A TEST OF TIME REVERSAL SYMMETRY USING ^{199}HG

Steve K. Lamoreaux
University of Washington
Physics Department, FM-15
Seattle, WA 98195 USA

An experimental measurement of the ^{199}Hg atomic electric dipole moment (EDM) has yielded the null result $d(^{199}\mathrm{Hg}) < 1.3 \times 10^{-27}$ e cm. This is the smallest limit ever set on a system electric dipole moment, and sets the most stringent limits to date on several sources of time-reversal violation, and gives limits comparable to those set by the neutron EDM. A brief review of the technical innovations which made such precision possible will be given.

I. Introduction

The nature of the interaction which leads to the observed violation of CP symmetry (combined operation of charge conjugation and parity inversion) in a rare decay mode of the K_0 meson remains and enigma.[1)] Since $CPT = 1$, the observed CP implies time reversal symmetry violation. Theories put forward to explain the observed CP violation predict the existence of permanent electric dipole moments (EDMs) of elementary particles (e.g., the electron) and more complex structures (e.g., neutron, atoms).

A system with angular momentum I which has an EDM interacts with electric and magnetic fields as described by the following Hamiltonian:

$$H = -(d\vec{E} + \mu\vec{B}) \cdot \vec{I}/I \tag{1}$$

where d and μ represent the electric and usual magnetic dipole moments, $\vec{E}$ and $\vec{B}$ are the applied electric and magnetic fields. The Hamiltonian is written in this form because any vector expectation value associated with the system must lie along $\vec{I}$, otherwise additional quantum numbers would be required to describe the system; that there are only two states associated with the neutron (ground state) is well-verified by the observation that nucleons in composite nuclei obey the Pauli exclusion principle.

An important feature of Eq. (1) is that the EDM is proportional to I, just as the magnetic moment is. The implication is that an EDM is the result of internal (time-dependent) dynamics, and represent it as a simple charge separation along I isn't correct. When the system is reflected in the mirror, the EDM direction must reverse with I, in order for there to be an observable which manifests T violation. This can be seen from Eq. (1); under time reversal, $\vec{E} \to \vec{E}$, $\vec{B} \to -\vec{B}$, while under parity, $\vec{E} \to -\vec{E}$, $\vec{B} \to \vec{B}$, and in order for the eigenvalues of Eq. (1) to show parity or time reversal effects, the EDM must be proportional to $\vec{I}$.

To measure the EDM of an object, one in principle could simply look for the precession of the spin about an applied electric field. In the case of spin $1/2$, any spin dependent interaction with the applied field is strictly forbidden (Kramer's theorem, which is a statement about time reversal symmetry). For spin $> 1/2$, there can be an electric polarizability effect, which should be the same independent of electric field direction, unlike a true EDM. Perfect reversal of an electric field is difficult in practice.

By Eq. (1), if parallel electric and magnetic fields are applied, on reversal of $\vec{E}$ relative to $\vec{B}$, there will be a shift in Larmor frequency

$$\omega = 2dE/\hbar. \tag{2}$$

Equation (1) is also applicable to the internal interactions within a molecule, and if one of the atoms of a polar molecule has an EDM, the effects can be evident in the molecular hyperfine structure.

II. Theoretical Interpretation of Atomic EDM Measurements

A splendid review of the fundamental processes which can lead to an EDM is given by S. Barr,[2] and a review of the calculation of atomic EDMs is given by A.-M. Martensson.[3] For the present discussion, I will compare limits set by our ^{199}Hg EDM experiment[4] to those of the neutron.[5] A full discussion of the ^{199}Hg result is given in Ref. 4).

It has been long known that a neutral bound system of point particles interacting electrostatically cannot manifest the effects of an edm in the nonrelativistic limit. This is simply because under equilibrium conditions, the average electric field at each constituent particle is zero. Thus, one might expect that to search for an atomic EDM is a bit pointless. Schiff discussed possible ways around this problem;[6] in the case of atoms, in addition to electrostatic interactions, there is also the magnetic fine structure and hyperfine interactions. Furthermore, the electrons are relativistic near the nucleus, and the nucleus is of finite extent. Thus, we can expect a non-zero atomic EDM if, for example, the electron has an EDM. In the case of the alkali atom Cs, the atomic EDM is actually about 120 times the electron EDM.[7] For ^{199}Hg, the effect is less favorable, where the atomic EDM is about 1/100 of the electron EDM. The difference between these two atoms is the electron spin: Hg in the ground state has none, and an electron EDM couples in third order through the hyperfine interaction.

