Magnetic Johnson noise constraints on electron electric dipole moment experiments

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Magnetic fields from statistical fluctuations in currents in conducting materials broaden atomic linewidths by the Zeeman effect. The constraints imposed by this broadening on the design of experiments that measure the electric dipole moment of the electron are analyzed. Contrary to the predictions of Lamoreaux [S. K. Lamoreaux, Phys. Rev. A **60**, 1717 (1999)], the standard material for high-permeability magnetic shields proves to be as significant a source of broadening as is an ordinary metal. A scheme that would replace this standard material with ferrite is proposed.

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I. INTRODUCTION

The *CP* violation contained within the Cabbibo-Kobayashi-Maskawa matrix of the standard model demands that the electron have an electric dipole moment. The largest contribution that is not known to vanish[1] arises from a multiloop diagram which gives rise to an electron electric dipole moment

$$d_e \sim 10^{-58}\ \mathrm{C\,m}, \tag{1}$$

which is more than 10 orders of magnitude below the experimental upper limit [3,4] of 2.6×10^{-48} C m. All proposed extensions of the standard model, such as grand unified, supersymmetric, or supergravity models, that in the low-energy limit can be approximated by the minimal supersymmetric standard model, admit sources of *CP* violation that couple directly to leptons. These extensions are capable of producing values of $|d_e|$ up to the experimental upper bound, as are left-right symmetric and multi-Higgs models. Lowering the experimental bound is therefore of great interest.

Existing and proposed experiments to measure d_e use paramagnetic atoms or molecules that respond via the Zeeman effect to magnetic noise produced by statistical fluctuations in the current density (by Johnson noise) in conductors. We show that the magnetic noise produced by components essential to these experiments, such as electric field plates and magnetic shields, can limit the sensitivity of the experiments. We suggest some remedies for this problem.

II. EXPERIMENTAL MODEL

To search for the electron electric dipole moment, a typical experiment examines some neutral atom (or molecule) that has nonzero atomic spin for an atomic transition whose energy is linear in an applied electric field. Such atomic systems have magnetic moments whose magnitudes are the order of the Bohr magneton μ_B, and have electric moments equal to Rd_e, where R, the enhancement factor, can for special systems have a magnitude much greater than 1 (though most systems have $R\ll1$). We examine a generic experiment where the transition studied is between different sublevels, with magnetic quantum numbers M_1 and M_2, of a hyperfine level of total spin F. The direction parallel to the applied electric field we assume to be the quantization axis; this axis we label as z.

If the electric and any applied magnetic fields are constant, then an atom that enters a set of electric field plates at time $t=0$ in a coherent superposition of magnetic sublevels

$$\Psi(0)=\frac{1}{\sqrt{2}}(|M_1\rangle+|M_2\rangle) \tag{2}$$

will evolve over time t to the superposition

$$\Psi(t)=\frac{1}{\sqrt{2}}e^{-iE_{M_1}t/\hbar}(|M_1\rangle+e^{-i\phi}|M_2\rangle), \tag{3}$$

where the accrued relative phase ϕ is

$$\phi=\frac{(E_{M_2}-E_{M_1})t}{\hbar}. \tag{4}$$

Counting the numbers of atoms found in the orthogonal states

$$\frac{1}{\sqrt{2}}(|M_1\rangle\pm|M_2\rangle) \tag{5}$$

in a bunch of N atoms provides a measurement of the phase for that bunch. The statistical error in that measurement is the smallest when the numbers in each orthogonal state are nearly equal; the standard deviation of the distribution of the phases recorded for different bunches is then

$$\sigma_\phi=\frac{1}{\sqrt{N}}. \tag{6}$$

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[1]For a discussion of known cancellations of contributions to d_e within the standard model, see Ref. [1]. For the estimate that results, see Eq. (3.1) of Ref. [2]; for an updated experimental value of the parameter J in that estimate see Ref. [3], p. 134. Upper bounds on the neutrino masses [2] bound the contribution to d_e from the *CP* violation within a neutrino analog of the CKM matrix to be no more than $\sim10^{-58}$ C m.

