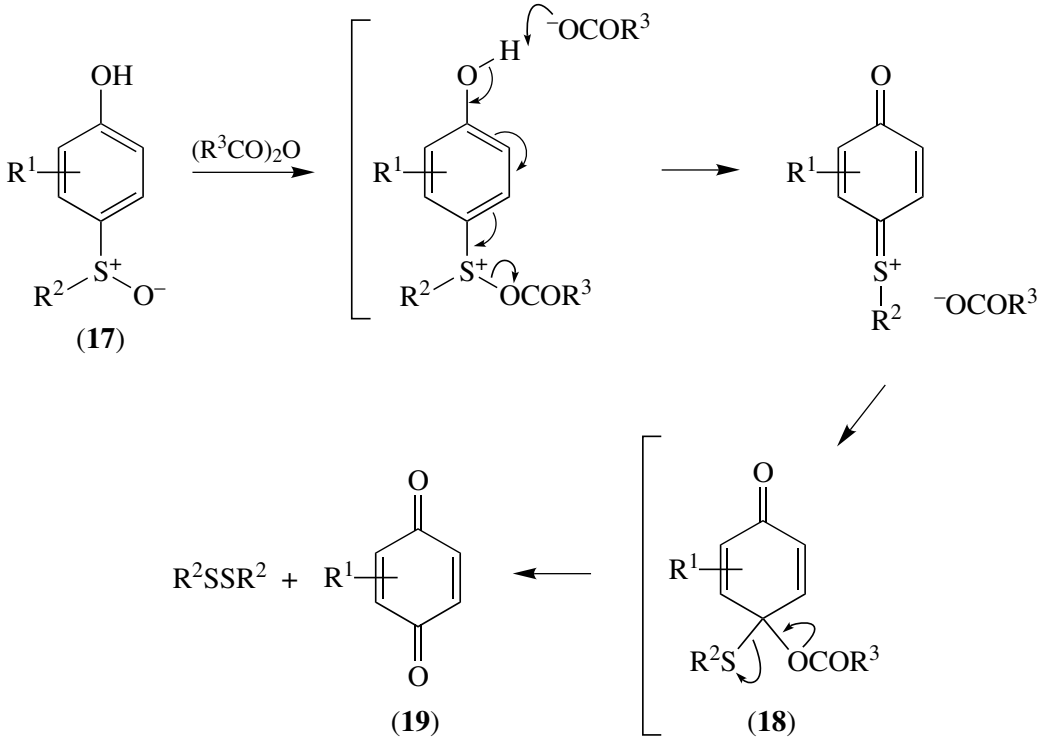
(**12**)

intermediate (**8**). A super acid-catalysed reductive Friedel–Crafts reaction of arenes using arenecarbaldehyde acetals has been reported.[12] The reaction, yielding diarylmethanes, is assumed to proceed through a redox process involving a hydride shift from the acetal moiety to the benzylic carbon. It has been reported[13] that photolysis of the charge-transfer complex of tetranitromethane and pentamethylbenzene yields the labile epimeric 1,2,3,4,6-pentamethyl-3-nitro-6-trinitromethylcyclohexane-1,4-dienes, one of which rearranges rapidly to afford 2,3,4,5-tetramethyl-1-(2′,2′,2′-trinitroethyl)benzene, 2,3,4,5-tetramethylphenylnitromethane, 2,3,4,5-tetramethylbenzyl nitrate, and 2,3,4,5-tetramethylbenzyl nitrite. α,α,α′,α′-Tetraaryl-1,4-benzenedimethanols (**10**), in the presence of a catalytic amount of acid, have been found[14] to rearrange to 3-aroyl-3-aryl-6-diarylmethylenecyclohexa-1,4-dienes (**12**), presumably by initial formation of carbocations (**11**) and subsequent intramolecular migration of an aryl group. Diels–Alder adducts (**13**), obtained from the reaction of *o*-benzoquinones substituted with electron-withdrawing groups at C(3) or C(4), with a variety of dienes, have been shown[15] to undergo migration of the 'angular' electron-withdrawing substituent with concomitant aromatization, to produce substituted catechols (**14**). A novel base-promoted oxidative rearrangement of 2-methyl-4-substituted phenols (**15**) to 1,2-(methylenedioxy)-4-substituted benzenes (**16**) has been reported.[16] The mechanism shown in Scheme 5 has been tentatively proposed for the process. Evidence for the mechanism of the aromatic Pummerer-type rearrangement of *p*-sulfinylphenols (**17**) has been obtained[17] from the isolation of acetal intermediates (**18**) during the acid anhydride-induced rearrangement of (**17**) to *p*-quinones (**19**).

The recently observed[18] silica gel-promoted lactonization of 4-aryl-5-tosyloxypentanoates represents the first instance of a phenonium ion inducing migration of an aryl


OH
O
R
O
R1
R2
R3
(13)
TFA
(R2 = H)
OH
HO
R
O
R1
R3
(14)
Me
HO
EWG
R
(15)
Base
O2
Me
O
EWG
R
Me
O
EWG
R
H2C
HO
EWG
R
O—O
HO
EWG
R
O—OH
O
EWG
R
O
O
EWG
R
O
O
EWG
R
O
O
EWG
R
O
O
O
EWG
R
(16)

SCHEME 5

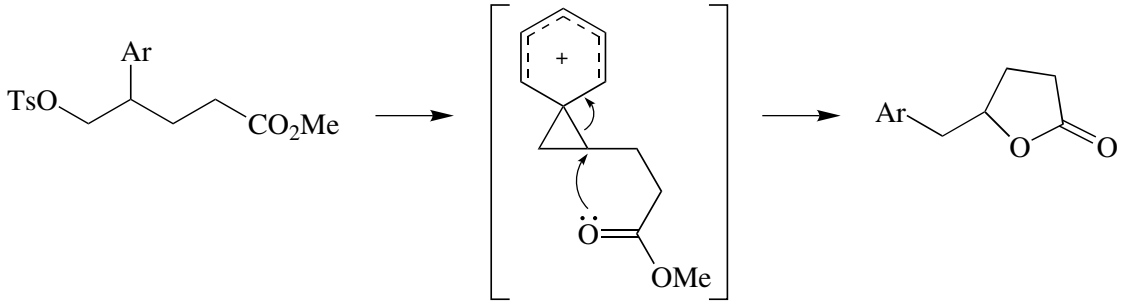


group in tandem with intramolecular attack by a nucleophilic functional group (see Scheme 6). An MO study[19] has been undertaken on the gas-phase phenyl group migration within protonated ketones, viz. (**20**) to (**21**), and a mechanism in which the

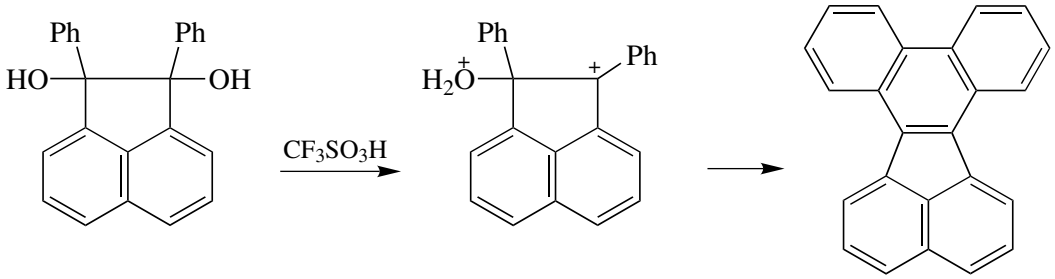
$$(p\text{-}RC_6H_4)MeCH\overset{+}{C}(OH)C_6H_4R'\text{-}p \longrightarrow Me\overset{+}{C}HC(OH)(C_6H_4R'\text{-}p)(C_6H_4R\text{-}p)$$

(**20**) (**21**)

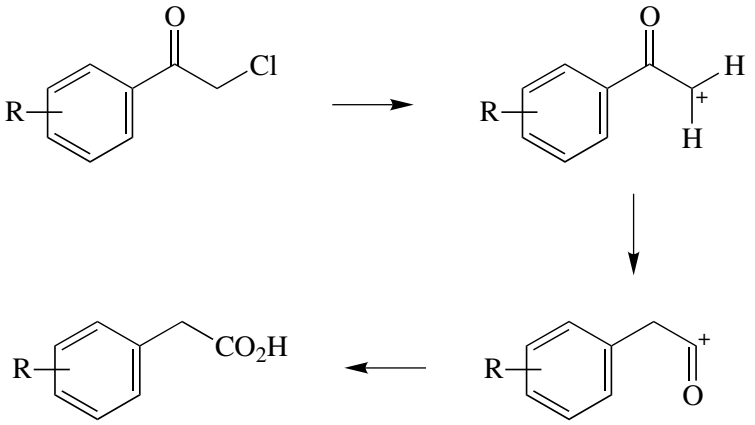
aromatic ring is involved has been proposed[20] for the novel rearrangement of ω-phenylalkanols to phenylalkyl ketones. A series of condensed aromatics have been prepared[21] by the superacidic dehydrative cyclization of aryl pinacols (see Scheme 7), and photolysis of α-chloroacetophenones in different solvents has shown[22] that the observed 1,2-aryl migration (see Scheme 8) is media controlled. A short-lived radical dication (**23**) has been postulated[23] as a key intermediate in the oxidative cyclization of



SCHEME 6

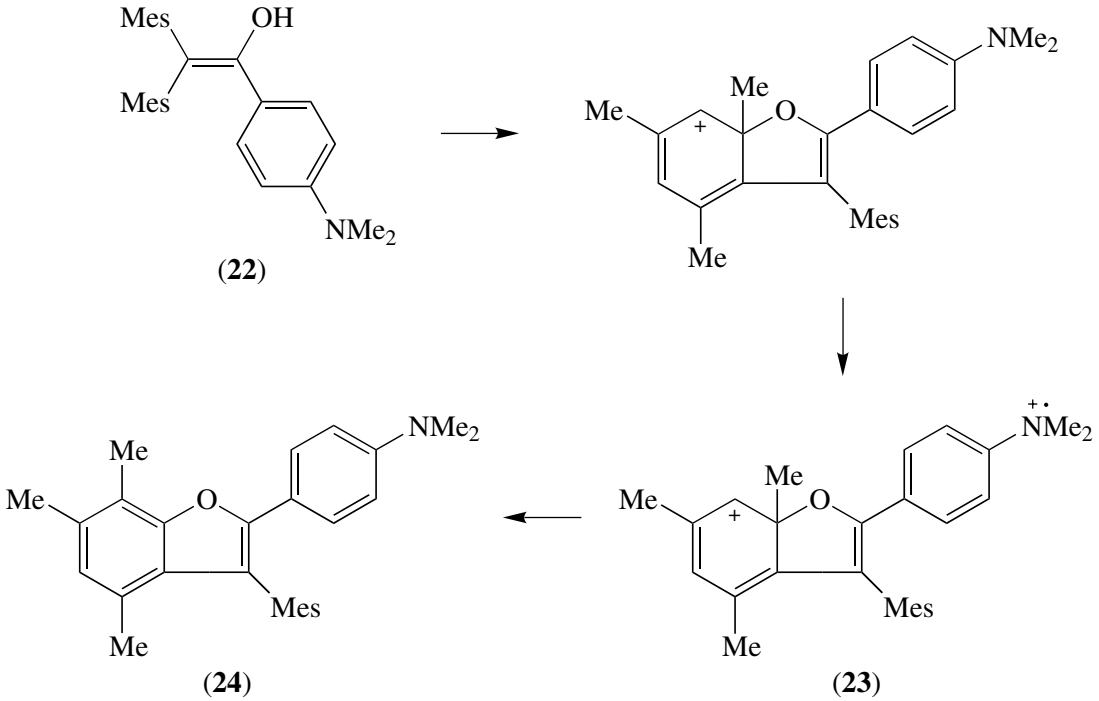


SCHEME 7



SCHEME 8

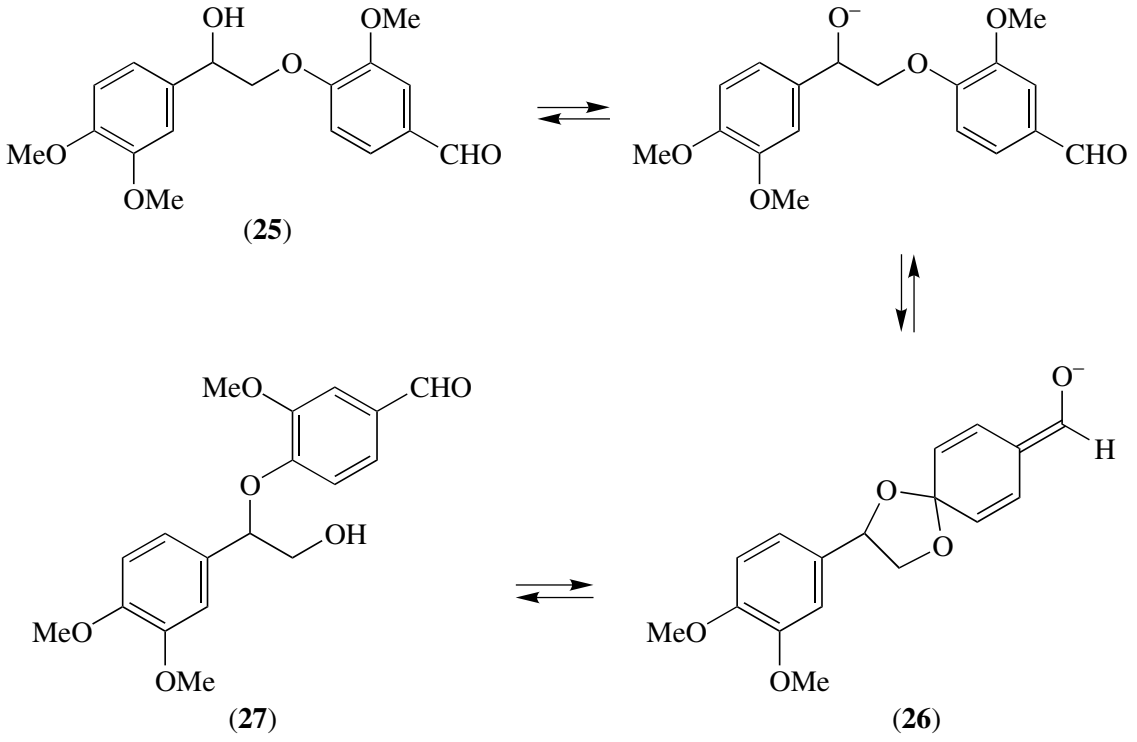
2,2-dimesityl-1-(4-*N*,*N*-dimethylaminophenyl)ethenol (**22**) to benzofuran (**24**). Bromination of the methyl ether of 3,6-di-*t*-butylnaphthalen-2-ol has been found to yield the 1-



(**22**) (**23**) (**24**)

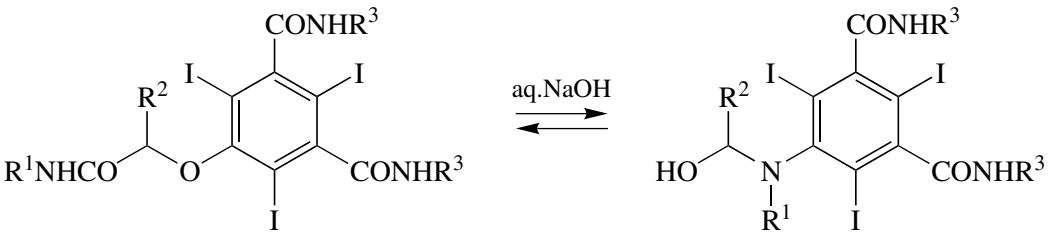
bromo product, which subsequently underwent a rapid proton-catalysed reversible reaction leading ultimately to the formation of the 8-bromo product by an intermolecular route. The authors[24] proposed that the driving force for this conversion is steric buttressing by the 3-*t*-butyl group which destabilizes the initial 1-bromo adduct towards 1-protonation, thus leading to facile loss of the bromonium ion. Low-temperature protonation of 9-isopropenylphenanthrene in FSO_3H–SO_2ClF has led to the direct observation of the 5,6-dihydrobenzanthracenium cation from which the corresponding benz[*de*]anthracene is obtained on quenching,[25] while stable and ultrastable carbocations have been generated spontaneously by inclusion of 4-vinylanisole within zeolites.[26]

Labelling studies have shown[27] that the unusual base-catalysed rearrangement of the *β*-*O*-4 lignin model (**25**) to (**27**) containing an α-*O*-4 linkage, proceeds by way of intermediate (**26**). Acylation of hydroxy aromatic compounds with 2-bromo-2-

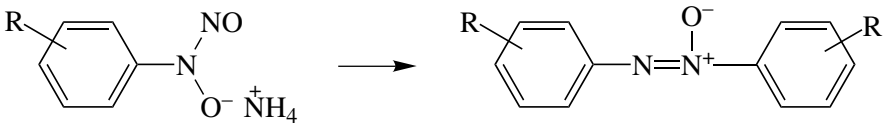


methylpropionamide, followed by Smiles rearrangement of the resulting 2-aryloxypropionamide in a one-pot procedure, has been shown[28] to produce the corresponding 2-hydroxy-2-methyl-*N*-arylpropionamides, while the Smiles rearrangement has been established[29] as a suitable method for the preparation of 5-[(2-hydroxyacyl)amino]-2,4,6-triiodo-1,3-benzenedicarboxamides; see (**28**)→(**29**). The effect of α- and *β*-cyclodextrins on the kinetics of the Smiles rearrangement of salicylic acid esters,[30,31] such as 4-nitrophenyl salicylate,[32] has been studied.

A study[33] has been made of the rearrangement of *N*-triarylmethylanilines to their *p*-triarylmethyl derivatives. *N*-Methyl-*N*-nitrosoaniline has been observed to undergo a Fischer–Hepp rearrangement when treated with montmorillonite clay,[34] and *N*-aryl-*N*-nitrosohydroxylamine ammonium salts (**30**) have been transformed[35] into azoxy

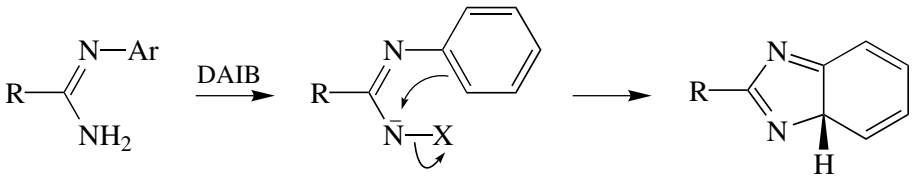


(**28**) (**29**)



(**30**) (**31**)

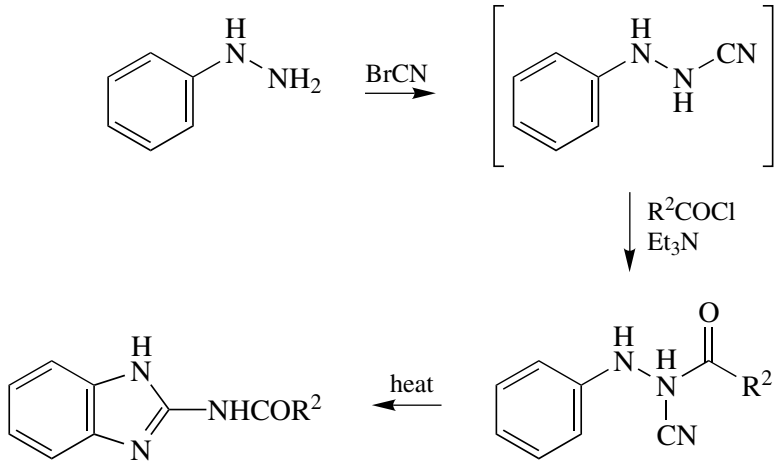
compounds (**31**) upon thermolysis or photolysis. The rearrangement mechanisms of several types of azoxy compounds, including PhN(O)NPh, have been studied[36] by density functional theory, and diazoaminobenzene has been rearranged to *p*-aminoazobenzene in the presence of a catalytic amount of clay.[37] A [9,9]-sigmatropic shift has been proposed[38] to account for the acid-catalysed benzidene rearrangement of bis[4-(2-furyl)-phenyl]diazane to 5,5′-bis(4-aminophenyl)-2,2′-bifuryl. 1-Aryl-2-acyl-2-cyanohydrazines have been found[39] to undergo a smooth thermal rearrangement to provide 2-aminoacylbenzimidazoles (see Scheme 9), while a study with particular emphasis on the influence of the leaving group on the mode of reaction has been made[40] of the oxidative rearrangement and cyclization of *N*-substituted amidines (**32**) to (**33**). A new aromatic rearrangement, observed during the cyclization of ylidenemalonodinitriles in strong acids, has been described,[41] and a free-radical mechanism has been suggested[42] to account for the plethora of products obtained on the pyrolysis of 1,4-diarylthiosemicarbazides.



(**32**) (**33**)

X = Cl, Me_2S^+, Me_3N^+, $PhSO_2O$

The first spectroscopic detection of singlet phenylnitrene has been reported,[43] and the ring-expansion reactions of several fluorinated arylnitrenes have been studied computationally[44] in an attempt to understand the dramatic difference in reactivity between phenylnitrene and pentafluorophenylnitrene. The effect of the trifluoromethyl group on the rearrangement of diarylcarbenes in the gas phase has been examined,[45] and it has been demonstrated that trifluoromethylated diphenylcarbenes can be regarded

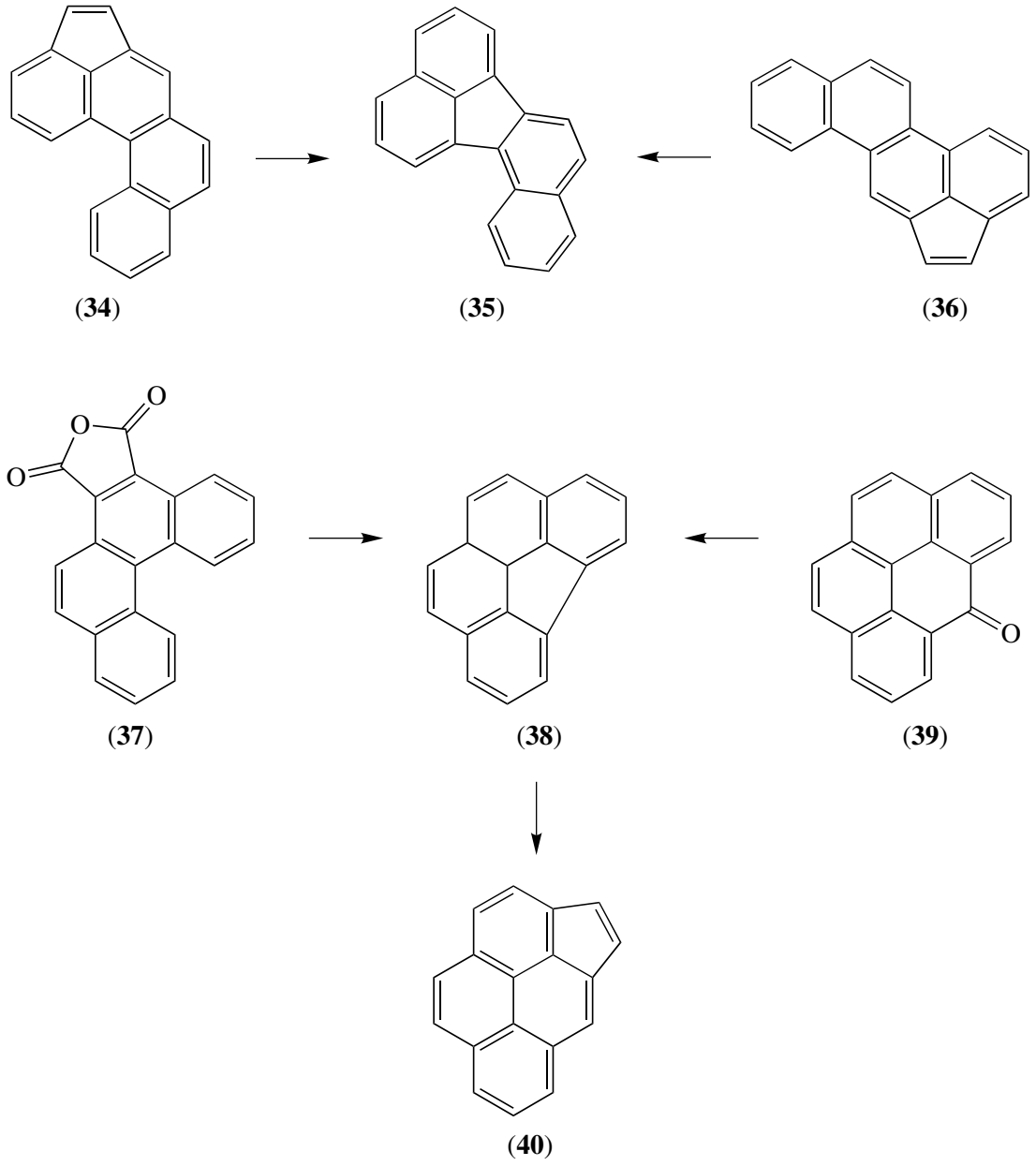


SCHEME 9

as synthetically useful intermediates for trifluoromethylated fluorene derivatives which are otherwise not easily obtainable. A kinetic study of the rearrangement of benzylfluorocarbene to β-fluorostyrenes has been undertaken,[46] and a theoretical study of the thermal isomerization of fulvene to benzene has identified three possible pathways for the process.[47]

Surprisingly smooth skeletal rearrangements, leading to planar polycyclic aromatic compounds, have been found to occur during the intramolecular cyclodehydrogenation of non-planar oligophenylenes,[48] thus providing evidence that the driving force for intramolecular cyclodehydrogenation is the considerable gain in energy of planar polycyclic aromatics compared with their more energetic oligophenylene precursors. Semiempirical AM1 calculations have provided a rationalization,[49] via consecutive ring contraction–ring expansion processes and vice versa, for the unexpected conversion of benz[*l*]acephenanthrylene (**34**) and its isomer, benz[*j*]acephenanthrylene (**36**), into benz[*j*]fluoranthene (**35**). It has been reported[50] that under high-temperature conditions the oxy-polycyclic aromatic hydrocarbons (**37**) and (**39**) are precursors to the $C_{18}H_{10}$ potential energy surface. Benzo[*ghi*]fluoranthene (**38**) was found to be the primary product and it rearranges to cyclopenta[*cd*]pyrene (**40**). An examination of the high-temperature behaviour of 1,8-diethynylanthracene has identified[51] benz[*mno*]aceanthrylene as a transient intermediate for the formation of cyclopenta[*cd*]pyrene in the thermolysis. The observed formation of (**40**) and (**38**) from 3,9-bisethynylphenanthrene and 8-ethynylfluoranthene, respectively,[52] under FVT conditions suggests that redundant ethynyl substituents, which cannot give five- and/or six-membered ring formation via ethynyl ethylidene carbene equilibration followed by carbene C—H insertion, can migrate along the polycyclic aromatic hydrocarbon periphery. The thermal interconversions of the cyclopenta-fused polycyclic aromatic hydrocarbons fluoranthene, acephananthrylene, and aceanthrylene have been re-examined.[53]

The FVP of angular [3]phenylene and bis(2-ethynylphenyl)ethyne has been found to produce benz[*gh*]fluoranthene and chrysene,[54] respectively. A non-chain stepwise radical mechanism which is initiated by hydrogen-atom transfer from the donor to azulene has been proposed[55] for the mechanism of the uncatalysed transfer–



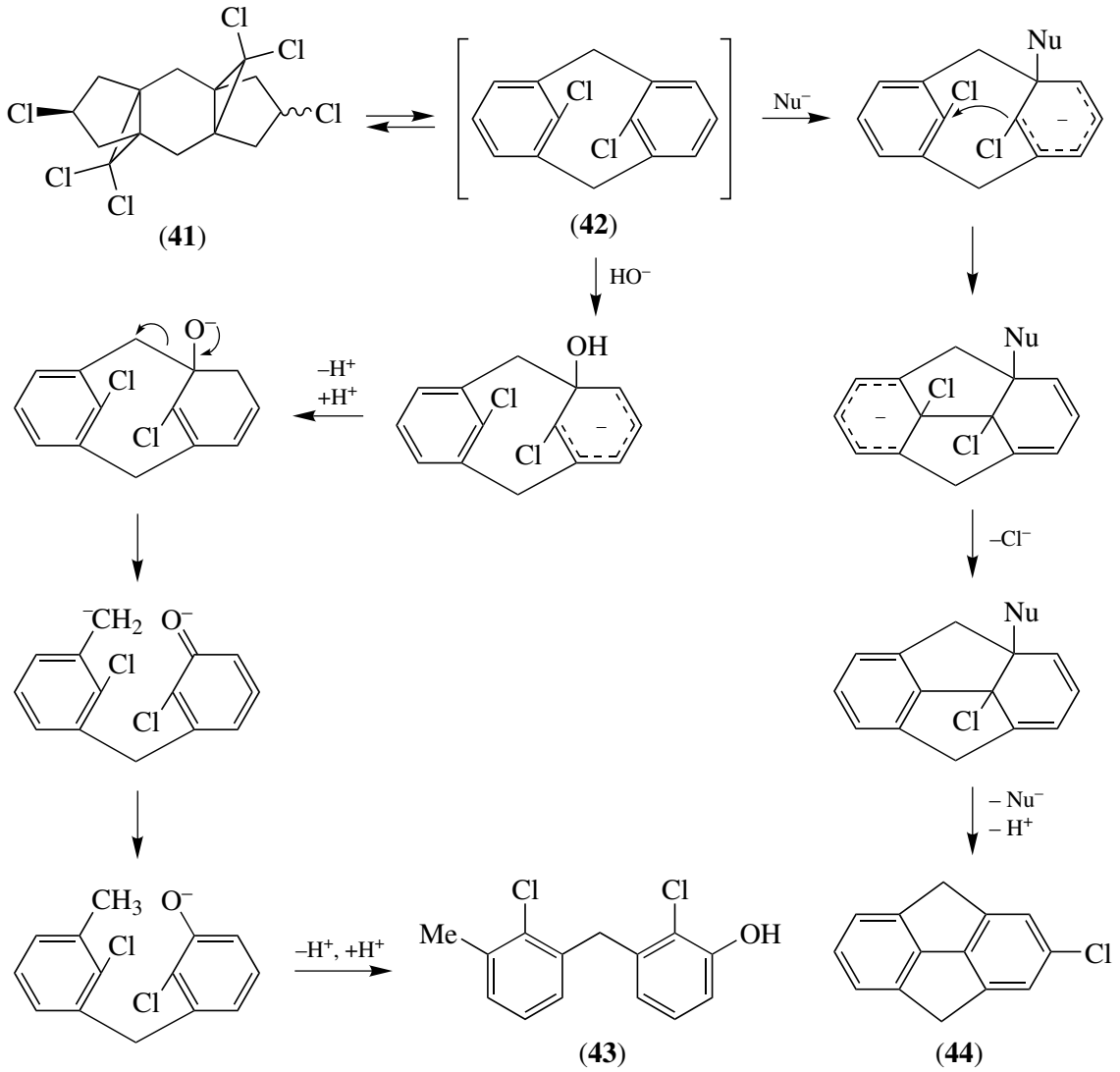
(**34**) (**35**) (**36**)

(**37**) (**38**) (**39**)

(**40**)

hydrogenation of azulene to the isomeric octahydroazulenes with hydrogen donors. Furthermore, the formation of naphthalene and tetralin via the azulene–naphthalene rearrangement, also found to occur under these conditions, has been explained by a combination of the Scott mechanism and the Alder 'walk' mechanism, which are initiated by the hydrogen-transfer step.

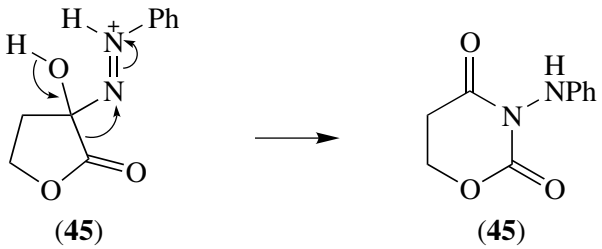
The first observation of the thermal transformation of a strained paracyclophane into its Dewar isomer has been reported.[56] Hexahalobispropellane (**41**), on treatment with potassium *t*-butoxide, has been shown to afford the phenol (**43**) along with (**44**). The formation of both these compounds has been rationalized[57] by invoking the intermediacy of (**42**) (see Scheme 10).

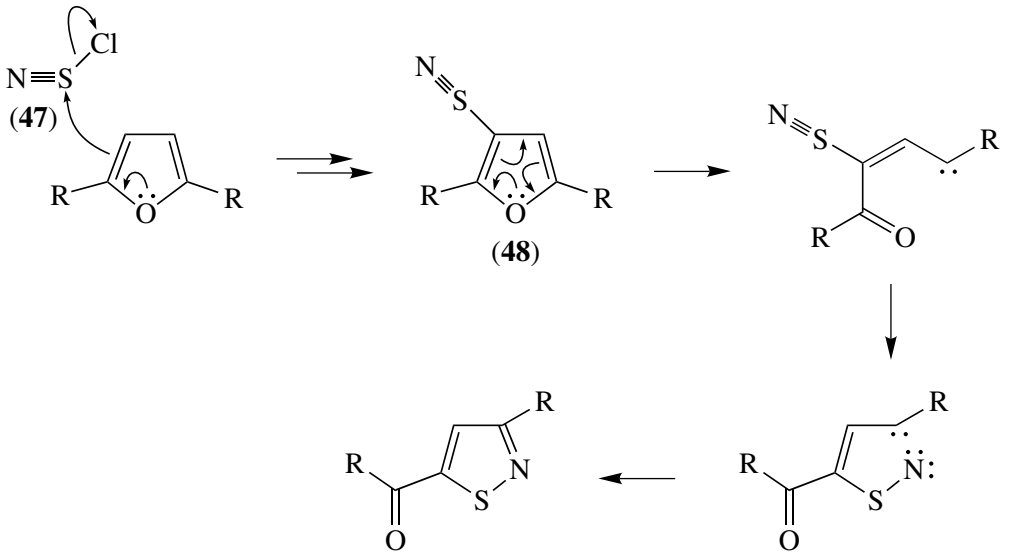


SCHEME 10

Heterocyclic Derivatives

A novel acid-catalysed rearrangement of 2-hydroxy-2-phenylazo-γ-butyrolactone (**45**) to the interesting *N*-substituted tetrahydro-1,3-oxazine-2,4-dione derivative (**46**) has been reported.[58] The photo- and thermo-chemistry of diazo(2-furyl)methane and diazo(3-furyl)methane have been investigated[59] using matrix isolation techniques, and 3,7-diphenylpyrano[4,3-*c*]pyran-1,5-diones have been prepared[60] from 5,5′-diphenyl-

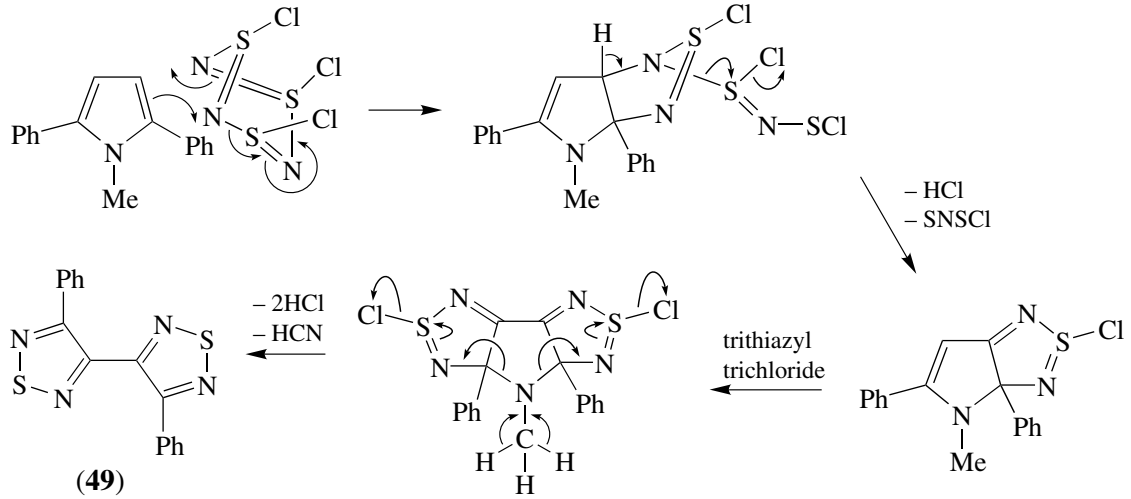




SCHEME 11

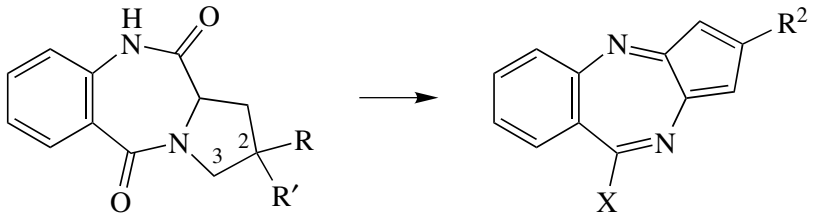
bifuranylidenediones. Thiazyl chloride (**47**) (generated from trithiazyl trichloride) has been found to convert 2,5-disubstituted[61] and 2,3,5-trisubstituted[62] furans into isothiazoles regiospecifically, thus providing a new one-step synthesis of isothiazoles, for which a novel mechanism involving the formation and ring opening of a *β*-thiazylfuran (**48**) has been proposed[63] (see Scheme 11). Although the same reagent converts 1-aryl-2,5-diphenylpyrroles into isothiazole imines, 1-alkyl-2,5-diphenylpyrroles have been found to react very differently with (**47**), yielding the bis-1,2,5-thiadiazole (**49**) in which two *N*−*S*−*N* units have been fused on to the pyrrole and the alkyl-*N* unit has been extruded in a new dissection of the pyrrole ring[64] (see Scheme 12).

The thermal reactions of indole have been studied. The authors[65] suggested that the indole to benzyl cyanide isomerization involves a series of unimolecular steps which



SCHEME 12

are preceded by a very fast indole ⇄ indolenine tautomerism. New arguments have been presented[66] against the direct rearrangement of a spiroindolenine intermediate into the *β*-carboline system in the Pictet–Spengler cyclization, and spiro(indan-2,4′-quinoline)-keto lactams have been obtained from the reaction of 1-keto-2-indanylacetic acid with substituted phenylhydrazine hydrochlorides.[67] The flash vacuum pyrolysis of a series of *N*-alkyl-(or -aryl)-substituted carbazole-1,2-dicarboxylic anhydrides has been shown to lead to 1,2-didehydrocarbazoles, which undergo ring expansion, cyclization, and other reactions.[68] Microwave heating of 2-hydroxy- or 2-oxo-pyrrolo[2,1-*c*][1,4]benzodiazepinediones (**50**) in boiling phosphoryl chloride has led[69] to cyclopenta[*b*][1,4]benzo-

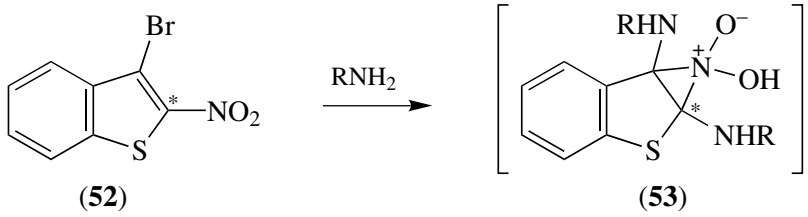


(**50**)

R = OH, R′ = H
R,R′ = O

(**51**)

X = Cl, OH
R^2 = H, Cl

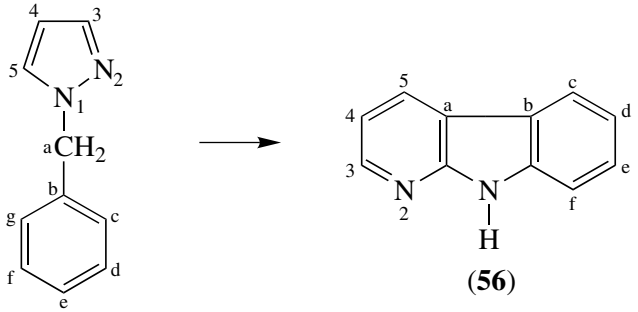


(**52**)

(**53**)

(**54**)

(**55**)



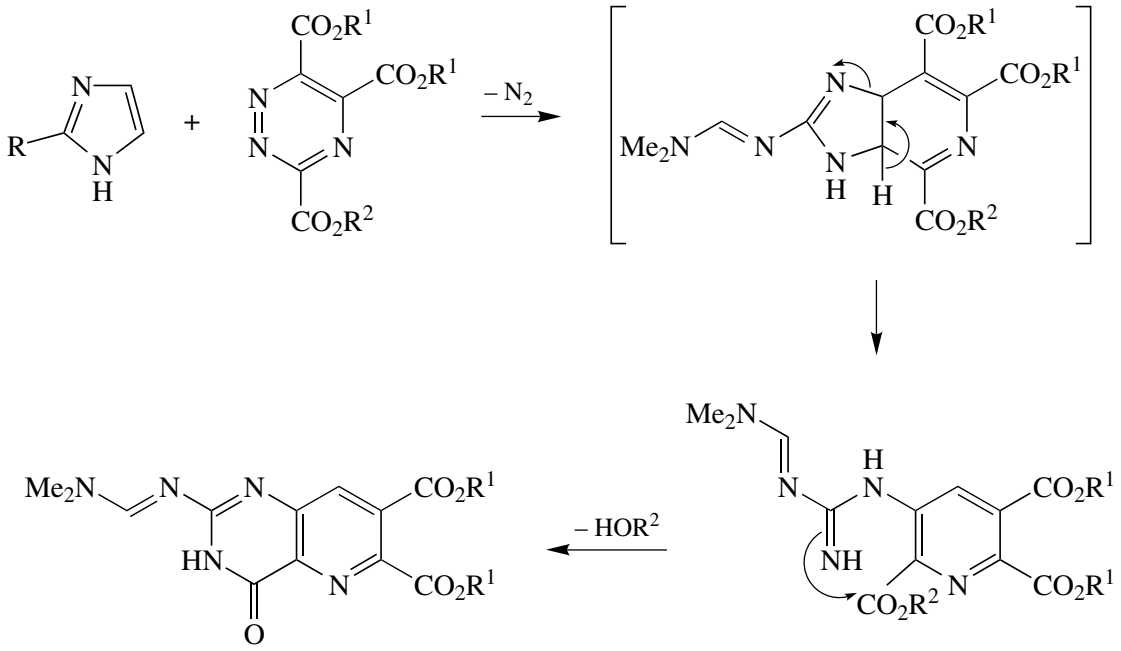
(**56**)

diazepines (**51**). This appears to be a general reaction which can be applied to derivatives bearing a substituent in the 2-position or a C(2)−C(3) double bond.

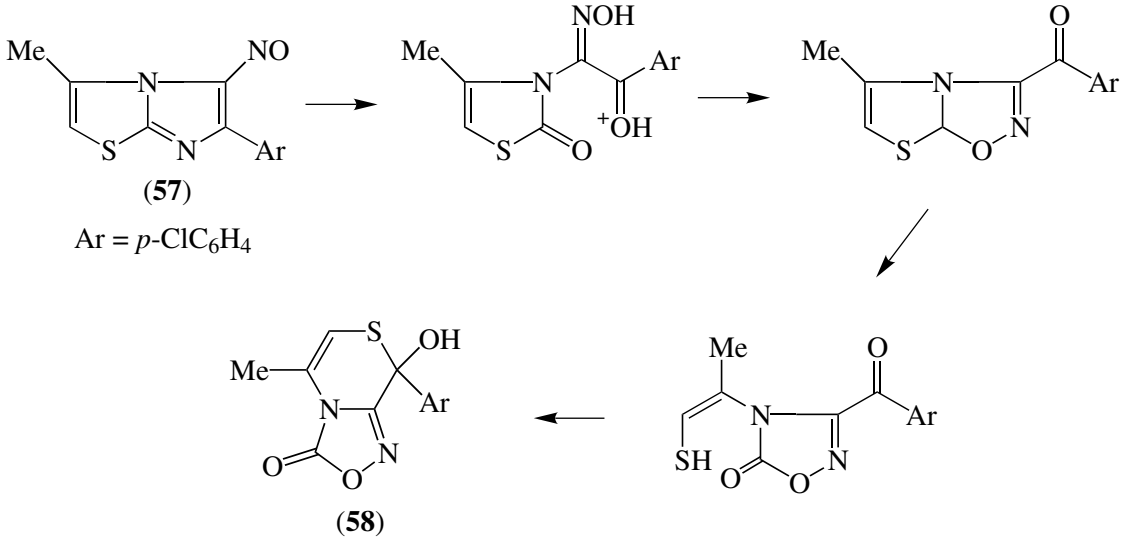
On the basis of labelling studies it has been concluded[70] that an intermediate of the type (**53**) must be involved in the reaction of 3-bromo-2-nitrobenzo[*b*]thiophene (**52**) with 3-(trifluoromethyl)aniline in order to account for the observed labelling patterns in the products (**54**) and (**55**).

A mechanism has been proposed[71] to account for the formation of α-carboline (**56**) as the major product from pyrolysis of 1-benzylpyrrole. 1,4-Dinitro- and 2-methyl-1,4-dinitro-imidazoles have been found to rearrange to their *C*-nitro isomers on heating in solution.[72] The photochemical isomerization of the *N*-oxides and *N*,*N*-dioxides of imidazoles have been reported.[73] Intermolecular cycloadditions between trialkyl 1,2,4-triazine-4,5,6-tricarboxylates and protected 2-aminoimidazole have been found to afford 1*H*-imidazo[4,5-*c*]pyridines and the rearranged 3*H*-pyrido[3,2-*d*]pyrimid-4-ones,[74] the latter presumably being formed by the pathway depicted in Scheme 13. This work has been extended[75] to the preparation of tetrahydro-1,5-naphthyridines. Recent attempts to synthesize the novel imidazo[4,5-*e*][1,2,4]triazocine ring system have been found to result in a number of novel rearrangements.[76] 3-Substituted 6*H*-imidazo[1,2-*c*]quinazolin-5-ones have been shown to undergo a Dimroth-type rearrangement to the thermodynamically more stable 2-substituted 6*H*-imidazo[1,2-*c*]quinazolin-5-ones.[77] Scheme 14 has been proposed[78] to account for the HCl-mediated rearrangement of 6-(4-chlorophenyl)-3-methyl-5-nitrosoimidazo[2,1-*b*][1,3][thiazole (**57**) into 8-(4-chlorophenyl)-8-hydroxy-5-methyl-8*H*-[1,4]thiazino[3,4-*c*][1,2,4]oxadiazol-3-one (**58**).

A common reaction intermediate (**59**) has been invoked[79] to account for the isomerization of 5-alkoxyisoxazoles to azirine derivatives, and the reductive cleavage of 5-alkyl(aryl)isoxazoles to enamino ketones, in the presence of a catalytic amount of

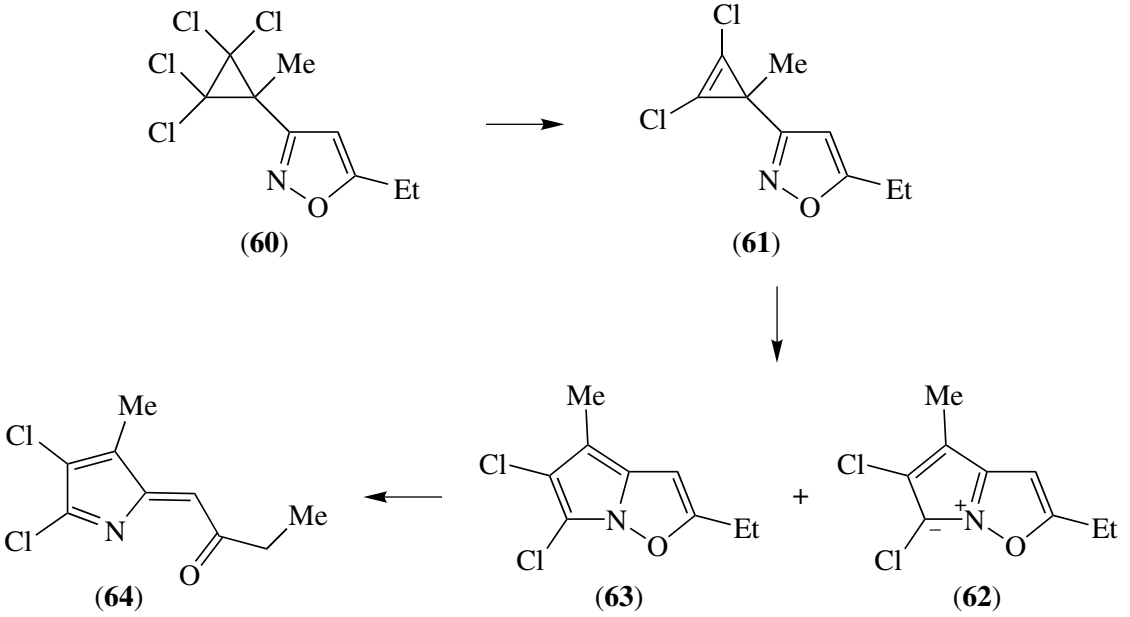


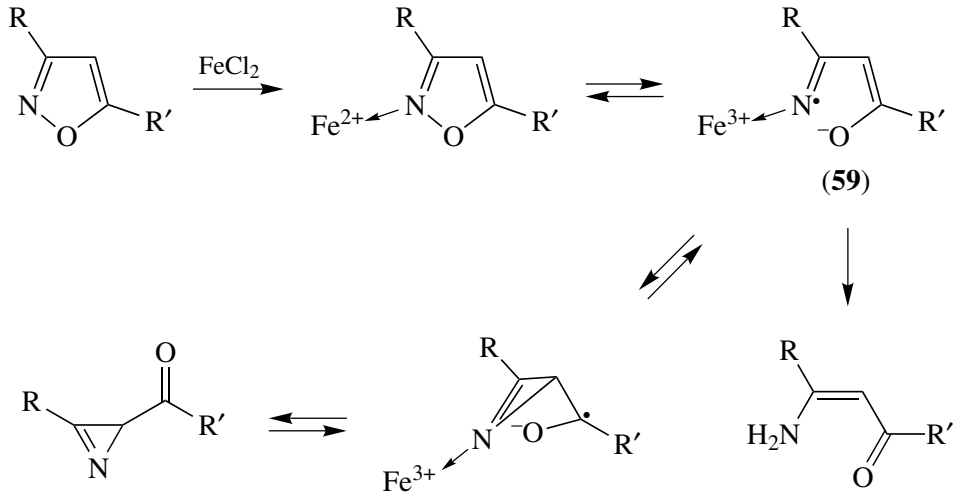
SCHEME 13



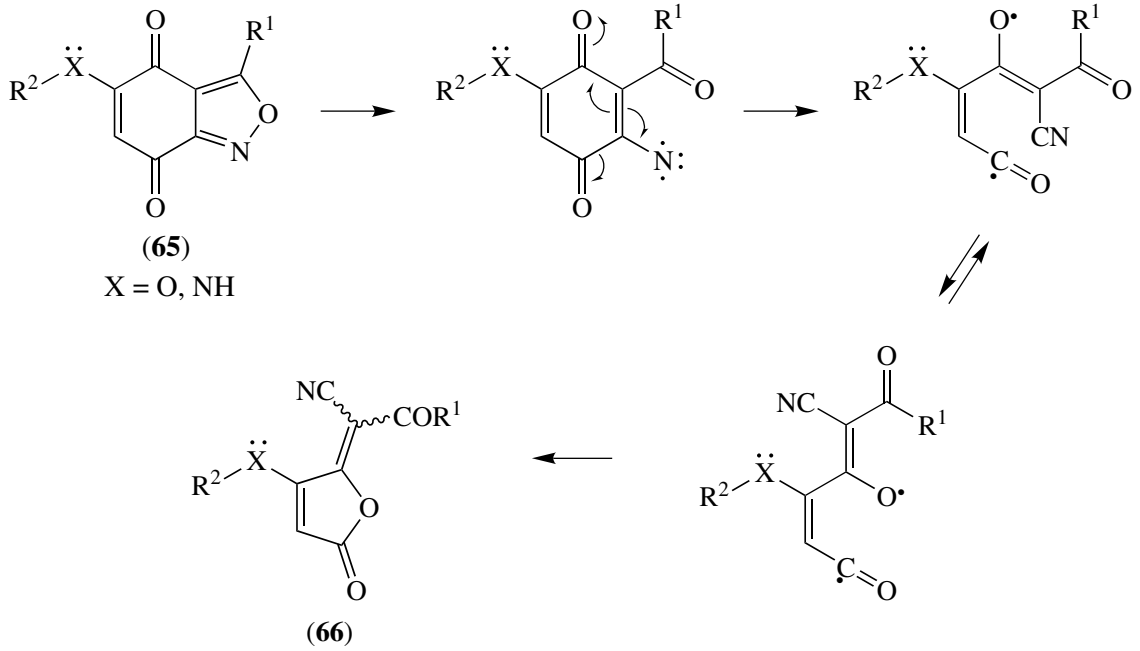
SCHEME 14

iron dichloride (see Scheme 15). It has been reported that a number of tetrachlorocyclopropanes bearing an isoxazole (**60**) or bicyclic isoxazoline at C(3), lead directly to 2-alkenoylpyrroles (**64**) on reaction with methyllithium. The formation of (**64**) has been explained[80] in terms of an initial 1,2-dechlorination to produce the cyclopropene (**61**) followed by ring opening of this to the corresponding vinylcarbene which cyclizes to (**62**) and (**63**); fragmentation would then account for (**64**). A new rearrangement of 2,3-dihydroisoxazoles has been described,[81] and a series of thiazolo[5,4-*d*]isoxazoles have been prepared[82] by the interaction of 4-bromo-3-substituted-(4*H*)-isoxazol-5-ones with alkyl(aryl)thiocarbamates and related derivatives. On direct irradiation, [2,1]benzisoxazolequinones (**65**) have been shown to rearrange to the corresponding γ-cyanoalkylidenebutenolides (**66**). A mechanism



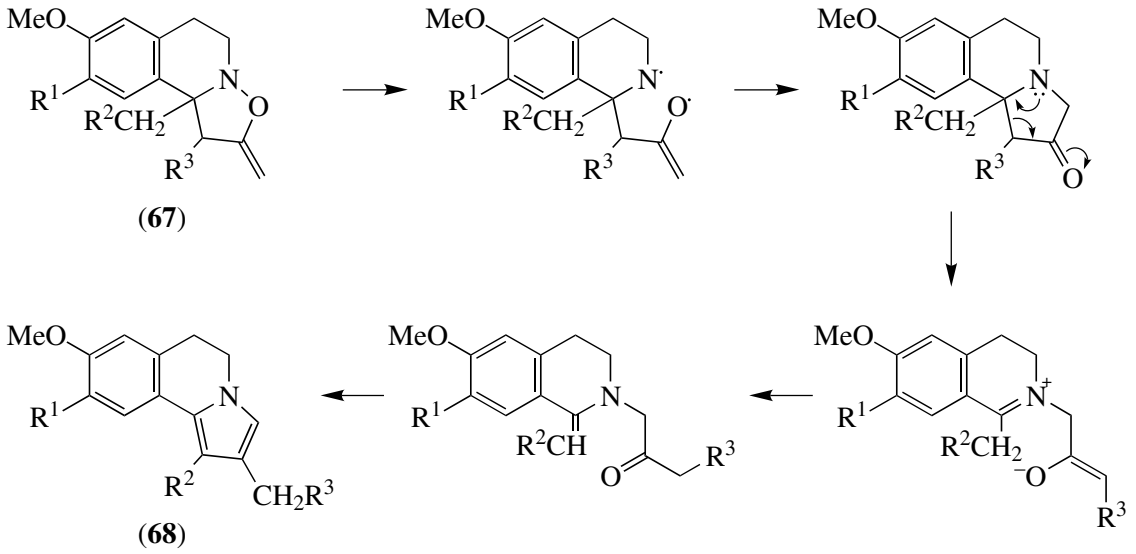


SCHEME 15



SCHEME 16

involving a triplet nitrene intermediate has been proposed[83] for the reaction (see Scheme 16). The formation of 5,6-dihydropyrrolo[2,1-*a*]isoquinoline derivatives (**68**) from 5-methyleneisoxazolidines (**67**) has been rationalized[84] on the basis of two competitive, consecutive rearrangements, the major route being the transient formation of pyrrolidin-3-ones followed by their novel rearrangement via 3,4-bond scission and cyclo-condensation (see Scheme 17). A new rearrangement of oxazolium salts to *δ*-3-pyrrolin-2-ones has been observed,[85] while oxazolium salts (**69**) produced from the reaction of tropones with nitrilium salts have been found to undergo cleavage of the N−C(3a) bond followed by a Chapman rearrangement to afford[86] stable *N*-acyliminium salts (**70**).



(**67**) (**68**)

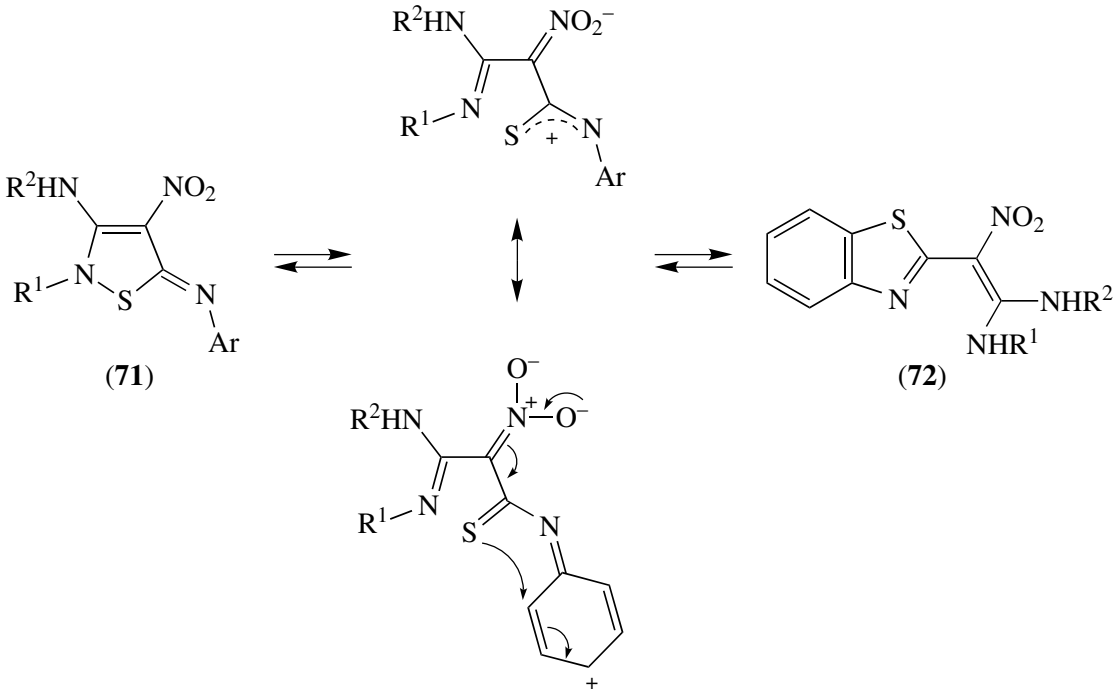
SCHEME 17

(**69**) (**70**)

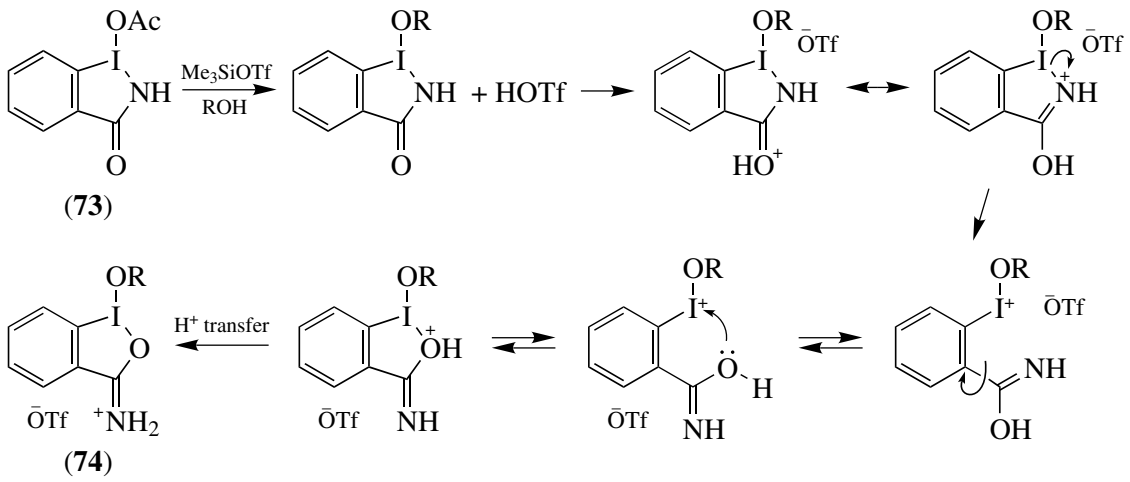
The 1,2-hydrogen shift isomers of neutral (singlet and triplet) thiazole and its radical cation have been investigated[87] by a combination of mass spectrometric experiments and hybrid density functional theory calculations. An unexpected isomerization of *N*-aryl-3-amino-4-nitroisothiazole-5(2*H*)-imines (**71**) to 2-(benzothiazol-2-yl)-2-nitroethene-1,1-diamines (**72**) has been reported.[88]

It has been demonstrated[89] that the reaction of acetoxybenziodazole (**73**) with alcohols in the presence of trimethylsilyl triflate produces 3-iminobenziodoxoles (**74**). A plausible mechanism for the process is shown in Scheme 18.

The rearrangements of 1,2,3-triazolines to aziridines and imines have been reviewed.[90] 1-Arylamino-2-(4-cyanobutyl)-3,4-bis(alkoxycarbonyl)pyrroles have been generated[91] by heating tricyclic 7,8,9,10-tetrahydro-3*H*,5*H*-benzo[*d*]pyrrolo[1,2-*c*]-[1,2,3]triazoles, while it has been shown that the reaction of 1,3-diaryl-*v*-triazolo-[1,5-*a*]benzimidazole (**75**) with dimethyl sulfate results in ring transformation to a benzimidazolylindazole (**77**). A process involving ring opening to a nitrenium cation (**76**) and subsequent electrophilic ring closure has been proposed[92] to account for product formation. A new fused nitrogen–phosphorus–sulfur ring system (**78**) has been identified[93] from the reaction of substituted 1,2,3-triazolium-1-imide 1,3-dipoles with Lawesson's reagent (see Scheme 19), and although flash vacuum pyrolysis of α-benzotriazolyl-β-oxophosphorus ylides generally leads to loss of both R_3PO and N_2, it

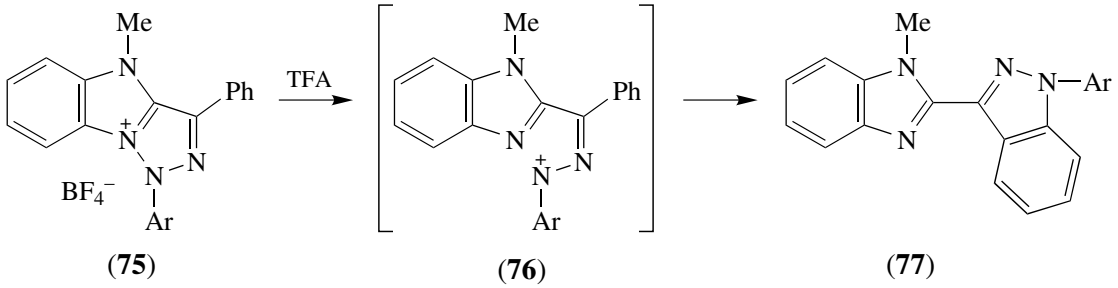


(**71**) (**72**)

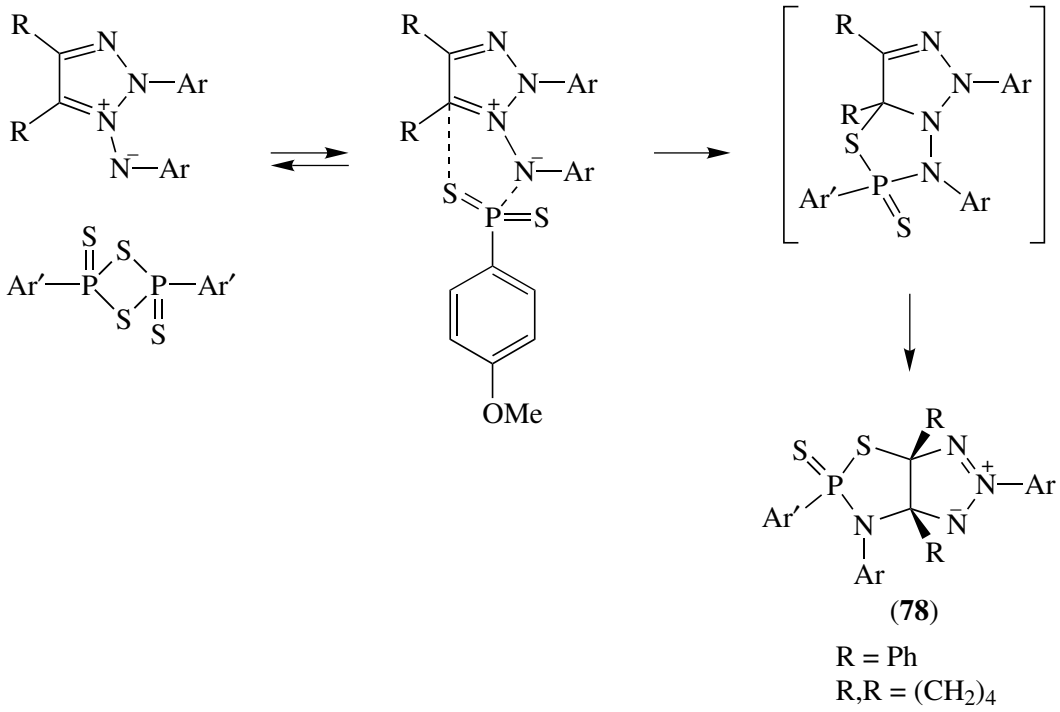


(**73**) (**74**)

SCHEME 18

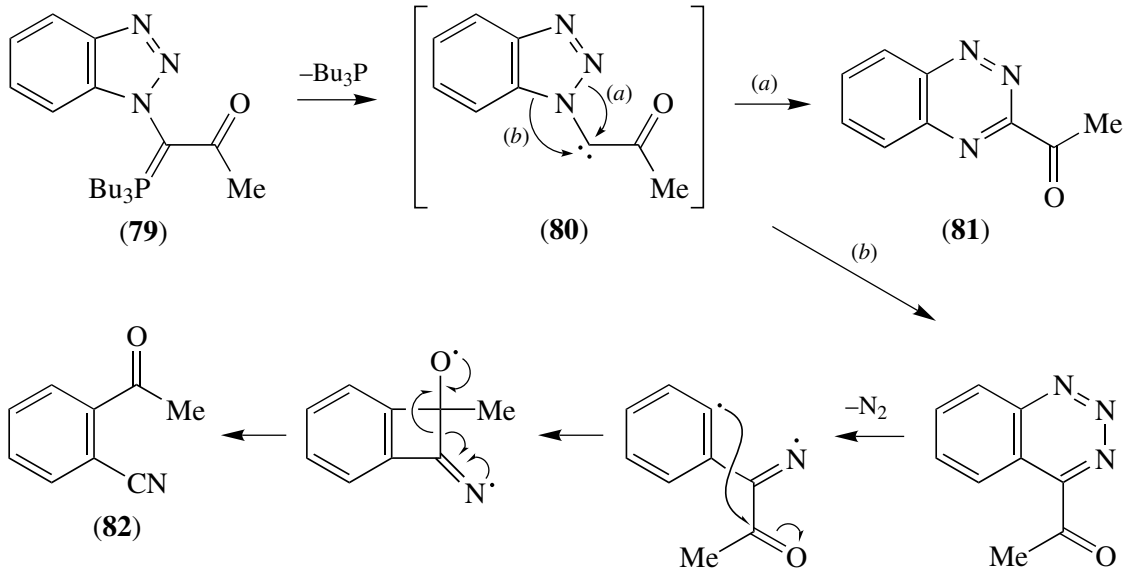


(**75**) (**76**) (**77**)

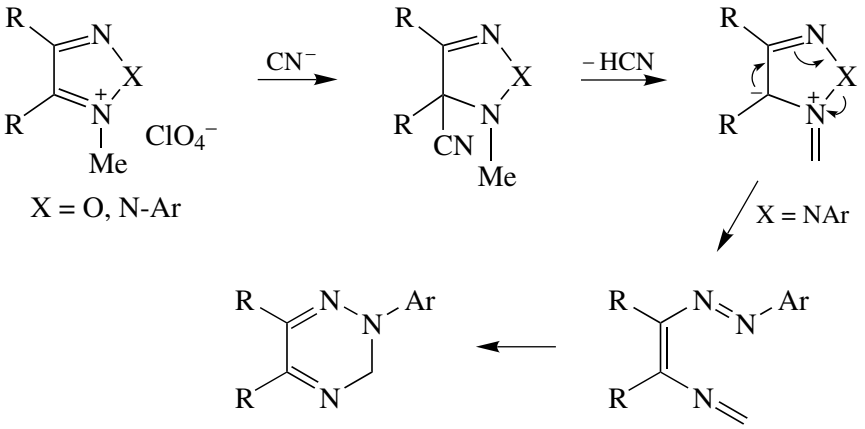


SCHEME 19

has been shown[94] that, in the case of (**79**), extrusion of Bu_3P occurs instead, with the formation of 3-acetyl-1,2,4-benzotriazine (**81**) and 2-cyanoacetophenone (**82**). These products appear to be derived from rearrangement of an initially formed carbene (**80**) (see Scheme 20). The mechanism of the base-catalysed ring expansion of 1,2,3-triazolium and *N*-methyl-1,2,5-oxadiazolium perchlorate salts to six-membered azines has been studied[95] (see Scheme 21).



