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Homochirality: A Perspective from Fundamental Physics

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Abstract: In this brief review, possible mechanisms which could lead to complete biological homochirality are discussed from the viewpoint of fundamental physics. In particular, the role played by electroweak parity violation, including neutrino-induced homochirality, and contributions from the gravitational interaction, will be emphasized.

Keywords: homochirality; parity violation; neutrinos; gravitation

1. Introduction

Life is not symmetric; i.e., left- and right-handed biological structures are not equivalent. In fact, there are almost only D-sugars and L-aminoacids in living systems. This remarkable fact is known as biological homochirality, this being one of the more intriguing fundamental problems of science for which an appropriate solution is still lacking [1]. Concerning possible routes which could led to complete homochirality, the idea of an extraterrestrial origin [2,3] for it has been reconsidered from the discovery of an enantiomeric excess of L-aminoacids in some meteorites [4]. Therefore, symmetry-breaking Earth-based mechanisms are actually not considered, these being superseded by universal mechanisms of chiral selection. Among these mechanisms, parity violation (PV) in (electro)weak interactions acquires special interest despite its tiny effects due to its ubiquity from particle physics to complex biological systems. We remark here that these effects have not been detected in molecular systems up till now, although several routes have been proposed in the past 40 years to succeed. Among the various proposals, here we remark on continuous efforts from several groups around the world, which include Quack [5], MacDermott [6,7], Chardonnet [8], Schwerdtfeger [9], Budker [10], DeMille [11,12], Hoekstra [13], Schnell [14] and Fujiki [15–17] groups and some proposals by Bargueño and coworkers [18–21] which were strongly influenced by the pioneering works of Harris [22]. In the context of blueautocatalysis and absolute asymmetric synthesis, the group of Soai has identified an interesting reaction [23] which was later interpreted by Lente [24] in the context of PV.

Concerning the evidence of the role played by PV effects in establishing biological homochirality, the works of MacDermott and coworkers have been decisive. They found [25] that the energy differences between two enantiomeric forms of all aminoacids found in the Murchison meteorite were negative due to PV (the so-called parity-violating energy differences (PVEDs)). Furthermore, they found intriguing correlations between the observed values for the enantiomeric excess (excess for the left enantiomer) and the calculated values for the PVEDs. Therefore, following these results, one could conclude that the PVED between enantiomers is, at least, consistent with the meteoritic enantiomeric excess [25]. At this point it is important to remark that an extremely small energy difference such as the PVED can only be interpreted statistically and it will not cause a deterministic excess of the favored enantiomer. Rather, it will cause a minor deviation from symmetry in the probability distribution, which has very important consequences as discussed, for example, in [26]. Among these consequences, Lente concluded that the PVED is very unlikely to be relevant regarding the origin of homochirality, based on calculations at room temperature. However, if the temperature of the medium is very cold, as for instance in the interstellar medium, the PVED still persists as a valid candidate to produce complete enantioselection.

Interestingly, in a different context but also related to PV, neutrino-induced homochirality is being considered a plausible source for biological homochirality. From the early works of Cline [27,28], it has been suggested that neutrinos emitted in a supernova explosion could lead to certain amount of enantiomerism. Different suggestions, which explicitly depend on PV effects, involve the effects of cosmological neutrinos [29,30], neutrinos from supernovae [31,32], or even dark-matter candidates [30] on molecular electrons. In addition, there are some interesting works by Boyd and coworkers concerning a mechanism from creating aminoacid enantiomerism by taking into account the couplings of certain spins with the chirality of the molecules. In addition, for this mechanism to work, neutrinos and the magnetic field coming from the supernova progenitor should be considered [33–36].

Finally, we would like to remark that even though the electroweak force is the only one among the fundamental interactions that incorporates PV naturally, there are some interesting models that extend the usual gravitational theory (Newtonian or Einsteinian) by incorporating PV effects. Although their possible effects towards establishing complete enantioselection have not been considered until very recently [37], here we remark that some of the parity-violating extensions of general relativity proposed in [37,38] have been already tested [39], therefore paving the way for future experimental observations of gravity-induced homochirality.

