The electron is so round that it excludes the possibility of new physics!

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Atomic Physics

Preliminaries

- Over the past few decades, a small group of physicists has steadfastly searched for any asymmetry in the shape of the electron.
- The studies are now so sensitive that they could find a bump on the North Pole the height of a single sugar molecule if an electron were the size of Earth.
- The electron is rounder than that, according to the most recent findings.
- Anyone hoping to find evidence of new physics is let down by the latest measurement.
- Theorists can still benefit from modeling constraints that indicate which undiscovered particles and forces might be absent from the existing picture.
- Despite performing remarkably well in experimental tests over the past two decades, the Standard Model of Particle Physics Theory nonetheless has some significant flaws.

Preliminaries

- One reason is that the Standard Model cannot account for our existence since, in accordance with the theory, the Big Bang should have produced an equal amount of matter and antimatter, which would have annihilated one another.
- Soviet physicist Andrei Sakharov put up a potential answer to this particular riddle in 1967. He reasoned that matter may eventually triumph over antimatter if there are some microscopic mechanisms in nature that appear different in reverse.
- Such a scenario had been identified by physicists a few years earlier in the disintegration of the Kaon particle. However, that wasn't sufficient to fully explain the imbalance.
- Theorists anticipate finding more CP violations in nature than what was discovered, and it is perplexing that hardly any more have been discovered afterwards. It is difficult to explain baryogenesis, or how the current abundance of matter over antimatter developed after the Big Bang, due to the lack of CP violation in the known universe.

Preliminaries

- Since that time, physicists have been looking for signs of brand-new particles that might further tip the scales. Some people achieve this directly by utilizing the Large Hadron Collider, which is frequently referred to as the most complex machine ever created.
- However, a relatively inexpensive alternative has arisen during the past few decades: examining how hypothetical particles would affect the characteristics of known particles. You can see the imprints of new physics, but not the object that created them.
- One such possible footprint might be seen in the electron's roundness. According to quantum mechanics, more particles are continually coming into and going out of existence inside the electron's cloud of negative charge.
- The electron's cloud might appear slightly more egg-shaped if certain "virtual" particles beyond the Standard Model were present; these are the kinds of particles that could aid in explaining the primordial dominance of matter.

Preliminaries

- Like the ends of a bar magnet, one tip would be somewhat more positively charged than the other. The electric dipole moment (EDM) is a term used to describe this charge separation.
- The EDM predicted by the Standard Model for the electron is about a million times smaller than what can currently be measured. As a result, finding an oblong form with current tests would demonstrate the presence of novel physics and indicate what the Standard Model might be lacking.
- Experimentalists look for a shift in the electron's spin, a characteristic that determines its orientation, in order to find the electron's EDM. Magnetic fields may easily twist an electron's spin, with its magnetic moment acting as a sort of handle. In these small-scale tests, the EDM serves as an electric handle in an attempt to rotate the spin using electric fields instead.
- The electron has no handles to grip onto in order to exert a torque if it is perfectly spherical. However, if there is a significant EDM, the electric field will use it to pull on the spin of the electron.

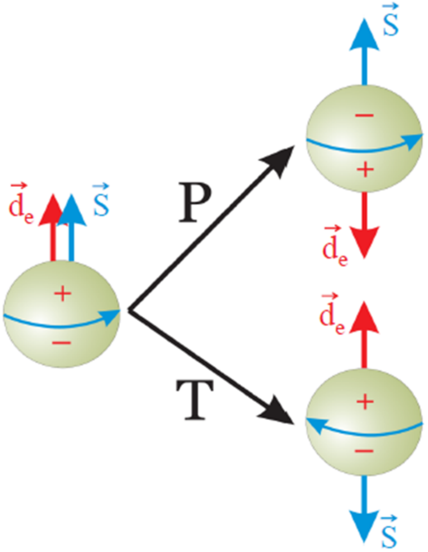
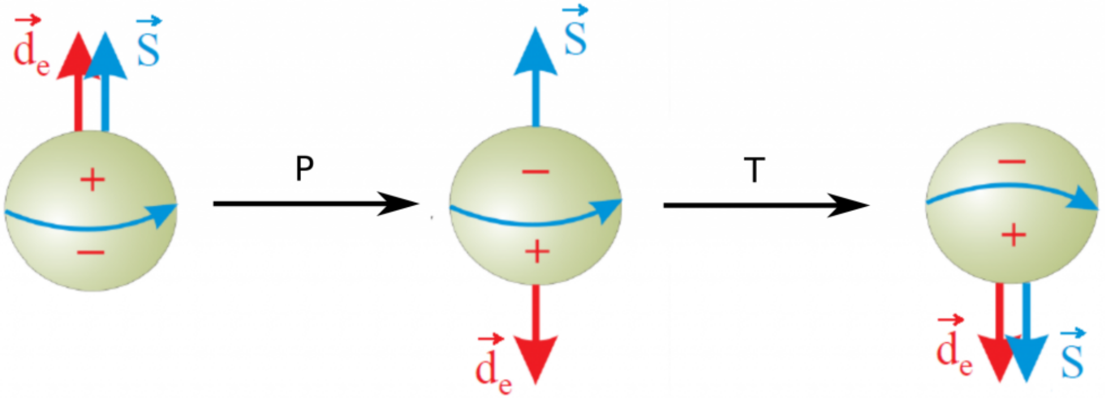


Illustration of how an electron with a non-zero EDM would change under a parity transformation and time.

