Chirality and Gravitational Parity Violation

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ABSTRACT In this review, parity-violating gravitational potentials are presented as possible sources of both true and false chirality. In particular, whereas phenomenological long-range spin-dependent gravitational potentials contain both truly and falsely chiral terms, it is shown that there are models that extend general relativity including also coupling of fermionic degrees of freedom to gravity in the presence of torsion, which give place to short-range truly chiral interactions similar to that usually considered in molecular physics. Physical mechanisms which give place to gravitational parity violation together with the expected size of the effects and their experimental constraints are discussed. Finally, the possible role of parity-violating gravity in the origin of homochirality and a road map for future research works in quantum chemistry is presented. *Chirality 27:375–381, 2015.* © 2015 Wiley Periodicals, Inc.

KEY WORDS: true chirality; parity violation; gravitation

INTRODUCTION

Biological homochirality, that is, the almost exclusive one-handedness of chiral molecules found in living systems (D-sugars and L-aminoacids) is one of the fundamental problems of science which still remains unsolved.[1] The discovery of an excess of L-amino acids in meteorites[2] has reinforced the idea of an extraterrestrial origin of biological homochirality.[3,4] In this context, universal mechanisms of chiroselection such as parity violation (PV) in weak interactions would acquire special interest in spite of their tiny effects, without, of course, underestimating other mechanisms. In fact, MacDermott and coworkers found recently[5] that, in the gas phase, the parity-violating energy differences (PVEDs) of the neutral L-forms of all four Murchison α-methyl aminoacids were decisively negative, showing some correlation between the magnitudes of the L-excesses and the magnitudes of the PVEDs. Therefore, this electroweak energy splitting between enantiomers is, at least, consistent with the enantiomeric excess found in meteorites.[5] We remind the reader that, although it is actually well known that PV lifts the degeneracy between the two enantiomers of a chiral molecule, some subtleties were shown to be hidden within this fact during the 1980s.

Specifically, in a different but related context, Barron applied fundamental symmetry arguments to tackle the problem of the nature of physical fields and forces that were able to induce absolute asymmetric synthesis.[6–13] During his *tour de force*, Barron coined the terms *true and false chirality*, which helped to clarify the situation with the following definitions:

- true chirality is exhibited by systems that exist in two distinct enantiomeric states that are interconverted by space inversion but not by time (T) reversal combined with any proper spatial rotation.
- false chirality is exhibited by systems that exist in two distinct enantiomeric states that are interconverted by time reversal as well as space inversion.

Barron noted that a truly chiral influence supports time-even pseudoscalar observables, breaking P but not T. Therefore, it lifts the degeneracy of chiral enantiomers. On the contrary, false chirality supports time-odd pseudoscalar observables, breaking P and T separately but being PT-conserving and, therefore, it cannot lift the degeneracy of chiral enantiomers. However, a truly chiral influence is enantio selective under all circumstances since it lifts the degeneracy of enantiomers, whereas a falsely chiral influence, although it does not lift the degeneracy of enantiomers, might nonetheless be enantio selective but only in processes involving chiral molecules far from equilibrium via a breakdown in microscopic reversibility (analogous to what is observed in particle physics due to CP violation[14]).

Thus, according to these definitions, electroweak PV was shown to possess true chirality.[10] But, if PV is a universal force possessing true chirality, is there any universal force that possesses false chirality?. Barron, who raised this question very recently,[15] also gave an answer to it by pointing out that the candidate for such a force comes from a CP-odd interaction mediated by axions, as proposed by Moody and Wilczek.[16] To see that it constitutes a falsely chiral influence, let us write, following,[17] the axion-mediated electron-nucleon interaction potential:

$$V^{\text{axion}} = g_s^N g_p^e \frac{\mathbf{s}\cdot\mathbf{r}}{8\pi m_e}\left(\frac{m_\varphi}{r}+\frac{1}{r^2}\right)e^{-m_\varphi r}, \tag{1}$$

where g_s^N is the scalar axion coupling constant to an unpolarized nucleon, g_p^e is the pseudoscalar axion coupling constant to a polarized electron, $\mathbf{s}$ is the electron spin, $\mathbf{r}$ is the nucleon-electron separation vector, and m_φ is the mass of the axion. As the operator $\mathbf{s}\cdot\mathbf{r}$ is P- and T-odd but PT-even, it exhibits false chirality.[15,17] Therefore, as pointed out recently by Barron[15] and by the author some years ago,[18] this interaction cannot lift the degeneracy between enantiomers, as wrongly suggested in.[19,20]

