Searching for a Permanent Electric Dipole Moment of ^{199}Hg

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Abstract

Permanent electric dipole moments are significant in the search for new physics. They would provide evidence for extensions of the Standard Model, as well as an additional example of CP violation in nature. The mercury EDM experiment at UW has been a forerunner in sensitivity, but recently has encountered problems that have impeded data collection. My work this summer has been to help eliminate any possible sources of the false magnetic signals and implement some general improvements to the apparatus.

Introduction

Permanent electric dipoles are very simple: a positive charge q and a negative charge $-q$ separated by a small distance r. Most physics students are familiar with induced dipole where an electric field is required to separate the charges, but permanent electric dipoles exist without any external field. The electric dipole moment $\boldsymbol{d}$ is defined as:

$$\boldsymbol{d} = q\boldsymbol{r},$$

where q is the charge and $\boldsymbol{r}$ is the distance between the two charges. The direction associated with $\boldsymbol{d}$ is along the spin axis of the particle. Any component of $\boldsymbol{d}$ perpendicular to the spin axis would cancel out due to symmetry. Another way to think about this would be that another quantum number would be needed to define the direction related to the EDM, but that would violate the Pauli Exclusion Principle.

A permanent electric dipole moment represents an example of CP violation. Figure 1 shows that an EDM violates time reversal (T) symmetry and by the CPT theorem, if T symmetry is broken, then the combination of the charge and parity (CP) symmetry is also violated. Since the CP operator treats matter and antimatter differently, CP violation is believed to be responsible for the matter-antimatter asymmetry in the universe. This is such a large effect that more experimental evidence should be found confirming CP violation, but to date, only two experiments have been found that verify CP violation; the K^0 meson decay in 1964 and the B meson decay in 2001. The search for EDMs is part of the search for more sources of CP violation.

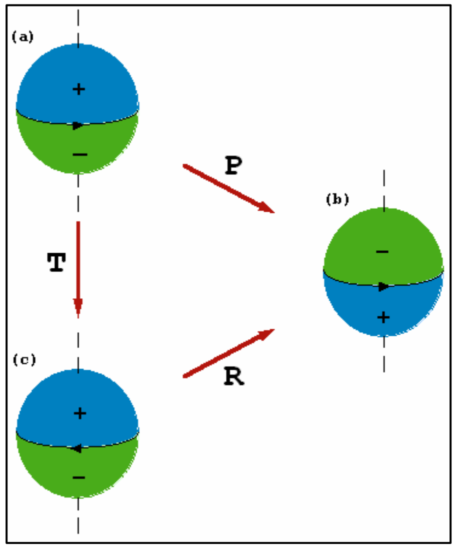

Figure 1: Applying the time reversal operator to an EDM produces a different EDM. Since the EDM violates T symmetry, it also violates CP symmetry.

Permanent electric dipole moments are also important to the quest for extensions of the Standard Model. The Standard Model has long been seen as incomplete, but there are not any theories yet that have been accepted as *the* theory to take up where the Standard Model left off. The Standard Model cannot explain where the CP violation present with EDMs comes from and it also predicts permanent EDMs so small that they cannot be measured with any equipment available today or in the foreseeable future. One possible extension of the Standard Model, Supersymmetry, predicts EDMs that are much larger and, depending on the variation of Supersymmetry, can be comparable or within current experimental limits. Thus, finding an EDM would also provide experimental confirmation for extensions to the Standard Model.

Theory

In order to detect EDMs, we apply an electric and magnetic field to our sample of ^{199}Hg and look for effects. The total energy of the system is given by the Hamiltonian:

$$H = -(\mu \boldsymbol{B} + d\boldsymbol{E}) \cdot \frac{\mathbf{F}}{|F|},$$

where μ is the magnetic moment, d is the dipole moment, and $\boldsymbol{F}$ is the total angular momentum.

