ON THE DETERMINATION OF THE PHYSICAL ORIGIN OF HOMOCHIRALITY IN LIFE

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ABSTRACT

There are many who believe that the observed molecular homochirality in all living things is actually required for life and must have preceeded it in the prebiotic medium. While the sign of the homochirality could be the result of chance, it is also possible that it is produced by the weak interactions being chirally broken. We consider three stages of this problem: (1) Fundamental interactions that may cause asymmetries; (2) Amplification and experimental tests of the effects through bifurcation processes; and (3) The possible influence of these effects on prebiotic molecules in pre-solar system (dense) molecular clouds. We critically review the experimental evidence for chiral-symmetry-breaking effects and discuss a possible new round of experiments using powerful GaAs polarized RF electron guns.

1. Homochirality of Life

For more than a century, there has been evidence for the chiral nature of life forms on Earth. Pasteur was among the first to point this out (1848-1880), and the universal nature of chiral symmetry breaking in DNA and RNA is now very well established for all life forms. Figure 1 shows how the homochirality is manifest at the molecular level. With the discovery of parity violation in charged current reactions in 1956 and of the weak neutral currents (WNCs) in 1973, two universal symmetry-breaking processes (WNC and β -decay) were uncovered that could have determined the handedness of DNA and RNA. These processes are shown at the fundamental level in Table 1. The main problem is the extremely small symmetry-breaking effects ($\Delta E/k_B T \sim 10^{-17}$). However, there are plausible non-linear mechanisms that could have amplified this small, symmetry-breaking phase transition up to the full symmetry-breaking level observed in life forms. There is, nevertheless, a long-standing controversy as to whether these non-linear effects are actually large enough to have determined the selection of the handedness of life [1-11].

Recently there has been increasing interest in the chiral nature or handedness of biomolecules. In fact there are some who claim that the complex biomolecular structure of life must have arisen from a "chiral pure" medium [12,13] and may be a precondition for the emergence of self-replicating biomolecular systems. Table 2 lists some of these ideas, which have been put forward largely by W. Bonner and V. Goldanskii [12,13]. We also point out a recent review in Ref. [14]. This concept, combined with the likelihood that the period on

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Figure 1. Examples of molecules that are isomers, some of which exist in nature and some that do not.

TABLE 1. History of physical chiral symmetry-breaking observation

Period	Observation	Consequences
1953-1955	τ - θ puzzle in Strange particles	Hints of parity violation
1957	Parity violation prediction/observation in Co^{60} and $\pi^\pm/\mu^\pm$ decays	V-A theory of weak interactions; ν_e , $\bar{\nu}_e$, $e^\pm$ have definite chirality
1964	CP violation ($K_L^0 \rightarrow \pi^+\pi^+$ observed)	$K_L^0 \rightarrow \pi^+e^-\bar{\nu}_e$ and $K_L^0 \rightarrow \pi^-e^+\nu_e$ have different rates
1973	Observation of WNC	Electroweak unification
1976-1978	Parity violation in WNC	Atomic parity violation
1983	$W^\pm/Z^0$ observation at CERN-UA1	Electroweak theory
1987	$\bar{\nu}_e$ detected from SN1987A	--
1986-1994	Precision measurements of electroweak parameters	--
FUTURE: Test of CPT; Origin of CP violation		

TABLE 2. Importance of Homochirality in Living Systems [12,13,15]

1. DNA: Self-replication would not work with heterochiral systems (50% L and 50% D).
2. Errors in DNA Replication: Without a pure chiral structure, the error rate in replication would be unacceptable to long-lived systems (higher animal forms, trees, etc.).
3. In a Prebiotic Medium: Homochirality must have been either
 - (A) Established in a very short time on earth (≤ 100 Myr), or
 - (B) Existed in ISM organic materials near the solar system.

Earth for life to have originated seems to be sometime between 3.8 and 3.5 billion years ago, leaves a small window of 300 million years or less for life to have emerged from the prebiotic medium. Indeed, some speculate that the time could be less than 10 million years.