SCHEME 20



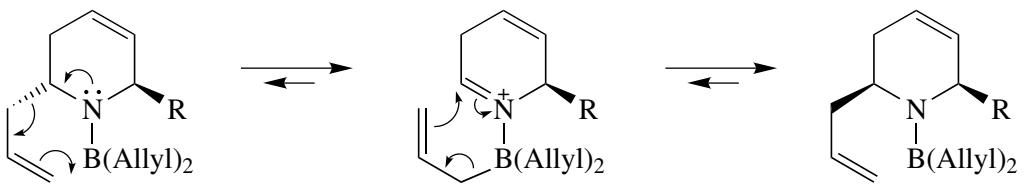
SCHEME 21

The photolysis of 1,2,4-oxadiazoles in the presence of sulfur nucleophiles has been shown to afford 1,2,4-thiadiazoles. N−S bond formation between the ring species and the sulfur nucleophile is thought to account for the observed products.[96] A review has appeared which includes an account of the rearrangement of 1,2,3-thiadiazoles to other heterocycles such as 1,2,3-triazoles and 1,2,3,4-thiatriazoles.[97]

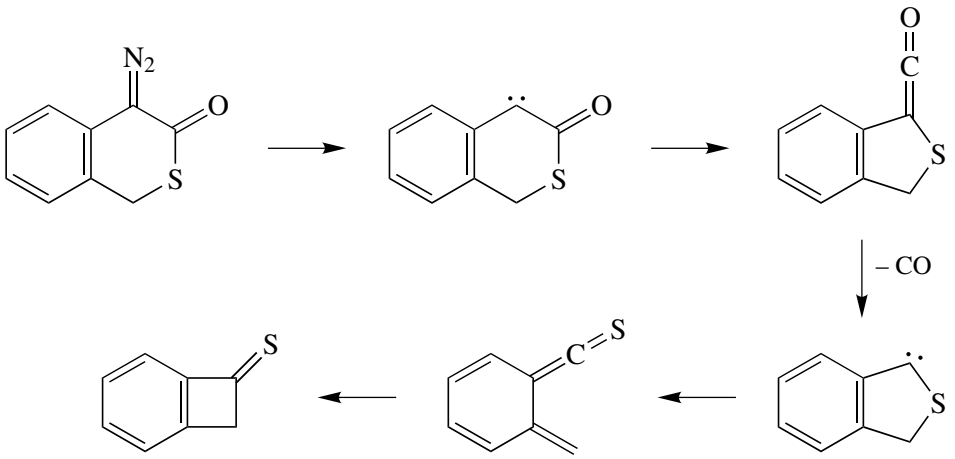
It has been shown[98] that when *N*-methyl-*N*-pyridylnitramines are heated they rearrange to the corresponding methylaminopyridines by an intramolecular pathway. A deallylboronation–allylboronation process outlined in Scheme 22 has been presented in order to account for the isomerization of *trans*-2-allyl-6-alkyl(aryl)-1,2,3,6-tetrahydropyridines into the corresponding *cis* isomers on heating with triallylboron. The authors[99] proposed that the driving force for this mechanism is the greater thermodynamic stability of the *cis* isomer (with two pseudo-equatorial groups) compared with the corresponding *trans* isomer.

The rearrangements of some quinoline-4-spiro heterocycles to fused heterocycles have been reported,[100] as has the thermal rearrangement of 4-alkoxy-3′-alkylthio-3,4′-diquinolinyl sulfides to 1-alkyl-1,4-dihydro-4-oxo-3′-alkylthio-3,4′-diquinolinyl sulfides.[101] It has been established[102] that aqueous 6-hydroxyquinoline in the first excited singlet state undergoes protonation of the amine group first, then deprotonation from the enol group, and finally rearrangement to the quinoid form.

A study of the vacuum pyrolysis of 4-diazoisothiochroman-3-one with ultraviolet photoelectron spectroscopy has established the mechanism shown in Scheme 23 for its decomposition,[103] while acid-catalysed hydrolysis of the same compound has been



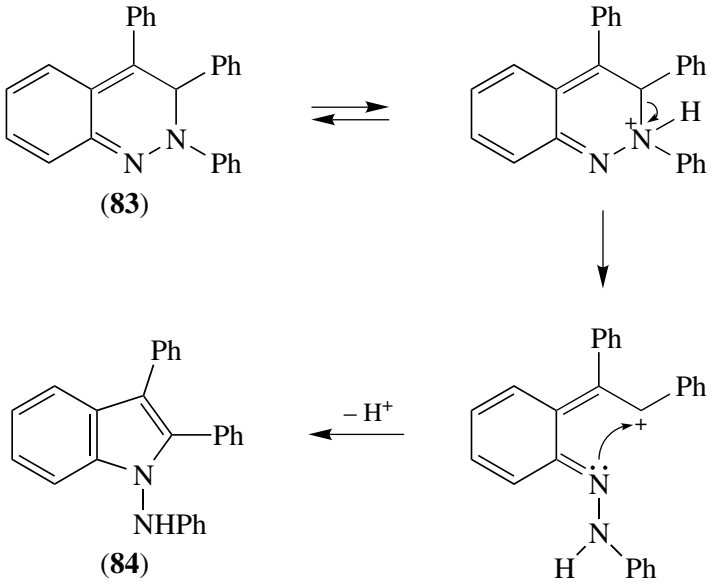
SCHEME 22



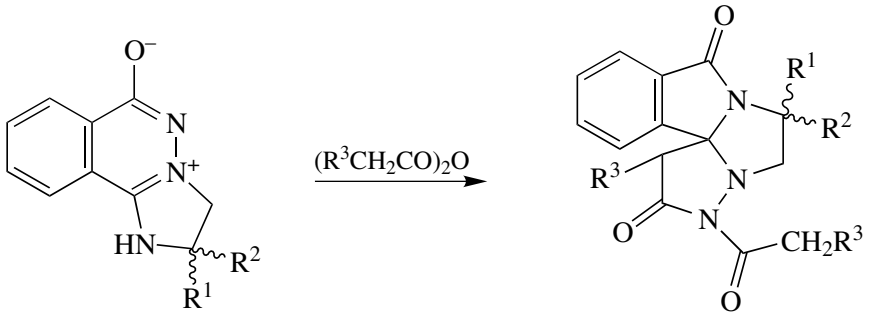
SCHEME 23

found to afford[104] the ring-contracted product, 1,3-dihydrobenzo[*c*]thiophene-1-carboxylic acid.

The mechanism presented in Scheme 24 is thought[105] to accommodate the formation of *N*-anilino-2,3-diphenylindole (**84**) from the acid-catalysed rearrangement of 2,3,4-triphenyl-2,3-dihydrocinnoline (**83**). On treatment with acetic or propionic anhydrides, 2,3-dihydroimidazo[2,1-*a*]phthalazin-4-ium-6-olates (**85**) have been found[106] to undergo an interesting ring transformation to afford triazapentalenoindanones (**86**). On boiling with HCl, *N*-6-methyl-8-oxoadenine has been shown to rearrange to 9-methyl-8-oxoadenine, presumably through fission and reclosure of the imidazole ring.[107] Under similar conditions, 3-methyl-8-hydroxyadenine afforded 1-methyl-8-oxoadenine and, on prolonged treatment with boiling water, 1-alkoxy-7-alkyladenines have been found



SCHEME 24

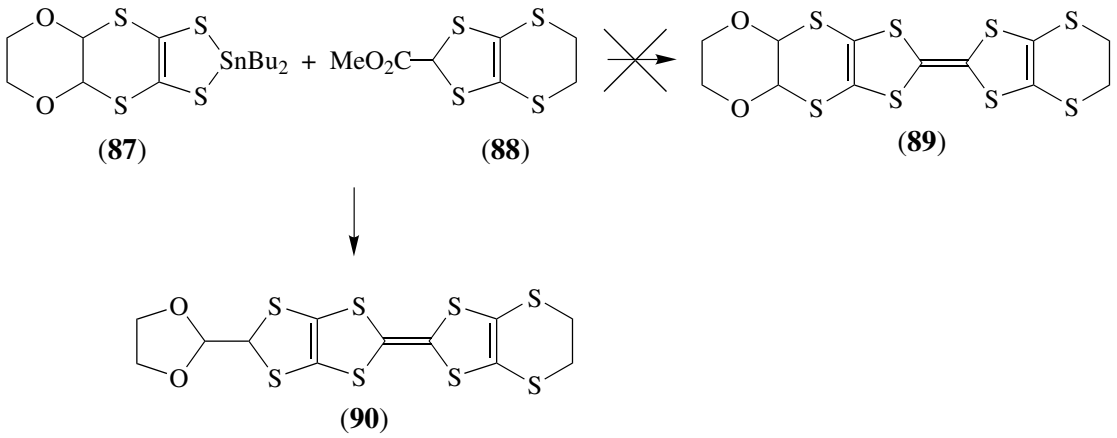


(**85**) (**86**)

to undergo hydrolytic cleavage at the N(1)−C(2) and the N(1)−C(6) bonds to produce imidazole-5-carboxamidines.[108]

An unexpected rearrangement of dihydro-1,4-thiazine has been reported.[109]

A recent attempt to prepare the bis(ethylenedithio)tetrathiafulvalene derivatives fused with a 1,4-dioxane ring, viz. (**89**), by the Me_3Al-promoted reaction of organotin thiolate (**87**) with ester (**88**) was unsuccessful; instead the reaction resulted[110] in the production



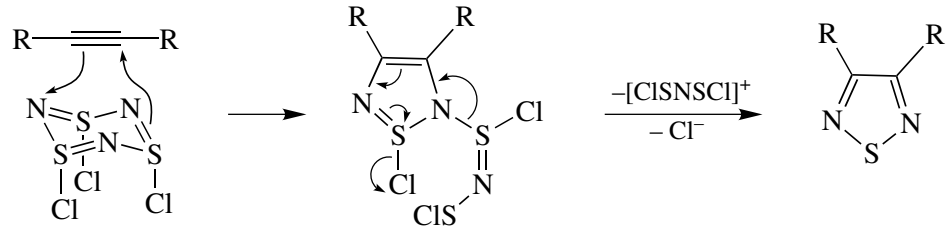
(**87**) (**88**) (**89**)

(**90**)

of a new tetrathiafulvalene derivative with a 1,3-dioxolane ring (**90**).

1,2,5-Thiadiazoles have been prepared[111] in a one-pot reaction of trithiazyl trichloride with alkynes (see Scheme 25).

A mechanism involving an azatropilium cation has been discussed[112] as a possibility for the observed ring contraction of 3,6- and 2,5-di-*t*-butyl-3*H*-azepines when these compounds are treated successively with bromine and aqueous K_2CO_3.



SCHEME 25

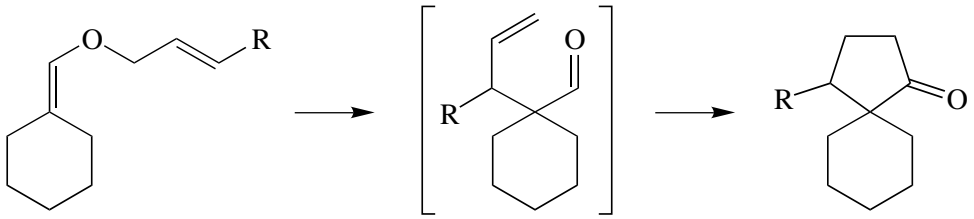
Sigmatropic Rearrangements

[3,3]-Migrations

Claisen and related rearrangements

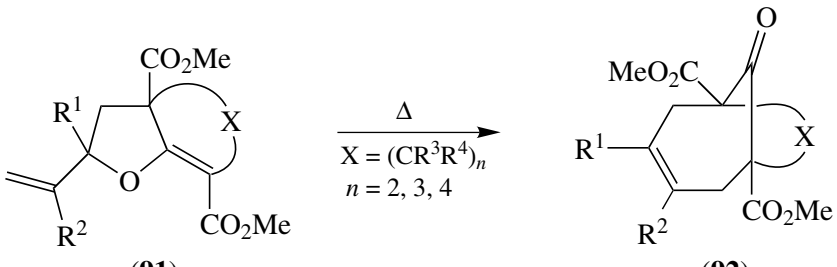
The symmetry and the corresponding selection rules of sigmatropic reactions have been studied.[113]

The response of the Claisen rearrangement to solvents and substituents has been reviewed.[114] Transition structures, activation energies, and reaction energies have been calculated[115] by *ab initio* quantum mechanical methods for the Claisen rearrangements of a number of hydroxy-substituted allyl vinyl ethers, and an analysis has been carried out[116] of the effect of various substituents on the Claisen rearrangement of 2- and 6-substituted allyl vinyl ethers, using *ab initio* and density functional theory. The effect of water on the Claisen rearrangement of allyl vinyl ether has been modelled[117] using both *ab initio* continuum and Monte Carlo simulation techniques, while the effect of water on the energetics of the Claisen rearrangement of chorismate to prephenate has been investigated[118] by *ab initio* electronic structure and simulation methods. A novel procedure for the synthesis of spiro[4.5]decan-1-ones has been described.[119] The key step in the synthesis is a one-pot combination of the Claisen rearrangement of allyl vinyl ethers followed by an intramolecular hydroacylation catalysed by RhCl(cod)(dppe) (see Scheme 26). Fused polycyclic enol ethers (**91**) have been found[120] to undergo a facile Claisen rearrangement leading to good yields of functionalized, bridged bicyclo[4.*n*.1]ring systems (**92**). The effect of β-cyclodextrin on



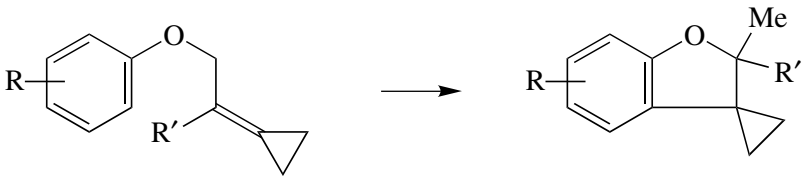
SCHEME 26

the photo-Claisen rearrangement of allyl phenyl ether has been studied,[121] as has the effect of solvent on the thermal Claisen rearrangement of cinnamyloxybenzene. The observed formation of diethylene glycol monocinnamyl ether when this reaction is carried out in diethylene glycol has been ascribed[122] to the acidic and high dielectric properties of the glycol solvent which allows the generation and capture of a cinnamyl



(**91**) (**92**)

cationic intermediate. The development of a highly enantioselective aromatic Claisen rearrangement has been achieved[123] by the reaction of catechol monoallylic ethers with a chiral boron reagent. This system has the benefit that it avoids the formation of *para* rearrangement and abnormal Claisen rearrangement products. The first synthesis of spiro[2,3-dihydro-2,2-dimethylbenzofuran-3,1′-cyclopropanes] (**94**) has been achieved[124] by way of an $Mo(CO)_6$-catalysed, one-pot Claisen rearrangement–cyclization reaction of 2-cyclopropylidenearyloxyalkanes (**93**), and a convenient,

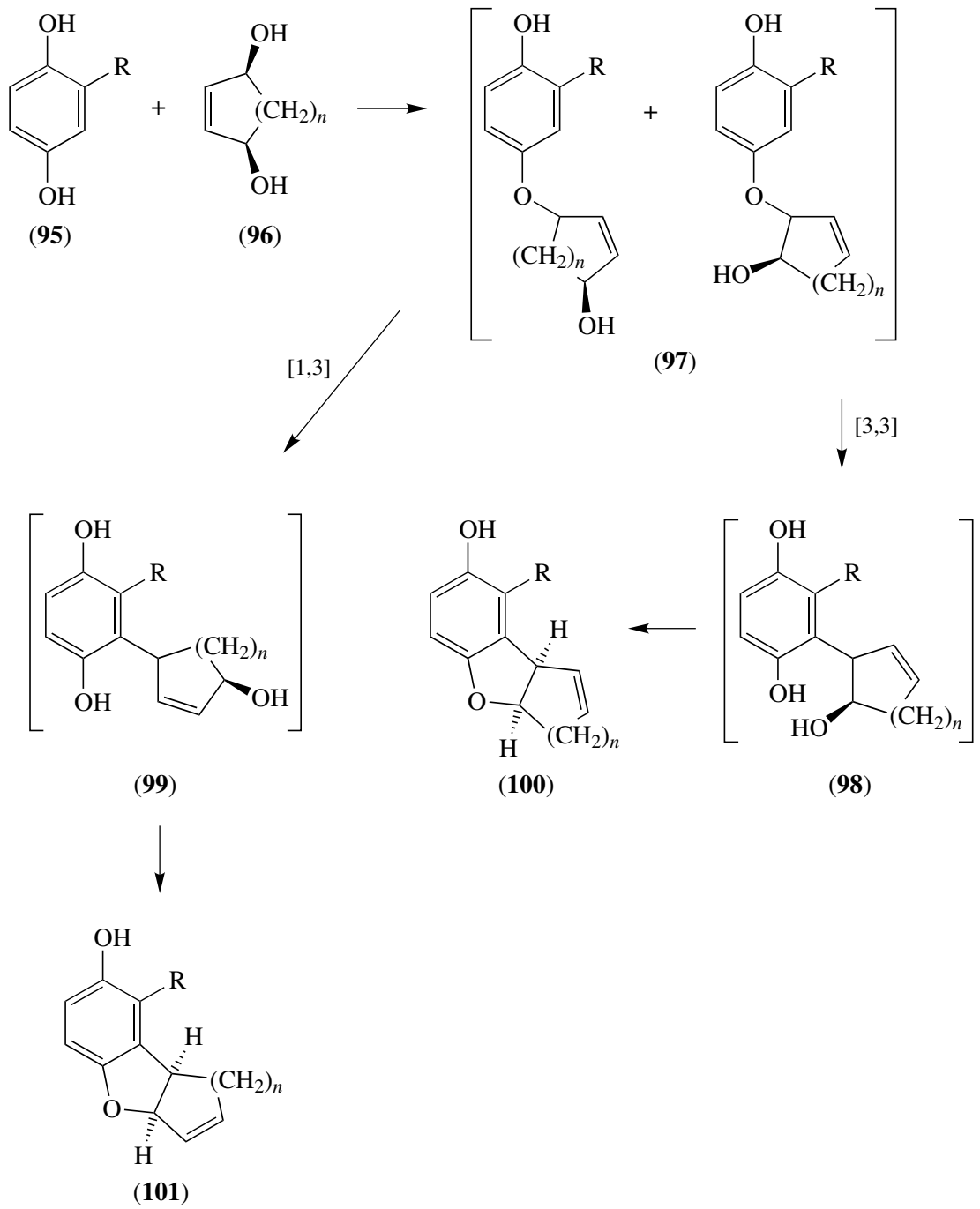


(**93**) (**94**)

one-pot synthetic method has been established[125] for the preparation of benzofuran derivatives (**100**) and (**101**) via the reaction of alkylhydroquinones (**95**) with cycloalkenediols (**96**), in a process which involves a sequence of acid-catalysed formation of ethers (**97**), [3,3]-(and/or [1,3]-)sigmatropic rearrangement, and acid-catalysed intramolecular cyclization of (**98**) and (**99**) generated as intermediates (see Scheme 27). An extension of this methodology using alkoxyhydroquinones with cycloalkenediols has been used[126] to prepare alkoxybenzofurans. A series of crownophanes containing two phenolic moieties within a macrocyclic ring, e.g. (**103**), have been synthesized[127] successfully by a one-step thermal reaction from macrocyclic ethers (**102**), via a tandem Claisen rearrangement. In addition to yielding hydrolysis products, acid-catalysed hydrolysis of propyl phenyl ethers has been found[128] to yield isopropylphenols, resulting from a Claisen rearrangement. 2-Alkenyl 2-bromophenyl ethers have been found to rearrange to 2-(2-alkenyl)phenols by bromine–lithium exchange and further transmetallation with copper(I) cyanide[129] (see Scheme 28). Formally, the transformation represents a Claisen rearrangement which proceeds with retention of the regiochemistry of the allyl fragment and without migration to the *para* position.

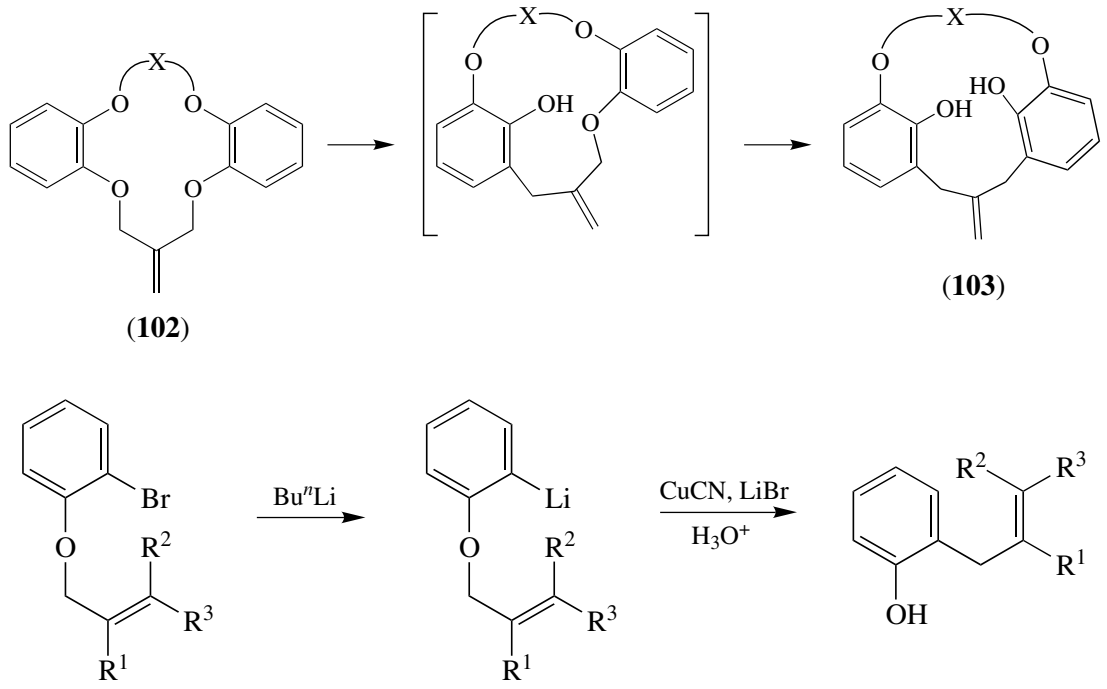
Reductive Claisen rearrangements of allyloxyanthraquinones have been reviewed,[130] and a number of new compounds, including doubly rearranged leuco-1,4-dihydroxy-anthraquinones in the diketo form, have been produced during a re-investigation[131] of the reductive Claisen rearrangement of bis(allyloxy)anthraquinones. At elevated temperatures, 3-(*meta*-substituted aryloxymethyl)coumarins have been found to undergo sigmatropic rearrangements to yield hydroxylated 3-benzylcoumarins.[132]

3-(4-Aryloxybut-2-ynyloxy)-1-methylquinolin-2-ones on heating have been found to undergo a sigmatropic rearrangement to yield 1-aryloxymethyl-6-methyl-3*H*-pyrano-[2,3-*c*]quinolin-5(6*H*)-ones and/or 1-aryloxymethyl-2,5-dimethylfuro[2,3-*c*]quinolin-4(5*H*)-ones,[133] while a number of 1,3-dimethyl-6*H*-pyrano[3,2-*d*]pyrimidine-2,4(1*H*)-diones and 1,3-dimethylfuro[3,2-*d*]pyrimidine-2,4(1*H*)-diones have been prepared from the thermal [3,3]-sigmatropic rearrangement of 1,3-dimethyl-5-(prop-2-ynyloxy)uracils.[134]



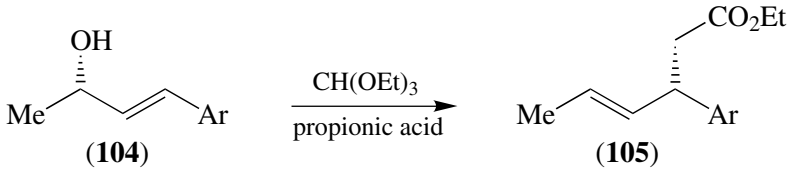
SCHEME 27

It has been demonstrated[135] that the ortho ester Claisen rearrangement of trisubstituted alcohols exhibits significant levels of diastereoselection. Thus, in (*E*)-allylic alcohols a 1,3-diaxial interaction develops in the chair-like transition structure, leading to the *anti* isomer and rendering the reaction *syn* selective, whereas in (*Z*)-allylic alcohols, the 1,3-diaxial interaction develops in the transition state, leading to the *syn* isomer and generating a significant *anti* : *syn* selectivity. A three-step synthesis of (*R*)-

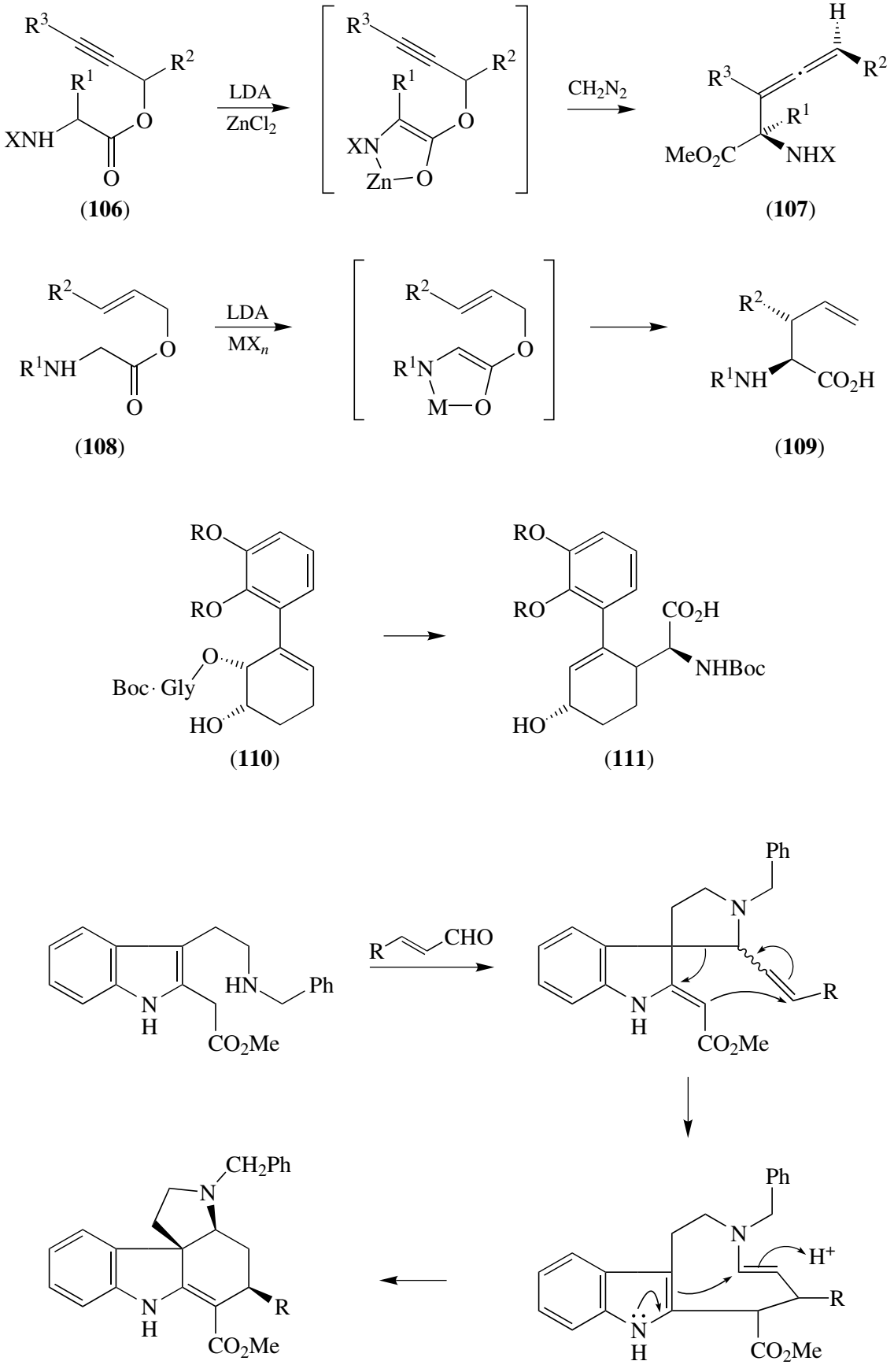


SCHEME 28

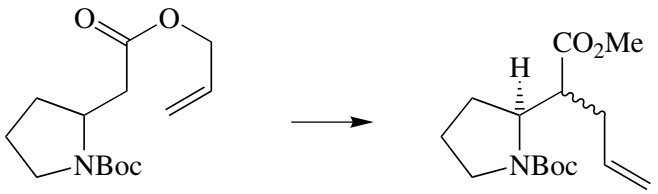
(−)-baclofen has been described[136] in which the key step is an ortho ester Claisen rearrangement of allylic alcohol (**104**) to produce the γ, δ-unsaturated ester (**105**) with high stereoselectivity.



The ester enolate Claisen rearrangements of amino acid propargylic esters (**106**) have been used[137] to produce α-allenic amino acids (**107**), and γ, δ-unsaturated amino acids (**109**) have been prepared[138,139] in a similar manner via the ester enolate Claisen rearrangement of chelated allylic esters (**108**). Unnatural amino acids, useful precursors of morphine, have been prepared[140] via a modified Claisen rearrangement, see (**110**)→(**111**), and the syntheses of morphine alkaloids involving sigmatropic rearrangements and novel ring closures of aromatic methyl pentenyl ethers have been described[141]. A detailed study has been made[142] of the tandem condensation [3,3]-sigmatropic rearrangement and cyclization reaction sequence outlined in Scheme 29, with a view to extending this methodology to the enantioselective generation of tetracyclic ABCE *Strychnos* alkaloid precursors. A diastereospecific approach to 2,6-diaryl-3,7-dioxabicyclo[3.3.0]octane lignans using the Ireland–Claisen rearrangement of unsaturated oxamacrolides has been described,[143] and an enolate Claisen rearrangement of the homoproline allyl ester (**112**) has been used[144] to obtain pyrrolizidine precursors (**113**). Trifluoromethylated compounds containing four

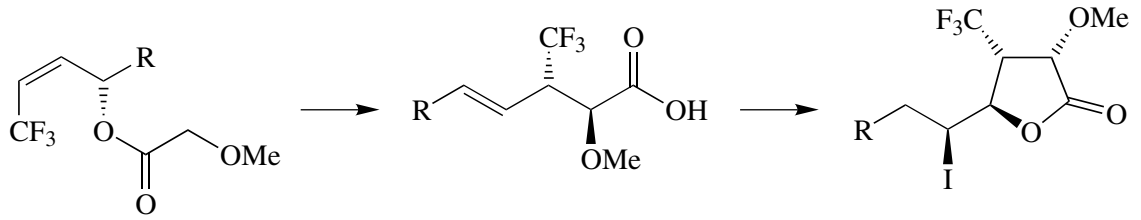

R3
R2
R1
XNH
O
O
LDA
ZnCl2
XN
Zn—O
CH2N2
H
MeO2C
NHX
(106)
(107)
R1NH
LDA
MXn
M—O
R1N
(108)
(109)
RO
Boc·Gly
HO
CO2H
NHBoc
(110)
(111)
HN
Ph
N
H
CO2Me
CHO
CH2Ph
H+

SCHEME 29



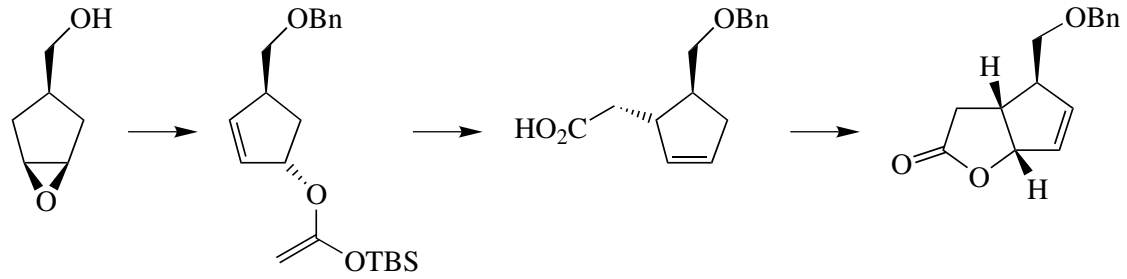
(**112**) (**113**)

consecutive asymmetric centres have been synthesized[145,146] via a sequential [3,3]-Ireland–Claisen rearrangement and iodolactonization (see Scheme 30). The asymmetric syntheses of a prostaglandin precursor and (+)-iridomyrmecin have been reported.[147]



SCHEME 30

The method involves a highly enantioselective rearrangement of an epoxide and a subsequent Ireland–Claisen rearrangement (see Scheme 31). The enolate Claisen rearrangements of [4-7-η^4-4-(1-acyloxy-2,4,6-octatrienyl)]tricarbonyliron complexes

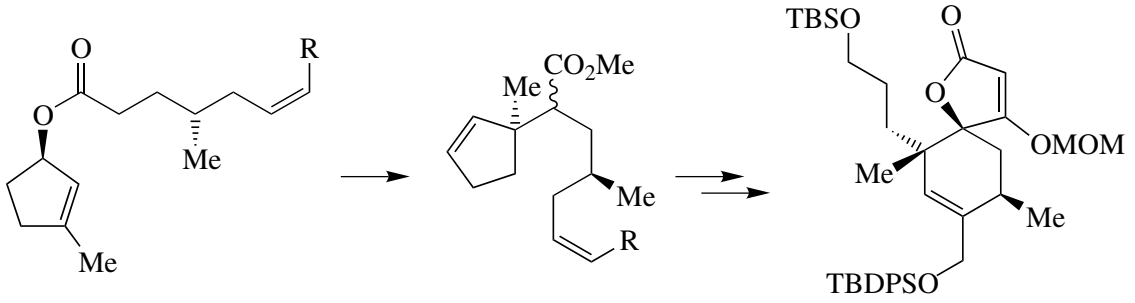


SCHEME 31

have been found to exhibit high diastereofacial selectivity with the developing carbon–carbon bond forming *anti* to the Fe(CO) substituent.[148] Spirotetronate (**114**) has been synthesized[149] by a route featuring a Claisen rearrangement and an intramolecular aldol reaction (see Scheme 32), and enantiomerically pure dihydrooxacenes (**116**) have been prepared[150] using the retro-Claisen rearrangement of vinylcyclobutane diesters (**115**).

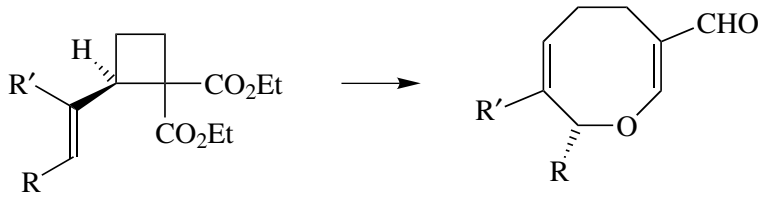
Whereas the lithium enolates of acetate and propionate esters of difluoroallylic alcohols are known to fragment rapidly, methoxy- and benzyloxy-acetates have been found[151] to form chelated enolates which undergo a smooth [3,3]-sigmatropic rearrangement as their silyl ketene acetals to afford highly functionalized difluoro compounds (see Scheme 33). Allenic silyl ketene acetals (**117**) have been used[152] to prepare 2-substituted methyl 3,4-dienoates (**118**).

The intramolecularity of the thermal rearrangement of 1-aryl-5-allyloxy-1*H*-tetrazoles to 1-aryl-4-allyl-1,4-dihydrotetrazol-5-ones has been investigated through

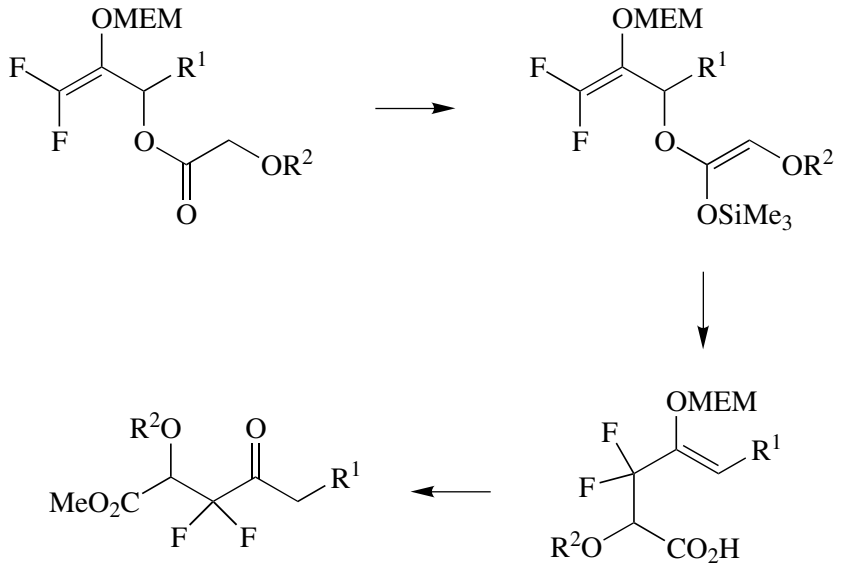


(**114**)

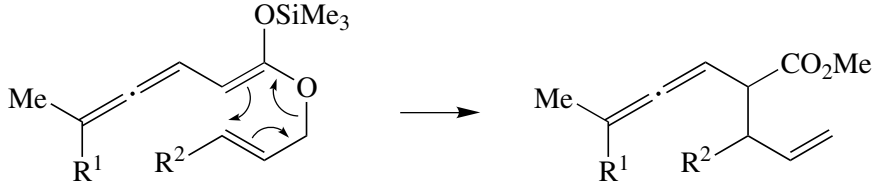
SCHEME 32



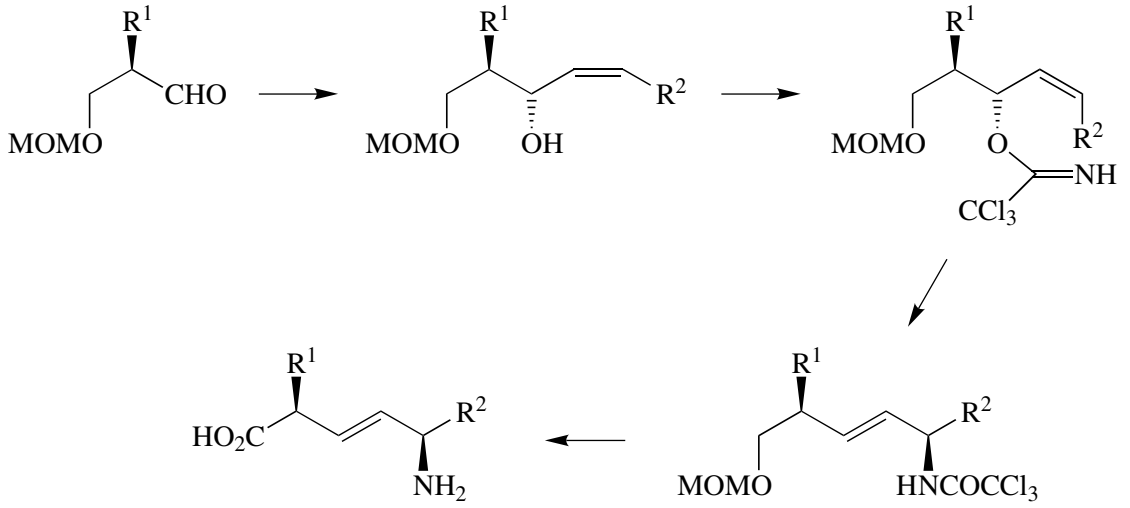
(**115**) (**116**)



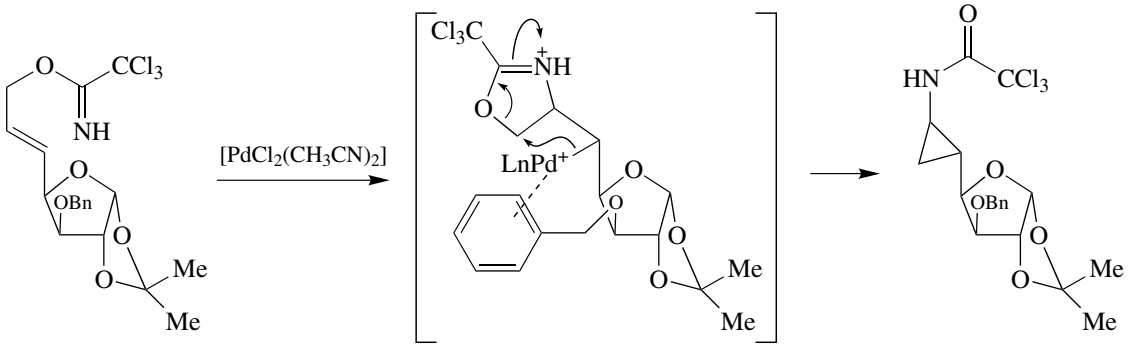
SCHEME 33



(**117**) (**118**)

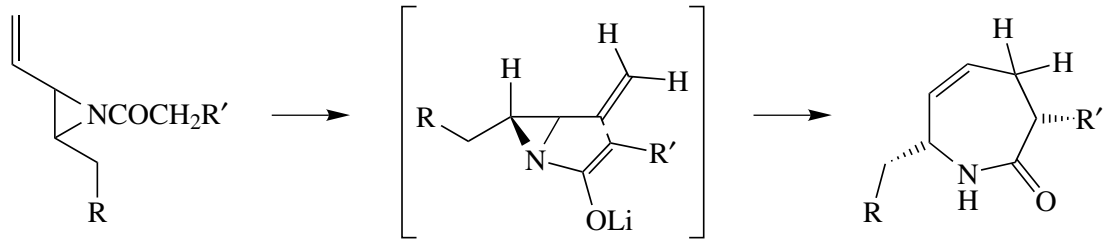


SCHEME 34



(**119**) (**120**)

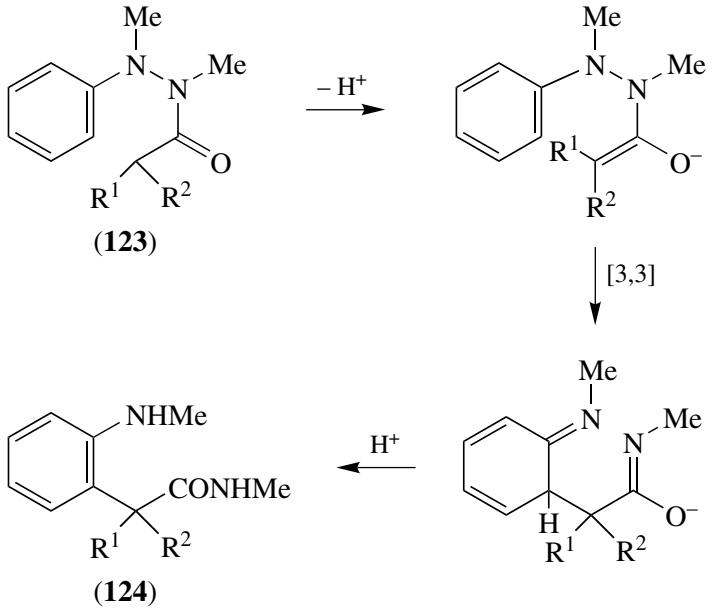
cross-over and kinetic studies. The results[153,154] support the hypothesis of a concerted sigmatropic rearrangement occurring through a highly polar transition state, in which a partially positively charged allyl group migrates from oxygen to nitrogen, without leaving the solvent cage. A stereo-controlled synthesis of (*E*)-alkene dipeptide isosteres using a [3,3]-allylic trichloroacetimidate rearrangement has been described[155] (see Scheme 34), and an attempted Pd(II)-catalysed aza-Claisen rearrangement of trichloroacetimidate (**119**) has provided,[156] unexpectedly, the diastereoisomerically pure cyclopropane derivative (**120**). A series of Pd(II) complexes containing chiral diamine ligands have been investigated[157] as asymmetric catalysts for the rearrangement of allylic imidates to allylic imides, and the [3,3]-sigmatropic rearrangement of allylic *N*-acylimidates to the corresponding allylic imides has been demonstrated for the first time.[158] Cyclopalladated ferrocenylamine has been used[159] to promote the rearrangement of 2-alkenyl imidates to allylically transposed amides in excellent yield and with moderate enantioselectivity, and a highly enantioselective and diastereoselective Claisen rearrangement of *N*-arylimidates derived from an axially chiral binaphthylamine auxiliary has been reported.[160] A highly stereoselective aza-[3,3]-Claisen rearrangement of vinylaziridines (**121**) has been utilized in a novel approach to



(**121**) (**122**)

seven-membered lactams (**122**). A six-membered boat-like transition state has been proposed[161] in order to rationalize the process.

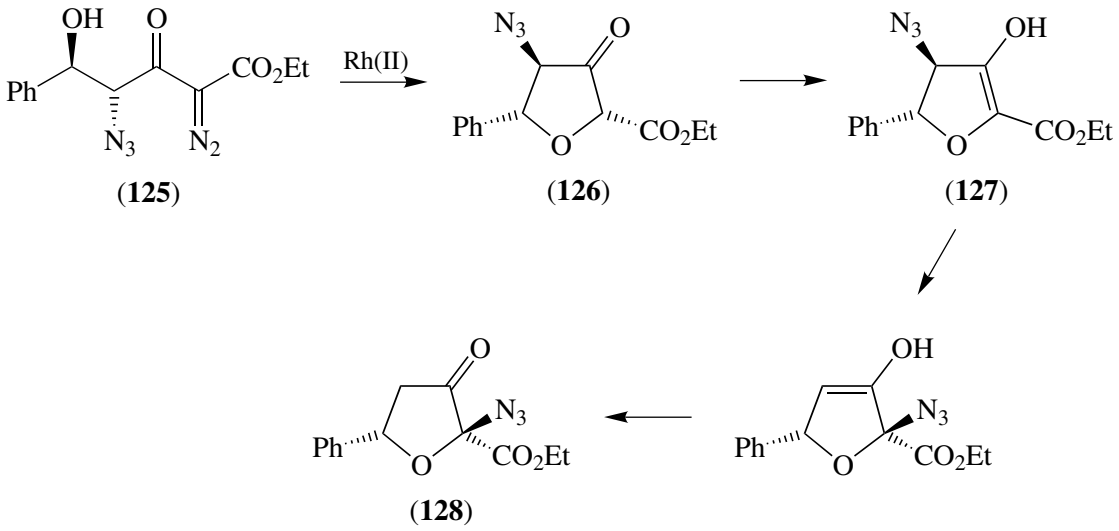
An account of [3,3]-sigmatropic reactions involving the cleavage of N−O and N−N bonds and their application to the synthesis of biologically active molecules has appeared.[162] A novel, abnormal rearrangement has been observed during the Fischer indole synthesis of *N*-methyl-*N*-(5,6,7,8-tetrahydro-1-naphthyl)hydrazone. The authors[163] invoked a [3,3]-sigmatropic rearrangement at the substituted and more hindered *ortho* position, and subsequent rearrangement of the fused six-membered ring via a spiro intermediate, to explain the formation of the unexpected product. *N*-Acyl-*N′*-phenylhydrazines (**123**) have been found to rearrange under basic conditions to afford *o*-aminophenylacetamides (**124**). The reaction has been rationalized[164] in terms of [3,3]-sigmatropic shifts of enolized intermediates (see Scheme 35). The Sommelet–Hauser-type and Stevens-type rearrangements of both aromatic and aliphatic acylhydrazines compete with the [3,3]-rearrangement.



(**123**) (**124**)

SCHEME 35

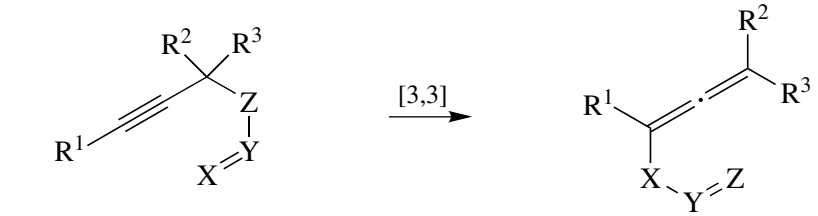
Various γ-azido-δ-hydroxydiazo keto esters, e.g. (**125**), have been found to undergo smooth Rh(II)-catalysed cyclization to afford 2-carboethoxy substituted 3(2*H*)-furanones as a single diastereoisomer. The authors[165] proposed that the formation of e.g. (**128**) involves insertion of the rhodium carbenoid into the adjacent O−H bond to



(**125**) (**126**) (**127**) (**128**)

first produce the 4-azido substituted 3(2*H*)-furanone (**126**), which rapidly rearranges to afford the observed product. The result strongly suggests that the enol form (**127**) of the initially generated furanone undergoes a subsequent [3,3]-sigmatropic shift with complete stereospecificity in a suprafacial manner. Moreover, the stereospecific transfer of the azido group to the migration terminus in the rearranged 3(2*H*)-furanone has provided convincing support for a concerted [3,3]-shift as the mechanism for the interconversion of allylic azides.

An account has appeared[166] of [3,3]-(and [2,3]-)sigmatropic rearrangements of propargyl precursors that lead to the synthesis of allenes bearing functional groups with at least two heteroatoms (see Scheme 36). The allyl cyanate to isocyanate rearrangement has been established as a new synthetic method for the construction

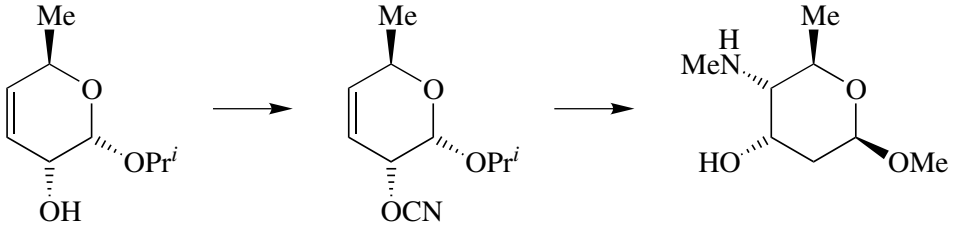


XYZ = NCO, NCS, NCSe, N_3, SCN, S(CO)OR

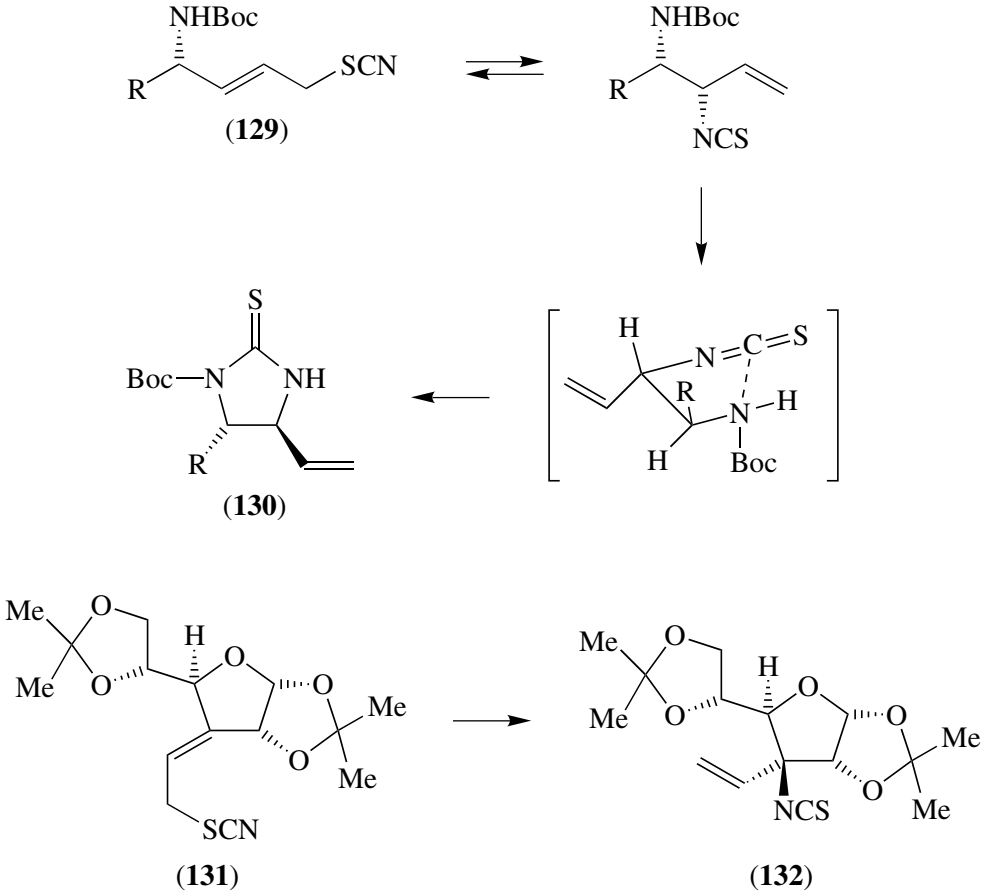
SCHEME 36

of an allyl amine moiety at sterically congested positions,[167] and as a new approach to the synthesis of amino sugars.[168] The key step in the latter methodology involves introduction of the nitrogen substituent into the pyranose framework by way of the [3,3]-sigmatropic rearrangement of an allyl cyanate (see Scheme 37).

Experimental and theoretical studies on the isomerization of allyl thiocyanate to allyl isothiocyanate have indicated[169] that the transformation proceeds by a [3,3]-sigmatropic rearrangement involving a cyclic transition state. A novel tandem [3,3]-sigmatropic rearrangement of allylic thiocyanates (**129**) followed by a stereo-controlled intramolecular addition of the amino function to the developing isothiocyanate group, has

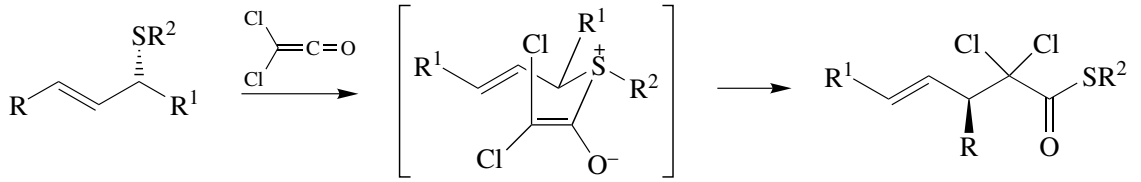


SCHEME 37

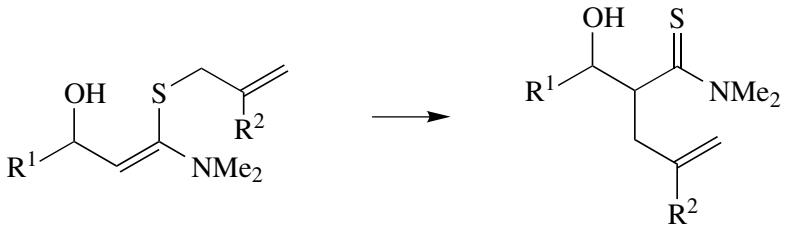


led[170] to diastereomerically pure 1,3-imidazolidin-2-thiones (**130**), and a stereoselective synthesis of the branched-chain sugar 3(*S*)-isothiocyanato-3-deoxy-3-*C*-vinylglucose (**132**) has been achieved[171] via a [3,3]-sigmatropic rearrangement of the allylic thiocyanate (**131**) prepared from D-glucose.

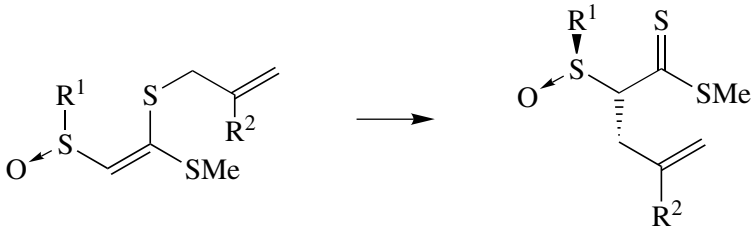
The stereochemistry of the 2-allylthio-5-acetyl-6-methyl-4-(2-nitrophenyl)-3-cyano-1,4-dihydropyridine [3,3]-sigmatropic rearrangement has been investigated.[172] A novel type of ketene-Claisen rearrangement has been described[173] in which the precursor of the rearrangement is generated *in situ* by reaction of optically active allyl thioethers with dichloroketene (see Scheme 38), and asymmetric induction by an external hydroxy group in the thio-Claisen rearrangement of *S*-allylic ketene aminothioacetals (**133**) has been used[174] to provide *syn*-*N*,*N*-dimethyl β-hydroxy α-allylic thioamides (**134**). The first example of a Claisen rearrangement of ketene dithioacetals in which the stereochemical course is controlled by a sulfinyl group has been reported,[175] see



SCHEME 38



(**133**) (**134**)



(**135**) (**136**)

(**135**) → (**136**), and a report has appeared[176] of diastereoselective asymmetric induction in the thio-Claisen rearrangement using zeolites.

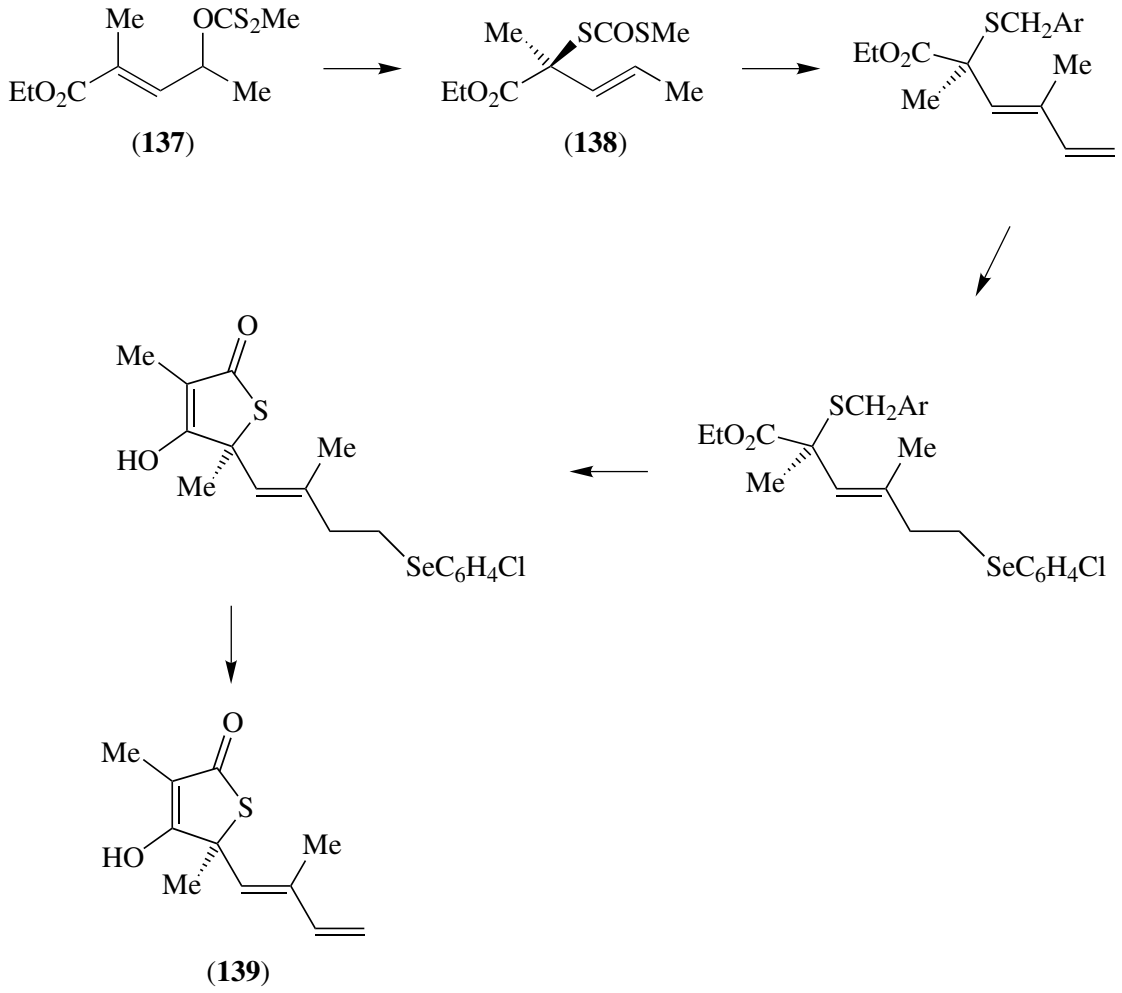
The utility of the [3,3]-sigmatropic rearrangement of eight-membered thionocarbonates for the highly stereo-controlled synthesis of *Z*- or *E*-double bonds in 10-membered thiolcarbonates has been reviewed.[177] 5,5-Disubstituted thiotetronic acids (**139**) have been synthesized[178] using an allylic xanthate (**137**) to dithiocarbonate (**138**) rearrangement which has permitted the introduction of a sulfur at a tertiary centre with concomitant deconjugation of the double bond (see Scheme 39).

A seleno-Claisen rearrangement has been used[179] to synthesise mono-, di-, and triallylated selenothioic and *S*-alkyl esters with high regio- and stereo-selectivity.

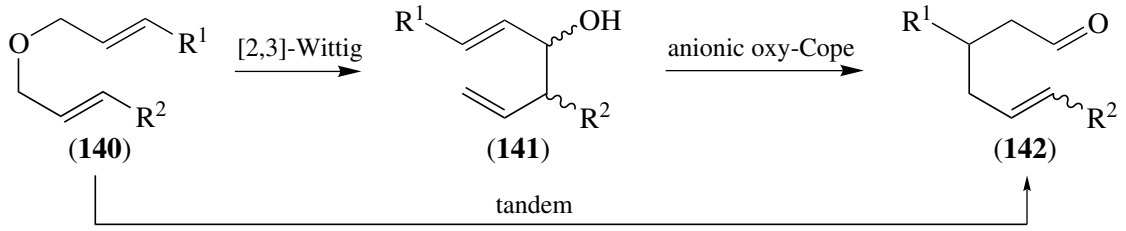
Unusual regioselectivity has been observed[180] during the reductive coupling of alkynes and allenes by hydrozirconation and zinca-Claisen rearrangement.

Cope and related rearrangements

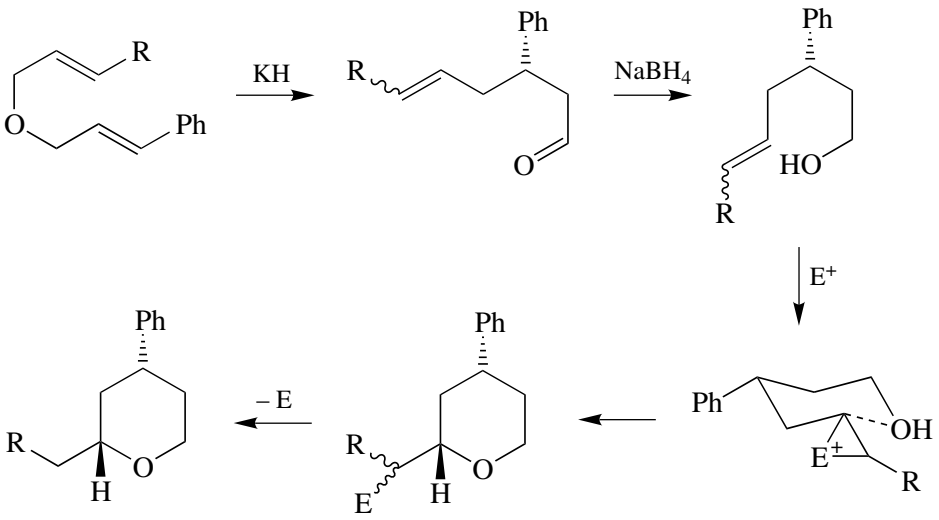
Recent applications of the anionic oxy-Cope rearrangements have been reviewed.[181] Acyclic bisallylic ethers (**140**) have been found to undergo *syn* or *anti* stereoselective [2,3]-Wittig rearrangements to give homoallylic alcohols (**141**), depending on the substituents, and *E*-selective tandem [2,3]-Wittig–anionic oxy-Cope rearrangement to yield δ, ϵ-unsaturated aldehydes. (**142**)[182] The application of this tandem process to the



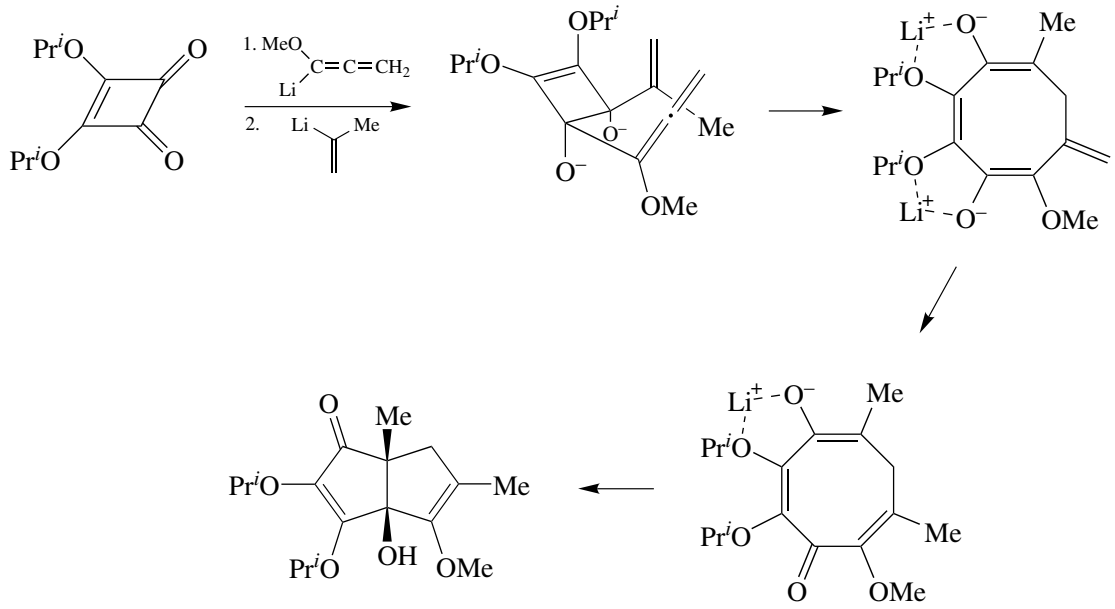
SCHEME 39



synthesis of single isomers of tetrahydropyrans by electrophilic cyclization with various electrophiles and acid-catalysed intramolecular ring opening has been reported[183] (see Scheme 40). Similarly, the highly diastereoselective preparation by trisubstituted δ-lactones and also related tetrahydropyrans has been achieved by exploiting the acyclic stereo-control of the above sequence.[184] Highly substituted and enantiopure tetrahydropyrans have been prepared[185] from chiral 7-hydroxyalk-2-enoic imides and esters using the silyloxy-Cope rearrangement. The ability of squarate ester (**143**) to undergo sequential pericyclic reactions following mixed addition of allenic and alkenyl anions has been investigated.[186] It has been shown (see Scheme 41) that, when *cis*

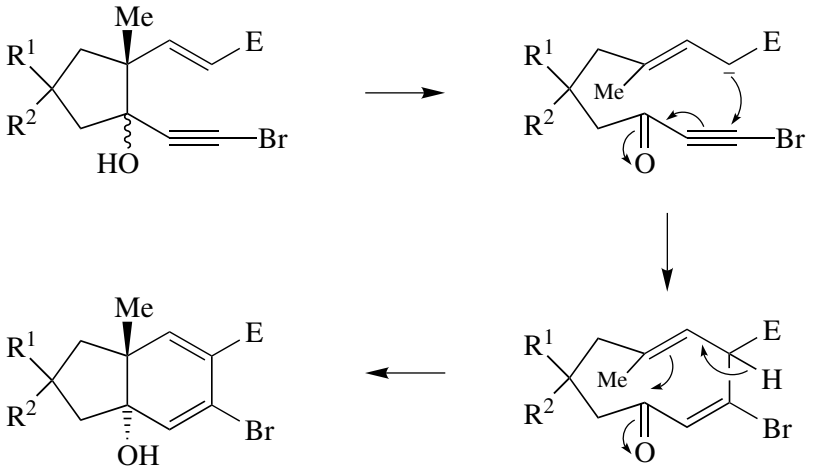


SCHEME 40

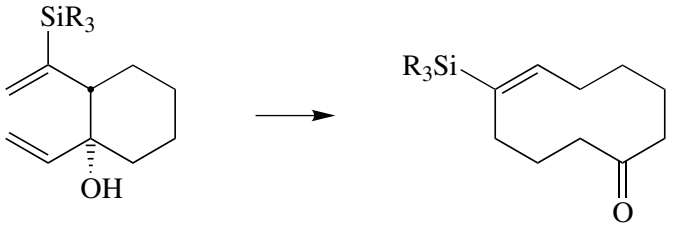


SCHEME 41

addition operates, a dianionic oxy-Cope rearrangement ensues, delivering diquinane products. Functionalized, medium-sized, bicyclic, and angularly fused tricyclic compounds have been synthesized[187] from bromoethynyl derivatives of cycloalkanes by anionic and thermal oxy-Cope rearrangements (see Scheme 42). In the course of preparing the trimethylsilyl substituted cyclodec-5-enone (**145**; R=Me) via an anionic oxy-Cope rearrangement of *trans*-1,2-divinylcyclohexanol (**144**; R=Me), Chu *et al.*[188] discovered that the silyl substituent in the substrate was so positioned that it destabilized the [3,3]-sigmatropic rearrangement through the normally observed chair-like transition state. However, in the case of the tri-*n*-propylsilyl derivative (**144**; R = Pr^n), an oxy-Cope rearrangement was observed to take place exclusively through a boat-like transition state to yield (*E*)-5-(tri-*n*-propylsilyl)cyclodec-5-enone (**145**; R = Pr^n).

