A Nuclear Physics Explanation of Biomolecular Homochirality: Theory and Experiment
Examining the Origin of Biomolecular Chirality

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Introduction
- Brief Astrobiology Background

Magnetochiral Effects in Chiral Selection

Results
- Shielding Tensor Anisotropy
- Astrophysical Sites

Experiment

Conclusion

Interdisciplinary project!
Proposal

- Can we simulate the astrophysical environment possibly responsible for the selection of biomolecular homochirality in a beam experiment?
- What is the energy sensitivity for polarized electrons to induce molecular chirality?
- With what sensitivity can we do this?

NAS Decadal Survey
Please interrupt any time!
Outline

1 Introduction
   - Brief Astrobiology Background
2 Magnetochiral Effects in Chiral Selection
3 Results
   - Shielding Tensor Anisotropy
   - Astrophysical Sites
4 Experiment
5 Conclusion

Proposal

Please interrupt any time!
Background: Astrophysics of Biomolecular Chirality
Building Blocks of Life: Amino Acids

Amino Acids

- An “alpha” carbon bonded to an amine group, a carboxyl group, and an additional side chain.
- Asymmetric
- Amino acids have two “chiral states”
Amino Acid Homochirality

**Enantiomeric Excess**

\[ ee = \frac{N_L - N_D}{N_L + N_D} \]

- Biologically relevant amino acids are left-handed! (\( ee = 1 \), with few exceptions)
- Meteoric abundances have abundance of L-amino acids.
- Molecular chirality is selected in space.
Extra-Terrestrial Amino Acids

**Glycine in Star-Forming Regions**
- Sgr 2B, Orion KL, W51
- NAO 12 m telescope
- Glycine and organics detected
- Other measurements as well


**Glycine in Comets**
- Comet 67P/ChuryumovGerasimenko
- Rosetta Mission
- Glycine and precursors detected during flyby

Isotopic Ratios
Clues to a Nuclear Physics Origin

Elsila et al. (2012)

$$\delta D \equiv \left[ \left( \frac{D}{H} \right)_{\text{sample}} \left( \frac{D}{H} \right)_0 - 1 \right] \times 1000\%$$

$$\delta^{15}N \equiv \left[ \left( \frac{^{15}N}{^{14}N} \right)_{\text{sample}} \left( \frac{^{15}N}{^{14}N} \right)_0 - 1 \right] \times 1000\%$$

$$\delta^{13}C \equiv \left[ \left( \frac{^{13}C}{^{12}C} \right)_{\text{sample}} \left( \frac{^{13}C}{^{12}C} \right)_0 - 1 \right] \times 1000\%$$
Brief Astrobiology Background

Models of Amino Acid Homochirality

- Origin of Life
- Origin of Homochirality
  
  **Stochastic Processes**
  - Statistical Fluctuations Of D- and L-Isomers
  - Crystalization Adsorption

  **Deterministic Processes**
  - Parity Violating Weak Force
  - EnantiomERIC Energy Difference
  - \( \beta \)-Decay Neutrinos Weak Interactions

  **Chiral Fields**
  - CPL Magnetic Fields

  **Amplification via autocatalysis**

Models of AA Chirality

- Models generally need only create a non-zero \( ee \).
- Multiple competing and overlapping theories.
- Significant physical chemistry required.
Models of Amino Acid Homochirality

- Origin of Life
- Origin of Homochirality
  - Stochastic Processes
    - Statistical Fluctuations Of D- and L- Isomers
      - Crystalization Adsorption
    - Enantiomeric Energy Difference
  - Deterministic Processes
    - Parity Violating Weak Force
      - $\beta$-Decay Neutrinos Weak Interactions
    - Chiral Fields
      - CPL Magnetic Fields

Magnetochiral Selection
- Overlap of chiral fields and weak force.
- “Magnetochiral” effect.
- Significant portion of several theories.

Famiano et al. (2018a)
Summary So Far....

- Amino acids are chiral.
- Chirality can be made in space.
- This could have something to do with chiral fields or chiral particles.
Amino acids are chiral.
Chirality can be made in space.
This could have something to do with chiral fields or chiral particles.