The viewpoint of this review is to consider three issues: (1) Fundamental interactions that could cause homochirality, (2) Amplification mechanisms, and (3) Application to the pre-solar system interstellar medium (ISM), which may be the natural origin of the prebiotic molecules. In this paper we refer to a recent conference, sponsored by UCLA, on the "Physical Origin of Homochirality in Life," held in Santa Monica, California in 1995 [15], and provide a critical review of the experimental evidence for asymmetric interactions in biological materials.

2. The Molecular Parity Selection of Charged and Weak Neutral Currents

Charged-current effects that violate parity is one candidate for the symmetry-breaking process [9,10]. The WNC, which interferes with the electromagnetic field and gives rise to weak distortions of virtually all electromagnetic effects, could be one of the candidates that causes symmetry breaking in the biosystem [11]. It could make the broken symmetry of the micro world translate to the macro world and, finally lead protein and both DNA and RNA to display, respectively, left-handed (L) and right-handed (D) forms. For organic molecules, however, the difference between the ground state energies of the L and D types is about $\Delta E \sim 10^{-17} k_B T$ of the thermal energy at room temperature [6,7].

There have been various experimental tests of the effects of weak interactions on biological materials, which have all been null to date. (See Refs. [12] and [13] for a review and for an excellent introduction to this subject.) We will return to this issue later when we discuss possible new experiments.

There are other processes that select chiral states, for example absorption of circularly polarized light [2,3]. For some time, there has been a debate as to whether combinations of electric and magnetic fields could cause a chiral symmetry breaking [3,13]; for a recent discussion see Barron [15], which was presented at the meeting by A. MacDermott, Oxford University.

In this review, we consider methods to investigate the origin of the homochirality by studying the internal properties of the biomolecules (illustrated in Fig. 2). These studies will

POSSIBLE TESTS FOR (A) OR (B) OR BOTH

1. CPL Destructive
2. Spin-Orbit Asymmetry of $e^\pm$ Beam Interactions

Figure 2. The various components of symmetry breaking in molecules.

amount to the detection of some sort of macroscopic form of parity violation using different types of probes. Rather than stress a personal opinion on the origin of homochirality, we intend here to point out the past and possible future experiments that may be relevant in answering this question.

The calculations of the effect of weak interactions in the scattering of $e^\pm$ in organic molecules are very incomplete. The most recent calculations of Hegstrom [16] provide an excellent set of references to the early work, and the most complete recent calculations have been carried out by W. R. Meiring with the mediated symmetry shown in Fig. 3 [17]. (At the end of this review, we will indicate some criticism of this calculation.) At high energy, the $e^\pm$ asymmetries are the same, since the product $q\vec{p} \cdot \vec{\sigma}$ is the same sign for $e^\pm$ emitted in β -decay. At low energy, these calculations are more difficult, since the effects of e^- exchange diagrams are very important. If these calculations are correct, at 100 eV the e^- asymmetry could be very large (10^{-2} - 10^{-4}).

We now turn to the experiments. Over the past 20 years, many experiments have been carried out (see Ref. [12] for a nearly complete list). However, it appears that nearly every positive effect that was observed has turned out to be incorrect. In Table 3, we list some

Figure 3. Most recent published calculation of the expected asymmetry for the scattering of $e^\pm$ from chiral molecules [17]. We also include some recent measurements or limits on such an asymmetry.