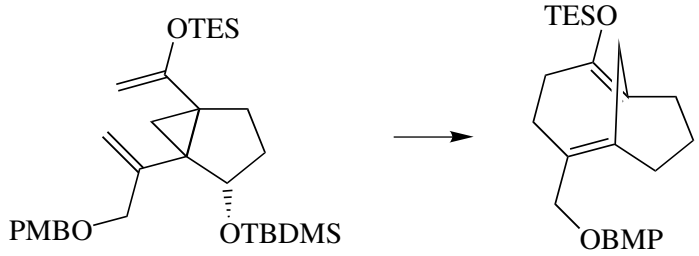


SCHEME 42



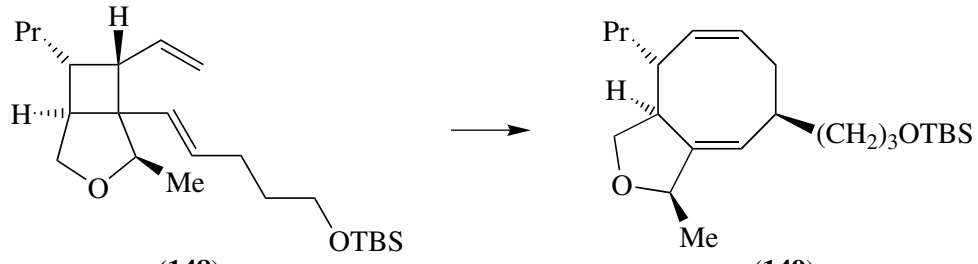
(**144**) (**145**)

A review has been published[189] that discusses the preparation of seven-membered ring compounds from α-diazocarbonyl compounds via cyclopropanation and Cope rearrangement, and the central core of the squalene inhibitor CP-225,917 has been synthesized[190] by a series of rearrangement steps including a divinylcyclopropane [3,3]-sigmatropic rearrangement of the carbenoid insertion product (**146**) to afford the bridged medium ring (**147**). It has been proposed[191] that the biosynthesis of the



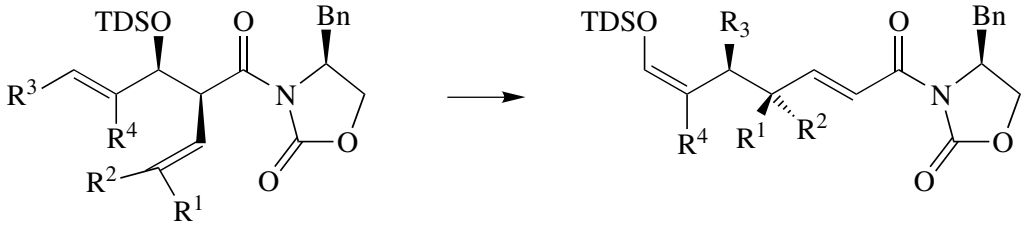
(**146**) (**147**)

6-substituted cyclohepta-1,4-dienes dictyotene, ectocarpene, desmarestene, vinylcycloheptadiene, and lamoxirene involves a spontaneous Cope rearrangement of thermolabile bisalkenylcyclopropane precursors. The ease with which substrates of the type (**148**) undergo Cope rearrangement to the eight-membered fused-ring product (**149**) has been noted.[192] A comparative study has been undertaken of the Cope rearrangement of hexa-1,5-diene and barbaralane, and it has been shown[193] that the rearrangement of the



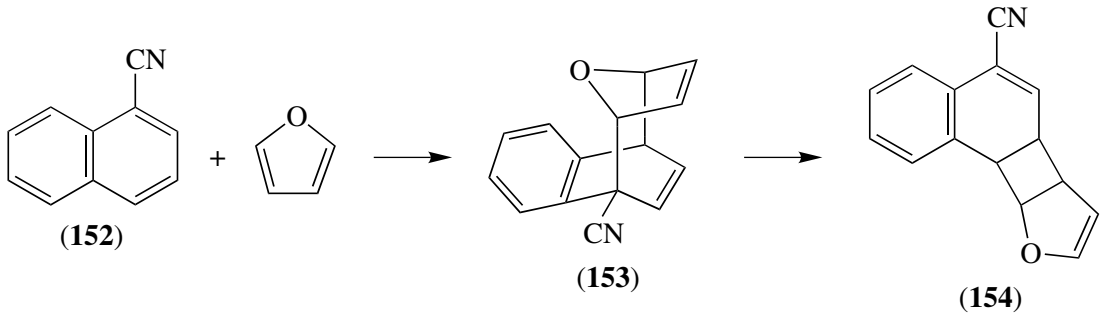
(**148**) (**149**)

latter compound, although belonging to the category of concerted reactions, is not synchronous. It has been established[194] that the photo-induced electron-transfer Cope rearrangement of (*E*,*E*)-3,6-bis(4-methoxyphenyl)octa-2,6-diene is kinetically controlled and affords quantitatively the thermodynamically less stable 3,4-dimethyl-2,5-bis(4-methoxyphenyl)hexa-1,5-diene at −80 °C, in sharp contrast to the thermodynamically controlled thermal Cope rearrangement. Enantiomerically pure 1,6-disubstituted 1,5-dienes with an aldol substitution pattern, e.g. (**150**), have been found[195] to undergo rapid thermal Cope rearrangement with high diastereoselection to yield (**151**). The kinetics of the racemization of (+)-tetracyclo[7.3.1.$0^{2,8}$.$0^{4,12}$]trideca-5,10-diene by

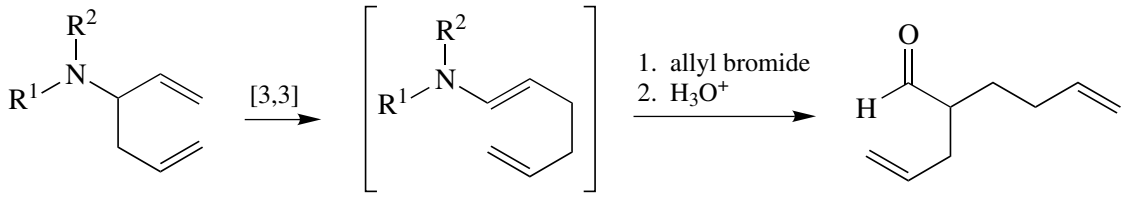


(**150**) (**151**)

a degenerate Cope rearrangement have been examined.[196] The photo-cycloaddition of furan to 1-naphthalenecarbonitrile (**152**) has been re-investigated, and it has been proposed[197] that the observed formation of the *syn*-2 + 2-adduct (**154**) can be best explained by the facile Cope rearrangement of (**153**) which was the expected major product in the singlet-state 4 + 4-photo-cycloaddition. Beck *et al*.[198] have demonstrated that, in the acid-catalysed 4 + 2-cycloaddition between cyclic azines and 1,3-dienes, both partners can play the role of the diene or the dienophile, depending on particular structural features. Moreover, it has been shown that the thermal or acid-catalysed



(**152**) (**153**) (**154**)



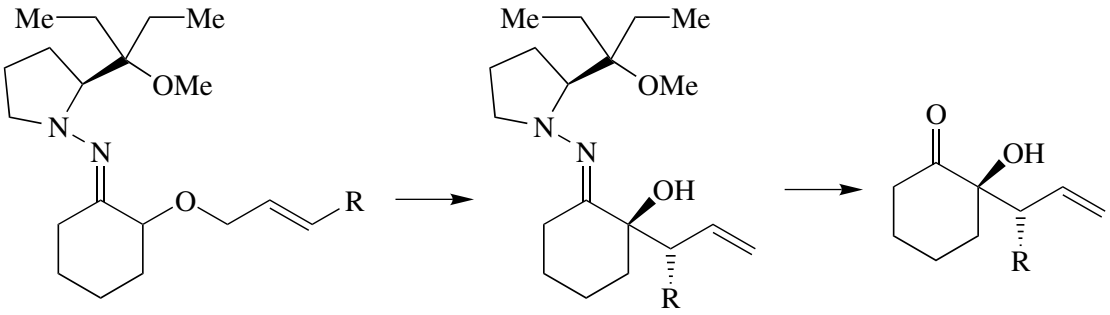
SCHEME 43

interconversion of 4 + 4-cycloadducts definitely occurs by a concerted [3,3]-sigmatropic rearrangement and not by a 4 + 2-cycloreversion.

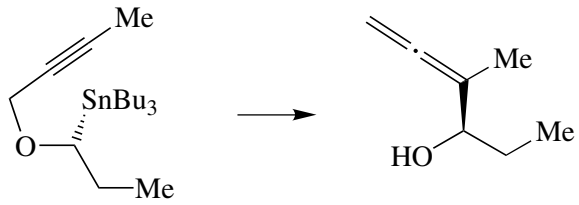
Computational modelling has shown[199] that circumambulatory rearrangements of allyl and heteroallyl groups in the cyclopropene ring are governed by the [3,3]-sigmatropic shift mechanism. An aza-Cope rearrangement in transition metal complexes has been described.[200] Unique intramolecular rearrangement product ions have been observed in the product ion spectra of a number of peptides. The authors[201] proposed that the process is driven by the transfer of a proton from the immonium nitrogen to the more basic primary amine on the *N*-terminus of the peptide. The proton transfer leads to a loss of NH_3 and loss of an internal residue by means of an intramolecular rearrangement that transposes the internal residue to the terminus of the peptide ion. The thermally induced [3,3]-sigmatropic rearrangement of 3-amino-1,5-diene substrates has been reported[202] to yield the corresponding enamine product with excellent *trans* : *cis* enamine selectivity. The enamine produced during the amino-Cope rearrangement has been directly derivatized, thus representing the first reported example of a tandem amino-Cope rearrangement–enamine alkylation reaction (see Scheme 43). A paper has appeared[203] which shows that stereoselectivity in the aza-Cope–Mannich reaction can be controlled by the nature of the nitrogen substituents.

[2,3]-Migrations

Asymmetric [2,3]-sigmatropic rearrangements have been reviewed,[204] and recent advances in the use of the [2,3]-Wittig rearrangement for the asymmetric synthesis of homoallylic alcohols have been described.[205] Transition structures for the [2,3]-Wittig rearrangement of the dilithium salts of 2-oxa-4-(*Z* and *E*)-methylhexene-1-carboxylic acids have been located using *ab initio* MO calculations, and the origin of the observed stereoselectivity of the [2,3]-Wittig rearrangement of these substrates has been clarified.[206] *Ab initio* MO calculations have also been used to optimize the transition structures for the [2,3]-Wittig rearrangement of (allyloxy)methyllithium.[207] An efficient, diastereoselective [2,3]-Wittig rearrangement of α-allyloxyamide enolates has been developed[208] using (1*S*,2*R*)-1-aminoindan-2-ol as a chiral auxiliary and polycyclic functional ketones containing neighbouring quaternary and tertiary stereogenic centres have been synthesized[209] diastereo- and enantio-selectively by way of the [2,3]-Wittig rearrangement of chiral hydrazones (see Scheme 44). The first enantioselective [2,3]-sigmatropic rearrangements of alkenyl benzyl ethers and acyclic diprop-2-ynyl ethers, mediated by a butyllithium–chiral ligand complex, have been reported,[210] and it has been shown[211] that the [2,3]-Wittig rearrangement of the



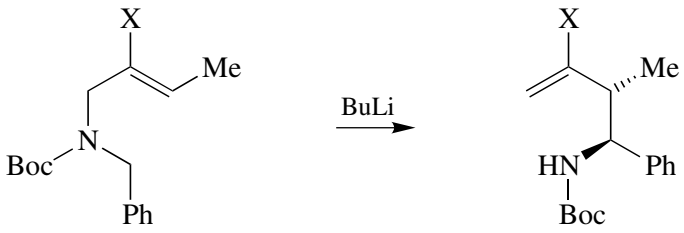
SCHEME 44



(**155**) (**156**)

enantiomerically defined α-propargyloxystannane (**155**) with butyllithium proceeds with complete inversion of configuration at the lithium-bearing terminus; see (**156**).

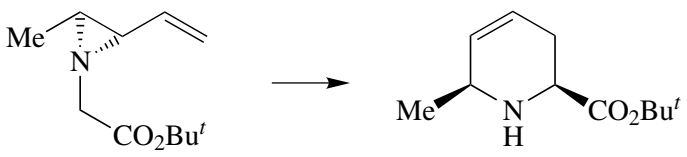
A review which describes recent developments of the aza-Wittig rearrangement and its application in alkaloid synthesis has appeared.[212] The aza-[2,3]-Wittig rearrangement (**157**) → (**158**) has been shown to be accelerated by the incorporation of certain anion-stabilizing substituents at the central vinyl carbon atom.[213] It has also been shown[214] that the phosphoramide group effectively assists the rearrangement regardless of the substitution pattern of the alkenes. The aza-[2,3]-Wittig rearrangement of a vinylaziridine (**159**) into a tetrahydropyridine (**160**) has been used[215] as a key step in



(**157**)

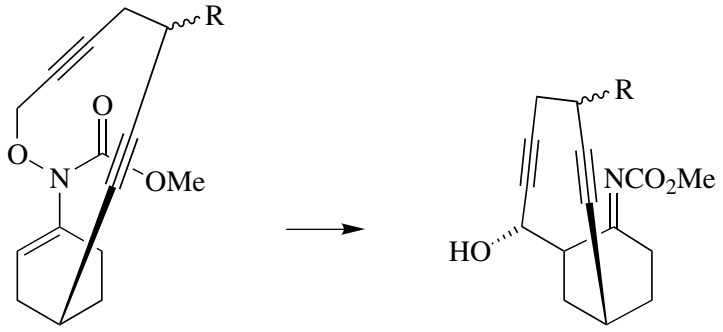
X = $SiPhMe_2$, Ph, SPh

(**158**)

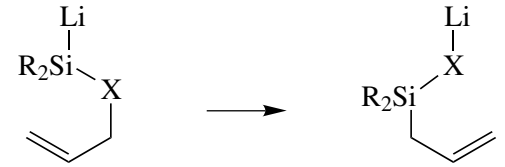


(**159**) (**160**)

novel and highly efficient syntheses of monomorine and indolizidine 195B, and a strategy based upon an 'azoxy' version of the [2,3]-Wittig rearrangement [see (**161**) → (**162**)] has been investigated[216] as a means of synthesizing the aglycone component of the enediyne antibiotics esperamicin A and calicheamicin-γ_1. The first examples of silicon analogues of the [2,3]-Wittig rearrangement, namely [2,3]-sila-Wittig and aza-sila-Wittig rearrangements, have been reported[217] in [(allyloxy)silyl]-lithium and [(allylamino)silyl]lithium, respectively; see (**163**) → (**164**).



(**161**) (**162**)

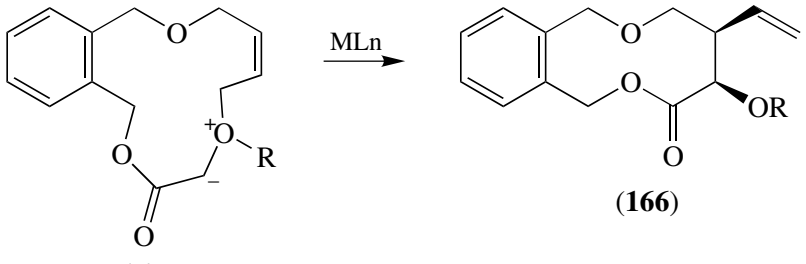


(**163**) (**164**)

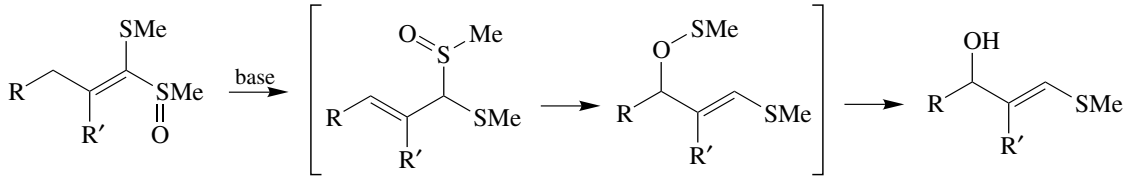
X = O, NR′

It has been reported that treatment of methyl 1-methylsulfanylvinyl sulfoxides with sodium thiophenolate in methanol affords 1-methylsulfanylalk-1-en-3-ols. A sequence has been proposed[218] (see Scheme 45) in which the thiophilic base first causes an *in situ* isomerization of the vinyl sulfoxide moiety into an allylic sulfoxide which then undergoes a [2,3]-sigmatropic rearrangement and subsequent thiophilic cleavage of the intermediate sulfenic ester.

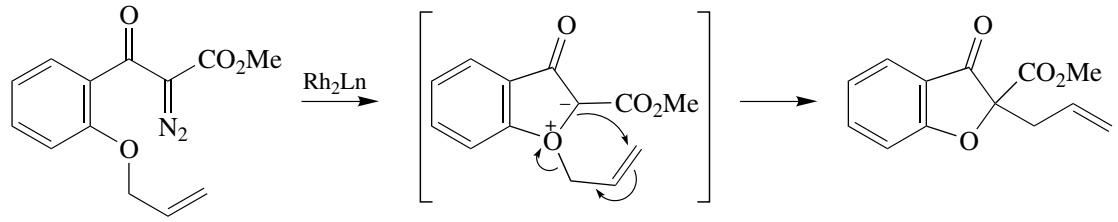
Several new chiral rhodium(II) catalysts have been synthesized for evaluation as catalysts in the asymmetric oxonium ylide-[2,3]-sigmatropic rearrangements of diazocarbonyl substrates[219] (see Scheme 46). The formation of 13-membered ring oxonium ylides (**165**) and their stereo-controlled [2,3]-sigmatropic rearrangement to 10-membered ring lactones (**166**) have been described.[220]



(**165**) (**166**)

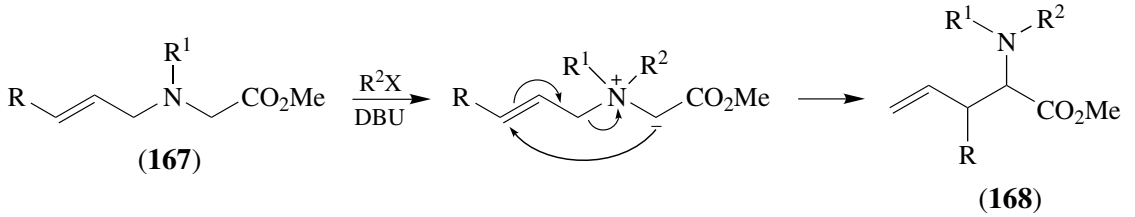


SCHEME 45



SCHEME 46

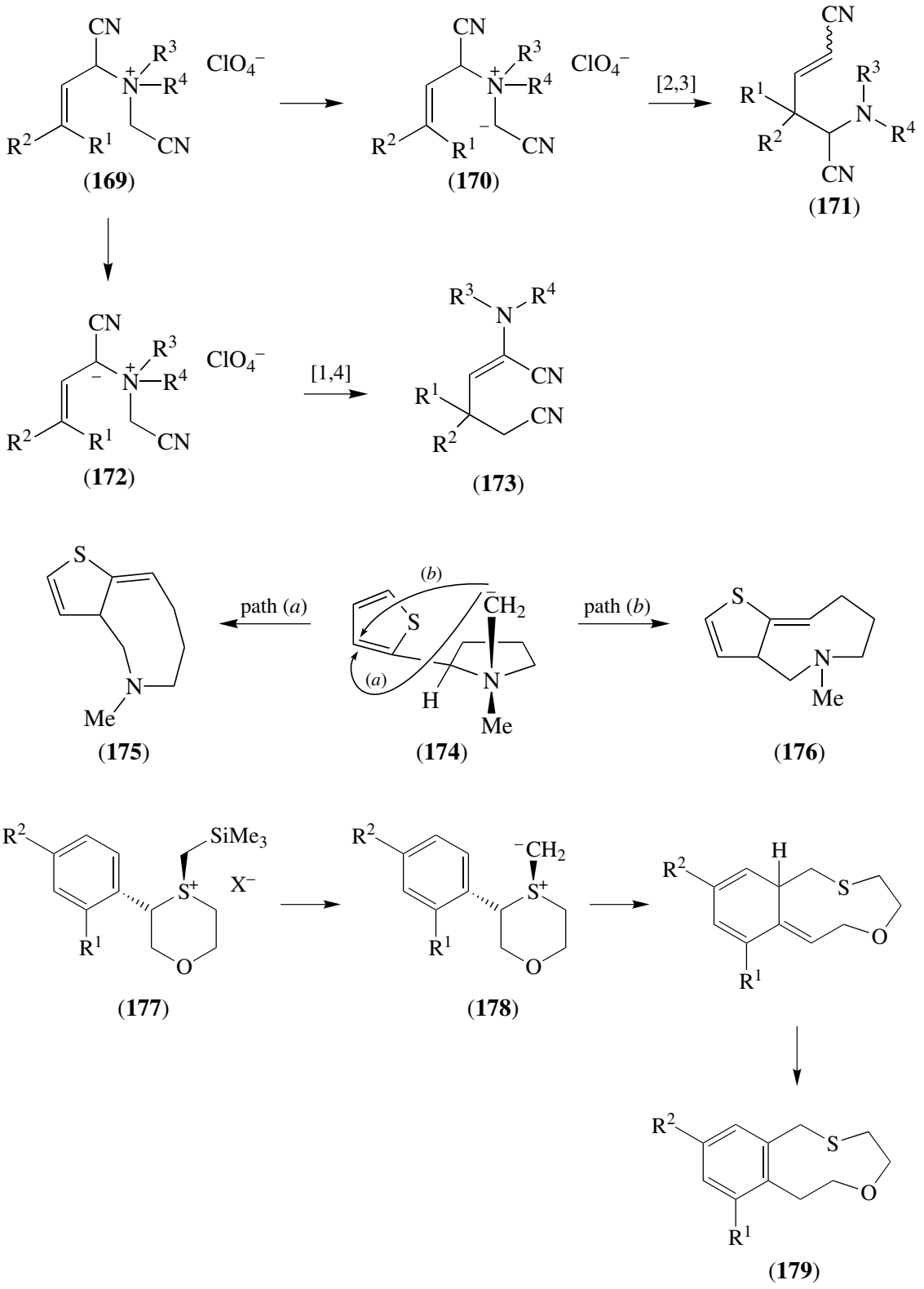
Studies have been carried out of the reactions of various benzylammonium *N*-methylides[221] and 2-benzocycloammonium *N*-methylides.[222] Some ylides were found to yield [2,3]-sigmatropic rearrangement products, while others gave Stevens rearrangement products via radical cleavage and recombination pathways. The [2,3]-sigmatropic rearrangement of cyclic ammonium ylides has been examined[223] with a view to optimizing the rearrangement at the expense of the competing elimination reaction. *N*,*N*-Dialkylated allylglycine derivatives (**168**) have been prepared[224] by a one-pot process involving *N*-alkylation of the *N*-allyl α-amino ester (**167**) and [2,3]-



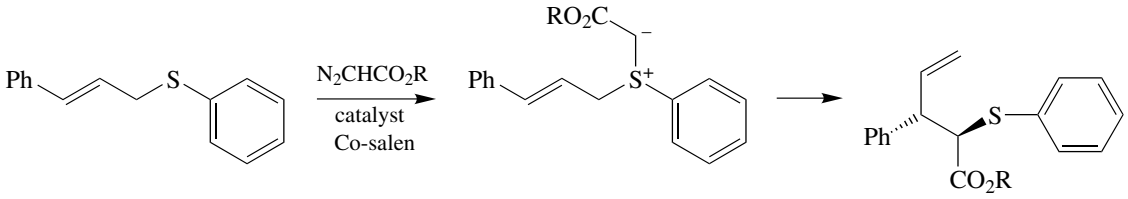
(**167**) (**168**)

sigmatropic rearrangement of the corresponding ylide. On treatment with solid $NaHCO_3$ in DMF, *N*-(α-cyano)allyl-*N*-cyanomethyl-*N*,*N*-dimethylammonium perchlorates (**169**) have been found[225] to afford α-aminonitriles (**171**) by a [2,3]-shift of the cyano methylides, (**170**) although, when treated with solid K_2CO_3 in DMSO, the substrates yielded α-cyanoenamines (**173**) by a [1,4]-shift of the α-cyano allylides (**172**). *cis*-1-Methyl-2-(2-thienyl)pyrrolidinium 1-methylide (**174**) generated in a non-basic medium was found to isomerize to a mixture of (*E*)- and (*Z*)-5-methyl-3*a*,4,5,6,7,8-hexahydrothien[3,2-*c*]azocine (**175**) and (**176**), respectively. In the case of *trans*-(**174**), carbon–carbon bond cleavage was found to occur instead of sigmatropic migration, presumably as a direct result of the increased distance between the ylide anion and the thienyl ring.[226]

Substituted 3,4,6,7-tetrahydro-1*H*-5,2-benzoxathionines (**179**) have been synthesized[227] by a sequence which involves [2,3]-sigmatropic rearrangement and

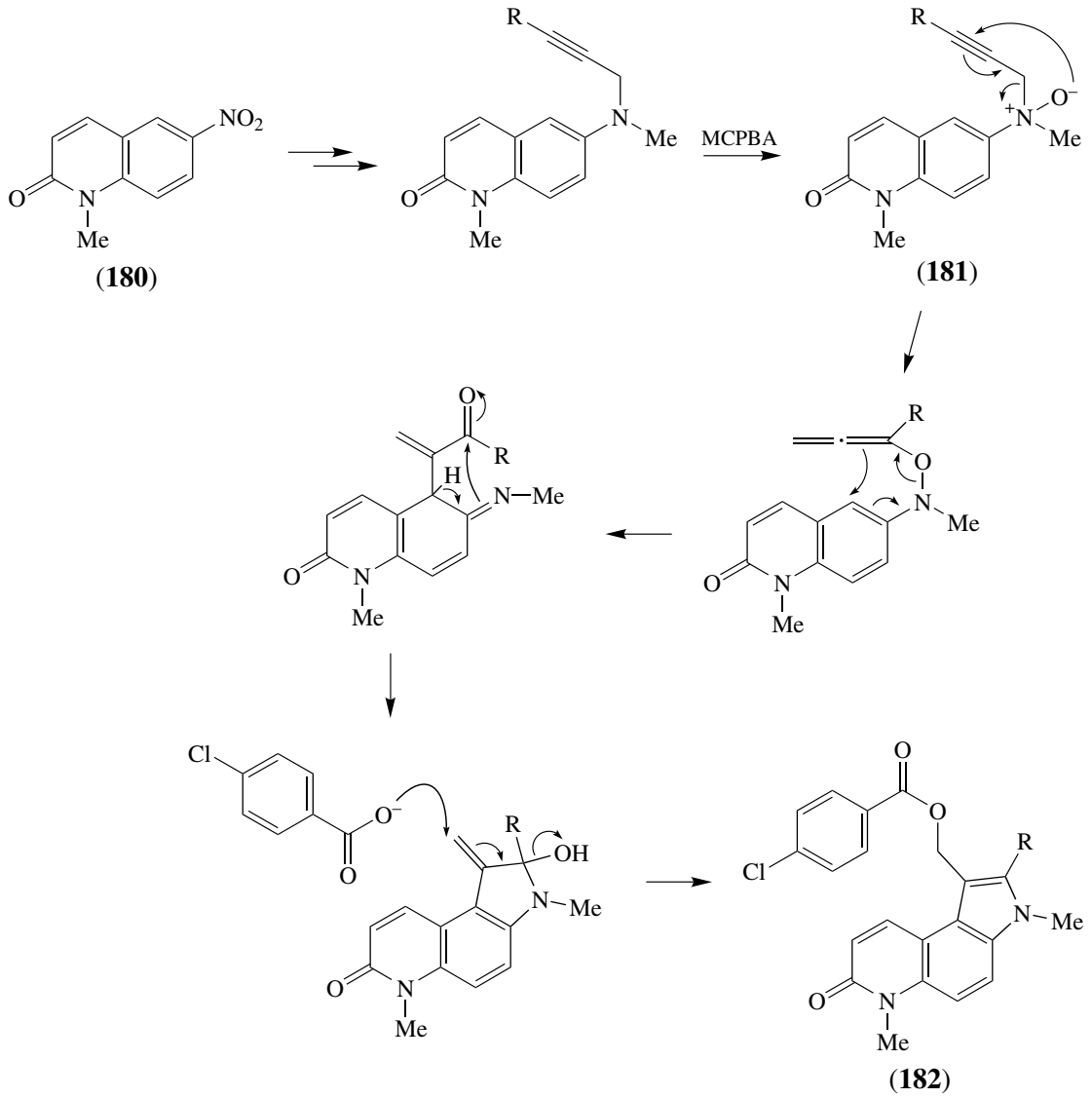


aromatization of the sulfur ylides of 1,3,4,11a-tetrahydro-6*H*-5,2-benzoxathionines (**178**) which were generated by the reaction of *trans*-3-(substituted phenyl)-4-(trimethylsilyl)methyl-1,4-oxathianium perchlorates (**177**) with caesium fluoride. Allyl

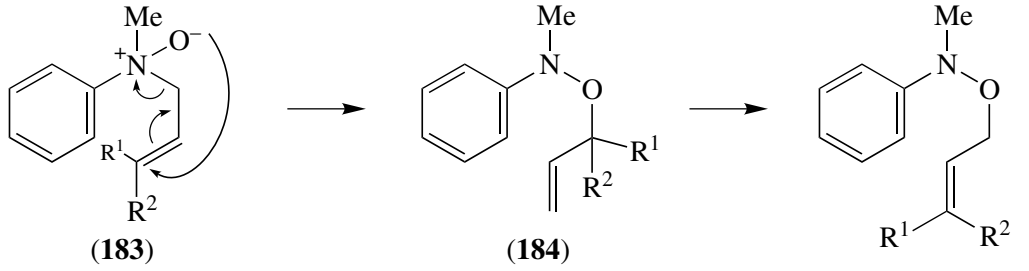


SCHEME 47

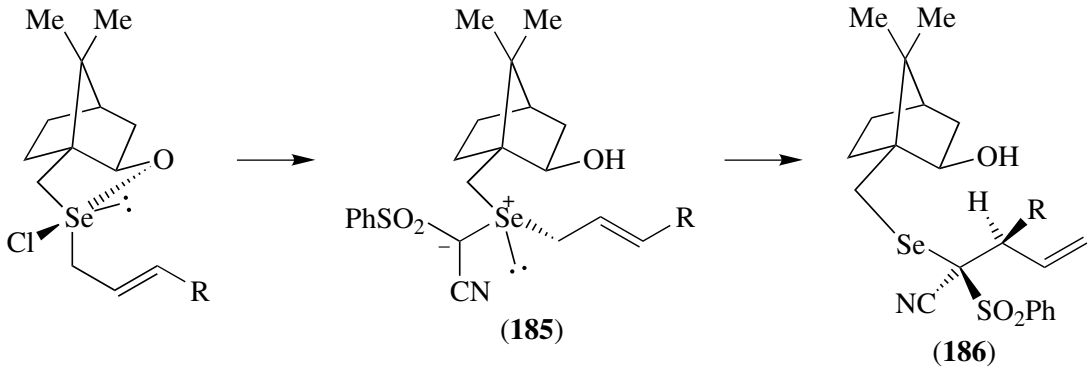
aryl sulfides and diazoacetic acetic ester have been reported[228] to react in the presence of optically active Co(III)–salen complex with good enantioselectivity to afford 2-arylthio-3-arylpent-4-enoic acid esters, via the corresponding sulfur ylides (see Scheme 47). The [2,3]-Wittig rearrangements of α-phosphonylated ammonium and sulfonium ylides have been reviewed.[229]



SCHEME 48

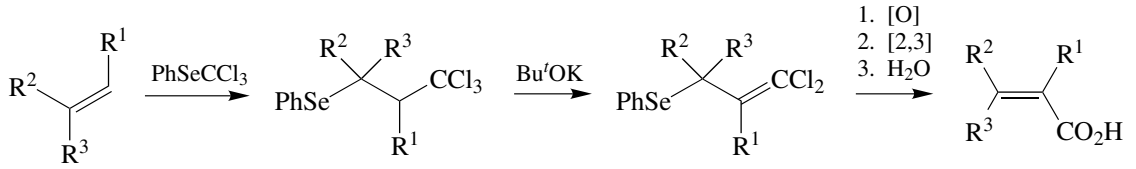


SCHEME 49

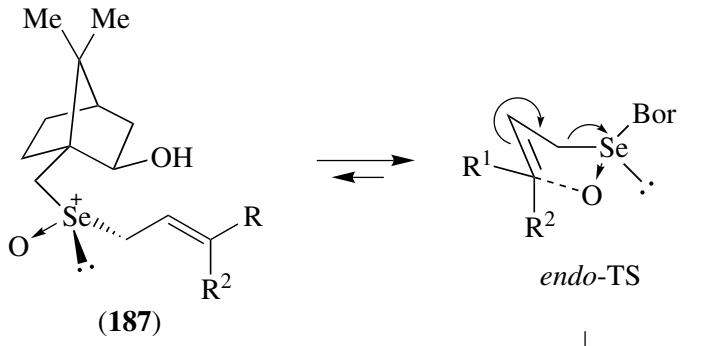


Several derivatives of the hitherto unreported pyrrolo[3,2-*f*]quinolin-7-one tricyclic system (**182**) have been prepared from 6-nitroquinolone (**180**). The authors[230] proposed that a key step in the transformation involves a Meisenheimer-type [2,3]-sigmatropic rearrangement of the *N*-oxide (**181**) (see Scheme 48). Chiral tertiary amine oxides, prepared from the oxidation of chiral camphidin-based allylic tertiary amines, have been found to undergo the [2,3]-Meisenheimer rearrangement with high levels of stereoselectivity.[231] A recent study[232] has shown that the Meisenheimer rearrangement products (**184**) of certain amine oxides (**183**) frequently undergo [1,3]-shifts of the oxygen heteroatom to carbon on further heating (see Scheme 49).

2-Phenylseleno-1-trichloromethylalkanes, generated by free-radical addition of trichloromethyl selenide to alkenes, have been converted into α,β-unsaturated carboxylic acids or amides, by base-promoted dehydrochlorination, followed by [2,3]-sigmatropic rearrangement of the corresponding selenoxides in the presence of water or diethylamine, respectively[233] (see Scheme 50). The [2,3]-sigmatropic rearrangement of allylic selenonium ylides (**185**) has been found to afford homoallylic selenides (**186**) with high diastereoselectivity.[234] The reaction has also provided an excellent method for carbon–carbon bond formation with chiral induction at a C(3) stereocentre. An extension of this strategy involving the [2,3]-sigmatropic rearrangement of allylic selenoxides (**187**) to the corresponding allylic alcohols (**188**) has been reported.[235] in this case the absolute configuration of the resulting allylic alcohols has indicated that the rearrangement of the selenoxide progresses predominantly via the *endo* transition state (see Scheme 51).



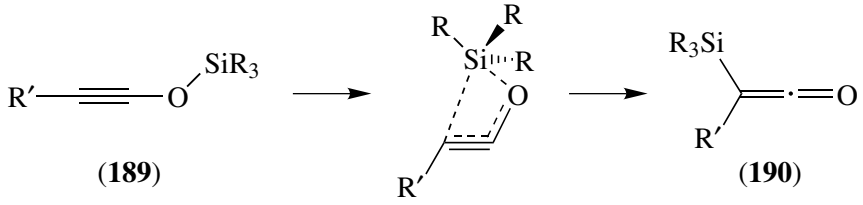
SCHEME 50



SCHEME 51

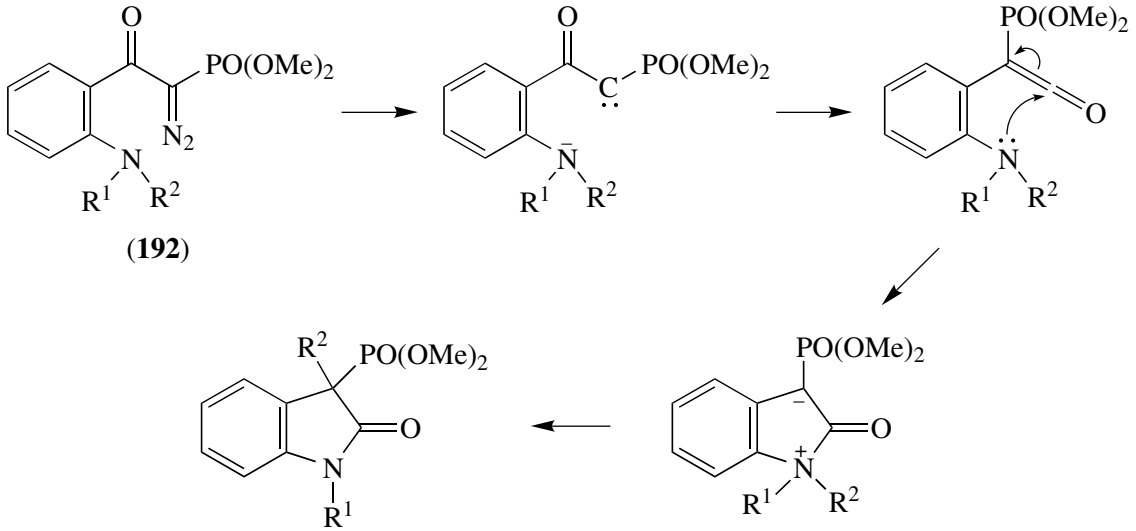
[1,3]-Migrations

Ab initio MO calculations of the [1,3]-sigmatropic silyl shift in allylsilane[236] and in related allylmetallic compounds[237] have been carried out and have shown that the shift proceeds with retention of the silicon configuration at the migrating centre. An NMR study of the sigmatropic [1,3]-boron shift in 7,8-dipropyl-7-borabicyclo[4.2.2]deca-2,4,9-triene has been undertaken,[238] and it has been reported[239] that, in solution, 1,2-dihydroborinines $Me_3EC_5H_5BMe$ (E=Si, Ge, Sn, Pb) are fluxional and undergo [1,3]-sigmatropic migrations of the Me_3E group from C(2) to C(6). A theoretical study[240] has shown that the formation of silylketenes (**190**) from silyloxyacetylenes (**189**) via a [1,3]-silyl shift should occur through a concerted closed-shell mechanism involving retention of configuration at the silicon centre. 2-Phospha-1,3-disilaallyl fluorides (**191**)



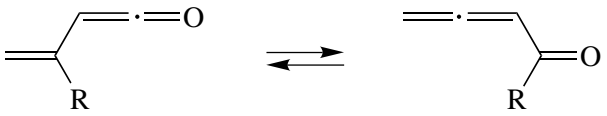
(**191**)

have been found to undergo a [1,3]-sigmatropic shift of fluorine. *Ab initio* calculations on $H_2Si{=}PSiH_2F$ were in agreement with this.[241] The influence of the *t*-amino moiety on the decomposition pathways followed during the thermal decomposition of α-diazo-β-ketophosphonates (**192**) has been studied. The study has established[242] that if the amino moiety was acyclic or bore a substituent of strong migratory aptitude, then indolinones (**194**) resulting from [1,3]-sigmatropic rearrangement of intermediate 2-oxoindolinium enolate derivatives (**193**) are the major products.



(**192**)

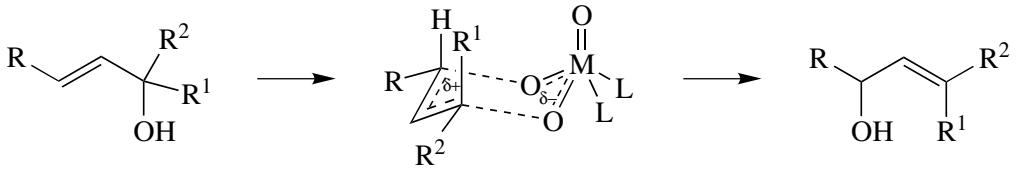
(**194**) (**193**)



(**195**) (**196**)

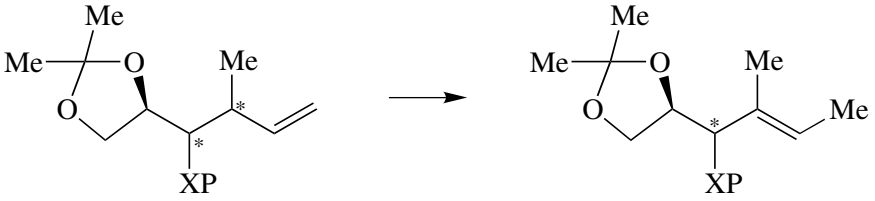
R = alkoxy

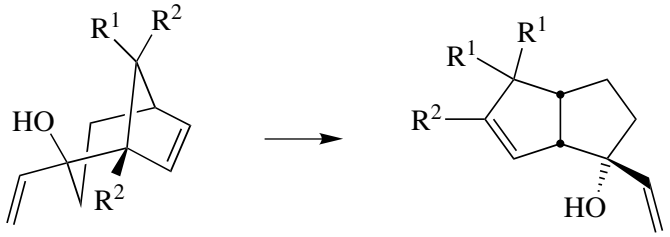
Alkoxyvinylketenes (**195**) have been found to undergo thermal [1,3]-shifts of the alkoxy groups, interconverting them with allenecarboxylic acid esters (**196**). Similar [1,3]-migrations of dimethylamino groups and of chlorine atoms have been described.[243] Isomerization of allyl alcohols has been carried out very rapidly in the presence of ReO_3OSiR_3 catalysts. Kinetic studies have indicated[244] that the rearrangement takes place via a cyclic transition state involving an Re=O group (see Scheme 52). Mulzer *et al.*[245] have reported that the non-racemic *O*-protected

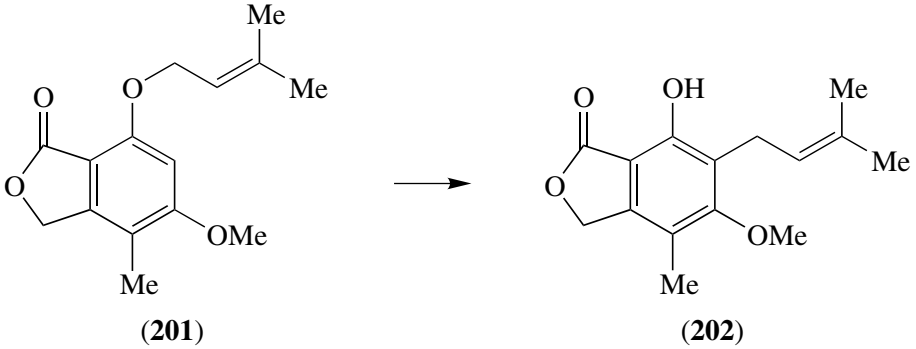


SCHEME 52

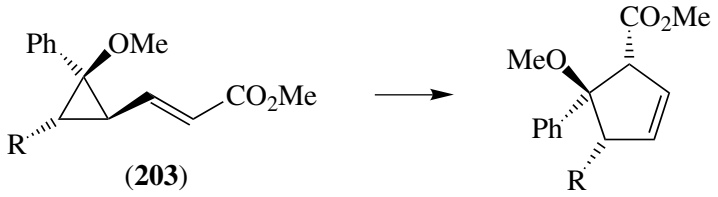
homoallylic alcohols (**197**) (and amines) undergo an intramolecular [1,3]-hydrogen shift under aprotic basic conditions to afford the trisubstituted (*E*)-alkenes (**198**), and diquinane structures (**200**) have been prepared successfully from bicyclo[3.2.1]oct-6-en-2-ones (**199**) by way of an anionic [1,3]-sigmatropic migration within the oxy-Cope system.[246] Florisil has been found to be effective in promoting the [1,3]-sigmatropic shift of allyl phenyl ethers, thus opening up a route to mycophenolic acid analogues;[247] see (**201**) → (**202**).





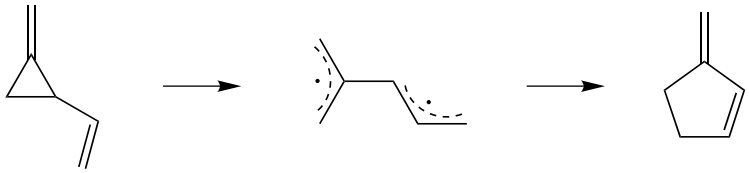


Donor–acceptor-substituted vinylcyclopropanes such as (**203**) have been shown to undergo thermal ring enlargement to functionalized cyclopentene derivatives (**204**) at

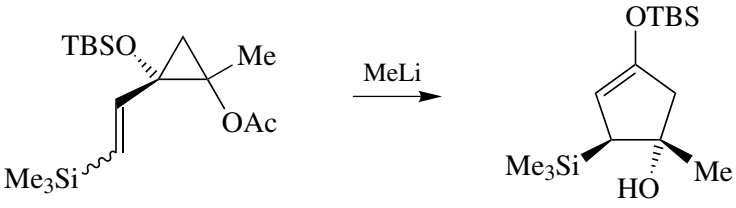


(**203**) (**204**)

relatively low temperatures.[248] Theoretical evidence has been produced[249] to account for the lack of intermediates in the thermal unimolecular vinylcyclopropane to cyclopentene [1,3]-sigmatropic shift, and a prototype thermal vinyl cyclopropane–cyclopentene rearrangement involving competing diradical concerted and stepwise mechanisms has been studied.[250] The kinetics of the thermal isomerization of gaseous vinylcyclopropane have been examined[251] and triplet 4-methylenepent-2-ene-1,5-diyl (**206**) has been generated and characterized[252] upon irradiation of 2-vinylmethylene-cyclopropane (**205**) in a bromine-doped xenon matrix. The first example of an oxyanion-accelerated vinylcyclopropane–cyclopentene rearrangement, which proceeds at unprecedentedly low temperatures, has been reported.[253] It involves the reaction of 2-[2-(trimethylsilyl)ethenyl]cyclopropane acetates (**207**) with methyllithium to provide a single cyclopentenol (**208**), irrespective of the vinylsilane geometry.



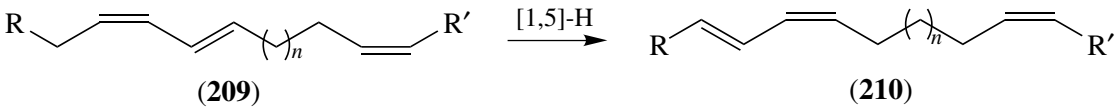
(**205**) (**206**)



(**207**) (**208**)

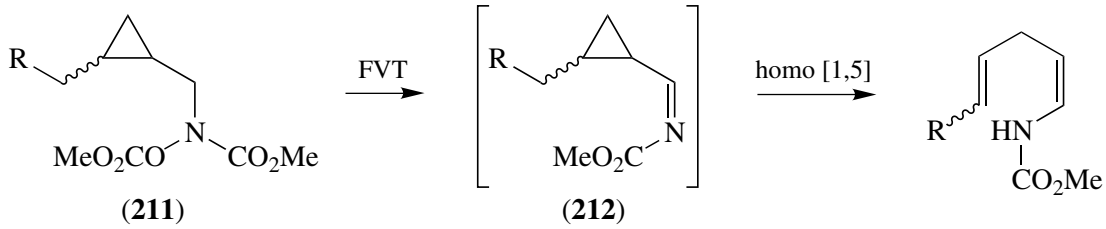
[1,5]-Migrations

It has been reported[254] that conjugated (*Z*,*E*)-dienoic structures in various ethyl octadecatrienoates undergo a [1,5]-hydrogen shift [see (**209**) → (**210**)] much more readily than isomerization to the conjugated (*E*,*E*)-dienoic structure. It has been suggested[255] that the cyclization of bis(2,4,6-trialkylphenyl)ketenes to isochromenes is



(**209**) (**210**)

a stepwise reaction involving a [1,5]-sigmatropic hydrogen shift to yield a conjugated tetraenal which rapidly cyclizes to the isochromene. Recent work has shown[256] that trimethylsilylindene exists as a pair of enantiomers which interconvert by successive [1,5]-suprafacial sigmatropic shifts of the trimethylsilyl group via the corresponding isoindene. The same group[257] has shown that strategically incorporating aromatic rings on to indenyltrimethylsilane lowers the barrier for [1,5]-silatropic shifts around the five-membered ring through retention of aromatic character in the transition state and in the intermediate isoindene. *cis*- and *trans*-*N*-acyl-2-alkylcyclopropylimines (**212**), obtained for the first time during thermolysis of diacylated hydroxylamines (**211**), have been found to undergo a symmetry-allowed homodienyl [1,5]-hydrogen shift rather than ring opening.[258]

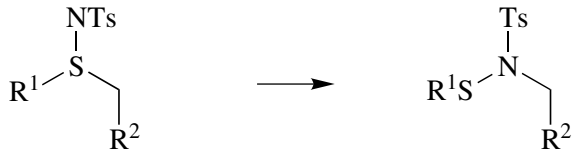


(**211**) (**212**)

Prolonged heating has been shown to convert 3*H*-pyrrole-3-carboxylic esters quantitatively into their isomeric 1*H*-pyrrole-4-carboxylic esters.[259] The [1,5]-sigmatropic rearrangements of hydrogen and other groups in pyrroles (furans and thiophenes) have been studied by semiempirical and *ab initio* methods. Such systems have been used as models to explain the ring D inversion in the biosynthesis of uroporphyrinogen III and the stereoselective shift of a methyl group in the biosynthesis of vitamin B_{12}.[260] Results obtained for the nitration of a series of dimethylpyridines with dinitrogen pentoxide have been shown to support a [1,5]-sigmatropic shift migration for the mechanism of the process.[261] The rearrangement of the indole alkaloid strictamine under flow thermolysis conditions has been found to produce akuammicine and indolenine resulting from [1,5]-sigmatropic shifts within the structure.[262]

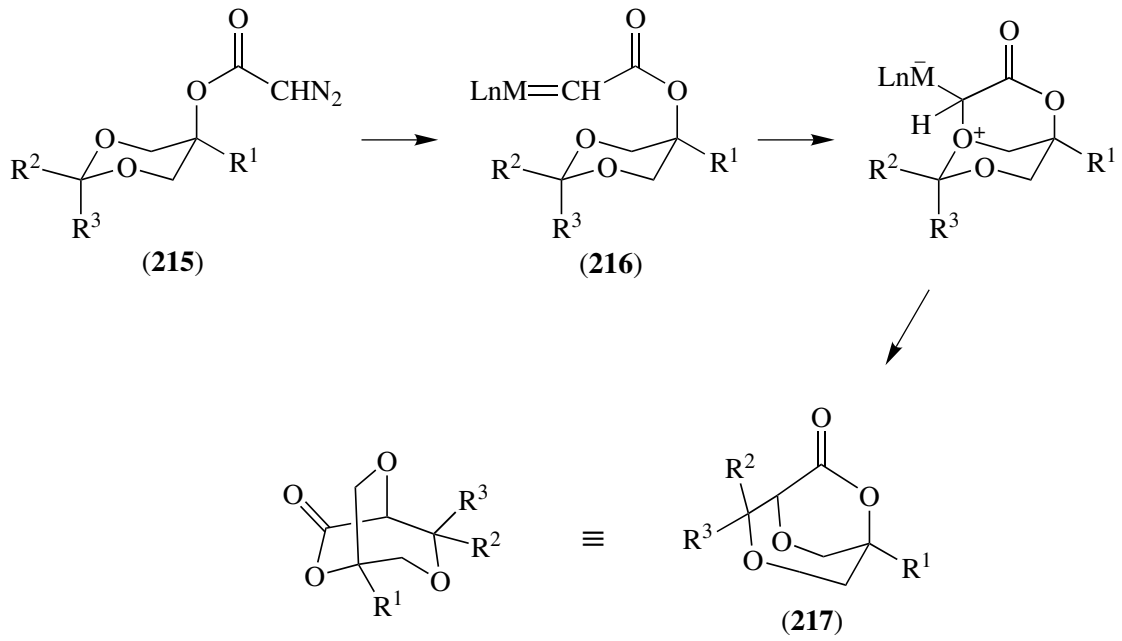
Miscellaneous

Semiempirical MO theory has been used[263] to study the effect of solvation by acetonitrile on the Stevens rearrangement of methylammonium formylmethylide to 2-aminopropanal. The Stevens rearrangement of bisammonium salts containing a common *p*-xylylenyl group has been examined,[264] while a study of the mechanism of the Stevens rearrangement of ammonium ylides has shown[265] that the rearrangement of trimethylammonium *N*-benzylide to *N*,*N*-dimethyl-1-phenylethylamine only takes place in the presence of butyllithium when the temperature is raised to room



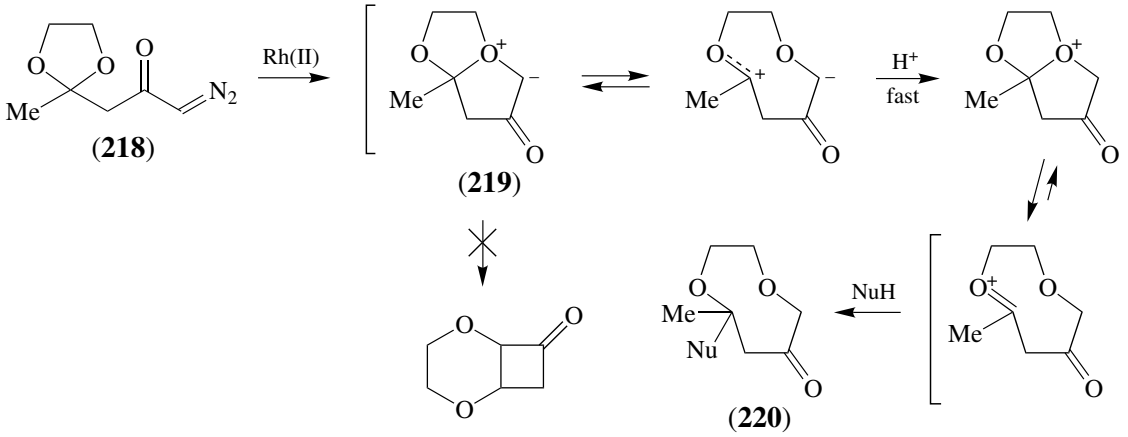
(**213**) (**214**)

temperature. Photolysis of *S*-naphthylmethyl-*N*-*p*-tosylsulfimides (**213**) has been shown[266] to lead unexpectedly to the Stevens rearrangement products (**214**), and Stevens rearrangement products (**217**) have been isolated[267] with high chemoselectivity and high enantioselectivity from the oxonium ylides (**216**) generated by chiral dirhodium(II) carboxamidate treatment of 1,3-dioxan-5-yl diazoacetates (**215**). It appears that diastereotopic association of the metal carbene at one of the two ether oxygens is the source of the enantio-control (see Scheme 53). Rhodium(II)-catalysed reaction of 2-(3′-diazo-2′-oxopropyl)-2-methyldioxolane (**218**) in the presence of a protic nucleophile has been shown to result in effective ring enlargement to yield dioxocanones (**220**). This transformation has been explained[268] by assuming that protonation of the intermediate bicyclooxonium ylide (**219**) takes place faster than its rearrangement to the Stevens product (see Scheme 54). The highly functionalized 2,9-dioxabicyclo[3.3.1]nonane skeleton (**222**) has been rapidly assembled[269] by rearrangement of oxonium ylide intermediates (**221**) generated from the exposure of cyclic acetals to metal carbenoids. The dyotropic ring enlargement of *β*-lactones (**223**) to *γ*-lactones (**225**) has been shown to proceed[270] via the zwitterionic intermediate (**224**). Kinetic studies have been undertaken[271] on the [1,2]-sigmatropic hydrogen shift in the photo-rearranged intermediate of *N*-acetylpyrrole. Both [1,2]- and [3,2]-phosphatoxy

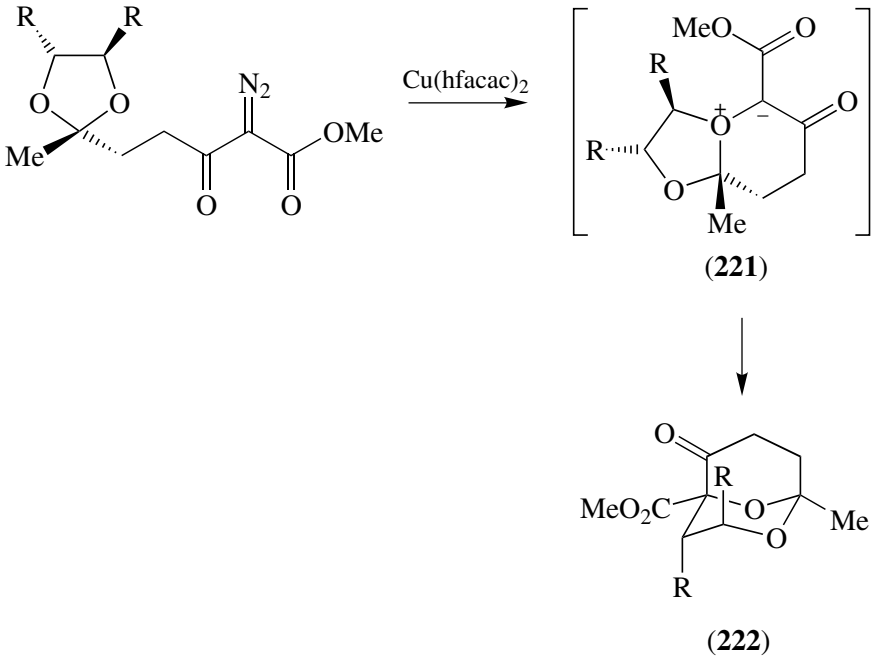


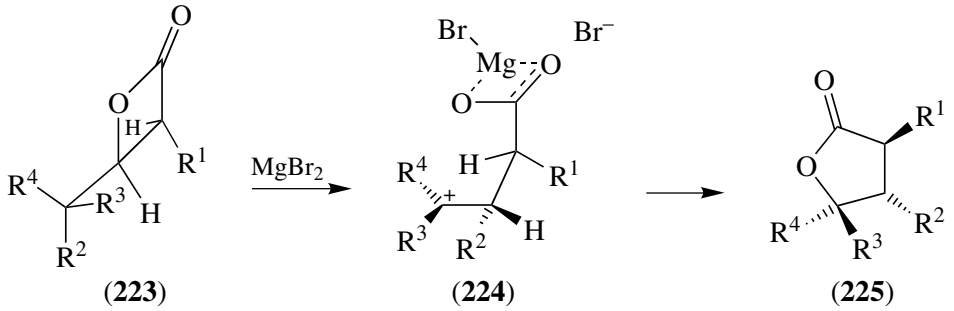
(**215**) (**216**) (**217**)

SCHEME 53


Rh(II)
H+
fast
NuH
Me
Nu
(218)
(219)
(220)

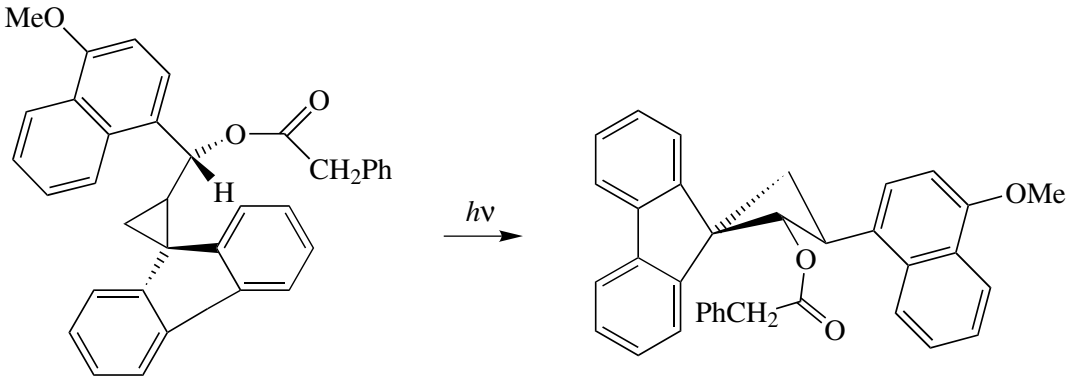
SCHEME 54


Cu(hfacac)2
OMe
MeO2C
(221)
(222)


MgBr2
Br
Br−
Mg
(223)
(224)
(225)

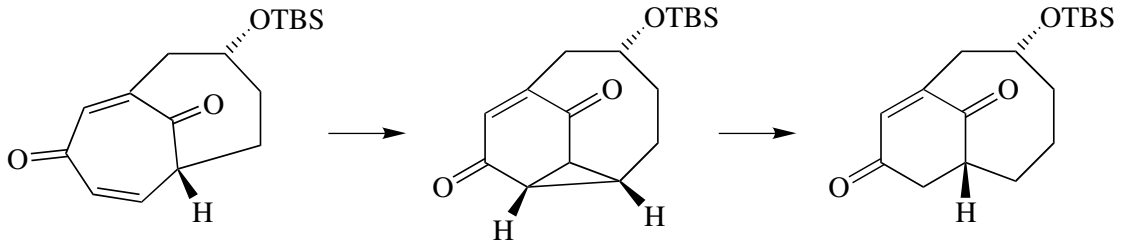
rearrangements have been studied[272] in 2-(phosphatoxy)ethyl, 2-(dimethylphosphatoxy)ethyl, and 2-(phosphatoxy)propyl radicals, and it has been found that in contrast to acyloxy rearrangements in otherwise identical systems, these compounds prefer the [1,2]-shift pathway.

Synthetic aspects of the di-π-methane rearrangement have been reviewed.[273] An aryl version of the cyclopropyl-π-methane rearrangement has been reported;[274] see (**226**) → (**227**). A model study of the mechanism of the di-π-methane and lumiketone



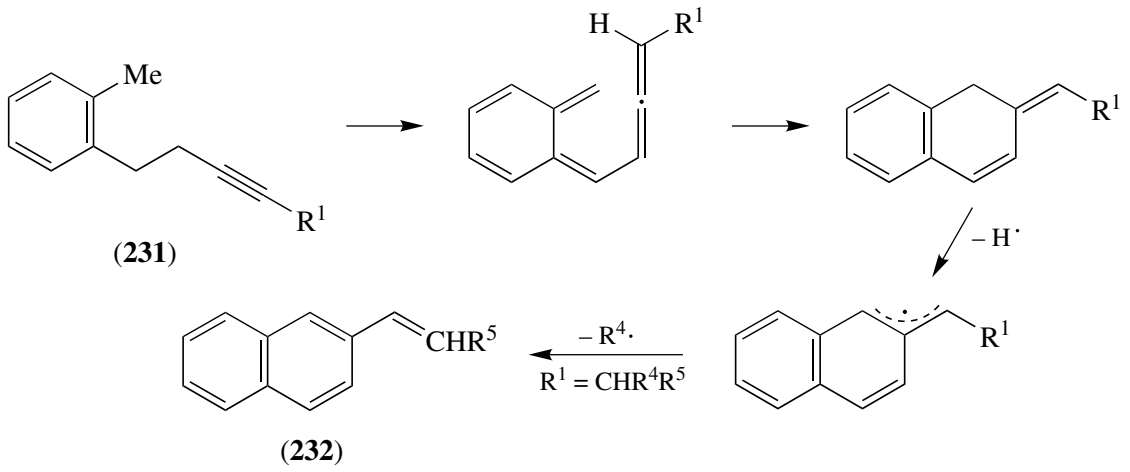
(**226**) (**227**)

rearrangement in rotationally constrained α, β-enones has been undertaken.[275] An application of an oxa-di-π-methane photo-isomerization of bicyclo[4.4.1]undecadiene (**228**) to the cyclopropyl ketone (**229**), which on selective reductive cleavage yielded bicyclo[5.3.1]undecene (**230**), has been examined,[276] and a series of tricyclic ketones have been obtained by utilizing the photochemical oxa-di-π-methane rearrangement of chiral bicyclic[2.2.2]oct-5-en-2-ones.[277]

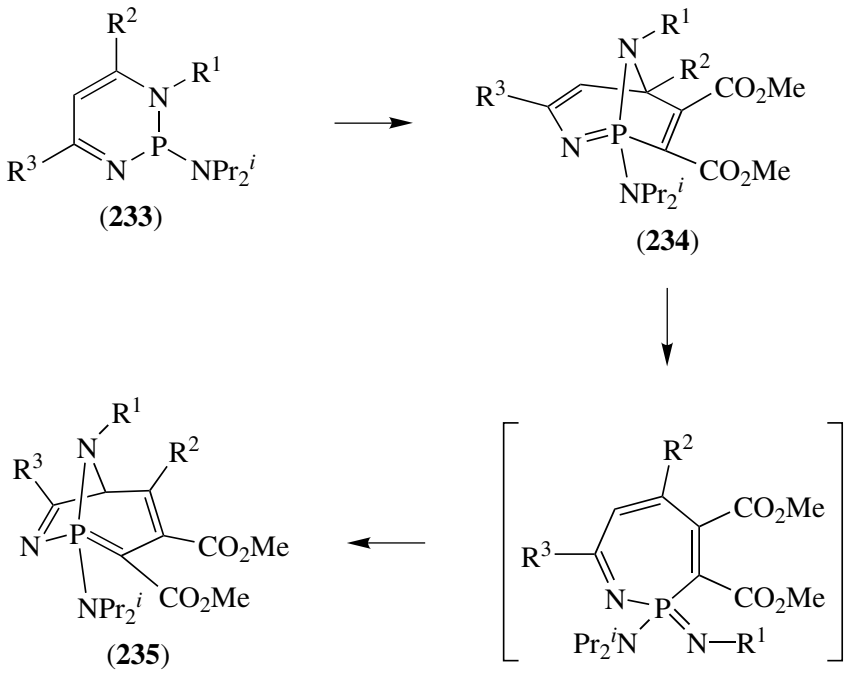


(**228**) (**229**) (**230**)

The generation of 2-methylstyrylalkynes (**231**) and their thermal cyclization to 2-alkenylnaphthalenes (**232**) have been reported.[278] The mechanism is considered to proceed via an initial [1,7]-hydrogen shift followed by a 6π electrocyclization (see Scheme 55). The rapid and reversible migrations of the phenylsulfanyl group around the seven-membered ring of 7-phenylsulfanylcyclohepta-1,3,5-triene have been proved to proceed through successive [1,7]-sigmatropic shifts.[279] Bicyclic iminophosphoranes (**234**), obtained by the treatment of 1,2-dihydro-1,3,2-diazaphosphinines (**233**) with dimethyl acetylenedicarboxylate, have been reported[280] to undergo a formal [1,7]-rearrangement to (**235**) at room temperature.