Next....
We will examine some of the mechanisms by which polarized leptons induce chirality.
This builds on the “Vester-Ulbright hypothesis.”
We will try to extend this model....
Chirality and Chiral Particles

Achiral Molecules → Polarized Electrons → Selective Destruction → Chiral Molecules
Polarized Leptons and Chiral Selection: The Vester-Ulbricht Hypothesis

**Brief Astrobiology Background**

**Polarized Electrons: DEA in Bromocamphor**

(Dreiling et al. (2014) Note energy scale:
eV: Atomic Scale, COLD astrophysics
MeV: Nuclear Scale, HOT astrophysics
No Magnetochiral Effect Studied

What About Astrophysics?

We need something that will penetrate meteorites.
Is There a Nuclear Effect? Magnetochiral Effect?

Higher Lepton Energies - A Toy Model

**Brief Astrobiology Background**

**Introduction**

**Magnetochiral**

**Results**

**Experiment**

**Conclusion**

**Polarized Lepton Interactions**

- Neutrinos or spin-polarized electrons
- Nitrogen: Lowest Q-value
- \( \langle \phi_f | \sigma \tau | \phi_i \rangle \)
  - Weak transitions: IBD
  - M1: Transitions above particle emission threshold
    - (cf., Fujita et al., PPNP 66, 549 (2011))
- HOWEVER, we still need to couple the nuclear spin to molecular chirality?
Summary So Far....

- Polarized electrons can interact with molecules.
- This is not well understood.
- Polarized leptons can also interact with nuclei in a spin-dependent way.
Introduction

Magnetochiral

Results

Experiment

Conclusion

Summary So Far....

- Polarized electrons can interact with molecules.
- This is not well understood.
- Polarized leptons can also interact with nuclei in a spin-dependent way.

Next....

- Nuclear spin is **not** molecular chirality.
- Can we couple the nuclear spin to molecular chirality?
- We need to align the nucleus (B-Field), align the molecule (B-Field, E-Field, Mechanical), and induce a chiral destruction mechanism (polarized lepton).
How Do We Couple the Nuclear Spin to Molecular Chirality?
Molecules in External B-Fields Alter the Field at the Nucleus

Effect of Orbital Electrons: Chemistry

Electronic Magnetic Hamiltonian

\[ H = \frac{1}{2} \sum_k \left[ \frac{1}{i} \nabla_k - \frac{1}{c} A_k \right]^2 + V(r_k) \]

\[ A_k(r_k) = \frac{1}{2} B \times r_k + \frac{\mu N \times r_{Nk}}{r_{Nk}^3} \]

B-Field ↔ Molecule; Molecule ↔ Nucleus

Shielding tensor. It’s asymmetric:

\[ \sigma_{\alpha\beta} \equiv \frac{\partial^2 E}{\partial \mu_\alpha \partial B_\beta} \neq \sigma_{\beta\alpha} \]

How Do We Couple the Nuclear Spin to Molecular Chirality?

Molecules in External B-Fields Alter the Field at the Nucleus

Field Shift Depends on Chirality

- Orbital electrons: shielding effect.
  \[ B_\alpha = B_{0,\alpha} - \sigma_{\alpha\beta} B_{0,\beta} \]

- Shielding tensor: shift in B field.
- Orientation is important!
- Depends on molecular shape = chirality.
- Nuclear spin direction is coupled to molecular chirality.
- Fixing molecular orientation minimizes energy for nuclear orientation.

How Do We Couple the Nuclear Spin to Molecular Chirality?

Molecules in External $B$-Fields Alter the Field at the Nucleus

\[ \hat{B} = B_0 \hat{z} \]

\[ \Delta B_y = \sigma_{yz} \hat{B} \]

\[ \hat{B} = -B_0 \hat{z} \]

\[ \Delta B_y = \sigma_{yz} \hat{B} \]

L-VAL

D-VAL
How Do We Couple the Nuclear Spin to Molecular Chirality?
Molecules in External B-Fields Alter the Field at the Nucleus

External Interactions Altered by Different Magnetizations

- **Nuclear M** coupled to chirality.
- Relativistic leptons (spin 1/2) - Nitrogen has lowest Q-value
- **Reaction cross section depends on relative alignment of spin.**
  \[ \Gamma \propto 1 - \cos \phi \]
- Nuclear recoil energy \( \gg \) Molecular binding energy

Famiano et al. (2018b)
Results: Shielding Tensor Calculations

Nucleus Surrounded by Molecular Electrons

Magnetic field at nucleus (N) is $B^{(N)}$.