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Thus, electroweak P-violating and CP-violating axion-mediated universal interactions show true and false chirality, respectively. But are they the only universal representatives of true and false chirality?. The purpose of the present review is to show the reader that some gravitational theories incorporate chiral terms of both types.[21] To this end, after giving a general overview of the history of PV together with its importance, we review the first ideas, the physical mechanisms, and the expected size of the effects of PV in gravitation. We will focus mainly on two of the theories that incorporate PV in gravitation, namely Chern-Simons (CS) gravity and loop quantum gravity (LQG). Finally, some intriguing similarities between electroweak and gravitational P-odd potentials will be pointed out. This fact will be commented on in light of the potentiality of gravitational PV for selecting life's handedness. Moreover, a possible road map for quantum chemists will be presented in order to obtain some valuable knowledge of PV in gravitation from the molecular perspective.

ELECTROWEAK PARITY VIOLATION AND MOLECULAR PHYSICS

In the second half of the twentieth century, it seemed that advances in fundamental physics would arise mostly through high-energy experiments, specifically those related to nuclear and particle physics. In fact, a fundamental symmetry violation was found by Wu[22] in the middle 1950s, after some pioneering theoretical works by Lee and Yang.[23] Since then, PV became one of the main ingredients of the Standard Model of Particle Physics (SMPP), along with the development of the electroweak theory by Glashow,[24] Salam,[25] Weinberg,[26] and its successive renormalization by 't Hooft[27] and Veltman.[28] With the ending of the twentieth century, experiments at ultrahigh collision energies became routine in particle accelerators. Specifically, further advances in fundamental physics came by the discovery of the Z boson[29] (one of the carriers of the weak force) in the 1980s. Very recently, the discovery of a Higgs-like bosonic particle, which is expected to correspond to the long-sought Higgs boson, predicted by the electroweak theory in the 1960s, has been announced by CERN.[30,31] It might thus appear that understanding fundamental aspects of nature and high-energy processes go hand-in-hand.

High-energy physics revealed that it was not so necessary to have access to fundamental questions. Specifically, the existence of low-energy PV was confirmed in the 1970s at Novosibirsk by observing spontaneous optical activity of bismuth atomic vapors.[32,33] Thus, the effects of the Z boson were confirmed not only at the particle and nuclear, but also at the atomic scale. Subsequent improvements in high-resolution spectroscopic techniques led to Wiemann and coworkers in the 1990s to the discovery of the nuclear anapole moment of cesium,[34] a parity-violating magnetic moment which results from the chirality acquired by the nucleon current when coupled to the spin of the electron (we note that the experimental techniques developed by Wieman and coworkers to address the existence of the anapole moment led finally to an important spin-off discovery that earned Wieman, Kettele, and Cornell the Nobel Prize in Physics, named Bose-Einstein condensation). Experimental measurements of the cesium anapole moment led to contradictions with the theoretical predictions of the SMPP, opening the window to new physics beyond it.[35] After further theoretical developments, experimental and theoretical discrepancies were shown to be not so large [35. However, experiments on atomic low-energy PV are routinely used to put stringent bounds on the existence of new physics.[36] Thus, it seems that high-energy physics is not the only way of testing fundamental aspects of nature.

To summarize, PV has been observed to date in particle, nuclear, and atomic physics. But, what about molecules? What is the role (if any) of PV in molecular physics? Could we gain new fundamental knowledge by studying it? Would it be possible to observe it in the laboratory? Here we anticipate that chiral molecules appear as an ideal and natural laboratory where PV and (possibly) other symmetry violations could be tested in the near future. In particular, with PV, we know today that there is a small PVED between the ground states of the enantiomers of chiral molecules due to the electroweak interaction (mainly) between the nuclei and electrons of the molecule.[37] Although extremely tiny (for instance, the PVED is on the order of 100 aeV for the two enantiomers of CHBrClF),[38,39] this PVED is expected to be detected and measured using different techniques such as vibrot spectroscopy,[40] Mössbauer/NMR spectroscopy,[41] dynamics in excited electronic states,[42,43] spin-spin coupling,[44] electronic spectroscopy,[45] and by employing cold molecules.[46] Different proposals to detect PV energy shifts between enantiomers of chiral molecules by measuring optical activity of a molecular sample prepared with chiral purity at the initial time have been studied[47,48] following earlier works by Harris and coworkers.[49] For a recent review on PV in chiral molecules (from both the theoretical and the experimental point of view), see[50] and references therein.