The present work is intended to provide a brief review of the theoretical description, together with their experimental relevance, of the universal mechanisms described in this introduction which could be related to biological homochirality. Therefore, we will focus on electroweak- (including neutrino-) and gravitational PV.

2. Electroweak Parity Violation

One could think that both from the theoretical and from the experimental points of view, the main advances in basic questions (in physics) usually come hand in hand with high-energy physics. Although this is a generalized belief, here we will point out that this is not the general rule. However, fundamental importance should be given to very important and exciting achievements within the field of high-energy physics. The first symmetry violation was found by Wu [40] in the mid-1950s, after some pioneering theoretical works by Lee and Yang [41]. After that, PV was naturally incorporated into the Standard Model of Particle Physics (SMPP) by means of the electroweak unification developed by Glashow [42], Salam [43] and Weinberg [44], together with its corresponding renormalization by 't Hooft [45] and Veltman [46]. Coming back again to the experimental side of the history, the main ingredients of the SMPP were found by the discovery of the Z boson [47] and, finally, of the Higgs boson [48].

However, as first noticed in the 1970s at Novosibirsk, also table-top experiments could serve to ask big questions. Specifically, spontaneous optical activity of Bismuth atomic vapors was observed [49,50], extending the validity of the electroweak theory not only to the subatomic but to the atomic realm. After this important low-energy experiment, by improving low-temperature and high-resolution spectroscopic techniques, Wiemann and coworkers discovered the nuclear anapole moment of Cesium [51]. Here we remark that the anapole moment results from a parity-violating interaction between the nucleons and the electron. These and other low-energy experiments within PV are used presently in the main laboratories around the world to search for new physics beyond the SMMP [52–54]. Therefore, one can conclude that high-energy physics is not the only way of knowing Mother Nature. For a recent review, please see Ref. [55].

Therefore, we have arrived at a point where PV has been observed in several energy scales ranging from particles and nuclei to atoms. However, if we continue towards highly complex systems we find... molecules! Therefore, it is legitimate to ask: is there any role for PV in molecular systems? Furthermore, could we gain valuable knowledge by studying it and by trying to observe it in the laboratory? In addition, finally, is the question: is there any connection between molecular PV and biological homochirality? Who knows?

2.1. Electron-Nucleon Interaction

What we already know is that with PV, there is a small enantiomeric energy difference between the corresponding molecular ground states, this being (mainly) due to the nuclear spin-independent interactions between nuclei and electrons [56]. Although these PVEDs are extremely small (of the order of 100 aeV for the two enantiomers of CHBrClF) [57,58], they are expected to be detected using different experimental techniques. Among them, we would like to point out rovibrational [8] and Mössbauer/NMR spectroscopies [9], dynamics in excited electronic states [5,59], spin–spin coupling [10], electronic spectroscopy [14] and a more recent technique that involves the use of cold molecules [13]. Finally, different proposals concerning measurements of the optical activity of a molecular sample with complete initial enantiomeric excess has been reported [18,19]. Despite all these efforts, no one has succeeded.

Up to this point we have mentioned the PVED several times. Now, it is time to define it. The PVED, ΔE^{ew}, between the L and R enantiomers is given by

$$\Delta E^{\mathrm{ew}} \equiv \langle L|V^{\mathrm{ew}}|L\rangle - \langle R|V^{\mathrm{ew}}|R\rangle = 2\langle L|V^{\mathrm{ew}}|L\rangle, \tag{1}$$

where V^{ew} is the electroweak parity-violating potential that uses a nonrelativistic approximation for the molecular electrons, reads [60,61]

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

Within this expression, G_F, Q_W and θ_W are Fermi's constant, the weak charge (corresponding to the considered nucleus), and Weinberg's angle, respectively. By m, $\mathbf{s}_i$ and $\mathbf{p}_i$ we denote the mass, spin, and momentum of the molecular electron. The delta function refers to the density of the nucleon, which has been considered to be point-like.