We adopt the convention[2] that the dipole moment of a system is positive if the dipole is aligned with the total spin, and negative if it is antialigned. The contribution to the phase due to the electron electric dipole moment is

$$-\frac{M_2-M_1}{F}Rd_eE_z\frac{t}{\hbar}, \tag{7}$$

where R is the enhancement factor for the atom, and E_z is the component of the electric field along the quantization axis.

If the atoms in a bunch are exposed to a common, time-dependent magnetic field $B_z(t)$, the Zeeman effect adds to the phase a contribution

$$G\int_0^t B_z(t')dt', \tag{8}$$

where $G=g_F(M'-M)\mu_B/\hbar$, and where g_F is the Landé g factor for the hyperfine level. If the magnetic field is different from bunch to bunch, then each bunch acquires a different phase; if the magnetic field fluctuates about zero, the standard deviation of the scatter in this contribution to the phase is the product GD, where

$$D \equiv \left(\int_0^t B_z(t')dt'\right)_{\text{rms}} \tag{9}$$

is the root-mean-square value of the time integral of the magnetic field. The error in the phase measured for each bunch is the sum of the statistical and magnetic field errors in quadrature. If an experiment accumulates data from M such bunches, then the standard deviation in the error in d_e is

$$\sigma_{d_e}=\frac{1}{\sqrt{M}}\sqrt{(GD)^2+\frac{1}{N}}\left|\frac{M_2-M_1}{F}RE_z\frac{t}{\hbar}\right|^{-1}. \tag{10}$$

Because it is futile to increase the number of atoms in each bunch past the point where the fluctuations in the magnetic field dominate the error in d_e, an efficient experiment will have

$$D \lesssim \frac{1}{G\sqrt{N}}. \tag{11}$$

III. MAGNETIC NOISE FROM CURRENT DENSITY FLUCTUATIONS

A conductor in a closed system at equilibrium has a statistical distribution of the point-to-point fluctuations in the electric current density, and so also of the magnetic fields generated by those fluctuations. The spectrum of the resulting magnetic noise found at a point a distance z from the surface of an infinite slab of thickness (or depth) d, electrical resistivity ρ, and magnetic permeability μ has been calculated by Nenonen *et al.* [9]. Following their conventions [10,11], let a function $B_{n,z}(\nu)$ be defined that describes as a function of frequency ν (in cycles/s) the noise in the z component of the magnetic field, such that the correlation between the magnetic field at the same point in space at different times is given by

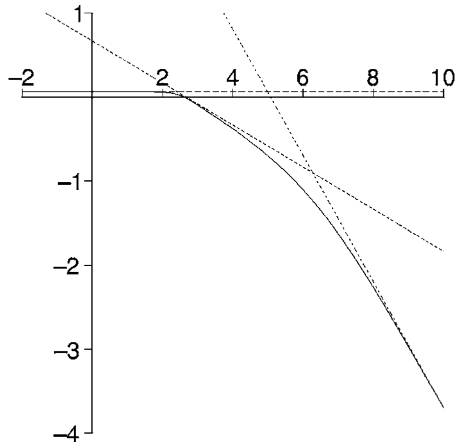

FIG. 1. Log-log plot (base 10) of θ as a function of ν, for a slab of MgZn ferrite ($\mu_{\text{rel}}=1.0\times10^4$ and $\rho=1\times10^{-1}\Omega$ m) that is 3 mm thick and 10 cm away. The solid curve is θ; the dotted, dashed, and dotted-dashed curves are, respectively, the approximations numbered 2, 4, and 5 in Table I.

$$\langle B_z(t_0)B_z(t_0+t)\rangle=\int_0^\infty B_{n,z}^2(\nu)\cos(2\pi\nu t)d\nu, \tag{12}$$

where the angle brackets indicate an average over all times t_0. This definition of $B_{n,z}(\nu)$ implies that the root-mean-square value of the magnetic field is simply

$$\left(\int_0^\infty B_{n,z}^2(\nu)d\nu\right)^{1/2}. \tag{13}$$

Nenonen *et al.* [9] find that the noise spectrum from the slab is given by

$$B_{n,z}(\nu)=\mu_0\sqrt{\frac{k_BT_0}{8\pi\rho}\frac{d}{z(z+d)}}\theta. \tag{14}$$