The angular moment vector ***F*** will rotate at the Larmor precession frequency since the magnetic moment feels a torque due to the magnetic field. By measuring the Larmor frequency when ***E*** and ***B*** are parallel and antiparallel, we can find our electric dipole moment *d.*

In the case when ***E*** and ***B*** are parallel, the Larmor frequency is given by:

$$\omega_p = (\mu B + dE)/(\hbar F),$$

and when they are antiparallel, the frequency is:

$$\omega_a = (\mu B - dE)/(\hbar F).$$

Thus, if we calculate the difference between the two measured frequencies, we can determine *d:*

$$\Delta\omega = \omega_p - \omega_a = \frac{2Ed}{F\hbar}.$$

Atoms with nuclear spin ½ and no net electronic spin and electronic angular moment are less susceptible to some undesirable systematic effects. ^{199}Hg is such an atom, so we can replace *F* in the above equation with ½, giving us:

$$\Delta\omega = \frac{4Ed}{\hbar}\ .$$

With this simple equation involving only the magnitude of the electric field that we apply and frequency which we measure, we can find the size of the electric dipole moments present.

Experimental Overview

The entire apparatus consists of two main parts: the "pink elephant" and the laser cavity, shown below.

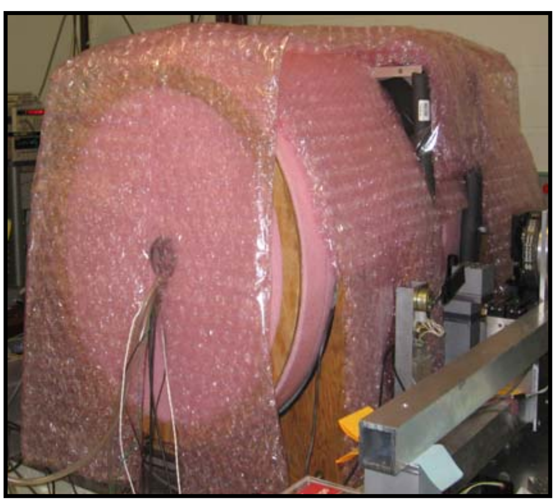

Figure 2: The "pink elephant" shown above houses the bulk of the experiment. The pink layers are insulation for external magnetic fields.

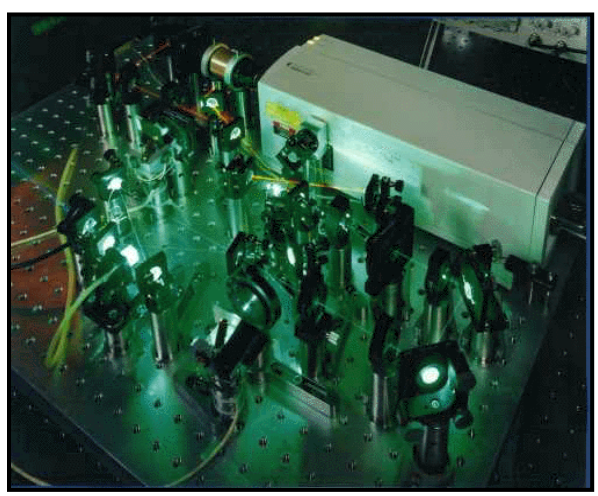

Figure 3: This photograph shows the laser cavity. If you look closely, you can see the infrared laser beam before it get frequency doubled into visible light.