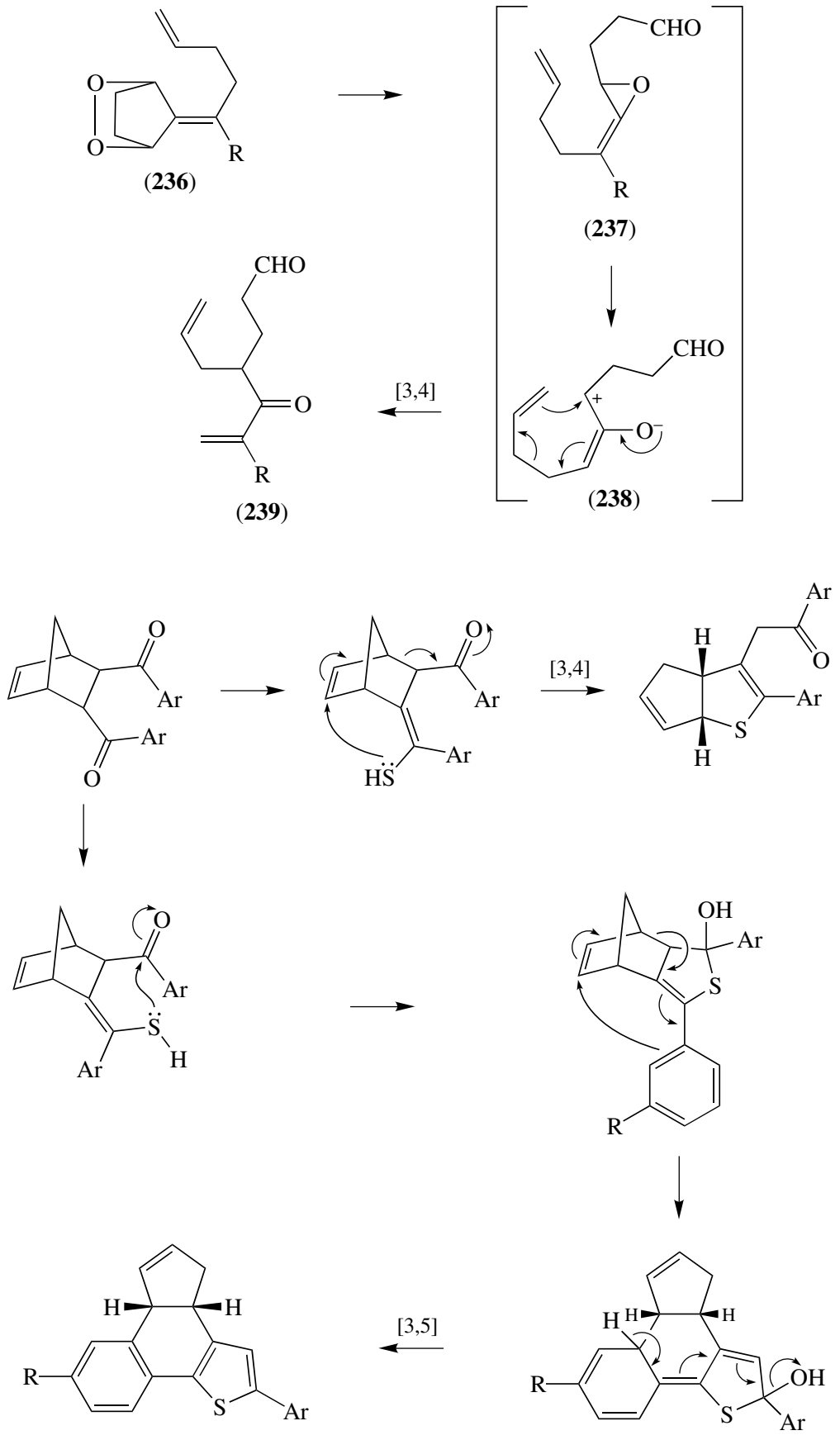


SCHEME 55

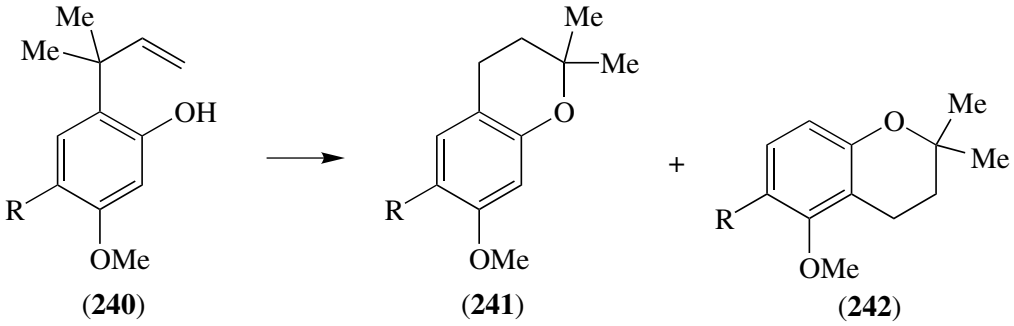


Erden *et al.*[281] have reported that endoperoxides (**236**) react at 60 °C via the allene oxides (**237**) and their ring-opened products (**238**) by a [3,4]-shift to afford 5-oxo-6-pentenal derivatives (**239**).

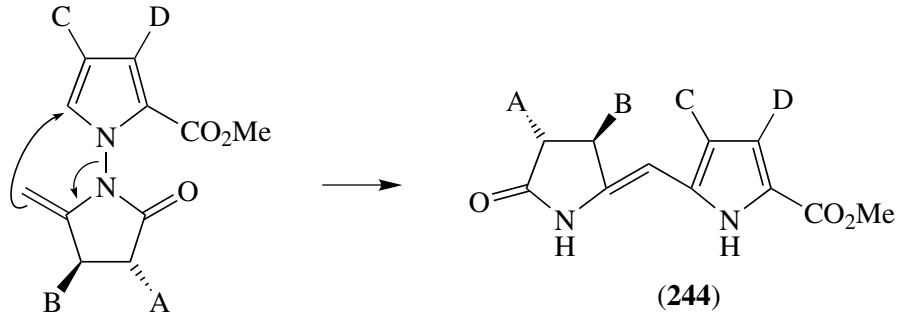
Thionation reactions of 2,3-diaroylbicyclo[2.2.1]hepta-5-enes with boron sulfide have been reported[282] to yield [3,4]- and [3,5]-sigmatropic rearrangement products. The release of ring strain in the norbornene system and formation of the thiophene ring system are thought to be the driving force behind these rearrangements (see Scheme 56). A [3,5]-charge-accelerated rearrangement has been invoked[283] to account for the formation of the two isomeric 2,2-dimethyl-4*H*-dihydropyrano[*b*]benzenes (**241**) and (**242**), on treatment of dihydrolicochalcone A (**240**) with acid, while a [3,5]-sigmatropic rearrangement of an *N*-pyrrolenamide (**243**) has been proposed[284] to account for its



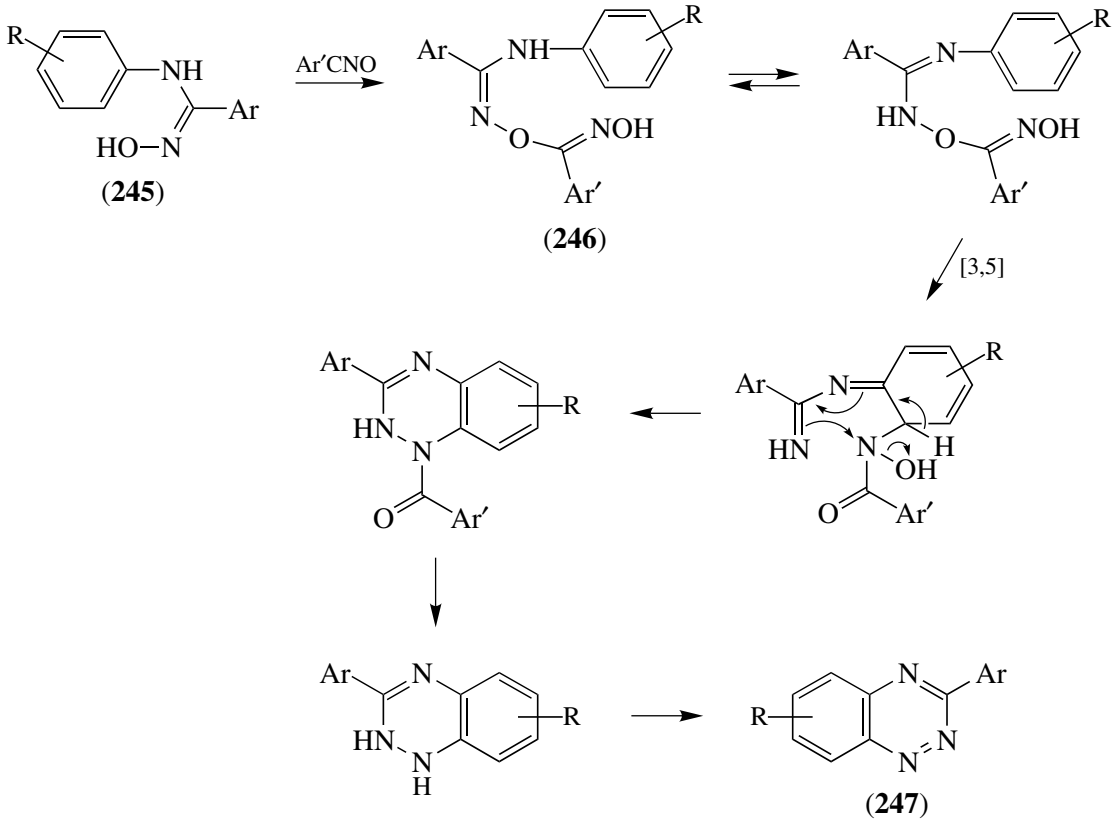
SCHEME 56



(**240**) (**241**) (**242**)

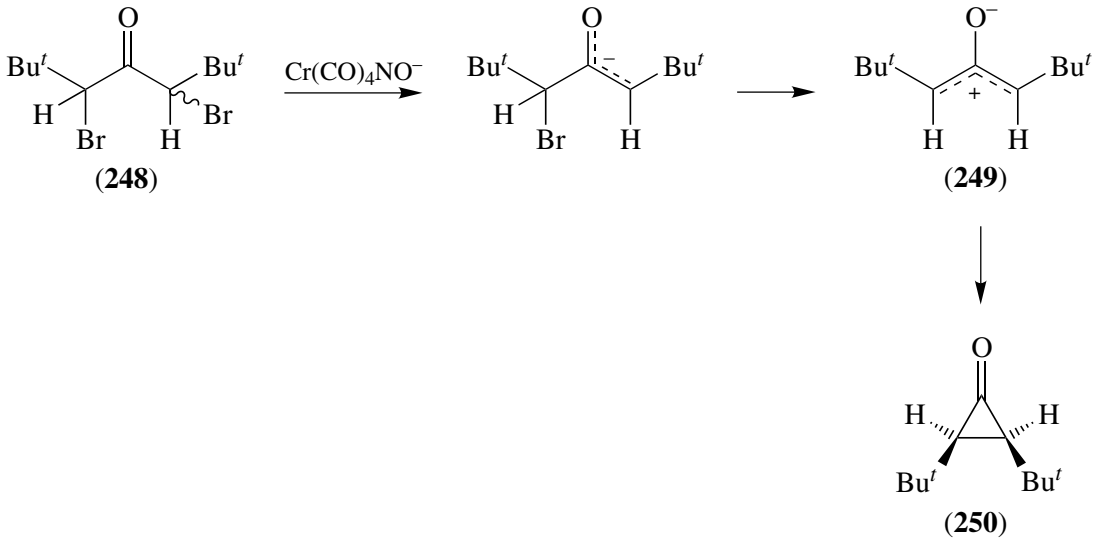


(**243**) (**244**)



(**245**) (**246**) (**247**)

SCHEME 57



(**248**) (**249**) (**250**)

observed photochemical conversion into enantiomerically pure ring A,B synthons of linear tetrapyrroles (**244**).

The reaction of *N*-arylbenzamidoximes (**245**) with nitrile oxides in refluxing toluene has been reported to lead mainly to benzotriazines (**247**), the formation of which has been explained[285] by postulating the occurrence of an unusual [3,5]-rearrangement of the non-isolated 1 : 1 adduct (**246**) (see Scheme 57).

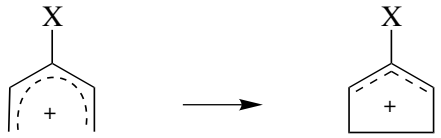
Electrocyclic Reactions

Enone cycloadditions and rearrangements that occur during the photo-reactions of dienones and quinones have been reviewed.[286] A review has appeared[287] which discusses computational studies for electrocyclic reactions, cycloadditions, and sigmatropic shifts, and this has been followed by a paper[288] which describes how computational results have contributed to an understanding of transition structures and the mechanisms of electrocyclic ring opening of cyclobutenes and Diels–Alder cycloaddition reactions. A method for estimating the activation energies of concerted, yet non-synchronous, thermal pericyclic reactions has been described,[289] and a recently proposed similarity index has been applied[290] to the quantitative justification of the empirical Hammond postulate for a series of selected pericyclic reactions.

The formation of *cis*-di-*t*-butylcyclopropanone (**250**) from the acyclic precursor (**248**) on treatment with $Cr(CO)_4NO^-$ has provided evidence both for the existence of oxyallyl intermediates (**249**) in the mechanism of this reaction and for the integrity with which oxyallyls ring close to cyclopropanones by a disrotatory route.[291]

Computational studies of the electrocyclic ring closures of cycloheptatetraene to bicyclo[3.2.0]hepta-1,3,6-triene and bicyclo[3.2.0]hepta-2,3,6-triene have been reported,[292] and the reaction of *P*-chloroiminophosphine with 1-(dialkylamino)alkynes has been shown to yield 1,2-azaphosphetines via the (*E*)-1-aza-2-phosphabuta-1,3-dienes.[293]

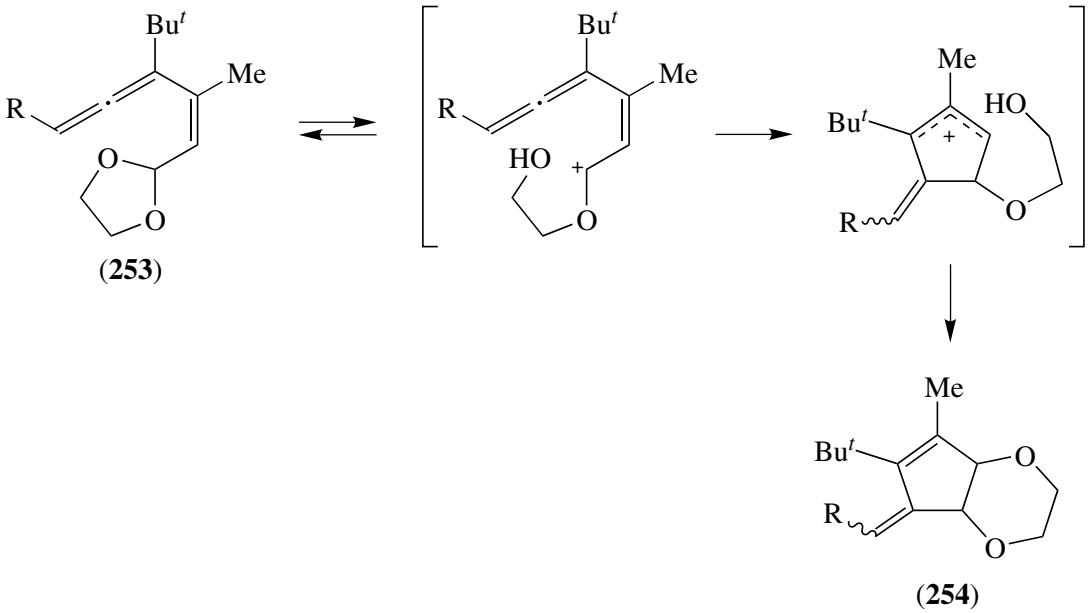
Ab initio MO calculations have been used to examine the conformational preferences, transition structures, and products of the 2 + 2-electrocyclization reaction of the penta-1,4-dienyl system bearing various substituents on C(3); see (**251**) → (**252**). The results



(**251**) (**252**)

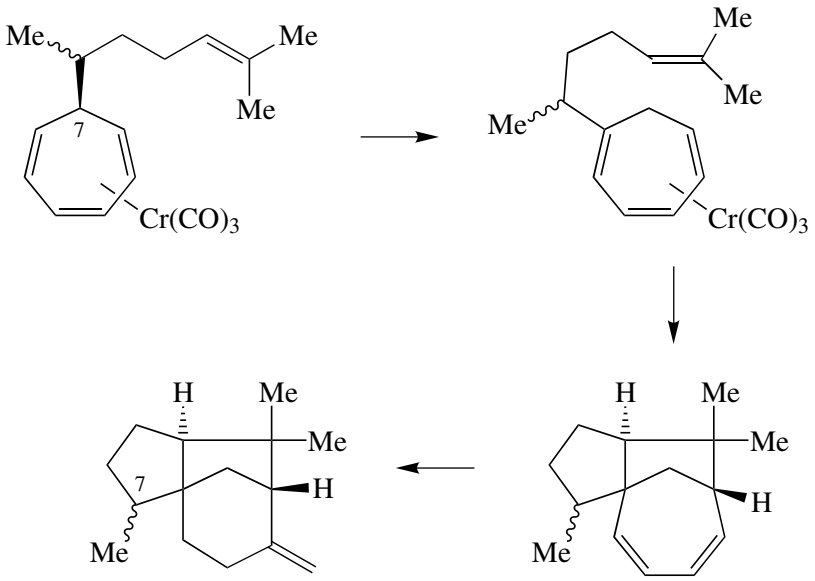
X = NH_2, PH_2, OH, SH, H, BH_4, AlH_2

have been explained by a combination of steric and electronic interactions.[294] *Ab initio* calculations of the superacid-catalysed electrocyclization of 1-phenylprop-2-en-1-ones to indan-1-ones have highlighted[295] the energetic favourability of these dicationic electrocyclizations over the monocationic mechanism. Divinylallene acetals (**253**) have been found to undergo facile acid-induced rearrangement to alkylidenecyclopentenes (**254**) by a mechanism which is consistent with electrocyclic ring closure of a pentadienyl carbocation[296] (see Scheme 58). A synthesis of *β*-cedrene featuring a chromium(0)-promoted, intramolecular $6\pi + 2\pi$-cycloaddition as the key ring-forming process has been described.[297] The basic strategy for this synthesis is depicted in Scheme 59. A methodology has been devised[298] with the potential for preparing enantiopure *α*, *β*-dihydroxy acids from achiral aldehydes using a novel chirally templated highly selective isomünchnone cycloaddition procedure in which the original chiral template can be recovered (see Scheme 60). It has been predicted[299] that, in the thermal transformation of the ring-opened 2 + 2 C_{60} dimer into a wide-bridged C_{120} isomer, the fulvalene bridge of the former rearranges into a naphthalene partial structure

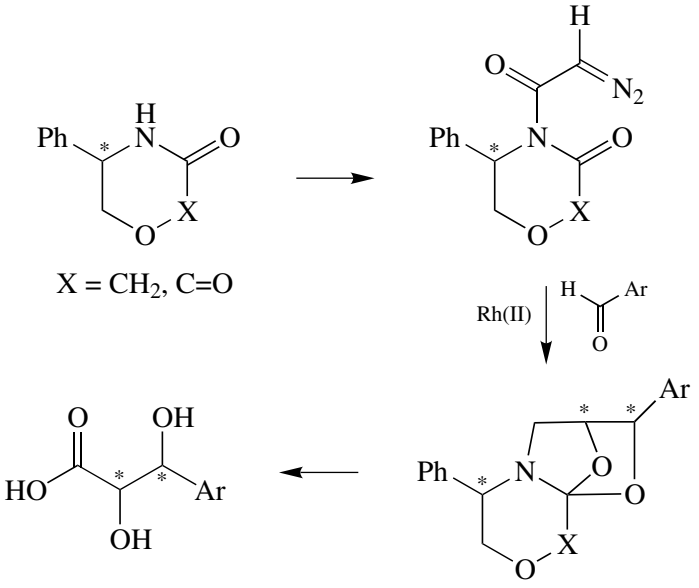


(**253**) (**254**)

SCHEME 58



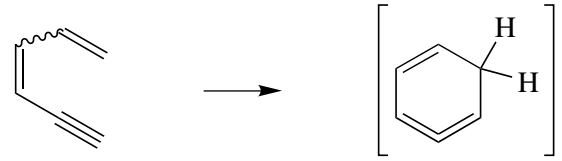
SCHEME 59



SCHEME 60

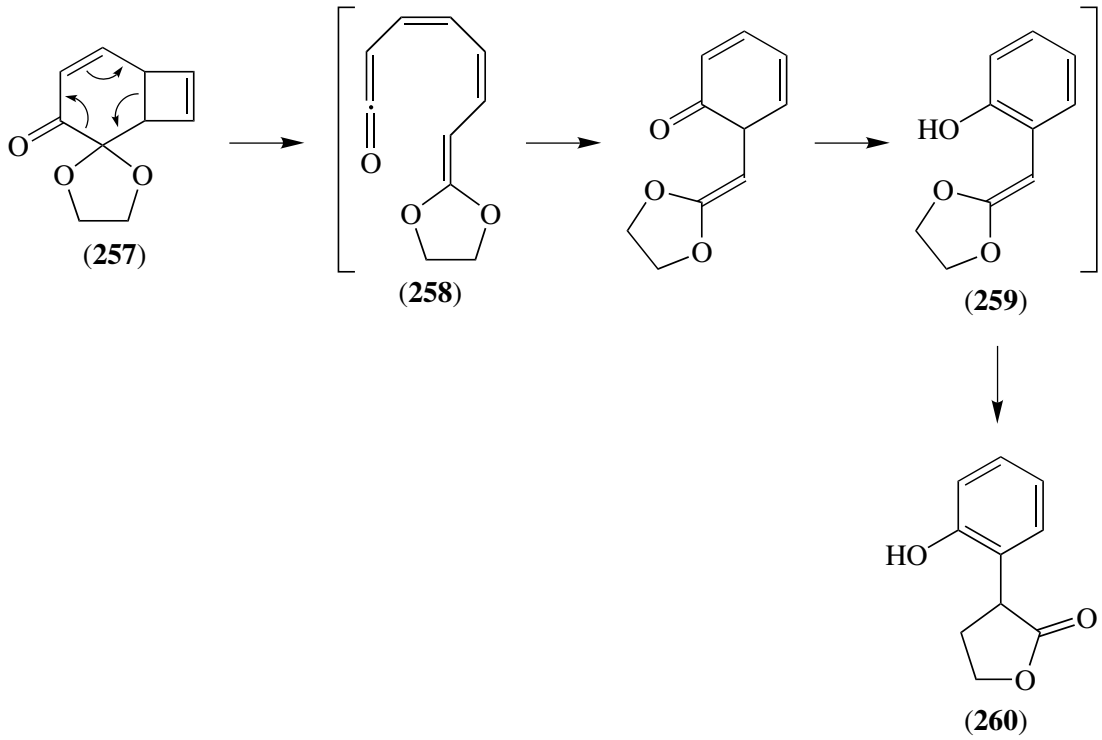
by a concerted in-plane mechanism to form a C_{120} intermediate having 20 five-membered rings and two ten-membered rings. It has also been shown[300] that the photochemical step in the thermal rearrangement of [6,5] open fulleroids to [6,6] closed fullerenes is the one responsible for the zero-order kinetics of the rearrangement.

Although a number of competing pathways have been shown to be involved[301] in the thermal cycloisomerization of hexa-1,3-dien-5-ynes (**255**), isobenzenes (**256**) have been established[302] as intermediates in their thermal rearrangement to arenes. On solvolysis, the diethylphosphate ester of 1-(2-ethynylphenyl)-4-trimethylsilyl-4-(trimethylsilyloxy)pent-2-yn-1-ol has been found[303] to afford 5-(2-ethynylphenyl)-3-trimethylsilyl-



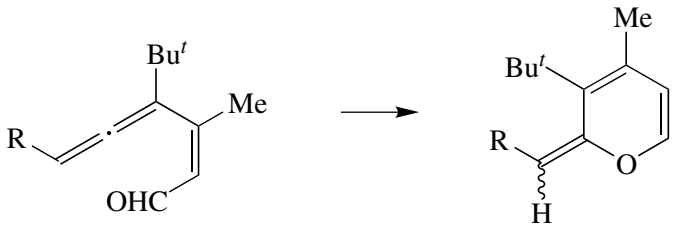
(**255**) (**256**)

penta-3,4-dien-2-one, which cyclizes *in situ* to 1-(2-naphthyl)-1-trimethylsilylpropan-2-one. Pyrolysis of the ethylene acetal of bicyclo[4.2.0]octa-4,7-diene-2,3-dione (**257**) at 400 °C has been found to yield α-(2-hydroxyphenyl)-γ-butyrolactone (**260**). A proposed mechanism for the transformation[304] is outlined in Scheme 61, where the formation of (**260**) is initiated by retro-Diels–Alder reaction of the six-membered ring of (**257**) to afford the ketene intermediate (**258**), which then undergoes electrocyclization and enolization to give the phenol derivative (**259**). Finally, a formal 1,3-shift of the ethylene portion of (**259**) gives (**260**). (2*Z*)-Divinylallenals (**261**) have been found to undergo electrocyclization to alkylidene-2*H*-pyrans (**262**), even though the product is



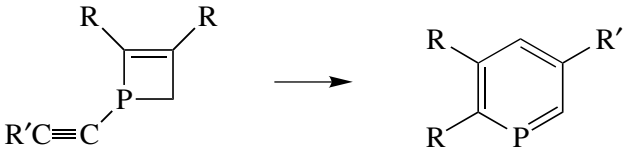
(**257**) (**258**) (**259**) (**260**)

SCHEME 61



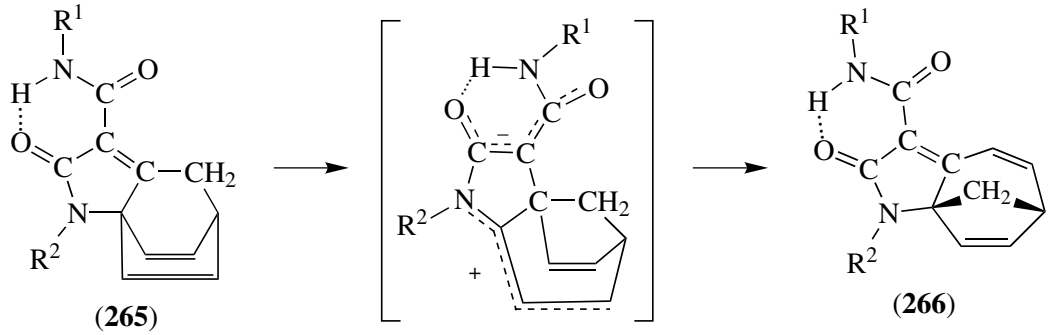
(**261**) (**262**)

not stabilized by a conjugated-aryl or electron-withdrawing substituent.[305] 1-Alkynyl-1,2-dihydrophosphetes (**263**) have been shown to rearrange to the corresponding phosphinines (**264**) via a 4π cycloreversion–6π electrocyclization mechanism.[306]



(**263**) (**264**)

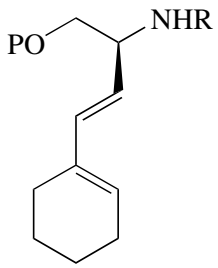
It has been suggested[307] that the observed thermal rearrangement of the bicyclo[2.2.2]- to the bicyclo[3.2.1]-octadiene skeleton in tricyclic lactams, viz. (**265**)→(**266**), is consistent with an intramolecular Diels–Alder reaction in which a zwitterion is formed by the migration of one vinyl group from C(1) to C(5) of the lactam moiety (see Scheme 62). It has been shown[308] that the π-facial selectivity of the Diels–Alder reaction of 1,3-dienes (**267**) having an attached stereogenic centre can be



(**265**) (**266**)

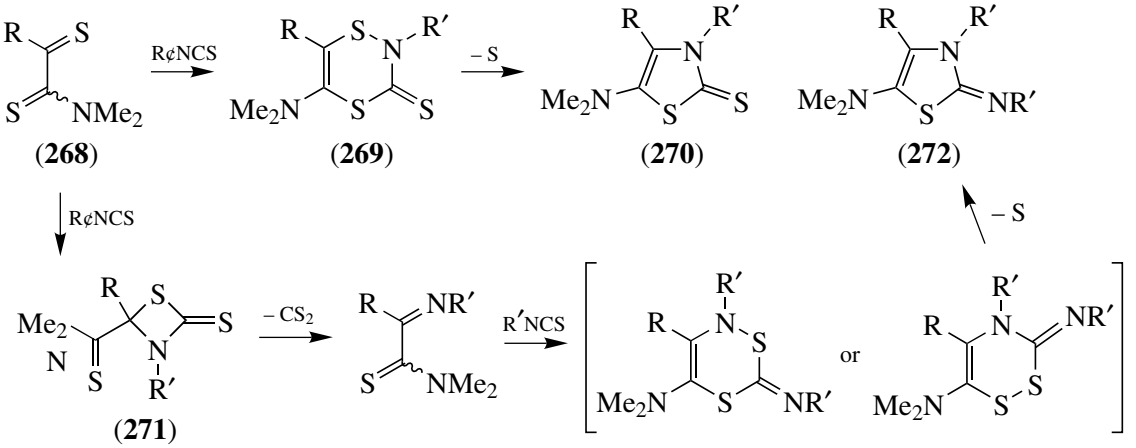
SCHEME 62

enhanced by increasing the size of the protecting group on the homoallylic hydroxyl group. Aryl and methyl isothiocyanates have been found to react with 1,2-dithiocarbonyl compounds (**268**) to give a mixture of 2,3-dihydro-2-thioxothiazoles (**270**) and 2-iminothiazoles (**272**). The formation of these products has been explained[309] by invoking $4+2$- and $2+2$-addition to the C=N bond of the heterocumulene followed by ring contraction of the 2,3-dihydro-1,4,2-dithiazine



(**267**)

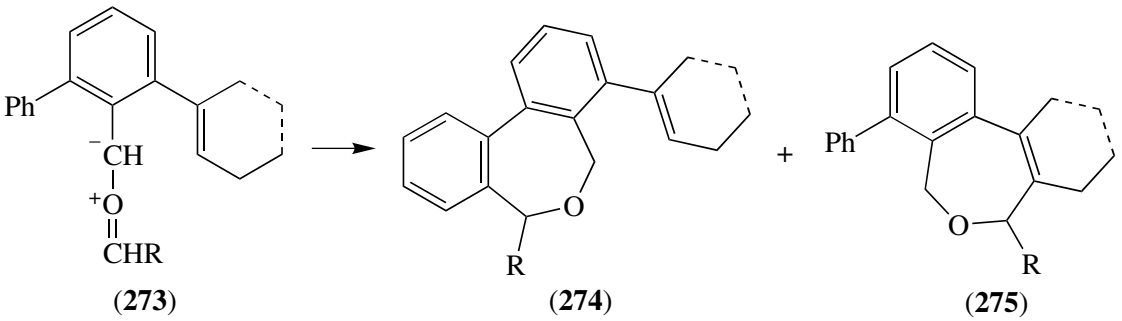
P = protecting group



SCHEME 63

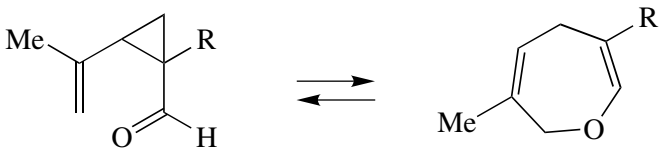
(**269**) with sulfur extrusion to give (**270**), or cycloreversion of the 2-thioxothiazetidine (**271**) and carbon disulfide elimination to give eventually (**272**) (see Scheme 63).

Azepine derivatives have been prepared in excellent yields by heating α,β-unsaturated aldehydes having a 2-alkenylamino moiety at the β-position. PM3 calculations of model reactions have indicated[310] that the azepine ring formation is constituted of two consecutive orbital-allowed reactions, a 1,6-hydrogen shift leading to conjugated azomethine ylides, and their electrocyclization. A study of the effective formation of benzoxepines (**274**) and (**275**) by the 1,7-electrocyclization of diene-conjugated carbonyl ylides (**273**) has shown that the rate of the 1,7-carbonyl ylide cyclizations is virtually unaffected by either the olefinic/aromatic character of the γ,δ-bond, or whether it is electron-rich or electron-poor.[311]



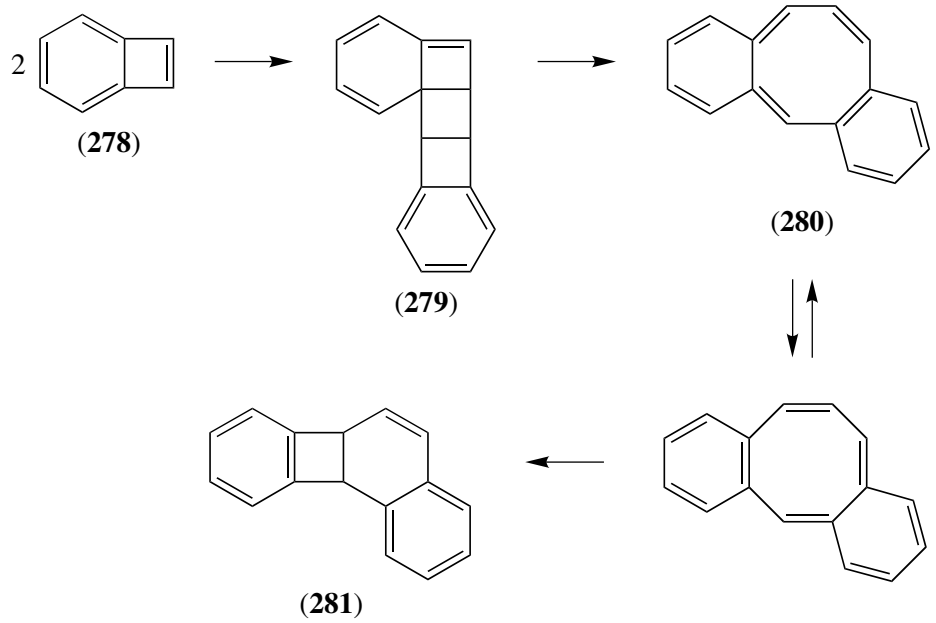
A direct dynamics technique has been employed[312] to study the thermal isomerization of (*S*,*S*)-*trans*-cyclopropane-1,2-d_2 and cyclopropane-1,2,3-d_3 in an attempt to examine the possibility of stereochemical control in the isomerization. The stereochemistry of the ring expansion of various 2-isopropenylcyclopropane-1-carbonyl compounds (**276**) to the corresponding methyldihydrooxepins (**277**) has been studied,[313] and the rearrangement of cyclopropylsilylene to silacyclobutene has been examined[314] by *ab initio* MO theory.

Substituted hydroazulenic derivatives have been constructed[315] using a photochemical ring-expansion reaction of readily available electrophilic cyclobutenes. Labelling



(**276**) (**277**)

studies have supported[316] a mechanism involving the formation of a 4 + 2-dimer (**279**), followed by its ring opening to afford the cyclooctatetraene (**280**), which closes to the final dimer (**281**), to account for the dimerization of benzocyclobutadiene (**278**). Work

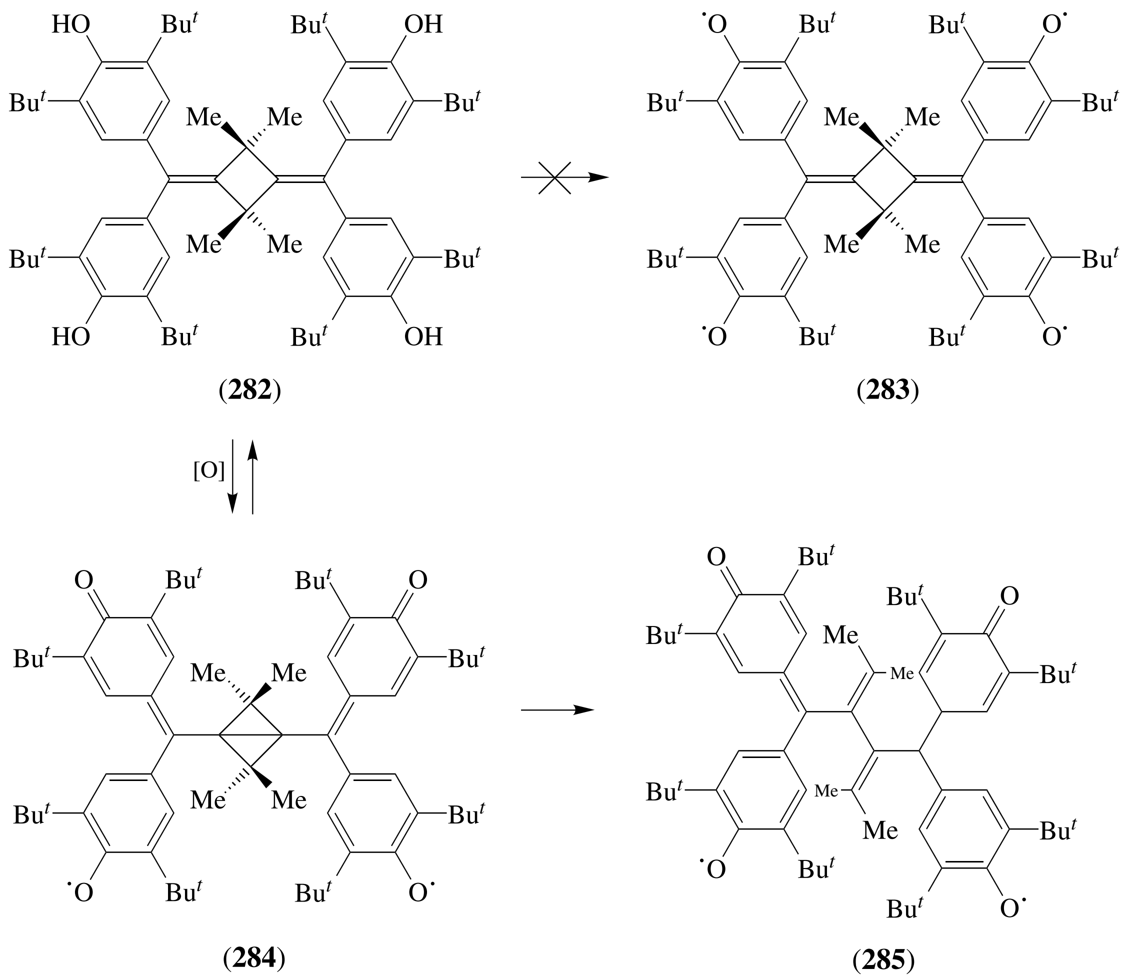


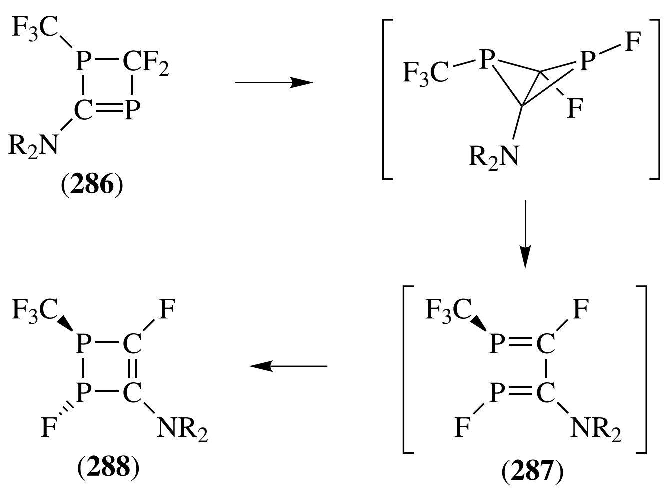
(**278**) (**279**) (**280**) (**281**)

seeking to prepare the tetraphenoxyl radical (**283**) from oxidation of tetraphenol (**282**) failed to produce (**283**) but supported the conclusion that (**283**), or an intermediate on the path to it, closed to a bicyclobutane such as (**284**), which then underwent a surprisingly facile rearrangement to produce ultimately the observed butadiene derivative (**285**).[317] 1,2-Dihydro-1,3-diphosphetes (**286**), prepared from reaction of perfluoro-2-phosphapropene with phosphaalkynes, have been found to undergo an interesting rearrangement to the thermodynamically more stable 1,2-dihydro-1,2-diphosphetes (**288**) via a 1,2-fluorine shift, an electrocyclic ring opening to a 1,4-diphosphabutadiene intermediate (**287**), and an intramolecular 2 + 2-cycloaddition. This mechanism, shown in Scheme 64, has been supported by high-level *ab initio* calculations.[318]

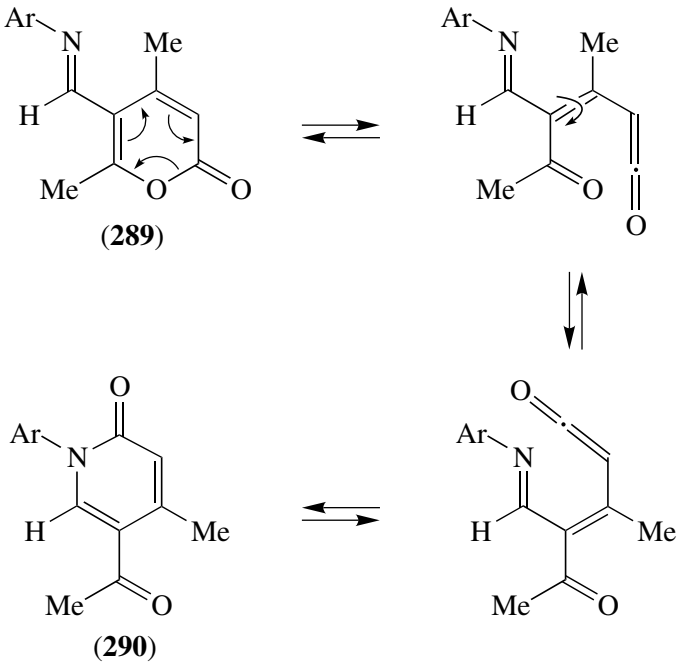
A sequence involving electrocyclic ring opening, *E–Z* isomerization, and ring closure (see Scheme 65) has been invoked[319] to account for the thermal rearrangement of 2-oxopyran-5-carbaldehyde derivatives of the type (**289**) to 2-pyridones (**290**).

Structural and energetic aspects of the ene reaction have been investigated[320] using a variety of computational methods incorporating different ways of accounting for electron configuration, and the mechanistic course of Lewis acid-catalysed cycloaddi-





SCHEME 64

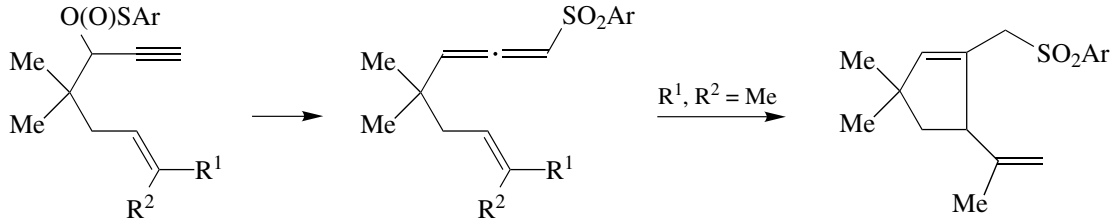


(**289**)

(**290**)

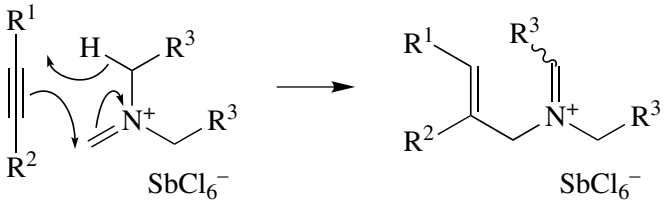
SCHEME 65

tions and ene reactions has been determined[321] using high-pressure kinetics. The transition structures for the ene reactions of cyclopropene with ethylene, propene, and cyclopropene have been located[322] with *ab initio* calculations. The ene reaction between maleimides and allyl-substituted aromatics has been investigated,[323] and the influence of a protected alcohol group adjacent to the ene or enophile component on diastereoselectivity in both thermal and Lewis acid-catalysed ene reactions of a series of 1,6-dienes has been studied.[324] The results have indicated that the effect can be considerable, and this new finding has been exploited in a synthesis of epijasmonoid natural products. It has been reported[325] that propargylic-*p*-toluenesulfenates (**291**), α-substituted by a 4,5-unsaturated side-chain, rearrange thermally to 1-tosylmethylcyclopentene derivatives (**293**) with prior isomerization into the corresponding allenic sulfones (**292**).



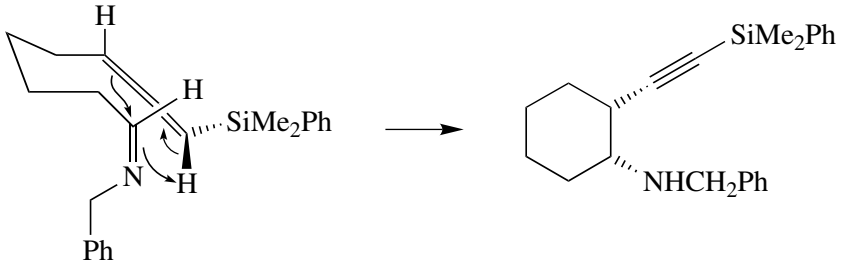
(**291**) (**292**) (**293**)

A new approach to spirolactams involving the thermal reaction of *N*-unsaturated alkyl *β*-carboxamidoenamines in which the enamine is the hetero-ene component has been reported.[326] *N*-Alkylnitrilium salts have been shown to undergo ene reactions with electron-rich alkenes to afford either 2-azoniaallene salts (where the nitrilium salt acts



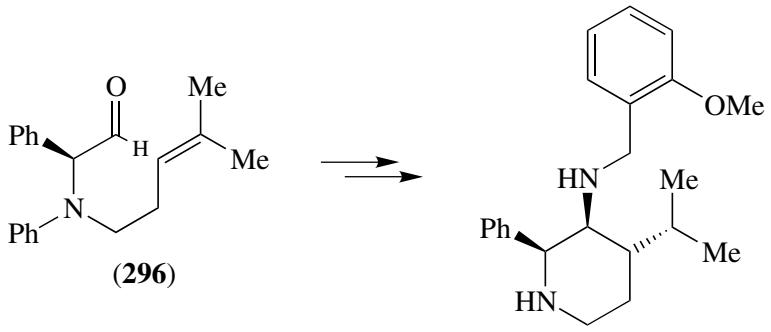
SCHEME 66

as ene and the alkene as enophile) or 1-azoniapenta-1,4-diene salts (where the alkene reacts as the ene and the nitrilium salt as the enophile).[327] A previously unknown ene reaction of iminium ions and alkynes has been found to occur when complex anions with low nucleophilicity[328] are used as counterions. This new reaction has provided stereo- and regio-selective access to substituted allylamines (see Scheme 66). Another new type of thermal intramolecular concerted ene reaction involving allenylsilane imines has been developed[329] [see (**294**)→(**295**)] and has proved to be useful in the



(**294**) (**295**)

enantioselective syntheses of a number of pentacyclic 5,11-methanomorphanthridine Amaryllidaceae alkaloids. Diastereoselective syntheses of 1-hydroxy-substituted benzo[*b*]quinolidines and 11-hydroxy-substituted azepino[1,2-*b*]isoquinolines via hetero-ene cyclization processes have been described,[330] and an enantioselective synthesis of the potential substance P antagonist 4-isopropyl-3-(2-methyoxybenzyl-amino)-2-phenylpiperidine (**297**) has been reported[331] in which the key reaction is a diastereoselective Lewis acid-catalysed hetero-ene reaction of aldehyde (**296**).

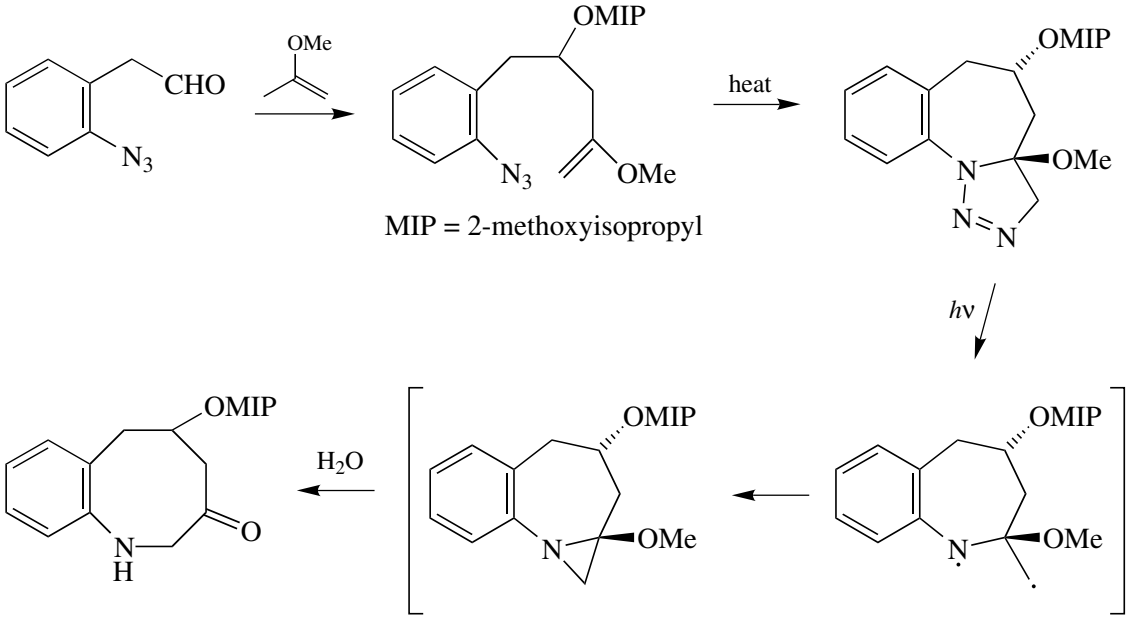


(**296**) (**297**)

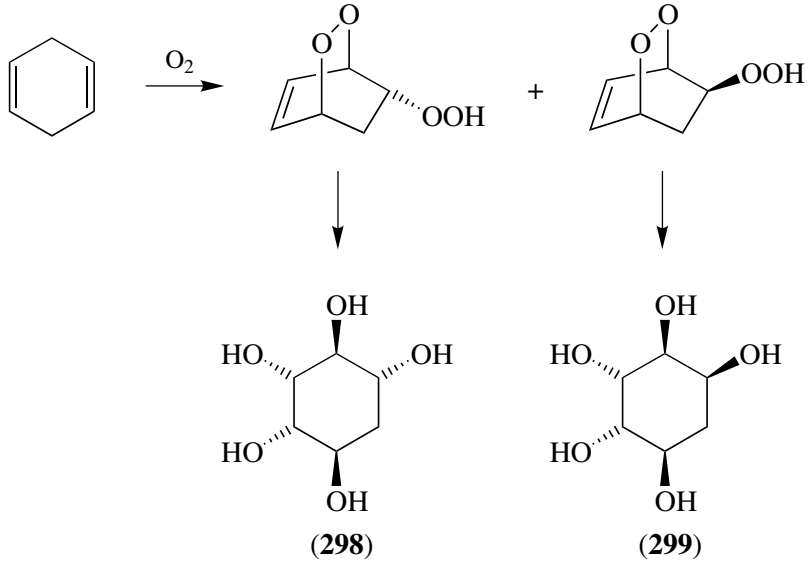
A logically derived mechanistic model has been presented[332] for the enantioselective ene reaction between glyoxylic (and related) aldehydes and terminal olefins under the influence of chiral Lewis acids, and a study has been made[333] of the asymmetric ene reaction of *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam with pent-1-ene and hex-1-ene. $Yb(OTf)_3$ has been used successfully to catalyse the glyoxylate-ene reaction,[334] while a number of metal cation exchanged montmorillonite-catalysed carbonyl ene reactions have been reported.[335] α, β-Unsaturated amides have been shown to undergo cyclo-condensation with *s*-trioxane to give 2*H*-3,6-dihydropyrans in an oxo-ene reaction,[336] while benzazocenones have been assembled efficiently[337] using an ene-type reaction of an azidoaldehyde with 2-methoxypropene, in tandem with a 1,3-dipolar azide cycloaddition and photolysis of the resulting triazoline (see Scheme 67).

A stepwise mechanism involving an aziridinium imide has been predicted[338] from *ab initio* studies for the transition structure of triazolinedione ene reactions. A mechanistic comparison in the regioselectivities of the ene reactions of 4-phenyl-1,2,4-triazoline-3,5-dione and singlet oxygen with a series of symmetrical tetrasubstituted alkenes has been made.[339] The results of the communication have indicated a significant difference in the structure of the product-forming transition states which is responsible for the distribution of the ene product. Electronic repulsions between a perepoxide intermediate and the allylic functionality in the product-forming transition state have been put forward as being responsible for directing regioselectivity in the photo-oxygenation of trisubstituted alkenes bearing an electron-withdrawing group at the β-position of the alkene.[340] Convenient syntheses of proto-quercitol (**298**) and gala-quercitol (**299**) have been accomplished[341] via the ene reaction of singlet oxygen combined with 2 + 4-cycloaddition to cyclohexadiene (see Scheme 68).

Phosphaalkynes have been found to participate readily in ene reactions, both with alkylidenecyclopropanes and with allenes, to form phosphaalkenes and phosphanes,

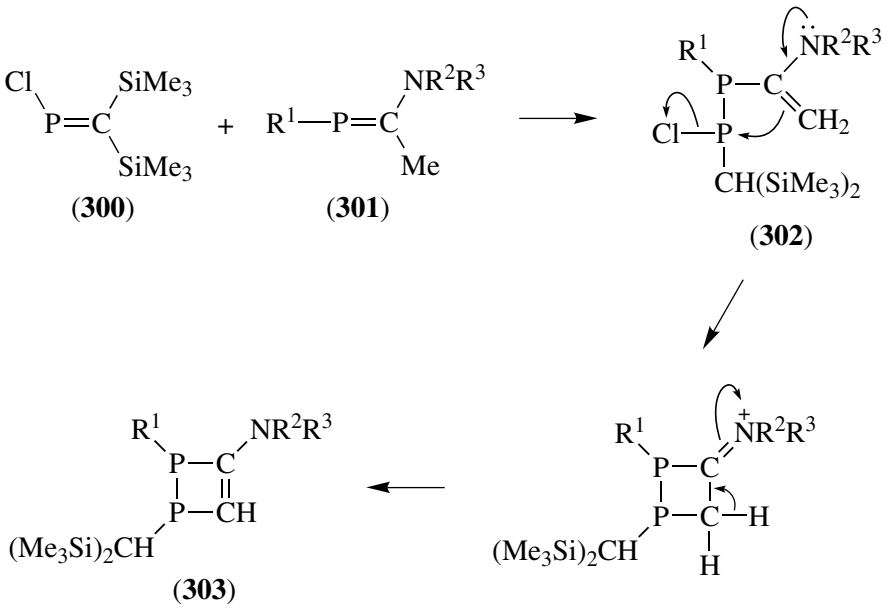


SCHEME 67



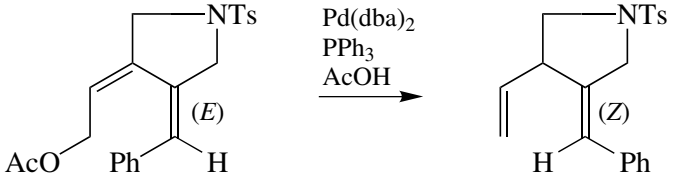
SCHEME 68

respectively.[342] The same group[343] has shown that phospha-ene reactions between methylidene phosphanes (**300**) as enophiles and *C*-aminophosphaalkenes (**301**) possessing allylic hydrogen atoms proceed by P−P bond formation to furnish the corresponding functionalized diphosphanes (**302**), which undergo a subsequent intramolecular ring closure to afford the previously unknown 3-amino-1,2-dihydro-1,2-diphosphetes (**303**).



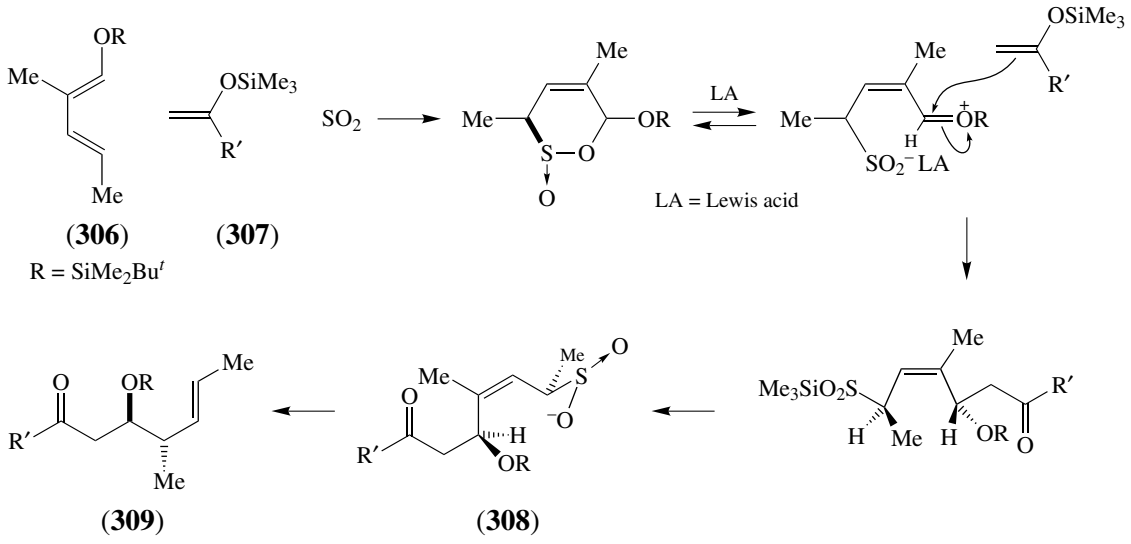
The synthesis of polysubstituted pyrrolidines has been achieved[344] in a diastereoselective and enantioselective manner via the zinca-ene–allene cyclization. In an extension of this work,[345] the zinca-ene–allene reaction of polysubstituted enynes lithiated on the propargylic position has been used to prepare polysubstituted

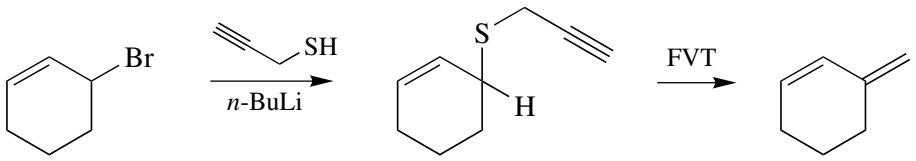
tetrahydrofurans and pyrrolidines of defined geometry. New ethylzinc reagents that show remarkable properties in palladium-catalysed zinca-ene reactions have been unearthed.[346] The palladium-catalysed metallo-ene step in a cyclization-β-elimination sequence has been shown to be suprafacial with respect to the olefinic component, and as a consequence the reaction has been applied with great effect to the synthesis of a trisubstituted exocyclic alkenylpyrrolidine with complete stereocontrol;[347] see (**304**) → (**305**). A study[348] of the enantioselective-catalysed metallo-ene reaction has shown clearly that ligands with closely related structures can have totally different behaviour.



(**304**) (**305**)

The parent methanimine, $H_2C{=}NH$, and *N*-dimethylsilylmethanimine have been generated conveniently by using a retro-ene reaction of the easily accessible allylic and propargylic precursors.[349] The reactive, unsubstituted cyclohex-2-enethione and cyclopent-2-enethione have also been synthesized[350] using as a key step a retro-ene reaction under FVT conditions (see Scheme 69). A new route to 4,5-dihydrooxazoles and 5,6-dihydro-4*H*-1,3-oxazines using a retro-ene reaction has been reported,[351] while mixtures of (*E*,*E*)-2-methyl-1-silyloxypenta-1,3-dienes (**306**), enoxysilanes (**307**), SO_2, and *t*-$BuMe_2SiOTf$ as catalyst have been used to generate (*Z*)-5-alkyl-1,3-dimethyl-6-oxo-4-silyloxyalk-2-enesulfinic acids (**308**) that undergo a stereoselective retro-ene elimination of SO_2, thus forming the corresponding (*E*)-3-hydroxy-2-alkyl-4-methylalk-5-en-1-ones (**309**) with 2,3-*syn* and 3,4-*anti* diastereoselectivity.[352]



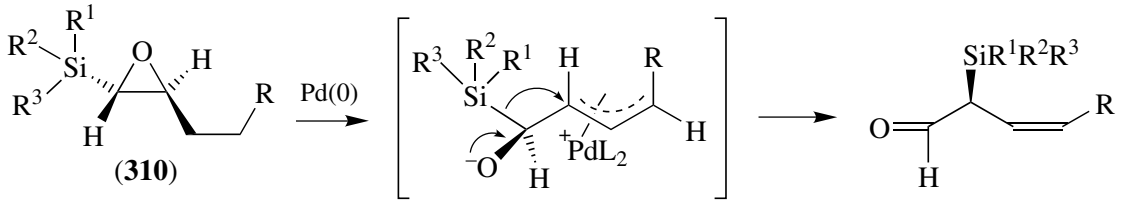


SCHEME 69

Anionic Rearrangements

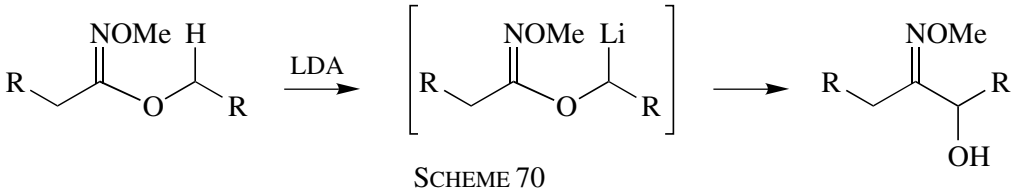
The stereochemical features and synthetic potential of the [1,2]-Wittig rearrangement have been reviewed,[353] as has its application to the conversion of *O*-glycosides into *C*-glycosides.[354] Recent developments in the [1,2]-Wittig rearrangement have been reviewed,[355] and a new imino-Wittig rearrangement of benzyl and allyl hydroximates (see Scheme 70) has been reported.[356] Theoretical studies of Wittig-type anionic migrations of alkyl, silyl, and germyl groups have shown[357] that such rearrangements involve cyclic pentavalent carbanionic species.

In the presence of a catalytic amount of palladium(0), silylated vinyloxiranes (**310**) have been found to rearrange into α-silylated-β, γ-unsaturated aldehydes (**312**), not only with complete chirality transfer, but also with total retention of the double bond stereochemistry. A mechanism involving a [1,2]-silicon shift from carbon to carbon via a π-allylic palladium complex (**311**) has been invoked[358] for the transformation. New

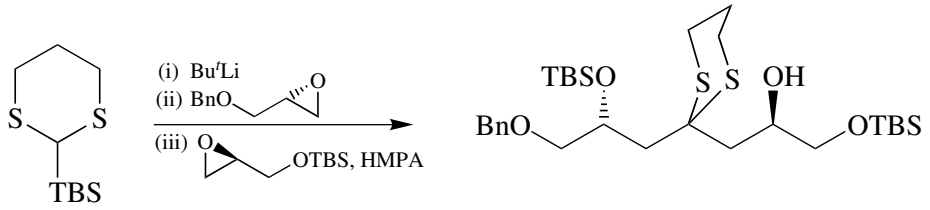


(**310**) (**311**) (**312**)

silicotropic rearrangements which involve [1,3]-trimethylsilyl, and possibly [1,5]-silatropic, shifts from carbon to carbon and carbon to nitrogen have been reviewed.[359] An *ab initio* study into [1,2]-homolytic translocation reactions of silyl, germyl, and stannyl groups between carbon, oxygen, and nitrogen centres has indicated[360] that transfers involving Group IV element-containing substituents proceed via a front-side mechanism in preference over the back-side (Walden inversion) mechanism. A report has appeared[361] of the one-pot coupling of 2-(trialkylsilyl)-1,3-dithianes with two different electrophiles via a solvent-controlled Brook rearrangement (see Scheme 71). The first example of a retro-[1,6]-Brook rearrangement has been observed which, in

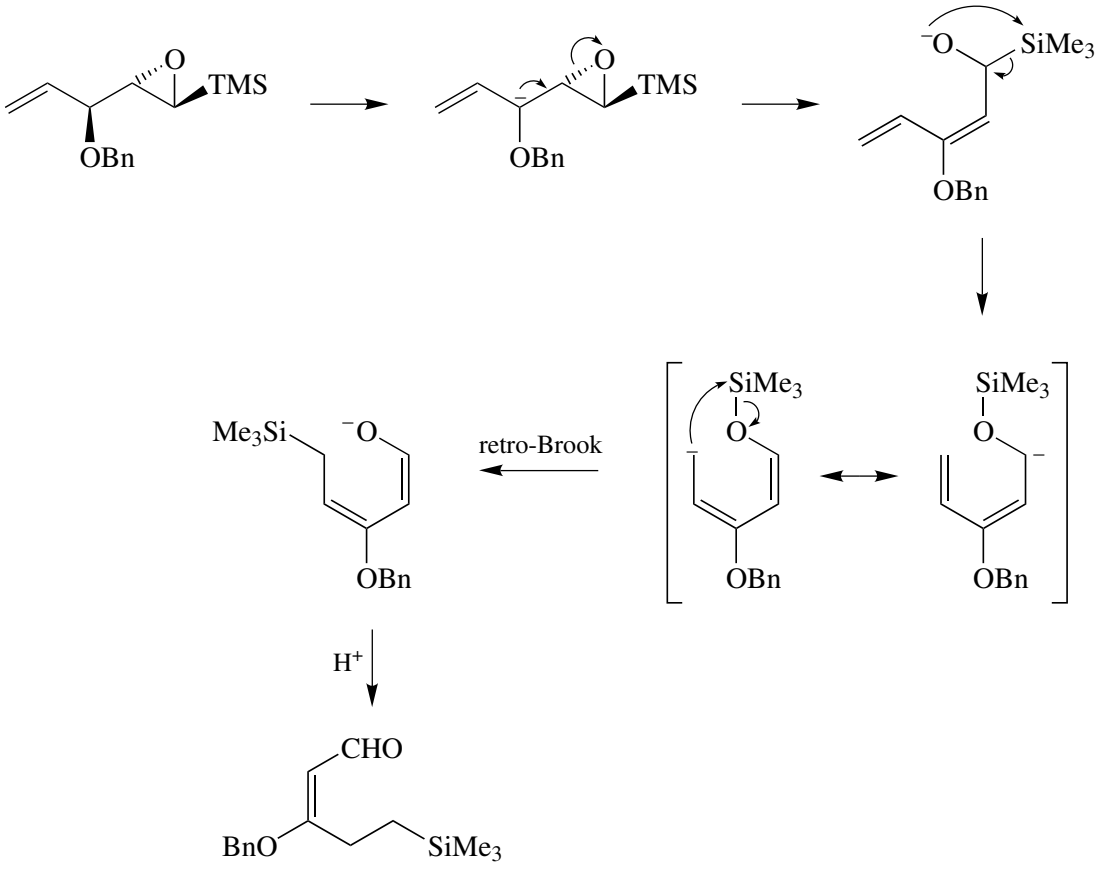


SCHEME 70

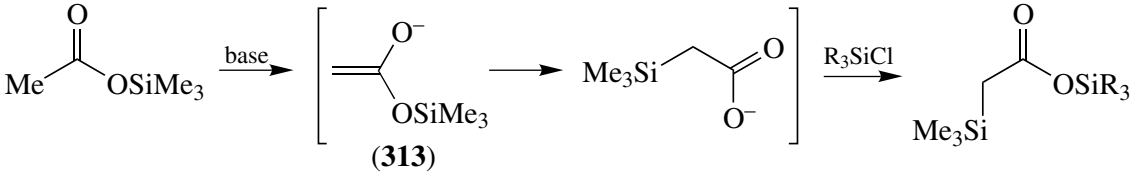


SCHEME 71

tandem with a [1,2]-Brook rearrangement, has been used[362] to transform a 1-(trimethylsilyl)penta-2,4-dien-1-ol anion into a 5-(trimethylsilyl)pent-2-enal (see Scheme 72). It has been reported[363] that reactions of the lithium enolates of trimethylsilyl esters (**313**) with Et_3SiCl or Bu^tMe_2SiCl resulted in α-trimethylsilyl esters by O → C migration of Me_3Si (see Scheme 73). The retro-[1,4]-Brook rearrangements of γ-siloxylated organolithium compounds have been investigated[364,365] as an approach to the stereoselective access to α-chiral allylsilanes with variable substitution patterns, and the first retro-[1,4]-Brook rearrangements of siloxylated propargyllithium compounds under the influence of a 1,3-asymmetric induction have been carried out.[366] Although γ-sulfonyloxybenzylselenides have been found to produce arylcyclopropanes stereospecifically on reaction with butyllithium, the corresponding γ-silyloxybenzylselenides under the same reaction conditions have been found to afford a stereomeric mixture of



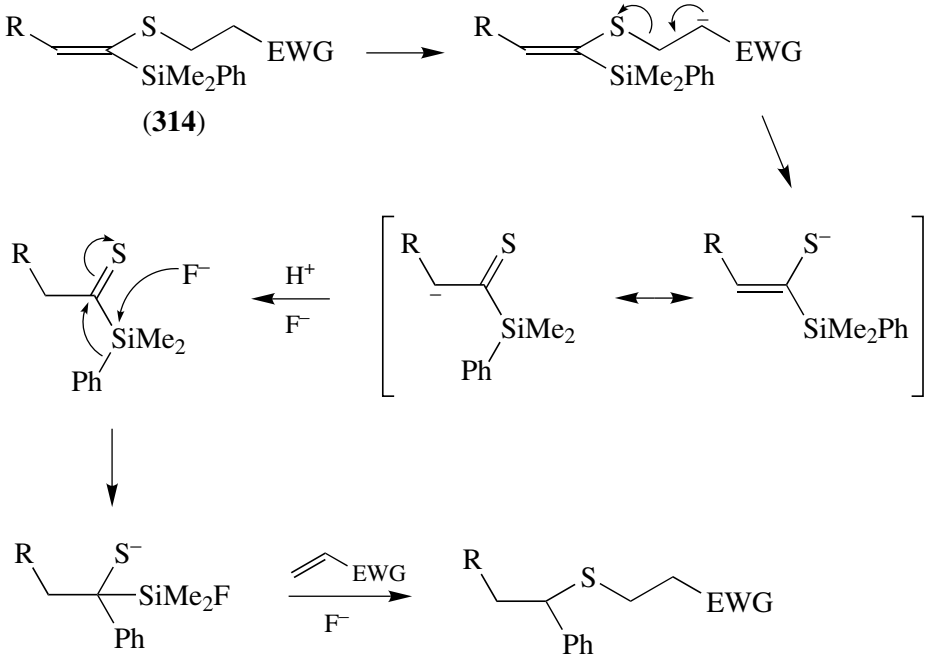
SCHEME 72



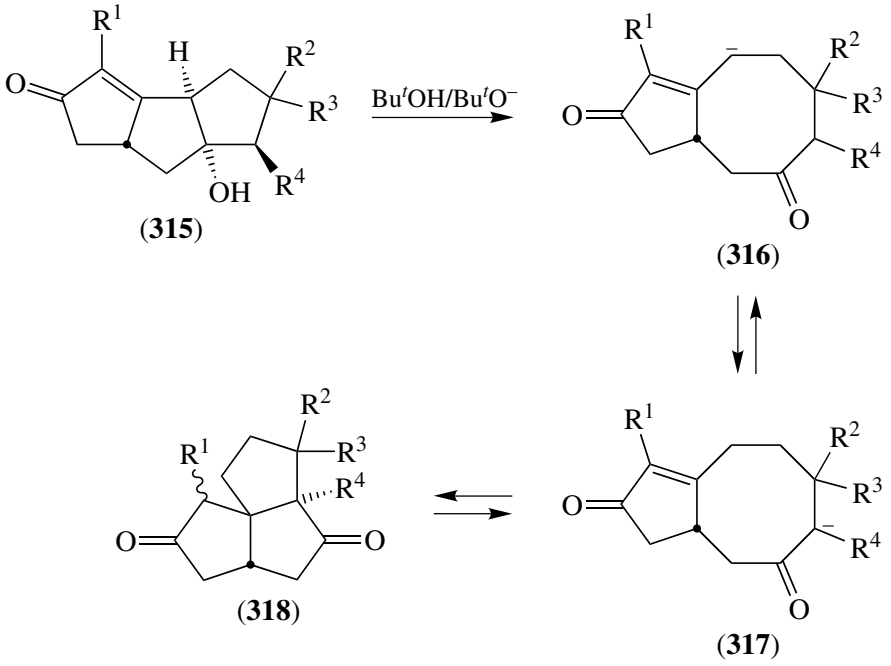
SCHEME 73

γ-hydroxy-α-silylbenzylselenides via a retro-[1,4]-Brook rearrangement. Apparently in the former instance the intermediate benzyllithium is alkylated before epimerization takes place, whereas in the latter case, epimerization occurs prior to the silyl group migration.[367] An examination of the desilylation of (*Z*)-α-dimethylphenylsilyl vinyl sulfides of the type (**314**) has been made and the observed migration of the phenyl group from the silicon to the adjacent carbon atom has been rationalized[368] in the manner shown in Scheme 74.