From the theoretical side of the history, the important point is to note that the PVED, ΔE^{ew}, between the L and R enantiomers is given by:

$$\Delta E^{\mathrm{ew}} \equiv \langle L|V^{\mathrm{ew}}|L\rangle - \langle R|V^{\mathrm{ew}}|R\rangle = 2\langle L|V^{\mathrm{ew}}|L\rangle, \tag{2}$$

where V^{ew} is the (nuclear spin independent) P-odd electroweak potential which, in the non-relativistic approximation for the molecular electrons can be written as[51]

$$V^{\mathrm{ew}} = \frac{G_F}{2\sqrt{2}m}\sum_{i=1}^{n}\sum_{A=1}^{N} Q_W(A)\{\mathbf{p}_i\cdot\mathbf{s}_i, \delta(\mathbf{r}_i - \mathbf{r}_A)\}. \tag{3}$$

In this expression, G_F is Fermi's constant, Q_W is the weak charge of the nucleus and θ_W is Weinberg's angle. We note that, as $sin^2\theta_W \approx 0.23$, $Q_W(A) \approx N$. The mass, spin, and momentum of the i-th molecular electron are given by m, $\mathbf{s}_i$ and $\mathbf{p}_i$, respectively. As usual, the nucleon density has been replaced by a delta-function in approximating the nucleus as pointlike.

The source of PV is the operator $\mathbf{s}\cdot\mathbf{p}$, which is P-odd, T-even, and, thus, PT-odd. Therefore, according to Barron's definition, it constitutes a universal truly chiral influence and, therefore, it lifts the degeneracy between enantiomers. In fact, not only is this P-odd electron-nucleon interaction the only universal mechanism related to the electroweak theory since a different source of PVED comes from P-odd neutrino/dark matter-molecule interactions.[52–54] In the first case, this neutrino-induced-homochirality is based on an interaction potential with also depends on the electron helicity ($\mathbf{s}\cdot\mathbf{p}$) but, in contrast with Eq. (3), it does not depend on Q_W but on $n_\nu - n\bar{\nu}$, the number density difference of neutrinos minus antineutrinos. In the dark mattercase, it depends on the number density difference between left- and right-handed WIMPs (weakly interacting massive particles).[52–54]

GRAVITATIONAL PARITY VIOLATION AND MOLECULAR PHYSICS

As we have seen in the previous section, electroweak PV is well established from the particle to the molecular scale. Moreover, quantum chemists perform routine calculations that incorporate these P-odd effects in the structure of chiral molecules. Unfortunately, no equivalent situation is found when the gravitational interaction is taken into account. In the rest of the article, we will try to show the reader that considering P-odd gravitational theories is closer to reality than one could think at first sight. Moreover, the study of parity-violating gravitational interactions could open a new field of research where quantum chemistry and fundamental physics could merge as a very fruitful *marriage*.

First Ideas

Correlations between the lack of P symmetry in the weak interaction and its corresponding weakness led Leitner and Okubo to inquire whether or not gravitation would share this kind of symmetry violation.[55] In,[55] the authors proposed a P-odd long-range gravitational potential that can be generalized to include terms that violate also charge conjugation (C) and P, and C and T symmetries. In addition to the generalized Leitner-Okubo parametrization, Hari Dass proposed phenomenologically a different potential[56] which can be written as:

$$V^{\mathrm{grav}}(r) = GM\left(\alpha_1\frac{\mathbf{s}\cdot\mathbf{r}}{r^3} + \alpha_2\frac{\mathbf{s}\cdot\mathbf{v}}{r^2} + \alpha_3\frac{\mathbf{s}\times(\mathbf{r}\cdot\mathbf{v})}{r^3}\right) \quad (4)$$

where M is the mass of the gravitating object and $\mathbf{r}$ is its separation vector from a test particle. The spin and velocity of this test particle are given by $\mathbf{s}$ and $\mathbf{v}$, respectively (its mass is already incorporated in the definition of the α_i dimensionless constants). We note that the α_i constants describe, asuming CPT conservation:

