T Symmetry and Its Violation

Part 2: Some Phenomenology

(1) Yoga of Moments

Fundamental Versus Effective

$$H = \begin{pmatrix} \Delta & (\sum e_j x^j) \cdot E \\ (\sum e_j x^j) \cdot E & 0 \end{pmatrix}$$

When the off-diagonal terms are much smaller than Δ, the response is quadratic.

When Δ is negligible, relative to the interaction terms, we get "electric dipole" response.

In general, effective electric and magnetic moments should be discussed within the framework of a description of the low-energy states.

In general, there’s more to life than spin.

Big molecules with rings can have low-energy states with non-trivial, dynamical distributions of charge and spin, and including currents of both.

Q1: When does it make sense to interpret measurements of electric dipole moments as evidence about fundamental T violation?

Q2: Is the neutron a Majorana fermion?

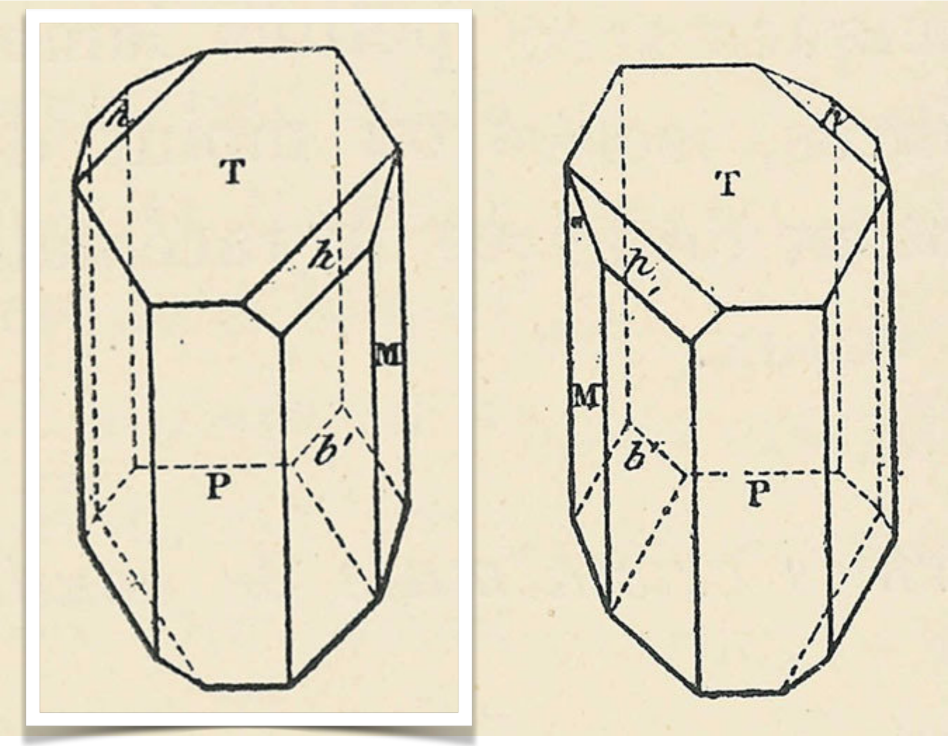
(2) Does Biology Break T?

Concept and Signatures

(2a) Biological P Breaking

Phenomena

The fact that biological systems generally work with molecules of a specific chirality was a famous discovery of Pasteur.



