Permanent EDM measurement in Cs using nonlinear magneto-optic rotation

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We use the technique of chopped nonlinear magneto-optic rotation in a paraffin-coated Cs vapor cell to look for a permanent electric dipole moment (EDM) in the atom. The signature of the EDM is a shift in the Larmor precession frequency correlated with application of an electric field. Using a field of 2.6 kV/cm, we place an upper limit on the electron EDM of $7.7 \times 10^{-22}$ e-cm. This limit can be improved by 5 to 6 orders-of-magnitude (and brought below the current best experimental limit) with simple improvements to the technique.

I. INTRODUCTION

The search for a permanent electric dipole moment (EDM) in an atom is motivated by the fact that it signifies violation of parity (P) and time-reversal (T) symmetries in the fundamental laws of physics. Since T violation has not been observed directly, EDM searches are among the most important experiments in physics today. Along with charge conjugation (C), there is a theorem—the CPT theorem—which says that the combined operation of these three symmetries is always obeyed in nature. As a consequence, the observation of CP violation in neutral kaon decay implies T violation. This is accommodated in the standard model of particle physics by predicting EDMs for fundamental particles like the electron and the neutron; but the value of the EDM predicted is about 8 to 10 orders-of-magnitude smaller than current experimental precision. However, theories that go beyond the standard model—such as supersymmetry—predict EDMs within experimental range. As a consequence, such theories are strongly constrained by measured experimental limits on EDMs.

If the electron has an intrinsic EDM, then it gets enhanced in heavy paramagnetic atoms—like Cs and Tl—due to relativistic effects. In fact, the best limit of $1.6 \times 10^{-27}$ e-cm on the electron EDM has been placed through a measurement on an atomic beam of Tl atoms. In earlier work, we have proposed a new technique to measure the existence of an EDM in Cs atoms using a paraffin-coated vapor cell. The technique is called chopped nonlinear magneto-optic rotation (NMOR), and allows us to measure the Larmor precession frequency with high precision. The signature of an EDM is a shift in the Larmor frequency correlated with the application of a large electric field.

In this work, we demonstrate the use of this technique to do an EDM measurement with an applied electric field of 2.6 kV/cm. From this, we put an upper limit on the atomic EDM of $8.8 \times 10^{-20}$ e-cm, which implies that the electron EDM is less than $7.7 \times 10^{-22}$ e-cm using the enhancement factor of 114 in Cs. Though this is not competitive with the best measurement for the electron EDM, the measurement is useful because it shows that previous reports of the presence of a non-zero EDM (of order $10^{-9}$ e-cm) are incorrect. In addition, there are simple improvements to the technique which will enable us to reach a precision better than the Tl value.

II. EXPERIMENTAL DETAILS

The experimental setup is shown schematically in Fig. It consists of a grating stabilized external cavity diode laser system operating on the 852 nm D2 line of $^{133}$Cs (6S$_{1/2} \rightarrow 6P_{3/2}$ transition). Part of its output is tapped for saturated-absorption spectroscopy in a Cs vapor cell. The laser is locked to the $F_g = 4 \rightarrow F_e = 5$ hyperfine transition using current modulation of the diode laser. The remaining part of the beam is used for chopped NMOR in the vapor cell. For this, it is passed through two acousto-optic modulators (AOMs)—AOM1 upshifts the laser frequency by about 90 MHz, while AOM2 downshifts by the same amount so that its output is at the same frequency as the laser. The rf driver for AOM1 is chopped (on-off modulated) at 2 kHz. The output beam is elliptic in shape with $1/e^2$ diameter of $3 \times 5$ mm. It is linearly polarized and has a power of 50 µW.

This beam goes into a spherical Cs vapor cell (7.5 cm diameter) with paraffin coating on the walls. The cell has aluminum plates on either side for applying the required...
electric field, and is inside a solenoid coil for applying a uniform magnetic field. The solenoid is wound on a plastic form of 190 mm diameter. It consists of 1800 turns of 0.35 mm magnet wire wound tightly over a length of 640 mm. The entire assembly—consisting of the cell, field plates, and solenoid—is placed inside a three-layer magnetic shield (Magnetic Shield Corp, USA) that reduces stray fields to nearly zero.

The plane of polarization of linearly polarized light going into the cell is rotated due to the phenomenon of NMOR. The output beam is split into its two polarization components using a Wollaston prism. The power in each component is measured using photodiodes 1 and 2. When the powers in the two beams are nearly equal (called balanced and achieved by adjusting the λ/2 waveplates in front of the PBS), and the angle of rotation is small, the optical rotation can be shown to be proportional to the difference between the two powers \( \text{[10]} \). Hence the difference of the photodiode signals is fed to the lock-in amplifier.

III. THEORETICAL ANALYSIS

As shown in our earlier work in Ref. \([7]\), the chopped NMOR technique relies on the laser beam (measuring the rotation) being modulated on and off. During the on time, the atoms are optically pumped into a \( \Delta m = 2 \) coherence of the ground state (atomic alignment). During the off time, the atoms freely precess around the magnetic field at the Larmor frequency \( \omega_L \). If the chopping frequency matches \( 2 \omega_L \) (the factor of 2 appears because the alignment has 2-fold symmetry), then the rotation is resonantly enhanced in every cycle.