- α_1: P violation but PT conservation
- α_2: P and PT violation
- α_3: P and T conservation

Therefore, the terms containing α_1 and α_2 are false and true chiral long-range interactions, respectively.

As far as the author knows, the first (and only) application of PV in molecular physics within the Leitner-Okubo-Hari-Dass potential is Ref. 54. We noted there that, on the one hand, although the α_2 long range P-odd gravitational interaction produces a PVED between enantiomers, $\Delta E^{\mathrm{grav}} = 2\langle L|V^{\mathrm{grav}}|L\rangle$, it is not possible to perform any kind of calculation since the value of α_2 is totally unknown. In fact, by noting the similarity between the α_2 -term in Eq. (4) and the electroweak PV interaction of Eq. (3), some bounds on the value of α_2 were reported from inconclusive searches of PVED in chiral molecules ($\alpha_2 < 10^{17}$ [21]). On the other hand, as neither the α_1 nor the axion-mediated interaction are truly chiral influences, they do not produce any energy splitting between enantiomers.

Although the main idea of Leitner and Okubo (*the weaker the interaction the more symmetries it violates*) is appealing, a physical explanation for a possible parity-violating gravitational interaction was needed at that time. Fortunately, the quest for a quantum theory of gravitation has provided us with some physical mechanisms that incorporate naturally P-odd gravitational effects, as will be commented on in the rest of the article.

Physical Mechanisms

- Chern-Simons (CS)-modified general relativity

CS-modified gravity (for an excellent and authoritative review, see[57]) is an effective extension of general relativity that includes gravitational PV. Such a theory is motivated by particle physics, string theory, and geometry. But, why is it interesting to look for a quantum theory of gravity? To give an example (apart from aesthetical considerations), the long-sought dark matter and dark energy might be a truly quantum gravitational effect or simply a modification of general relativity at large distances. Big bang and black hole physics are also appropriate places where quantum gravitational effects might play a fundamental role. The problem is that, in absence of a complete theory of quantum gravity and, more important, in the absence of experimental results, only theoretical unifying principles can be used to make some advances. Among the most important unifying principles in physics is the gauge principle,[58] which played a fundamental role in the development of the SMPP. It was this gauge principle that pointed the community in a peculiar direction towards the modification of general relativity, consisting of the addition of a CS term to the Einstein-Hilbert action. The CS-corrected Einstein equations have the usual form *geometry = matter* but, this time, their geometric content is not only encoded in the Einstein tensor but also in a different geometrical object called the *C*-tensor.[59] To summarize, the most common attitute of the scientific community is to view the CS correction as a model-independent way of studying gravitational PV, its signatures, and potential detectability.

But, how does PV emerge from CS theory? At this point, PV is defined as the purely spatial reflection of the triad that defines the coordinate system. It can be seen that the complete action for the theory violates or conservates P depending on the pseudoscalar character of an extra scalar field wich enters into the equations.[57] As this character is not completelly fixed, the P-odd behavior of the theory can be taken as a choice. However, although a theory is P-even, some of its solutions could not respect this symmetry (think, for example, in the natural optical rotation from chiral molecules, which transforms as a time-even pseudoscalar, that is, P-odd, T-even) and this could be the case for CS gravity.

Moreover, signals of PV can be shown by studying perturbations about the background solutions of the theory. Similar to the Maxwell theory, CS gravity promotes the vacuum to a medium in which left- and right-handed gravitational waves are enhanded or suppressed with propagation distance.[60] This effect is somehow analogous to electromagnetic birefringence. Therefore, one could say that CS gravity *prefers a chirality* since certain polarization modes will be annihilated. Other signals of gravitational PV appeared after the quintessence model was proposed[61,62] to account for the acceleration in the expansion of the universe seen from Type Ia supernovae.[63] In addition, CS-modified gravity was considered[64] as a way to search for P-odd effects from the gravitational wave sector of the cosmic microwave background.