Please note that when only electromagnetic interactions are considered, as is usually done in molecular physics computations, the two enantiomers become degenerate and, thus, following simple energetic considerations, equally probable. However, this time, the molecular Hamiltonian contains a new term, given by Equation (2), which makes things very different. The most important point to remark here is the following:

The helicity operator, $h = \mathbf{s} \cdot \mathbf{p}$, is chiefly responsible for PV. This operator is P-odd, T-even and, therefore, PT-odd. Thus, following Barron's definition of what a truly chiral influence is [62–72], we see that h constitutes a universal truly chiral influence. Therefore, it lifts (as the PVED does, which in fact is based on the h operator) the degeneracy between enantiomers. Thus, if this small enantiomeric excess coming from P-odd effects could be amplified by some mechanisms such as, for example, the Kondepudi one [73] (for a review of amplification mechanisms with emphasis on stochastic models, see, for example, Ref. [74]) and references therein, at the levels seen in the Murchison meteorite, this would mean, at least, a big step towards establishing biological homochirality towards PV.

2.2. Electron-Neutrino Interaction

As previously mentioned in the introduction concerning the role of PV effects towards chiral selection, the electroweak-mediated interaction between both neutrino and dark-matter candidates (WIMPS) with molecular electrons have been reported in previous works [29–31]. In the first case, the interaction is also based on an interaction potential with depends on h but, in contrast with Equation (2), it crucially depends on the number-density difference between neutrinos and antineutrinos. In the

WIMP-mediated case, it depends on the number-density difference between left- and right-handed WIMPs [29–31].

As with the electron-nucleon interaction previously reviewed, one can obtain, for Dirac neutrinos and assuming nonrelativistic electrons, a P-odd potential which reads

$$V^{\nu-e} \sim \frac{G_F}{m_e}(n_\nu - n_{\bar{\nu}}) \sum_i \mathbf{p}_i \cdot \mathbf{s}_i. \tag{3}$$

As in the electron-nucleon case, this interaction causes a PVED between enantiomers because the helicity of a molecular electron has a different sign for each molecule depending of its chirality. Specifically, a surprisingly large energy split comparable with the thermal energy associated with the interstellar medium (10 K) was obtained when considering supernova neutrinos [31]. Therefore, although the model presented in Ref. [31] can be considerably improved, we think the large energy split between enantiomers due to supernova neutrinos is large enough to include it as a plausible mechanism for the origin of homochirality (we remark we are mainly reviewing the *origin* but not the *amplification* of homochirality). Concerning cosmological neutrinos and dark-matter candidates, the energy splits could reach, in the most favorable case, 10^{-21} eV [30].

3. Gravitational Parity Violation

The first ideas on gravitational PV appeared when Leitner and Okubo thought that if the weakness of the weak interaction had something to do with the violation of the parity symmetry, then, following the same reasoning, maybe there was some PV also present in the gravitational interaction [75]. After their proposal concerning a modified gravitational potential [75], Hari Dass extended it by writing a potential of the form ($c = 1$) [76]

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

In this equation, M stands for the mass of the gravitating object and $\mathbf{r}$ is its separation vector from a test particle whose spin and velocity are given by $\mathbf{s}$ and $\mathbf{v}$, respectively. It is interesting to note that under CPT conservation, only the α_2 term represents a true chiral interaction within this extension.

As pointed out in [37] and, as far as the author knows, the first (and only) application of PV within chiral molecules and the generalized gravitational potential of Equation (4) is Ref. [38]. The problem to compute the corresponding PVED between enantiomers, $\Delta E^{\text{grav}} = 2\langle L|V^{\text{grav}}|L\rangle$, is that α_2 is totally unknown. Despite this, what can be done is to put some bounds on the value of α_2 using non-conclusive experimental efforts towards establishing a clear signal of PV in chiral molecules ($\alpha_2 < 10^{17}$ [38]).

