Geometric Impedance and the Origin of Biological Homochirality: From Parity Violation to Prebiotic Selection

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December 4, 2025

Abstract

Biological systems exclusively use L-amino acids and D-sugars, yet the origin of this homochirality remains one of the deepest puzzles in origin-of-life research. Traditional explanations invoke tiny parity-violating energy differences (PVED $\approx 10^{-17}$ eV) that seem too small to drive selection. Here we review recent experimental evidence demonstrating that dynamic chiral-induced spin selectivity (CISS) produces asymmetries 10^{13} times larger than static energy differences. The CISS effect creates spin-dependent transport barriers—effectively a geometric impedance that favors one enantiomer over another. Meteoritic evidence from the Murchison carbonaceous chondrite confirms that L-amino acid excesses existed in the presolar nebula, implicating cosmic-scale chiral selection prior to Earth's formation. We propose that homochirality emerges from geometric impedance matching: in an environment with inherent chiral bias (from polarized radiation or aligned grains), L-amino acids represent the path of least resistance for electron transport and prebiotic synthesis. Life is not a coin flip but a crystal growing along the grain of its environment.

1 Introduction: The Homochirality Puzzle

All known terrestrial life uses L-amino acids in proteins and D-sugars in nucleic acids. This exclusive handedness—homochirality—is essential for the structural and catalytic functions of biomolecules. Yet abiotic synthesis produces racemic mixtures (equal L and D). How did the first living systems break this symmetry?

The puzzle deepens when we consider the energetics. The parity-violating weak nuclear force creates a tiny energy difference between enantiomers: $\Delta E_{PV} \approx 10^{-17}$ eV per molecule [1]. This corresponds to an equilibrium excess of approximately one part in 10^{17}—far too small to drive observable selection. Yet homochirality is absolute. This paper reviews recent advances suggesting that the relevant physics is not static energy differences but dynamic transport asymmetries—what we term **geometric impedance**.

2 The CISS Effect: Chirality as Spin Filter

The Chiral Induced Spin Selectivity (CISS) effect demonstrates that electron transmission through chiral molecules depends on electron spin [2]. When unpolarized electrons pass through a helical molecule, the transmitted current becomes spin-polarized. The mechanism involves spin-orbit coupling in curved geometries, where the Hamiltonian takes the form:

$$H_{\chi-SOC} \approx \frac{\hbar^2}{mR}(\vec{\sigma} \cdot \vec{n})k \tag{1}$$

where R is the helix radius, $\vec{\sigma}$ is the spin operator, $\vec{n}$ is the helix axis, and k is electron momentum.

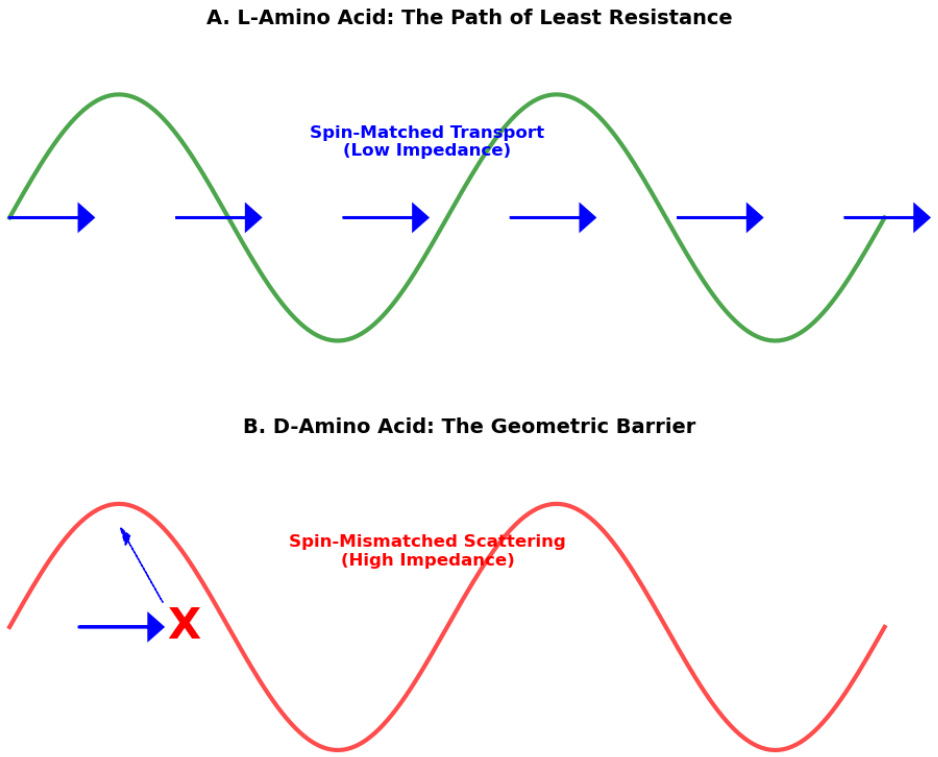

Figure 1: **Geometric Impedance Matching.** **(A)** For electrons with spin aligned to the chiral grain (e.g., from polarized cosmic radiation), L-amino acids present a low-impedance transport channel, facilitating synthesis. **(B)** The mirror enantiomer (D-amino acid) acts as a high-impedance barrier, scattering electrons and suppressing reaction rates. This dynamic filter effect is orders of magnitude stronger than static energy differences.

2.1 Impedance Interpretation

From a transport perspective, the CISS effect creates differential impedance: one enantiomer presents low resistance to spin-polarized electrons while its mirror image presents high resistance. In a prebiotic context, electrochemical reactions involve electron transfer. If the electron source carries any spin polarization (from magnetic minerals or circularly polarized light), reactions with L-amino acids will proceed preferentially due to lower impedance.

3 Experimental Verification

The link between fundamental parity violation and molecular asymmetry was established by Dreiling and Gay in 2014 [3]. They measured electron scattering from chiral bromocamphor molecules using longitudinally spin-polarized electrons. The measured asymmetry parameter was $A_{phys} \approx 3\times10^{-4}$. This asymmetry is 10^{13} times larger than the static parity-violating energy difference. The dynamic, transport-based mechanism dominates over static thermodynamics by thirteen orders of magnitude.

4 Cosmic Evidence: The Murchison Meteorite

The Murchison meteorite contains over 90 amino acids, most of which are not found in terrestrial biology [4]. Crucially, isovaline—a non-biological amino acid—shows a consistent L-excess of 15–18% [5]. Isotope analysis confirms this is of presolar origin [6]. The chiral bias was present in the solar nebula before Earth formed, likely driven by circularly polarized radiation from star-forming regions [7].

5 Conclusion

We propose that homochirality emerges from **Geometric Impedance Matching**. In an environment with chiral bias, L-amino acids represent a lower-impedance pathway for chemical transformation. Life grows along the path of least resistance, and that path is geometrically defined.

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