$$B^{(N)} = \left( I - \sigma^{(N)} \right) \cdot B_0(t)$$

$$\sigma_{\alpha\beta} \equiv \frac{\partial^2 E}{\partial \mu_\alpha \partial B_\beta}$$

$$\hat{H} = -\hat{M} \cdot B^{(N)}$$

$$\frac{\Delta B_\alpha}{B_\beta} = \frac{\Delta M_\alpha}{M_\beta} = \frac{\Delta \mu_E}{\mu_E} = \sigma_{\alpha\beta}$$

$$\sigma^{(N)} \sim 10^{-8} - 10^{-4}$$

(Matched subscripts imply sum. Greek symbols indicate coordinates.)
**Results: Shielding Tensor Calculations**

**Shielding Tensor Components**

- **Diagonal Components (Trace)**
  \[ \sigma_d = \begin{pmatrix} \sigma_{xx} & 0 \\ 0 & \sigma_{yy} \\ 0 & \sigma_{zz} \end{pmatrix} \]

- **(Anti-)Symmetric Traceless Part**
  \[ \sigma_{s/a} = \begin{pmatrix} 0 & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & 0 & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & 0 \end{pmatrix} \]

\[ \sigma_{xy,L} = -\sigma_{xy,D} \text{ (e.g.)} \]
Results: Shielding Tensor Calculations

**Shielding Tensor Components**

**Diagonal Components (Trace)**

\[
\sigma_d = \begin{pmatrix}
\sigma_{xx} & 0 \\
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\end{pmatrix}
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\[\sigma_{xy,L} = -\sigma_{xy,D} \text{ (e.g.)}\]
Enantiomeric Excess
Many Possible Scenarios

NS Merger Scenario?

- B-Field from NS
- Molecular alignment from meteoric motion in induced E-Field
- Debris field in vicinity of neutron star binary.
- Rapid processing
- Slow processing might include debris field surrounding NS, cosmic rays, others?
- Neutrino flux profile of Rosswog & Liebendorfer (2012)
Enantiomeric Excess
Many Possible Scenarios

**NS Merger Scenario?**

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- Slow processing might include debris field surrounding NS, cosmic rays, others?
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Enantiomeric Excesses
Isovaline Cation Calculations: Alignment In External E-Field From Meteoroid Motion

High lepton flux, low magnetic field.
\[ B = 30 \, \text{T} \]
\[ f = \lambda_{\bar{\nu}} \times 2T_{\text{rel}} \sim 1 \]
Case: MHD Jets, NS merger.

Famiano et al. (2018a,b,c)

High magnetic field, low lepton flux.
\[ B = 800 \, \text{T} \]
\[ f = \lambda_{\bar{\nu}} \times 2T_{\text{rel}} \sim 10^{-8} \]
Case: Neutron Star/BH flyby.
Isotopic Abundances

![Graph showing isotopic abundances with δD vs. δ15N and δ13C vs. δ15N plots.](image)
Summary So Far....

- We have a model in which there is a nuclear contribution to selecting molecular chirality.
- This model works at astrophysically interesting energies and fields.
- The model requires polarized leptons and a magnetic field at a minimum.
We have a model in which there is a nuclear contribution to selecting molecular chirality.

This model works at astrophysically interesting energies and fields.

The model requires polarized leptons and a magnetic field at a minimum.

We have the theory. We’d like to proceed to the next step - experiment.

Is it possible to measure this effect?

There are several things we can measure.

Some measurements are conceptually simple, but technically difficult.
Experimental Goals

Questions

- Is there a nuclear enhancement to the VU hypothesis (especially at high energy)?
- What is the magnitude of this effect?
- Can we test magnetochiral influences on the formation of biomolecules?
- What is the effect from molecular polarization? Nuclear polarization?