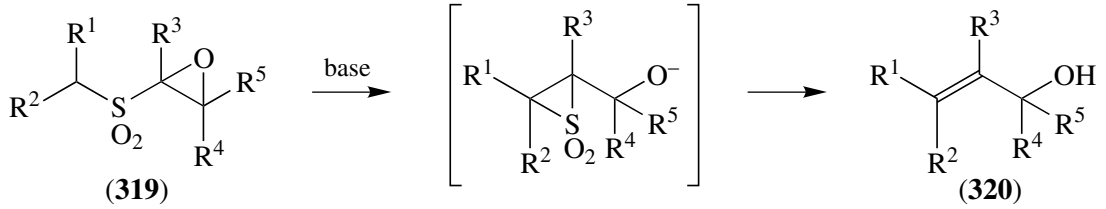
A theoretical study of the Favorskii rearrangement of α-chlorocyclobutanone has been undertaken.[369] 3-Bromo-2,2,6,6-tetramethyl-4-oxopiperidine-1-oxyl has been found[370] to react with aqueous ammonia to yield 3-carbamoyl-2,2,5,5-tetramethylpyrrolidine-1-oxyl, the product of a Favorskii rearrangement. The rearrangement of 11,13-dibromo-9,10-dimethoxy-9,10-propanoanthracen-12-one to the corresponding Favorskii products has been studied,[371] and an unusual variant of the Favorskii rearrangement has been reported.[372] A new general method for the regiospecific synthesis of angular triquinanes (**318**) via a novel retro-aldol rearrangement of the corresponding linear isomers (**315**) has been described. It is envisaged[373] that this rearrangement involves formation and equilibration of the enolates (**316**) and (**317**) followed by an intramolecular Michael addition of the enolate anion in (**317**) to the enone moiety.



SCHEME 74

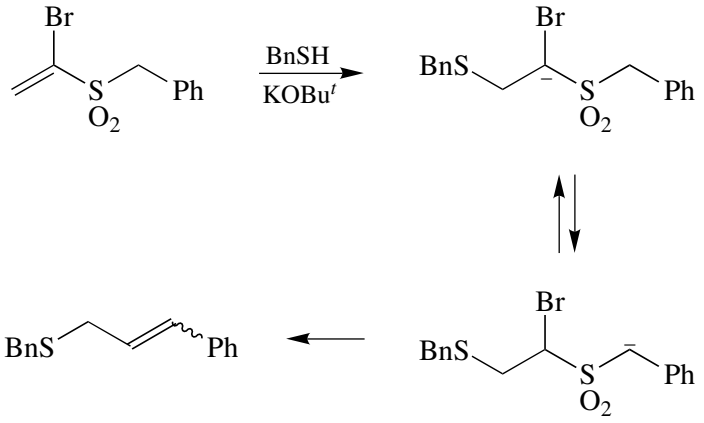


A novel tandem process has been reported[374] for the preparation of allylic amines, ethers, and sulfides from α-bromo-α, β-unsaturated sulfones. The process is believed to proceed via an initial conjugate addition followed by proton exchange and Ramberg–Bäcklund rearrangement (see Scheme 75). A new variant of the Ramberg–Bäcklund reaction has been described[375] in which α, β-epoxy sulfones (**319**), on treatment with base, are converted into a range of mono-, di-, and tri-substituted allylic alcohols (**320**).

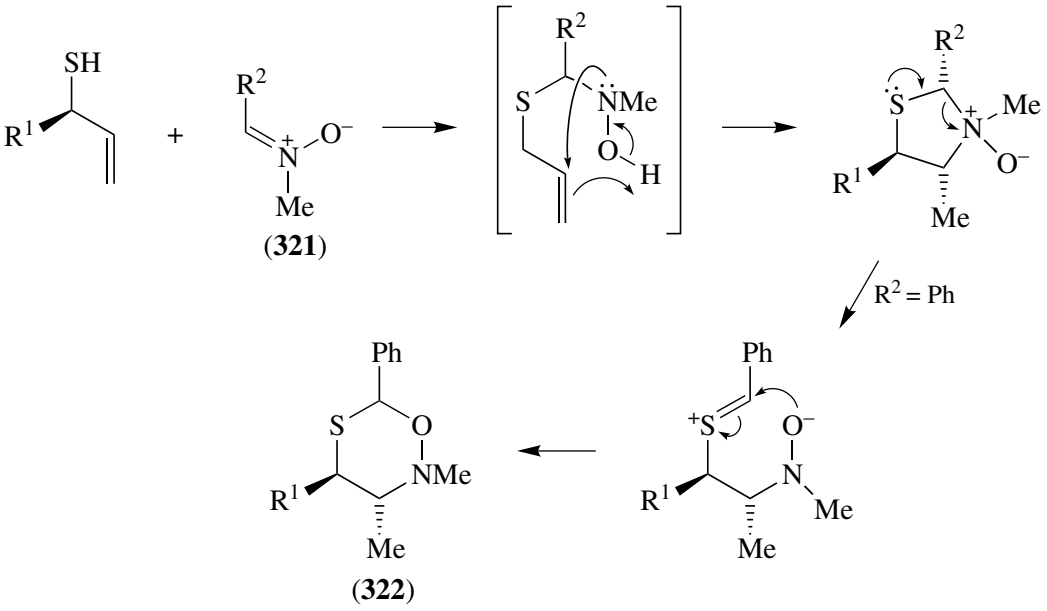


Allylthiols[376] and unsaturated lithio sulfones[377] have been found to react as nucleophiles with nitrones to yield intermediate hydroxylamines which undergo reverse-Cope cyclization to provide 1,3-thiazolidine *N*-oxides and pyrrolidine *N*-oxides, respectively. In the case of derivatives of *C*-phenyl nitrone (**321**; $R^2 = Ph$), thermolysis was found to result in smooth Meisenheimer rearrangement leading to 1,5,2-oxathiazinane (**322**) (see Scheme 76).

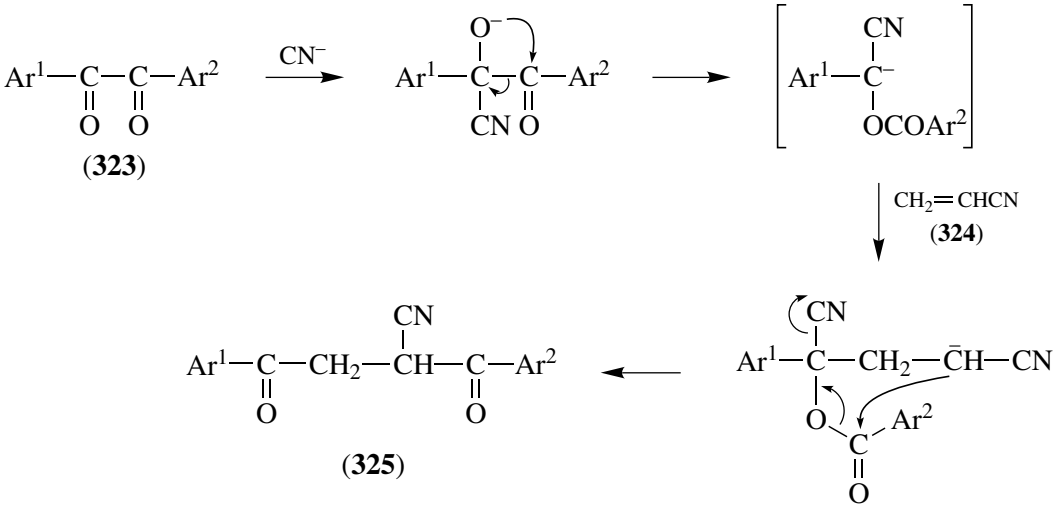
It has been shown that benzils (**323**) react with Michael addition acceptors (**324**) in the presence of a catalytic amount of cyanide ion to yield 1,4-diketones (**325**). The authors[378] proposed that (**325**) are produced through the formation of the *O*-aroylmandelonitrile anion, followed by Michael addition and rearrangement of the aroyl group with decyanation (see Scheme 77). The mechanism of the base-catalysed ring fission of 2,2-dihydroxyindane-1,3-diones has been investigated and the pathway set out in Scheme 78 has been proposed[379] for the transformation. The base-catalysed ring



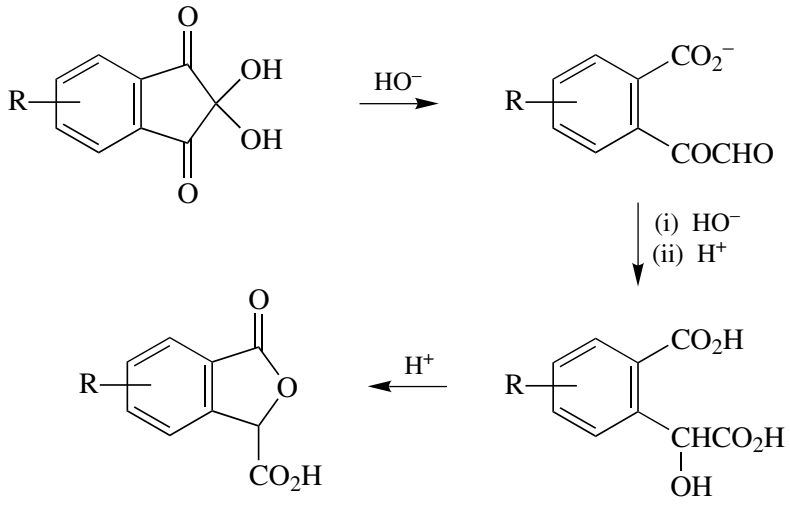
SCHEME 75



SCHEME 76



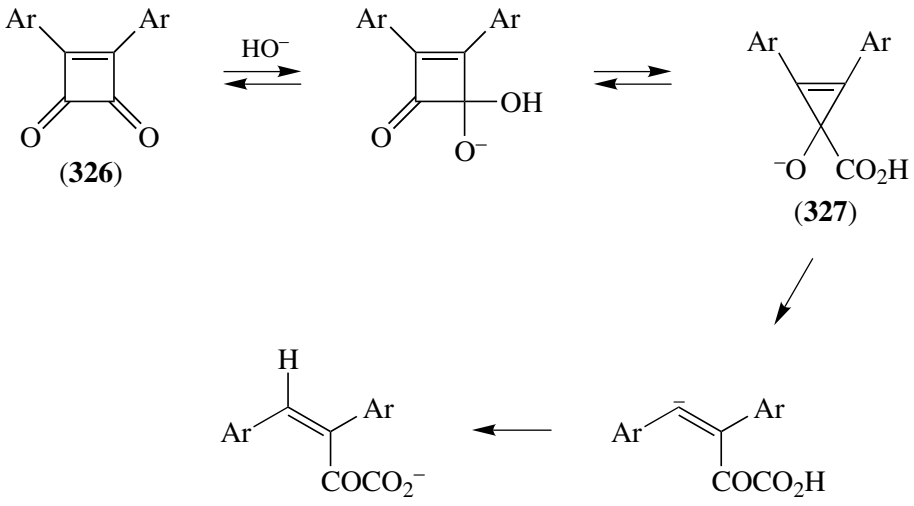
SCHEME 77



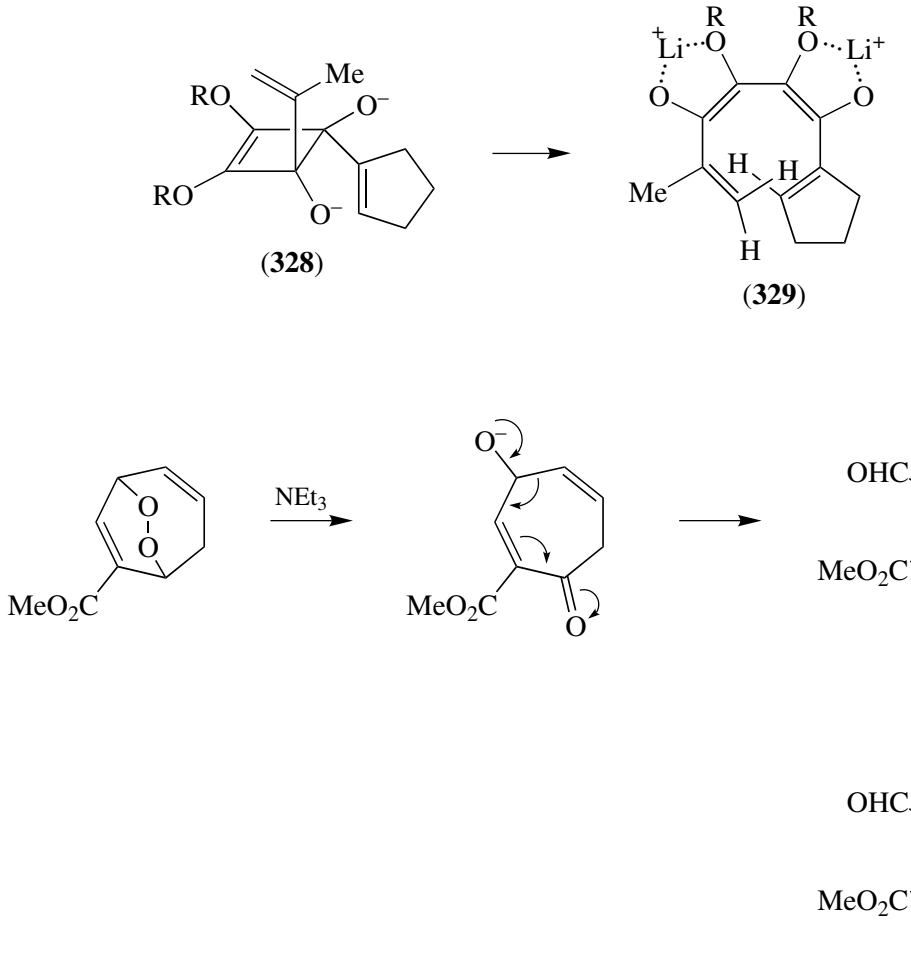
SCHEME 78

fission of benzocyclobutenediones has been shown to result in the formation of 2-formylbenzoic acid, a fact which clearly indicates fission of the carbonyl carbon–carbonyl carbon bond in the cyclobutenedione ring.[380] On the other hand, a detailed study[381] of the base-catalysed ring fission of a series of substituted 3,4-diphenylcyclobut-3-ene-1,2-diones (**326**) has shown that this reaction probably proceeds by the pathway shown in Scheme 79, where the rate-determining step is the formation of the cyclopropene intermediate (**327**). A study of the squarate ester cascade has established[382] that the initially formed *trans*-cyclobutene dianions, represented by (**328**), undergo relatively rapid conrotatory ring opening with a strong kinetic preference for positioning the oxido substituents outside, as in (**329**).

Unusual triethylamine-catalysed rearrangements of bicyclic endoperoxides derived from substituted cycloheptatrienes have produced[383] a variety of products (see, e.g., Scheme 80). *Ab initio* calculations have shown that energised 2,3-epoxypropoxide anions undergo a degenerate Payne rearrangement in the gas phase via a three-centre mechanism.[384] It has been reported[385] that treatment of isonitrile epoxides (**330**) with



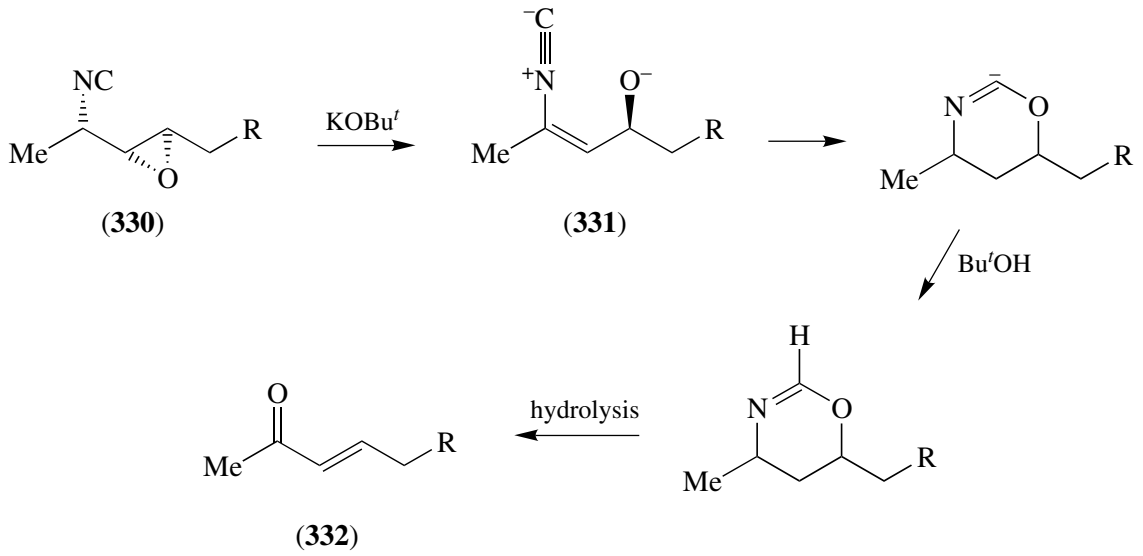
SCHEME 79



SCHEME 80

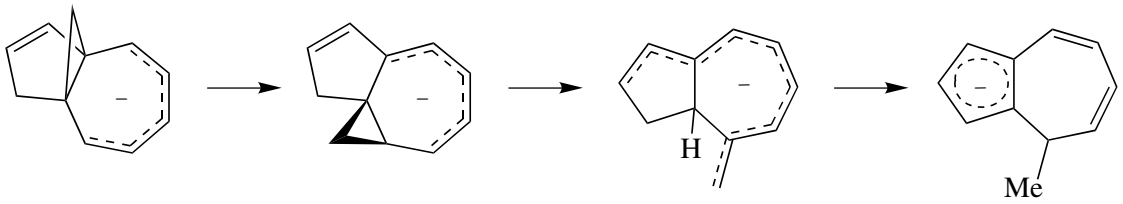
KOBu^t–Bu^{t}OH results only in the formation of the α,β-unsaturated ketones (**332**), thought to arise by rearrangement of the initially formed oxyanions (**331**), as outlined in Scheme 81. The rearrangement of epoxides with lithium diethylamide and with LDA in conjunction with lithium *t*-butoxide has been studied in different solvents.[386] Previously unreported base-induced transformations of rigid bicycloalkene-derived epoxides[387] and simple deuteriated cycloalkene-derived epoxides[388] have been described, thus providing an insight into the rearrangement mechanisms which operate following α-lithiation in such systems.

The tricyclic undecatrienyl anion (**333**), generated from the corresponding hydrocarbon with *n*-BuLi, has been found to undergo a cyclopropane ring circumambulation at −78 °C to afford the anion (**334**), which undergoes a further rearrangement to the cyclopentadienyl anion derivative (**335**) at elevated temperatures.[389] A high-level *ab initio* study[390] has been shown that the rearrangement of the fulminate anion (CNO^-) to the cyanate anion (OCN^-) proceeds via an oxazirinyl anion intermediate. Studies of a model of the vitamin B_{12}-catalysed methylmalonyl–succinyl rearrangement have established[391] the influence of the non-covalent association of vitamin B_{12} and the substrate on the ratio of reduced and rearranged products.



(**330**) (**331**) (**332**)

SCHEME 81

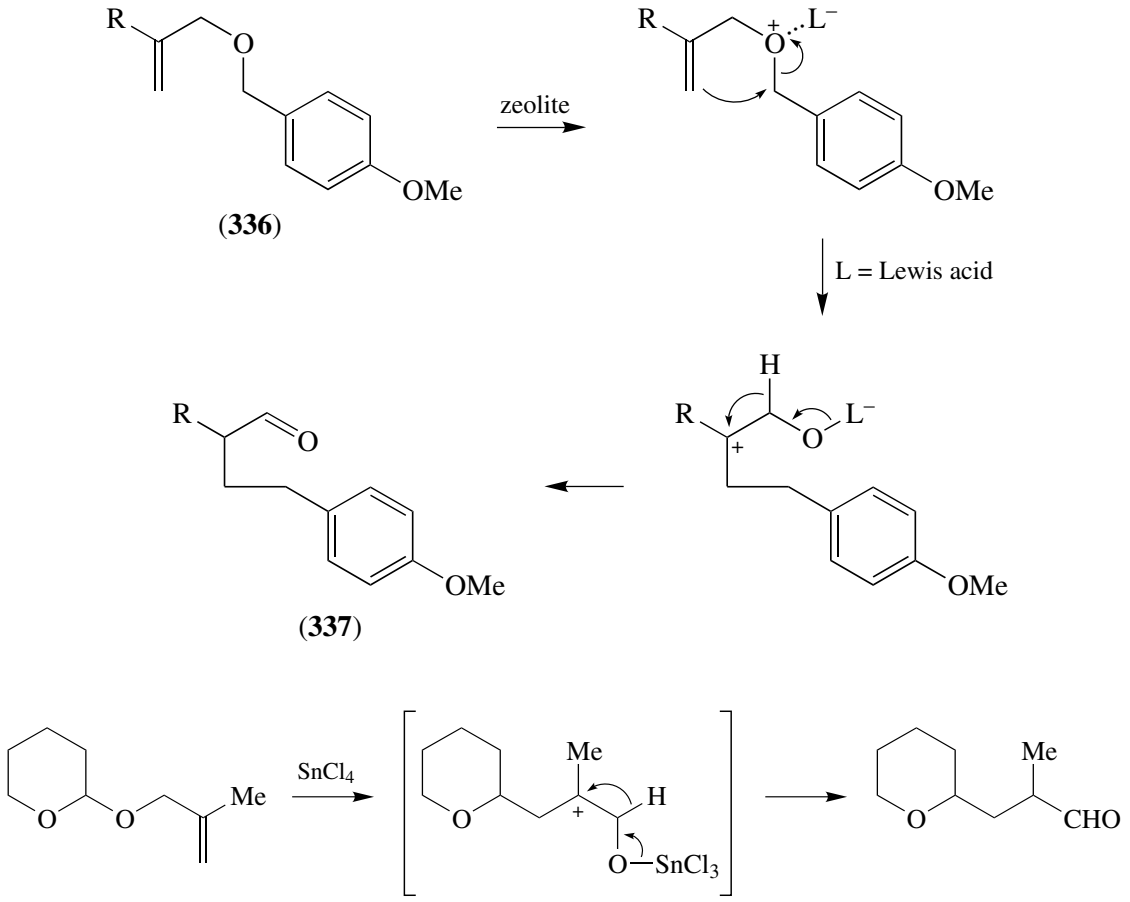


(**333**) (**334**) (**335**)

Cationic and Related Rearrangements

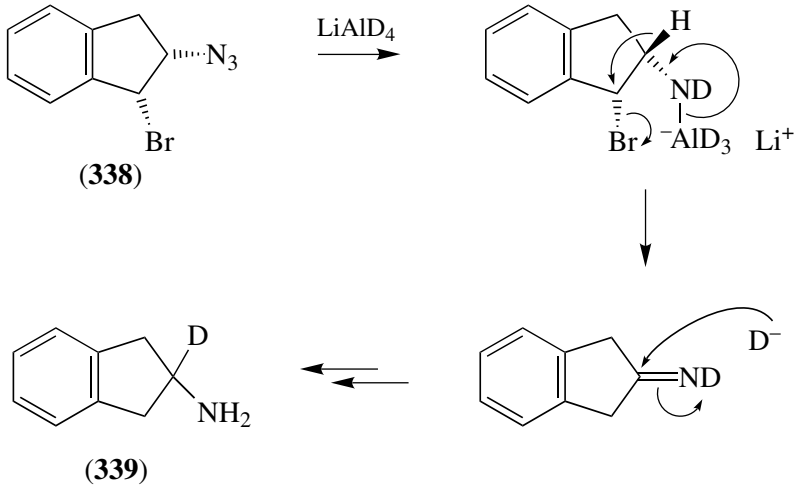
Various aspects of carbocation rearrangements have been reviewed.[392] A theoretical study of the mechanism of the branching rearrangement of carbocations has been undertaken,[393] while a study of the interconversions of *t*-2-methylbutyl cations in the gas phase has shown[394] that two stable conformers with the structure of a *t*-pentyl cation exist as energy minima. A systematic *ab initio* study has been carried out[395] on the rearrangement of the isoformyl cation (HOC^+) to the formyl cation (HCO^+), and kinetic studies have been undertaken for the first time on the solvolytic generation of antiaromatic cyclopentadienyl cations.[396] Substantive evidence has been obtained[397] to suggest that there is a build up of positive charge adjacent to the carbonyl carbon during the nitration of α,β-unsaturated esters. Electrophilic 5-*endo-trig* cyclizations of 2-silylalk-3-enols have been carried out leading to tri- and tetra-substituted tetrahydrofurans with excellent diastereoselectivities.[398]

A 1,2-hydride shift has been invoked[399] to account for the formation of *p*-methoxyphenylbutyraldehyde derivatives (**337**) during the treatment of *p*-methoxybenzyl-protected allylic alcohols (**336**) with zeolites. A similar *C*-glycosidation procedure involving Lewis acid-catalysed anomeric oxygen to carbon rearrangement of tetrahydropyranyl ether derivatives has been reported[400] (see Scheme 82). It has been

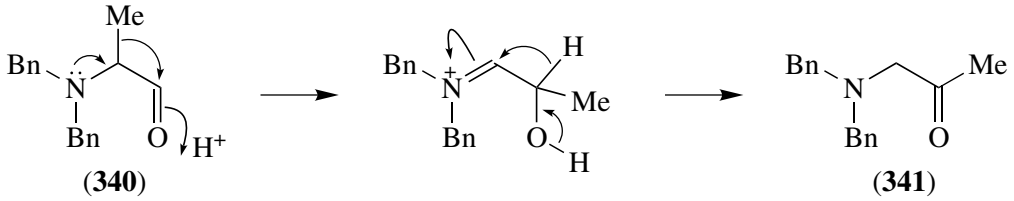


SCHEME 82

shown that reduction of the *cis*-1-bromoindane (**338**) with $LiAlD_4$ does not follow the predicted pathway, but instead gives 2-amino-2-*d*-indane (**339**) in which the deuterium atom is incorporated adjacent to the amino group. The authors[401] showed that (**339**) arises from a stereospecific 1,2-hydride rearrangement (see Scheme 83). A mechanism



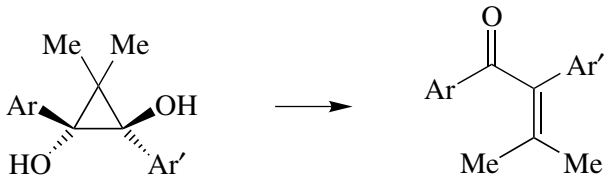
SCHEME 83



(**340**) (**341**)

involving a series of consecutive 1,2-hydride transfers, rather than a direct 1,4-hydride transfer, has been invoked[402] to account for the $AlCl_3$-induced rearrangement of 1,1′-dideuterio-3-butylphthalide to 1-methyl-5-carboxy-3,4-dideuteriotetrahydronaphthalene. An asymmetric 1,7-hydride shift has been observed[403] for the first time, during the reduction of α,β-unsaturated ketones to saturated secondary alcohols via a novel Michael addition–Meerwein–Pondorf–Verley reduction. An unusual rearrangement of *N*,*N*-dibenzyl-2-aminopropanal (**340**) to *N*,*N*-dibenzyl-1-aminopropanone (**341**) upon its exposure to either silica gel or pyridinium acetate has been recorded. One mechanistic explanation that has been proposed[404] for the rearrangement involves a facile 1,2-methyl shift followed by a 1,2-hydride shift.

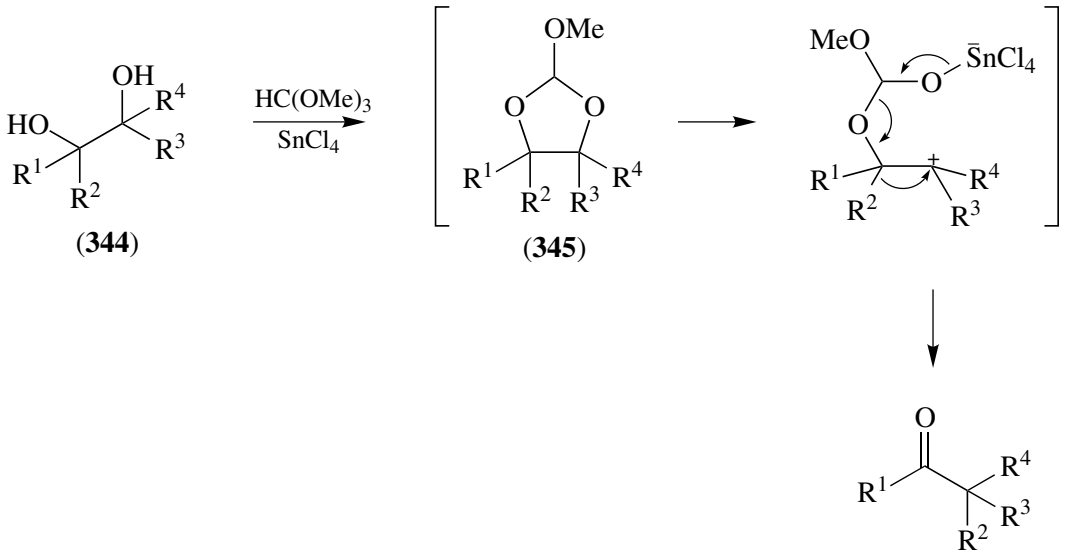
The MNDO method has been employed[405] to study the reaction pathway and to optimize the structures of reactant, product, and transition state of the acid-catalysed rearrangement of 1,2-propylene glycol, and the unimolecular dehydration of protonated α,ω-diols in the gas phase has been examined[406] by tandem mass spectrometric experiments. It has been shown that the reaction of 1,2-diarylcyclopropane-1,2-diols (**342**) with acids yields primarily the α,β-unsaturated ketones (**343**) in which the aryl



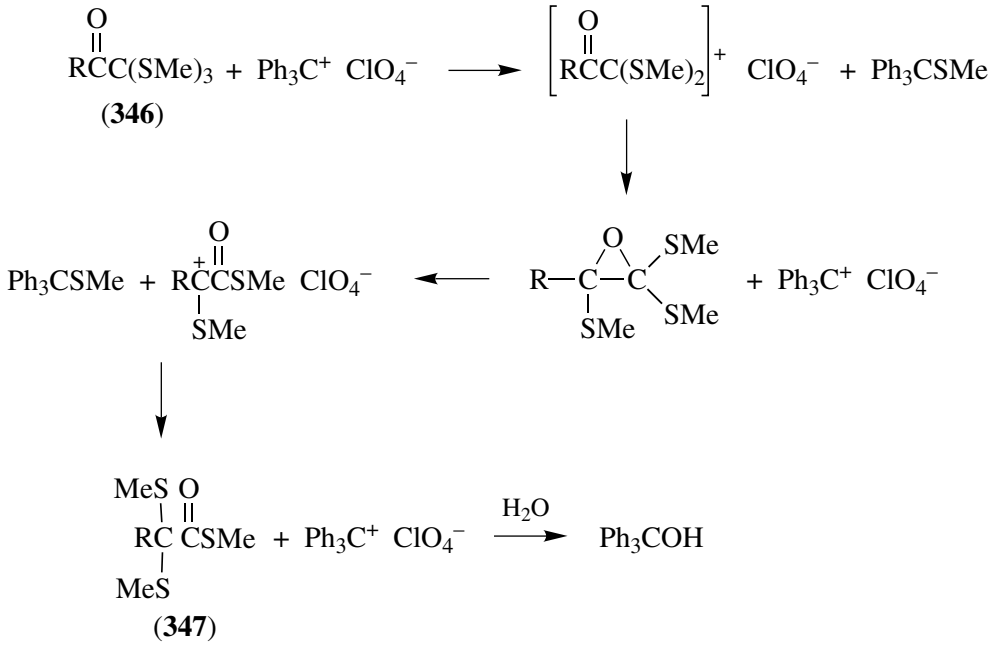
(**342**) (**343**)

substituent attached to the double bond is that which is best able to stabilize a benzylic cation. The authors[407] proposed that the reaction proceeds by *O*-protonation of the 1,2-diol followed by loss of water, opening of the resulting cyclopropyl cation and final deprotonation. The pinacol rearrangement of various diols (**344**) with a catalytic amount of Lewis acid in the presence of trimethyl orthoformate has been shown[408] to proceed via a cyclic ortho ester intermediate (**345**). A study of the pinacol–pinacolone rearrangement in *vic*-dihydroxychlorins and bacteriochlorins has shown[409] that the migratory behaviour of the substituents depends largely upon the position and the number of electron-withdrawing substituents present, while it has been observed that the trifluoromethyl group imparts specific orientation to the course of the semipinacol rearrangement of trifluoromethyl-substituted *vic*-diol monomethyl ethers.[410]

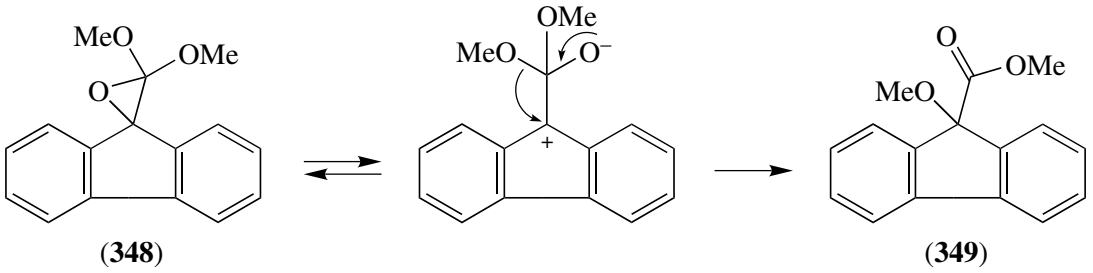
The mechanism outlined in Scheme 84 has been proposed[411] to account for the isomerization of trimethyl α-keto trithioorthocarboxylates (**346**) into α, α-bis-



(methylthio)thiocarboxylates (**347**) in the presence of trityl perchlorate. It has been reported that dimethoxycarbene generated from the thermolysis of 2,2-dimethoxy-5,5-dimethyl-Δ^3-1,3,4-oxadiazoline reacts with the carbonyl group of 9-fluorenone to yield 9-(dimethoxymethylene)fluorene oxide (**348**). The authors[412] subsequently found that (**348**) rearranges thermally to methyl 9-methoxyfluorene-9-carboxylate (**349**) by a process which involves ring opening and intramolecular methoxy transfer (see Scheme 85). Aryl- and ethenyl-substituted oxiranes have been shown to rearrange readily to optically active alcohols in the presence of triethylsilane and boron trifluoride. This study also showed that a vinyl group migrates to a benzylic cation faster than a phenyl group migrates to an allyl cation.[413] The successful rearrangement of acyclic α,β-epoxy

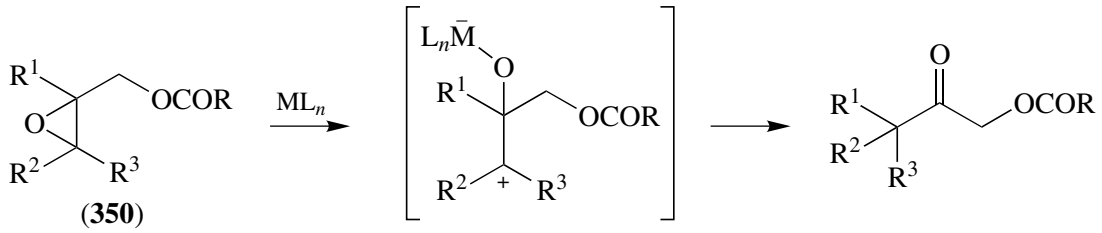


SCHEME 84



(**348**) (**349**)

SCHEME 85



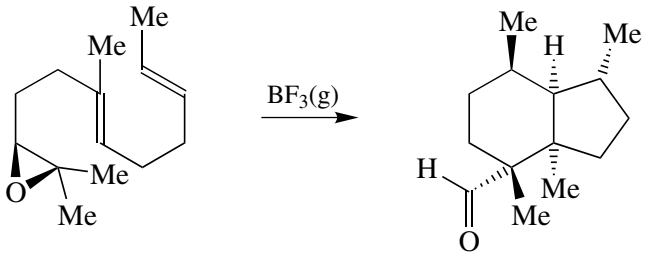
(**350**)

ML_n = $BF_3{\cdot}OEt_2$ or bis(4-bromo-2,6-di-*t*-butylphenoxide)

R = Ph, *p*-O_2NPh or COR = (–)-camphanoyl

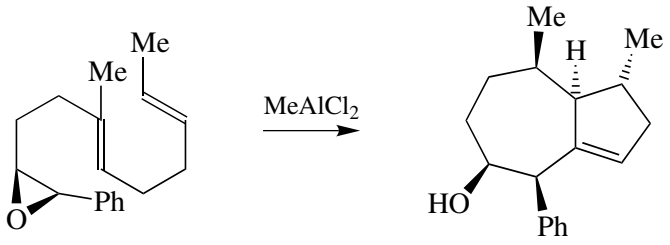
SCHEME 86

acylates (**350**) has been achieved[414] (see Scheme 86) by using a combination of an acyl group and a Lewis acid, which can suppress the neighbouring-group participation of the acyloxy group. A detailed description of the Lewis acid-catalysed rearrangement reactions of α,β-epoxy acylates in cyclic systems has also appeared.[415] Corey and Roberts[416] described some extraordinary results from a study of the cyclization and rearrangement reaction of cations derived from unsaturated oxiranes; see (**351**) → (**352**) and (**353**) → (**354**). On treatment with Lewis acids in anhydrous medium, *syn*- and *anti*-anthracenic and naphthalenic *vic*-diepoxides have been found to rearrange into 1-acylnaphtho[2,3-*c*]- or benzo[*c*]-pyrans, presumably by way of a Grob-type fragmentation followed by recyclization[417] (Scheme 87).



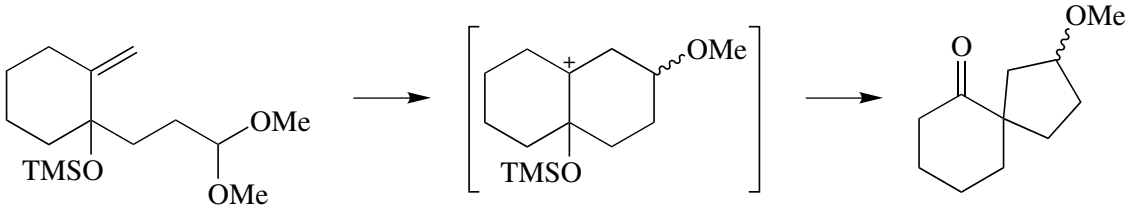
(**351**) (**352**)

Stereochemical aspects of the thallium trinitrate-mediated ring contraction of 3- and 4-alkylcyclohexanones to alkylcyclopentanecarboxylic acids have been investigated.[418] TMSOTf-promoted cyclization of several methylenecyclohexanesiloxy acetals of the



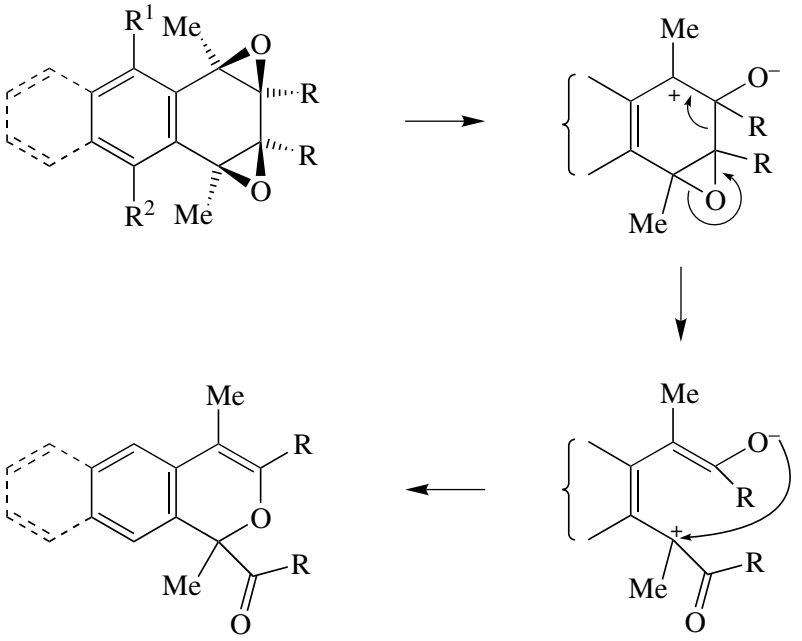
(**353**) (**354**)

type (**355**) have been found to proceed with exclusive pinacol rearrangement of the C(1) bond of the original three-carbon acetal side-chain[419] to afford spiro[5.4]decan-

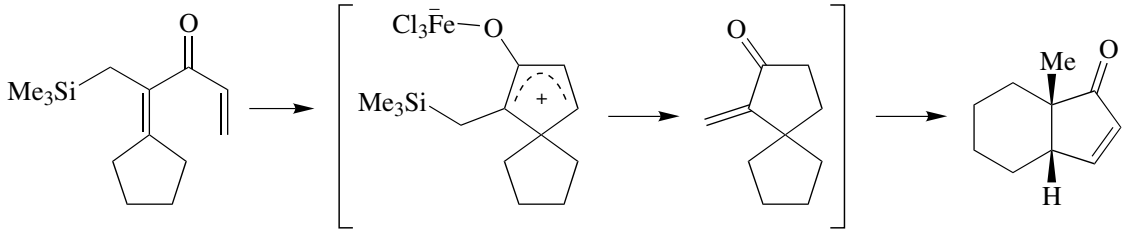


(**355**) (**356**)

ones (**356**). Incorporation studies with ^{13}C-labelled acetates and methionine in *Acremonium strictum* have unearthed a remarkable and unprecedented pathway in which the cyclopentenone moiety of xenovulene A is formed from a *C*-methylated precursor which undergoes ring expansion to a tropolone followed by two successive ring contractions resulting in incorporation of the *C*-methyl carbon into the five-membered ring.[420] A new entry to the bicyclo[4.3.0]nonane carbon skeleton (**359**) has

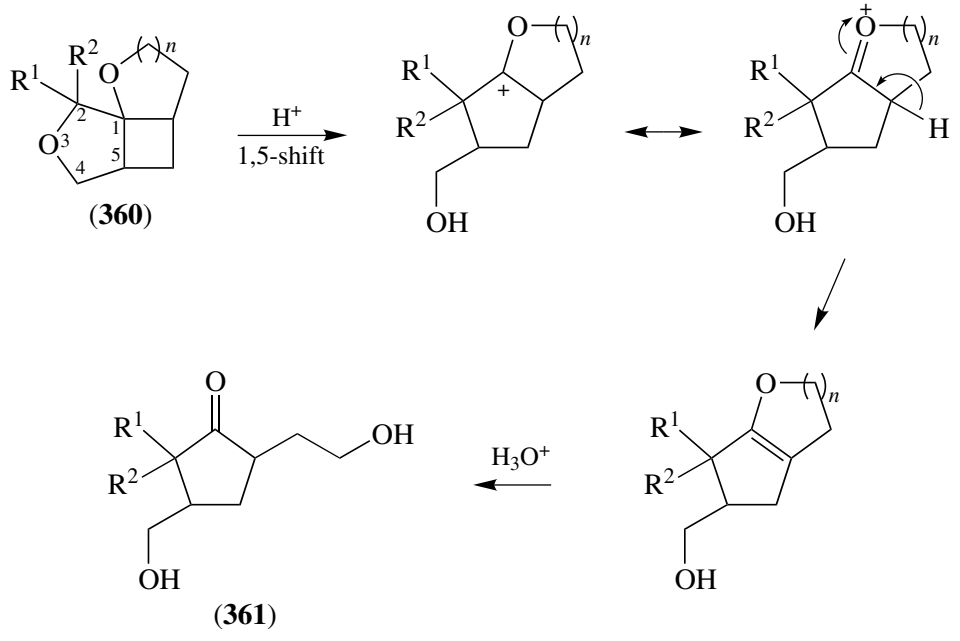


SCHEME 87

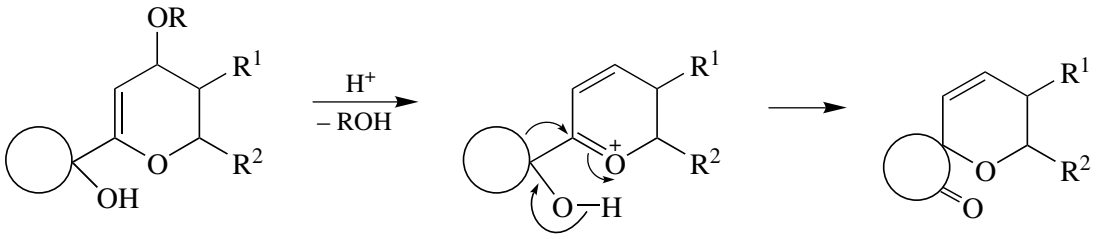


(**357**) (**358**) (**359**)

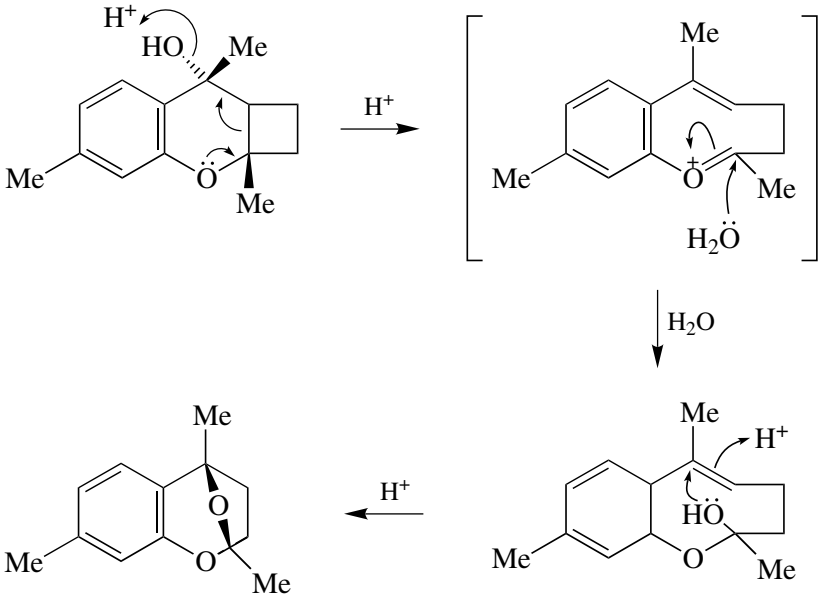
been established[421] via a tandem Nazarov cyclization–skeletal rearrangement of α-(trimethylsilylmethyl)divinyl ketone (**357**) via 1-methylenespiro[4.4]nonan-2-one (**358**) as an intermediate. The stereoselectivity of the acid-promoted rearrangement of dihydrofuranyl and dihydropyranyl carbinols to spirocyclic ketones has been examined.[422] The study has shown that the kinetically controlled isomerization results in the ring expansion of the hydroxyl-substituted ring with generation of a new stereogenic spirocyclic carbon atom. The same group of workers described[423] the synthesis of spirocyclic bis-*C*,*C*-glycosides by a similar acid-catalysed ring expansion of glycal-derived carbinols. This efficient process resulted in the generation of a new stereogenic centre by means of a controlled pinacol-like 1,2-migration to a cyclic oxonium ion (see Scheme 88). A novel and facile route to the benzo-1,3-dioxane ring system of averufin has been developed[424] by way of an acid-catalysed rearrangement of cyclobutachromanols (see Scheme 89), and the acid-catalysed rearrangement of cyclobutane derivatives of the type (**360**) has opened up[425] a general route for the direct synthesis of highly functionalized cyclopentenones (**361**). In this latter transformation, it appears that the stability of the carbocation formed after cyclobutane bond migration dictates the course of the reaction.



(**360**) (**361**)



SCHEME 88

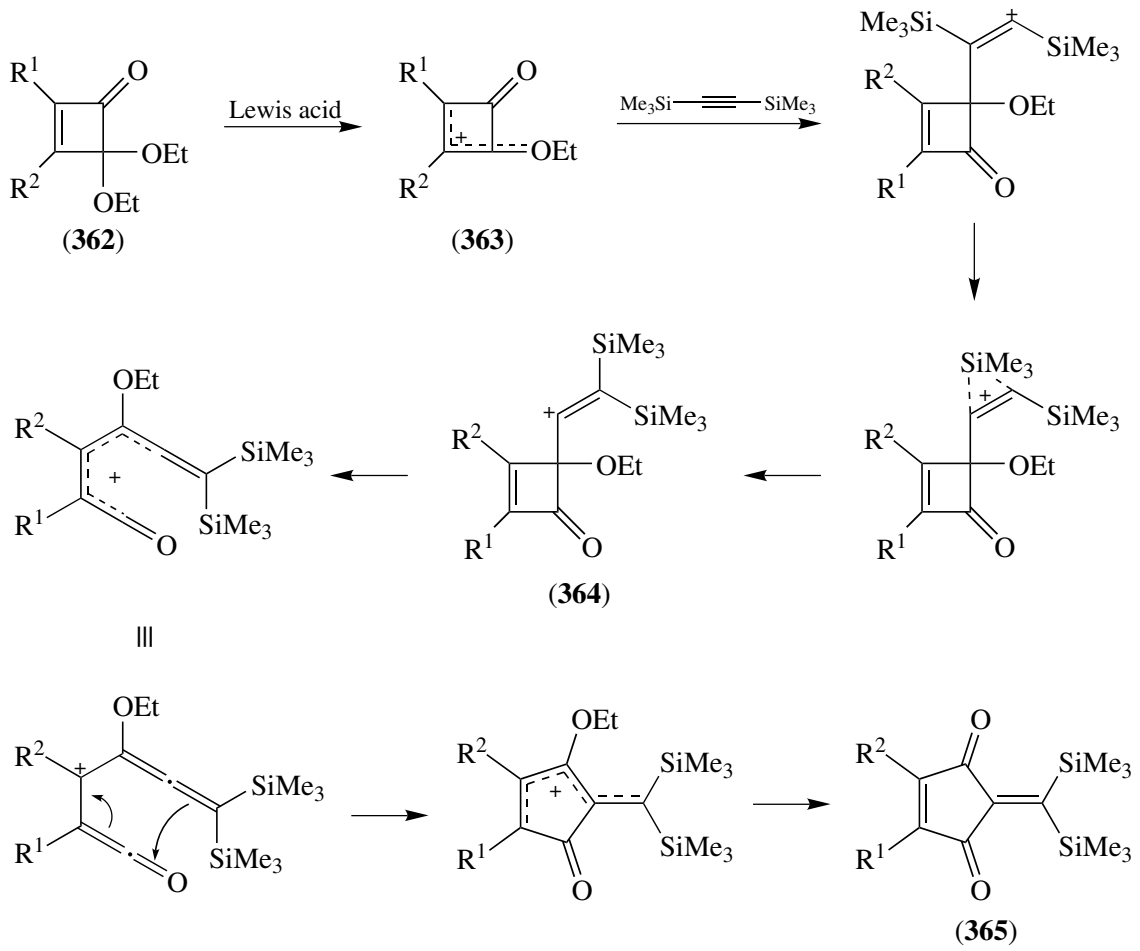


SCHEME 89

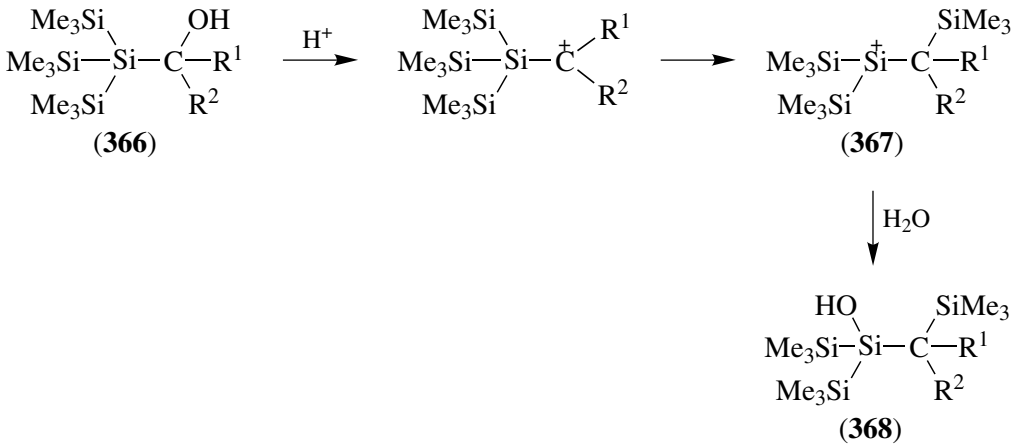
The ethoxycarbocation intermediate (**363**) produced by the action of acid on the cyclobutenedione monoacetal (**362**) has been found to react with bis(trimethylsilyl)-acetylene to afford a 2-methylenecyclopent-4-ene-1,3-dione derivative (**365**). The authors[426] proposed that the rearrangement results from an unprecedented cationic 1,2-silyl migration on the alkynylsilane, subsequent ring expansion via a vinyl cation intermediate (**364**), and re-closure by intramolecular addition of an acyl cation to a silylallene in a 5-*exo*-*trig* mode (see Scheme 90).

In the presence of strong acids, 1-hydroxyalkyltris(trimethylsilyl)silanes (**366**) have been found to undergo rearrangement with the formation of bis(trimethylsilyl)-1-trimethylsilylalkylsilanols (**368**). The conversion has been interpreted[427] as proceeding through a silylium ion intermediate (**367**) (see Scheme 91). Mechanistic implications of the 1,3-migration of a methyl group in the reactions of $(Me_3Si)_3CSi(CD_3)_2I$ with silver salts in alcohols have been discussed. It is now thought that the mechanism probably involves initially the formation of an unbridged cation which can sometimes be captured before conversion into the bridged form.[428]

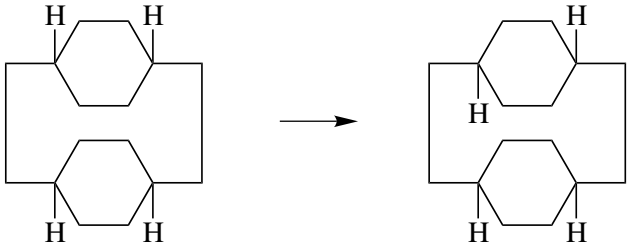
It has been suggested[429] that the observed acid-catalysed isomerization of perhydro[2.2]paracyclophane (**369**) to (**370**) is initiated by protonation of a bridgehead



SCHEME 90

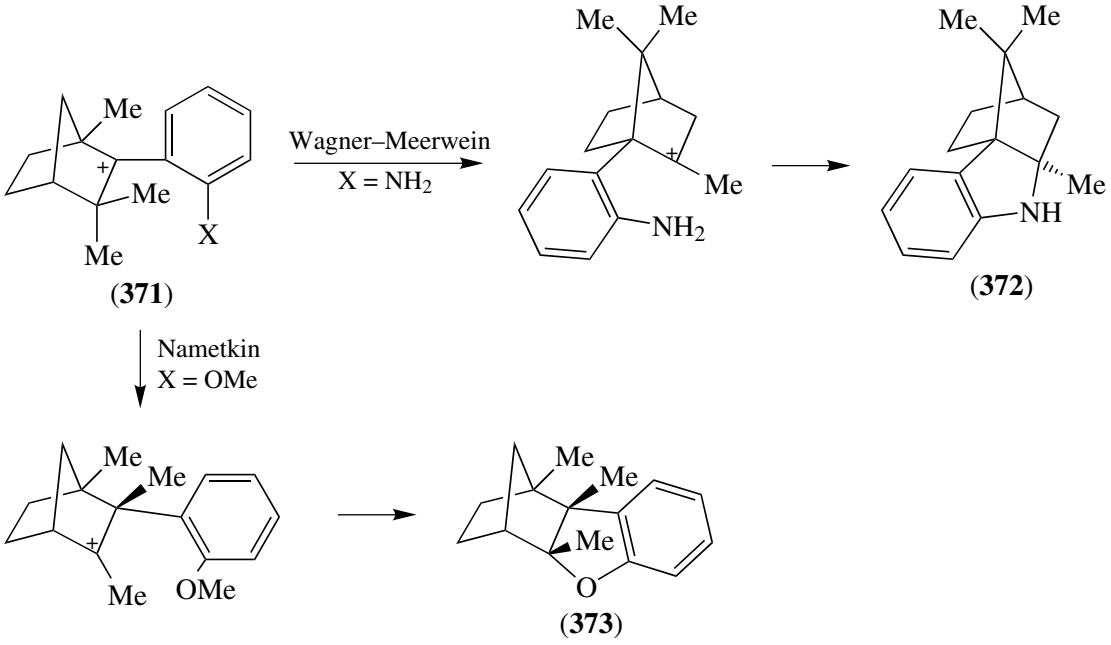


SCHEME 91



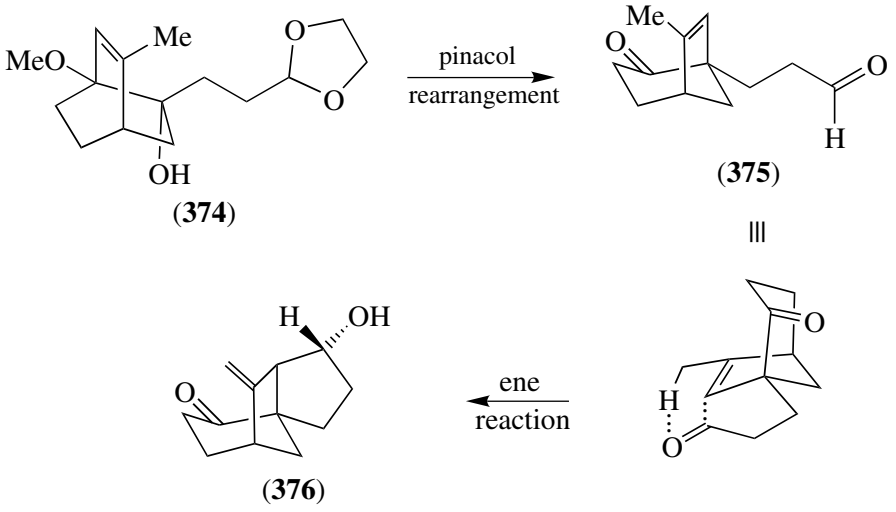
(**369**) (**370**)

C−H bond in (**369**). It has been shown that treatment of (+)-fenchone with *ortho*-lithiated protected anilines and phenols provides adducts which under acidic conditions generate carbocations (**371**) that rearrange to yield new enantiomerically pure five-membered heterocycles fused to a benzene ring and a terpenic carbocycle. The nature of the rearrangement has been shown to be dependent on the donor group and its ability to stabilize a positive charge.[430] With an amino donor group a product due to a Wagner–Meerwein rearrangement is formed [see (**371**) → (**372**)], whereas with a methoxy donor group Nametkin rearrangement [(**371**) → (**373**)] is the preferred



(**371**) (**372**) (**373**)

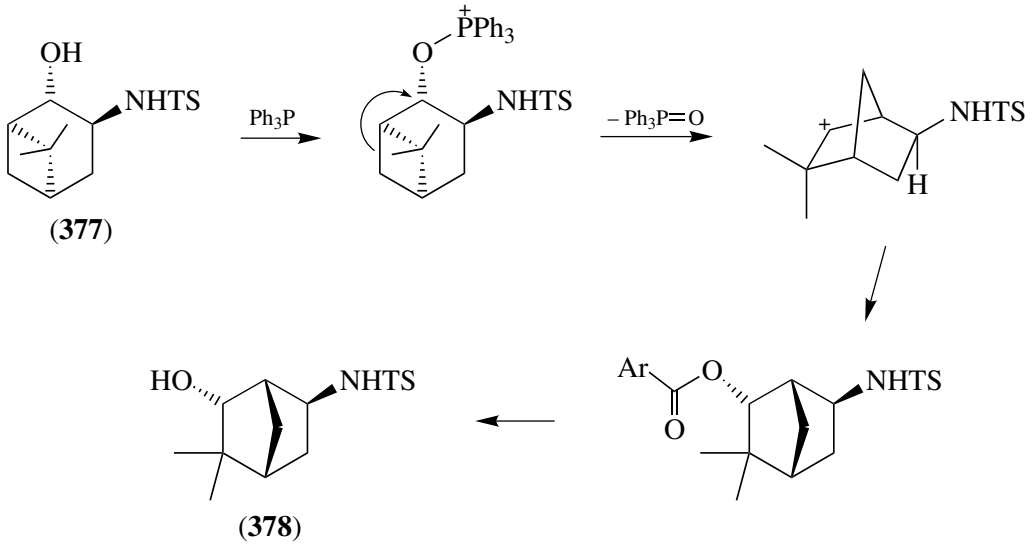
pathway. Construction of the tricyclo[5.3.1.$0^{1,5}$]undecane skeleton (**376**) has been accomplished[431] by utilizing a novel tandem pinacol rearrangement–ene strategy on a Diels–Alder-derived bicyclo[2.2.2]octene (**374**) via the intermediacy of a bicyclo-[3.2.1]octene derivative (**375**) (see Scheme 92). Successive processes involving demethylation or desilylation and acyloin rearrangement have been proposed[432] to account for the formation of 1-hydroxy- or 1,8-dihydroxy-bicyclo[3.2.1]oct-3-en-2-ones on treatment of 1-methoxy- or 1-*t*-butyldimethylsilyloxybicyclo[2.2.2]oct-5-en-2-ones with acids or tetrabutylammonium fluoride, respectively. It has been reported[433] that treatment of the bicyclo[3.1.1]heptanol (**377**) under Mitsunobu conditions affords,



(**374**) (**375**) (**376**)

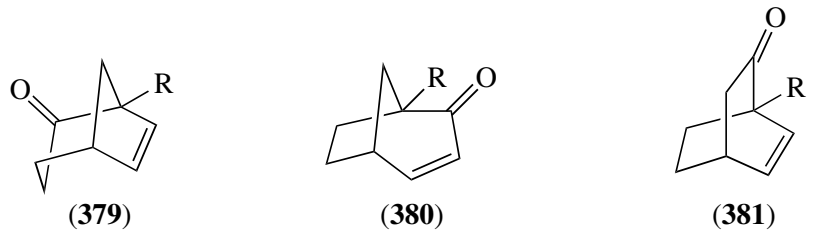
SCHEME 92

after hydrolysis, the rearranged bicyclo[2.2.1]heptanol (**378**). A likely pathway for the conversion is outlined in Scheme 93. A mixture of bicyclo[3.2.1]oct-3-en-2-ones (**380**) and bicyclo[2.2.2]oct-5-en-2-ones (**381**), the ratio of which is influenced by the substituent R, have been found[434] to result from acid treatment of bicyclo[3.2.1]oct-6-en-2-ones (**379**). The pathway outlined in Scheme 94 has been invoked[435] to explain the unexpected acid-catalysed rearrangement of 13-methoxy-1,6,8-trioxadispiro[4.1.5.3]-

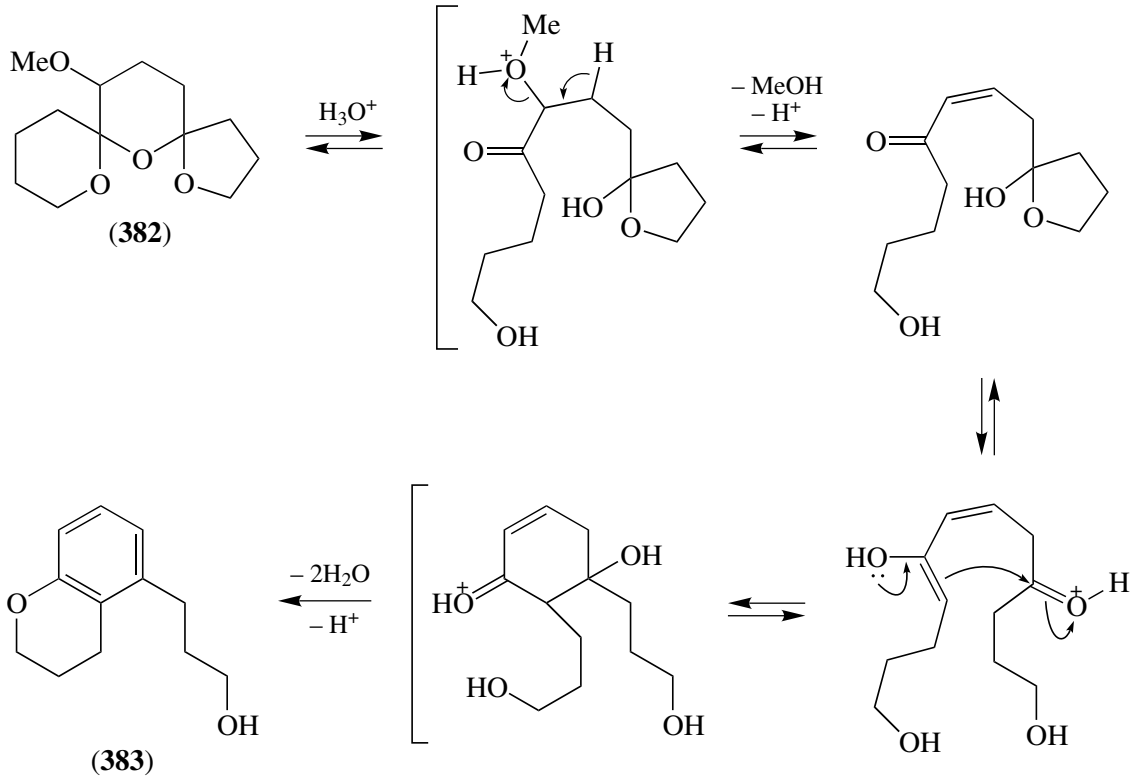


(**377**) (**378**)

SCHEME 93

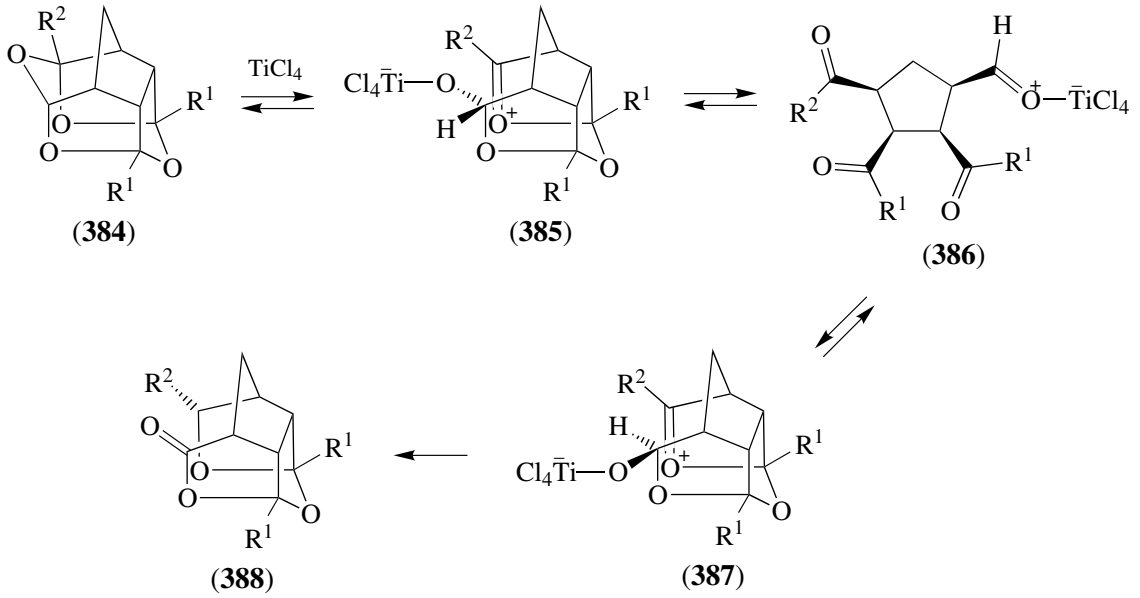


(**379**) (**380**) (**381**)



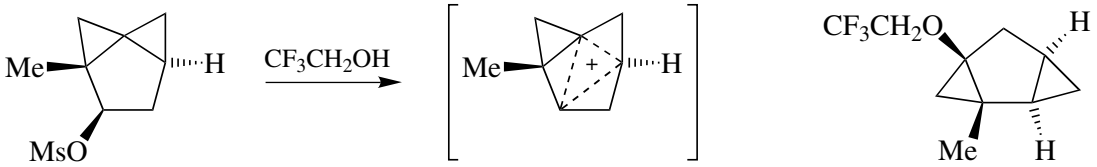
SCHEME 94

pentadecane (**382**) to 3-chroman-5-ylpropan-1-ol (**383**), while a remarkable effect of the C−O−C bond angle strain on the regioselective double-nucleophilic substitution of the acetal group of tetraacetal tetraoxa cages has been reported,[436] and a novel regioselective and stereoselective hydride rearrangement of the acetal group has been discovered; see (**384**) → (**388**). A mechanism involving coordination of the Lewis acid to the oxygen atom of (**384**) followed by cleavage of the C(8)−O(13) bond to give the



oxonium ion (**385**), fragmentation of (**385**) to a monocyclic species (**386**), followed by zipping back up to the stereoisomer (**387**) and subsequent intramolecular hydride transfer to (**388**), has been proposed for the rearrangement.[437]

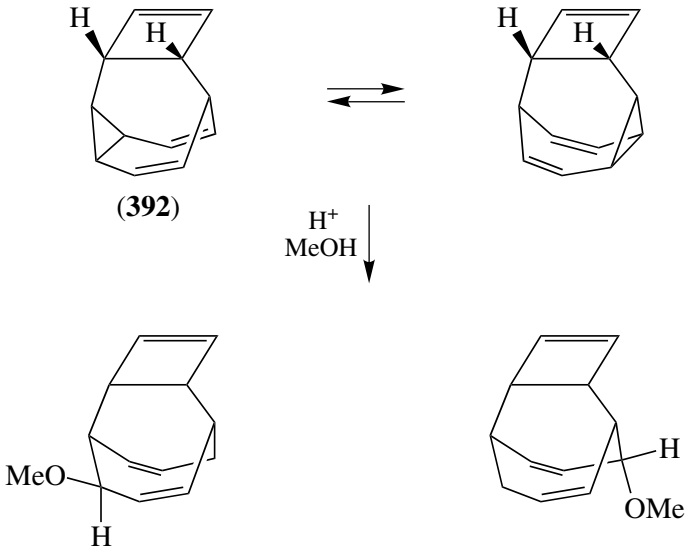
A study of the preparation and solvolysis of *syn*- and *anti*-1-methyltricyclo-[4.1.0.0^{4,6}]heptan-2-ol derivatives has shown that the *syn*-mesylate (**389**) yields the product of a solvent-trapped cyclopropyl cation, viz. (**391**), thus suggesting the



(**389**) (**390**) (**391**)

intermediacy of a novel trihomocyclopropenyl cation (**390**) in the transformation.[438] The rearrangements of carbocation sulfinate ion pairs have been studied in some detail,[439] and the mechanisms of solvolysis and rearrangement of 2,2-dimethyl-3-pentyl and 1-(1-adamantyl)propyl sulfonates have been compared.[440] It has been shown[441] that aqueous ethanolysis of an unstrained homoallylic secondary adamantyl toluene-*p*-sulfonate proceeds through a solvent-equilibrated allylic carbocation to afford rearranged protoadamantyl-substituted products. The highly diastereoselective, acid-catalysed addition of acetic acid and methanol to the vinylcyclopropane moiety of tetracyclo[5.3.2.0.^{2,10}0^{3,6}]dodeca-4,8,11-triene (**392**) has been rationalized[442] on the basis of a two-step process which involves proton attack to the homotropylidene moiety of (**392**) with formation of a cyclopropylcarbinyl carbocation, followed by opening of the cyclopropane ring under tight assistance by the nucleophilic solvent to give the products with high β-diastereoselectivity (see Scheme 95).