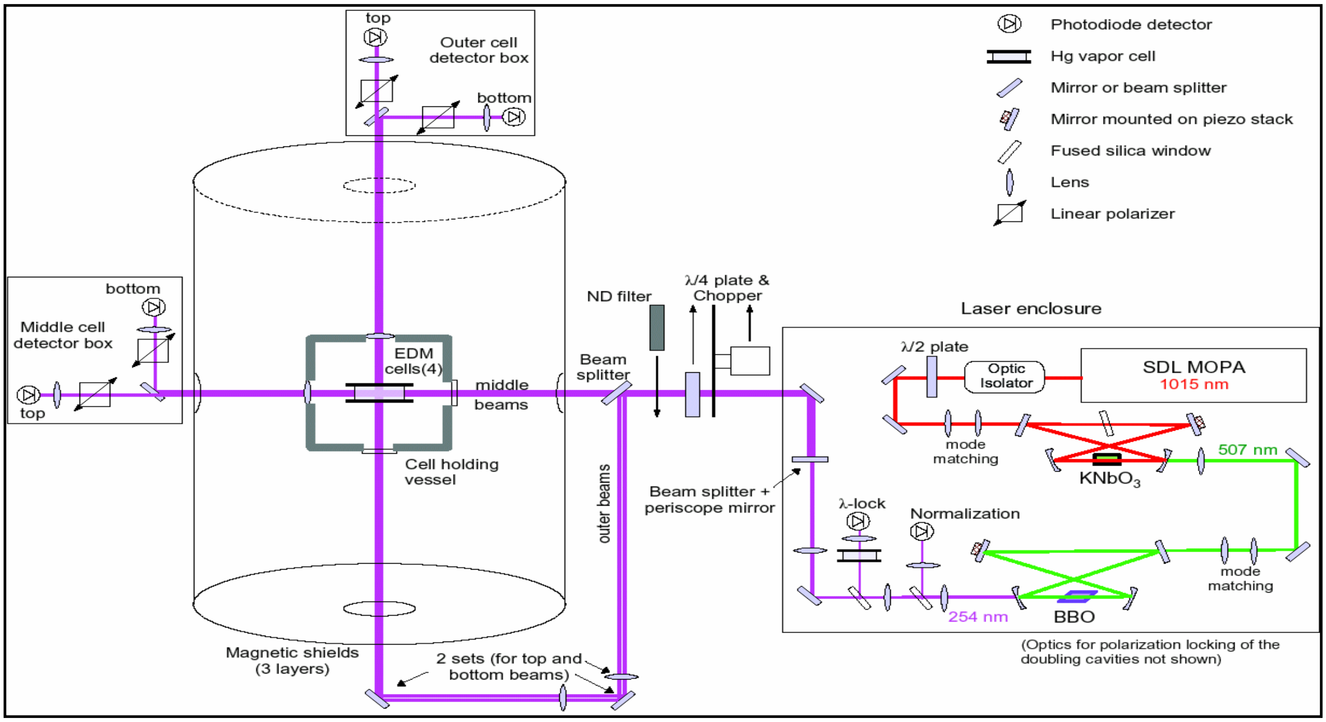

Figure 4: The above diagram shows a schematic of the entire apparatus. The "pink elephant" is the large cylinder on the left and the laser cavity is on the right.

It was previously stated that the ^{199}Hg atoms have a nuclear spin of ½ but they can be either spin up (+½) or spin down (-½) and they need to all be aligned one way. It is convenient to make them all spin up. We use circularly polarized ultraviolet laser with λ=254 nm, which excites a transition in only spin down atoms, which can then relax into either spin state. First, we must make an ultraviolet laser out of an infrared laser using two frequency doubling cavities that use nonlinear crystals (See Figure 4). Once the laser has been converted to an ultraviolet wavelength, it passes through a quarter-wave plate to circularly polarize the light before entering the pink elephant.

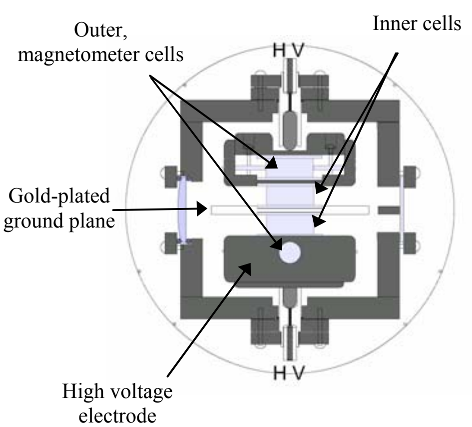

Figure 5: Above drawing is a schematic of the four cell vessel configuration.

Inside the elephant, surrounded by three layers of magnetic shielding, lie four quartz cells containing mercury vapor. The four cells are stacked on top of each other, with the two inner cells sandwiching a central, gold-plated ground plane (See Figure 5). The outer cells sit on either side of the inner cells and inside high voltage electrodes. All four cells feel the same magnetic field, but only the two inner cells feel the electric field. We only use one polarity of high voltage at a time, so the *E*-field points in opposite directions in the inner cells. The outer cells act as magnetometers and can be used to subtract out any strange magnetic field fluctuations, without disturbing an EDM signal. As well as ^{199}Hg, the vapor cells also contain carbon monoxide and are coated on the inside with paraffin. These additives help to extend the spin polarization of the mercury.