- This may not be as difficult as it seems....
If We Can Do Anything We Want: An Ideal Measurement

Chiral Molecule
- L-Valine, up
- L-Valine, down
- D-Valine, up
- D-Valine, down

Nuclear Spin States
- Perfect World...
  - Every chirality, molecular alignment, nuclear alignment, beam spin.
  - We expect two possible results.
  - NOTE: Chirality-dependent shift in nuclear spin: $\sim 10^{-6} - 10^{-4}$
## Separating the Molecular and Nuclear Components

### Polarized Beam Experiment

<table>
<thead>
<tr>
<th>Polarized Nucleus</th>
<th>Unpolarized Nucleus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polarized Molecule</strong></td>
<td><strong>Unpolarized Molecule</strong></td>
</tr>
<tr>
<td>Test Shielding Tensor Effects</td>
<td></td>
</tr>
<tr>
<td>Requires molecular alignment</td>
<td></td>
</tr>
<tr>
<td>Polarized nuclear target</td>
<td></td>
</tr>
<tr>
<td>Tricky?</td>
<td></td>
</tr>
<tr>
<td>Test Nuclear Contribution</td>
<td></td>
</tr>
<tr>
<td>Nuclear alignment only</td>
<td></td>
</tr>
<tr>
<td>Target not so important</td>
<td></td>
</tr>
<tr>
<td>Maybe solid N target only?</td>
<td></td>
</tr>
<tr>
<td>Test Nuclear Contribution</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unpolarized Nucleus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test Molecular Contribution</strong></td>
</tr>
<tr>
<td>Requires molecular alignment</td>
</tr>
<tr>
<td>Electric field?</td>
</tr>
<tr>
<td>Crystal/solid target</td>
</tr>
<tr>
<td><strong>Average Cross Section</strong></td>
</tr>
<tr>
<td>Control target</td>
</tr>
<tr>
<td>Any target</td>
</tr>
<tr>
<td>Simple</td>
</tr>
</tbody>
</table>
Beam Experiment: Conceptually Simple, Technically Difficult
Perhaps We Don’t Need the Molecule?

**Nuclear Contribution**
- Polarized beam
- Polarize nuclear target
- HPGE (4π)
- Faraday Cup

**Molecular Contribution**
- Polarized beam
- Polarized molecular target
- CSGC (chemistry)

**Experimental Setup**
- Polarized targets?
- Polarized molecules may be pretty easy to obtain.
- Magnetochiral influence: Combine molecular and nuclear
- Molecular magnetochiral influence.
Conclusions

- **Weak interactions: A truly chiral influence.**

- Weak interactions in high magnetic fields can produce significant enantiomeric excesses.

- Spin dependence of electromagnetic transitions could be a good experimental substitute.

- **Future experimental work?**
  - Polarized nuclear targets: difficult.
  - Polarized molecular targets: fairly easy?

- Could the same sites responsible for the formation of the heavy elements be responsible for life?
Thank You!

Nuclear Astrobiochemistry???
EE Dependence on Site Parameters

![Graph showing EE dependence on site parameters.](image-url)
**Why Would This Model Work?**

- Symmetry Breaking: Neutrino it truly chiral.
- Angular Momentum: Reactions are enhanced, but only the right ones.
- Nitrogen is the only nucleus with a non-zero spin except Hydrogen, but...
- Shielding tensors are tiny for hydrogen $\rightarrow$ huge effect for Nitrogen.
- Also works for electrons and muons (cosmic rays).

**Why Would This Model NOT Work?**

- Where in blazes are we going to find neutrinos/electrons?
- Where in blazes are we going to find neutrinos/electrons, magnetic fields, and electric fields all in the same place?
- Cross-sections are tiny $\rightarrow$ need many neutrinos/electrons.
- Still need to get the meteorite to earth.
Where in the World Can This Happen
As it turns out... nowhere.

**What Is Needed for this Model**

- External magnetic field
- External electric field
- Source of polarized leptons
- Extraterrestrial origin

**Possible Sites**

- Meteoroids in vicinity of high magnetic fields
- Neutron stars or magnetars
- Neutron star mergers
- Binary star-BH/NS systems