- Loop quantum gravity

In the quest for a complete theory of quantum gravity, LQG[65–67] is one of the proposals (non perturbative and background-independent) that reconciles general relativity and quantum mechanics at the Planck scale. In this approach, the Einstein-Hilbert action is first expressed in such a way that it resembles Yang-Mills theory and can therefore be quantized via standard methods. To point out some important results obtained by LQG techniques, let us mention the solution to the initial singularity problem[68,69] and the exact calculation of black hole entropies.[70,71] Although CS gravity can be considered as emerging from LQG,[57] here we consider them separately for the sake of simplicity.

In spite of the high mathematical sophistication needed to properly understand the existing quantum approaches to gravity, it is noteworthy that there are results obtained by coupling matter to some models of quantum gravity which resemble the usual electroweak interactions between electron and quarks induced by Z exchange. The key point to obtain these results is to introduce one of the fundamental objects that appears in the general-relativity action used as a starting point for the LQG quantization of gravity, namely the Immirzi parameter (γ).[72] In fact, it can be seen[73] that the coupling of gravity to fermions in the presence of torsion and of the Immirzi parameter gives place to a P-odd effective interaction, provided that fermions do not couple to gravity minimally. This nonminimal coupling, α, appears in the effective Lagrangian of the gravitational parity violating theory as

$$\mathcal{L}_{GPV} = \frac{3}{2}\pi\beta G_N\left(\overline{\psi}\gamma_\mu\psi\right)(\overline{\psi}\gamma^\mu\gamma_5\psi), \tag{5}$$

where G_N is Newton's constant, γ_μ are the Dirac matrices and $\beta = \frac{2\gamma}{\gamma^2+1}\alpha$.

Interestingly, Eq. (5) has the same form of the P-odd part of the electroweak interaction between electrons and quarks induced by Z exchange, which reads[51]

$$\mathcal{L}_{EPV} = \frac{G_F}{\sqrt{2}}\sum_q\left[C_{1q}\left(\bar{q}\gamma_\mu q\right)\left(\bar{e}\gamma_\mu\gamma^5 e\right) + C_{2q}(\bar{q}\gamma^\mu\gamma_5 q)\left(\bar{e}\gamma_\mu e\right)\right], \tag{6}$$

where the C_{iq} $(i = 1, 2)$ are constants expressed in terms of the electron-quark coupling constants (their explicit expressions can be seen in Ref. 51).

Given the similarities between Eqs. (5) and (6), let us look for a (nuclear spin independent) gravitational P-odd potential. In the non-relativistic approximation for the molecular electrons, it can be written as

$$V^{\mathrm{GPV}} = \frac{9\pi\beta G_N}{2m}\sum_{i=1}^{n}\sum_{A=1}^{N}(Z+N)\{\mathbf{p}_i\cdot\mathbf{s}_i, \delta(\mathbf{r}_i - \mathbf{r}_A)\}. \tag{7}$$

By comparing Eqs. (5) and (6) it can be seen that both are equivalent provided

$$-G_F Q_W \leftrightarrow 9\pi\sqrt{2}\beta G_N(Z+N). \tag{8}$$

Therefore, the *effective weak charge* associated with the Immirzi parameter is[73]

$$Q_\gamma = -9\pi\beta(Z+N)\frac{\sqrt{2}G_N}{G_F} \tag{9}$$

Note that, as the operator structure of this short-range P-odd gravitational potential remains in the form $\mathbf{s}\cdot\mathbf{p}$, it constitutes a truly chiral influence.

Therefore, although we considered initially phenomenological potentials which lead to long-range truly chiral gravitational interactions, we have seen that there are some models[73] that extend general relativity including also coupling of fermionic degrees of freedom to gravity in the presence of torsion, which predict short-range gravitational PVEDs much more similar to their electroweak counterparts than those given by Eq. (3). Let us remember that β is the unknown constant related to the kind of fermionic-gravity coupling and with the Immirzi parameter. As in the α_2 case, its value can be bounded using nonconclusive searches of PVEDs in chiral molecules ($\beta < 10^{16}$ [21]).