In the experiment, we fix the chopping frequency and scan the magnetic field by applying a triangular waveform to the solenoid. The out-of-phase component output of the lock-in amplifier shows two peaks as seen in Fig. 2—one at negative field and the other at positive field. The horizontal time axis is scaled so that the difference between the two peaks is equal to the magnetic field required for the particular value of \( \omega_L \).

The Wigner-Eckart theorem tells us that the total angular momentum \( \vec{J} \) is the only vector in the body fixed frame—therefore, both the magnetic moment \( \vec{\mu} \) and electric dipole moment \( \vec{d} \) have to point along \( \vec{J} \). Hence the interaction energy of the atom in the presence of the two fields can be written as

\[
U = (d \vec{E} + \mu \vec{B}) \cdot \vec{J}
\]  

(1)

This shows that if the atom has an electric dipole moment, then there will be change in the Larmor precession frequency correlated with the application of an electric field. The Larmor precession frequency in the presence of only a magnetic field is

\[
\omega_L = g_F \mu_B B / \hbar
\]  

(2)

where \( g_F \) is the Landé g factor of the level, and \( \mu_B \) is the Bohr magneton. The change in the Larmor precession frequency is equivalent to a change in the magnetic field—thus if the separation between the peaks in Fig. 2 changes by \( \delta B \) when an electric field \( E \) (parallel to \( B \)) is applied, then the resultant atomic EDM is

\[
d_A = \frac{g_F \mu_B \delta B}{2E}
\]  

(3)

The factor of 2 accounts for the fact that the peaks in the figure appear when the \( B \) field is either parallel or anti-parallel to \( E \).

IV. RESULTS AND DISCUSSION

The first experimental run consisted of taking a set of 200 points—100 points without an E field, and 100 points with an E field of 2.6 kV/cm. The data were analyzed statistically, and the results of this analysis are shown in Table I.

| TABLE I. Statistical distribution of a data set comprising of 100 points without an electric field, and 100 points with an electric field of 2.6 kV/cm. |
|---|---|---|---|
| No E field | With E field |
| Average (mG) | Std dev (µG) | Average (mG) | Std dev (µG) |
| Left | Right | Separation | Linewidth |
| Left | -2.859 | 4.5 | -2.859 | 7.3 |
| Right | 2.859 | 3.4 | 2.859 | 5.0 |
| Separation | 5.718 | 3.4 | 5.718 | 5.0 |
| Linewidth | 0.384 | 6.4 | 0.429 | 26.0 |

Within the accuracy of the experiment, the peak separation does not change. The two data sets are combined into one consisting of 200 points. The standard deviation
for the combined set is 4.2 µG. This is reduced by a factor of 14 for the 200 points measured because the error in the mean is smaller by \( \sqrt{\frac{1}{N}} \) for an error distribution that is Gaussian. Eq. (3) then gives the atomic EDM as

\[
d_{A} = 8.8 \times 10^{-20} \text{ e-cm}
\]

Using the enhancement factor over the intrinsic electron EDM of 114 in Cs, this implies that

\[
d_{e} \leq 7.7 \times 10^{-22} \text{ e-cm}
\]

There are two interesting things to be noticed from the data in the table. One is that the separation between the peaks has the less error than the individual peaks. This is because the separation is less susceptible to stray fields—e.g., a constant external field will cause both peaks to shift to the right while keeping their separation constant. The second one is that the linewidth of the peaks increases upon application of an electric field, indicating an increase in the spin-relaxation time. This could be due to a decrease in the quality of the paraffin coating when the electric field is applied. We have noticed that the linewidth recovers to its zero-field value over a period of a few months, indicating that the damage is irreversible on the time scale of the experiment.

Though our limit is not competitive with the most accurate value for the electron EDM of \( 1.6 \times 10^{-27} \text{ e-cm} \) (from a measurement on an atomic beam of Tl atoms \[6\], it is still useful because (i) it is a new technique, and (ii) there are some reports of a non-zero electron EDM \[8\] which are therefore shown to be incorrect from our measurement. In addition, there are simple improvements to our technique that can result in an improvement in precision by several orders of magnitude, and bring it below the Tl value.

1. Each measurement takes only a few seconds to complete. Therefore, the number of points can be easily increased to about 100 million. This should result in a 1000-fold increase in precision.
2. The applied electric field can be increased by a factor of 4—from the existing 2.6 kV/cm to 10 kV/cm.
3. With the same cell we have obtained a linewidth of 100 µG for the peaks \[7\]. There is no reason that we cannot reach this number. In fact, with improved shielding and better paraffin coating, we expect to get a linewidth of about 4 µG, which is 100 times smaller than the present value.

In summary, all these improvements are easily implementable, and should together result in a \( 4 \times 10^5 \) increase in precision.

V. CONCLUSION

In conclusion, we have demonstrated a new method for the measurement of the electron EDM using chopped NMOR in a paraffin-coated vapor cell containing Cs atoms at room temperature. Using an electric field of 2.6 kV/cm, we put an upper limit of \( 7.7 \times 10^{-22} \) e-cm for the electron EDM. Though this is not the most precise measurement to date, there are foreseeable improvements to the technique that should result in 5 to 6 orders-of-magnitude improvement in precision, making it competitive with the best measurements.

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