

Solid-state systems for the electron electric dipole moment and other fundamental measurements

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In 1968, Shapiro published the suggestion that one could search for an electron dipole moment (EDM) by applying a strong electric field to a substance that has an unpaired electron spin; at low temperature, the EDM interaction would lead to a net sample magnetization that can be detected with a superconducting quantum interference device (SQUID) magnetometer. One experimental EDM search based on this technique was published, and for a number of reasons including high sample conductivity, high operating temperature, and limited SQUID technology, the result was not particularly sensitive compared to other experiments in the late 1970s. Advances in SQUID and conventional magnetometry led us to reconsider this type of experiment, which can be extended to searches and tests other than EDMs (e.g., test of Lorentz invariance). In addition, the complementary measurement of an EDM-induced sample electric polarization due to application of a magnetic field to a paramagnetic sample might be effective using modern ultrasensitive charge measurement techniques. A possible paramagnetic material is Gd-substituted yttrium iron garnet which has very low conductivity and a net enhancement (atomic enhancement times crystal screening) of order unity. Use of a reasonable volume (hundreds of cm^3) sample of this material at 50 mK and 10 kV/cm might yield an EDM sensitivity of 10^{-32} e cm or better, a factor of 10^5 improvement over current experimental limits.

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I. INTRODUCTION

The idea of using solid-state systems for permanent electric dipole moment (EDM) and other fundamental measurements has been around for quite some time; with the exception of one EDM measurement of rather unremarkable sensitivity, (spin polarized) solid-state systems have found their only applications in Lorentz violation and long-range force tests using torsion pendulums; see [1] for an overview.

Shapiro, in 1968, put forward the idea that one could test for the presence of an EDM by applying a strong electric field to a material with unpaired electron spins; the EDMs of the sample atoms (or ions), and therefore the spins, become spin polarized [2]. The degree of spin polarization can be determined, in conjunction with the Boltzmann equation, from the Hamiltonian

$$H = -d \frac{\mathbf{E} \cdot \mathbf{J}}{J}, \quad (1)$$

where d is the EDM (measured in e cm), E is the applied electric field, and J is the total atomic (or ionic) angular momentum. Because each spin also carries a magnetic moment, the sample will become magnetized. The change in magnetic flux Φ at the surface of a flat sheet of material with the application of an electric field is

$$\Delta\Phi = 4\pi\chi A d E^* / \mu_a, \quad (2)$$

where χ is the magnetic susceptibility, A is the sample area, d is the EDM associated with the spin of interest, E^* is the effective electric field at the location of the spins of interest, and $\mu_a = g[J(J+1)]^{1/2}\mu_B$ is the atomic or ionic magnetic moment. The diamagnetic susceptibility is determined by the ratio of the magnetization M to the magnetic induction B ,

$$\chi = \frac{M}{B} \approx \frac{N\mu_a^2}{3k_B T}, \quad (3)$$

where N is the number density of spins of interest, k_B is Boltzmann's constant, and T is the sample temperature, in the cases where simple Langevin paramagnetism is applicable (which we will assume for demagnetized soft ferro- and ferrimagnetic materials).

We should note that any Hamiltonian of the form of Eq. (1) will lead to a sample magnetization, e.g., a Lorentz violation would lead to a sample orientation dependent magnetization, or some long-range force would lead to a magnetization that depends on the separation between the paramagnetic material and a laboratory source. Such experiments will not be directly discussed here; the possible improvements for limits on such interactions can easily be determined by scaling the potential EDM limits presented here with previous EDM results.

II. PREVIOUS WORK

The one experiment to measure an EDM by the Shapiro technique employed a nickel-zinc ferrite which could support an electric field of 2 kV/cm and had high resistivity at low temperature [3]. The ion of interest in this case is Fe^{3+} . Because of the low atomic number of Fe, the net EDM of the atom is $d = 0.5d_e$, where d_e is the bare EDM.