TABLE 3. Experiments where a chiral effect has been observed (and not refuted)

	Experiment	Beam/Source	Target	Detection	Comments	Ref.
1	CPL on L/D photo absorption	UV/keV radiation	DC tartaric acid, DL alanine, DL glutamic	Observe destructive difference in one chirality	To be expected from optical activity	Norden [19]
2	e^- target - $\bar{C}$ light	P^{32} source and Ca^{137} (no chiral electrons)	R- or S-PBA	Observe different $\bar{C}$ light intensity due to chiral electrons	Effect too large to be due to $\bar{C}$ radiation from spin effects	Garay et al. [20]
3	Co^{60} - γ + [L,D]	Co^{60} γ s	D or L alanine	Observe different amounts of L, D after irradiation	Other experiments did not produce this effect	Akabosh et al. [21]
4	Introduction of L/D chiral particles	Sr^{90} , Y^{90} β -decay	Y^{90} D or L alanine	Detect effects by electron spin resonance technique	The electron spin resonance may be sensitive to spin dependence	Conte et al. [22]
5	Low-energy polarized e^- beam	GaAs polarized source, 5 eV	Camphor L, D	Observe different electron polarization and beam attenuation in L/D	At such low energy, asymmetry may be too large	Campbell et al. [23]

experimental results that are not yet refuted or in direct conflict with previous null effects. We will discuss two of these experiments here. The observation that circularly polarized light destroys L and D isomers selectively (entry 1 in Table 3) is now well established. Figure 4 shows a fairly recent observation, and there is no doubt that this effect is real. (We understand from a private communication from L. Keszthely that there are now experiments that seem to contradict the results of entry 5 on Table 3).

The other experiment to which we will refer is that of entry 2 (also on Table 3), the study of Cherenkov light in L or D material with chiral e^- (β -decay) [20]. The main results from this experiment are shown in Fig. 5. The authors claim an effect of perhaps 10^{-2} magnitude. This is, in our belief, far too large an effect, but a future study of Cherenkov radiation from L or D materials with polarized e^- beams could be promising.

In Fig. 3, we show the current limits or observations of asymmetry. The e^- measurement of Gidley *et al.* [18] is a very nice experiment. Our conclusion is that no present experiment has reached the level of sensitivity needed to observe an effect. Therefore, it is premature to count out the weak force as a determining factor in the origin of homochirality in life.

3. The Conditions for the Small Electroweak Asymmetries in the Prebiotic Medium to Be Amplified—Simulations

If it is possible for the WNC interaction to provide additional parity-selection energy difference in an organic biosystem, the handedness of the organic molecules might appear. Such additional parity-selection energy difference could be thought of as a small bias in this transition process. For simulation, this small bias is converted into a non-dimensional parameter, $g(\Delta E/k_B T)$, to characterize the relative difference in the time to effect the phase transition. The work of Kondapudi and Nelson is seminal in this regard [1]. At UCLA, a series of simulations with constant g has been done that shows that an amplification process can occur [8,24].

Figure 4. Effects of polarized light on racemic organic molecules.

FIG. 1. a, Cerenkov pulse-height spectrum of ^{32}P dissolved in R- or S-PBA. Differential spectra (b-f) are generated by subtraction of the count rate in each channel of S from those of R. Differential spectra of b, R- and S-PBA shown in a; c, external ^{32}P and d, Compton electrons from ^{137}Cs . Scintillation differential spectra for e, ^{35}S and f, ^{32}P . Scintillation solutes were PPA and POPOP, see ref. 12 for method. A smaller amplitude for these processes may reflect the multiple achiral energy transfer processes of the liquid scintillation measurement. The first part of the ^{32}P spectra was removed to minimize the Cerenkov effect recorded in low-energy channels and concomitant irradiation from β -particles from unavoidable ^{33}P contamination. The latter may contribute to the high standard deviation on the ^{32}P differential scintillation spectrum. Note the different scales on the ordinates of the differential spectra. All spectra represent the average of four PBA samples measured in random order; the instrument was calibrated before each measurement. Saturation of photomultiplier and overspill between channels were avoided by assuring low count rates; samples of <200,000 total c.p.m. were used. All spectra were taken in five-channel increments and normalized to the total count rate. Error bars represent the standard deviation for each point. This set of experiments was repeated eight times with different batches of enantiomers and ^{32}P , a total of 32 spectra. All measurements yielded consistent results.