Although Leitner, Okubo, and Hari Dass's phenomenological ideas were appealing at that time, the quest for a complete quantum theory of gravitation has provided us with well-motivated physical mechanisms which naturally incorporate PV in the gravitational sector, as will be commented on in the next section.

3.1. Chern-Simons Modified General Relativity and Loop Quantum Gravity

Chern-Simons (CS) theory is a modified theory for gravity [77] that extends general relativity by including PV. This is done by considering not only the Einstein tensor (as usually done in general relativity) but also the C–tensor [78] and an extra pseudoscalar (as the h operator previously defined) field [77]. From the point of view of PV, one of the most important points to be remarked is that CS gives place to some kind of birefringence somehow analogous to its electromagnetic counterpart (left- and right-handed gravitational waves are selectively suppressed and, therefore, one could say that the CS theory has preference for a particular chirality) [79]. The interested reader can have a look at other signals of gravitational PV in Ref. [37] and references therein.

Regarding the experimental constraint for the CS energy scale (E_{cs}), which will be of interest when interpreted in terms of a possible enantioselection route, see Table 1. In view of these numbers, it is not surprising to say that CS effects remain elusive. However, we ask the interested reader to remain alert to the near future, in particular with relation to gravitational wave experiments.

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

E_{cs} (eV)	Ref.	Method
10^{-14}	[80]	LAGEOS satellites
$5 \cdot 10^{-10}$	[81]	Double binary pulsar
10^{-14}	[82]	EMRIs

Other important candidates that incorporate P violation in the gravitational sector is Loop Quantum Gravity (LQG) [83–85], a theory which reconciles general relativity and quantum mechanics at the Planck scale. Without entering into mathematical details, here we note that there are some models within LQG [86] that give place to a nuclear spin-independent gravitational P-odd potential between electrons and nuclei of the form

$$V^{\mathrm{GPV}} = -\frac{9\pi\beta G_N}{2m} \sum_{i=1}^{n} \sum_{A=1}^{N} (Z+N)\{\mathbf{p}_i \cdot \mathbf{s}_i, \delta(\mathbf{r}_i - \mathbf{r}_A)\}. \quad (5)$$

Therefore, an *effective weak charge* appears when comparing Equations (2) and (5) [86] as

$$Q_\gamma = -9\pi\beta(Z+N)\frac{\sqrt{2}G_N}{G_F} \quad (6)$$

As the reader can see, the operator entered into Equation (5) is again h and, therefore, we have a short-ranged P-odd gravitational potential which constitutes a truly chiral influence.

3.2. *Gravitationally Selected Homochirality?*

As noted before, the comparison between the two charges, *weak* and *effective weak* of Equations (2) and (5) permits the opening of the way for treating PV in LQG as a possible candidate which could contribute to the selection of biological homochirality. However, extremely precise experimental constraints on β must be reported to finally see if the energy scale associated with it could reach the electroweak one (which is about 1 Hz $\simeq 10^{-14}$ eV). Concerning CS gravity, and as Table 1 shows, its corresponding energy scale could reach (or even supersede) the electroweak one. Therefore, CS gravity could also be also considered an interesting candidate towards establishing molecular homochirality.

4. Conclusions

In this work we have briefly reviewed possible ways to obtain complete biological homochirality for the point of view of fundamental physics. Emphasis has been given to electroweak, neutrino, and gravitational PV. Although the hypotheses here presented are well sustained from a theoretical point of view, specific calculations (quantum chemistry-like) would be desirable to test them. We remark that the work here presented refers to the origin but not to the amplification of molecular homochirality. In this sense, amplifications mechanisms adapted to the initial biases here described could be designed to see if the effects here presented remain realistic.

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