Preliminaries

- Let's assume that initially the spin vector (MDM) and the dipole vector (EDM) are pointing in the same direction.
- *P transformation*:
  P shifts the orientation of a dipole, but keep in mind that P also shifts helicity. This implies that following the P transformation, the MDM, and EDM vectors will point in opposite directions.
- *T transformation = C transformation followed by P transformation*:
  If there is a non-zero EDM, the transformation after C would flip, but the transformation after P would flip it once more. P also alters the helicity, so the MDM and EDM vectors would point in different directions.



Transformation of an electron with an EDM under parity and time. At the end, we get the same electron as we started with, only that it's upside down.

Preliminaries

- Now, since PT is maintained by the electron EDM and CPT symmetry is always true, it follows that C symmetry must also be maintained, preserving the product:

$$CPT = C \times PT = 1 \times 1 = 1.$$

- This also suggests that CP would be broken, for the reason:

$$1 = CPT = CP \times T = CP \times -1.$$

  This implies:

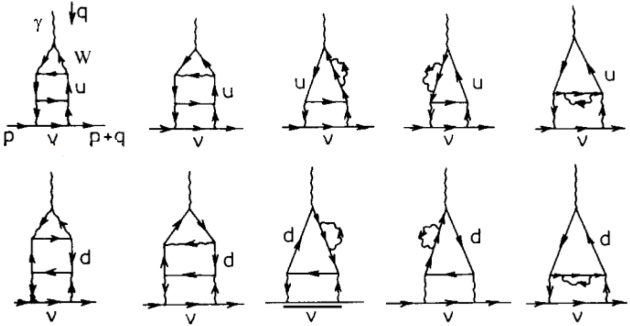
$$CP = -1.$$

- Assuming CPT symmetry, the presence of an electron EDM would therefore indicate a CP violation.

Experiments

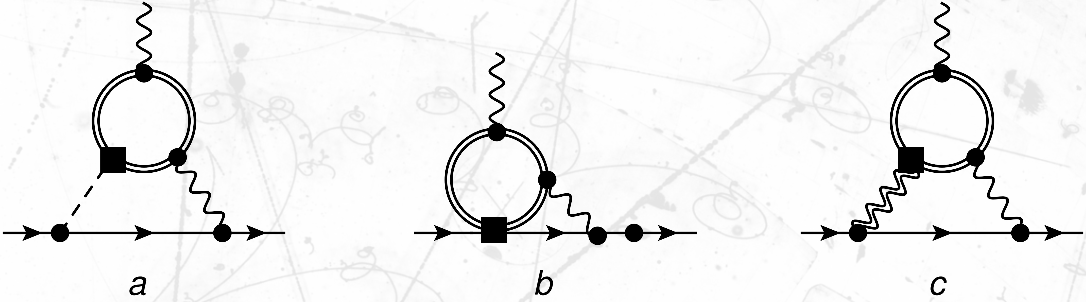
- Advanced Cold Molecule Electron EDM, or ACME, is the name of one experiment that is currently being conducted at Northwestern University. The JILA Institute at the University of Colorado is home to another. In the last ten years, the sensitivity of the measurements made by the rival teams has increased by a factor of 200, but EDM has not materialized.

$$i\partial_t \Phi = \left[\frac{(\boldsymbol{p}-e\boldsymbol{A})^2}{2m} + eA^0 - g\frac{e}{2m}\boldsymbol{B}\cdot\boldsymbol{S} - 2d_e\boldsymbol{E}\cdot\boldsymbol{S}\right]\Phi$$



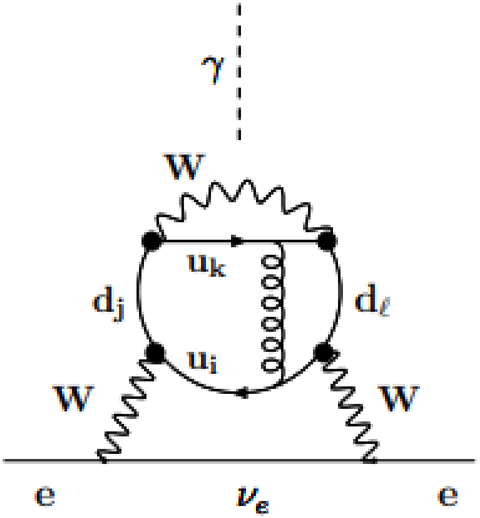
Ten diagrams contributing to electron EDM with W-propagators.