**Advantage:** Neutrino source is truly chiral.
## Possible Sites

<table>
<thead>
<tr>
<th></th>
<th>SNeII</th>
<th>NS Merger</th>
<th>NSs, BNS systems, WR Stars</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distance</strong></td>
<td>1 AU</td>
<td>6000 km</td>
<td>500 km</td>
</tr>
<tr>
<td><strong>Flux (s(^{-1}) cm(^{-2}))</strong></td>
<td>(\sim 10^{30})</td>
<td>(\sim 10^{38})</td>
<td>(\sim 10^{28})</td>
</tr>
<tr>
<td><strong>Rate Ratio, f</strong></td>
<td>(\sim 10^{-8})</td>
<td>(\sim 140)</td>
<td>(\sim 10^{-8})</td>
</tr>
<tr>
<td><strong>(B_0)</strong></td>
<td>(10^{10})</td>
<td>(10^{10})</td>
<td>(10^8)</td>
</tr>
<tr>
<td><strong>(B_r)</strong></td>
<td>(10^{-12})</td>
<td>50</td>
<td>800</td>
</tr>
<tr>
<td><strong>Timescale</strong></td>
<td>(\sim 2) s</td>
<td>(\sim 1) s</td>
<td>(\sim 10^5) yr</td>
</tr>
<tr>
<td><strong>ee(_{max})</strong></td>
<td>(&lt; 10^{-10})</td>
<td>(\sim 10^{-5})</td>
<td>(\sim 10^{-2})</td>
</tr>
<tr>
<td><strong>NOTES</strong></td>
<td>Common</td>
<td>Rare, long time</td>
<td>Many possibilities</td>
</tr>
</tbody>
</table>
## Table of Possibilities: Relative Effects
### Sampling of Other Amino Acids: Geometry Factor

- **Bigger Number → Bigger Effect**

<table>
<thead>
<tr>
<th>Amino Acid</th>
<th>Ligand</th>
<th>Zwitterion</th>
<th>Optimized</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alanine</td>
<td>-3.87</td>
<td>31.79</td>
<td>39.39</td>
<td>LALNIN59, XIYSAA</td>
</tr>
<tr>
<td>Arginine</td>
<td>7.79</td>
<td>-44.11</td>
<td>-160.41</td>
<td>TAQBIY, ARGHCL11</td>
</tr>
<tr>
<td>Histidine</td>
<td>-10.55</td>
<td>-44.58</td>
<td>-31.20</td>
<td>LHISTD13, HISTCM12</td>
</tr>
<tr>
<td>Isovaline</td>
<td>-0.63</td>
<td>-1.92</td>
<td>-16.67</td>
<td>KIMKUO</td>
</tr>
<tr>
<td>Norvaline</td>
<td>5.49</td>
<td>26.24</td>
<td>33.26</td>
<td>USOHUH04, VUKQID</td>
</tr>
<tr>
<td>Proline</td>
<td>-3.68</td>
<td>17.5</td>
<td>47.25</td>
<td>PROLIN01</td>
</tr>
<tr>
<td>Valine</td>
<td>1.01</td>
<td>4.44, 34.52</td>
<td>19.94</td>
<td>LVALIN05, VALEHC11</td>
</tr>
</tbody>
</table>
Possible Sites

Relative Ratios Compared to Meteorites
Geometry Factor Ratios compared to Alanine

<table>
<thead>
<tr>
<th>Ligand</th>
<th>Zwitterion</th>
<th>Optimized Cation</th>
<th>Murchison</th>
<th>Murray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isovaline</td>
<td>0.16</td>
<td>-0.06</td>
<td>2.20</td>
<td>7.00</td>
</tr>
<tr>
<td>Norvaline</td>
<td>-1.42</td>
<td>0.83</td>
<td>0.20</td>
<td>0.30</td>
</tr>
<tr>
<td>Valine</td>
<td>-0.26</td>
<td>0.14, 1.09</td>
<td>0.16</td>
<td>1.83</td>
</tr>
</tbody>
</table>

We are excluding aqueous effects, auto-catalysis, and racemization.
Theoretical Work

Astrophysical Effects

- Realistic orbital mechanics
- Time-dependent fields
- Rotating neutron stars
- Compare to other chiral effects: CPT, polarized leptons, cosmic rays
- Autocatalysis: Biological? Chemical? Mechanical?
Amino Acids in Meteorites

<table>
<thead>
<tr>
<th></th>
<th>Isovaline</th>
<th>Norvaline</th>
<th>Alanine</th>
<th>Valine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murray</td>
<td>6.0</td>
<td>0.8</td>
<td>0.4</td>
<td>-0.4</td>
</tr>
<tr>
<td>Murchison</td>
<td>8.4</td>
<td>0.4</td>
<td>1.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>


- Isovaline is special! It is not found on earth, and it racemizes slowly. (Contamination and preservation.)
- They are not homochiral. We need autocatalysis.
The Bigger Picture

Meteoritic Delivery System
The Bigger Picture

Meteoritic Delivery System
Models of Autocatalysis

Meteorites

Chemical Autocatalysis

Prebiotic Soup

Biological Autocatalysis

Chemical Autocatalysis

Eukaryotes

Archaea

Bacteria
Optical & Magnetochiral Effects

Optical Dichroism
Absorption of specific polarizations.

\[
\text{CD Signal} = A_L - A_R
\]

\[\vec{B}\] (Barron et al. 1984)

Magnetochiral Dichroism
Absorption modified by magnetic field.