The ultraviolet laser beam is split into two beams that pass through the two inner cells. For a prescribed period of time called the pumping phase, the laser is circularly polarized and is used to spin polarize the atoms. After that stage is complete, the probing stage begins and the laser is switched to being linearly polarized.

The linearly polarized light reacts with the spin polarized, precessing mercury atoms in such a way that the linearly polarization of the light is rotated by an angle:

$$\varphi(t) = \varphi_0\, e^{-t/\tau} \sin \omega t,$$

where τ is the beam coherence time and ω is the Larmor precession frequency. $\varphi(t)$ varies in time depending on the alignment of the mercury atoms. Once passing through the cells, the newly rotated linearly polarized light is passed through another linear polarizer that is set at an angle α with respect to the original, non-rotated linearly polarized light. A photodiode can then measure the intensity of the light:

$$I = I_0 \sin 2(\alpha + \varphi(t)).$$

From this, $\varphi(t)$ can be found, which will give us ω, which can be used to calculate the size of d.

Previous Results and Current Work

When the experiment was last operational, it was sensitive to EDMs with d< 2.1×10-28 *e* cm. To demonstrate how sensitive this is, if one of the Hg atoms 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. The upper bound quoted in this result implies that the EDM must be smaller than that size; otherwise they would have found one. Unfortunately, a long search for the source for false signals has prevented any new data from being collected recently.

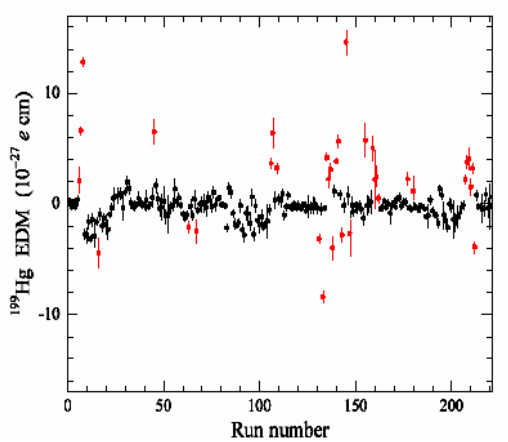

Figure 6: Sample plot of data with the false signals colored red.

When the four cell design replaced an earlier two cell design, the data collected began to contain a large number of false signals. These signals, colored in red in Figure 6, varied in sign and magnitude and did not seem to be correlated with anything. The signals are much too large and inconsistent to be indicative of an EDM and they did not disappear if they switched back to the two cell vessel. They show up more often after the apparatus has been opened up, which would imply that they are the result of some outside contamination. Many possible sources have been considered, including the rate at which the high voltage polarity was switched, the possibility that the cells were moving, the leakage currents produced by the large *E*-field, and sparks magnetizing material. The most likely explanation is that there are sparks inside that magnetize some material inside, which in turn produces a magnetic field and if this *B*-field has any component in the same direction as the applied magnetic field, it will produce a signal similar to an EDM.

The general strategy for eliminating these false signals has been to get rid of any and all material inside the apparatus that could be magnetized. All of the material has been tested for iron content and magnetic properties. Anything with bad or questionable results from these tests has been replaced with something new. New insulation for the pink elephant has replaced older insulation that was starting to crumble and the dust, which was feared to be magnetizable, was getting inside the apparatus. Everything inside the box housing the vapor cells has been meticulously cleaned with acid.

Other general improvements to the apparatus have been made. A new wavelength lock was designed and built to reduce the noise of the overall system. The old, plastic ground plane was replaced with a fused silica one. All of the high voltage cable, along with the high voltage supply, was replaced.

There are still a few remaining things to clean and replace before the four cell vessel can be reinstalled. When that finally happens, new data will be collected to see if any of the improvements have helped. Then, if all goes well, the mercury EDM experiment will resume looking for new physics.

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All figures compliments of W. C. Griffith.