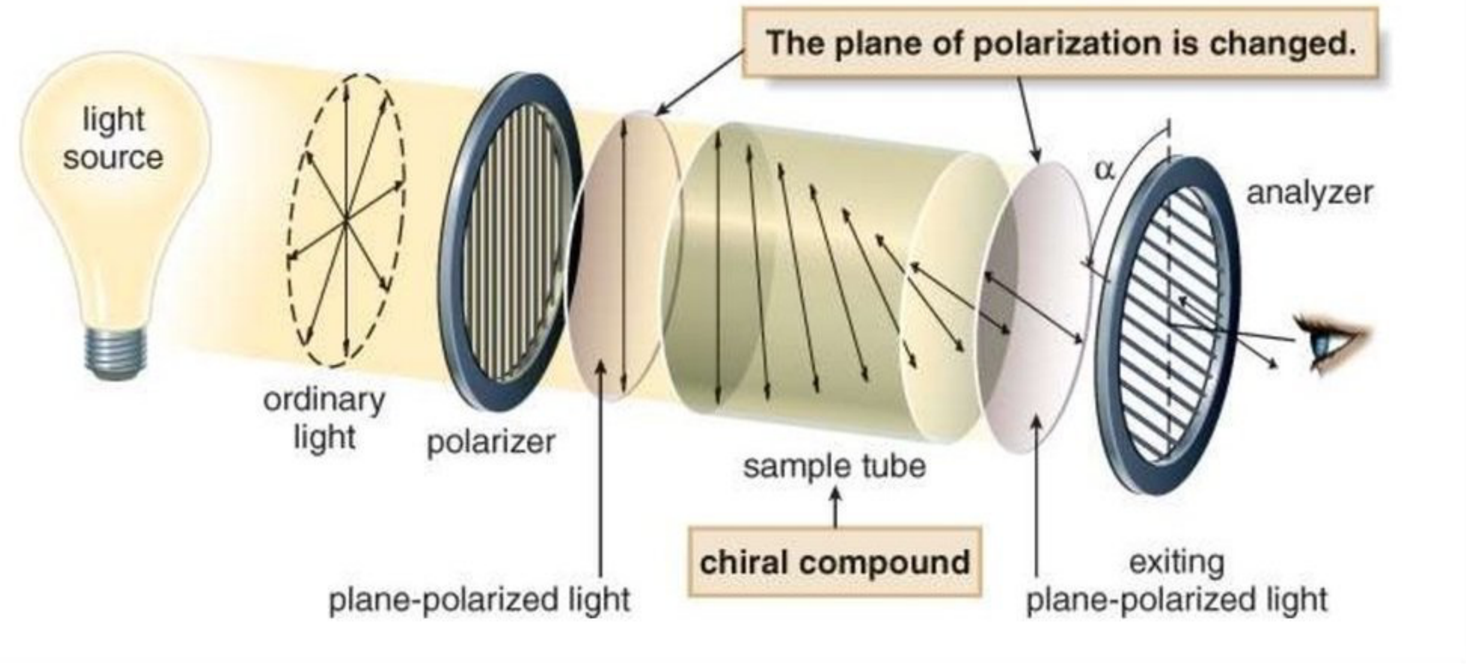
Anti-Racemic Crystallization

Biological chirality makes sense, intuitively, if we think of biology as an industrial economy.

It useful to have universal agreement about what sort of screws to use!

“Dissenters” will lack infrastructure, and it will be hard for them to compete.

Pasteur also pioneered the study of optical activity.



Optical Activity: A Signature of P Violation

Optical Activity as an Effective Lagrangian

(Methodological note: When we treat rapidly oscillatory phenomena using effective Lagrangians, we should allow for arbitrary powers of time derivatives. This leads to the appearance of frequency-dependent coupling parameters, … Here I will leave that implicit.)

$$\Delta L \;=\; \kappa B \cdot (\nabla \times B)$$

P odd, T even

$$\rho^{\text{eff}} \;=\; 0$$

$$j_\alpha^{\text{eff}} \;=\; 2\kappa \nabla^2 B_\alpha$$

$$\nabla \cdot B = 0 \qquad \nabla \cdot E = 0$$

$$\nabla \times E = -\partial_t B \qquad \nabla \times B = \partial_t E + 2\kappa \nabla^2 B$$

$$A = \varepsilon\, e^{i(kx-\omega t)}$$

$$B = ik \times \varepsilon\, e^{i(kx-\omega t)} \qquad E = i\omega\varepsilon\, e^{i(kx-\omega t)}$$

$$k \cdot \varepsilon = 0$$

$$-k^2\varepsilon = -\omega^2\varepsilon - 2i\kappa k^2\, k \times \varepsilon$$

$$\mathbf{k} \cdot \boldsymbol{\varepsilon} = 0 \qquad -k^2 \boldsymbol{\varepsilon} = -\omega^2 \boldsymbol{\varepsilon} - 2i\kappa k^2 \mathbf{k} \times \boldsymbol{\varepsilon}$$

$$\mathbf{k} = (0, 0, k) \qquad \boldsymbol{\varepsilon} \propto (1, \pm i, 0)$$ (Circular Polarizations)

$$\omega^2 - k^2 \mp 2\kappa k^3 = 0$$

$\Rightarrow$ Different circular polarizations travel at different speeds

$\Leftrightarrow$ Optical activity

(2b) Symmetry Breaking by Cooperative Kinetics

Abstracting from Biological P Breaking

Clearly, there is a strong sense in which “Biology Breaks P”.

But what do we mean, more precisely, by biological P breaking?

- *Systematic choice of one chirality of an enantiomer for a given use, across a significant piece of the living world.*

Note: This is generally not the molecular ground state. Nevertheless the choice is stable, because of the watched kettle effect.

This is neither intrinsic nor conventional spontaneous symmetry breaking, but rather cooperative kinetics enforcing a “frozen accident”.