One possible source of shielding of the electric field in the crystal was neglected in this work. As is well known in the case of atoms, the net electric field at the site of the nucleus and at each electron in the atom must be zero for the system to be in equilibrium (when only electrostatic forces are present). In the case of a bulk crystal, E^* is determined by the average of $\langle \mathbf{d} \cdot \mathbf{E} \rangle$ over the position of the ion in the crystal lattice. We must recall that for the system to be in equilibrium, when only electrostatic forces are present, the

average of $\langle q(r)E(r) \rangle$, e.g., the atomic charge density times the electric field (which varies rapidly in the crystal), must be zero. This effect was not taken into account in [3], but is likely not a large effect. This is because a system bound only by electrostatic forces is not stable, so there are additional forces within the crystal. Exchange forces (which represent dynamic quantum fluctuations in the fields) that ultimately keep the ions separated are roughly as important as the electrostatic interactions between ions in a crystal. This is equivalent to saying that if an ion is “large” it really cannot move much in the crystal, and the displacement due to the applied electric field is against the exchange force which has a different spatial functional dependence compared to the crystal electrostatic forces.

However, there is an effective screening due to the high dielectric constant which was taken into account in [3]. The experimental result $d_e = -(8.1 \pm 11.6) \times 10^{-23}$ represent a magnetic sensitivity of 3×10^{-11} G, which was obtained in 3.5 h with a superconducting quantum interference device (SQUID) magnetometer, with the experiment operated at 4 K. The flux detection sensitivity corresponds to about $5 \mu\Phi_0$ where $\Phi_0 = 2.07 \times 10^{-7}$ G cm². We can conclude that the SQUID sensitivity was $800 \mu\Phi_0/\sqrt{\text{Hz}}$. In addition, A in Eq. (2) is coupled to a SQUID that has a small area, resulting in an effective sampling area 2×10^{-2} smaller than the “true” sample area. As will be discussed, this is a general problem with SQUID magnetometry.

Further experiments with EuS and EuO proved unsuccessful due to large leakage currents with application of the high voltage.

III. A MODERN SOLID-STATE SQUID EDM EXPERIMENT

A. Materials

For a modern experiment, we are considering garnet crystals. The iron and gadolinium rare-earth garnets are cubic insulating crystals so they have sufficient symmetry to suppress quadratic effects [4]. The rare-earth iron garnets (IG) (RIG, where R is Y, Gd, etc., and is in the R^{3+} ionization state) are ferrimagnetic while the rare-earth gallium garnets (RGG) are Langevin paramagnets (Ga has no paramagnetism) and follow the Brillouin formula Eq. (3) [5]. For the case of an EDM-induced magnetization, the ferrimagnetism presents some complications, so for the arguments presented in this section, GdGG will be considered. The formula of this material is $\text{Gd}_3\text{Ga}_5\text{O}_{12}$, which represents the general garnet formula where other rare-earth elements, either singly or in mixtures, can be in place of some or all of the Gd; Ga is replaced by Fe for RIG. All these materials have volume resistivities of greater than $10^{16} \Omega \text{ cm}$ at temperatures at or below 77 K. The issues of dielectric strength remain to be investigated. Also questions of whether spin-glass or ferro-magnetic transitions occur remain to be investigated (note that GdGG is used in adiabatic demagnetization refrigerators).

Gd^{3+} is experimentally attractive because it has total angular momentum $L=0$ and total spin $S=7/2$. The lack of orbital angular momentum makes it easy to magnetize the material. Ga has no magnetic moment so Gd^{3+} determines

all the magnetic properties of GdGG. The electronic configuration in Gd^{3+} is complicated, but it has at least one 6s valence electron; we might expect a net atomic enhancement of $d = \alpha^2 Z^3 \approx 10$, while the shielding of the electric field in the crystal might be around an order of magnitude. A preliminary estimate by Sushkov and Kuenzi [6] for GdIG shows a net enhancement times screening of order unity. We can thus assume in Eq. (2) that $dE^* = d_e E$ where E is the electric field applied to the crystal.

The density of Gd in GdGG is about $10^{22}/\text{cm}^3$, somewhat low, but given the excellent insulating properties, this is an acceptable sacrifice. From Eq. (3), assuming an EDM of 10^{-27} e cm and an electric field of 10 kV/cm implies

$$\Delta\Phi = d_e \frac{3.16 \times 10^{-16}}{T} \frac{GA}{10^{-27} \text{ e cm} \times 10 \text{ kV/cm}}, \quad (4)$$

so, for $T=10$ mK, $A=100$ cm² and $\Delta\Phi = 17 \mu\Phi_0/d_e$.

