In Search of a Permanent Electric Dipole Moment of $^{199}$Hg

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Outline

- Introduction to EDMs
  - Theoretical implications
- Experimental Overview
- False Signals
  - Completed improvements
  - Future work
What Is a Permanent Electric Dipole Moment (EDM)?

- A dipole, very simply, is a positive charge $q$ and negative charge $-q$ that are separated by a small distance $r$.

- The electric dipole moment $d$ is given by:
  \[ d = qr. \]

- The EDM of a neutral particle would necessarily lie along its spin axis because all the other components would cancel.
Violating T and P Symmetry

- Reversing time (going from a to c) changes the spin of the particle.
- Switching the spatial coordinates (going from a to b) swaps the charges.
- By the CPT theorem, if T is violated, then CP is also violated.
Implications of CP violation

- Believed to be responsible for the matter-antimatter asymmetry in the universe → Should be more common.
- The decay of $K^0$ and $B$ mesons confirm CP violation experimentally.
- EDM experiments are part of search for new sources of CP violation.
- The Standard Model contains a mechanism for handling the CP violations that occur with EDMs, but the EDMs predicted are negligibly small.
- One of the possible extensions of the standard model, Supersymmetry, predicts EDMs that are much larger and within current experimental limits.
**Background Theory**

- Basic idea: Apply an electric field $E$ and a magnetic field $B$ to the sample and then look for effects.

- The Hamiltonian (total energy) of the system is:
  \[
  H = -(\mu B + dE) \cdot F,
  \]
  where $\mu$ is the magnetic moment, $d$ is the dipole moment, and $F$ is the total angular momentum.

- $F$ will rotate at the Larmor precession frequency because $\mu$ feels a torque due to $B$.

- This frequency, measured when $E$ and $B$ are parallel and antiparallel, is used to find EDMs.
In the parallel case, the Larmor frequency is given by:

\[ \omega_p = \frac{\mu B + dE}{\hbar F}, \]

and the antiparallel case is:

\[ \omega_a = \frac{\mu B - dE}{\hbar F}. \]

Thus, if we calculate the difference between the two measured frequencies, we can determine \( d \):

\[ \Delta \omega = \omega_p - \omega_a = \frac{2E_d}{F\hbar}. \]

Atoms, like \(^{199}\text{Hg} \), with nuclear spin \( \frac{1}{2} \) and no net electronic spin are less susceptible to some undesirable systematic effects. We can replace \( F \) in the above equation with \( \frac{1}{2} \), giving us:

\[ \Delta \omega = \frac{4E_d}{\hbar}. \]
Experimental Setup

When looking at the apparatus used to detect EDMs, there are two main sections, the “pink elephant” and the laser cavity:
Above is the entire apparatus. The “pink elephant” section is the large cylinder on the left and the laser cavity is on the right.
Optical Pumping

- $^{199}$Hg atoms have $\pm \frac{1}{2}$ nuclear spin. Must align them one way.

- A circularly polarized ultraviolet laser with $\lambda=254$ nm excites a transition in only spin $-\frac{1}{2}$ atoms, which can then relax into either spin state.

- An infrared laser with $\lambda=1016$ nm goes through two frequency doubling cavities to output an ultraviolet laser.

- The laser beam passes through a $\lambda/4$ wave plate to circularly polarize it and an optical chopper rotating at the Larmor frequency.
Inside the Elephant

- Four quartz Hg vapor cells inside three layers of magnetic shielding.
- Two inner cells are sandwiched between the outer cells and a central gold-plated ground plane.
- The two outer cells sit inside the high voltage electrodes, act as magnetometers.
- Same B-field for all cells.
- The $E$-field points in opposite directions in inner cells (no $E$-field in outer cells).
Hg vapor cells

- The vapor cells also contain 475 Torr of CO, used to help the Hg atoms hold their spin polarization longer.
- Insides of the cells are coated in paraffin, also extends spin relaxation time.
- Circularly polarized laser light is split into two beams that pass through the inner two cells.
- Once the pumping stage is complete, the laser is switched to being linearly polarized for the probing stage.
Optical Probing

- Linearly polarized laser light passes through the cells and is rotated by angle:
  \[ \varphi(t) = \varphi_0 e^{-t/\tau} \sin \omega t, \]
  where \( \tau \) is the beam coherence time.

- In order to measure \( \varphi \), must measure the intensity:
  \[ I = I_0 \sin 2(\alpha + \varphi(t)), \]
  where \( \alpha \) is angle of polarizer, relative to non-rotated light.

- Intensity decreases exponentially as it varies sinusoidally.
Previous Results

- When the experiment was last operational, it was sensitive to EDMs with $d^{(199\text{Hg})} < 2.1 \times 10^{-28} \text{ e cm}$.
  
  → If the Hg atom was the size of the Earth, they could detect a 0.001 angstrom bump in the charge distribution at the north pole.

- Even with this level of sensitivity, no EDMs have been found to date, in this lab or any others.

- Unfortunately, a long search for the source for false signals has prevented any new data from being collected recently.
False signals of varying sign and magnitude began in 4-cell vessel.

Showed up more often after apparatus had been open.

Most likely due to small spark that magnetizes some material → greater B-field (in same direction as applied B-field) increases Larmor frequency like an EDM would.
Working to reduce problems

- Reducing possible materials inside that can be magnetized should eliminate problem.
  - All materials have been tested for magnetic properties.
  - Questionable materials have been replaced.
  - Old insulation was replaced for fear that its dust was magnetic.
  - All parts of the apparatus have been meticulously cleaned.
General Improvements

- Other improvements have been made to overall apparatus.
  - Less noisy wavelength lock was built for laser.
  - Metal photodiode shields were replaced with plastic ones.
  - New and improved ground plane was installed
  - High voltage cable and supply replaced.
Future Work

- Still looking for non-ferromagnetic conductive paint for cells.
- When all current work and cleaning are complete, 4-cell vessel will be reinstalled.
- New EDM data will be taken to see if improvements have eliminated false signals.
Special Thanks:

- Everyone in the Fortson lab, especially Matt Swallows, Clark Griffith, and Norval Fortson.
- Jerry Seidler, Maya Kimura, and everyone in REU program.
- The UW Physics Department
- NSF