Figure 5. Possible evidence for different intensities of Cherenkov light from chiral electrons on dissolved PBA (liquid) samples [20].

In contrast to the gradual buildup of symmetry breaking [1,8], as proposed by Kondepudi, we also studied a more general condition that also allows for an impulse of chiral symmetry breaking [24,25]. For example, a natural fission reaction, where a large amount of U^{235} may have accumulated by accident, or a nearby supernova explosion could provide such a chiral impulse. Initially this might seem to be an unimportant effect that has been ignored in the past literature on this subject but, with increasing interest currently, more attention should be paid to this issue. Here we present some results based on our previous work [8] [$\alpha = (X_L - X_D)/(X_L + X_D)$, the concentration of L and D isomers]:

$$\frac{d\alpha}{dt} = -A\alpha^3 + B(\lambda - \lambda_c)\alpha + \epsilon^{1/2}f(t) + Cg \quad (1)$$

becomes

$$\frac{d\alpha}{dt} = -A\alpha^3 + B(\lambda - \lambda_c)\alpha + \epsilon^{1/2}f(t) + Cg + d\delta_{\gamma\gamma'} \quad (2)$$

where α is the amplitude of the symmetry-breaking solution, λ is the control parameter, λ_c is the symmetry-breaking transition (critical) point, $\epsilon^{1/2}$ is the rms value of fluctuation (noise), $f(t)$ is the normalized fluctuation (noise), g is the interaction or bias symmetry-breaking selector, d is the amplitude of a quasi δ -pulse, and $\delta_{\gamma\gamma'}$ is the δ -function, which gives $\delta_{\gamma\gamma'} = 1$ when $\lambda = \lambda'$ and $\delta_{\gamma\gamma'} = 0$ when $\lambda \neq \lambda'$. Therefore,

$$\lambda = \lambda_c + \gamma t \quad (3)$$

where λ_c is the initial value of λ , γ is the evolution rate, and t is the evolution time.

To solve the first-order stochastic equation numerically, we designated the initial symmetry-breaking amplitude, α , as zero at time $t = 0$, but the $f(t)$ is a random number generated by the computer. To obtain the trace of α at a different time for each trial, we just sampled it at different times. (Our studies confirm the results of Kondepudi and Nelson [1].) One simulation assumes that the impulse takes place near and after the critical point ($\lambda_c = 1.0$) at $\lambda = 1.5$, and $\delta = d/g = 100$ is shown in Fig. 6. In this case, the impulse plays a dominant role to push the process toward a favored state! We have studied over 40,000 trials and find a trend that the early chiral impulse produces a significant bias towards the preferred state. Furthermore, we found an 88% probability of the favored state being selected [8,24]. This illustrates the effect of a small symmetry-breaking process on a slowly evolving system. In essence, the small bias is magnified by the process of signal averaging, where the noise effect essentially cancels out. This process is sometimes called the Kondepudi effect [1].

The addition of a chiral impulse to the gradual bifurcation process of Kondepudi and Nelson could provide arguments in favor of a rapid buildup of the homochiral prebiotic medium, either in the ISM before the solar system was formed, and/or during the evolution of the medium in the water-based system on Earth. We have also studied the system near the critical point in our simulations and do not observe the effect discussed in Refs. [3, 13, and 14].

Recently, we have developed an electronic circuit to study the bifurcation process, as shown in Fig. 7(A) [25]. We have paid special attention to the noise generator, which is crucial if a noise-averaged process is to be studied (as in Ref. [1]). Figure 7(B) shows the scope trace for the bifurcation studies, showing clear evidence that a small bias can shift a state even in the presence of large noise! We are continuing parameter studies with this electronic circuit to further investigate this noise-averaged bifurcation process.

Figure 6. Single trial with an impulse at $\lambda = 1.5$, where $\delta = dg = 100$. The impulse strongly affects the phase transition.