B. Magnetometry

The best possible energy resolution that a SQUID magnetometer can achieve is dictated by the energy uncertainty principle, $\Delta E \Delta t \geq \hbar$. A useful way to parametrize the sensitivity of a SQUID is by its intrinsic energy resolution $dE_{sq} t = n\hbar$, where $n \geq 1$, relative to a perfect SQUID:

$$dE_{sq} t = \frac{d\Phi_{sq}^2}{2c^2 L_{sq}} = n\hbar, \quad (5)$$

where $d\Phi_{sq}$ is the flux through the SQUID loop, L_{sq} is the intrinsic inductance of the SQUID, and t is the measurement time. Modern SQUID magnetometers routinely achieve an intrinsic energy sensitivity of order $10\hbar$. For comparison, the SQUID used with the work described in [3] had sensitivity of order $6.4 \times 10^7 \hbar$.

Equation (5) represents the energy noise per second integration time t , implying a flux sensitivity of

$$d\Phi = \sqrt{2n\hbar c^2 L_{sq}/t} \approx 0.2 \mu\Phi_0 \sqrt{\text{sec}/t}, \quad (6)$$

where t is the integration time. For modern commercially available SQUIDS, typically $L_{sq} = 10^{-12}$ s²/cm = 0.2 nH, with an input coupler inductance of $L_i = 500$ nH, and the input mutual inductance is $M = \sqrt{L_{sq} L_i} = 10$ nH. (For convenience, we will use MKSA inductance units for describing SQUID properties.) Thus, the fraction of flux picked up from the sample that is delivered to the SQUID is

$$d\Phi_{sq} = d\Phi_p \frac{M}{L_p + L_i}, \quad (7)$$

where L_p is the inductance of the pickup coil around the sample. Therefore we see a loss of sensitivity over that intrinsic to the SQUID; this is due to the mismatch between the sample and SQUID areas. We could imagine building a SQUID with a lower input inductance, perhaps achieving $L_i = L_{sq} = M$. In this case, L_i is much smaller than any imaginable L_p ; because L_p scales as the diameter of the sample,

$$L = 6.27 \times 10^{-3} D \left[\ln \frac{D}{d} - 2 \right] \mu\text{H}, \quad (8)$$

where D is the diameter of a circular pickup loop in cm, and d is the diameter in cm of the superconducting wire used in its construction [7]. Because $\Delta\Phi_p$ scales as the sample area (proportional to D^2), while the inductance scales as the sample diameter D , we see the sensitivity scale linearly in the sample size, or sample volume $V^{1/3}$; in the case that $L_p \ll L_i$, the scaling is $V^{2/3}$.

With a $10\hbar$ SQUID magnetometer, with a 100 nH pickup coil around a 100 cm^2 area sample, we might expect a sensitivity of

$$d_e \approx (0.2 \mu\Phi_0 \sqrt{s}) \left[\frac{17 \mu\Phi_0}{10^{-27} e \text{ cm}} \frac{M}{L_i + L_p} \right]^{-1} \\ = 0.7 \times 10^{-27} e \text{ cm} \sqrt{s}, \quad (9)$$

which leads to a sensitivity of $10^{-30} e \text{ cm}$ in 10 days of averaging.

However, it is possible to do much better. Magnetometry based on the nonlinear Faraday effect in atomic vapors [8] has produced a sensitivity of $3 \times 10^{-12} \text{ G}/\sqrt{\text{Hz}}$ and might be improved by several orders of magnitude by producing and interrogating atoms contained in a cold dense buffer gas [9]. The improvement comes from a narrowing of the magnetic resonance lines to a few millihertz. This system has the advantage that the large sample can be conveniently matched to the magnetometer; if we assume the magnetometer volume diameter is 1 cm, and the sample diameter is 10 cm a superconducting transformer can be used to pick up the sample magnetization and then step up the magnetic induction at the magnetometer. From Eq. (8), the ratio of the inductances of the two coils is roughly 1/10; the magnetic induction at the center of the small coil is 10 times that of the large coil with a given current in the series-connected coils. The magnetometer would have to be operated near a temperature of 2 K, while the sample is at 0.01 K. This would pose no problem because the superconducting transformer connection can be between two regions that are at different temperatures; the thermal conductivity of superconductors is very small so the heat load can be controlled.