In the case of a nuclear EDM, the atomic effect can be estimated, following arguments used in a related calculation of an intrinsic proton EDM:[8]

$$d_{atom} \approx Z^2 K_r (R_{nucleus}/R_{atom})^2 d_{nucleus} \tag{3}$$

where Z is the atomic number and K_r is a relativistic enhancement factor of order 10 for Hg; we thus see an atomic EDM about a factor of 100 less than the nucleus. If we think of the nuclear EDM as being that of the valence nucleon, we can thus think of our atomic Hg experiment having an inherent factor of 100 reduction in sensitivity over the neutron. In fact, our measurement[4]

$$d(^{199}\mathrm{Hg}) < 1.3 \times 10^{-27} \mathrm{e} \cdot \mathrm{cm}$$

(95% confidence) limits the QCD θ parameter to

$$\theta_{QCD} < 7 \times 10^{-10}$$

whereas the neutron limit

$$d(n) < 1.2 \times 10^{-25} \mathrm{e} \cdot \mathrm{cm}$$

limits

$$\theta_{QCD} < 4 \times 10^{-10}.$$

Limits on T-odd quark-quark interactions are also comparable between the two.[9]

III. Experimental Technique

Our first measurement of the ^{199}Hg EDM was completed in 1987 set a limit of 3×10^{-26} e cm;[10] our recently completed work has improved this limit by a factor of 25. This work is fully described in Refs. 4) and 11)

The major factors contributing to the increased sensitivity are as follows: use of isotopically enriched ^{199}Hg, improved optical pumping cells, and the use of a transverse pumping scheme (also, considerably more data was taken with the new apparatus). The transverse pumping scheme, first suggesting in 1987 and described in Ref. 12), eliminates possible effects due to the AC Stark shift of the optical pumping light since the light propagation direction and magnetic fields are perpendicular. In addition, fluctuations in this "light shift" seemed to be a source of excess noise in the earlier version of the experiment. The transverse pumping scheme gives a factor of two increase in inherent sensitivity.

We opted to use atomic oscillators as opposed to a pump/probe free precession technique because the latter requires switching static magnetic fields within the shields. At our level of sensitivity, magnetic field drifts associated with such switching would be unacceptable. However, I have proposed a new technique which gets around this problem, and has a number of advantages, as will be described later.

The optical pumping cells are the heart of the experiment, and took about 7 years to develop. The spin relaxation lifetime is about 70 seconds, electric fields up to 10kV/cm can be applied, and about 5×10^{12} atoms are contained in the cell (of total volume 5 cc). Two cells are used in the experiment; the electric field is applied oppositely between the two cells, and an EDM would be evident by a relative phase change between the respective atomic oscillator signals. This differential measurement discriminates drifts in the static homogeneous field, which tend to be about a factor of 10 greater than drifts in the gradient. So far, our result is consistent with the shot noise limit, however, a future increase in precision will require better field stability, or auxillary measurements.

To search for an EDM, one simply periodically reverses the direction of the electric field; a correlation with the atomic oscillator frequency with electric field direction would be evidence of an EDM. The experiment operates with a 1/8 duty cycle for the following reasons: the atomic oscillators take about 20 seconds to respond, displacement currents associated with field-reversal charging currents can give a transient shift so we give the system time to respond, and data is taken with no voltage applied (between field reversals) to test for systematic effects. The electric field is reversed every 1000 seconds, and about 1/8 to 1/16 of the data can be used with confidence.

IV. Statistical Limits to Sensitivity

The basic experimental idea is to measure the spin precession frequency difference for

parallel and antiparallel magnetic fields. We have N uncorrelated atoms per cell, and on reversal of the electric field, for each cell, from Eq. (2), a net frequency uncertainty of

$$\delta\omega = \sqrt{2}\frac{1}{\tau}\frac{1}{\sqrt{N}} \tag{4}$$

is expected by the Heisenberg relation over an observation time $\tau \approx 25$ sec, the effective spin lifetime. After many such measurements, over a time T, the final uncertainty is

$$\delta\omega = \frac{\sqrt{2}}{\tau}\frac{1}{\sqrt{N}}\sqrt{\frac{\tau}{T}} = \sqrt{\frac{2}{\tau TN}}. \tag{5}$$