Figure 7. (A) Schematic of the UCLA chiral symmetry-breaking electronic circuit for bifurcation processes. (B) Scope trace of the output of the electronic circuit of (A), showing that a small bias in the presence of large noise can still switch the system into a preferred state.

4. The Santa Monica Symposium

For many years, there have been several issues associated with the homochiral structure of biomolecules, as first observed by L. Pasteur in 1848:

- (A) Is a homochiral structure necessary for life as we know it?
- (B) Did homochirality precede the formation of life (homochiral prebiotic medium hypothesis)?
- (C) Is there any reasonable physical mechanism that could have produced the large chiral symmetry breaking in the prebiotic medium or in the observed homochiral structure?
- (D) Is the homochiral structure an accident that occurred in the biological systems and was later amplified?
- (E) Can the homochirality be used as a signature for existing or previous living systems in the solar system or other parts of our galaxy?
- (F) Are there any experiments that can be carried out now to clarify the origin of homochirality?

These and many other questions were the basis for organizing the first symposium on this subject in Santa Monica, California. Some of the leaders in this field attended the meeting, made presentations, and joined the discussions. The following is a brief review of this meeting.

The Santa Monica meeting started with an overview of the importance of homochirality in biomolecular life by W. Bonner (Stanford) and V. I. Goldanskii (Moscow). Their conclusions were that homochirality is almost certainly required for the formation of the complex, self-reproducing biomolecular structures (*i.e.*, DNL) required for life. They both stated that the prebiotic medium should have been homochiral, although they differed on how and even where this may have happened. A. K. Mann (U. Penn.) and D. B. Cline (UCLA) discussed the possible physical processes that could have helped produce chiral symmetry breaking. Radioactive β -particle interactions and the influence of WNC all "violate parity" but are also very small effects. There was a brief discussion of the role that nearby supernovas could have played in the ISM before the solar system formed. It was agreed that some powerful amplification mechanism must have intervened to achieve any large effect.

On February 16, the first session was "Biomolecular Aspects of Homochirality." There were four very interesting presentations: Goldanskii (Moscow), G. Gilat (Technion), V. A. Avetisov (Moscow), and S. Miller (UCSD). Goldanskii discussed the Frank process (invented by and named after the British chemist), which can be used to amplify physical or spontaneous chiral symmetry breaking in so far as no definite chemical reaction has been proposed as an example of the Frank process. Goldanskii showed that formaldehyde could be assembled in a Frank-type process. Gilat indicated some other types of chiral symmetry-breaking processes that should be studied in the laboratory. Avetisov discussed the very interesting question of assembling a complex structure like DNA out of homochiral monomers. He indicated that even with a homochiral prebiotic medium, a "complexity threshold" would be reached, the passing through of which is hard to understand. Part of the final talk in this session by Miller dealt with the famous Miller-Urey experiment, which showed many years ago how amino acids can be formed using an electrical discharge in a methane-water, *etc.* gas medium. In his talk, Miller indicated that homochirality is not needed to give birth to biomolecules, however, it is a very great aid to life. He also pointed

out that the organic materials produced in the famous Miller-Urey experiment were tested and found to be racemic!

The next part of the meeting, "Physical Origin of Homochirality-Symmetry Breaking," took the better part of February 16 and the first part of the morning of February 17, and caused the most controversy. There were three themes:

1. The weak interaction, which is the only universal chiral symmetry-breaking system -- A. MacDermott (Oxford Univ.), R. A. Hegstrom (Wake Forest Univ.);
2. Small effects might be amplified by autocatalytic Frank-type processes -- D. D. Kondepudi (Wake Forest Univ.), Goldanskii, and MacDermott;
3. There may be more useful mechanisms for breaking the symmetry (*e.g.*, a biochemical process or if the organic molecules are formed in the ISM and subjected to polarized light from neutron stars) -- A. Eschenmoser (Zurich), P. E. Nielsen (Copenhagen), and Bonner.

