Big Question: Why the Matter — Antimatter Asymmetry?
Looking for clues with (relatively) small scale experiments

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Anti-matter Review

History:

- Dirac, 1928: Electrons "could" have positive or negative charge
- Anderson 1932: First definitive observation of particles with the mass of the electron, but positive charge, e^+
- β decay:

$$n \longrightarrow p + e^- + \overline{\nu}_\mathrm{e}$$

$$\mathrm{Co}^{60} \longrightarrow {}^{60}_{49}\mathrm{Ni} + p + e^- + \overline{\nu}_\mathrm{e}$$

- Present:
  - We make exotic atoms with antimatter, e.g., positronium, a hydrogen-like atom with the proton replaced by a positron.
  - We make and trap anti-hydrogen made from an anti-proton and an anti-electron.

Anti-matter Review, cont'd

- Matter – Anti-matter Annihilation

$$
\begin{aligned}
e^- + e^+ &\longrightarrow \gamma + \gamma \\
p + \overline{p} &\longrightarrow \gamma + \gamma \\
u + \overline{u} &\longrightarrow \gamma + \gamma \\
\mu^- + \mu^+ &\longrightarrow \gamma + \gamma
\end{aligned}
$$

etc.

Anti-matter in the Universe

- Matter and anti-matter produced in big bang
- Current understanding: equal matter and anti-matter produced
- Anti-matter not present in contemporary universe
- Either:
  - asymmetric production, or
  - asymmetric process later on

PROBLEM: We don't know of any process that would result in this asymmetry.

Why this talk (from me)?

Historical Diversion: Symmetry and Physics, Part 1

Interesting (and powerful) symmetries I am **not** going to discuss today

- Point symmetries and group theory

Historical Diversion: Symmetry and Physics, Part 1

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- Point symmetries and group theory
- Continuous symmetries:
  - Translational invariance $\longrightarrow$ conservation of momentum
  - Rotational invariance $\longrightarrow$ conservation of angular momentum

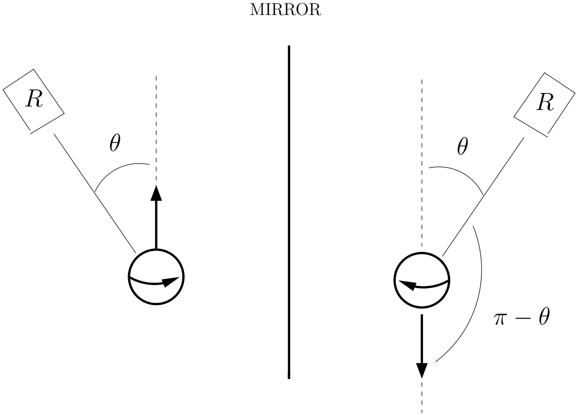
Historical Diversion: Symmetry and Physics, Part 2A

One powerful symmetry I *am* going to discuss:

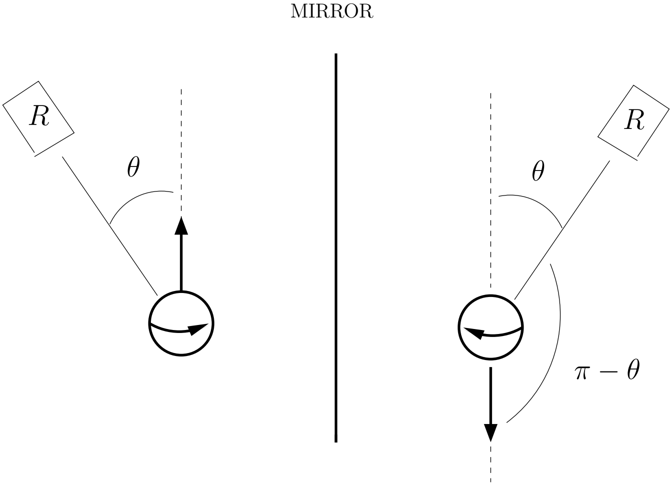
Discrete symmetry I: Reflection Symmetry

Reflection symmetry — An example from E&M

Reflection symmetry and β decay

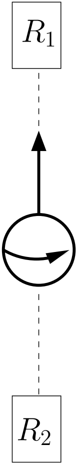


Reflection symmetry and β decay



Conclusion: $R(\theta) = R(\pi - \theta)$ IF . . .