Taking an electric field of 10 kV/cm, and taking a difference between two cells (a net factor $\sqrt{2}$ increase in sensitivity over a single cell), we might expect a daily uncertainty of

$$\delta d \approx 3.4 \times 10^{-30} \text{e} \cdot \text{cm}.$$

However, there are a number of reduction factors. The spin precession is detected by the absorption of photons. First, the signal modulation is only a fraction of the total transmitted photon flux detected (1/8). Next, the light collection is efficiency is 25%, the photomultiplier quantum efficiency is 10%, and the net transmitted photon flux is $e^{-1.8} = .17$, and the incident flux is determined by N/τ. Finally, the duty cycle is 1/8. The last four factors enter as the square root, whereas the overall signal to noise factor 1/8 enters linearly (in addition, the effective linewidth of the atomic oscillator is twice the Heisenberg limit because not all atoms live for τ; this also enters linearly); we thus have a reduction factor

$$\frac{\sqrt{0.25 \times 0.10 \times 0.17 \times \frac{1}{8}}}{16} = 1.4 \times 10^{-3}$$

giving a daily statistical accuracy of about 2.5×10^{-27} e cm, which is experimentally observed (at 10kV/cm).

V. Systematic Effects Considered

A "quadratic" effect due to changes in the light shift of the pumping light (1mHz) with application of high voltage through the usual Stark effect is possible; field perpendicularity and polarization averaging to zero reduces the effective light shift to $< 1\mu$Hz, and the high voltage symmetry, certainly better than 10%, gives an EDM signal $< 10^{-28}$ e cm.

Leakage currents in the steady state of order 1 pA,by flowing in a loop around the cell, can give rise to an EDM of 5×10^{-29}e cm.

Displacement currents from the high voltage application can permanently magnetize the shield. Simulating these currents with wires placed in the shields but with current increase by 100-1000 times showed no remanance effects.

In addition, the zero-voltage data (i.e., atomic oscillator phase after each high voltage application) yielded no resolved effect.

Magnetic fields associated with the high voltage supply are 1μG 1 meter from the shields; the shielding factor on the gradient is $20 \times 70,000$ which gives an EDM of 10^{-28}e cm.

Changes in spatial dependence of the atomic polarization due to application of the high voltage was explored by applying a magnetic field gradient 50 times larger, along various directions, than is normally present, and no effects were observed.[13)]

The time dependence of the atomic oscillator signals, after application and removal of the high voltage, showed no resolved systematic effects.

The possibility of a $v \times E$ systematic magnetic field exists due to the difference between the spatial average of pumping vs. detection; this is estimated to be $< 10^{-28}$e cm.

VI. Future Prospects

In order to reduce dead-time effects and increase the signal-to-noise, we are now considering a pump/probe type of experiment. Furthermore, background effects inherent in the atomic oscillator effects will be reduced, and higher quantum efficiency photomultipliers (which have a light polarization dependent sensitivity) can be used, and the collection efficiency increased. In total, a factor of about 3 increase in sensitivity is expected.

Since the switching of static fields must be avoided, a coherent precessing polarization must be produced by other means. One possibility is to pump the atoms along the fixed static field direction, then use an RF pulse to rotate the polarization by $\pi/2$, thereby creating the precessing spin polarization. Unfortunately, the electrodes of the cells are not transparent to the 254 nm ultraviolet pumping light, so this is not possible; also, the application of the RF magnetic field could lead to drifts.

This led to the proposal of a "pulse pump" system; pumping light is incident on the cells from a direction perpendicular to the applied static magnetic field, and this light is pulsed at the Larmor frequency. A net spin polarization builds up, because each time the polarization precesses a cycle, it gets reinforced.

A Zeeman-shifted high intensity pump light has been constructed; the idea is that non-resonant light from ^{202}Hg can be Zeeman shifted to resonance, and the light parallel to the magnetic field is circulary polarized. Thus, the pumping light needs no additional polarizer. The light is the chopped by a toothed disk turning at a frequency such that the pulses occur at the Larmor frequency. The pump light is only used for polarization, after which it is blocked. An atomic polarization of 80% has been produced by this method.

The probe light has its polarization modulated at high frequency by use of a photoelastic Lame plate modulator. Thus, the light shift is again reduced by this, and by having the incident probe light perpendicular to the applied field.

The gain in sensitivity comes about from an increased atomic polarization, decreased dead time (pump time is of order 10 sec, no waiting for atomic oscillator response or displacement current effects), and increased detection efficiency. At least a factor of three increase in sensitivity is expected, and systematic effects associated with the atomic oscillators will be eliminated, although the new technique will certainly have its own set of systematic problems.

We also hope to fabricate cells with a longer spin lifetime, and to incorporate either a Cs or Squid magnetometer system to monitor systematic and background magnetic fields, which are anticipated to be a problem at the new level of sensitivity. High T_c Squid magnetometers, or a High T_c flux transformer coupling to a conventional Squid outside the magnetic shield are being considered.

VII. References

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