Let us elaborate a little on some of the newer results presented at the meeting. MacDermott has carried out some very interesting calculations of the energy difference of several chirality biomolecular configurations resulting from the WNC and has found that some systems could have 10^{-14} kT energy difference, which is orders of magnitude larger than all previous estimates. Kondepudi once again emphasized the importance of the Frank/autocatalytic process and has even tested one of the ideas by studying salt crystals where the symmetry is broken by stirring the liquid! Eschenmoser showed how p-RNA could have symmetry breaking effects. Finally, Bonner elaborated on the "abiotic" possibilities of the homochirality and indicated that the time available on the early Earth for such a process to take place was less than 300 million years and could be even less than that. He indicated that a more viable possibility could be the formation of homochiral molecules in the ISM, and he proposed a specific mechanism caused by the absorption of polarized UV light from one or many neutron stars in the ISM. These ideas and others led to a healthy debate at the meeting. One issue was associated with so-called "false" chirality caused by electric and magnetic fields recently proposed by L. Barron (Univ. of Glasgow), whose talk was presented by MacDermott; similar ideas were discussed by Gilat.

The third session was devoted to "Astrophysical and Planetary Aspects of Homochirality and Origin of Life on Earth." The presentations by J. Bada (Scripps/UCSD) and J. M. Greenberg (Leiden) were very interesting. Bada first showed that biomolecular systems (*i.e.*, human teeth) progressively racemize as they age and indicated that the age of the Swiss Iceman is being determined this way. Then Bada pointed out that there is no evidence for non-racemized organic molecules in micrometeorites in the polar ice or at the K-T edge in sediments. This is a serious constraint on the theories that the organic molecules were brought in by comets, *etc.* Of course, it may not be directly relevant to what happened four billion years ago. The highlights of Greenberg's talk, "Photochemical Production of Non-Chiral and Chiral Organics in the Interstellar Dust: Laboratory, Observation, and Theory," were: Organic materials make up $\sim 10^{-4}$ of the mass in the galaxy (as dust); Halley's comet carries 10% of the biomass on earth; and Organisms in dust undergo complex chemical reactions with the help of UV light (this has been studied in the laboratory where amino acids and other biochemicals are produced). Greenberg's main theme was that homochiral biomolecules could be produced from the polarized light from neutron stars over a long evolutionary period of the large gas clouds in the galaxy (this concept was first discussed by Bonner, see Ref. [12] for example). Greenberg went on to describe an experiment carried

out with polarized UV light where selective destruction of L or D molecules was observed, thus confirming the Bonner hypothesis that comets could have brought in both homochiral organisms and water to the early Earth approximately 4 billion years ago. (There was also a discussion that supernova in the ISM could provide a chiral impulse by producing the antineutrino and Al^{26}).

The final section of the meeting was "Future Perspectives and Experiments." It is clear that some experimental results are needed if this is to be a viable field of study. I. Khriplovich (Novosibirsk) discussed a possible investigation of high-frequency radiation on homochiral substances, a careful study of which could yield the energy differences resulting from the WNC. An open discussion on future experiments was held with many participants providing suggestions. One interesting possibility is to use the new high-intensity, polarized electron guns for linear colliders in order to study the effects of polarized electrons on homochiral materials. This suggestion and other proposed experiments will be summarized in the Proceedings.

5. Organic Molecules in Space and the Possible Role of Nearby Supernovae and Neutron Stars

One of the main themes of the Santa Monica meeting was the likelihood that most of the early organic material on Earth was brought in by comets and asteroids. References [26-29] give a nice introduction, from different points of view, to this concept. There are some interesting "large numbers" to consider in this regard:

1. The estimated amount of dust matter in the galaxy is $\sim 10^{-4} m_G$, or $\leq 10^7$ solar masses, largely in the form of dust grains. A fraction of that material is in the form of organic materials [26].
2. It has not been possible to measure the amount of interstellar dust that has accumulated on the Earth (bringing organic material) [27,28].
3. In a molecular cloud of density $10^4 M/cm^3$ and 1 parsec radius, there could be complex organic matter equal to 100 solar masses.
4. The Earth revolves around the galaxy with a period of ~ 250 million years, and it likely encounters several dense molecular clouds in this trajectory.
5. It is likely that large quantities of organic material were deposited in the Earth in the first one billion years.