Wu experiment simplified



$R_1 = R_2$?

Save the day with an additional discrete symmetry?

Reflection Symmetry $\longrightarrow$ Reflection Symmetry combined with Charge Conjugation Symmetry

a.k.a.

$$P \longrightarrow PC$$

CP symmetry and neutrinos

- All neutrinos are left-handed
- All neutrinos are right-handed

CP symmetry not enough

- Fitch/Cronin experiment (1964):

  Obeserved

  $$K^0 \longrightarrow \pi^0 + \pi^0$$

  when it could only be result of CP violation.

- Fitch/Cronin Nobel prize (1980).

What symmetry isn't violated?

TCP

i.e., symmetry under the combination of

Time Reversal
and
Charge Conjugation
and
Parity (Reflection)

"It s simply impossible to construct a quantum field theory in which the product TCP is violated."

David Griffiths

Time reversal symmetry

Compare, e.g.,

$$n + p \longrightarrow d + \gamma$$

with

$$\gamma + d \longrightarrow n + p$$

or

$$\Lambda \longrightarrow p + \pi^-$$

with

$$p + \pi^- \longrightarrow \Lambda$$

Back to original puzzle. Where to look for clues?

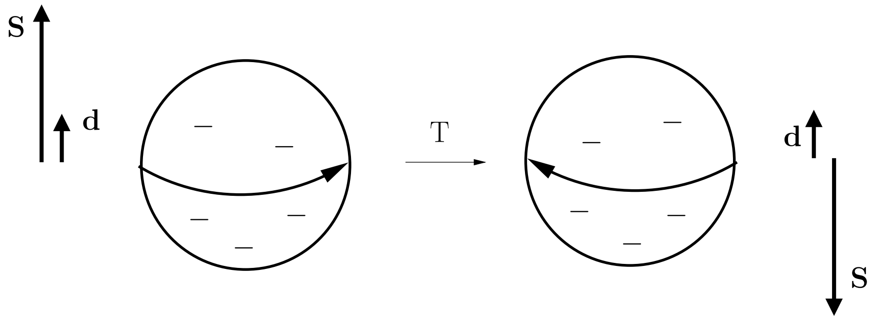
- Higher energy collisions in particle accelerators. (Lower energy phenomena mapped out *very* well in Standard Model.
- Higher energy collisions in astrophysical settings.
- Indirect consequences of particle–antiparticle assymmetry (Use the TCP theorem!) See below:

"An improved bound on the electron's electric dipole moment"
Roussy, et al., Science **381**, 46 (2023)

Abstract:

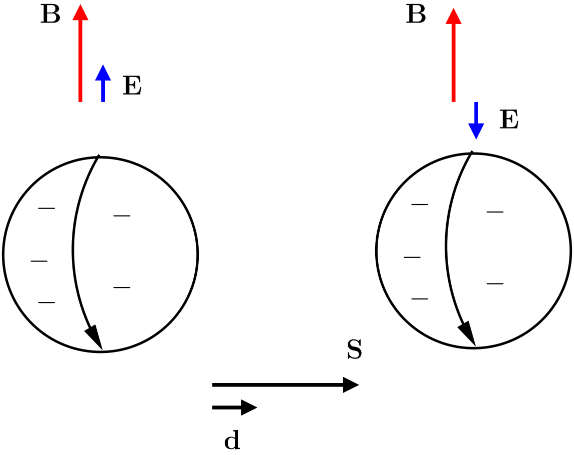
The imbalance of matter and antimatter in the Universe provides compelling motivation to search for undiscovered particles that violate charge-parity symmetry. Interactions with vacuum fluctuations of the fields associated with these new particles will induce an electric dipole moment of the electron (eEDM) . . .

eEDMs and Time Reversal Symmetry



eEDM detection

COMPARE PRECESSION RATES



Results from Science article

"Our result is consistent with zero and improves on the previous best upper bound by a factor of ~ 2.4. Our results provide constraints on broad classes of new physics about 10^{13} electron volts, beyond the direct reach of the current particle colliders or those likely to be available in the coming decades."