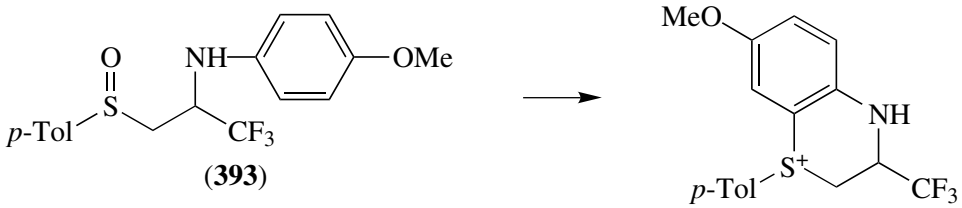
A number of reviews of different aspects of the Pummerer reaction have been published.[443,444] Chiral non-racemic α-substituted sulfoxides have been shown to react



(**392**)

SCHEME 95

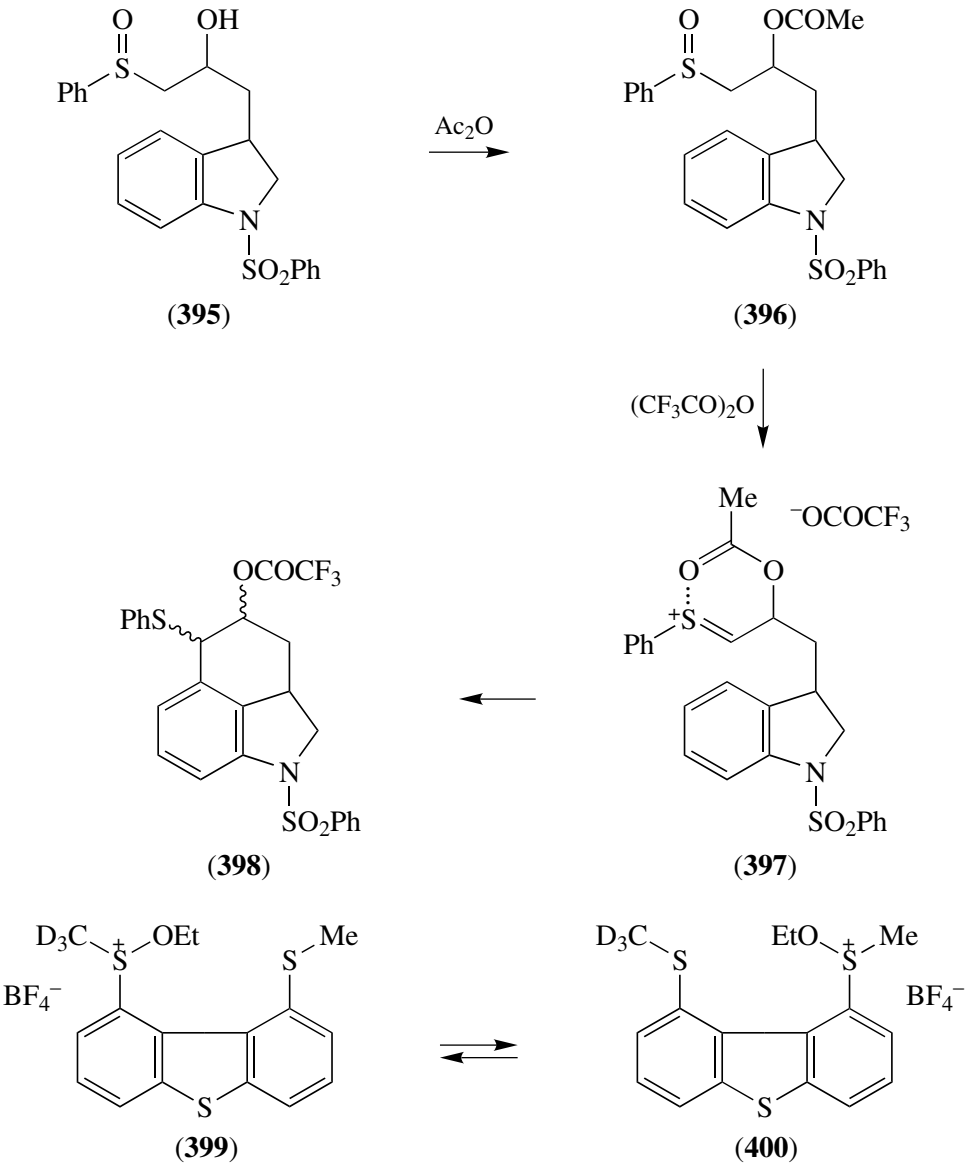
with *O*-silylated ketene acetals in the presence of a catalytic amount of ZnI_2 to yield non-racemic α-siloxy sulfides with high enantioselectivity.[445] The highly stereospecific tandem Pummerer reaction–α-hydroxyimine rearrangement of (*R*)-α-(fluoroalkyl)-*β*-sulfinylenamines to yield (*R*)-fluoropyruvaldehyde *N*,*S*-acetals has been described.[446,447] The reaction of *γ*,*γ*,*γ*-trifluoro-*β*-(*p*-methoxyphenylamino)sulfoxide (**393**) with trifluoroacetic anhydride, under Pummerer conditions, has been found to occur in an abnormal fashion, providing the six-membered cyclic sulfonium salt (**394**)



(**393**) (**394**)

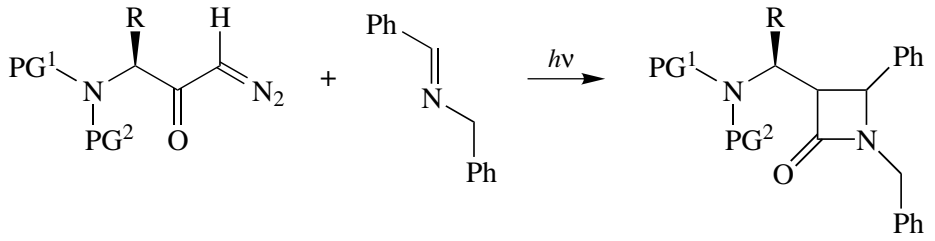
which is thought to arise from intramolecular interception of the expected trifluoroacetoxysulfonium intermediate by the electron-rich *p*-methoxyphenyl group.[448] Direct conversion of various thermally labile *n*,*n*-dihalobicyclo[*n*-3.1.0]alkanes to 2-halo-2-cycloalkenols has been achieved[449] by heating the dihalo compound in DMSO. Nucleophilic attack by DMSO followed by a Pummerer rearrangement and hydrolytic decomposition has been proposed as a possible mechanism for the conversion. Treatment of 1-(1′-benzenesulfonyl-3′-indolinyl)-3-benzenesulfinylmethylpropan-2-ol (**395**) with trifluoroacetic anhydride has been found to initiate rearrangement to (1-benzenesulfonyl-3-indolinyl)methyl benzenethiomethyl ketone. However, when the acetylated derivative (**396**) was treated with trifluoroacetic anhydride in the presence of a Lewis acid, two *cis*-cyclized conformers of 1-benzenesulfonyl-4-acetoxy-5-benzenethio-1,2,2a,3,4,5-hexahydrobenz[*cd*]indole (**398**) were produced,[450] presumably by way of the intermediate (**397**). The ethoxy group migration of 1-(methylethoxysulfonio)-9-(methylthio)dibenzothiophene, viz. (**399**) ⇄ (**400**), has been identified[451] by ^{1}H NMR spectroscopy.

Ab initio calculations have been carried out[452] on the isomerization of the dimethylenecyclobutene and 1,2,4,5-hexatetraene radical cations to the benzene structure. Similar calculations have indicated[453] that the hexa-1,5-diyne radical cation is not stable but isomerizes to the 1,2,4,5-hexatetraene radical cation without a barrier. High-level *ab initio* theory has been used[454] to investigate the effect of the neutral bases HF, H_2O, and NH_3 on the mechanism for isomerization of the conventional radical cations $CH_3X^{+\cdot}$ (X=F, OH, NH_2) to their corresponding distonic isomers $^{\cdot}CH_2X^+H$. *Ab initio* and density functional theory have been used to investigate the quadricyclane to norbornadiene radical cation rearrangement,[455] and the electron-transfer photosensitized reaction of 7-(spirocyclopropane)quadricyclane with methanol has been shown to produce two rearranged monomethanol adducts and a bismethanol adduct.[456] It has been proposed[457] that the products arising from the photo-induced electron transfer and electrochemical oxidations of 1,4-bis(methylene)cyclohexane in the



presence and absence of nucleophiles are consistent with the initial formation of a radical cation. Radical cations of vinyl cyclopropane have been found to rearrange in $CF_2ClCFCl_2$ with ring opening to afford different distonic radical cations.[458]

The ground-state vinylidene–acetylene isomerization has been investigated[459] by *ab initio* molecular electronic structure theory, and absolute rate constants have been determined[460] for [1,2]-acetyl, -carbon and -hydride shifts in cyclobutylacetoxy- and isopropylacetoxy-carbenes. A detailed theoretical study[461] has shown that, in simple acyclic dialkylcarbenes, the [1,2]-hydrogen migration pathway is the preferred intramolecular reaction. However, for cyclic carbenes, the study has shown that [1,2]-hydrogen migration is generally higher in energy, owing to the rigid carbon framework which does not always allow the ideal orientation of the migrating hydrogen, and also due to the formation of a double bond in the ring. Evidence has been presented[462] for the thiacyclohexatriene–thiopheneylcarbene rearrangement, the sulfur analogue of the cycloheptatetraene–phenylcarbene rearrangement.



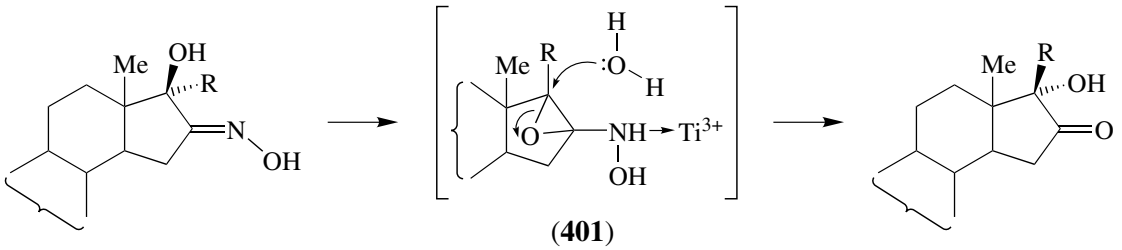
SCHEME 96

A density functional study of the competition between the Wolff rearrangement and the [1,2]-hydrogen shift in *β*-oxy-α-diazocarbonyl compounds has been presented,[463] and substituent effects in the gas-phase Wolff rearrangement of α-ketocarbenes has been investigated[464] using the AM1 method. The Wolff rearrangement of diazoketones from amino acids has been used[465] as a synthetic method for the preparation of oligonucleopeptides, while diazo ketones derived from suitably protected amino acids have been photochemically rearranged[466] to the corresponding ketene intermediates which have been trapped with *N*-benzylbenzaldimine to give aminoalkyl-substituted *β*-lactams (see Scheme 96).

Rearrangements in Natural-product Systems

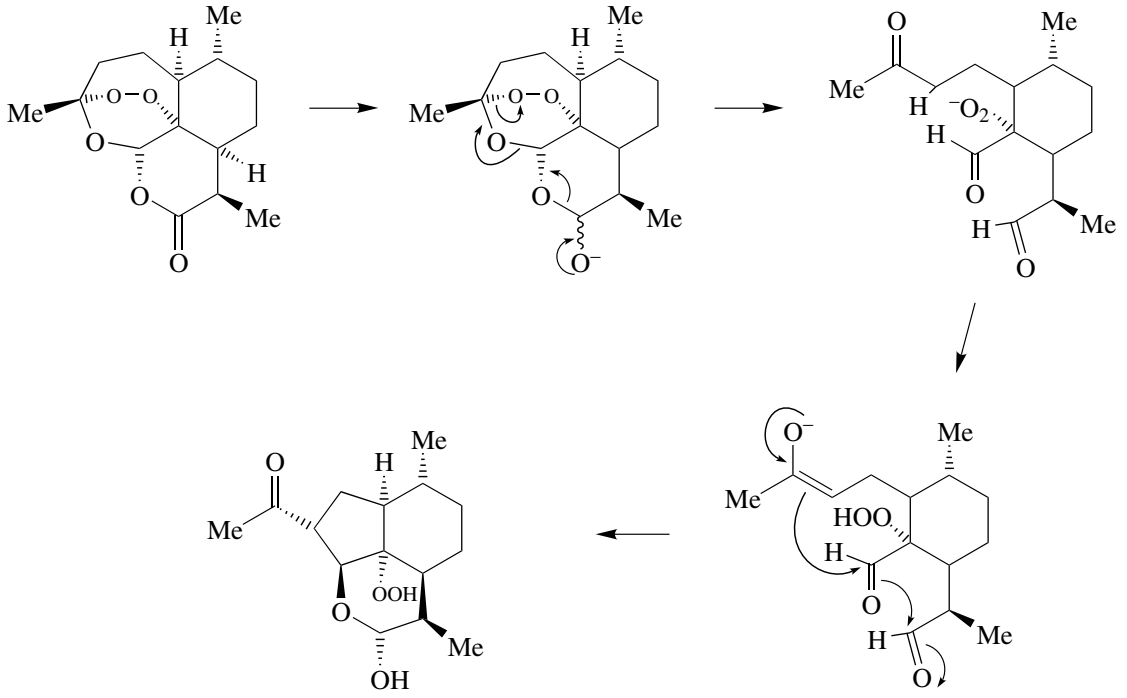
Evidence has been obtained[467] for the involvement of a tertiary cyclopropylcarbinyl cationic intermediate in the rearrangement of presqualene diphosphate to squalene. 16-Oximino-17α-benzyl-17*β*-hydroxy derivatives in the androstane and estrane series have been converted into 16-oxo-17*β*-benzyl-17α-hydroxy derivatives with inversed configuration at C(17), on treatment with titanium trichloride. It has been suggested[468] that the rearrangement occurs through the key intermediate (**401**) (see Scheme 97).

The rearrangements of perezone have been studied[469] in some detail. A boron trifluoride–acetic anhydride-catalysed rearrangement of dihydroarteannuin B has been reported,[470] and a concise annulation fragmentation strategy has been elaborated[471] for the construction of the bridged nine-membered ring ether moiety of the eunicelline diterpenes. It has been shown[472] that $LiAlH_4$ reduction of artemisin results in an unexpected rearrangement yielding a novel tertiary hydroperoxide (see Scheme 98). Homologation of the taxol side-chain via an Arndt–Eistert reaction has been achieved,[473] and biological rearrangement reactions of taxoids have been reported.[474] Methanolysis of taxicin I esters has been found to afford a 1,15-secotaxane as the result of a vinylogous retro-aldol reaction followed by acetalization and a transannular hydride



(**401**)

SCHEME 97

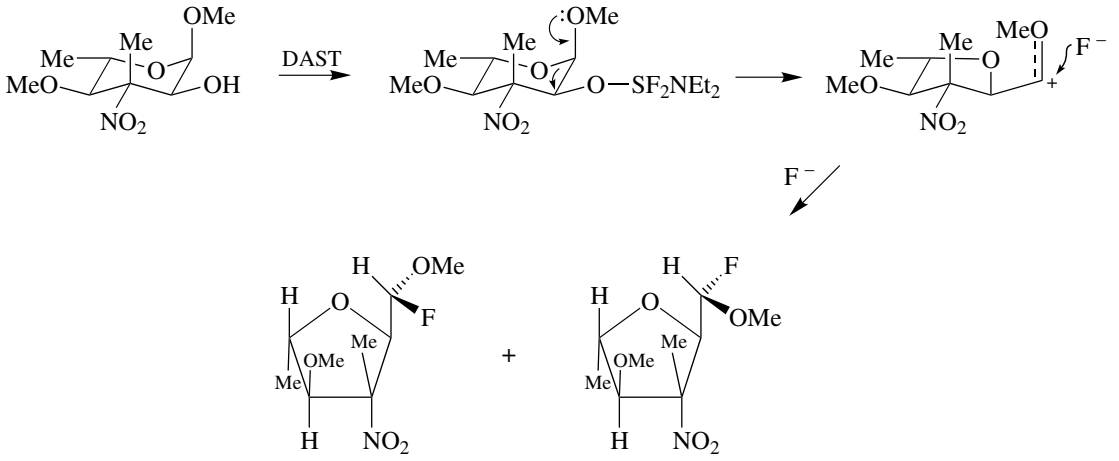


SCHEME 98

shift.[475] Treatment of 13-oxo-7-triethylsilyl baccatin III with bifluoroacetic anhydride in the presence of pyridine has been reported[476] to yield both A- and B-ring contraction products in reasonable yields. The sequence of reactions involved in the acid-catalysed rearrangement of 9-dihydro-13-acetylbaccatin III has been described.[477]

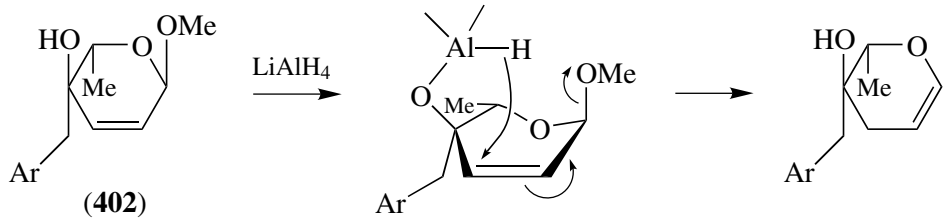
Acetic acid-catalysed cleavage of proanthocyanidins in the presence of phloroglucinol has been reported to afford a series of 2*R* procyanidin– and prodelphinidin–phloroglucinol adducts together with a novel 2*S* all-*cis* derivative, thus implicating cleavage of the pyran ring and subsequent inversion of stereochemistry at C(2).[478] Treatment of the neolignan aurein with trifluoroacetic acid has been found to furnish the rearranged product 2-(2-allyl-4-hydroxy-3,5-dimethoxyphenyl)-1-(3,4,5-trimethoxyphenyl)propane.[479]

It has been shown[480] that terpenoid biosynthesis in higher plants arises from 1-deoxy-D-xylulose by an intramolecular skeletal rearrangement. A novel glycosylation of 3-deoxy-D-glycero-D-galacto-2-nonulosonic acid via an *in situ* pyranose to furanose rearrangement has been described,[481] and an unusual rearrangement involving the formation of an α-(1 → 2)-linked disaccharide has been observed[482] during the treatment of 3,4,6-tri-*O*-acetyl-1,2-*O*-(allyloxyethylidene)-β-D-mannopyranose with TMS-triflate. A simple method for the preparation of 1-fluoro- and/or 5-fluoro-3-branched-chain sugar derivatives by reaction of diethylaminosulfur trifluoride (DAST) with methyl 3-*C*-methyl-3-nitro-α-L-hexopyranosides has been presented.[483] The reaction involves rearrangement without or with (see Scheme 99) ring contraction depending to a large extent on the 1,2-relative configuration. It has been reported[484] that 4-*C*-substituted α-*erythro*- and β-*threo*-hex-2-enopyranosides of the type (**402**) readily undergo a reductive rearrangement to the respective 3-deoxy glycals when



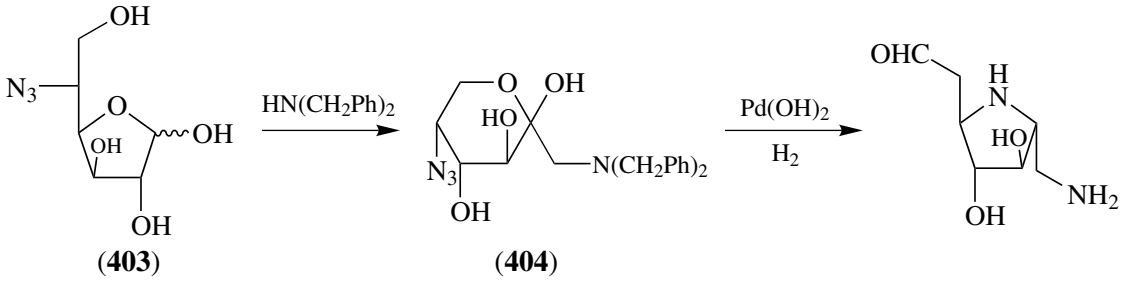
SCHEME 99

treated with $LiAlH_4$ (see Scheme 100). A convenient and apparently general entry to 1-aminodeoxyketopyranoses has been achieved[485] via Amadori rearrangement of 5-azido-5-deoxy-D-glucofuranose (**403**) with dibenzylamine and subsequent catalytic hydrogenation of the resulting 5-azido-1-dibenzylamino-1,5-dideoxy-D-fructopyranose (**404**). An intramolecular phosphorylation–elimination sequence (see Scheme 101) has



(**402**)

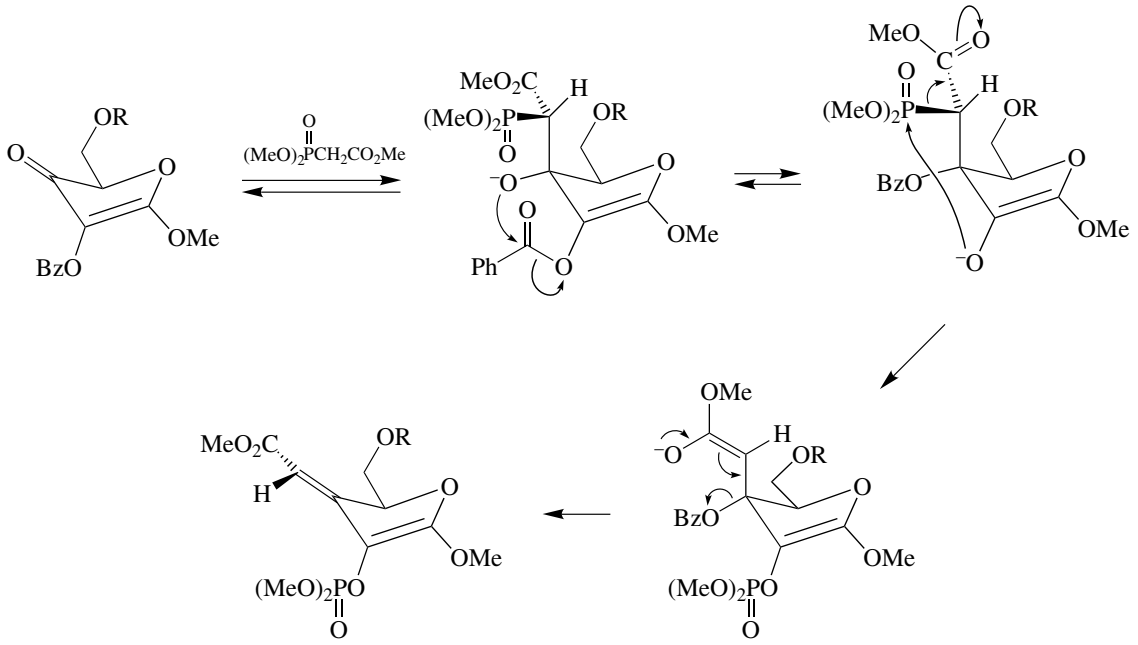
SCHEME 100



(**403**) (**404**)

been proposed[486] to account for the unusual stereospecificity and 3-*O*-phosphorylation observed when olefination reactions under Horner–Wadsworth–Emmons conditions were performed on methyl 2-deoxy-α-D-*glycero*-hex-2-enopyranosid-4-uloses. A pancratistatin C-ring precursor has been synthesized from methyl α-D-glucopyranoside utilizing a Ferrier rearrangement and a *β*-hydroxy-ketone transposition.[487]

It has been demonstrated[488] that appropriate modification of the tryptamine chain of aspidosperma alkaloids can afford deep-seated skeletal rearrangement under relatively

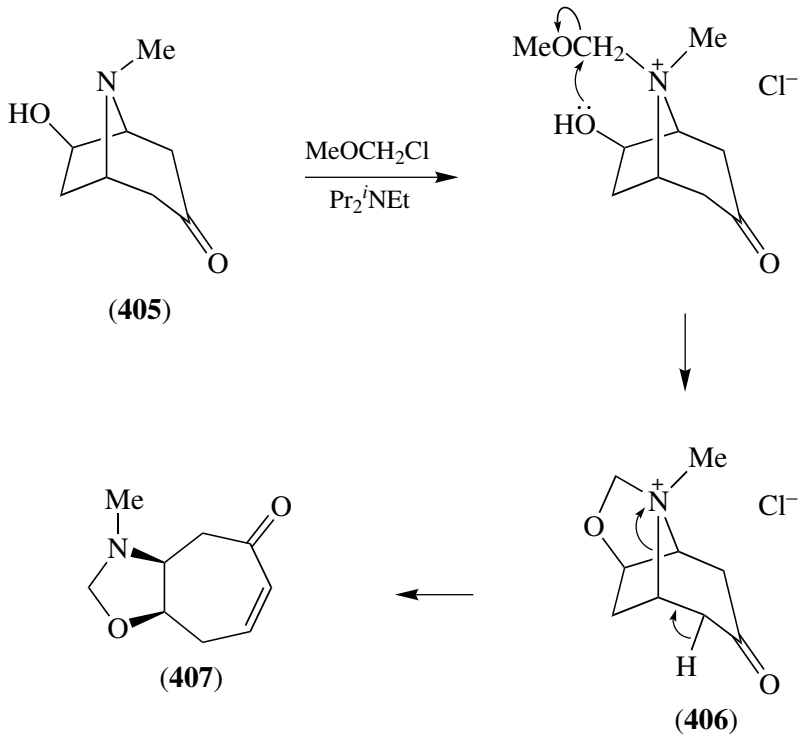


SCHEME 101

mild conditions. The rearrangement reactions of denudatine have been examined,[489] and a single aldehydic compound has been obtained from the acid-catalysed rearrangement of dihydroveatchine.[490] Modifications have been made to the structure of the antileukaemic alkaloid homoharringtonine through unusual skeletal rearrangements of the parent compound.[491] In the presence of diisopropylethylamine, the methoxymethyl-protected 6*β*-hydroxytropinone (**405**) has been found to undergo a ring-opening rearrangement to yield the novel bicyclic oxazolidine (**407**). An oxazolidinium (**406**) has been postulated[492] as a key intermediate in this transformation (see Scheme 102).

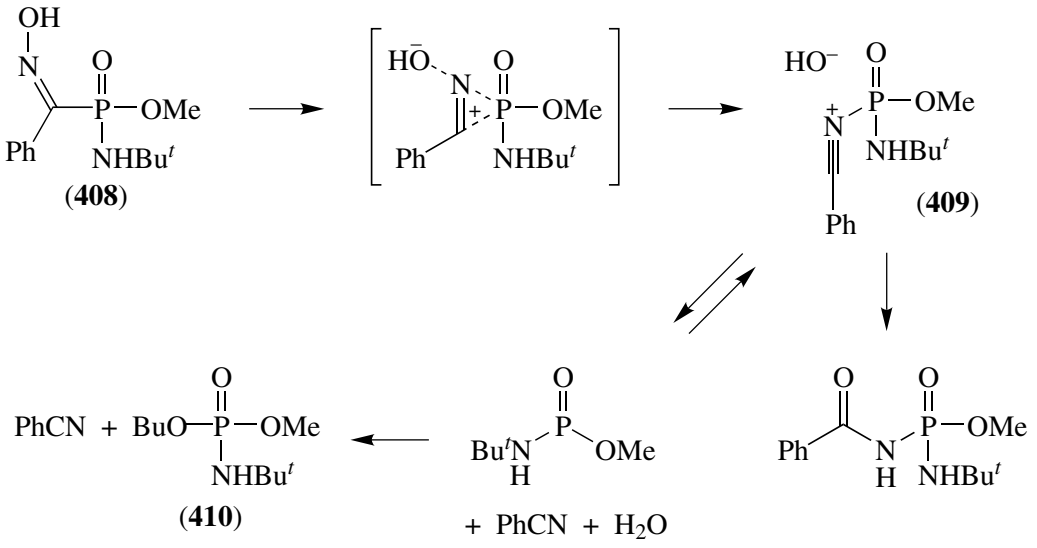
Rearrangements Involving Electron-deficient Heteroatoms

Ab initio calculations have been performed[493] to probe the mechanism of the Beckmann rearrangement of formaldehyde oxime in concentrated sulfuric acid, and substituent and solvent effects on the reaction pathway of the Beckmann rearrangement have been studied.[494] The results of this study have indicated that the solvent molecules act as homogeneous catalysts in the rearrangement. Several vapour-phase Beckmann rearrangements have been carried out on zeolite catalysts,[495–497] and the catalytic properties of mesoporous silica for the vapour-phase Beckmann rearrangement of cyclohexanone oxime have been compared with those of other typical solid acid catalysts.[498] Montmorillonite K10 impregnated with iron(III) chloride has been found to be an effective catalyst for the Beckmann rearrangement of substituted diaryl ketoximes, giving selective *anti* migration.[499] A study[500] of the Beckmann rearrangement of *syn*- and *anti*-3,4-diphenylcyclohexenone oximes in polyphosphoric acid has supported earlier work that suggests alkyl migration is preferred over vinyl

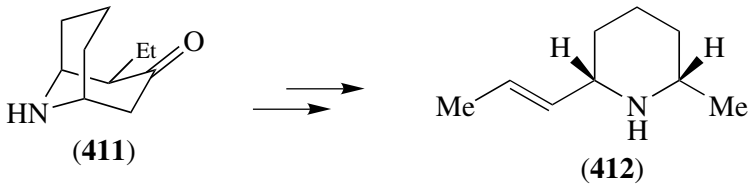


SCHEME 102

migration in the Beckmann rearrangement of unsaturated cyclic ketoximes. A systematic study has been made of the Beckmann rearrangement of aldonitrones using sodium iodide–trifluoroacetic anhydride, and mechanistic proposals on the transformation have been presented.[501] A novel synthesis of 1,2-dehydro-1-aminophosphonates via a Beckmann rearrangement has been applied to the synthesis of α-aminophosphonic acid derivatives.[502] The fact that methyl α-hydroxyiminobenzyl-*N*-*t*-butylphosphonamidate (**408**) has been found to undergo Beckmann rearrangement when heated in toluene, but fragmentation to a phosphoramidate (**410**) and phenyl cyanide when heated in butanol, has supported[503] the assumption that a common intermediate (**409**) participates in the rearrangement and in the fragmentation (see Scheme 103). An asymmetric route to benzophenone frameworks utilizing a Beckmann rearrangement–allylsilane cyclization via planar chiral η^6-chromium arene complexes has been described.[504] 17-Oximino-3β-pyrrolidinoandrost-5-ene has been found to afford the unusual lactam, 3β-pyrrolidino-17-aza-D-homoandrost-5-en-17a-one,[505] and treatment of 4-methyldihydrofuro[2,3-*h*]- coumarin-9-one oxime under Beckmann conditions (HOAc–HCl or $POCl_3$) has been found to produce the corresponding 8-halo-4-methyldihydrofuro[2,3-*h*]coumarin-9-ones.[506] The pathway outlined in Scheme 104 has been presented[507] as a possible route for the rearrangement of α-hydroxylamino oximes to cyclic amidoximes by the action of sodium borohydride. A variety of new heterocyclic systems have been formed[508] via novel Beckmann-type rearrangements from cyclobutanone oximes and a mixture of disulfur dichloride, *N*-chlorosuccinimide, and Hünig's base. Efficient synthetic routes to piperidine alkaloids such as (+)-pinidine (**412**), starting from (+)-benzyl 2-ethyl-3-oxo-9-azabicyclo[3.3.1]nonane-9-carboxylate

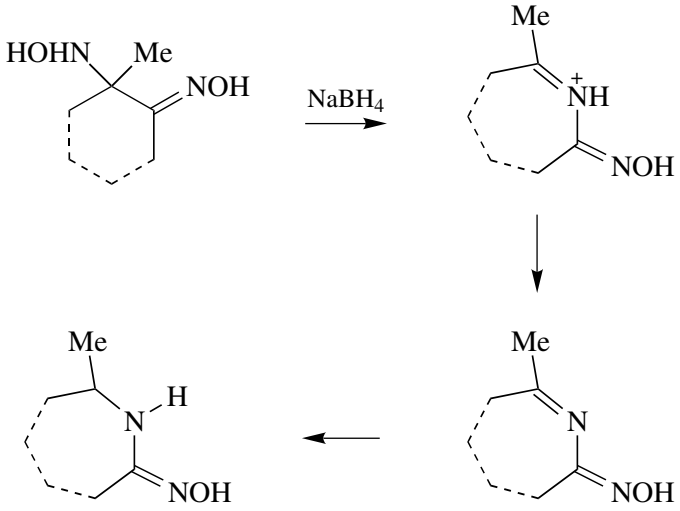


SCHEME 103



(**411**), have been devised[509] using a tandem Beckmann and Huisgen–White rearrangement as an alternative to the Baeyer–Villiger oxidation.

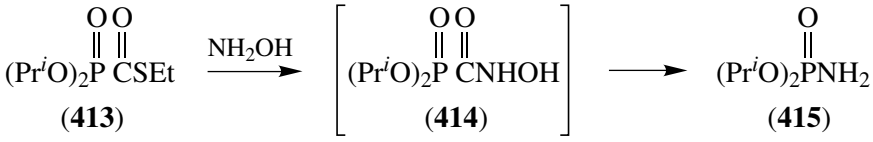
Ab initio and semiempirical studies on the transition structure of the Baeyer–Villiger rearrangement of acetone with performic acid have been undertaken,[510] and a theoretical investigation has been made[511] of the mechanism of the Baeyer–Villiger reaction in non-polar solvents. The effect of fluoromethyl groups on the Baeyer–



SCHEME 104

Villiger rearrangement of di- and tri-fluoromethyl ketones has been investigated.[512] The Baeyer–Villiger oxidation of 4-formyl β-lactams has been found to represent one of the few examples of a reaction in which the preferred migration of the carbon moiety involves an aliphatic aldehyde function. The process has led to an efficient and totally stereoselective entry to 4-(formyloxy)-β-lactams.[513] The Baeyer–Villiger oxidation (and Beckman rearrangement) of *N*-benzyl-2-*C*: 1-*N*-carbonyl-2-deoxy-5,6-*O*-isopropylidene-3-keto-α-D-ribofuranosylamine have been studied.[514]

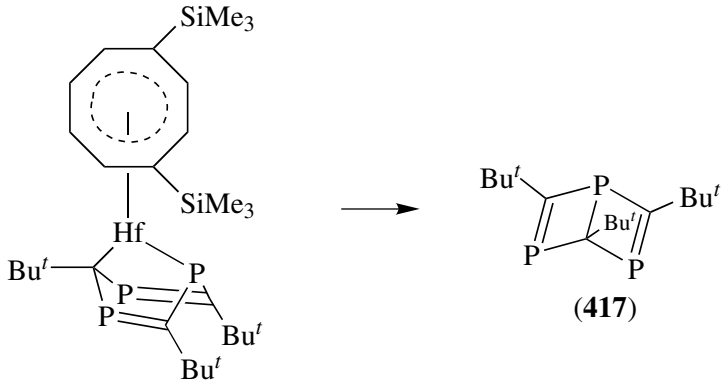
A mild and efficient Hofmann rearrangement has been developed using *N*-bromosuccinimide and sodium methoxide in methanol[515] and/or *N*-bromosuccinimide and DBU in methanol,[516] and a general synthetic method for the Hofmann rearrangement of *N*-α-protected L-asparagines has been described.[517] This latter reaction involves reaction of the asparagine derivative with iodosobenzene diacetate in mixed solvents and has produced β-amino-L-alanines in good yield. A new solvent system has been described[518] for the electrochemically induced Hofmann rearrangement of primary carboxamides. This methodology has made it possible to prepare alkyl carbamates possessing various alkoxy moieties under mild conditions. A chemoselective Curtius rearrangement of 1-(2-azidocarbonyl-3-furylmethyl)-5-pyrrolidone-2-carboxylic acid has been reported,[519] and Curtius rearrangements have been utilized as key steps in syntheses of (+)-preussin[520] and (−)-normalindine.[521] The formation of the diisopropylphosphoramidate (**415**) from the reaction of (diisopropylphosphono)-thiolformate (**413**) with hydroxylamine in pyridine has been interpreted[522] in terms of a spontaneous Lossen rearrangement of diisopropoxyphosphinylformylhydroxamic acid (**414**) formed in the reaction. A number of mechanistic studies have been undertaken[523–526] aimed at determining the mechanism of the base-induced rearrangements of suitably activated *N*-phosphinoylhydroxylamines.



(**413**) (**414**) (**415**)

Rearrangements Involving Organometallic Compounds

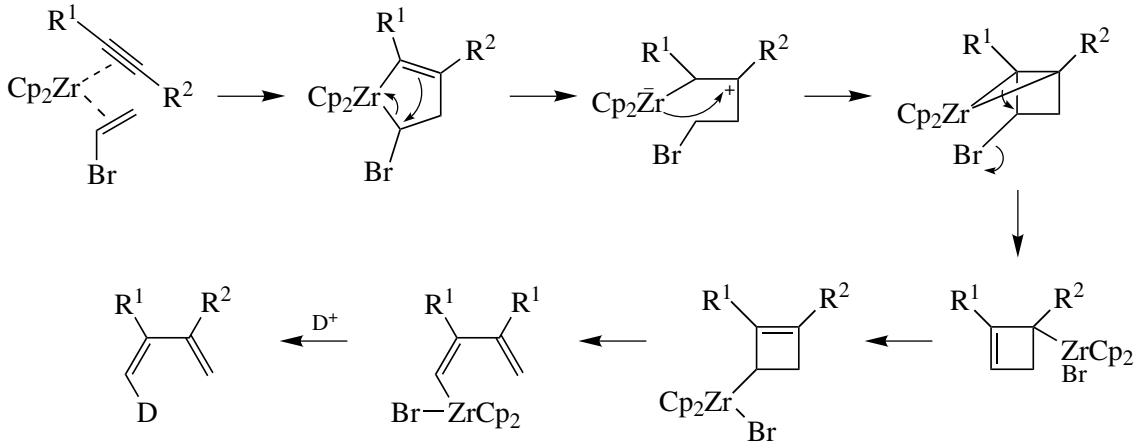
Rearrangement processes of alkyltitanocene dichlorides that occur under electron impact have been investigated[527] using deuterium labelling. A novel type of zirconium-mediated coupling reaction of alkynes with vinyl bromide to afford 2,3-disubstituted dienes has been reported[528] (see Scheme 105), and an inter–intramolecular reaction sequence has been proposed[529] for the observed formation of vinylcyclohexadienes and/or methylenecycloheptadienes from the copper-catalysed reaction of zirconacyclopentadienes with allylic dichlorides. The essential step in these processes appears to be transmetallation of the zirconium–carbon bond of the zirconacyclopentadiene to produce a more reactive copper–carbon bond. New phosphorus heterocycles, e.g. (**417**), have been constructed[530] by the thermal rearrangement of a [1,4-bis(trimethylsilyl)-η^8-cyclooctatetraene]-1,3,5-triphospha-7-hafnanorbornadiene complex (**416**).



A study has been made of the reactivity of high-oxidation state tantalum–alkylidene complexes stabilized by the aryldiamine ligand $[C_6H_3(CH_2NMe_2)_2\text{-}2,6]^-$, and an unusual rearrangement involving the unique activation of an aryl C−H bond by the alkylidenetantalum moiety has been observed.[531]

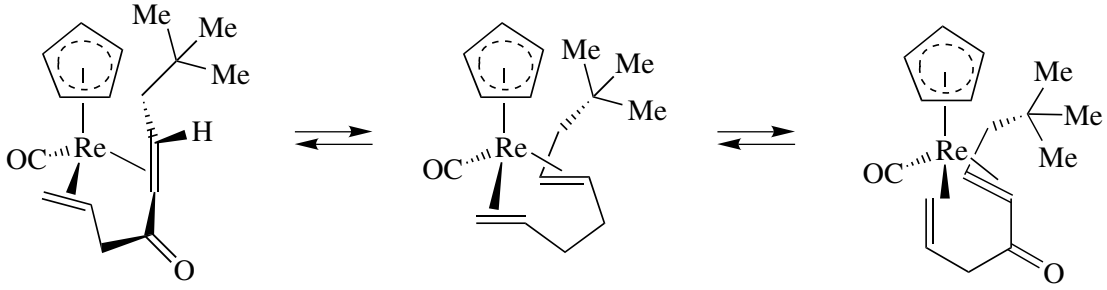
The rearrangement of a tungsten carbonyl-complexed 7-phosphanorbornadiene to its 7-phosphatricyclo[3.2.0^{4,6}]hept-2-ene complex has been analysed[532] by *ab initio* MO calculations, and it has been shown that the reactions of molybdenum and tungsten metallates of the type $[CpM(CO)_2CNR]^-$ with methyl iodide yield methyl complexes of the composition $[CpM(CO)_2(CNR)]$, which subsequently rearrange to η^2-iminoacyls and η^3-1-azaallyls depending on the nature of the metal, the isocyanide R substituent, and the solvent used.[533]

The use of single-enantiomer chiral ligands as a mechanistic probe for dynamic structural rearrangements in organo-transition metal complexes has been ably demonstrated in a study of the tricarbonylhalogenorhenium(I) and halogenotrimethyl-platinum(IV) complexes of 2,6-bis[4-(*S*)-methyloxazolin-2-yl]pyridine.[534] Rhenium hydroxide and amide complexes of the type $Re(X)(EtC{\equiv}CEt)_3$, where X = OH or NH_2, respectively, have been found to rearrange with migration of a hydrogen from oxygen or nitrogen to the rhenium centre,[535] while it has been suggested[536] that the



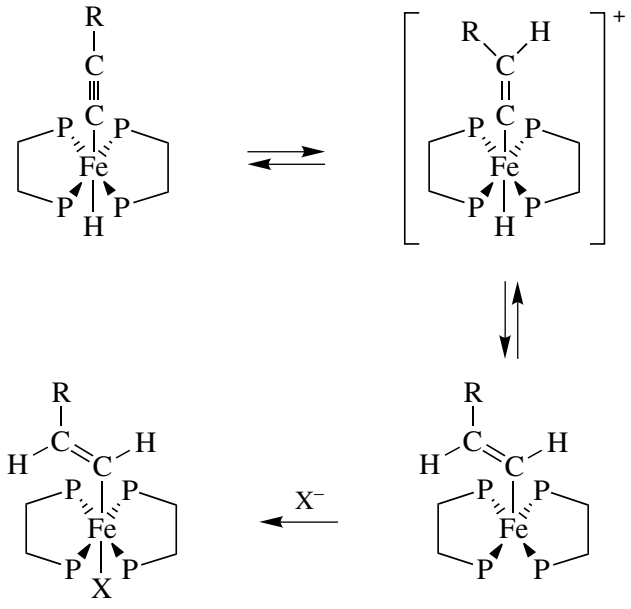
SCHEME 105

isomerization of the parallel–perpendicular rhenium–allyl vinyl ketone complex (**418**) to the diastereomeric perpendicular–parallel complex (**420**) occurs by migration of the rhenium from one enantioface of the vinyl double bond to the other to produce the parallel–parallel diastereoisomer (**419**). In a second step, rhenium is suggested to migrate from one enantioface of the allyl double bond to the other.



(**418**) (**419**) (**420**)

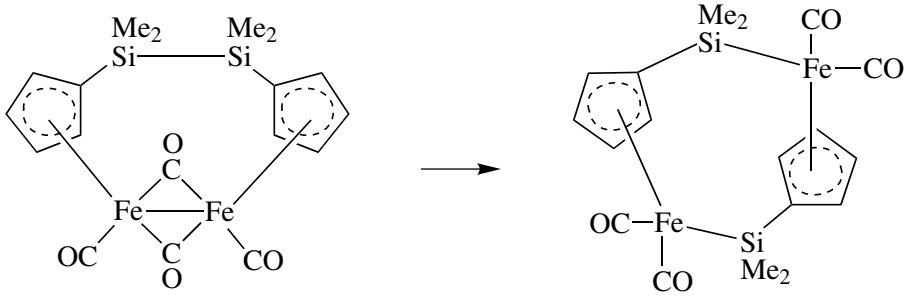
Acetylene–vinylidene rearrangements of silylacetylene–iron carbonyl complexes have been observed,[537] while iron–acetylide hydride complexes of the type [Fe(H)(C≡CR)(dmpe)$_2$], where dmpe=1,2-bis(dimethylphosphino)ethane, have been found to react with anions to afford substituted alkenyl complexes. It has been proposed[538] that a likely reaction course for this latter rearrangement involves initial protonation of the σ-bound acetylide ligand at the carbon β to the metal centre to form a vinylidene complex. Metal-to-carbon hydride migration in this vinylidene complex with attack by the anion would then lead to the neutral complex (see Scheme 106). A detailed mechanistic investigation has been carried out[539] on the novel metathetical



$X^- = N_3^-, Cl^-, SCN^-$

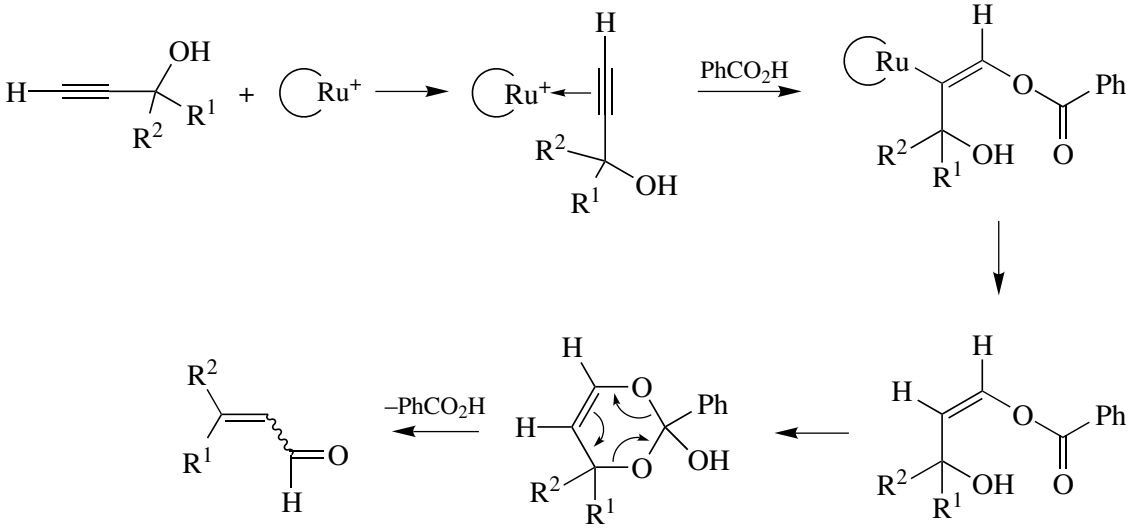
SCHEME 106

reaction (**421**) → (**422**) observed between intramolecular Si−Si and Fe−Fe bonds when the disilane-bridged bis(cyclopentadienyl)tetracarbonyldiiron complex (**421**) is

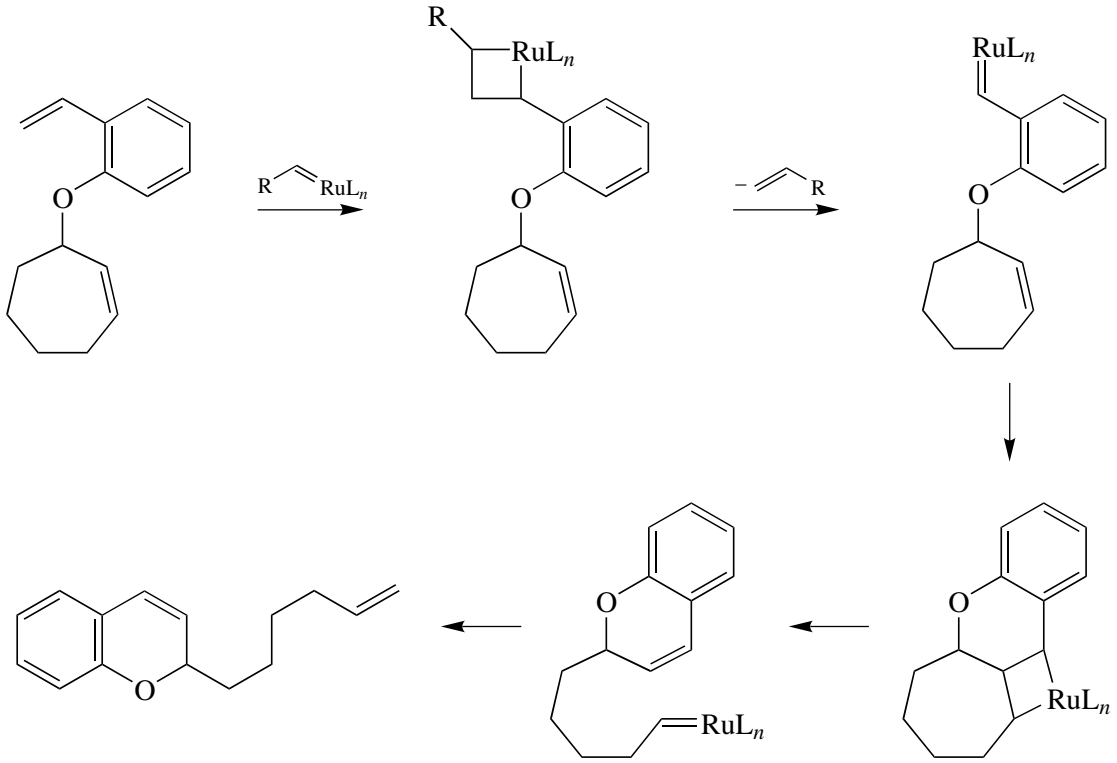


(**421**) (**422**)

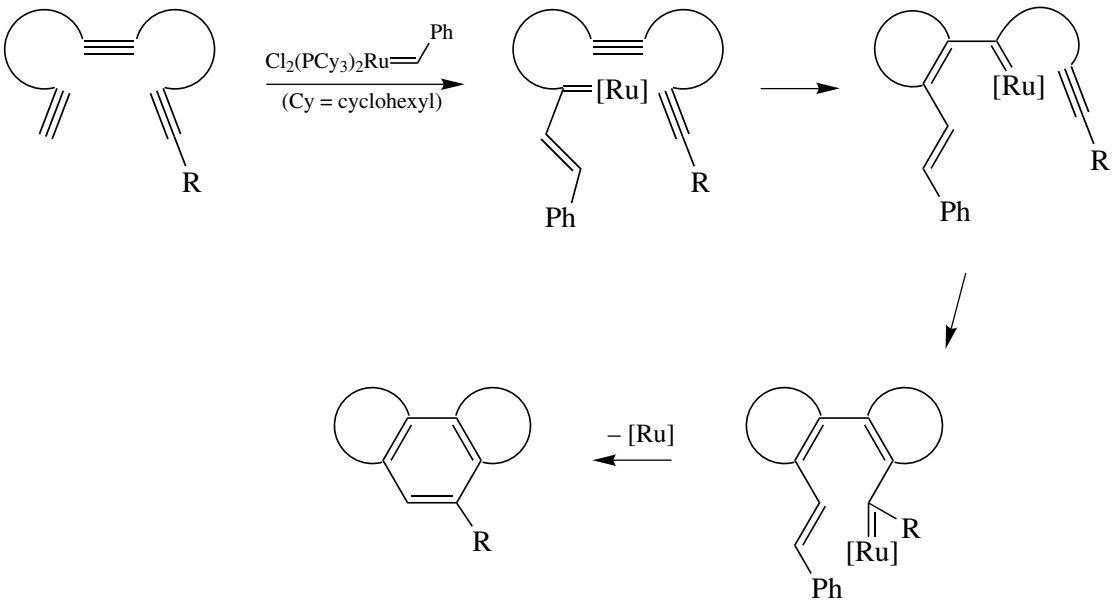
heated in boiling xylene, and the reaction specificity has been examined in more detail by studying the reaction of the related indenyl analogues.[540,541] A number of novel structural rearrangements induced by metal–metal interactions in ruthenium(II) ruthenocenyl- and (pentamethylruthenocenyl)-acetylide complexes have been unearthed,[542] and alternative mechanisms have been presented[543] for the alkyne to vinylidene isomerization promoted by half-sandwich ruthenium complexes. A new, efficient method for the transformation of prop-2-yn-1-ols into α,β- unsaturated aldehydes catalysed by a (diphosphine)ruthenium(II) complex in the presence of benzoic acid has been reported. The authors[544] showed that the key step involves the regioselective catalytic addition of the carboxylate to the terminal carbon atom of the C≡C triple bond, giving a (*Z*)-3-hydroxyprop-1-en-1-yl benzoate intermediate, followed by thermal elimination of the acid (Scheme 107). An enantioselective synthesis of chromenes from styrenyl ethers has been achieved[545] by way of a ruthenium-catalysed rearrangement which can be represented by the pathway outlines in Scheme 108. A cascade of four metathesis reactions (see Scheme 109) has been



SCHEME 107



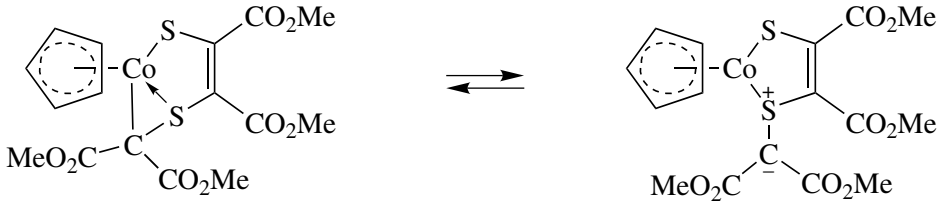
SCHEME 108



SCHEME 109

proposed[546] as a mechanistic explanation for the ruthenium-catalysed isomerization of triynes into benzene derivatives. The rearrangement of the uncoordinated allyl fragment of the carboxamide ligand in the complex $(\mu\text{-H})Os_3(CO)_{10}(\mu\text{-OCNHCH}_2\text{CH}{=}\text{CH}_2)$ has been observed[547] at room temperature.

The reduction behaviour of the alkylidene adduct of a cobalt–dithiolene complex (**423**) has been examined[548] and the study has shown that, when the alkylidene-bridged structure (**423**) is reduced by one electron, it isomerizes rapidly and quantitatively to the ylide form (**424**). This represents the first example of reversible isomerization of the metal–carbon bond in a cobaltadithiolene complex. A surprising *cis*- to *trans*-dihydride isomerization which is unprecedented for 18-electron six-coordinate complexes has been observed[549] in an octahedral iridium–*cis*-dihydride complex.

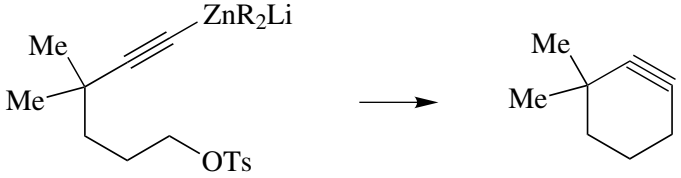


(**423**) (**424**)

A cyclic species involving the palladium moiety is thought to be involved[550] as the reaction intermediate in the palladium-catalysed transformation of 2-alkynyl sulfinates, HC≡CCH(R)OS(O)Tol, into sulfonylallenes, $RHC{=}C{=}CHSO_2Tol$. The reversibility of the rearrangement between hydrazo and azo tautomers in palladium metallocycles has been shown for the first time,[551] and several (η^1–η^2-enyl)palladium derivatives have been detected[552] as intermediates during a study of palladium insertion and migration along the chain of a number of linear terminal dienes. Mechanistic aspects of the unprecedented rearrangement of *cis*-platinum(II)(alkyl,alkyne) complexes to π-allyl derivatives have been discussed,[553] and evidence has been provided[554] for the intramolecular platinum migration from a kinetically favoured methionine residue to a thermodynamically preferred histidine side-chain in peptides.

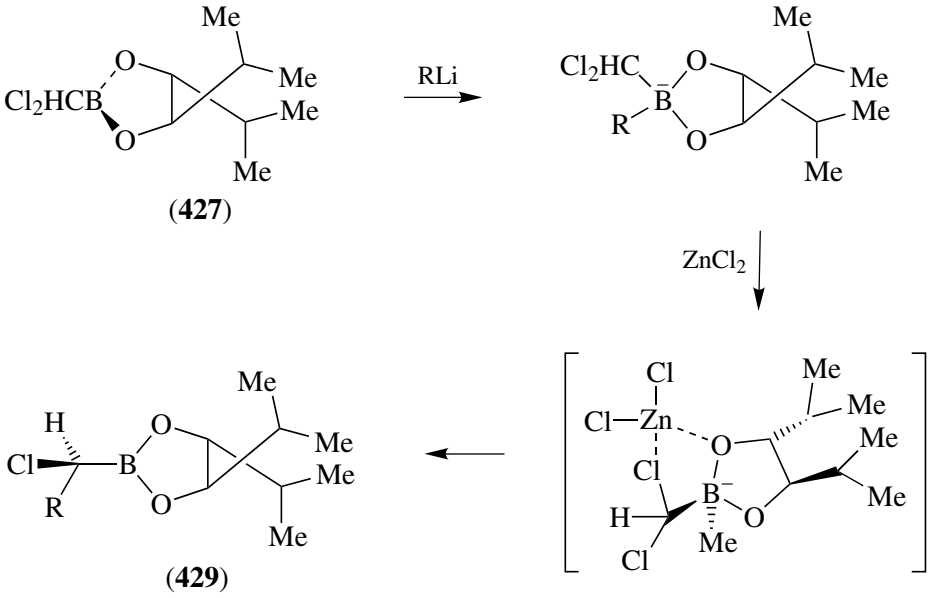
Manoalide, a marine anti-inflammatory sesterterpenoid, has been synthesized[555] using a 1,2-metallate rearrangement of a higher order cuprate and a Pd(0)-catalysed carbonylation of an iodoalkene to generate the central dihydropyranone ring.

The π-type *endo*-cyclization of metal acetylides (**425**) to form strained cyclohexynes (**426**) has been observed[556] for the first time in the reaction of alkynylzincates derived from 5-hexynyl tosylates.



(**425**) (**426**)

A chiral Lewis acid-catalysed method for the 1,2-migration of (dichloromethyl)borate complexes to provide synthetically useful (α-chloroalkyl)boronates has been developed,[557] and the diastereoselective rearrangement of the α,α-dichloromethylboronate derivatives of 1,2-diols, (**427**) → (**429**), has been explained[558] on the basis of a bidentate interaction between the catalytic Lewis acid and the substrate, leading to a favoured transition state (**428**).