Why Spin-Dependent?

As we have seen, both the long-range Leitner-Okubo-Hari-Dass potential of Eq. (4) and the short-ranged gravitational parity violating potential of Eq. (7) are spin-dependent. Looking for a reason (other than the desire to get PV in the gravitational force) to make gravity spin-dependent, we show that LQG (and, in a certain sense CS gravity) provides the answer in terms of unifying principles. To see this more clearly, let us consider the following example. It is well known that there is an energy associated with the spin-orbit interaction. This form of energy clearly involves the spin of the particle considered. But, as we learned from Einstein, energy is a form of matter and, therefore, by Einstein's equations, it can be considered as a source of gravity. Therefore, spin and gravity must be linked. Moreover, it can be shown that long-range spin-dependent forces between macroscopic objects could exist given general assumptions within quantum field theory.[74]

This fact presents a problem. The weak equivalence principle (which corresponds to the universality of free fall and goes back to Galileo's idea that the motion of a mass in a gravitational field is independent of its structure and composition) is violated if spin-gravity couplings are considered. However, violations of the equivalence principle are expected in attempts to unify general relativity with the other fundamental interactions and in some theoretical models (see, for example,[75] and references therein). Therefore, only the experiment could show us the right way (more on experimental results in the following section).

Expected Size of the Effects and Experimental Constraints

We have seen that two seriously considered theories that extend classical general relativity give place to PV in gravitation. This can be taken, in mathematical language, as a proof for existence. But, following the analogy, is it sufficient for us, physicists and chemists? Moreover, we are used to consider PV in the electroweak scale but, what is the corresponding energy scale for gravitational PV?

Chern-Simons gravity. The experiments usually employed to tackle the problem of the detection of gravitational PV are of an astrophysical nature. In particular, one of the most recent attempts towards the detection of CS gravity involve the use of a series of scientific research satellites designed to provide an orbiting laser-ranging benchmark for geodynamical studies of the Earth (LAGEOS)[76] and the other (EMRI) makes use of techniques designed to detect gravitational waves with the proposed Laser Interferometer Space Antenna (LISA), which is capable of observing gravitational wave sources at cosmological distances[77] (specifically, EMRI stands for extreme mass ratio inspiral, which is the orbit of a light object around a much heavier that gradually decays due the emission of gravitational waves).

TABLE 1. Experimental bounds for the CS energy scale. See text for details

E_{cs} (eV)	Ref.	Method
$\geq 10^{-14}$	78	LAGEOS satellites
$\geq 5 \cdot 10^{-10}$	79	Double binary pulsar
$\geq 10^{-14}$	80	EMRIs

Without having to enter into the mathematical details of the CS theory, let us summarize some experimental constraints recently obtained for the CS energy scale (E_{cs}), which could be useful for the readers of *Chirality* (see Table 1).

In view of the energy scale associated with CS gravity shown in Table 1, it is not surprising that CS effects remain elusive. However, given the increasing community devoted to the study of this modification of usual gravitational theories, including PV, from both the theoretical and the experimental sides (see a very recent review in[77]), interesting results are expected to appear in the near future.

Loop quantum gravity. Measurements of the weak charges of heavy nuclei (using atomic parity violation experiments) imply $\beta < 10^{30}$[73] As pointed out in,[54] this bound can be obtained looking for some β such that $Q_{\gamma} = Q_{exp}$, where Q_{exp} is the experimental measured value of the weak charge. Although the most precise measurement of the weak charge has been performed by the Boulder group,[34] being $Q_W = -72.69 \pm 0.68$ for the Cs atom (taking into account the combined experimental and theoretical uncertainty about 0.6%), it is doubtful that more restrictive bounds on β can be derived following this approach. However, as chiral molecules are sensitive to any kind of pseudoscalar interaction, they can be used to put some limits on possible P-odd gravitational interactions (equivalently, it is difficult to distinguish experimentally between energy splittings in chiral molecules due to electron-nucleon interactions and those due to some gravitational P-odd effect). Therefore, bounds on parity violation from atomic and molecular physics experiments can be interpreted in terms of bounds on parity violation in other theories (for example, gravitation). Specifically, more stringent limits can be put on β by equating the magnitude of the most recent experimental bound on PVEDs with the corresponding magnitude of a similar effect due to the potential given by Eq. (7). If we take the tightest bound on PVED for CHFClBr, we obtain $\beta < 10^{16}$ [54] which is, to the best of our knowledge, the most stringent bound on β found in the literature. Therefore, the more precise and nonconclusive the PVED measurement, the more tight the value for β one can obtain (some experimental bounds for long-range P-odd gravitation given by the Leitner-Okubo-Hari-Dass potentials have been briefly discussed above and in Ref. 54).