Here μ_0 is the magnetic permeability of the vacuum, k_B is Boltzmann's constant, and T_0 is the absolute temperature of the slab; ρ is the resistivity, d is the thickness of the slab, and z is the distance from the point of observation to the near surface of the slab. Our function θ is a dimensionless integral that depends on three dimensionless parameters, which may conveniently be taken to be the combinations $\zeta^2=2\pi\nu\mu/\rho$ and $\mu_{\text{rel}}=\mu/\mu_0$ and $\tau=2d/z$, where μ is the magnetic permeability of the slab. In the low-frequency limit $\nu\to0$ the value of θ is always of order unity, and θ remains essentially constant provided $\zeta\lesssim1$, equivalently, for frequencies less than a cutoff frequency of roughly $\rho/(2\pi\mu z^2)$. At higher frequen-

[2]By this convention, standard in nuclear physics [5] and used in the 1998 CODATA *Recommended Values of the Fundamental Constants* [6], the magnetic dipole moment and g-factor of the electron are negative, while those of the proton are positive. The reader is cautioned that many prominent collections of particle data tacitly adopt the older convention that only the magnitudes of the moments are denoted by symbols such as μ_e or g_e. Collections that use this older convention are the Particle Data Book [3], on p. 33 and p. 408; or Ref. [7]; or the 1986 CODATA set of constants [8].

TABLE I. Analytic approximations to the value of the function θ^2 evaluated in various limits. In the following we use the dimensionless parameters $\zeta^2=2\pi\nu\mu/\rho$ and $\mu_{\rm rel}=\mu/\mu_0$ and $\tau=2d/z$.

Number	θ^2	Approximation
1	1	for $\mu_{\rm rel}=1$, $\lim_{\nu\to 0}\theta^2$
2	4/3	$\lim_{\mu_{\rm rel}\to\infty}\lim_{\nu\to 0}\theta^2$, for $\tau\ll 1$
3	4	$\lim_{\mu_{\rm rel}\to\infty}\lim_{\nu\to 0}\theta^2$, for $\tau\gg 1$
4	$2+\tau/\tau\mu_{\rm rel}^2 3\sqrt{2}/\zeta^3$	for $e^{-\zeta\tau}\ll 1$ and $\zeta\gg 1$ and $\zeta/\mu_{\rm rel}\gg 1$
5	$2+\tau/\tau 2\sqrt{2}/\zeta$	for $e^{-\zeta\tau}\ll 1$ and $\zeta\gg 1$ and $\zeta/\mu_{\rm rel}\ll 1$

cies, θ falls towards zero. Because of the factor of $1/\mu$ in the cutoff, the limits

$$\lim_{\nu\to 0}\lim_{\mu\to\infty}\theta \text{ and } \lim_{\mu\to\infty}\lim_{\nu\to 0}\theta \tag{15}$$

are not the same; a simple formula valid for all small frequencies ν and all large magnetic permeabilities μ is therefore not to be expected. The integral must therefore be evaluated numerically except in certain limiting approximations, some of which are tabulated in Table I, and some of which are plotted in Fig. 1 along with the noise spectrum computed for a slab of high magnetic permeability.

We need to deduce from the fluctuations in the magnetic field itself the fluctuations in the value of its time integral, which is what affects experiments that measure the electron electric dipole moment. The following general result from statistical mechanics is easily proved using standard [12] Fourier techniques.