With the factor of 10 due to magnetic induction step-up, along with a two-order-of-magnitude increase in sensitivity due to the linewidth improvement, we could expect a magnetic induction sensitivity of $3 \times 10^{-15} \text{ G}/\sqrt{\text{Hz}}$, or an EDM sensitivity of $10^{-29} e \text{ cm}/\sqrt{\text{Hz}}$; in 10 days of averaging, the sensitivity is $10^{-32} e \text{ cm}$.

As a comparison, a direct measure of the EDM of the magnetometer atoms, by applying 10 kV/cm, would be around $5 \times 10^{-31} e \text{ cm}$, a factor of 200 worse than one can obtain by measuring the induced magnetization of the solid system.

By operating the experiment at an even lower temperature, say 10 μK , which is not technically impossible, a sensitivity of $10^{-35} e \text{ cm}$ is conceivable.

C. Systematics

The usual systematics that one encounters with EDMs based on magnetometry with atomic vapors will be present for the solid-state experiment. The leakage current danger in this case is a magnetic field that is picked up directly by the SQUID or Faraday magnetometer. As an example, a 10 cm diameter quarter-turn leakage current of 10^{-14} A , which might be expected at low temperatures with 10 kV/cm and a large sample, corresponds to a spurious field of $1 \times 10^{-15} \text{ G}$, or 2000 times the expected 10-day sensitivity. Even more worrisome is the displacement current magnetic field; if the electric field is reversed at 10 Hz (to avoid the $1/f$ corner of SQUID magnetometers) the displacement current is 10 μA for a 100 pF sample, assuming $E = 10 \text{ kV/cm}$. The sample magnetization would be measured after the high voltage has stabilized, but the displacement current magnetic field is so enormous that we can be concerned about hysteretic or other nonlinear effects. Another limitation to the reversal frequency is the spin-lattice relaxation time—this can be measured using standard techniques. Another concern is energy dissipation in the sample with electric field reversal, which, when the experiment is performed at 10 mK, must be limited to 10 μW as set by the cooling power of a typical dilution refrigerator at low temperature. The $1/f$ corner of a Faraday magnetometer might occur at much lower frequency, allowing less frequent field reversals. The high-voltage properties of materials remain to be studied; the numbers presented here show some limits to the technique. Clearly, if one applied 100 V to the sample, an EDM sensitivity of $10^{-30} e \text{ cm}$ could be achieved, and the leakage and displacement current problems would be reduced to a manageable level.

A separate class of systematics arises from macroscopic parity and time-reversal odd effects due to the crystalline structure. Such effects have been predicted [4] and observed [10,11] in noncentrosymmetric single crystals. These effects are absent for symmetric crystals but a realistic system will always have strains and imperfections. Use of a polycrystalline sintered sample would tend to randomize these effects.

IV. MAGNETIZATION-INDUCED SAMPLE ELECTRIC POLARIZATION DUE TO AN EDM

A. Introduction

As suggested by DeMille [12] if the paramagnetic atoms responsible for the magnetic properties of a material also have an EDM, then when the sample is magnetized there will be an induced sample electric polarization. If the sample is ferromagnetic, the coercive magnetic field H_c that must be applied to attain the remnant saturation magnetization is fairly small, 20–500 Oe. Materials such as GdIG or GdYIG might be of considerable interest; more will be said about their properties later.

Let us estimate the size of the induced electric polarization. Again, take the present electron EDM limit of $10^{-27} e \text{ cm}$ as the characteristic EDM scale. Also, take the density of Gd in GdIG as $\rho = 10^{22}/\text{cm}^3$. The induced electric field is calculated as

$$\mathcal{E} = 4\pi\rho dP = 6 \times 10^{-14} \text{ statvolt/cm} = 1.8 \times 10^{-11} \text{ V/cm}, \quad (10)$$

where P represents the degree to which the spins are polarized in the sample, and it is possible that $P \approx 1$ for ferro- and ferrimagnetic materials. The voltage across a capacitor is obtained by multiplying \mathcal{E} by the sample length L and dividing by the dielectric constant ϵ . For GdIG, etc., $\epsilon \approx 15$; we might also expect that $d \approx 15d_e$ as discussed previously. We can assume that the atomic enhancement roughly cancels the reduction in voltage due to the dielectric constant. Therefore, if we consider a sample 10 cm thick, the EDM-induced voltage for an EDM of 10^{-27} e cm will be 0.18 nV, assuming $P = 1$.