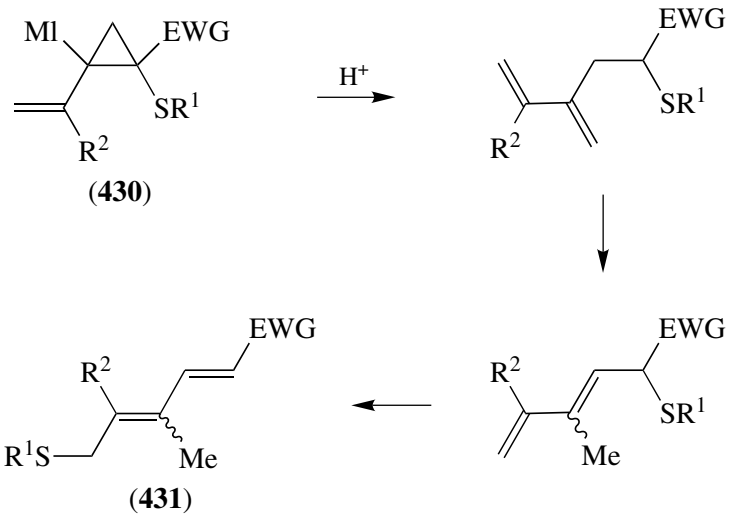
(**427**)

(**429**)

A detailed examination of the reactivity of organo-aluminium derivatives of *O*, *O*′-bifunctional ligands has been undertaken,[559] and the effect of substituents on the reversible rearrangements of chlorophosphane–dichlorogermylene ylides to trichlorogermylphosphanes has been investigated.[560]

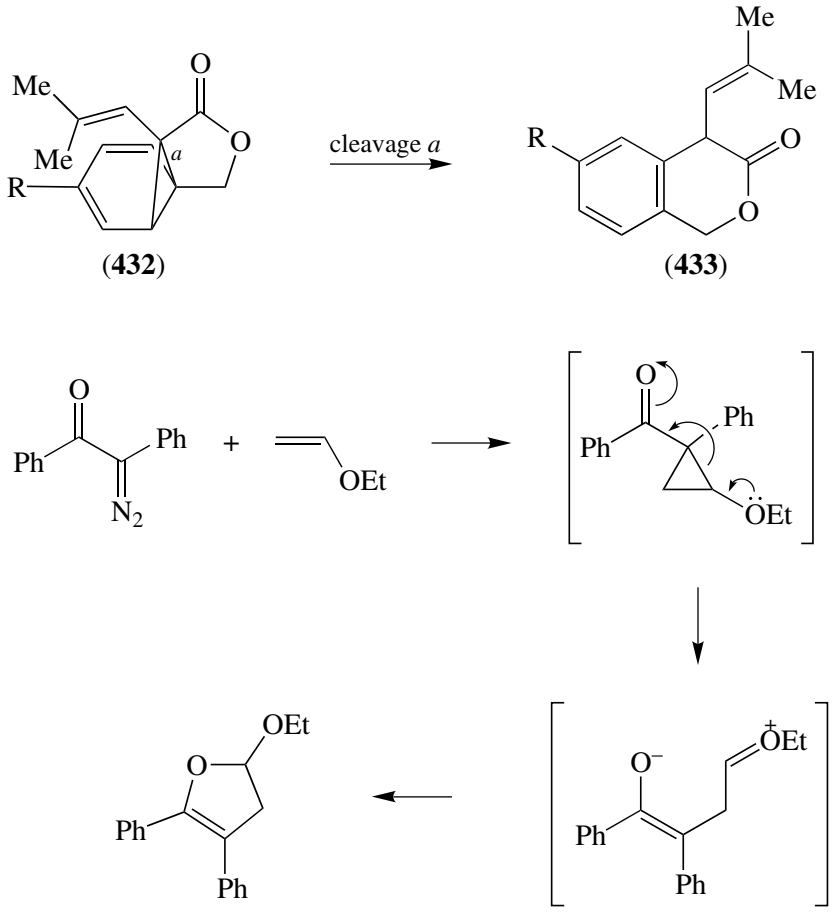
Rearrangements Involving Ring Opening

MO calculations have been carried out on the isomerization of cyclopropane to propene,[561] and the MNDO method has been used to study the reaction pathway and to optimize the structure of reactant, transition structure, and product of the ring opening reaction of bicyclo[1.1.0]butane.[562] Various methods have been employed[563] to estimate the rate constants for ring opening of the 2-cyclopropyl-2-propyl radical. 1-Acceptor-1-sulfenyl-substituted 2-vinylcyclopropanes of the type (**430**) have been found to afford 6-sulfenyl-$\alpha,\beta:\gamma,\delta$-unsaturated carboxylic esters and nitriles (**431**) upon treatment with acid, by a process which involves C(1)−C(2) bond fission and a novel 1,5-sulfenyl rearrangement[564] (see Scheme 110). It has been shown[565] that the benzophenone-sensitized photolysis of vinyl norcaradiene derivatives, such as 5-(2-methylprop-1-enyl)-3-oxatricyclo[4.4.0.$0^{1,5}$]deca-7,9-dien-4-ones (**432**), results in the regioselective cleavage of only one of the cyclopropyl σ-bonds to afford isochroman-3-one derivatives (**433**). It has been reported that the major product obtained from the reaction of structurally diverse α-diazo ketones with an electron-rich alkene in the

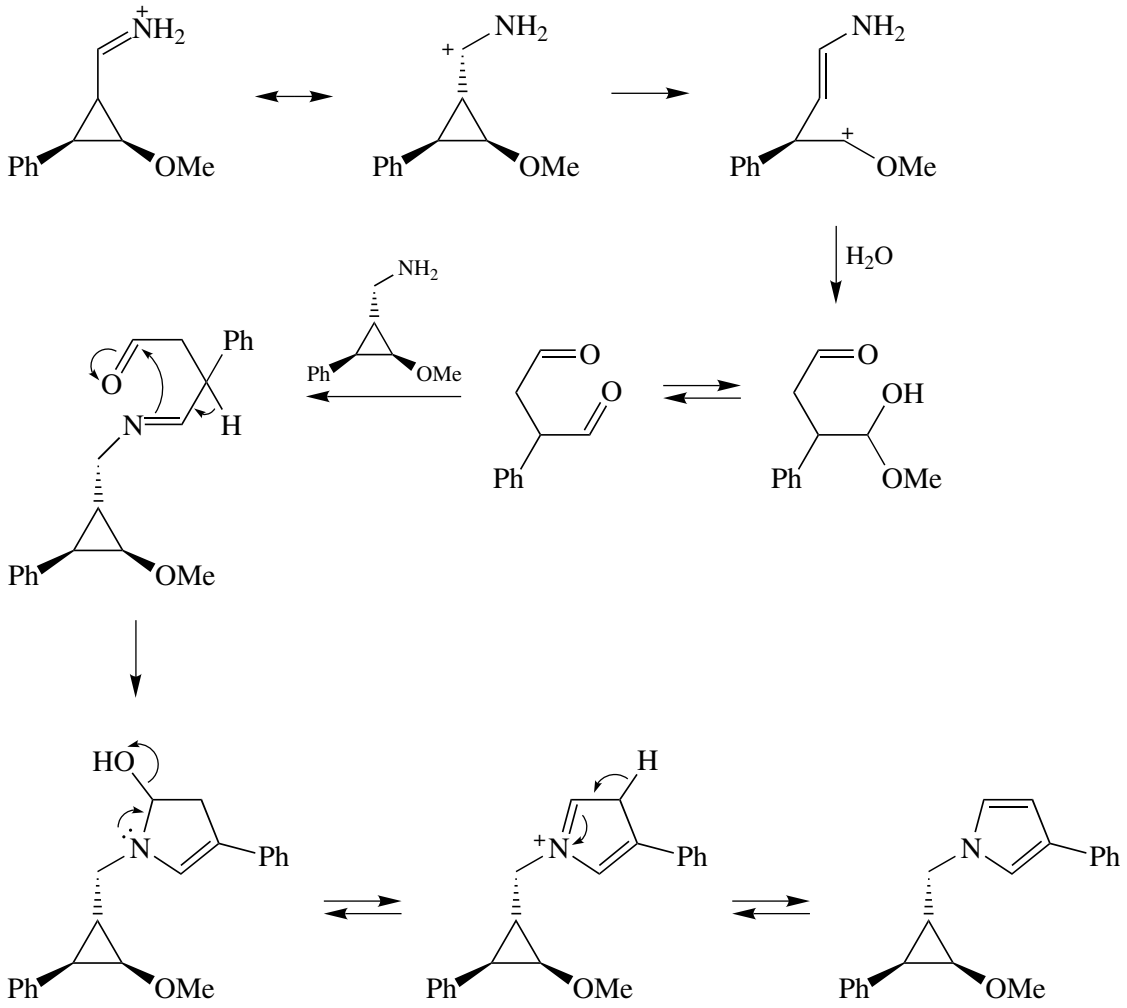


SCHEME 110

presence of rhodium(II)acetate is a dihydrofuran. The authors[566] proposed that the transformation involves a cyclopropanation–ring opening–cyclization pathway (see Scheme 111). Evidence has been produced[567] to support the hypothesized mechanism (see Scheme 112) as a possible pathway for the monoamine oxidase-catalysed oxidative

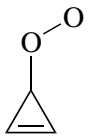


SCHEME 111

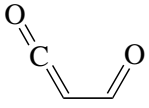


SCHEME 112

rearrangement of *trans*,*trans*-1-(aminomethyl)-2-methoxy-3-phenylcyclopropane to *trans*,*trans*-2-methoxy-3-phenyl-1-*N*-pyrrolyl)methyl]cyclopropane. An unprecedented photochemical ring opening to yield 2-phenyl-3-[*N*-(pentafluorophenyl)amino]acrylic acid has been observed[568] during the flash photolysis of 2-[*N*-(pentafluorophenyl)-amino]-3-phenylcyclopropenone. It has been shown[569] that the remarkable interconversion of cyclopropenes upon heating takes place via unsaturated carbenes that are also involved in the ring opening of these compounds. A theoretical investigation of the *syn–anti* interconversion of cyclopropenone carbonyl oxide (**434**) and its isomerization to formyl ketene (**435**) has been carried out.[570]

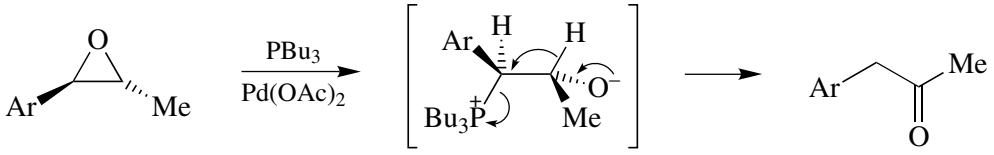


(**434**)

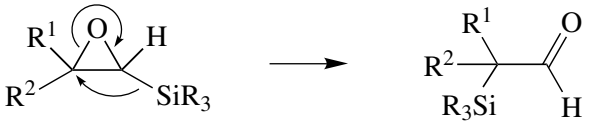


(**435**)

Ab initio calculations of the potential-energy surfaces for the unimolecular dissociation reaction of ethylene oxide have been made,[571] while MO calculations have shown[572] that there are concerted asynchronous pathways connecting the rearrangement of protonated propene oxide to protonated propanal. The regioselective ring-opening isomerization of epoxides to carbonyl compounds has been effectively catalysed by iron(III) tetraphenylporphyrin,[573] and aryl-substituted epoxides (**436**) have been found to isomerize in the presence of $Pd(OAc)_2$–PR_3 to produce the corresponding benzylic aldehyde or ketone (**437**) with complete regioselectivity.[574] The selective rearrangement of epoxysilanes (**438**) to α-silylaldehydes (**439**) has been

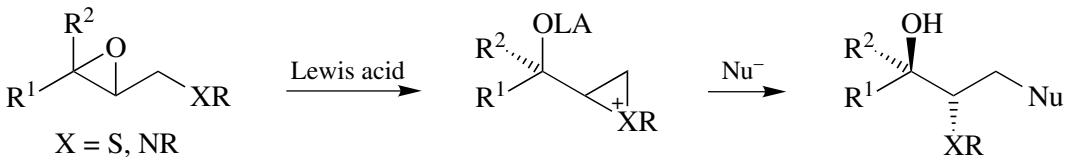


(**436**) (**437**)

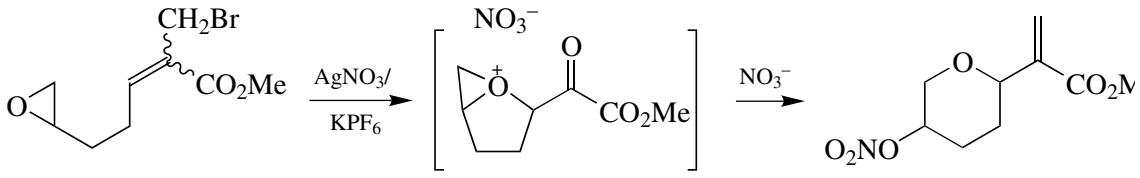


(**438**) (**439**)

achieved[575] with high efficiency by using the exceptionally bulky methylaluminium bis(4-bromo-2,6-di-*t*-butylphenoxide) as a stoichiometric reagent. Isotopic labelling has been used[576] as a probe in the study of a degenerate Payne rearrangement in a *t*-epoxide system. 2-Amino-3-phenylpropan-1-ols have been identified as the products from the reaction of various 1-phenyloxiranemethanamines with sodium cyanoborohydride in the presence of boron trifluoride. The authors[577] proposed that the products are derived from Lewis acid-mediated ring opening of the epoxide in an aza-Payne manner, followed by benzylic reduction of the intermediate aziridinium species. Both 2,3-epoxy sulfides and 2,3-epoxyamines have been found to undergo Lewis acid-induced rearrangement[578] via the corresponding thiiranium and aziridinium ions respectively (see Scheme 113), and an extension of this work in which 3-trimethylsilyloxy-1,2-aziridinium triflates are ring opened regiospecifically, using α-aminoesters, has opened up a route[579] to products that are structurally related to the aminopeptidase inhibitor pestatin. The stereoselective ring opening of a bromooxirane (**440**) to a tetrahydropyranylacrylate (**441**) has been reported[580] (see Scheme 114), and the novel diepoxide



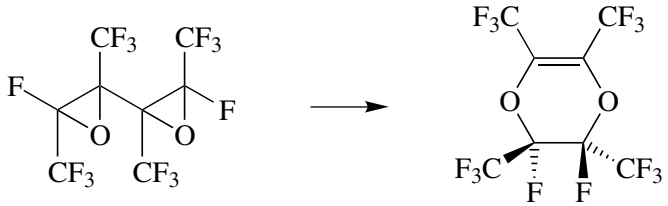
SCHEME 113



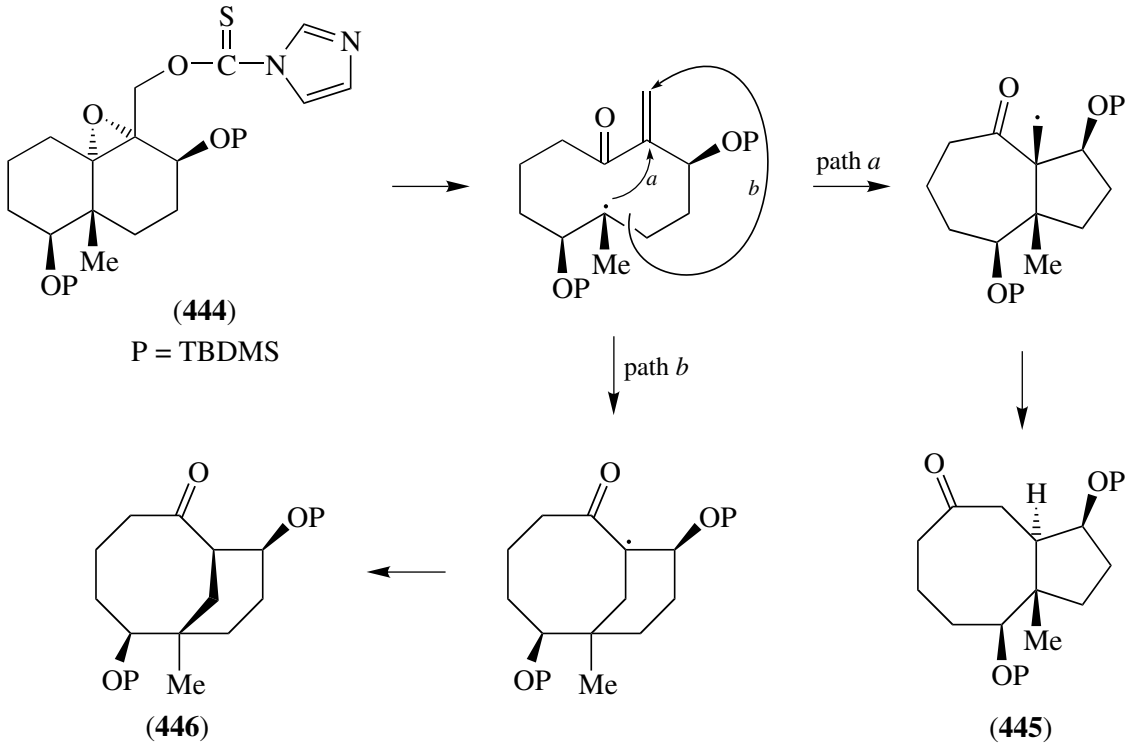
(**440**) (**441**)

SCHEME 114

(**442**) has been shown[581] to undergo a novel rearrangement on heating to afford the 1,4-dioxine derivative (**443**). A kinetic study has been made[582] of the oxiranylcarbinyl radical rearrangement, and it has been proposed[583] that the radical conversion of epoxydecalin thiocarbonylimidazolide (**444**) into bicyclo[6.3.0]undecanone (**445**) and bicyclo[5.3.1]undecanone (**446**) proceeds via a β-cleavage reaction of alkoxy radicals (see Scheme 115).



(**442**) (**443**)

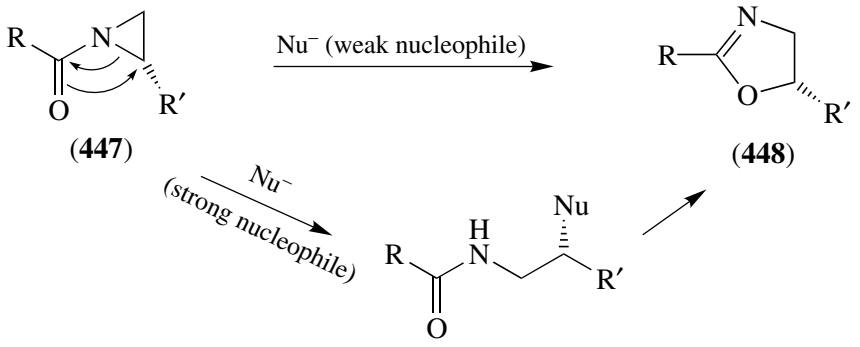


(**444**)
P = TBDMS

(**446**) (**445**)

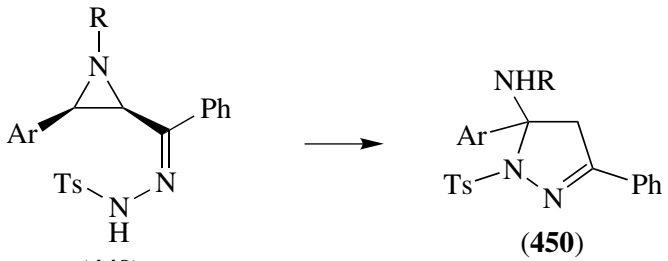
SCHEME 115

Details of the regioselective preparation of a variety of new 2,4-disubstituted oxazoles, using both iodide- and acid-promoted rearrangements of *N*-acylaziridines, have been presented.[584] It has been shown[585] that two plausible mechanisms (S_Ni and/or two S_N2 reactions) can account for the acid-catalysed transformation of 1-acylaziridines (**447**) to oxazolines (**448**), while the regioselective rearrangement of



(**447**) (**448**)

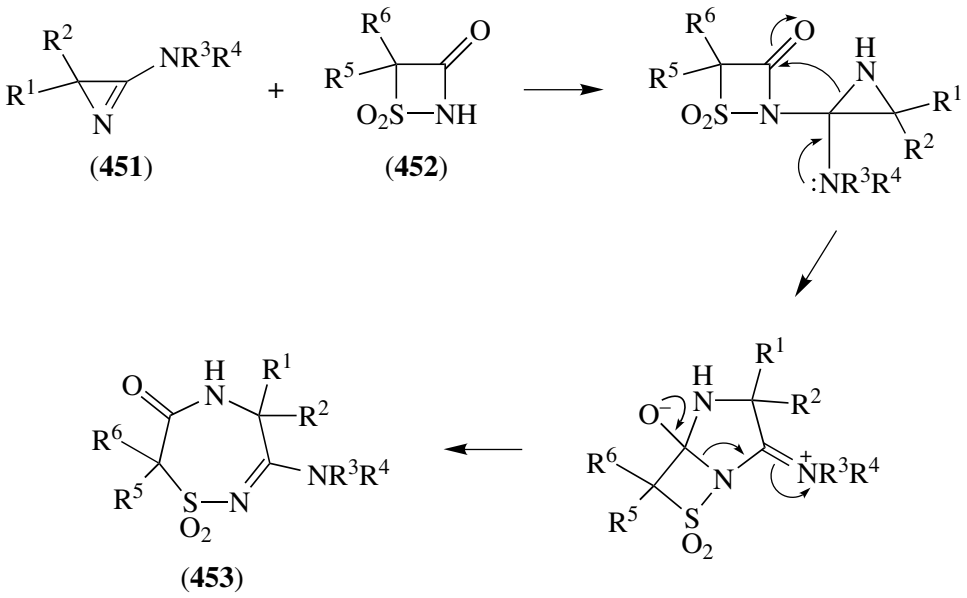
N-acylaziridine-2-imides to oxazoline-4-imides, followed by hydrolysis of these latter compounds, has been used[586] to afford chiral *β*-hydroxy-*α*-amino acid precursors. It has been suggested[587] that the observed thermal rearrangement of *cis*-aziridinyl ketone tosylhydrazones (**449**) to 5-alkylamino-3,5-diphenyl-1-tosyl-2-pyrazolines (**450**) is



(**449**) (**450**)

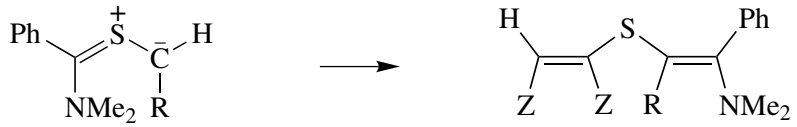
initiated by ionic cleavage of the bond between the ring nitrogen and the C(2) carbon, while it has been shown[588] that aziridinylbenzaldoximes undergo ring opening to yield (*Z*)-*N*-hydroxy-*N′*-(2-chloro-2-methylpropyl)benzenecarboximidamides on treatment with HCl. Pd(0)-catalysed isomerization of a number of 4,5-epimino 2-enoates has been shown to afford mixtures of four possible stereoisomers in which the *cis*-*E*-isomers predominate.[589] 1,2,5-Thiadiazepin-6-one 1,1-dioxides of the type (**453**) have been obtained[590] in good yield from the reaction of 2,2-disubstituted 3-amino-2*H*-azirines (**451**) and 4,4-disubstituted 1,2-thiazetidin-3-one 1,1-dioxides (**452**) at 0 °C in MeCN (see Scheme 116).

Evidence has been presented[591] that favours the involvement of thiirane intermediates in the formation of (*E*,*E*)-divinyl sulfides (**455**) from the reaction of thiocarbonyl ylides (**454**) with activated alkynes, while the reaction of 1-alkynyl-2,3-epithio alcohols (**456**) with a catalytic amount of Hg(II) has been shown to afford[592] substituted thiophenes (**457**) (see Scheme 117).



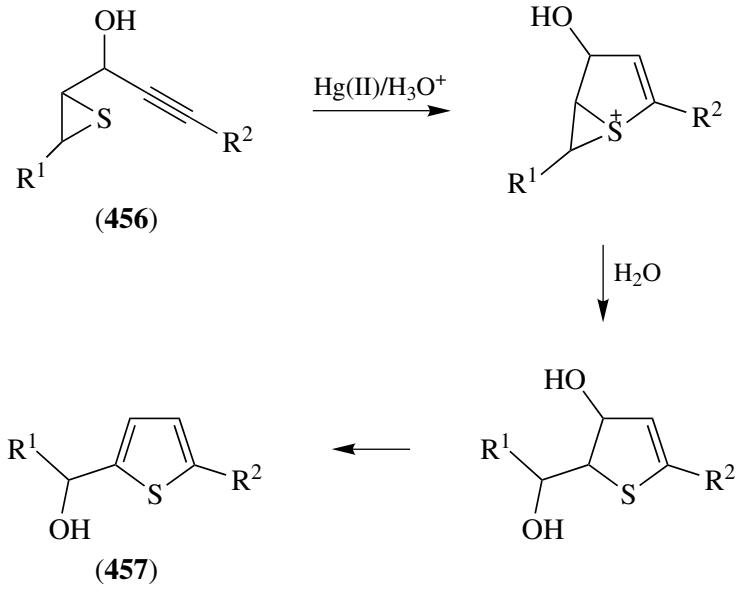
(**451**) (**452**) (**453**)

SCHEME 116



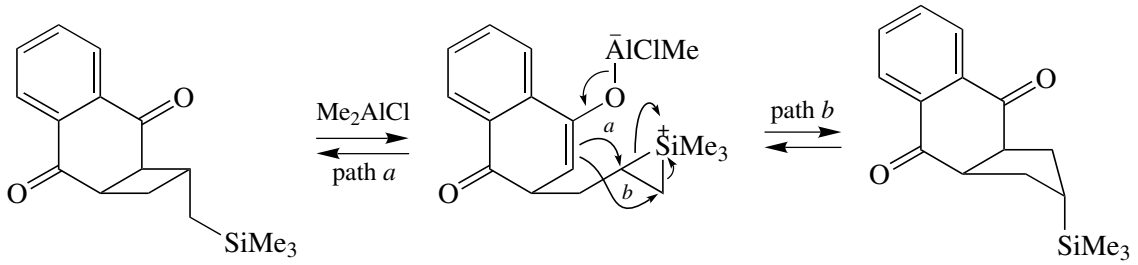
(**454**) (**455**)

R = COPh, CO_2Me, etc. Z = COPh, CO_2Me



(**456**) (**457**)

SCHEME 117

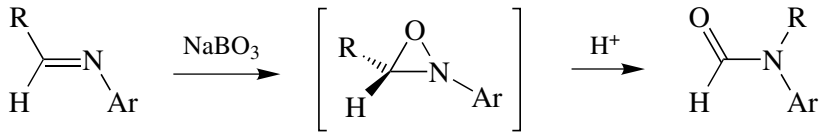


SCHEME 118

A computational study has been carried out[593] on the rearrangement reactions of methylsilacyclopropane, and the pathway shown in Scheme 118 has been put forward[594] to account for the formation of product (**459**) from the reaction of Me_2AlCl with the (2 + 2)-cycloadduct (**458**) between naphthoquinone and allyl trimethylsilane.

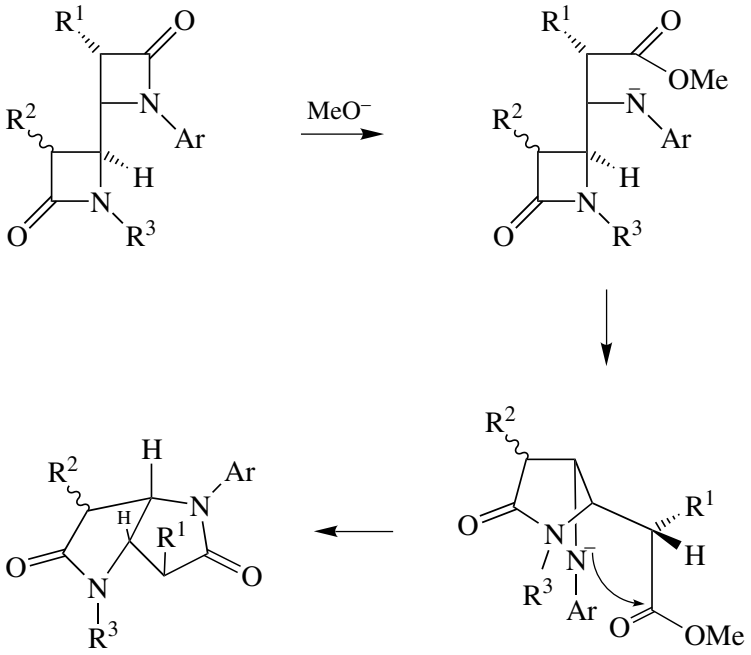
Results obtained with semiempirical MO methods have supported[595] a mechanism for the pyrolysis of vinylphosphirane to phosphapropyne, in which extrusion of ethylene leads to a vinylphosphinidene intermediate.

Applications of oxaziridine rearrangements in asymmetric syntheses have been reviewed,[596] and the formation of *N*,*N*-disubstituted formamides (**462**) on sodium perborate oxidation of alkyl *N*-arylaldimines (**460**) has been rationalized[597] in terms of an intermediate oxaziridine (**461**) that rearranges via acid-catalysed O−N cleavage.

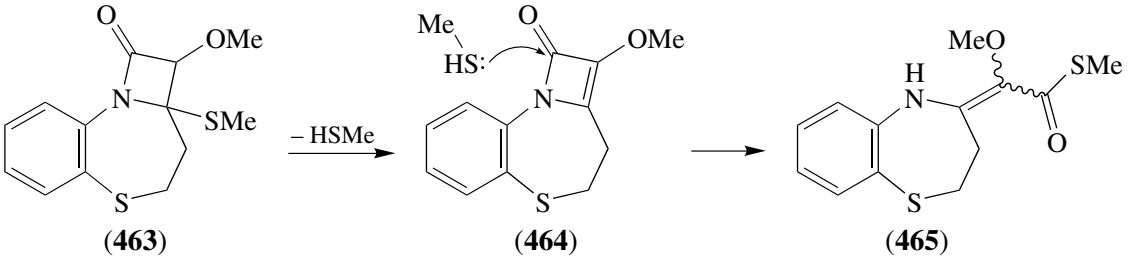


trans-3-(2-*t*-Butylcyclopropyl-3*H*-diazirine has been found to decompose both thermally and photochemically to yield the anticipated ring-expanded 3-*t*-butylcyclobutene product along with azine and products of trapping by solvent.[598] A stereochemical study of the methoxide-catalysed rearrangement of menthyl α-bromomethylphosphonamidate has produced evidence[599] for the intermediacy of an azaphosphiridine oxide in the reaction. A mechanism involving homolysis of the S−S bond at the rate-controlling step has been proposed[600] to account for the isomerization of dithiirane 1-oxides.

The structural and stereochemical requisites for the base-catalysed C_4, C_4'-bis-β-lactam to fused bis-γ-lactam rearrangement have been studied[601] and a pathway involving opening of the 2-azetidinone (see Scheme 119) has been proposed for the transformation. Acid-catalysed elimination of methanethiol to yield an azetinone intermediate (**464**) which, by nucleophilic addition of the eliminated agent, is converted into the isomeric thioesters (**465**) has been proposed[602] to account for the formation of these bicyclic thioesters on reaction of tricyclic azetidinone (**463**) with trifluoroacetic acid. A new base-catalysed rearrangement of *N*-substituted 4,4-dimethyl-1,2-thiazet-



SCHEME 119



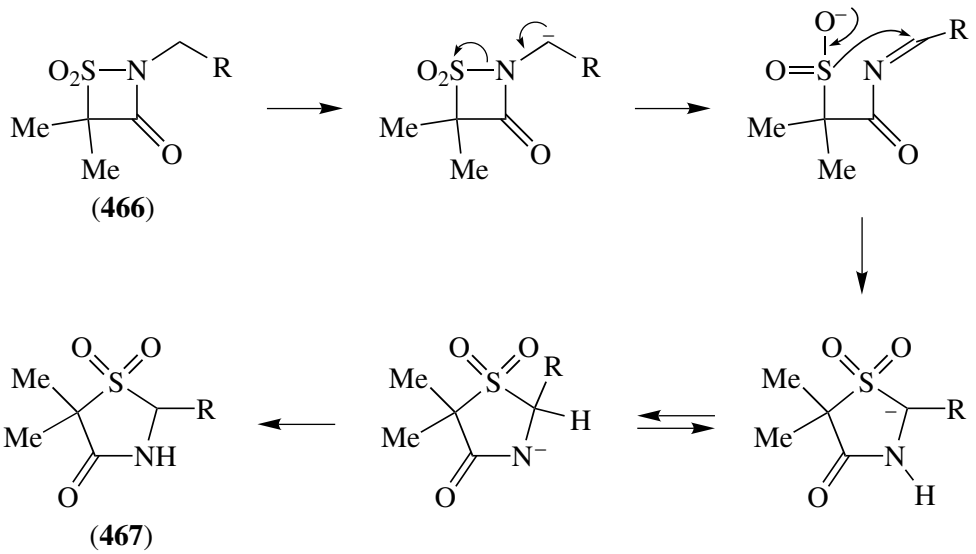
(**463**) (**464**) (**465**)

idin-3-one 1,1-dioxides (**466**) to thiazolidin-4-one 1,1-dioxides (**467**) has been reported[603] (see Scheme 120).

Evidence has been provided[604] for intramolecular nucleophilic catalysis by the carbonyl group during methanolysis of *o*- and *p*-formylbenzenesulfonates in basic media (see Scheme 121). A theoretical study of the zwittazido cleavage of 4-azido-2-pyrrolinones has been undertaken,[605] and *ab initio* calculations have been carried out to examine the possibility of the existence of a hexacoordinate phosphorus intermediate (**469**) in the migration reaction (**468**) → (**470**) of dimethyloxyphosphorylthreonine.[606]

A novel approach to the synthesis of dipyridinyls (**472**) and terpyridinyls with phenyl and 1,3-terphenyl spacers has been delineated[607] by the base-induced ring transformations of 6-pyridyl-3-carbomethoxy-4-methylthio-2*H*-pyran-2-ones (**471**) (see Scheme 122).

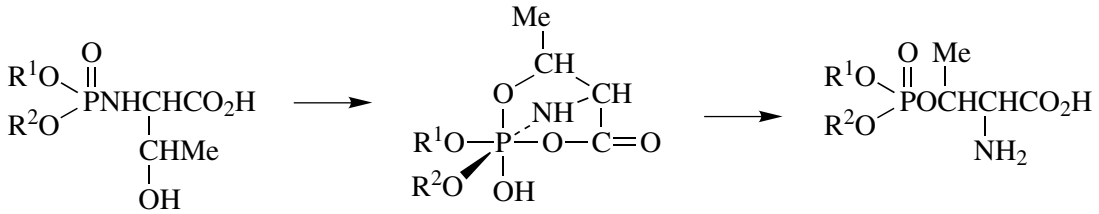
The dehydration of aldoximes with 2-methylene-1,3-dioxepane has been found to proceed smoothly in the presence of a catalytic amount of scandium(III) triflate to give the corresponding nitriles. The authors[608] proposed that coordination of $Sc(OTf)_3$ to the oxygen atom of the 1,3-dioxepane ring induces C−O bond cleavage to form a cationic



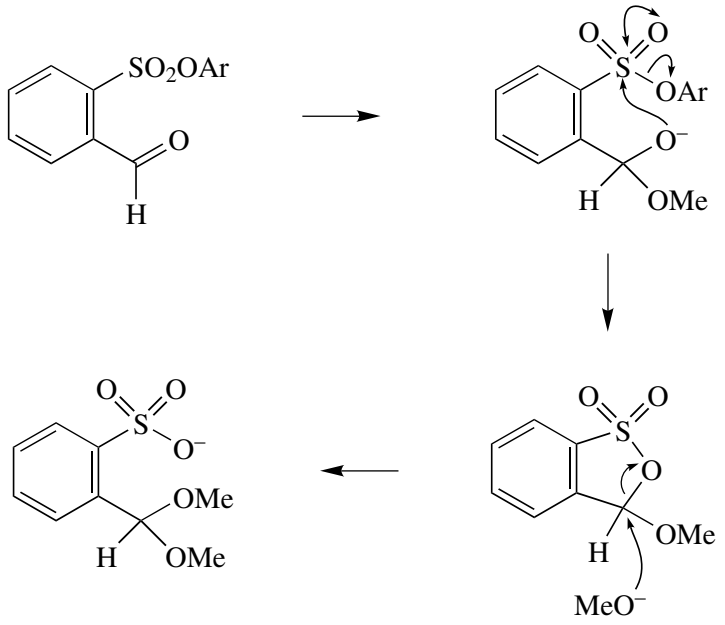
(**466**)

(**467**)

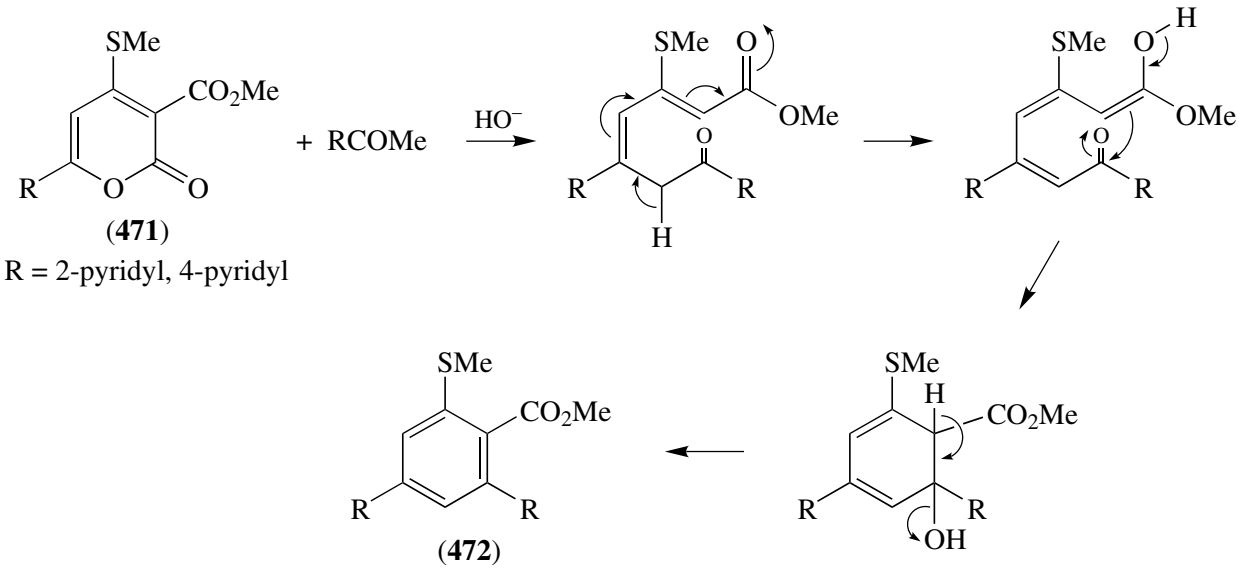
SCHEME 120



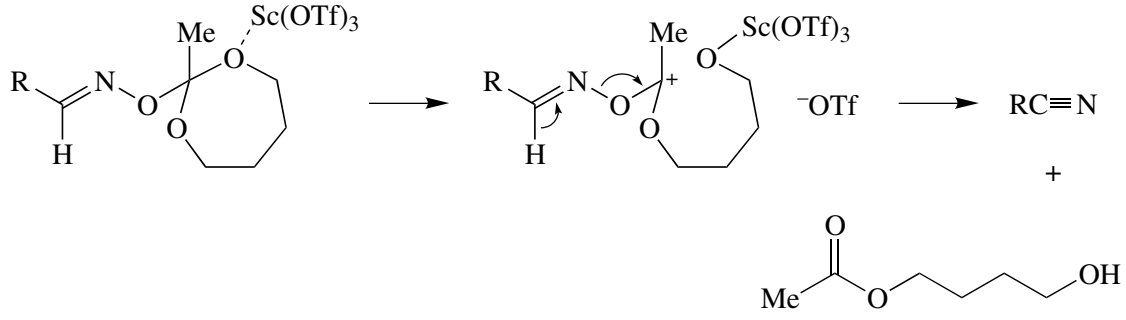
(**468**) (**469**) (**470**)



SCHEME 121



SCHEME 122



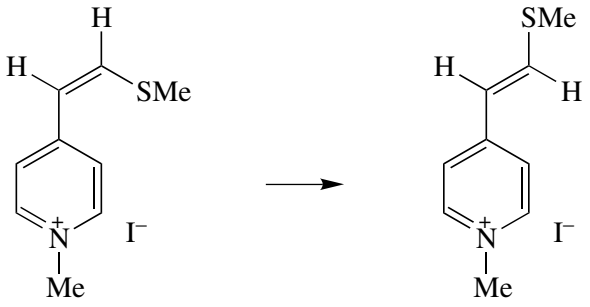
SCHEME 123

intermediate. Subsequent elimination of the hydrogen atom of the oxime and the ortho-ester moiety leads to production of the nitrile (see Scheme 123).

Isomerizations

CaY zeolite has been found either to act as a reagent to reduce stilbenes to 1,2-diarylethanes or to act as a catalyst and isomerize (*Z*)-stilbenes to the more stable *E*-form, depending on the number of Brønsted acid sites present in the zeolite.[609] It has also been suggested[610] that *Z*-to-*E* one-way isomerization of (*Z*)-stilbene through proton addition–elimination and electron-transfer processes occurs in acidic zeolite cavities. The isomerization reaction of (*E*)- and (*Z*)-α-phenylcinnamic acid molecules has been studied[611] at the level of semiempirical quantum chemical methods. The calculations revealed that the (*Z*)-α-phenylcinnamic acid is slightly more stable than the *E*-isomer. Kinetic studies have been made on the thermal *Z–E* isomerization of C(40)-carotenoids,[612] and the rotational barriers for *Z–E* isomerization of different proline analogues have been investigated[613] by dynamic ^{1}H NMR spectroscopy. The effects of

solvent viscosity on the thermal *Z–E* isomerization of three substituted *N*-benzylideneanilines have been studied[614] in a non-polar aprotic solvent. 2-[2(2-Pyrrolyl)ethenyl]quinoxaline has been found to undergo one-way *E–Z* isomerization in benzene,[615] whereas preparation of (*Z*)-1-methyl-4-(2′-methylthiovinyl)pyridinium iodide (**473**) from the corresponding pyridine was found[616] to result in irreversible isomerization to the *E*-isomer (**474**). Calculation of the activation parameters for the



(**473**) (**474**)

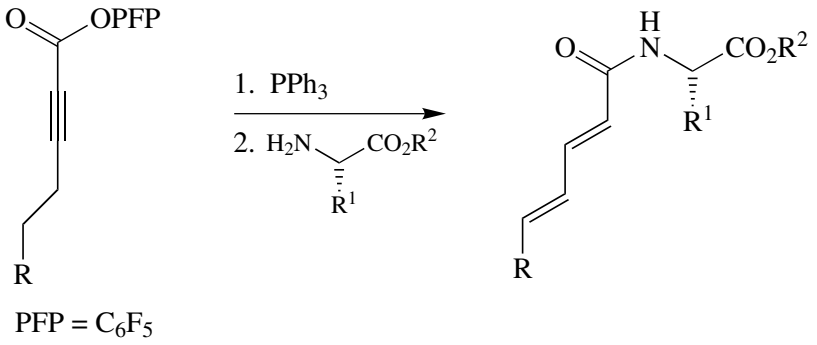
process showed one of the lowest barriers to an irreversible isomerization ever determined. The *E–Z* isomerization of 9,10-di-*t*-butyl-9,10-dihydro-9,10-disilaanthracenes has been shown to proceed via the inversion of the silyl radical centre, indicating the considerable stability of the intermediate silyl radicals.[617] A report has appeared on the *Z–E* isomerization of an ozonide.[618]

An *ab initio* method has been employed to study the mechanism of the thermal isomerization of buta-1,2-diene to buta-1,3-diene. The results of the study have indicated[619] that the transformation proceeds in a stepwise manner via a radical intermediate. Experimental free energies of activation for the bond shift in halocyclooctatetraenes have been reported and analyzed by using *ab initio* MO calculations.[620] The isomerization of hexene using a dihydridorhodium complex in dimethyl sulfoxide has been reported,[621] and it has been suggested[622] that the Pd(II)-catalysed homogeneous isomerization of hexenes proceeds by way of π-allylic intermediates. A study has been made[623] of alkene isomerization catalysed by the rhodium *t*-phosphine–tin dichloride dimeric complex, and the double-bond isomerization of olefinic amines over potassium amide loaded on alumina has been described.[624]

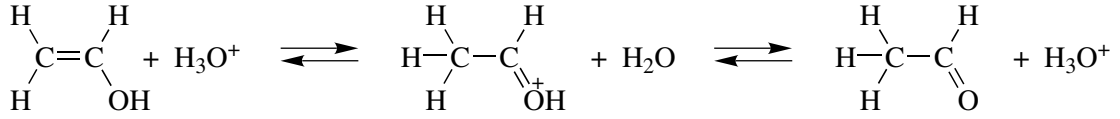
It has been demonstrated[625] that ytterbium–aromatic imine dianion complexes can act as effective catalysts for the isomerization of terminal alkynes to internal alk-2-ynes. Isomerization of acetylenic pentafluorophenyl esters in the presence of phosphines has been found to give rise to activated dienoic acids, which have been coupled directly with amines (and alcohols) in a simple one-pot procedure[626] (see Scheme 124).

Tautomerism

The hydroniumm ion-catalysed vinyl alcohol–acetaldehyde isomerization has been investigated[627] via *ab initio* MO calculations, and the results have supported the stepwise mechanism shown in Scheme 125. A theoretical study of the tautomeric rearrangements in mono- and di-chalcogenide analogues of formic acid, [HC(X)YH;



SCHEME 124



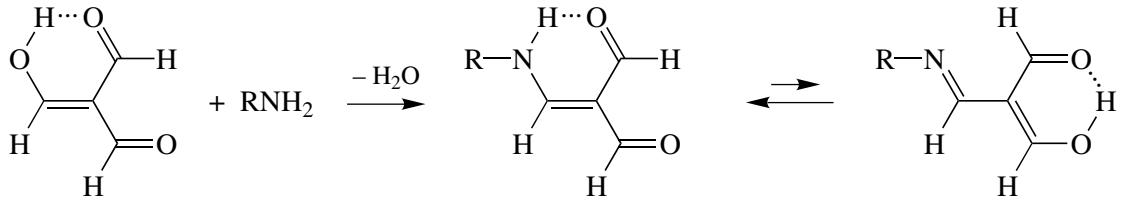
SCHEME 125

X,Y=O,S,Se,Te], has been undertaken.[628] The stabilities of different tautomeric forms of 4-hydroxycoumarins have been evaluated[629] by MNDO calculations, and the four lowest-energy oxo–hydroxy tautomers of 5-fluorouracil have been studied[630] using density functional methods. Semiempirical calculations have been carried out on the keto–enol tautomerism of triazolopyrimidines.[631] A base-catalysed keto–enol tautomerism has been proposed[632] to be responsible for the observed deuterium exchange of the hydrogens at the 3-position of diazepam when the molecule is treated with alkaline deuteriated methanol.

AM1 semiempirical calculations have shown[633] that, as far as tautomerism is concerned, there is a structural relationship between *β*-dicarbonyl compounds and NH-pyrazoles, and in a wide variety of NH-pyrazoles studied[634] the most stable tautomer was found to be that having the largest single-bond character between the C(3)−C(4) bond. The problem of proton transfer in NH-pyrazole crystals has been subjected to a detailed theoretical study,[635] while a study of the tautomerism of 2-aryl and 2-heteroaryl derivatives of benzimidazole has indicated[636] that tautomerism takes place by the intermolecular relay of protons between stacked molecules. The first report of the stable co-existence of two different histidine tautomers in one peptide crystal structure has appeared.[637] *Ab initio* calculations have been used to study the tautomerism of both histamine[638] and pyrazolo[3,4-*d*]pyridazine[639] in the gas phase and in aqueous solution, and a theoretical study of the NH tautomerism in free-base porphyrin has been undertaken.[640]

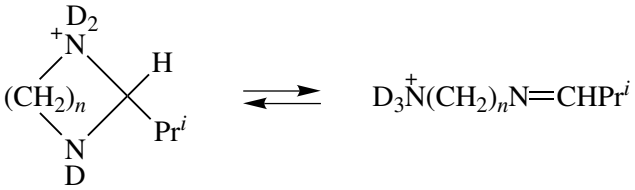
The *N*-acylimine–enamide tautomerism of methyl 2-acetamidoacrylate has been studied[641] by means of *ab initio* calculations. A ^{13}C NMR investigation has been undertaken to study the tautomerism between the hydrazone imine and diazenylenamine forms of 3-(arylhydrazono)methyl-2-oxo-1,2-dihydroquinoxalines,[642] and the effects of temperature and side-chain on the imine–enamine tautomerism in quinoxalinone and pyridopyrazinone systems have been studied.[643] A detailed

theoretical study[644] of the tautomerism of neutral 9-acridinamine in gaseous and condensed media failed to conclude definitively in which tautomeric form the molecule exists. Treatment of several heteroaromatic amines with triformylmethane (**475**) afforded 1 : 1 condensation products which have been assigned[645] as *N*-substituted aminomethylenemalonaldehydes, strongly preferring the amino–keto form (**476**) over the imino–enol tautomer (**477**). With cytosine, unequivocal evidence for ring–chain tautomerism was additionally obtained.



(**475**) (**476**) (**477**)

Rate constants and activation parameters for ring–chain tautomerism in five-, six- and seven-membered ring 1,3-dinitrogen heterocycles (**478**) have been calculated,[646] and σ^+



(**478**)

$n = 2, 3, 4$

values for a number of heteroaryl-substituted phenyl groups have been estimated[647] via the ring–chain tautomeric equilibria of oxazolidines and 1,3-oxazines in deuteriochloroform solution. A study of the tautomerism of 1,2-diaminoethyl and 1,3-diaminopropyl derivatives of aldoses has shown that in some cases ring–chain interconversion between pyranose and piperimidine tautomers can take place.[648] Finally, it has been reported that the ring–chain tautomerism of the Schiff bases of (*l*)-*p*-nitrophenylserinol can be accurately depicted as at least one distinct nucleophilic equilibrium involving largely the secondary hydroxyl group.[649]

References

[1] Trehan, I. R., Brar, J. S., Arora, A. K., and Kad, G. L., *J. Chem. Educ.*, **74**, 324 (1997).
[2] Jayat, F., Picot, M. J. S., and Guisnet, M., *Catal. Lett.*, **41**, 181 (1996).
[3] Sasidharan, M. and Kumar, R., *Stud. Surf. Sci. Catal.*, **105**, 1197 (1997).
[4] Venkatachalapathy, C. and Pitchumani, K., *Tetrahedron*, **53**, 17171 (1997).
[5] Kobayashi, S., Moriwaki, M., and Hachiya, I., *Bull. Chem. Soc. Jpn*, **70**, 267 (1997).
[6] Kalinin, A. V., Miah, M. A. J., Chattopadhyay, S., Tsukazaki, M., Wicki, M., Nguen, T., Coelho, A. L., Kerr, M., and Snieckus, V., *Synlett*, **1997**, 839.
[7] Masson, S., Saint-Clair, J.-F., Dore, A., and Saquet, M., *Bull. Soc. Chim. Fr.*, **133**, 951 (1996).

[8] Jiménez, M. C., Miranda, M. A., Scaiano, J. C., and Tormos, R., *J. Chem. Soc., Chem. Commun.*, **1997**, 1487.
[9] MacKnight, E. and McClelland, R. A., *Can. J. Chem.*, **74**, 2518 (1996).
[10] Harrowven, D. C. and Dainty, R. F., *Tetrahedron*, **53**, 15771 (1997).
[11] Bodajla, M., Jones, G. R., and Ramsden, C. A., *Tetrahedron Lett.*, **38**, 2573 (1997).
[12] Fukuzawa, S., Tsuchimoto, T., and Hiyama, T., *J. Org. Chem.*, **62**, 151 (1997).
[13] Eberson, L., Hartshorn, M. P., and Timmerman-Vaughan, D. J., *Acta Chem. Scand.*, **50**, 1121 (1996).
[14] Wada, M., Wei, W., Kirishima, K., Natsume, S., and Erabi, T., *Bull. Chem. Soc. Jpn*, **70**, 1413 (1997).
[15] Carlini, R., Higgs, K., Taylor, N., and Rodrigo, R., *Can. J. Chem.*, **75**, 805 (1997).
[16] Kuo, G. H. and Eissenstat, M. A., *Tetrahedron Lett.*, **38**, 3343 (1997).
[17] Kita, Y., Takeda, Y., Matsugi, M., Ioi, K., Gotanda, K., Murata, K., and Akai, S., *Angew. Chem., Int. Ed. Engl.*, **36**, 1529 (1997).
[18] Nagumo, S., Furukawa, T., Ono, M., and Akita, H., *Tetrahedron Lett.*, **38**, 2849 (1997).
[19] Kim, C. K., Lee, J. K., Park, H. Y., and Lee, I., *Bull. Korean Chem. Soc.*, **18**, 657 (1997).
[20] Kloetstra, K. R., van den Broek, J., and van Bekkum, H., *Catal. Lett.*, **47**, 235 (1997).
[21] Klumpp, D. A., Baek, D. N., Prakash, G. K. S., and Olah, G. A., *J. Org. Chem.*, **62**, 6666 (1997).
[22] Dhavale, D. D., Mali, V. P., Sudrik, S. G., and Sonawane, H. R., *Tetrahedron*, **53**, 16789 (1997).
[23] Schmittel, M. and Langels, A., *Angew. Chem., Int. Ed. Engl.*, **36**, 392 (1997).
[24] Braddock, C. D., Tucker, S. C., and Brown, J. M., *Bull. Soc. Chim. Fr.*, **134**, 399 (1997).
[25] Hollenstein, S. and Laali, K. K., *J. Chem. Soc., Chem. Commun.*, **1997**, 2145.
[26] Rao, V. J., Prevost, N., Ramamurthy, V., Kojima, M., and Johnston, L. J., *J. Chem. Soc., Chem. Commun.*, **1997**, 2209.
[27] Criss, D. L., Ingram, L. L., Schultz, T. P., Fisher, T. H., and Saebo, D. B., *J. Org. Chem.*, **62**, 7885 (1997).
[28] Weidner, J. J., Weintraub, P. M., Schnettler, R. A., and Peet, N. P., *Tetrahedron*, **53**, 6303 (1997).
[29] Anelli, P. L., Brocchetta, M., Calabi, L., Secchi, C., Uggeri, F., and Verona, S., *Tetrahedron*, **53**, 11919 (1997).
[30] Yatsimirsky, A. K. and Bezsoudnova, K. Y., *Izv. Akad. Nauk, Ser. Khim.*, **1996**, 2658.
[31] Yatsimirsky, A. K. and Bezsoudnova, K. Y., *Russ. Chem. Bull.*, **45**, 2517 (1996).
[32] Bezsoudnova, K. Y. and Yatsimirsky, A. K., *React. Kinet. Catal. Lett.*, **62**, 63 (1997).
[33] Siskos, M. G., Tzerpos, N. I., and Zarkadis, A. K., *Bull. Soc. Chim. Belg.*, **105**, 759 (1996).
[34] Kannan, P., Pitchumani, K., Rajagopal, S., and Srinivasan, C., *J. Mol. Catal.*, **118A**, 189 (1997).
[35] Hwu, J. R., Yau, C. S., Tsay, S.-C., and Ho, T.-I., *Tetrahedron Lett.*, **38**, 9001 (1997).
[36] Basch, H. and Hoz, T., *Mol. Phys.*, **91**, 789 (1997).
[37] Pitchumani, K., Venkatachalapathy, C., and Sivasubramanian, S., *Indian J. Chem.*, **36B**, 187 (1997).
[38] Park, K. H. and Kang, J. S., *J. Org. Chem.*, **62**, 3794 (1997).
[39] Carvalho, M. T. V. L., Lobo, A. M., Branco, P. S., and Prabhakar, S., *Tetrahedron Lett.*, **38**, 3115 (1997).
[40] Ramsden, C. A. and Rose, H. L., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2319.
[41] Sepiol, J. J. and Wilamowski, J., *Chem. Listy*, **91**, 671 (1997).
[42] Atalla, A. A., El-Dean, A. M. K., and Gaber, A. M., *Phosphorus Sulfur Silicon Relat. Elem.*, **117**, 205 (1996).
[43] Gritsan, N. P., Yuzawa, T., and Platz, M. S., *J. Am. Chem. Soc.*, **119**, 5059 (1997).
[44] Karney, W. L. and Borden, W. T., *J. Am. Chem. Soc.*, **119**, 3347 (1997).
[45] Tomioka, H. and Taketsuji, K., *J. Chem. Soc., Chem. Commun.*, **1997**, 1745.
[46] Moss, R. A., Maksimovic, L., and Merrer, D. C., *Tetrahedron Lett.*, **38**, 7049 (1997).
[47] Madden, L. K., Mebel, A. M., Lin, M. C., and Melius, C. F., *J. Phys. Org. Chem.*, **9**, 801 (1996).
[48] Muller, M., Iyer, V. S., Kubel, C., Enkelmann, V., and Mullen, K., *Angew. Chem., Int. Ed. Engl.*, **36**, 1607 (1997).
[49] Sarobe, M., Jenneskens, L. W., Wesseling, J., and Wiersum, U. E., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 703.
[50] Sarobe, M., Jenneskens, L. W., and Wiersum, U. E., *Tetrahedron Lett.*, **38**, 4689 (1997).
[51] Sarobe, M. and Jenneskens, L. W., *J. Org. Chem.*, **62**, 8247 (1997).
[52] Sarobe, M., Jenneskens, L. W., Kleij, A., and Petroutsa, M., *Tetrahedron Lett.*, **38**, 7255 (1997).
[53] Sarobe, M., Jenneskens, L. W., Wesseling, J., Snoeijer, J. D., Zwikker, J. W., and Wiersum, U. E., *Liebigs Ann. Chem.*, **1997**, 1207.
[54] Matzger, A. J. and Vollhardt, K. P. C., *J. Chem. Soc., Chem. Commun.*, **1997**, 1415.
[55] Keller, F., Beckhaus, H. D., and Ruchardt, C., *Liebigs Ann. Chem.*, **1997**, 2055.
[56] Okuyama, M., Ohkita, M., and Tsuji, T., *J. Chem. Soc., Chem. Commun.*, **1997**, 1277.
[57] van Eis, M. J., de Kanter, F. J. J., de Wolf, W. H., and Bickelhaupt, F., *J. Org. Chem.*, **62**, 7090 (1997).
[58] Barton, D. H. R. and Liu, T., *J. Chem. Soc., Chem. Commun.*, **1997**, 571.
[59] Albers, R. and Sander, W., *Liebigs Ann. Chem.*, **1997**, 897.

[60] Bowden, K. and Ranson, R. J., *J. Phys. Org. Chem.*, **10**, 191 (1997).
[61] Duan, X.-L., Perrins, R., and Rees, C. W., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1617.
[62] Rees, C. W. and Yue, T.-L., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2247.
[63] Duan, X.-L., Rees, C. W., and Yue, T.-Y., *J. Chem. Soc., Chem. Commun.*, **1997**, 367.
[64] Duan, X.-G. and Rees, C. W., *J. Chem. Soc., Chem. Commun.*, **1997**, 1493.
[65] Laskin, A. and Lifshitz, A., *J. Phys. Chem. A*, **101**, 7787 (1997).
[66] Kowalski, P. and Mokrosz, J. L., *Bull. Soc. Chim. Belg.*, **106**, 147 (1997).
[67] Palluotto, F., Delle-Monache, G., Casini, G., and Campagna, F., *Heterocycles*, **45**, 1337 (1997).
[68] Brown, R. F. C., Choi, N., Coulston, K. J., Eastwood, F. W., Ercole, F., Horvath, J. M., Matlinson, M., Mulder, R. J., and Ooi, H. C., *Liebigs Ann. Chem.*, **1997**, 1931.
[69] Gillard, A. C., Fabis, F., Jolivet-Fouchet, S., and Rault, S., *Tetrahedron Lett.*, **38**, 2271 (1997).
[70] Spinelli, D., Zanirato, P., Di Miceli, E., Lamartina, L., and Guerrera, F., *J. Org. Chem.*, **62**, 4921 (1997).
[71] Bhatti, I. A., Busby, R. E., bin Mohamed, M., Parrick, J., and Shaw, C. J. G., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 3581.
[72] Llempen, C. and Humberto, C., *Bol. Soc. Quim. Peru*, **62**, 99 (1996); *Chem. Abs.*, **125**, 328602 (1997).
[73] Nechepurenko, I. V., Petrenko, O. P., Grigorev, I. A., and Volodarskii, L. V., *Zh. Org. Khim.*, **33**, 767 (1997).
[74] Wan, Z. and Snyder, J. K., *Tetrahedron Lett.*, **38**, 7495 (1997).
[75] Neipp, C. E., Ranslow, P. B., Wan, Z., and Snyder, J. K., *Tetrahedron Lett.*, **38**, 7499 (1997).
[76] Burnett, F. N. and Hosmane, R. S., *Heterocycles*, **45**, 857 (1997).
[77] Arnold, W., Buttelmann, B., Heitz, M. P., and Wyler, R., *Heterocycles*, **43**, 2607 (1996).
[78] Andreani, A., Billi, R., Cosimelli, B., Mugnoli, A., Rambaldi, M., and Spinelli, D., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2407.
[79] Auricchio, S., Bini, A., Pastormerlo, E., and Truscello, A. M., *Tetrahedron*, **53**, 10911 (1997).
[80] Al Dulayymi, A. R., Baird, M. S., and Clegg, W., *Tetrahedron Lett.*, **38**, 8271 (1997).
[81] Huisgen, R., Giera, H., and Polborn, K., *Liebigs Ann. Chem.*, **1997**, 1691.
[82] Chande, M. S. and Joshi, R. M., *Indian J. Chem.*, **36B**, 403 (1997).
[83] Armesto, D., Rodríguez-Morgade, S., Oritz, M. J., Vázquez, P., and Torres, T., *Tetrahedron*, **53**, 3363 (1997).
[84] Zhao, B.-X. and Eguchi, S., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2973.
[85] Fisyuk, A. S. and Vorontsova, M. A., *Khim. Geterotsikl. Soedin.*, **1997**, 979.
[86] Abu-El-Halawa, R., Wirschun, W., Moustafa, A. H., and Jochims, J. C., *J. Prakt. Chem.*, **338**, 598 (1996).
[87] McGibbon, G. A., Hrusak, J., Lavorato, D. J., Schwarz, H., and Terlouw, J. K., *Chemistry*, **3**, 232 (1997).
[88] Argilagos, D. M., Trimino, M. I. G., Caprera, A. M., Linden, A., and Heimgartner, H., *Helv. Chim. Acta*, **80**, 273 (1997).
[89] Zhdankin, V. V., Arbit, R. M., McSherry, M., Mismash, B., and Young, V. G., *J. Am. Chem. Soc.*, **119**, 7408 (1997).
[90] Semenov, V. P., *Zh. Org. Khim.*, **33**, 1627 (1996).
[91] Butler, R. N. and Grogan, D. C., *J. Chem. Res. (S)*, **1997**, 428.
[92] Soos, T., Hajos, G., and Messmer, A., *J. Org. Chem.*, **62**, 1136 (1997).
[93] Butler, R. N., McKenna, E. C., and Grogan, D. C., *J. Chem. Soc., Chem. Commun.*, **1997**, 2149.
[94] Aitken, R. A., Fairhurst, I. M., Ford, A., Milne, P. E. Y., Russell, D. W., and Whittaker, M., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 3107.
[95] Butler, R. N., McKenna, E. C., McMahon, J. M., Daly, K. M., Cunningham, D., and McArdle, P., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2919.
[96] Vivona, N., Buscemi, S., Asta, S., and Caronna, T., *Tetrahedron*, **53**, 12629 (1997).
[97] L'Abbé, G., D'hooge, B., and Dehaen, W., *Molecules*, **1**, 190 (1996); *Chem. Abs.*, **127**, 34153 (1997).
[98] Daszkiewicz, Z., Domanski, A., and Kyziol, J. B., *Chem. Zvesti*, **51**, 22 (1997); *Chem. Abs.*, **126**, 317310 (1997).
[99] Bubnov, Y. N., Klimkina, E. V., Ignatenko, A. V., and Gridnev, I. D., *Tetrahedron Lett.*, **38**, 4631 (1997).
[100] Ibrahim, E. S. I., *Heterocycl. Commun.*, **3**, 29 (1997).
[101] Boryczka, S. and Maslankiewicz, A., *Pol. J. Chem.*, **71**, 519 (1997).
[102] Yu, H., Kwon, H. J., and Jang, D. J., *Bull. Korean Chem. Soc.*, **18**, 156 (1997).
[103] Werstuik, N. H., Ma, J., Roy, C. D., Kresge, A. J., and Jefferson, E. A., *Can. J. Chem.*, **74**, 2536 (1996).
[104] Jefferson, E. A., Kresge, A. J., and Paine, S. W., *Can. J. Chem.*, **75**, 56 (1997).
[105] Dürr, U., Heinemann, F. W., and Kisch, H., *J. Organomet. Chem.*, **541**, 307 (1997).
[106] Szabó, A., Csámpai, A., Körmendy, K., and Böcskei, Z., *Tetrahedron*, **53**, 7021 (1997).
[107] Itaya, T., Takada, Y., Kanai, T., and Fujii, T., *Chem. Pharm. Bull.*, **44**, 2318 (1996).
[108] Itaya, T., Ito, N., Kanai, T., and Fujii, T., *Chem. Pharm. Bull.*, **45**, 832 (1997).
[109] Mah, H., Nam, K. D., and Hahn, H. G., *Bull. Korean Chem. Soc.*, **18**, 563 (1997).

[110] Yamada, J., Hamasaki, M., Jinih, O., Tanaka, S., Haguja, K., and Anzai, H., *Tetrahedron Lett.*, **38**, 3439 (1997).
[111] Duan, X.-G., Duan, X.-L., Rees, C. W., and Yue, T.-Y., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2597.
[112] Satake, K., Takaoka, K., Hashimoto, M., Okamoto, H., Kimura, M., and Morosawa, S., *Chem. Lett.*, **1996**, 1129.
[113] Pan, Y., Cai, Z., Song, H., and Zhao, X., *Huaxue Wuli Xuebao*, **9**, 401 (1996); *Chem. Abs.*, **126**, 171143 (1997).
[114] Gajewski, J. J., *Acc. Chem. Res.*, **30**, 219 (1997).
[115] Yoo, H. Y. and Houk, K. N., *J. Am. Chem. Soc.*, **119**, 2877 (1997).
[116] Aviyente, V., Yoo, H. Y., and Houk, K. N., *J. Org. Chem.*, **62**, 6121 (1997).
[117] Guest, J. M., Craw, J. S., Vincent, M. A., and Hillier, I. H., *J. Chem. Soc., Chem. Commun.*, **1997**, 71.
[118] Davidson, M. M., Guest, J. M., Craw, J. S., Hillier, I. H., and Vincent, M. A., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1395.
[119] Sattelkau, T., Hollmann, C., and Eilbracht, P., *Synlett*, **1996**, 1221.
[120] Lavoisier-Gallo, T., Charonnet, E., and Rodriguez, J., *Synthesis*, **1997**, 1258.
[121] Sanchez, A. M., Veglia, A. V., and de Rossi, R. H., *Can. J. Chem.*, **75**, 1151 (1997).
[122] Hayashi, T., Okada, Y., Arita, K., and Kuromizu, H., *Nippon Kagaku Kaishi*, **1997**, 255.
[123] Ito, H., Sato, A., and Taguchi, T., *Tetrahedron Lett.*, **38**, 4815 (1997).
[124] Bernard, A. M. and Piras, P. P., *Synlett*, **1997**, 585.
[125] Novak, L., Kovacs, P., Kolonits, P., Hanania, M., Fekete, J., Szabo, E., and Szantay, C., *Synthesis*, **1997**, 909.
[126] Novak, L., Kovacs, P., Pirok, G., Kolonits, P., Hanania, M., Donath, K., and Szantay, C., *Tetrahedron*, **53**, 9789 (1997).
[127] Hiratani, K., Uzawa, H., Kasuga, K., and Kambayashi, H., *Tetrahedron Lett.*, **38**, 8993 (1997).
[128] Lajunen, M., Laine, R., and Aaltonen, M., *Acta Chem. Scand.*, **51**, 1155 (1997).
[129] Barluenga, J., Sanz, R., and Fananas, F. J., *Tetrahedron Lett.*, **38**, 6103 (1997).
[130] Cambie, R. C., Milbank, J. B. J., and Rutledge, P. S., *Org. Prep. Proced. Int.*, **29**, 365 (1997); *Chem. Abs.*, **127**, 176211 (1997).
[131] Harrington-Frost, N. M., Milbank, J. B. J., and Rutledge, P. S., *Aust. J. Chem.*, **50**, 379 (1997).
[132] Majumdar, K. C., Jana, G. H., Ghosh, S. K., and Saha, S., *Monatsh. Chem.*, **128**, 641 (1997).
[133] Majumdar, K. C. and Kundu, A. K., *Heterocycles*, **45**, 1467 (1997).
[134] Majumdar, K. C. and Das, U., *J. Chem. Res. (S)*, **1997**, 309.
[135] Daub, G. W., Edwards, J. P., Okada, C. R., Allen, J. W., Maxey, C. T., Wells, M. S., Goldstein, A. S., Dibley, M. J., Wang, C. J., Ostercamp, D. P., Chung, S., Cunningham, P. S., and Berliner, M. A., *J. Org. Chem.*, **62**, 1976 (1997).
[136] Brenna, E., Caraccia, N., Fuganti, C., Fuganti, D., and Grasselli, P., *Tetrahedron: Asymmetry*, **8**, 3801 (1997).
[137] Kazmaier, U. and Gorbitz, C. H., *Synthesis*, **1996**, 1489.
[138] Kazmaier, U., *Amino Acids*, **11**, 283 (1996).
[139] Kazmaier, U., *Liebigs Ann. Chem.*, **1997**, 285.
[140] Gonzalez, D., Schapiro, V., Seoane, G., Hudlicky, T., and Abboud, K., *J. Org. Chem.*, **62**, 1194 (1997).
[141] Mulzer, J., Bates, J. W., List, B., Opatz, T., and Trauner, D., *Synlett*, **1997**, 441.
[142] Kuehne, M. E. and Xu, F., *J. Org. Chem.*, **62**, 7950 (1997).
[143] Hull, H. M. and Knight, D. W., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 857.
[144] Knight, D. W., Share, A. C., and Gallagher, P. T., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2089.
[145] Konno, T., Umetani, H., and Kitazume, T., *J. Org. Chem.*, **62**, 137 (1997).
[146] Konno, T. and Kitazume, T., *Tetrahedron: Asymmetry*, **8**, 223 (1997).
[147] Hodgson, D. M. and Gibbs, A. R., *Synlett*, **1997**, 657.
[148] Roush, W. R. and Works, A. B., *Tetrahedron Lett.*, **38**, 351 (1997).
[149] Roush, W. R. and Barda, D. A., *Tetrahedron Lett.*, **38**, 8785 (1997).
[150] Boeckmam, R. K. and Reeder, M. R., *J. Org. Chem.*, **62**, 6456 (1997).
[151] Broadhurst, M. J., Percy, J. M., and Prime, M. E., *Tetrahedron Lett.*, **38**, 5903 (1997).
[152] Becker, M. and Krause, N., *Liebigs Ann. Chem.*, **1997**, 725.
[153] Cristiano, M. L. S. and Johnstone, R. A. W., *J. Chem. Res. (S)*, **1997**, 164.
[154] Cristiano, M. L. S. and Johnstone, R. A. W., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 489.
[155] Imogai, H., Petit, Y., and Larcheveque, M., *Synlett*, **1997**, 615.
[156] Ammenn, J., Altmann, K. H., and Bellus, D., *Helv. Chim. Acta*, **80**, 1589 (1997).
[157] Calter, M., Hollis, T. K., Overman, L. E., Ziller, J., and Zipp, G. G., *J. Org. Chem.*, **62**, 1449 (1997).
[158] Overman, L. E. and Zipp, G. G., *J. Org. Chem.*, **62**, 2288 (1997).
[159] Hollis, T. K. and Overman, L. E., *Tetrahedron Lett.*, **38**, 8837 (1997).