Let $y(t)$ be a fluctuating quantity whose correlation function is given by the following integration over the product of a noise spectrum $N(\nu)$ and a cosine:

$$\langle y(t_0)y(t_0+t)\rangle = \int_0^\infty N(\nu)\cos(2\pi\nu t)d\nu; \tag{16}$$

from which it follows that

$$\langle y^2\rangle = \int_0^\infty N(\nu)d\nu. \tag{17}$$

Then if a second quantity Y is defined as the time integral

$$Y(t,T) = \int_0^T y(t+t')dt', \tag{18}$$

then

$$\langle Y^2\rangle = \int_0^\infty N(\nu)\frac{\sin^2(\pi\nu t)}{(\pi\nu)^2}d\nu, \tag{19}$$

which if the noise spectrum $N(\nu)$ is essentially constant for $0\leqslant\nu\lesssim 1/t$ then we have the approximation

$$\langle Y^2\rangle \approx \tfrac{1}{2}N(0)T. \tag{20}$$

Applying this result to the study of magnetic noise, we find

$$D = \sqrt{T/2}\left(\int_0^\infty B_{n,z}^2(\nu)\frac{2\sin^2(\pi\nu T)}{(\pi\nu T)^2}Td\nu\right)^{1/2}. \tag{21}$$

In Table II are displayed, for various slabs, values of D from a numerical integration over their noise spectrum. Except for the one indicated example of a material whose conductivity and magnetic permeability are both high, the noise spectra are sufficiently constant for $0\leqslant\nu\lesssim 1/T$ that both the simple approximation

TABLE II. For various slabs we list values of D, the root-mean-square value for the time integral of magnetic noise, computed from a numerical integration of Eq. (21); and corresponding values of the ratio $D/D_{\rm Cs}$. For infinite slabs, and for the noise measured by a single atom or by a cluster of atoms of negligible extent, the values of D are accurate to the number of significant figures given.

Material	ρ (Ω m)	$\mu_{\rm rel}$	d (m)	z (m)	T_0 (K)	D (fTs)	$D/D_{\rm Cs}$
Aluminum	2.73×10^{-8}	1	1.0×10^{-2}	2.0×10^{-3}	300	1.41×10^{3}	3.71×10^{3}
Titanium[a]	1.71×10^{-6}	1	1.0×10^{-2}	2.0×10^{-3}	300	1.73×10^{2}	4.68×10^{2}
Tungsten	5.44×10^{-8}	1	5.0×10^{-6}	2.0×10^{-3}	300	2.45×10^{1}	6.43×10^{1}
InSnO[b]	5.0×10^{-5}	1	5.0×10^{-6}	2.0×10^{-3}	300	1.77×10^{0}	4.72×10^{0}
Soda lime glass[c]	$1.0\times 10^{+4}$	1	1.0×10^{-2}	2.0×10^{-3}	475	3.06×10^{-3}	8.05×10^{-3}
Type 304 stainless steel	7.20×10^{-7}	1	3.0×10^{-3}	1.0×10^{-1}	300	7.25×10^{1}	1.92×10^{1}
HPM[d]	5.50×10^{-7}	3×10^{4}	5.0×10^{-4}	1.0×10^{-1}	300	2.64×10^{0}[e]	6.94×10^{0}
Ferrite[f]	1.0×10^{-1}	1×10^{4}	3.0×10^{-3}	1.0×10^{-1}	300	2.27×10^{-2}	5.98×10^{-2}
Copper	1.73×10^{-8}	1	2.0×10^{-7}	1.0×10^{-1}	300	3.87×10^{-1}	1.02×10^{0}

[a]Alloy 6Al4V.
[b]The resistivity of indium tin oxide films ranges between $5\times 10^{-5}\Omega$ m and $5\times 10^{-4}\Omega$ m, depending on the degree of oxidation.
[c]Corning 0800.
[d]Fully annealed CO-NETIC AA™, Magnetic Shield Corporation, shields@magnetic-shield.com
[e]Equation (22) predicts inaccurately 3.95×10^{0}.
[f]MgZn, product 10 000 HM™ of the Ferrite Domen Co., www.domen.ru

$$D \approx B_{n,z}(0)\sqrt{T/2} \tag{22}$$

and a numerical integration give the same results to the number of significant figures given.