B. Voltage measurement

We are interested in measuring subnanovolt voltages at modulation frequencies in the range 10–100 Hz, a practical range considering the time to reverse the sample magnetization in a controlled way, and to allow for spurious electric fields associated with the time varying magnetic fields to dissipate.

For reasons outlined below, a total sample capacitance of about 100 pF would be ideal for this experiment; this sample would be 10 cm thick and 30 cm diameter, and likely represents a practical maximum for sample preparation.

The parallel input resistance of the sample and amplifier, together with the summed capacitances, should give an input time constant much longer than the inverse modulation frequency:

$$\tau_c = (R_s || R_a)(C_s + C_a), \quad (11)$$

where $R_{s,a}$ and $C_{s,a}$ are the sample and amplifier resistances and capacitances, respectively. The Johnson (voltage) noise on the amplifier input is, ignoring the total capacitance,

$$V_n(0) = (R_s || R_a) \sqrt{\frac{4k_B T_s}{R_s} + \frac{4k_B T_a}{R_a}}, \quad (12)$$

where the possibility for the amplifier and sample temperatures to be different has been explicitly included; a practical limit for the amplifier is 120 K (see below). The net time constant at the amplifier input will limit the frequency response:

$$V_n(\omega) = \frac{V_n(0)}{\sqrt{1 + (\omega\tau_c)^2}} \approx \frac{V_n(0)}{\omega\tau_c}, \quad (13)$$

where we assumed $\omega\tau_c \gg 1$. The noise, assuming $10^{15} \Omega$ for net amplifier and sample resistance (with the amplifier and sample at the same temperature), is $V_n(0) = 2 \text{ mV}/\sqrt{\text{Hz}}$; if the modulation frequency is 10 Hz, with $\tau_c = 10^{15} \Omega \times 100 \text{ pF} = 10^5 \text{ s}$, we have $2 \text{ mV}/\sqrt{\text{Hz}} / (2\pi f \tau_c) = 0.3 \text{ nV}/\sqrt{\text{Hz}}$.

The combined requirements of high amplifier input resistance, low $1/f$ noise, and low bias current imply the use of a JFET input amplifier. The $1/f$ noise, input resistance, and input bias current are all consequence of the same physical

mechanism: the generation current from Shockley-Read-Hall generation-recombination ($g-r$) centers in the gate $p-n$ junction depletion region [13]. The $1/f$ corner is determined by the $g-r$ time constant, which at room temperature for modern JFETs is of order 1 ms, and varies with temperature as

$$\tau_{gr} = \tau_0 e^{E/k_B T}. \quad (14)$$

The total noise voltage and bias current noise are determined by the square root of the total number of $g-r$ centers (impurities) in the depletion region; because the total number depends on the depletion region volume and the depletion depth is constant independent of specific JFET, the $1/f$ (and some other types of noise) noise voltage scales inversely as the square root of the depletion region area (roughly the gate area, and hence gate capacitance). The $g-r$ center density is a function of preparation technology and therefore also independent of the specific JFET, for modern low-noise devices. This scaling is accurate as can be seen by comparing the intrinsic $1/f$ noise of various JFETs as a function of gate capacitances.

JFETs can be operated to temperatures down to about $T_{min} = 120\text{--}140 \text{ K}$; g_m , the transconductance, continues to increase until that temperature and for lower temperatures, the carriers freeze out so g_m decreases, and the noise increases. There is a modest decrease in device noise with decreasing temperature due to the \sqrt{T} dependence of Johnson noise; however, the $g-r$ time constant increases exponentially. For many devices, the noise becomes frequency independent (above 10 Hz) at temperatures around T_{min} and is about a factor of 2 lower than the room temperature high-frequency noise. The JFET gate capacitances are almost independent of temperature.

By operating at 77 K, the input bias (gate leakage) current i_b and its associated noise $i_n = \sqrt{2ei_b}$ can be reduced to extremely low levels. For frequencies $f \gg 1/2\pi R_{in} C_{in}$, where R_{in} and C_{in} are the net input resistance and capacitance, the input noise voltage due to input current noise is $V_n(f) = i_n/2\pi f C_{in}$. This is independent of R_{in} . Typically, $i_n \approx 10^{-15} \text{ A}/\sqrt{\text{Hz}}$ at room temperature, and i_b decreases by an order of magnitude per 25 K reduction in temperature. At 77 K, if this scaling holds, the device voltage noise will be the dominant noise source.