By analogy, for (hypothetical) T breaking

- *Systematic choice of one of a pair of* T *related molecules for given use, across a significant piece of the living world.*

Note: This is generally not the molecular ground state. Nevertheless the choice is stable, because of the watched kettle effect.

This is neither intrinsic nor conventional spontaneous symmetry breaking, but rather cooperative kinetics enforcing a “frozen accident”.

T violation makes sense, intuitively, if we think of biology as an industrial economy. It could be useful to have universal agreement about what kind of clocks to use!

(Do the hands progress clockwise, or anti-clockwise?)

More generally: Does evolution design quantum dots, nanoparticles, and metamaterials?

(2c) Signatures of T Breaking in Matter

A Smörgåsbord

Potential T violating* effects and signatures:

correlation of moments - $\langle d \cdot \mu \rangle \;\neq\; 0$

static response

propagation of light through solutions and crystals

scattering at interfaces

violation of Onsager reciprocal relations

failure of detailed balance

(*Here we are speaking of non-dissipative T violation. Of course, exploitation of entropy gradients - “burning” - is an extremely common way to make progress through time.)

correlation of moments - $\langle d \cdot \mu \rangle \neq 0$

This could be accessed through Spectroscopy or Spin Resonance.

Possibly useful for magnetic field sensing - provides a labelled compass needle; or in signaling.

Multiferroic condensation is a real phenomenon.

static response

e.g., $\Delta L \propto E \cdot B$ - applied E yields some B, or vice versa

(more generally,
$\Delta L \propto \eta_{jk} E_j B_k$)

effects in propagation of light through solutions and crystals

e.g., $\Delta L \propto \eta_{jk} E_j B_k$ - complicated to analyze

simplest qualitative possibility seems to be *electric* Faraday effect

(Magnetic) Faraday Effect

$$\Delta L \;=\; \kappa \left(E \times (\nabla \times B)\right) \cdot B$$

P even, T even

$$\Delta L \;=\; \kappa \left(E \times (\nabla \times B)\right) \cdot B^0$$

$$\rho^{\text{eff}} \;=\; 0$$

$$j_\alpha^{\text{eff}} \;=\; 2\kappa\, B_p^0\, \partial_0 \partial_p B_\alpha$$

Analysis similar to optical activity.

Different circular polarizations propagate at different speeds.

Linear polarization rotates proportional to distance.

The absolute sense of rotation is even in k.

Electric Faraday Effect

$$\Delta L \;=\; \kappa \Big(B \times (\nabla \times E) \Big) \cdot E$$

P odd, T odd

$$\Delta L \;=\; \kappa \Big(B \times (\nabla \times E) \Big) \cdot E^0$$

$\Rightarrow$ Same equations as magnetic Faraday effect.

E B terms

$$\Delta L \;=\; \kappa E \cdot B$$

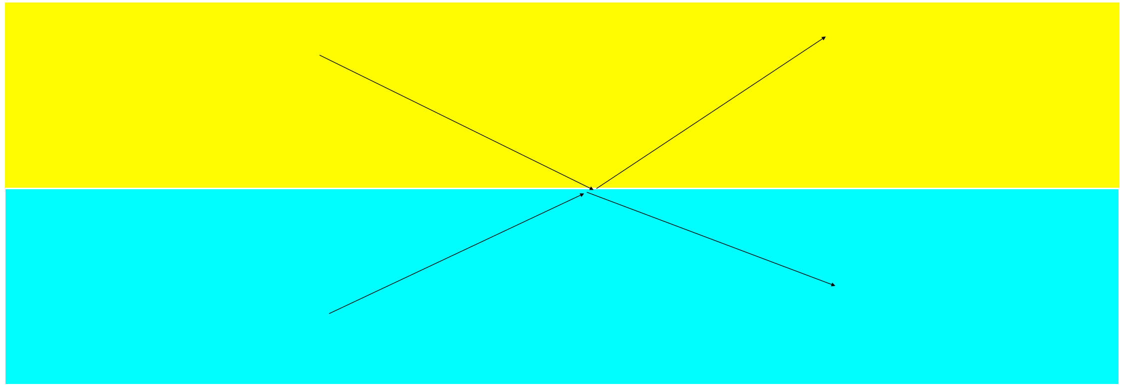
P odd, T odd

$$\rho^{\text{eff}} \;=\; 0 \qquad\qquad (-\kappa_{lm}\,\partial_l B_m)$$

$$j_\alpha^{\text{eff}} \;=\; 0 \qquad\qquad (\kappa_{lm}\,\epsilon_{\alpha pm}\,\partial_p E_l \;+\; \kappa_{\alpha m}\,\partial_0 B_m)$$

Scattering at Interfaces

S-Matrix constraints



4-channel S Matrix

“bounce back”
experiments?

other geometries …