Real experiments deal with bunches and beams of atoms with finite spatial extent, and while the noise recorded at points very close together will be highly correlated it will not be identical. Nenonen *et al.* [9] computed the correlation between the different values of the component of the magnetic field perpendicular to a slab that are measured at different locations near the slab. The correlation falls to 0.5 for points at a common distance z from the slab that are separated in a direction parallel to the slab by a distance of approximately $2z$. For separations perpendicular to the slab, the correlation persists to greater distances, falling to 0.5 for one point at separation z and a second point at approximately $6z$. We will suppose that the correlations in the relevant quantity $\int_0^t B_z(t')dt'$ will be similar to the correlations in $B(t)$.

Equations (10) and (11) were derived under the assumptions that the noise in each bunch of N atoms was totally correlated, and that the noise of each of M different bunches was totally uncorrelated. We may nevertheless use these equations to model the noise from a continuous beam that runs parallel to a slab. Suppose this beam has its center at separation z, has an extent transverse to the slab of $2z$, and is of width $4z$. We assert that the effect of correlation can be crudely modeled by imagining the beam to be chopped into sections of length $4z$, where all the atoms within a section have noise that is assumed to be totally correlated, and where the noise from section to section is assumed to be totally uncorrelated. We use the notation N^{eff} for the number of atoms within each such section that contribute to the signal. Now Eqs. (10) and (11) apply, with N replaced by N^{eff}, and with M interpreted as the number of sections accumulated over the experiment.

Finally we must adapt the values of D available for a single, infinite slab to get estimates of D for experimentally useful geometries. This too we will do crudely, estimating the noise at the center of a pair of electric field plates separated by a distance $2z$ to be that of a single plate at a distance z, and estimating the noise at the center of a cylindrical shell of radius r to be the noise due to a slab of equal thickness at a separation $z=r$. Thus if a flux of f atoms per second travel at velocity v down the axis of a cylinder of radius r, the effective number of atoms within each section is taken to be

$$N^{\text{eff}} \approx 4rf/v, \tag{23}$$

and the noise due to the cylinder we will approximate by substituting r for z everywhere in Eq. (14).

IV. MAGNETIC NOISE IN COMPLETED EXPERIMENTS

We examine first the effect of magnetic noise on the pair of experiments [4,13] that set the best independent upper limits on d_e. The Regan experiment [4] uses a thermal thallium beam that passes between electric field plates made of oxygen-free high-conductivity copper, 1 m long, 2.3 cm thick, and with a gap of 2 mm; the time a typical atom spends within the plates is 2.4 ms. Given the quoted statistical uncertainty in d_e, and assuming at first the magnetic noise to be negligible, we compute using Eq. (10) the total number of atoms NM that were in effect counted in the experiment. The time over which the beam was on and data actually recorded then determines the flux f; the value of N^{eff} for a single plate follows from Eq. (23), and the corresponding experimentally tolerable value for the magnetic noise is computed from Eq. (11). For this experiment the tolerable noise is $D_{\text{Tl}}=1120$ fT s, while the noise from a single copper plate is 130 fT s. Therefore the magnetic noise from the electric field plates in this experiment is about a factor of 10 below the shot noise.

The experiment of Hudson *et al.* [13] used a thermal molecular beam of YbF to set the second most stringent upper limit on d_e (about a factor of 40 larger than that of Regan *et al.* [4]). The size of the tolerable value of D scales with the magnitude of the enhancement factor R, because less experimental sensitivity is required to get equivalent limits on d_e; in YbF under the experimental conditions [13] the magnitude of R is a factor of 2700 larger than the magnitude in thallium. Magnetic noise will not be a consideration for experiments on YbF or other diatomic molecules with comparably large enhancement factors at least until such experiments begin to probe values of d_e that are very much less than 10^{-50} C m.