[160] Metz, P. and Hungerhoff, B., *J. Org. Chem.*, **62**, 4442 (1997).
[161] Lindström, U. M. and Somfai, P., *J. Am. Chem. Soc.*, **119**, 8385 (1997).
[162] Lobo, A. M. and Prabhakar, S., *Pure Appl. Chem.*, **69**, 547 (1997).
[163] Fujii, H., Mizusuna, A., Tanimura, R., and Nagase, H., *Heterocycles*, **45**, 2109 (1997).
[164] Endo, Y., Uchida, T., and Shudo, K., *Tetrahedron Lett.*, **38**, 2113 (1997).
[165] Padwa, A. and Sa, M. M., *Tetrahedron Lett.*, **38**, 5087 (1997).
[166] Banert, K., *Liebigs Ann. Chem.*, **1997**, 2005.
[167] Ichikawa, Y., *J. Synth. Org. Chem. Jpn*, **55**, 281 (1997).
[168] Ichikawa, Y., Osada, M., Ohtani, I. I., and Isobe, M., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1449.
[169] Kotani, M., Shigetomi, Y., Imada, M., Oki, M., and Nagaoka, M., *Heteroatom Chem.*, **8**, 35 (1997).
[170] Martinkova, M. and Gonda, J., *Tetrahedron Lett.*, **38**, 875 (1997).
[171] Gonda, J. and Bednarikova, M., *Tetrahedron Lett.*, **38**, 5569 (1997).
[172] Nesterov, V. N., Rodinovskaya, L. A., Shestopalov, A. M., and Struchkov, Y. T., *Khim. Geterotsikl. Soedin.*, **1997**, 643.
[173] Ernst, B., Gonda, J., Jeschke, R., Nubbemeyer, U., Dehrlein, R., and Bellus, D., *Helv. Chim. Acta*, **80**, 876 (1997).
[174] Beslin, P. and Lelong, B., *Tetrahedron*, **53**, 17253 (1997).
[175] Alayrac, C., Fromont, C., Metzner, P., and Anh, N. T., *Angew. Chem., Int. Ed. Engl.*, **36**, 371 (1997).
[176] Sreekumar, R. and Padmakumar, R., *Tetrahedron Lett.*, **38**, 2413 (1997).
[177] Harusawa, S. and Kurihara, T., *Rev. Heteroat. Chem.*, **16**, 137 (1997).
[178] Chambers, M. S. and Thomas, E. J., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 417.
[179] Murai, T., Takada, H., Kakami, K., Fujii, M., Maeda, M., and Kato, S., *Tetrahedron*, **53**, 12237 (1997).
[180] Suzuki, K., Imai, T., Yamanvi, S., Chino, M., and Matsumoto, T. *Angew. Chem., Int. Ed. Engl.*, **36**, 2469 (1997).
[181] Paquette, L. A., *Tetrahedron*, **53**, 13971 (1997).
[182] Greeves, N. and Lee, W. M., *Tetrahedron Lett.*, **38**, 6445 (1997).
[183] Greeves, N. and Lee, W. M., *Tetrahedron Lett.*, **38**, 6449 (1997).
[184] Greeves, N., Lee, W. M., and Barkley, J. V., *Tetrahedron Lett.*, **38**, 6453 (1997).
[185] Schneider, C., *Synlett*, **1997**, 815.
[186] Morwick, T. M. and Paquette, L. A., *J. Org. Chem.*, **62**, 627 (1997).
[187] Shanmugam, P., Devan, B., Srinivasan, R., and Rajagopalan, K., *Tetrahedron*, **53**, 12637 (1997).
[188] Chu, Y. L., Colclough, D., Hotchkin, D., Tuazon, M., and White, J. B., *Tetrahedron*, **53**, 14235 (1997).
[189] Zheng, H., Wang, Y., Cai, Z., and Ling, Y., *Hecheng Huaxue*, **4**, 358 (1996); *Chem. Abs.*, **127**, 33885 (1997).
[190] Nicolaou, K. C., Postema, M. H. D., Miller, N. D., and Yang, Z., *Angew. Chem., Int. Ed. Engl.*, **36**, 2821 (1997).
[191] Pohnert, G. and Boland, W., *Tetrahedron*, **53**, 13681 (1997).
[192] Snapper, M. L., Tallarico, J. A., and Randall, M. L., *J. Am. Chem. Soc.*, **119**, 1478 (1997).
[193] Baumann, H. and Voellinger-Borel, A., *Helv. Chim. Acta*, **80**, 2112, (1997).
[194] Ikeda, H., Ishida, A., Takasaki, T., Tojo, S., Takamuku, S., and Miyashi, T., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 849.
[195] Schneider, C. and Rehfeuter, M., *Tetrahedron*, **53**, 133 (1997).
[196] Grimme, W. and Krauthauser, S., *Tetrahedron*, **53**, 9903 (1997).
[197] Noh, T. and Kim, D., *Tetrahedron Lett.*, **37**, 9329 (1996).
[198] Beck, K., Hoffman, P., and Hunig, S., *Chemistry*, **3**, 1588 (1997).
[199] Minkin, V. I., Minyaev, R. M., and Dorogan, I. V., *THEOCHEM*, **398**, 237 (1997).
[200] Winter, R. F. and Hornung, F. M., *Organometallics*, **16**, 4248 (1997).
[201] Vachet, R. W., Bishop, B. M., Erickson, B. W., and Glish, G. L., *J. Am. Chem. Soc.*, **119**, 5481 (1997).
[202] Allin, S. M., Button, M. A. C., and Shuttleworth, S. J., *Synlett*, **1997**, 725.
[203] Overman, L. E. and Trenkle, W. C., *Isr. J. Chem.*, **37**, 23 (1997).
[204] Li, A. H., Dai, L. X., and Aggarwal, V. K., *Chem. Rev.*, **97**, 2341 (1997).
[205] Nakai, T. and Tomooka, K., *Pure Appl. Chem.*, **69**, 595 (1997).
[206] Okajima, T. and Fukazawa, Y., *Chem. Lett.*, **1997**, 81.
[207] Okajima, T., *Nippon Kagaku Kaishi*, **1997**, 529.
[208] Kress, M. H., Yang, C. H., Yasuda, N., and Grabowski, E. J. J., *Tetrahedron Lett.*, **38**, 2633 (1997).
[209] Enders, D., Bartsch, M., Backhaus, D., Runsink, J., and Raabe, G., *Synthesis*, **1996**, 1438.
[210] Manabe, S., *J. Chem. Soc., Chem. Commun.*, **1997**, 737.
[211] Tomooka, K., Komine, N., and Nakai, T., *Synlett*, **1997**, 1045.
[212] Vogel, C., *Synthesis*, **1997**, 497.
[213] Anderson, J. C., Smith, S. C., and Swarbrick, M. E., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1517.

[214] Manabe, S., *Tetrahedron Lett.*, **38**, 2491 (1997).
[215] Somfai, P., Jarevang, T., Lindstrom, U. M., and Svensson, A., *Acta Chem. Scand.*, **51**, 1024 (1997).
[216] Audrain, H., Riche, C., Chiaroni, A., and Grierson, D. S., *Bull. Soc. Chim. Fr.*, **133**, 987 (1996).
[217] Kawachi, A., Doi, N., and Tamao, K., *J. Am. Chem. Soc.*, **119**, 233 (1997).
[218] Bonini, B. F., Franchini, M. C., Mazzanti, G., Slief, J. W., Wegman, M. A., and Zwanenburg, B., *J. Chem. Soc., Chem. Commun.*, **1997**, 1011.
[219] Pierson, N., Fernandez-Garcia, C., and McKervey, M. A., *Tetrahedron Lett.*, **38**, 4705 (1997).
[220] Doyle, M. P. and Peterson, C. S., *Tetrahedron Lett.*, **38**, 5265 (1997).
[221] Zhang, C., Maeda, Y., Shirai, N., and Sato, Y., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 25.
[222] Narita, K., Shirai, N., and Sato, Y., *J. Org. Chem.*, **62**, 2544 (1997).
[223] Hyett, D. J., Sweeney, J. B., Tavassoli, A., and Hayes, J. F., *Tetrahedron Lett.*, **38**, 8283 (1997).
[224] Coldham, I., Middleton, M. L., and Taylor, P. L., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2951.
[225] Jonczyk, A., Zdrojewski, T., Grzywacz, P., and Balcerzak, P., *J. Chem. Soc., Perkin Trans. 1*, **1996**, 2919.
[226] Kawanishi, N., Fujiwara, K., Shirai, N., Sato, Y., Hatano, K., and Kurono, Y., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 3013.
[227] Kitano, T., Shirai, N., and Sato, Y., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 715.
[228] Fukuda, T. and Katsuki, T., *Tetrahedron Lett.*, **38**, 3435 (1997).
[229] Makomo, H., Saquet, M., Simeon, F., Masson, S., About-Jaudet, E., Collignon, N., and Gulea-Purcarescu, M., *Phosphorus Sulfur Silicon Relat. Elem.*, **1996**, 109.
[230] Majumdar, K. C., Biswas, P., and Jana, G. H., *J. Chem. Res. (S)*, **1997**, 310.
[231] Buston, J. E. H., Coldham, I., and Mulholland, K. R., *Synlett*, **1997**, 322.
[232] Majumdar, K. C. and Jana, G. H., *J. Org. Chem.*, **62**, 1506 (1997).
[233] Back, T. G. and Minksztym, K., *J. Chem. Soc., Chem. Commun.*, **1997**, 1759.
[234] Kurose, N., Takahashi, T., and Koizumi, T., *J. Org. Chem.*, **62**, 4562 (1997).
[235] Kurose, N., Takahashi, T., and Koizumi, T., *Tetrahedron*, **53**, 12115 (1997).
[236] Yamabe, T., Nakamura, K., Shiota, Y., Yoshizawa, K., Kawauchi, S., and Ishikawa, M., *J. Am. Chem. Soc.*, **119**, 807 (1997).
[237] Takahashi, M. and Kira, M., *J. Am. Chem. Soc.*, **119**, 1948 (1997).
[238] Gridnev, I. D., Gurskii, M. E., Krasavin, A. O., and Bubnov, Y. N., *Russ. Chem. Bull.*, **45**, 2127 (1996).
[239] Herberich, G. E., Rosenplanter, J., Schmidt, B., and Englert, U., *Organometallics*, **16**, 926 (1997).
[240] Oblin, M., Fotiadu, F., Rajzmann, M., and Pons, J.-H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1621.
[241] Driess, M., Rell, S., Pritzkow, H., and Janoschek, R., *Angew. Chem., Int. Ed. Engl.*, **36**, 1326 (1997).
[242] Leost, F., Chantegrel, B., and Deshayes, C., *Tetrahedron*, **53**, 7557 (1997).
[243] Bibas, H., Wong, M. W., and Wentrup, C., *Chemistry*, **3**, 237 (1997).
[244] Stéphane, B.-H., Gisie, H., Le Ny, J. P., and Osborn, J. A., *Angew. Chem., Int. Ed. Engl.*, **36**, 976 (1997).
[245] Mulzer, J., Wille, G., Bilow, J., Arigoni, D., Martinoni, B., and Roten, K., *Tetrahedron Lett.*, **38**, 5469 (1997).
[246] Seki, K., Kiyokawa, W., Hashimoto, H., Uyehara, T., Ueno, M., and Sato, T., *Chem. Lett.*, **1996**, 1035.
[247] Talamas, F. X., Smith, D. B., Cervantes, A., Franco, F., Cutler, S. T., Loughhead, D. G., Morgans, D. J., and Weikert, R. T., *Tetrahedron Lett.*, **38**, 4725 (1997).
[248] Buchert, M. and Reissig, H.-U., *Liebigs Ann. Chem.*, **1996**, 2007.
[249] Davidson, E. R. and Gajewski, J. J., *J. Am. Chem. Soc.*, **119**, 10543 (1997).
[250] Houk, K. N., Nendel, M., Wiest, O., and Storer, J. W., *J. Am. Chem. Soc.*, **119**, 10545 (1997).
[251] Lewis, D. K., Charney, D. J., Kalra, B. L., Plate, A.-M., Woodard, M. H., Cianciosi, S. J., and Baldwin, J. E., *J. Phys. Chem. A*, **101**, 4097 (1997).
[252] Maier, G. and Senger, S., *J. Am. Chem. Soc.*, **119**, 5857 (1997).
[253] Takeda, K., Sakurama, K., and Yoshii, E., *Tetrahedron Lett.*, **38**, 3257 (1997).
[254] Matikainen, J., Kaltia, S., Hamalainen, M., and Hase, T., *Tetrahedron*, **53**, 4531 (1997).
[255] Sigalov, M. and Rappoport, Z., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1911.
[256] Stradiotto, M., Rigby, S. S., Hughes, D. W., Brook, M. A., Bain, A. D., and McGlinchey, M. J., *Organometallics*, **15**, 5645 (1996).
[257] Rigby, S. S., Gupta, H. K., Werstiuk, N. H., Bain, A. D., and McGlinchey, M. J., *Inorg. Chim. Acta*, **251**, 355 (1996).
[258] Wu, P.-L., Chen, H.-C., and Line, M.-L., *J. Org. Chem.*, **62**, 1532 (1997).
[259] Perrin, S., Monnier, K., and Laude, B., *Bull. Soc. Chim. Belg.*, **105**, 777 (1996).
[260] Tietze, L. F. and Schulz, G., *Chemistry*, **3**, 523 (1997).
[261] Bakke, J. M. and Ranes, E., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1919.
[262] Hugel, G., Royer, D., Le Men Olivier, L., Richard, B., Jacquier, M. J., and Levy, J., *J. Org. Chem.*, **62**, 578 (1997).
[263] Heard, G. L. and Yates, B. F., *J. Comput. Chem.*, **17**, 1444 (1996).

[264] Karapetyan, V. E., Kocharyan, S. T., and Babayan, A. T., *Zh. Org. Khim.*, **32**, 1190 (1996).
[265] Maeda, Y. and Sato, Y., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1491.
[266] Morita, H., Kamiyama, H., Kyotani, M., Fujii, T., Yoshimura, T., Ono, S., and Shimasaki, C., *J. Chem. Soc., Chem. Commun.*, **1997**, 1347.
[267] Doyle, M. P., Ene, D. G., Forbes, D. C., and Tedrow, J. S., *Tetrahedron Lett.*, **38**, 4367 (1997).
[268] Oku, A., Murai, N., and Baird, J., *J. Org. Chem.*, **62**, 2123 (1997).
[269] Brogan, J. B., Zercher, C. K., Bauer, C. B., and Rogers, R. D., *J. Org. Chem.*, **62**, 3902 (1997).
[270] Mulzer, J., Hoyer, K., and Müller-Fahrnow, A., *Angew. Chem., Int. Ed. Engl.*, **36**, 1476 (1997).
[271] Kimura, Y., Yamamoto, M., Tobita, S., and Shizuka, H., *J. Phys. Chem. A*, **101**, 459 (1997).
[272] Zipse, H., *J. Am. Chem. Soc.*, **119**, 2889 (1997).
[273] Zimmerman, H. E. and Armesto, D., *Chem. Rev.*, **96**, 3065 (1996).
[274] Nevill, S. M., Pincock, A. L., and Pincock, J. A., *J. Org. Chem.*, **62**, 2680 (1997).
[275] Reguero, M., Bernardi, F., Olivucci, M., and Robb, M. A., *J. Org. Chem.*, **62**, 6897 (1997).
[276] Corbett, R. M., Lee, C. S., Sulikowski, M. M., Reibenspies, J., and Sulikowski, G. A., *Tetrahedron*, **53**, 11099 (1997).
[277] Srikrishna, A. and Danieldoss, S., *Synth. Commun.*, **27**, 655 (1997).
[278] Aitken, R. A., Boeters, C., and Morrison, J. J., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2625.
[279] Dushenko, G. A., Mikhailov, I. E., Zschunke, A., Hakam, N., Mugge, C., and Minkin, V. I., *Mendeleev Commun.*, **1997**, 50.
[280] Barluenga, J., Tomas, M., Bieger, K., Garcia-Granda, S., and Santiago-Garcia, R., *J. Organomet. Chem.*, **529**, 233 (1997).
[281] Erden, I., Xu, F. P., and Cao, W. G., *Angew. Chem., Int. Ed. Engl.*, **36**, 1516 (1997).
[282] Kim, D. S. H. L. and Freeman, F., *Tetrahedron Lett.*, **38**, 799 (1997).
[283] Nielsen, S. F., Olsen, C. E., and Christensen, S. B., *Tetrahedron*, **53**, 5573 (1997).
[284] Jacobi, P. A., Buddhu, S. C., Fry, D., and Rajeswari, S., *J. Org. Chem.*, **62**, 2894 (1997).
[285] Risitano, F., Grassi, G., Foti, F., and Filocamo, F., *Tetrahedron*, **53**, 1089 (1997).
[286] Horspool, W. M., *Photochemistry*, **27**, 80 (1996).
[287] Wiest, O. and Houk, K. N., *Top. Curr. Chem.*, **183**, 1 (1996).
[288] Wiest, O., Montiel, D. C., and Houk, K. N., *J. Phys. Chem. A*, **101**, 8378 (1997).
[289] He, G., *Huaxue Yanjiu Yu Yingyong*, **8**, 430 (1996); *Chem. Abs.*, **125**, 327773 (1997).
[290] Ponec, R., Yuzhakov, G., and Pecka, J., *J. Math. Chem.*, **19**, 265 (1996).
[291] Sorensen, T. S. and Sun, F., *Can. J. Chem.*, **75**, 1030 (1997).
[292] Patterson, E. V. and McMahon, R. J., *J. Org. Chem.*, **62**, 4398 (1997).
[293] Averin, A. D., Lukashev, N. V., Borisenko, A. A., Kazankova, M. A., and Beletskaya, I. P., *Zh. Org. Khim.*, **32**, 425 (1996).
[294] Smith, D. A. and Ulmer, C. W., *J. Org. Chem.*, **62**, 5110 (1997).
[295] Suzuki, T., Ohwada, T., and Shudo, K., *J. Am. Chem. Soc.*, **119**, 6774 (1997).
[296] de Lera, A. R., Rey, J. G., Hrovat, D., Iglesias, B., and López, S., *Tetrahedron Lett.*, **38**, 7425 (1997).
[297] Rigby, J. H. and Kirova-Snover, M., *Tetrahedron Lett.*, **38**, 8153 (1997).
[298] Drew, M. G. B., Fengler-Veith, M., Harwood, L. M., and Jahans, A. W., *Tetrahedron Lett.*, **38**, 4521 (1997).
[299] Honda, K., Osawa, E., Slanina, Z., and Matsumoto, T., *Fullerene Sci. Technol.*, **4**, 819 (1996).
[300] Li, Z. Z. and Shevlin, P. B., *J. Am. Chem. Soc.*, **119**, 1149 (1997).
[301] Nuchter, U., Zimmermann, G., Francke, V., and Hopf, H., *Liebigs Ann. Chem.*, **1997**, 1505.
[302] Hopf, H., Berger, H., Zimmermann, G., Nuchter, U., Jones, P. G., and Dix, I., *Angew. Chem., Int. Ed. Engl.*, **36**, 1187 (1997).
[303] Cunico, R. F. and Nair, S. K., *Tetrahedron Lett.*, **38**, 25 (1997).
[304] Oda, M., Kamata, Y., Nishii, S., Miyatake, R., Kuroda, S., and Oda, M., *Recl. Trav. Chim. Pays-Bas*, **115**, 445 (1996).
[305] de Lera, A. R. and Torrado, A., *Tetrahedron Lett.*, **38**, 7421 (1997).
[306] Avarvari, N., Le Floch, P., Charrier, C., and Mathey, F., *Heteroat. Chem.*, **7**, 397 (1996).
[307] Himbert, G. and Diehl, K., *Liebigs Ann. Chem.*, **1997**, 1255.
[308] Crisp, G. T. and Gebauer, M. G., *J. Org. Chem.*, **61**, 8425 (1996).
[309] Marchand, E. and Morel, G., *Bull. Soc. Chim. Fr.*, **134**, 623 (1997).
[310] Noguchi, M., *J. Synth. Org. Chem. Jpn*, **55**, 725 (1997).
[311] O'Shea, D. F. and Sharp, J. T., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 3025.
[312] Bolton, K., Hase, W. L., and Doubleday, C., *Ber. Bunsen-Ges. Phys. Chem.*, **101**, 414 (1997).
[313] Yamaguchi, S., Arisawa, A., Katoh, N., Hatanaka, K., Yokoyama, H., and Hirai, Y., *Bull. Chem. Soc. Jpn*, **70**, 2215 (1997).
[314] Feng, S. Y., Feng, D. C., and Deng, C. H., *Acta Chim. Sin.*, **55**, 747 (1997).

[315] Miesch, M., Mislin, G., and Franck-Neumann, M., *Tetrahedron Lett.*, **38**, 7551 (1997).
[316] Trahanovsky, W. S. and Arvidson, K. B., *J. Org. Chem.*, **61**, 9528 (1996).
[317] Anderson, K. K., Shultz, D. A., and Dougherty, D. A., *J. Org. Chem.*, **62**, 7575 (1997).
[318] Grobe, J., Le Van, D., Broschk, B., Hegemann, M., Luth, B., and Becker, G., *J. Organomet. Chem.*, **529**, 177 (1997).
[319] Cartwright, G. A., Gould, R. O., and McNab, H., *J. Chem. Soc., Chem. Commun.*, **1997**, 1293.
[320] Pranata, J., *Int. J. Quantum Chem.*, **62**, 509 (1997).
[321] Jenner, G., *New J. Chem.*, **21**, 1085 (1997).
[322] Deng, Q., Thomas, B. E., Houk, K. N., and Dowd, P., *J. Am. Chem. Soc.*, **119**, 6902 (1997).
[323] Cunningham, I. D., Brownhill, A., Hamerton, I., and Howlin, B. J., *Tetrahedron*, **53**, 13473 (1997).
[324] Sarkar, T. K., Ghorai, B. K., Nandy, S. K., Mukherjee, B., and Banerji, A., *J. Org. Chem.*, **62**, 6006 (1997).
[325] Bintz-Giudicelli, C. and Uguen, D., *Tetrahedron Lett.*, **38**, 2973 (1997).
[326] Cossy, J., Bouzide, A., and Pfau, M., *J. Org. Chem.*, **62**, 7106 (1997).
[327] Moustafa, A. H., Wirschun, W., Freyhardt, C. C., and Jochims, J. C., *J. Prakt. Chem.*, **339**, 615 (1997).
[328] Ofial, A. R. and Mayr, H., *Angew. Chem., Int. Ed. Engl.*, **36**, 143 (1997).
[329] Jin, J. and Weinreb, S. M., *J. Am. Chem. Soc.*, **119**, 5773 (1997).
[330] Monsees, A., Laschat, S., Kotila, S., Fox, T., and Wurthwein, E. U., *Liebigs Ann. Chem.*, **1997**, 533.
[331] Laschat, S. and Fox, T., *Synthesis*, **1997**, 475.
[332] Corey, E. J., Barnes-Seeman, D., Lee, T. W., and Goodman, S. N., *Tetrahedron Lett.*, **38**, 6513 (1997).
[333] Jezewski, A., Chajewska, K., Wielogorski, Z., and Jurczak, J., *Tetrahedron: Asymmetry*, **8**, 1741 (1997).
[334] Qian, C. T. and Huang, T. S., *Tetrahedron Lett.*, **38**, 6721 (1997).
[335] Tateiwa, J., Kimura, A., Takasuka, M., and Uemura, S., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2169.
[336] Marson, C. M. and Fallah, A., *Tetrahedron Lett.*, **38**, 9057 (1997).
[337] Ciufolini, M. A., Chen, M., Lovett, D. P., and Deaton, M. V., *Tetrahedron Lett.*, **38**, 4355 (1997).
[338] Chen, J. S., Houk, K. N., and Foote, C. S., *J. Am. Chem. Soc.*, **119**, 9852 (1997).
[339] Elemes, Y., Stratakis, M., and Orfanopoulos, M., *Tetrahedron Lett.*, **38**, 6437 (1997).
[340] Stratakis, M. and Orfanopoulos, M., *Tetrahedron Lett.*, **38**, 1067 (1997).
[341] Salamci, E., Seçen, H., Sütbeyaz, Y., and Balci, M., *J. Org. Chem.*, **62**, 2453 (1997).
[342] Mackewitz, T. W., Ullrich, D., Bergstrasser, U., Leininger, S., and Regitz, M., *Liebigs Ann. Chem.*, **1997**, 1827.
[343] Mackewitz, T. W., Peters, C., Bergstrasser, U., Leininger, S., and Regitz, M., *J. Org. Chem.*, **62**, 7605 (1997).
[344] Lorthiois, E., Marek, I., and Normant, J. F., *Tetrahedron Lett.*, **38**, 89 (1997).
[345] Lorthiois, E., Marek, I., and Normant, J. F., *Bull. Soc. Chim. Fr.*, **134**, 333 (1997).
[346] Oppolzer, W., Schroder, F., and Kahl, S., *Helv. Chim. Acta*, **80**, 2047 (1997).
[347] Oppolzer, W. and Stammen, B., *Tetrahedron*, **53**, 3577 (1997).
[348] Oppolzer, W., Kuo, D. L., Hutzinger, M. W., Leger, R., Durand, J. O., and Leslie, C., *Tetrahedron Lett.*, **38**, 6213 (1997).
[349] Systermans, A., Lefevre, V., Ripoll, J. L., Pieplu, T., Hoggan, P. E., Joanteguy, S., Chrostowska-Senio, A., and Pfister-Guillouzo, G., *New J. Chem.*, **21**, 383 (1997).
[350] Briard, E., Levillain, J., and Ripoll, J. L., *Tetrahedron Lett.*, **38**, 8707 (1997).
[351] Ito, K. and Miyajima, S., *J. Heterocycl. Chem.*, **34**, 501 (1997).
[352] Roulet, J. M., Puhr, G., and Vogel, P., *Tetrahedron Lett.*, **38**, 6201 (1997).
[353] Tomooka, K. and Nakai, T., *Yuki Gosei Kagaku Kyokaishi*, **54**, 1000 (1996); *Chem. Abs.*, **126**, 18412 (1997).
[354] Tomooka, K., *Kagaku to Kogyo (Tokyo)*, **50**, 159 (1997); *Chem. Abs.*, **126**, 156951 (1997).
[355] Tomooka, K., Yamamoto, H., and Nakai, T., *Liebigs Ann. Chem.*, **1997**, 1275.
[356] Miyata, O., Koizumi, T., Ninomiya, I., and Naito, T., *J. Org. Chem.*, **61**, 9078 (1996).
[357] Antoniotti, P., Canepa, C., and Tonachini, G., *Trends Org. Chem.*, **5**, 189 (1995); *Chem. Abs.*, **126**, 317108 (1997).
[358] Courillon, C., Le Fol, R., Vandendris, E., and Malacria, M., *Tetrahedron Lett.*, **38**, 5493 (1997).
[359] Hitchcock, P. B., Lappert, M. F., Liu, S., and Tian, S., *Prog. Organosilicon Chem.*, **1995**, 345; *Chem. Abs.*, **126**, 18918 (1997).
[360] Schiesser, C. H. and Styles, M. L., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 2335.
[361] Smith, A. B. and Boldi, A. M., *J. Am. Chem. Soc.*, **119**, 6925 (1997).
[362] Jung, M. E. and Nichols, C. J., *J. Org. Chem.*, **61**, 9065 (1996).
[363] Hudrlik, P. F., Roberts, R. R., Ma, D., and Hudrlik, A. M., *Tetrahedron Lett.*, **38**, 4029 (1997).
[364] Gibson, C., Buck, T., Noltemeyer, M., and Brückner, R., *Tetrahedron Lett.*, **38**, 2933 (1997).
[365] Goeppel, D. and Brückner, R., *Tetrahedron Lett.*, **38**, 2937 (1997).

[366] Sammtleben, F., Noltemeyer, M., and Brückner, R., *Tetrahedron Lett.*, **38**, 3893 (1997).
[367] Bousbaa, J., Ooms, F., and Krief, A., *Tetrahedron Lett.*, **38**, 7625 (1997).
[368] Bonini, B. F., Franchini, M. C., Fochi, M., Mazzanti, G., and Ricci, A., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 3211.
[369] Moliner, V., Castillo, R., Safont, V. S., Oliva, M., Bohn, S., Tunon, I., and Andres, J., *J. Am. Chem. Soc.*, **119**, 1941 (1997).
[370] Krinitskaya, L. A., *Russ. Chem. Bull.*, **46**, 1140 (1997).
[371] Sarhan, A. O., *Monatsh. Chem.*, **128**, 79 (1997).
[372] Elwareth, A., Sarhan, A. O., and Hoffmann, H. M. R., *J. Prakt. Chem.*, **339**, 390 (1997).
[373] MacDougall, J. M. and Moore, H. W., *J. Org. Chem.*, **62**, 4554 (1997).
[374] Evans, P. and Taylor, R. J. K., *Synlett*, **1997**, 1043.
[375] Evans, P. and Taylor, R. J. K., *Tetrahedron Lett.*, **38**, 3055 (1997).
[376] Coogan, M. P., Gravestock, M. B., Knight, D. W., and Thornton, S. R., *Tetrahedron Lett.*, **38**, 8549 (1997).
[377] Wheildon, A. R., Knight, D. W., and Leese, M. P., *Tetrahedron Lett.*, **38**, 8553 (1997).
[378] Miyashita, A., Numata, A., Suzuki, Y., Iwamoto, K., and Higashino, T., *Chem. Lett.*, **1997**, 697.
[379] Bowden, K. and Rumpal, S., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 983.
[380] Bowden, K. and Horri, M. V., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 989.
[381] Al-Najjar, A., Bowden, K., and Horri, M. V., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 993.
[382] Paquette, L. A., Kuo, L. H., Hamme, A. T., Kreuzholz, R., and Doyon, J., *J. Org. Chem.*, **62**, 1730 (1997).
[383] Sengul, M. E., Ceylan, Z., and Balci, M., *Tetrahedron*, **53**, 10401 (1997).
[384] Dua, S., Taylor, M. S., Buntine, M. A., and Bowie, J. H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1991.
[385] Baldwin, J. E., Chen, D., and Russell, A. T., *J. Chem. Soc., Chem. Commun.*, **1997**, 2389.
[386] Saravanan, P., Datta-Gupta, A., Bhuniya, D., and Singh, V. K., *Tetrahedron*, **53**, 1855 (1997).
[387] Hodgson, D. M. and Marriott, R. E., *Tetrahedron Lett.*, **38**, 887 (1997).
[388] Hodgson, D. M. and Gibbs, A. R., *Tetrahedron Lett.*, **38**, 8907 (1997).
[389] Oda, M., Masaki, Y., Okazaki, Y., Kajioka, T., Izawa, M., Miyatake, R., Kuroda, S., and Scott, L. T., *Chem. Lett.*, **1997**, 595.
[390] Cheung, Y. S. and Li, W. K., *Aust. J. Chem.*, **50**, 169 (1997).
[391] Darbre, T., Keese, R., Siljegovic, V., and Wolleb-Gygi, A., *Helv. Chim. Acta*, **79**, 2100 (1996).
[392] Shubin, V. G. and Borodkin, G. I., *Stable Carbocation Chem.*, **1992**, 231 (Pub. 1997); *Chem. Abs.*, **126**, 143789 (1997).
[393] Boronat, M., Viruela, P., and Corma, A., *Appl. Catal.*, **146A**, 207 (1996); *Chem. Abs.*, **125**, 327877 (1997).
[394] Fărcaşiu, D. and Norton, S. H., *J. Org. Chem.*, **62**, 5374 (1997).
[395] Chalk, A. J. and Radom, L., *J. Am. Chem. Soc.*, **119**, 7573 (1997).
[396] Allen, A. D., Sumonja, M., and Tidwell, T. T., *J. Am. Chem. Soc.*, **119**, 2371 (1997).
[397] Hewlins, S. A., Murphy, J. A., Lin, J., Hibbs, D. E., and Hursthouse, M. B., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1559.
[398] Andrey, O., Ducry, L., Landais, Y., Planchenault, D., and Weber, V., *Tetrahedron*, **53**, 4339 (1997).
[399] Wennerberg, J., Eklund, L., Polla, M., and Frejd, T., *J. Chem. Soc., Chem. Commun.*, **1997**, 445.
[400] Buffet, M. F., Dixon, D. J., Edwards, G. L., Ley, S. V., and Tate, E., *Synlett*, **1997**, 1055.
[401] Mitrochkine, A. A., Blain, I., Bit, C., Canlet, C., Pierre, S., Courtieu, J., and Reglier, M., *J. Org. Chem.*, **62**, 6204 (1997).
[402] Xu, B. L., Guo, Z. R., Liang, X. T., and Yang, G. Z., *Chin. Chem. Lett.*, **8**, 479 (1997); *Chem. Abs.*, **127**, 176075 (1997).
[403] Nishide, K., Shigeta, Y., Obata, K., and Node, M., *J. Am. Chem. Soc.*, **118**, 13103 (1996).
[404] Adia, M., Henaff, N., and Whiting, A., *Tetrahedron Lett.*, **38**, 3101 (1997).
[405] Li, L. C., Tang, Z. H., Tian, A. M., and Yan, G. S., *Acta Chim. Sin.*, **55**, 952 (1997).
[406] Bouchoux, G., Choret, N., and Flammang, R., *J. Phys. Chem. A*, **101**, 4271 (1997).
[407] Davis, B. R. and Hinds, M. G., *Aust. J. Chem.*, **50**, 309 (1997).
[408] Kita, Y., Yoshida, Y., Mihara, S., Fang, D.-F., Higuchi, K., Furukawa, A., and Fujioka, H., *Tetrahedron Lett.*, **38**, 8315 (1997).
[409] Pandey, R. K., Isaac, M., MacDonald, I., Medforth, C. J., Senge, M. O., Dougherty, T. J., and Smith, K. M., *J. Org. Chem.*, **62**, 1463 (1997).
[410] Hornyak G., Fetter, J., Nemeth, G., Poszavacz, L., and Simig, G., *J. Fluorine Chem.*, **84**, 49 (1997).
[411] Degani, I., Dughera, S., Fochi, R., and Gazzetto, S., *J. Org. Chem.*, **62**, 7228 (1997).
[412] Pole, D. L. and Warkentin, J., *J. Org. Chem.*, **62**, 4065 (1997).
[413] Jung, M. E. and Anderson, K. L., *Tetrahedron Lett.*, **38**, 2605 (1997).
[414] Kita, Y., Kitagaki, S., Yoshida, Y., Mihara, S., Fang, D.-F., and Fujioka, H., *Tetrahedron Lett.*, **38**, 1061 (1997).

[415] Kita, Y., Kitagaki, S., Yoshida, Y., Mihara, S., Fang, D.-F., Kondo, M., Okamoto, S., Imai, R., Akai, S., and Fujioka, H., *J. Org. Chem.*, **62**, 4991 (1997).
[416] Corey, E. J. and Roberts, B. E., *Tetrahedron Lett.*, **38**, 8921 (1997).
[417] Rigaudy, J. and Lachgar, M., *Tetrahedron Lett.*, **38**, 2267 (1997).
[418] Ferraz, H. M. C. and Silva, L. F., *Tetrahedron Lett.*, **38**, 1899 (1997).
[419] Minor, K. P. and Overman, L. E., *Tetrahedron*, **53**, 8927 (1997).
[420] Raggatt, M. E., Simpson, T. J., and Chicarelli-Robinson, M. I., *J. Chem. Soc., Chem. Commun.*, **1997**, 2245.
[421] Kuroda, C., Sumiya, H., Murase, A., and Koito, A., *J. Chem. Soc., Chem. Commun.*, **1997**, 1177.
[422] Paquette, L. A., Lanter, J. C., and Johnston, J. N., *J. Org. Chem.*, **62**, 1702 (1997).
[423] Paquette, L. A., Kinney, M. J., and Dullweber, U., *J. Org. Chem.*, **62**, 1713 (1997).
[424] Mal, J., Nath, A., and Venkateswaran, R. V., *J. Org. Chem.*, **61**, 9164 (1996).
[425] Haque, A., Ghatak, A., Ghosh, S., and Ghoshal, N., *J. Org. Chem.*, **62**, 5211 (1997).
[426] Yamamoto, Y., Noda, M., Ohno, M., and Eguchi, S., *J. Org. Chem.*, **62**, 1292 (1997).
[427] Sternberg, K., Michalik, M., and Oehme, H., *J. Organomet. Chem.*, **533**, 265 (1997).
[428] Black, J. R., Eaborn, C., Garrity, P. M., and Happer, D. A. R., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1633.
[429] Ernst, L., Hopf, H., and Savinsky, R., *Liebigs Ann. Chem.*, **1997**, 1915.
[430] Starling, S. M. and Vonwiller, S. C., *Tetrahedron Lett.*, **38**, 2159 (1997).
[431] Kim, D., Hong, S. W., and Park, C. W., *J. Chem. Soc., Chem. Commun.*, **1997**, 2263.
[432] Katayama, S., Hiramatsu, H., Aoe, K., and Yamauchi, M., *Chem. Pharm. Bull.*, **45**, 1419 (1997).
[433] Evans, P. A., Nelson, J. D., and Rheingold, A. L., *Tetrahedron Lett.*, **38**, 2235 (1997).
[434] Uyehara, T., Inayama, T., Kobari, T., Kimura, Y., and Yoneta, N., *Bull. Chem. Soc. Jpn*, **70**, 1919 (1997).
[435] Dorta, R. L., Martin, A., Suarez, E., and Betancor, C., *J. Org. Chem.*, **62**, 2273 (1997).
[436] Wu, H. J. and Chern, J. H., *J. Chem. Soc., Chem. Commun.*, **1997**, 547.
[437] Wu, H. J. and Chern, J. H., *J. Org. Chem.*, **62**, 3208 (1997).
[438] Dombrowski, G. W., Gassman, P. G., and Kass, S. R., *Tetrahedron Lett.*, **38**, 7819 (1997).
[439] Herpers, E. and Kirmse, W., *Liebigs Ann. Chem.*, **1997**, 2031.
[440] Shiner, V. J., Neumann, T. E., and Basinger, B. B., *Croat. Chem. Acta*, **69**, 1405 (1996); *Chem. Abs.*, **126**, 185681 (1997).
[441] Huang, X. and Bennet, A. J., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1027.
[442] Freccero, M., Gamba, A., Gandolfi, R., and Amade, M. S., *Tetrahedron*, **53**, 4869 (1997).
[443] Hedhli, A. and Baklouti, A., *J. Soc. Chim. Tunis.*, **3**, 847 (1996); *Chem. Abs.*, **126**, 46732 (1997).
[444] Kita, Y., *Yakugaku Zasshi*, **117**, 282 (1997); *Chem. Abs.*, **126**, 330218 (1997).
[445] Kita, Y., Shibata, N., Fukui, S., Bando, M., and Fujita, S., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 1763.
[446] Bravo, P., Crucianelli, M., Volonterio, A., and Zanda, M., *Phosphorus Sulfur Silicon Relat. Elem.*, **120**, 353 (1997).
[447] Volonterio, A., Zanda, M., Bravo, P., Fronza, G., Cavicchio, G., and Crucianelli, M., *J. Org. Chem.*, **62**, 8031 (1997).
[448] Arnone, A., Bravo, P., Bruché, L., Crucianelli, M., Zanda, M., and Zappalà, C., *J. Chem. Res. (S)*, **1997**, 416.
[449] Wessjohann, L. A., Mühlbauer, A., and Sinks, U., *Acta Chem. Scand.*, **57**, 1112 (1997).
[450] Stamos, I. K., *J. Heterocycl. Chem.*, **34**, 1487 (1997).
[451] Kimura, T., Nakayama, H., Obinata, T., and Furukawa, N., *Chem. Lett.*, **1997**, 301.
[452] van der Hart, W. J., *J. Am. Chem. Soc. Mass Spectrom.*, **8**, 594 (1997).
[453] van der Hart, W. J., *J. Am. Chem. Soc. Mass Spectrom.*, **8**, 599 (1997).
[454] Gauld, J. W. and Radom, L., *J. Am. Chem. Soc.*, **119**, 9831 (1997).
[455] Clark, T., *Acta Chem. Scand.*, **51**, 646 (1997).
[456] McIlroy, S., Weng, H. X., and Roth, H. D., *J. Phys. Org. Chem.*, **10**, 607 (1997).
[457] de Lijser, H. J. P. and Arnold, D. R., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 1369.
[458] Belevskii, V. N. and Shchapin, I. Y., *Acta Chem. Scand.*, **51**, 1085 (1997).
[459] Chang, N. Y., Shen, M. Y., and Yu, C. H., *J. Chem. Phys.*, **106**, 3237 (1997).
[460] Moss, R. A., Xue, S., Ma, W., and Ma, H. R., *Tetrahedron Lett.*, **38** 4379 (1997).
[461] Sulzbach, H. M., Platz, M. S., Schaefer, H. F., and Hadad, C. M., *J. Am. Chem. Soc.*, **119**, 5682 (1997).
[462] Pan, W., Balci, M., and Shevlin, P. B., *J. Am. Chem. Soc.*, **119**, 5035 (1997).
[463] Calvo-Losada, S. and Quirante, J. J., *THEOCHEM*, **398**, 435 (1997).
[464] Kim, C. K. and Lee, I., *Bull. Korean Chem. Soc.*, **18**, 395 (1997).
[465] Guibourdenche, C., Seebach, D., and Natt, F., *Helv. Chim. Acta*, **80**, 1 (1997).
[466] Podlech, J. and Linder, M. R., *J. Org. Chem.*, **62**, 5873 (1997).
[467] Jarstfer, M. B., Blagg, B. S. J., Rogers, D. H., and Poulter, C. D., *J. Am. Chem. Soc.*, **118**, 13089 (1996).
[468] Miljkovic, D., Penov-Gasi, K., Djurendic, E., and Sakac, M., *Tetrahedron Lett.*, **38**, 4683 (1997).

[469] Burgueno-Tapia, E. and Joseph-Nathan, P., *Monatsh. Chem.*, **128**, 651 (1997).
[470] Bhattacharya, A. K., Jain, D. C., Sharma, R. P., Roy, R., and McPhail, A. T., *Tetrahedron*, **53**, 14975 (1997).
[471] Nowakowski, M. and Hoffmann, H. M. R., *Tetrahedron*, **53**, 4331 (1997).
[472] Sy, L.-K., Hui, S.-M., Cheung, K.-K., and Brown, G. D., *Tetrahedron*, **53**, 7493 (1997).
[473] Huang, G. Y., Guo, S. Y., and Liang, X. T., *Chin. Chem. Lett.*, **7**, 1077 (1996).
[474] Hu, S. H., Sun, D. A., Tian, X. F., and Fang, Q. C., *Tetrahedron Lett.*, **38**, 2721 (1997).
[475] Appendino, G., Fenoglio, I., and Vander-Velde, D. G., *J. Nat. Prod.*, **60**, 464 (1997).
[476] Yu, C. Z. and Liu, Z. Y., *Tetrahedron Lett.*, **38**, 4133 (1997).
[477] Zamir, L. O., Balachandran, S., Zheng, Y. F., Nedea, M. E., Caron, G., Nikolakakis, A., Vishwakarma, R. A., Sauriol, F., and Mamer, O., *Tetrahedron*, **53**, 15991 (1997).
[478] Steynberg, P. J., Steynberg, J. P., Hemingway, R. W., Ferreira, D., and McGraw, G. W., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 2395.
[479] Velandia, J. R., Decarvalho, M. G., and Braz-Filho, R., *J. Brazil. Chem. Soc.*, **7**, 275 (1996).
[480] Arigoni, D., Sagner, S., Latzel, C., Eisenreich, W., Bachar, A., and Zenk, M. H., *Proc. Natl. Acad. Sci. USA*, **94**, 10600 (1997).
[481] Sun, X. L., Kai, T., Fujita, S., Takayanagi, H., and Furuhata, K., *Chem. Pharm. Bull.*, **45**, 795 (1997).
[482] Lindhorst, T. K., *J. Carbohydr. Chem.*, **16**, 237 (1997).
[483] Borrachero-Moya, P., Cabrera-Escribano, F., Gómez-Guillén, M., and Madrid-Díaz, F., *Tetrahedron Lett.*, **38**, 1231 (1997).
[484] Achmatowicz, O. and Szechner, B., *Tetrahedron Lett.*, **38**, 4701 (1997).
[485] Wrodnigg, T. M., Stutz, A. E., and Withers, S. G., *Tetrahedron Lett.*, **38**, 5463 (1997).
[486] Moradei, O. M., du Mortier, C. M., and Cirelli, A. F., *Tetrahedron*, **53**, 7397 (1997).
[487] Friestad, G. K. and Branchaud, B. P., *Tetrahedron Lett.*, **38**, 5933 (1997).
[488] Lewin, G., Schaeffer, C., Morgant, G., and Nguyen-Huy, D., *J. Org. Chem.*, **61**, 9614 (1996).
[489] Wang, F. P., Wang, J. Z., and Zhang, R., *Heterocycles*, **45**, 659 (1997).
[490] Desai, H. K., Bai, Y. L., and Pelletier, S. W., *J. Nat. Prod.*, **60**, 684 (1997).
[491] Takano, I., Yasuda, I., Nishijima, M., Hitotsuyanagi, Y., Takeya, K., and Itokawa, H., *J. Org. Chem.*, **62**, 8251 (1997).
[492] Chen, Z. M., Gonzalez, M. D., Blundell, P., and Meltzer, P. C., *Tetrahedron Lett.*, **38**, 6823 (1997).
[493] Nguyen, M. T., Raspoet, G., and Vanquickenborne, L. G., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 821.
[494] Nguyen, M. T., Raspoet, G., and Vanquickenborne, L. G., *J. Am. Chem. Soc.*, **119**, 2552 (1997).
[495] Yashima, T., Oka, N., and Komatsu, T., *Catal. Today*, **38**, 249 (1997).
[496] Dai, L. X., Iwaki, Y., Koyama, K., and Tatsumi, T., *Appl. Surf. Sci.*, **121**, 335 (1997).
[497] Roseler, J., Heitmann, G., and Holderich, W. F., *Stud. Surf. Sci. Catal.*, **105**, 1173 (1997).
[498] Nakajima, T., Nakajima, T., and Mishima, S., *Nippon Kagaku Kaishi*, **1997**, 565.
[499] Pai, S. G., Bajpai, A. R., Deshpande, A. B., and Samant, S. D., *Synth. Commun.*, **27**, 379 (1997).
[500] Lyga, J. W., *J. Heterocycl. Chem.*, **33**, 1631 (1996).
[501] Drabowicz, J., Kotynski, A., Kudzin, Z. H., Nazarski, R. B., and Tasz, M. K., *Tetrahedron*, **53**, 14169 (1997).
[502] Yokomatsu, T., Minowa, T., Yoshida, Y., and Shibuya, S., *Heterocycles*, **44**, 111 (1997).
[503] Kehler, J. and Breuer, E., *J. Chem. Soc., Chem. Commun.*, **1997**, 1751.
[504] Schinzer, D., Abel, U., and Jones, P. G., *Synlett*, **1997**, 632.
[505] Bhandari, K., Sharma, V. L., and Singh, C. M., *Indian J. Chem.*, **36B**, 352 (1997).
[506] Kravtchenko, D. V., Chibisova, T. A., and Traven, V. F., *Heteroat. Commun.*, **3**, 331 (1997).
[507] Petukhov, P. A., Denisov, A. Y., and Tkachev, A. V., *Tetrahedron*, **53**, 2527 (1997).
[508] Rakitin, O. A., Rees, C. W., Williams, D. J., and Torroba, T., *J. Org. Chem.*, **61**, 9178 (1996).
[509] Muraoka, O., Zheng, B. Z., Okumura, K., Tabata, E., Tanabe, G., and Kubo, M., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 113.
[510] Cárdenas, R., Cetina, R., Lagúnez-Otero, J., and Reyes, L., *J. Phys. Chem. A*, **101**, 192 (1997).
[511] Okuno, Y., *Chem. Eur. J.*, **3**, 212 (1997).
[512] Kitazume, T. and Kataoka, J., *J. Fluorine Chem.*, **80**, 157 (1996).
[513] Alcaide, B., Aly, M. F., and Sierra, M. A., *J. Org. Chem.*, **61**, 8819 (1996).
[514] Abramski, W., Urbanczyk-Lipkowska, Z., and Chmielewski, M., *J. Carbohydr. Chem.*, **16**, 63 (1997).
[515] Huang, X. and Keillor, J. W., *Tetrahedron Lett.*, **38**, 313 (1997).
[516] Huang, X., Seid, M., and Keillor, J. W., *J. Org. Chem.*, **62**, 7495 (1997).
[517] Zhang, L. H., Kauffman, G. S., Pesti, J. A., and Yin, J. G., *J. Org. Chem.*, **62**, 6918 (1997).
[518] Matsumura, Y., Maki, T., and Satoh, Y., *Tetrahedron Lett.*, **38**, 8879 (1997).
[519] Povazanec, F., Remen, L., Chedru, C., and Morel, J., *Chem. Listy*, **91**, 670 (1997).
[520] Verma, R. and Ghosh, S. K., *J. Chem. Soc., Chem. Commun.*, **1997**, 1601.

[521] Ohba, M., Kubo, H., Fujii, T., Ishibashi, H., Sargent, M. V., and Arbain, D., *Tetrahedron Lett.*, **38**, 6697 (1997).
[522] Salomow, C. J. and Breuer, E., *J. Org. Chem.*, **62**, 3858 (1997).
[523] Harger, M. J. P., *J. Chem. Soc., Chem. Commun.*, **1997**, 403.
[524] Harger, M. J. P., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 3205.
[525] Harger, M. J. P., *Tetrahedron Lett.*, **38**, 4507 (1997).
[526] Harger, M. J. P., *J. Chem. Soc., Chem. Commun.*, **1997**, 1503.
[527] Maryin, V. P., Andrianov, Y. A., and Faerman, V. I., *Russ. Chem. Bull.*, **45**, 1917 (1996).
[528] Takahashi, T., Xi, Z. F., Fischer, R., Huo, S. Q., Xi, C. J., and Nakajima, K., *J. Am. Chem. Soc.*, **119**, 4561 (1997).
[529] Kotora, M., Umeda, C., Ishida, T., and Takahashi, T., *Tetrahedron Lett.*, **38**, 8355 (1997).
[530] Binger, P., Leininger, S., Gunther, K., and Bergstrasser, U., *Chem. Ber.*, **130**, 1491 (1997).
[531] Rietveld, M. H. P., Klumpers, E. G., Jastrzebski, J. T. B. H., Grove, D. M., Veldman, N., Spek, A. L., and van Koten, G., *Organometallics*, **16**, 4260 (1997).
[532] Wang, B., Lake, C. H., and Lammertsma, K., *Organometallics*, **16**, 4145 (1997).
[533] Daff, P. J., Monge, A., Palma, P., Poveda, M. L., Ruiz, C., Valerga, P., and Carmona, E., *Organometallics*, **16**, 2263 (1997).
[534] Heard, P. J. and Jones, C., *J. Chem. Soc., Dalton Trans.*, **1997**, 1083.
[535] Tahmassebi, S. K., McNeil, W. S., and Mayer, J. M., *Organometallics*, **16**, 5342 (1997).
[536] Casey, C. P., Underiner, T. L., Vosejpka, P. C., Slough, G. A., Gavney, J. A., and Hayashi, R. K., *Organometallics*, **16**, 2189 (1997).
[537] Gauss, C., Veghini, D., and Berke, H., *Chem. Biol.*, **130**, 183 (1997).
[538] Field, L. D., George, A. V., Malouf, E. Y., Hambley, T. W., and Turner, P., *J. Chem. Soc., Chem. Commun.*, **1997**, 133.
[539] Zhou, X. Z., Zhang, Y. Q., Xie, W. H., Xu, S. S., and Sun, J., *Organometallics*, **16**, 3474 (1997).
[540] Wang, B. Q., Xu, S. S., and Zhou, X. S., *J. Organomet. Chem.*, **540**, 101 (1997).
[541] Wang, B. Q., Zhang, Y. Q., Xu, S. S., and Zhou, X. Z., *Organometallics*, **16**, 4620 (1997).
[542] Sato, M., Kawata, Y., Shintate, H., Habata, Y., Akabori, S., and Unoura, K., *Organometallics*, **16**, 1693 (1997).
[543] de Los-Ríos, I., Tenorio, M. J., Puerta, M. C., and Valerga, P., *J. Am. Chem. Soc.*, **119**, 6529 (1997).
[544] Picquet, M., Bruneau, C., and Dixneuf, P. H., *J. Chem. Soc., Chem. Commun.*, **1997**, 1201.
[545] Harrity, J. P. A., Visser, M. S., Gleason, J. D. and Hoveyda, A. H., *J. Am. Chem. Soc.*, **119**, 1488 (1997).
[546] Peters, J.-U. and Blechert, S., *J. Chem. Soc., Chem. Commun.*, **1997**, 1983.
[547] Maksakov, V. A., Ershova, V. A., Kirin, V. P., and Golovin, A. V., *J. Organomet. Chem.*, **532**, 11 (1997).
[548] Takayama, C., Kajitani, M., Sugiyama, T., Akiyama, T., Shimizu, K., and Sugimori, A., *Organometallics*, **16**, 3498 (1997).
[549] Rybtchinski, B., Ben-David, Y., and Milstein, D., *Organometallics*, **16**, 3786 (1997).
[550] Kato, F., Tokairin, M., and Hiroi, K., *Annu. Rep. Tohoku Coll. Pharm.*, **42**, 123 (1995); *Chem. Abs.*, **125**, 247305 (1996).
[551] Albert, J., Gonzalez, A., Granell, J., Moragas, R., Puerta, M. C., and Valerga, P., *Organometallics*, **16**, 3775 (1997).
[552] Albeniz, A. C., Espinet, P., and Lin, Y. S., *Organometallics*, **16**, 4138 (1997).
[553] Cucciolito, M. E., de Felice, V., Orabona, I., and Ruffo, F., *J. Chem. Soc., Dalton Trans.*, **1997**, 1351.
[554] Fröhling, C. D. W. and Sheldrick, W. S., *J. Chem. Soc., Chem. Commun.*, **1997**, 1737.
[555] Pommier, A. and Kocienski, P. J., *J. Chem. Soc., Chem. Commun.*, **1997**, 1139.
[556] Harada, T., Otani, T., and Oku, A., *Tetrahedron Lett.*, **38**, 2855 (1997).
[557] Jadhav, P. K. and Man, H.-W., *J. Am. Chem. Soc.*, **119**, 846 (1997).
[558] Corey, E. J., Barnes-Seeman, D., and Lee, T. W., *Tetrahedron: Asymmetry*, **8**, 3711 (1997).
[559] Lewinski, J., Zachara, J., and Justyniak, I., *Organometallics*, **16**, 4597 (1997).
[560] du Mont, W.-W., Karnop, M., Mahnke, J., Martens, R., Druckenbrodt, C., Jeske, J., and Jones, P. G., *Chem. Ber.*, **130**, 1619 (1997).
[561] Fan, K. N., Li, Z. H., Wang, W. N., Huang, H. H., and Huang, W., *Chem. Phys. Lett.*, **277**, 257 (1997).
[562] Tang, Z.-H., Chen, J.-S., Sun, Z.-M., and Yan, G.-S., *Huaxue Xuebao*, **54**, 937 (1996); *Chem. Abs.*, **126**, 46779 (1997).
[563] Engel, P. S., He, S. L., Banks, J. T., Ingold, K. U., and Lusztyk, J., *J. Org. Chem.*, **62**, 1210 (1997).
[564] Iwama, T., Matsumoto, H., and Kataoka, T., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 835.
[565] Kohmoto, S., Yajima, H., Takami, S., Kishikawa, K., Yamamoto, M., and Yamada, K., *J. Chem. Soc., Chem. Commun.*, **1997**, 1973.
[566] Lund, E. A., Kennedy, I. A., and Fallis, A. G., *Can. J. Chem.*, **74**, 2401 (1996).
[567] Lu, X. L., Yang, S. T., and Silverman, R. B., *J. Org. Chem.*, **61**, 8961 (1996).

[568] Chiang, Y., Grant, A. S., Guo, H. X., Kresge, A. J., and Paine, S. W., *J. Org. Chem.*, **62**, 5363 (1997).
[569] Hopf, H., von der Schulenburg, W. G., and Walsh, R., *Angew. Chem., Int. Ed. Engl.*, **36**, 381 (1997).
[570] Anglada, J. M. and Bofill, J. M., *J. Org. Chem.*, **62**, 2720 (1997).
[571] Belbruno, J. J., *J. Phys. Org. Chem.*, **10**, 113 (1997).
[572] Coxon, J. M., MacLagan, R. G. A. R., Rauk, A., Thorpe, A. J., and Whalen, D., *J. Am. Chem. Soc.*, **119**, 4712 (1997).
[573] Takanami, T., Hirabe, R., Ueno, M., Hino, F., and Suda, K., *Chem. Lett.*, **1996**, 1031.
[574] Kulasegaram, S. and Kulawiec, R. J., *J. Org. Chem.*, **62**, 6547 (1997).
[575] Ooi, T., Kiba, T., and Maruoka, K., *Chem. Lett.*, **1997**, 519.
[576] Bajwa, J. S. and Sunay, U. B., *J. Labelled Compd. Radiopharm.*, **39**, 787 (1997).
[577] Harden, R. C., Hodgkinson, T. J., McKillop, A., Prowse, W. G., and Urquhart, M. W. J., *Tetrahedron*, **53**, 21 (1997).
[578] Rayner, C. M., *Synlett*, **1997**, 11.
[579] Liu, Q. Y., Marchington, A. P., and Rayner, C. M., *Tetrahedron*, **53**, 15729 (1997).
[580] Tokumasu, M., Sasaoka, A., Takagi, R., Hiraga, Y., and Ohkata, K., *J. Chem. Soc., Chem. Commun.*, **1997**, 875.
[581] Chambers, R. D., Vaughan, J. F. S., and Mullins, S. J., *Res. Chem. Intermed.*, **22**, 703 (1996); *Chem. Abs.*, **125**, 300709 (1996).
[582] Krishnamurthy, V. and Rawal, V. H., *J. Org. Chem.*, **62**, 1572 (1997).
[583] Nishida, A., Kakimoto, Y.-I., Ogasawara, Y., Kawahara, N., Nishida, M., and Takayanagi, H., *Tetrahedron Lett.*, **38**, 5519 (1997).
[584] Eastwood, F. W., Perlmutter, P., and Yang, Q., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 35.
[585] Hori, K., Nishiguchi, T., and Nabeya, A., *J. Org. Chem.*, **62**, 3081 (1997).
[586] Cardillo, G., Gentilucci, L., Tolomelli, A., and Tomasini, C., *Tetrahedron Lett.*, **38**, 6953 (1997).
[587] Morioka, M., Kato, M., Yoshida, H., and Ogata, T., *Heterocycles*, **45**, 1173 (1997).
[588] Johnson, J. E., Nwoko, D., Hotema, M., Sanchez, N., Alderman, R., and Lynch, V., *J. Heterocycl. Chem.*, **33**, 1583 (1996).
[589] Ibuka, T., Mimura, N., Ohno, H., Nakai, K., Akaji, M., Habashita, H., Tamamura, H., Miwa, Y., Taga, T., Fujii, N., and Yamamoto, Y., *J. Org. Chem.*, **62**, 2982 (1997).
[590] Mihova, T. R., Linden, A., and Heimgartner, H., *Helv. Chim. Acta*, **79**, 2067 (1996).
[591] Magedov, I. V., Przhevalskii, N. M., Yufit, D. S., and Drozd, V. N., *Russ. Chem. Bull.*, **46**, 759 (1997).
[592] Marson, C. M. and Campbell, J., *Tetrahedron Lett.*, **38**, 7785 (1997).
[593] Skancke, P. N., *J. Phys. Chem. A*, **101**, 5017 (1997).
[594] Murphy, W. S. and Neville, D., *Tetrahedron Lett.*, **38**, 7933 (1997).
[595] Berger, D. J., Gaspar, P. P., Le Floch, P., Mathey, F., and Grev, R. S., *Organometallics*, **15**, 4904 (1996).
[596] Aubé, J., *Chem. Soc. Rev.*, **26**, 269 (1997).
[597] Nongkunsarn, P. and Ramsden, C. A., *Tetrahedron*, **53**, 3805 (1997).
[598] Platz, M. S., Huang, H. Y., Ford, F., and Toscano, J., *Pure Appl. Chem.*, **69**, 803 (1997).
[599] Harger, M. J. P. and Sreedharan-Menon, R., *J. Chem. Soc., Perkin Trans. 1*, **1997**, 527.
[600] Ishii, A., Nakamura, S., Yamada, T., and Nakayama, J., *Tetrahedron*, **53**, 12203 (1997).
[601] Alcaide, B., Martín-Cantalejo, Y., Pérez-Castells, J., Sierra, M. A., and Monge, A., *J. Org. Chem.*, **61**, 9156 (1996).
[602] Pippich, S., Bartsch, H., and Holzer, W., *Tetrahedron*, **53**, 8439 (1997).
[603] Glasl, D., Rihs, G., and Otto, H. H., *Helv. Chim. Acta*, **80**, 671 (1997).
[604] Shashidhar, M. S., Rajeev, K. G., and Bhatt, M. V., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 559.
[605] Suárez, D. and Sordo, T. L., *J. Am. Chem. Soc.*, **119**, 10291 (1997).
[606] Zhan, C.-G. and Iwata, S., *Chem. Lett.*, **1997**, 3.
[607] Ram, V. J. and Goel, A., *Chem. Lett.*, **1997**, 1021.
[608] Fukuzawa, S., Yamaishi, Y., Furuya, H., Terao, K., and Iwasaki, F., *Tetrahedron Lett.*, **38**, 7203 (1997).
[609] Pitchumani, K., Joy, A., Prevost, N., and Ramamurthy, V., *J. Chem. Soc., Chem. Commun.*, **1997**, 127.
[610] Kojima, M., Takeya, H., Kuriyama, Y., and Oishi, S., *Chem. Lett.*, **1997**, 997.
[611] Tasi, G., Palinko, I., Kortvelyesi, T., and Nyerges, L., *THEOCHEM*, **391**, 189 (1997).
[612] Molnar, P., Kortvelyesi, T., Matus, Z., and Szabolcs, J., *J. Chem. Res. (S)*, **1997**, 120.
[613] Kern, D., Schutkowski, M., and Drakenberg, T., *J. Am. Chem. Soc.*, **119**, 8403 (1997).
[614] Asano, T., Matsuo, K., and Sumi, H., *Bull. Chem. Soc. Jpn*, **70**, 239 (1997).
[615] Arai, T. and Maeda, Y., *Chem. Lett.*, **1997**, 335.
[616] Sin, H.-S., Holler, M., Burger, A., and Biellmann, J.-F., *Tetrahedron Lett.*, **38**, 3585 (1997).
[617] Kyushin, S., Shinnai, T., Kubota, T., and Matsumoto, H., *Organometallics*, **16**, 3800 (1997).
[618] Griesbaum, K. and Quinkert, R. O., *J. Prakt. Chem.*, **339**, 650 (1997).
[619] Feng, W. L., Lei, M., Wang, Y., and Qian, Y., *Chin. Chem. Lett.*, **8**, 71 (1997).

[620] Staley, S. W., Grimm, R. A., Martin, G. S., and Sablosky, R. A., *Tetrahedron*, **53**, 10093 (1997).
[621] Kameda, N. and Sango, R., *Nippon Kagaku Kaishi*, **1996**, 1014; *Chem. Abs.*, **126**, 46862 (1997).
[622] Dahl, D. B., Davies, C., Hyden, R., Kirova, M. L., and Lloyd, W. G., *J. Mol. Catal.*, **123A**, 91 (1997).
[623] Permin, A. B. and Petrosyan, V. S., *Russ. Chem. Bull.*, **46**, 1104 (1997).
[624] Handa, H., Baba, T., Yamada, H., Takahashi, T., and Ono, Y., *Catal. Lett.*, **44**, 119 (1997).
[625] Makioka, Y., Taniguchi, Y., Kitamura, T., Fujiwara, Y., Saiki, A., and Takaki, K., *Bull. Soc. Chim. Fr.*, **134**, 349 (1997).
[626] Kazmaier, U., *J. Chem. Soc., Chem. Commun.*, **1997**, 2305.
[627] Nagaoka, M., Suenobu, K., and Yamabe, T., *J. Am. Chem. Soc.*, **119**, 8023 (1997).
[628] Jemmis, E. D., Giju, K. T., and Leszczynski, J., *J. Phys. Chem. A*, **101**, 7389 (1997).
[629] Traven, V. F., Negrebetsky, V. V., Vorobjeva, L. I., and Carberry, E. A., *Can. J. Chem.*, **75**, 377 (1997).
[630] Marino, T., Russo, N., and Toscano, M., *Int. J. Quantum Chem.*, **62**, 489 (1997).
[631] Koch, A., Thomas, S., and Kleinpeter, E., *THEOCHEM*, **401**, 1 (1997).
[632] Yang, S. K., *J. Chin. Chem. Soc.*, **44**, 401 (1997).
[633] Ramos, M., Alkorta, I., and Elguero, J., *Tetrahedron*, **53**, 1403 (1997).
[634] Alkorta, I. and Elguero, J., *Struct. Chem.*, **8**, 189 (1997).
[635] de Paz, J. L. G., Elguero, J., Foces-Foces, C., Llamas-Saiz, A. L., Aguilar-Parrilla, F., Klein, O., and Limbach, H. H., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 101.
[636] Lee, I. S. H., Jeoung, E. H., and Lee, C. K., *J. Heterocycl. Chem.*, **33**, 1711 (1996).
[637] Steiner, T. and Koellner, G., *J. Chem. Soc., Chem. Commun.*, **1997**, 1207.
[638] Karpinska, G., Dobrowolski, J. C., and Mazurek, A. P., *THEOCHEM*, **369**, 137 (1996).
[639] Contreras, J. G., Madariaga, S. T., and Aldertete, J. B., *Bol. Soc. Chil. Quim.*, **42**, 17 (1997); *Chem. Abs.*, **126**, 330390 (1997).
[640] Boronat, M., Orti, E., Viruela, P. M., and Tomas, F., *THEOCHEM*, **390**, 149 (1997).
[641] Cativiela, C., Garcia, J. I., Mayoral, J. A., and Salvatella, L., *THEOCHEM*, **368**, 57 (1996).
[642] Kurasawa, Y., Takano, A., Kato, K., Kim, H. S., and Okamoto, Y., *J. Heterocycl. Chem.*, **34**, 305 (1997).
[643] Seki, T., Iwanami, Y., Kuwatani, Y., and Iyoda, M., *J. Heterocycl. Chem.*, **34**, 773 (1997).
[644] Rak, J., Skurski, P., Gutowski, M., Jozwiak, L., and Blazejowski, J., *J. Phys. Chem. A*, **101**, 283 (1997).
[645] Neuvonen, K., Zewi, C., and Lönnberg, H., *Acta Chem. Scand.*, **50**, 1137 (1996).
[646] Moodie, R. B., Moustras, M. Z., Read, G., and Sandall, J. P. B., *J. Chem. Soc., Perkin Trans. 2*, **1997**, 169.
[647] Fulop, F., Forro, E., Bernath, G., Miskolczi, I., Martinsen, A., and Vainiotalo, P., *J. Heterocycl. Chem.*, **34**, 289 (1997).
[648] Zelenin, K. N., Alekseyev, V. V., Ukraintsev, I. V., and Tselinsky, I. V., *Mendeleev Commun.*, **1997**, 111.
[649] Darabantu, M., Ple, G., Mager, S., Cotora, E., Gaina, L., Costas, L., and Mates, A., *Tetrahedron*, **53**, 1873 (1997).

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