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Magnetic Johnson noise constraints on electron electric dipole moment experiments*

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Abstract

Magnetic fields from statistical fluctuations in currents in conducting materials broaden atomic linewidths by the Zeeman effect. The constraints so imposed on the design of experiments to 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 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 has an electric dipole moment. The largest contribution not known to vanish[25] arises from a multi-loop diagram which gives rise to an electron electric dipole moment

$$d_{\mathrm{e}} \sim 10^{-58}\,\mathrm{C\,m}\ ,$$

which is more than ten orders of magnitude below the experimental upper limit [1, 2] of $2.6 \times 10^{-48}\,\mathrm{C\,m}$. 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 new sources of CP-violation that couple directly to leptons and are capable of producing values of $|d_{\mathrm{e}}|$ up to the experimental upper bound, as can left-right symmetric and multi-Higgs models. Lowering the experimental bound is therefore of great interest.

Existing and proposed new experiments to measure d_{e}, however, use paramagnetic atoms or molecules making the experiments sensitive to magnetic noise produced by statistical fluctuations in the current density in conductors (Johnson noise). We analyze these effects and show that the magnetic noise produced by essential components such as electric field plates and magnetic shielding can limit the sensitivity of the experiments. We suggest some possible remedies for this problem.

II. EXPERIMENT MODEL

To search for the electron electric dipole moment a generic experiment examines some neutral atom (or molecule) with nonzero atomic spin for an atomic transition whose energy is linear in an applied electric field. All such systems have magnetic moments with magnitudes the order of the Bohr magneton μ_{B}, but have electric moments Rd_{e} where R, the enhancement factor, can for special systems have magnitude much greater than 1. We examine the generic experiment where the transition studied is between different magnetic sublevels M_1 and M_2 of a hyperfine level of total spin F. The quantization (z) axis is taken to be parallel to the applied electric field.

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

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

will evolve at time t to the superposition

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

where the accrued relative phase is

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

Counting, in a bunch of N atoms total, the numbers of atoms found in the orthogonal states

$$\frac{1}{\sqrt{2}}\Big(\big|M_1\big\rangle \pm \big|M_2\big\rangle\Big)$$

provides a measure of the phase for the bunch. The smallest error results if the numbers are nearly equal, when the standard deviation of the distribution of the phases recorded for different bunches is

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

We adopt the convention[26] that the dipole moment of a system is positive if it is aligned with the total spin, and negative if anti-aligned. The contribution to the phase due to d_e is

$$-\frac{M_2 - M_1}{F}Rd_\mathrm{e}E_z\frac{t}{\hbar} ,$$

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

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

$$G\int_0^t B_z(t')\,dt' ,$$

where $G = 2\pi g_F(M' - M)\mu_\mathrm{B}$, and where g_F is the Landé g-factor for the hyperfine level. If the magnetic field fluctuates about zero and is different from bunch to bunch, then each bunch acquires a different phase; the standard deviation of the scatter in this phase, bunch to bunch, is then GD, where

$$D \equiv \left(\int_0^t B_z(t')\,dt'\right)_\mathrm{rms} .$$

The error in the phase measured for the bunch is the sum of the statistical and magnetic field errors in quadrature. If an experiment accumulates data from M such bunches, the standard deviation in the error for $d_{\rm e}$ is

$$\sigma_{d_{\rm e}} = \frac{1}{\sqrt{M}}\sqrt{(GD)^2 + \frac{1}{N}} \times \left| \frac{M_2 - M_1}{F} R E_z \frac{t}{\hbar} \right|^{-1} . \quad (1)$$

It is futile to increase the number of atoms in each bunch past the point where the fluctuations in the magnetic field dominate, and so an efficient experiment will have

$$D \lesssim \frac{1}{G\sqrt{N}} . \quad (2)$$

III. MAGNETIC NOISE FROM THERMAL CURRENTS

A conductor in a closed system at equilibrium has a statistical distribution of the point-to-point fluctuations in the 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 infinite slab of thickness (or depth) d, electrical resistivity ρ, and magnetic permeability μ has been calculated by Nenonen et al. [3]. Following their conventions[4, 5], 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 the magnetic field, such that the correlation between the magnetic field at different times is given by

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

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

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

Nenonen et al.[3] find that the noise spectrum from the slab is given by

$$B_{n,z}(\nu) = \mu_0\sqrt{\frac{k_B T_0}{8\pi\rho}\frac{d}{z(z+d)}} \times \theta \ . \quad (3)$$