Potential for Selecting Life's Handedness

As mentioned in the Introduction, the electroweak energy splitting between enantiomers is, at least, consistent with the enantiomeric excess found in meteorites.[5] The key point of this consistency lies mainly in the electroweak energy scale together with appropriate Z^5 enhancement mechanisms (atomic electroweak electron-nucleus interaction is amplified by a Z^3 factor, Z being the atomic number.[32] Usually, in molecules, the energy splitting due to electroweak electron-nucleus interaction is estimated as the second-order perturbative energy together with the spin-orbit interaction, which is proportional to $\alpha^2 Z^2$, Z being the atomic number of the heaviest nucleus and α the fine structure constant[37]).

Therefore, by comparing Eqs. (3) and (7) we conclude that parity-violating LQG effects could be considered a serious candidate for selecting life's handedness if extremely tight experimental constraints on β are reported and the energy scale associated with β becomes similar to the electroweak one (remember that the energy scale associated with electroweak effects is on the order of $1\,\mathrm{Hz} \simeq 10^{-14}$ eV). Moreover, as Table 1 shows, recent bounds on the CS energy scale indicates that it is of the same order (or even larger) than the electroweak one. Therefore, CS parity-violating gravity could be also taken into account as a serious candidate (at least as serious as the usual electroweak interaction) responsible for selecting molecular homochirality. Regarding long-range-P-odd gravity (Leitner-Okubo-Hari-Dass and related potentials[54,74]), more detailed calculations are needed (see next section).

ROADMAP FOR QUANTUM CHEMISTS

Although it is well known that with the study of PV in chiral molecules one will gain knowledge of some fundamental aspects of the SMPP, we would like to conclude this review showing quantum chemists (molecular physicists, chemical physicists, or theoretical physicists) a possible route that could shed some light on both left and right directions of the diagram

$$\boxed{\text{Gravitational Physics} \leftrightarrow \text{Molecular Chirality}}$$

This could be done following these steps (of course they are not mandatory but only a suggestion). Be careful, maybe some of them are difficult!

- Obtain explicit gravitational P-odd potentials (relativistic and non-relativistic) for CS theory
- Calculate *ab initio* the corresponding CS-PVEDs for some selected chiral molecules
- Interprete these findings in terms of experimental results (positive or negative) on electroweak PVED detection
- Using the previous point, obtain some interesting bound on the energy scale of CS P-odd gravity
- Go deep in the analogy between Eqs. (3) and (7)
- Try to design a (very clever) experiment with chiral molecules to put a really stringent bound on β
- Calculate *ab initio* the corresponding PVEDs for the α_2 term of Eq. (4). Note that the interaction is now long-range, contrary to the usual electroweak one
- Interprete these findings in terms of experimental results (positive or negative) on electroweak PVED detection
- Using the previous point, obtain some interesting bound on the energy scale of long-range P-odd gravity

CONCLUSION

In this work we have reviewed possible universal sources of both true and false chirality related to the gravitational interaction. In the former case, both phenomenological and first-principles-derived parity violating gravitational potentials have been discussed and compared to their usual electron-nucleon electroweak counterpart, widely used in the field of molecular physics. In the latter case, a phenomenological parity-violating gravitational potential with the same structure as the axion-mediated one has been introduced. Although these gravitational parity violation effects in molecular physics remain, for the moment, speculative, their classification as truly or falsely chiral influences might be of interest for those readers interested in chirality from an interdisciplinary point of view. Moreover, although their role in establishing molecular homochirality is not clear at this time, recent findings indicate that it is far from being negligible. Maybe future quantum chemical calculations will shed some light on this and other intriguing aspects related to parity violation in gravitation.

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