The above information is obtained by the infrared scattering from the dust in the galaxy and by modeling various UV-driven processes here on Earth [26]. Ultraviolet photo processing plays an important role in the organic chemistry of the dust particles [27]; see also Ref. [29], from which Fig. 8, showing the nature of the dust grain with prebiotic molecules inside, is taken.

We discuss here two scenarios where chiral interactions in the ISM could have led to a preponderance of homochiral molecules. These two concepts are outlined in Table 4, with Fig. 9 giving a fairly complete description of the hypothesis. The second hypothesis is illustrated in Fig. 10, where the possibility of the relative survival of the $e^\pm$ polarization deep within the cloud is also illustrated. Of course, during this time the effect of the WNC can be driving the system towards a homochiral state, as shown previously by Eqs. (1) and (2).

STRUCTURE OF GRAINS when they initially accrete is inferred from laboratory simulations in which mixtures of water, methane, ammonia and other simple molecules are subjected to ultraviolet irradiation at a temperature of 10 degrees K. Each grain begins as a silicate core that condensed in the atmosphere of a cool giant star. Around this core a mantle of ice forms. Ultraviolet radiation breaks some of the mantle molecules into radicals, or reactive molecular fragments (a). The radicals can then recombine in new ways (b). Over a longer period the continued ultraviolet irradiation of the grain can give rise to ever more complex mixtures of molecules and radicals (c).

Figure 8. From [29] and used in the talk of M. Greenberg at the Homochirality Symp., Santa Monica, CA, 1995.

TABLE 4. Possible sources of CPL (UV-keV) radiation in dense molecular clouds

Primordial Soup - Molecular Clouds (ISM)	
1.	Synchrotron radiation from neutron stars ([12,26]
	<ul style="list-style-type: none"> • CPL helicity depends on position (<i>i.e.</i>, above or below star); • In principle, this mechanism works. However, on the 250-Myr orbit around the galaxy, this effect is expected to average out.
2.	Radiation from weak interaction processes [30] - injection into molecular cloud
	<ul style="list-style-type: none"> • Processes: supernova $\bar{\nu}_e$ interaction, Al^{26} from nearby supernovas, <i>etc.</i> • Because of grain structure, dE/dx will be very different from that of solids, gases, or liquids; • Always gives the same chiral symmetry breaking; • Can act as a chiral impulse along with WNC

Let us consider the rate of these three effects:

1. For $\bar{\nu}_e$ absorption and a supernova 1 parsec away (or inside a 1-parsec dense cloud), the number of interactions will be $\sim 10^{-3}$ / kg of material for $100 M_{\odot}$ of organic material (which would be 10^{12} grams of organic matter that is *active*), therefore the positrons from the $\bar{\nu}_e$ interactions would lose energy at a rate of 10^{-19} MeV/cm and thus travel over a parsec.
2. For the coherent $\nu_x + N \rightarrow \nu_x + N$, and for the carbon in the hydrocarbons, we would have $\sim 10^2$ more or $\sim 10^{14}$ grams of *active* material. This effect could be very important in light of the small energy difference that separates L and D molecules and the possibility of large coherent effects.
3. For the Al^{26} over the half-life, there would be $\sim 10^{50}$ decays producing $\sim 10^{50}$ positrons that lose energy at the rate of 10^{-19} MeV/cm; for MeV positrons, the range of which would be of order of a parsec (ignoring possible magnetic-field effects).

*Observed experimentally.

Figure 9. Possible extraterrestrial origin of terrestrial homochirality.