V. MAGNETIC NOISE IN PROPOSED EXPERIMENTS

We examine two proposed cesium experiments whose goal is to probe for a value of d_e of order 10^{-50} C m. Chin *et al.* [14] propose to trap $\sim 10^8$ Cs atoms in an optical lattice trap, these atoms to be observed for a time of ~ 1 s set by the anticipated decoherence time of the atoms within the trapping laser fields. Gould [15] proposes to examine 3×10^8 atoms initially collected in a magneto-optical trap, to be observed for a time also of ~ 1 s set by the atoms' rise and fall under gravity when launched in an atomic fountain. Because the parameters of these two experiments are fortuitously so similar, the effect of magnetic noise on both of them is essentially the same; for definiteness, we choose to examine the work of Gould, who proposes to study the $M_1 \rightarrow M_2$ transitions $4\rightarrow -3$ and $-4\rightarrow +3$ of the cesium $F=4$ ground-state hyperfine level. To an experiment with a statistical error in d_e of 10^{-50} C m there corresponds from Eq. (11) a value of

$$D_{\text{Cs}} = 0.38 \text{ fT s}, \tag{24}$$

which we take as our upper limit to the acceptable magnetic noise.

Values for the noise parameter D for slabs of a variety of materials and geometries are shown in Table II; the values greatly constrain the design of any experiment. In the following discussion references to soda lime glass, stainless steel, high-permeability metal (HPM), and to MgZn ferrite are references to the specific, commercially available materials listed in Table II. We will take the ratio D/D_{Cs}, when D is computed for an infinite slab, as a rough estimate for the significance of the noise to be expected from different geometries, for example, for the noise from plates whose finite transverse extent is much greater than z, and for the noise from cylindrical and spherical shells whose radius is z. We judge such estimates to be accurate to within a factor of 3 or so.

Aluminum electric field plates 1 cm thick and spaced by 4 mm contribute noise three orders of magnitude above our limit and are precluded; plates made of (the more resistive) titanium are precluded by a factor of roughly 500. Plates made of a 5 micron layer of tungsten on an insulating substrate are precluded by a factor of 64; the same thickness of the (still more resistive) metallic oxide InSnO is precluded by a factor of 5. Because noise scales with the layer thickness d only as $\sqrt{d}$, the tolerable thickness of a layer of InSnO is less than 200 nm. Materials exist whose resistivity at room temperature is low enough that solid 1 cm plates will still function as electrodes but whose resistivity is high enough that the resulting magnetic noise is negligible (e.g., doped silicon and silicon carbide), but no examples of the use of such materials as high-voltage electrodes are known to the author. Electrodes made of heated glass [16,17] are suitable; Gould [18] employed such plates made of soda lime glass (heated to 475 K to lower the electrical resistivity to $\sim 1 \times 10^4 \Omega$ m) to reverse electric fields of 35 MV/m. Such plates would generate noise roughly 2 orders of magnitude below the desired upper limit.

The noise from the wall of a standard 10 cm radius stainless-steel vacuum pipe (3 mm wall) is a factor of 20 above our limit. There must therefore either be magnetic shielding inside the vacuum system,[3] or the vacuum system itself must be made of some high-resistivity material such as glass or quartz.

A high-permeability magnetic shield made from HPM is itself a significant source of magnetic noise. A standard 50 micron sheet of HPM at a distance of 10 cm contributes noise a factor of 7 above the acceptable limit. This result contradicts a prediction of Lamoreaux [19], who claimed that the spectrum of magnetic noise from a metal should be suppressed by a factor of order $1/\mu_{\rm rel}$ as the relative magnetic permeability $\mu_{\rm rel}$ of the metal is increased. If this prediction were correct, the small frequency limit of the function θ, computed using the theory of Nenonen *et al.* [9] and shown in Fig. 1, would not be of order unity but instead be the order of 10^{-4}. This prediction is also in conflict with the measurements by Allred *et al.* [20], who found that the magnetic noise of metal plates of relative permeability 1, and the noise of plates of very high relative permeability, matched the predictions of Nenonen *et al.* [9] to within an experimental precision of 30%.