(Duran et al. 1984)
Circularly Polarized Light

- Can be produced in Mie scattering in interstellar dust.
- Peaks in the infrared. Experiments performed in the UV.
- Does not penetrate surfaces.
- Varies with wavelength.

Meinert et al. (2014)
Weak Interactions Can Also Be Chiral in Nature

- Weak interactions are reactions between leptons (electrons, neutrinos, muons, tau) and atomic nuclei.
- In fact, weak interactions are really the only truly chiral reaction in nature.
Some Basic Nuclear Physics

Basic Nuclear Physics: A Primer

Nuclear Physics in Biology?

**Particle Spin**

Subatomic particle have an intrinsic angular momentum. The total angular momentum depends on the particle type. Angular momentum is quantized and conserved.

![Spin up](image1)

![Spin down](image2)

Notes about Particle Spin

*Leptons*, like electrons and neutrinos, have only two spin states. Their spin is $1/2$.

*Nucleons*, like protons and neutrons, have three spin states. Their spin is $1$.

Units of spin is $\hbar$. 
Basic Nuclear Physics: A Primer

Nuclear Physics in Biology?

**Particle Helicity**

Helicity is defined by the direction of the particle spin relative to its velocity. That is, does the spin point in the direction of motion, opposite the direction of motion, or some other way.

**Notes about Particle Helicity**

Relativistic leptons (moving VERY fast), have *definite helicity*. Their spin points forwards or backwards.
Magnetic Moments

Magnetic Moment Description

- Particles with charge and spin have magnetic moment (think “electromagnet”).
- They behave like compass needles.
- Particles with magnetic moments orient in magnetic fields.
- Magnetic moment is related to the spin through the gyromagnetic ratio.
- This principle is exploited in NMR.
A Particle Zoo

Atomic Nuclei

- Oxygen: Zero spin, zero magnetic moment.
- Carbon: Zero spin, zero magnetic moment.

Anti-Neutrinos

- **Truly Chiral Particle!!!!**
- **All** anti-neutrinos are right-handed.
- **All** Neutrinos are left-handed.
Basics of NMR

- Nuclear magnetic moments determine chemical shifts $\rightarrow$ NMR frequency.
- Chemical shifts are further modified by “shielding.”
- Shielding occurs because the electrons create a counter field.
- The magnetic field at the nucleus is then changed.
- Definition of diamagnetism.
Shielding Tensor For An Asymmetric Molecule

Asymmetric Shielding: Valine, $B_z$, $\sigma_{xy}^{(N)}$
Brief Review
We Now Have All the Pieces We Need

Weak Interaction Model for Amino Acid Chiral Selection

- We know what particle spin is.
- We know what magnetic moment is.
- We know what shielding is.
- We know what a lepton is.
- We know about atomic nuclei.

All of these pieces come together to produce amino acid chirality in space.
Nuclear Magnetic Shielding Polarizability: Rank-3

**Shielding Polarizability**

\[ \sigma_{\alpha\beta} \rightarrow \sigma_{\alpha\beta} + \sigma_{\alpha\beta\gamma} E_{\gamma} \]

\[ \sigma_{\alpha\beta\gamma} \equiv \frac{\partial^3 E}{\partial \mu_\alpha \partial B_\beta \partial E_\gamma} \]

\[ B_\alpha^{(N)} = (1 - \sigma_{\alpha\beta} - \sigma_{\alpha\beta\gamma} E_{\gamma}) B_\beta \]

\[ \bar{\sigma} = \frac{1}{6} \varepsilon_{\alpha\beta\gamma} \sigma_{\alpha\beta\gamma} \]

This term does change under a parity transform.

An external electric field can induce a chirality-dependent shift in the shielding tensor.