If we choose a sample capacitance, the amplifier capacitance to optimize the signal-to-noise ratio (assuming the noise is only due to the JFET) can be determined by minimizing

$$\frac{S}{N} \propto \frac{(C_a + C_s)^{-1}}{(C_a)^{-1/2}}, \quad (15)$$

which has a maximum when $C_a = C_s$. If C_a is fixed, the optimum sample capacitance can be determined; the sample capacitance is $C_s = \epsilon A/L$, where A is the area and L the length. Therefore the optimum S/N is (the total charge on each end of the polarized sample is proportional to $\pm dA$, independent of L)

$$S/N \propto \frac{A(C_a + \epsilon A/L)^{-1}}{(C_a)^{-1}} \propto L \sqrt{C_a/2} \quad (16)$$

when $C_a = C_s$, implying that L and C_a should be as large as possible. The dimensions given above for a 100 pF sample represent a practical maximum. After choosing a sample, C_a can be set by choice of JFET, or by placing several JFETs in parallel (the capacitance increases linearly with the number in parallel, N_j , while the noise decreases as the square root $\sqrt{N_j}$, which is consistent with the early discussion of JFET noise). The overall sensitivity scales as $L \sqrt{A} \propto V^{2/3}$.

A JFET that might be useful in this application is the Interfet IF3601 (or the IF3602 dual JFET model). This device has a rather high input capacitance $C_{iss} = 300$ pF and high reverse transfer capacitance $C_{rss} = 200$ pF, but with noise of 0.3 nV/ $\sqrt{\text{Hz}}$ at 100 Hz. In a properly designed cascade configuration [14], the input capacitance will be $C_{iss} - C_{rss} = 100$ pF, with the intrinsic noise unmodified [15]. If this device is cooled to 120 K, we might expect a noise of 0.2 nV/ $\sqrt{\text{Hz}}$ at 10 Hz and above. Thus, the EDM sensitivity is (neglecting a possible 0.3 nV/ $\sqrt{\text{Hz}}$ Johnson noise mentioned above; this can be reduced by operating at higher than 10 Hz, or if the net input resistance is $10^{16} \Omega$ or larger) $d_e = 10^{-27} e \text{ cm}/\sqrt{\text{Hz}}$, or a sensitivity of $10^{-30} e \text{ cm}$ in 10 days of operation.

C. Materials

GdIG might be an ideal material for this type of experiment. At 4 K, the Gd ion spin is completely polarized by the ferrimagnetic sublattices.

It should be noted that the magnetic susceptibility of GdIG is very temperature dependent, and is zero at a specific temperature near room temperature. The point where the magnetic susceptibility is zero is called the compensation temperature T_c and results from the polarization of the Gd ions in the lattice exactly canceling the magnetization of the Fe^{2+} and Fe^{3+} paramagnetic ions (see, e.g., [16] for an excellent discussion). By mixing in ytterbium, which carries no magnetization, the compensation temperature can be adjusted. With approximately 1:2 Gd:Yb, $T_c \approx 77$ K. An advantage to use of such a material is that the sample magnetization is very small, reducing some possible systematic effects [17]. On the other hand, the coercive field is roughly given by $H_c = 250/(|T_c/T - 1| + 1)$ Oe for polycrystalline GdYIG and the increase near T_c is due to the low B for a given H when the magnetization of the material is small; this describes the primary dependence of H_c on T and the composition [18]. Another interesting point is that the hysteresis loop becomes very square near T_c ; this is attributed to the domains being very large when the magnetization of the sample is small [19,20]. The switching speed is determined by the domain wall velocity, which is typically 10^4 cm/s. Thus, a sample of 10 cm length could be switched in 1 ms.

The Yb concentration is determined by the operating temperature, which is chosen so that the sample resistivity is high. A convenient temperature is $T = 77$ K, corresponding to liquid nitrogen at 1 bar pressure; as discussed before, the

Gd density is reduced by a factor of 3 to achieve $T_c = 77$ K. Also, the Gd polarization as given by the Boltzmann distribution at 77 K is reduced by a factor of 2/3 compared to its value at $T < 4$ K. Thus, the signal is reduced by a factor of nearly 5 compared to an ‘‘ideal’’ experimental situation. (Note that we must also have $T \neq T_c$ so that there is some magnetization; $T < T_c$ by a few Kelvin should be sufficient.)