A spherical shield of thickness d, radius $b \gg t$, and relative magnetic permeability $\mu_{\rm rel} \gg 1$ will reduce an external field by a factor [21] of approximately $3b/(2\mu_{\rm rel} d)$. A 50 micron shield of HPM with a radius of 10 cm divides external magnetic fields by a factor of no more than 10. Because a shield's ratio of external to internal magnetic field scales as d, while the magnetic noise scales as $\sqrt{d}$, it is difficult to reduce the magnetic noise enough by thinning the shield without making the shield ineffective. A plausible solution is to replace HPM with a magnetically permeable material with a higher resistivity.

Ferrites, which are used in high frequency transformers, have in addition to a high permeability, a high resistivity (necessary to prevent eddy current losses at high frequency). An inner layer of magnetic shielding fabricated from a ferrite would have the desired properties, allowing it to screen the magnetic noise from external sources without generating its own.

Ferrites are ceramic materials composed of the oxides of iron with various proportions of other metal oxides, commonly MgZn or ZnNi. Ferrites are widely used industrial materials [22–24] and are readily sintered into simple shapes. The MgZn ferrite of Table I combines high relative magnetic permeability ($\mu_{\rm rel}=10^4$) with a high resistivity ($\gtrsim 0.1 \Omega$ m, about a factor of 2×10^8 greater than that of HPM). A 10 cm radius shell 3mm thick would contribute magnetic noise a factor of 16 below our limit, while still reducing externally applied magnetic fields by a factor as large as 200, which is enough to reduce the magnetic noise from outer layers of ordinary HPM shields, or even of a stainless steel vacuum pipe, to negligible levels. This ferrite also has a suitably low coercive force of 4 A/m, somewhat higher than but comparable to the 1.2 A/m of HPM.

A potential difficulty with setting a thick cylinder of ferrite inside a delicate onion of carefully annealed HPM shields is getting the residual field to be as small as the ~ 1 nT achievable (before the use of trim coils) with the HPM alone. Fortunately the Curie temperature of ferrites is set by their composition; the particular ferrite modeled in Table II has a Curie temperature of approximately 110 °C, lower than the temperature to which a vacuum system is typically baked, which in turn is much lower than the 454 °C Curie temperature of HPM. During bakeout the ferrite shield will be heated above its Curie temperature and be completely demagnetized, and after bakeout it will cool and become again ferromagnetic while exposed to only the tiny residual magnetic field provided by the outer HPM shields. The residual field left within the ferrite shield when cool should also then be very small.

Last, we note that a sheet of copper only 200 nm thick and fully 10 cm away generates noise equal to our limit. This fact suggests that within the innermost magnetic shield the noise from conducting materials in coils, support structures, and perhaps even from wires and fasteners, will have to be carefully assessed. Computation of the exact magnetic noise to be expected from conductors shaped not as slabs but as cylinders (to model wires) and as spheres (to model lumps) have not been done.

While it is in principle possible to measure and to subtract the contribution of magnetic noise to electric dipole moment experiments by including within each bunch of atoms two kinds of atoms (or two different atomic states) that have different ratios of electric and magnetic dipole moments, one would still wish to keep the magnitude of the subtraction to be small, and one would therefore still favor building an

[3]Type 304 stainless steel has trace magnetism low enough that it could probably be used for the walls of a vacuum chamber of an electric dipole moment experiment if some magnetic shielding were set inside the chamber. Titanium alloy 6Al4V is truly nonmagnetic; however its greater strength and higher resistivity only lower the noise by a factor of roughly 2, if used in place of stainless steel in a pipe of given diameter.

apparatus of materials with a high electrical resistivity.

VI. CONCLUSIONS

Magnetic noise from statistical fluctuations in electric currents in conductors impose severe constraints on the design of atomic experiments to measure the electric dipole moment of the electron. For atomic systems with enhancement factors of order 100 or less, if the precision of the experiment is to be limited by shot noise, then the use of electric field plates made of metal is precluded. Magnetic noise from the walls of a vacuum system must either be screened or else the walls must be made of a high-resistivity material. Standard high-permeability, metallic magnetic shields generate magnetic noise comparable to the noise generated by ordinary metals, and it is suggested the innermost of a nested set of magnetic shields be made of ferrite or some other material that combines magnetic permeability and low coercivity with high electrical resistivity.

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