The standard model prediction for the electric dipole moment of the electron,
F. Hoogeveen,
Nuclear Physics B, Volume **341**, *Issue 2, 10 September 1990, Pages 322-340*



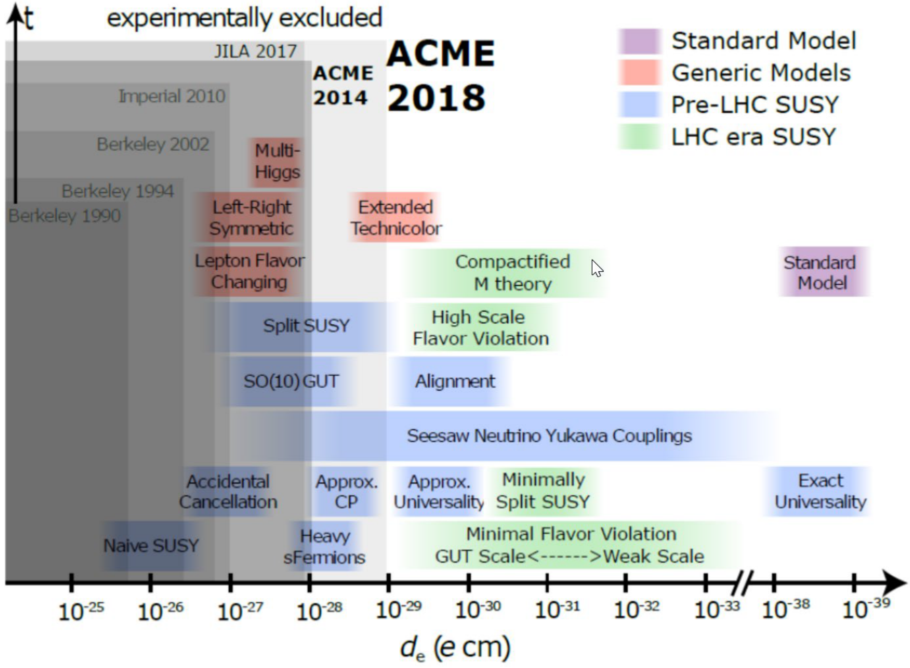
Two-loop diagrams contributing to the electron EDM. Single (double) lines denote the electrons (top quarks), dashed lines the Higgs boson, and wavy single (double) lines the photons (Z-bosons). Circles denote SM vertices, while squares denote CPV dimension-six vertices. Only one topology for each diagram is shown.

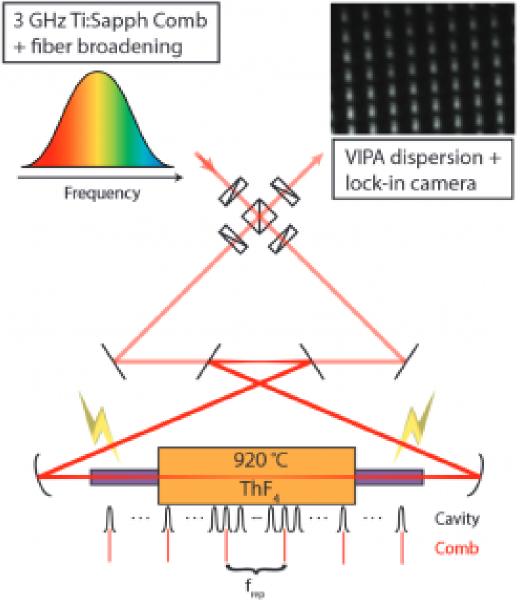
Electroweak baryogenesis and the standard model effective field theory, Jordy de Vries, Marieke Postma, Jorinde van de Vis, and Graham White, Journal of High Energy Physics, **2018**, *Article number: 89 (2018) arXiv:1710.04061 (hep-ph)*



Example of one-gluon four-loop diagram.

Electric Dipole Moment of the Electron


t
experimentally excluded
JILA 2017
Imperial 2010
Berkeley 2002
Berkeley 1994
Berkeley 1990
ACME 2014
ACME 2018
Standard Model
Generic Models
Pre-LHC SUSY
LHC era SUSY
Multi-Higgs
Left-Right Symmetric
Extended Technicolor
Lepton Flavor Changing
Compactified M theory
Standard Model
Split SUSY
High Scale Flavor Violation
SO(10) GUT
Alignment
Seesaw Neutrino Yukawa Couplings
Accidental Cancellation
Approx. CP
Approx. Universality
Minimally Split SUSY
Exact Universality
Naive SUSY
Heavy sFermions
Minimal Flavor Violation
GUT Scale<------>Weak Scale
10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29} 10^{-30} 10^{-31} 10^{-32} 10^{-33} 10^{-38} 10^{-39}
d_e (e cm)



EDM with ThF+ (Gen III) JILA - Exploring the Frontiers of Physics

A new bound on the electron's electric dipole moment:

$$|d_e| < 4.1 \times 10^{-30}\, e\, cm \text{ (90\% confidence).}$$

This is an upper bound using a folded Gaussian distribution.

A new bound on the electron's electric dipole moment,
Tanya S. Roussy, Luke Caldwell, Trevor Wright, William B. Cairncross, Yuval Shagam, Kia Boon Ng, Noah Schlossberger, Sun Yool Park, Anzhou Wang, Jun Ye, and Eric A. Cornell,
arXiv:2212.11841 (Atomic Physics)