Consider the example where $0.001 M_{\odot}$ of Al^{26} is produced and assume, for simplicity, that the energy of the e^+ is 1 MeV and is contained in the gas cloud. Assume that the cloud has a density of 10^4 atoms/cm³ and that 10^{-3} of the atoms are organic, then the stopping power for e^+ will be

$$\frac{dE}{dx} \sim \text{MeV/g/cm}^3, \quad (4)$$

and for a density of $\rho = 10^4$ atoms/cm³ $\sim 10^{-17}$ g/cm³, we find

$$dx = \frac{dE}{\rho} (\text{MeV}) \sim 10^{19} \text{ cm } (\sim 3 \text{ parsec}), \quad (5)$$

and for an average energy exchange of 10 eV, we have

$$\frac{10^5 \text{ collisions}}{Al^{26} \text{ decay}} \quad (6)$$

For $0.001 M_{\odot}$ of Al^{26} and 10^{-3} organic fraction, we obtain a total of $\sim 10^{50}$ collisions of polarized positrons, with organic materials in the cloud assuming all of the e^+ stop in the cloud. (We assume that only one of the collisions can result in spin exchange.) There will also be the same order of polarized photons from the $e^+e^- \rightarrow \gamma\gamma$ annihilation. It is estimated in Refs. [17 and 24] that the asymmetry due to the weak interaction would be of order 10^{-11} to 10^{-6} , depending on the positron energy {it scales like $\alpha^2[\alpha/(v/c)]^2$ }. Thus, it takes $N \sim 10^{22}$ interactions for the asymmetric to become statistically important. In this example there are far more interactions.

Figure 10. (A) Schematic of the effect of a supernova II on the organic molecules in a dense molecular cloud. (B) Estimated polarization of the $\beta^\pm$ decay particles as the energy decreases by ionization in H_2O and in the dense molecular cloud. One observation of the polarization of low energy e^+ by the Michigan group.

6. Future Tests in the Laboratory, Alternative Viewpoints, and Summary

In this brief review, we have only covered part of the many ideas for the physical origin of homochirality (see Ref. [31] for another viewpoint). However, we conclude that it is premature to rule out the weak force as the main effect behind homochirality in life. In this sense, we disagree with the viewpoint of Refs. [12, 13, and 15]. It is clear that only future experiments can help decide this question -- not personal opinions.

As a by-product of the Santa Monica meeting, there is now a renewed effort to study the effect of weak interactions on biological materials. Two types of particle physics experiments are being studied:

1. With the powerful RF electron guns, which provide polarized electrons for the Stanford Linear Collider and other laboratories, one can imagine a new round of experiments to search for parity violation in biological materials. In this experiment, it would be possible to decelerate the electrons to low energy where the effects should be relatively large. A Novosibirsk-UCLA team is preparing a proposal for these experiments. One initial experiment would be to study the Cherenkov light from L material (PBA) while reversing the polarization.
2. The possible use of reactor antineutrinos to simulate the effects of weak interactions, including coherent scattering from the nucleus, is being considered. (This could simulate the effect of supernova $\bar{\nu}_e$, e.g., by taking very long time exposures to obtain an equivalent flux.) It is essential to get new calculations of the scattering asymmetry [24,32].

Other terrestrial experiments will include searches for homochiral materials in meteorites, and experiments with crossed electrical and magnetic fields and purely chemical methods of inducing homochirality.

Another class of extraterrestrial experiments will involve the search for homochiral materials in comets, asteroids and, perhaps, Mars. It is obvious that, if homochiral materials are found in these systems and all display the same homochirality as that of living systems

on Earth, the case for a common physical origin is made much stronger. One intriguing possible experiment would use a future Rosetta Mission to a comet. The suggested detector, SETH (search for extraterrestrial homochirality), which would be the size of a cigar, would measure the optical activity of the samples in situ. (A. MacDermott is leading this effort and reported on it at this symposium.)

We may be entering into a new era where the very foundation of life and the physical forces of nature are seen to have a strong connection.

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