D. Systematic effects

In order to reverse the magnetization of a sample, a magnetic pulse with amplitude larger than H_c must be applied to the sample for a time somewhat longer than the switching time estimated above as 1 ms, after which the field can be reduced to a value just sufficient to ‘‘hold’’ the magnetization. The switching rate is also determined by the $1/f$ corner of the amplifier; the transient effects favor a lower rate of magnetization reversal (< 1 kHz), while the $1/f$ corner favors a faster rate (> 100 Hz). Thus, a reversal rate of a few hundred hertz satisfies both constraints.

There are induced voltages associated with the reversal pulse, and the system must be carefully designed to avoid overloading the amplifiers. In addition, slowly decaying eddy currents, etc., could create a time-dependent induced voltage that masks or mimics an EDM. The time variation of the EDM signal should be an exponential decay with time constant τ_c given above. If the switching spurious signal is rectified by the amplifier input, the effect will look exactly like an EDM signal.

Another concern is magnetostriction; if there is a permanent magnetized strain in the material, there could be a magnetization-dependent distortion of the sample. One fixed electron coupled with a change in sample dimension of 10^{-4} cm would give a $10^{-30} e \text{ cm}$ signal.

V. CONCLUSIONS

We have described a series of solid-state-based EDM experiments that offer more than a factor of 1000 improvement on the EDM limit, and perhaps up to a factor of 10^6 improvement when a different type of magnetometer is employed. These experiments are intrinsically ‘‘easy’’ compared to the more traditional atomic cell or beam resonance experiments, and suffer from many of the same systematics. Given that the experiments proposed here are not terribly elaborate, they would be worth doing simply to see what happens. There are a number of issues to be studied; these include the following: atomic (ionic) enhancement of d_e in Gd and other rare earths; screening of the applied electric field at the ion locations; screening of the induced dipole in the voltage measurement experiment; properties of materials, in particular dielectric strength and leakage currents as a function of applied voltage; and resistivity as a function of temperature. The various garnet materials might not be the best choice due to the relatively low rare-earth density. Perhaps some other materials would be a better choice. The garnets were chosen here for discussion because it is well known that they have excellent insulating properties.

As an interesting aside, an experiment using a rotating YIG rod to test special relativity was performed by Hertzberg *et al.* [21]; in this experiment, a voltage was induced between the ends of the rod due to the rotation. Agreement with special relativity was obtained, and required measurement of voltages at the millivolt level with microvolt accuracy. Given the success of this experiment, the work proposed here does not seem unreasonable.

The proposed techniques can also be applied to other fundamental studies. For example, if the nucleus has an anapole moment, the electron cloud around the nucleus will be displaced. This is because the low-energy parity violating weak interaction, being proportional to the momentum \hat{p} , can be written as the operator of parallel displacement (of the electron cloud relative to the nucleus) with an imaginary amplitude [22]. If the electron spins \mathbf{J}_i and the nuclear spins \mathbf{I} of a material are polarized in a strong magnetic field \mathbf{B} at low temperature, and if the direction of the electron spins is reversed to \mathbf{J}_f with an NMR pulse, there will be a change in

voltage across the sample, as measured along the magnetic field. In this case, the parity-odd time-reversal-even operator describes the displacement of charge along a specified direction resulting in a voltage or electric field \mathbf{E} across the sample is [9]

$$(\mathbf{B} \cdot \mathbf{I})(\mathbf{J}_i - \mathbf{J}_f) \cdot \mathbf{E}$$

and the voltage would persist for a time of order of the inverse hyperfine frequency. The magnitude of this voltage can be estimated as a few microvolts using expected values of nuclear anapole moments.

In conclusion, there is hope of improving the EDM experimental limit by at least three orders of magnitude by use of the experimental techniques proposed here. By operating the system proposed in Sec. III at a temperature of 10 μK , a sensitivity of 10^{-35} e cm is not beyond conception. Such a sensitivity is several orders of magnitude better than any currently proposed experiment.

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