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 the distance from the point of observation to the near surface of the slab. The 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 $\mu_{\mathrm{rel}} = \mu/\mu_0$ and $\tau = 2d/z$, where μ is the magnetic permeability of the slab. In the low-frequency limit $\nu \to 0$ the value of θ is always of order unity, and it remains remains essentially constant provided $\zeta \lesssim 1$, that is, out to frequencies $\nu \lesssim \rho/(2\pi\mu z^2)$, whereupon θ falls towards zero. Because of of the factor $1/\mu$ in the cutoff, in considering the low-frequency limit of highly permeable materials the limits

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

are not the same; a simple formula valid for all small ν and all large μ cannot then be expected. The integral must be evaluated numerically except in various approximations, some of which are tabulated in Table I, and some of which are plotted in Figure 1 along with the noise spectrum computed for a slab of high magnetic permeability.

We need to connect the fluctuations in the value of the field to the fluctuations in the value of its time integral. The following result from statistical mechanics is easily proved using standard[6] Fourier techniques.

Let $y(t)$ be a fluctuating quantity whose correlation function is given by the integration over a noise spectrum,

$$\left\langle y(t_0)y(t_0+t)\right\rangle = \int_0^\infty N(\nu)\cos(2\pi\nu t)\,d\nu\ ,$$

so that

$$\left\langle y^2\right\rangle = \int_0^\infty N(\nu)\,d\nu\ .$$

Then if a second quantity Y is defined as the integral

$$Y(t,T) = \int_0^T y(t+t')\,dt'$$

then

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

which if the noise spectrum $N(\nu)$ is essentially constant for $0 \le \nu \lesssim 1/t$ gives the approximation

$$\left\langle Y^2\right\rangle \approx \frac{1}{2}N(0)T\ .$$

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

$$D = \sqrt{T/2}\left\{\int_0^\infty B_{n,z}^2(\nu)\times\frac{2\sin^2(\pi\nu T)}{(\pi\nu T)^2}\,T\,d\nu\right\}^{1/2} \qquad (4)$$

In Table II are displayed, for various slabs, values of D from a numerical integration over the 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 $0 \leq \nu \lesssim 1/T$ that the simple approximation

$$D \approx B_{n,z}(0)\sqrt{T/2} \tag{5}$$

gives the same results to the number of significant figures given.

Real experiments deal with bunches and beams of atoms with finite spatial extent. Nenonen et al.[3] studied the correlation at different locations near a slab between the component of the magnetic field perpendicular to the slab. recorded 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 $\approx 2z$. 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 $\approx 6z$. We will suppose that similar results will hold for correlations not just in $B(t)$ but in the time integral $\int_0^t B_z(t')\,dt'$. Given a beam parallel to a slab and with a center at separation z, extent transverse to the slab of $2z$, and width $4z$, we assert that the effect of correlation can be crudely modeled by imagining the beam to be chopped into sections $4z$ long, where all the atoms within a section have noise that is assumed to be totally correlated, while 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.

Equations (1) and (2) and were derived under the assumption that the noise in each bunch of N atoms was totally correlated, and that the noise of M different bunches totally uncorrelated. For continuous beams of atoms, these same equations apply, with N replaced by N^{eff}, and where M now denotes the number of such effective bunches accumulated over the experiment.

Finally we have to adapt the exact formulas for the value of D from infinite slabs to get estimates 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 as the noise due to a slab of equal thickness at a separation $z = r$. Thus if a flux of f atoms per second that contribute to the signal travel at velocity v down the axis of a cylinder of radius r, the effective number of atoms within each section taken to be

$$N^{\mathrm{eff}} \approx 4rf/v \ , \tag{6}$$

and the noise due to the cylinder is approximated by substituting r for z everywhere in Eq. (3).

IV. MAGNETIC NOISE IN COMPLETED EXPERIMENTS

We examine first the effect of magnetic noise on the pair of experiments[1, 7] that set the best independent upper limits on d_{e}. The Regan experiment[1] 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, 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. (1) the total number of atoms NM 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. (6), and the corresponding experimentally tolerable value for the magnetic noise is computed from Eq. (2). For this experiment the tolerable noise is $D_{\mathrm{Tl}} = 1120\,\mathrm{fT\,s}$, while the noise from a plate is 130 fT s. Therefore the magnetic Johnson 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.[7] used a thermal molecular 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.[1]. 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[7] the magnitude of R is a factor of 2700 larger than the magnitude in thallium. Magnetic noise from a vacuum pipe 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 $\ll 10^{-50}\,\mathrm{C\,m}$.

V. MAGNETIC NOISE IN PROPOSED EXPERIMENTS

We examine two proposed Cs experiments whose goal is to probe for a value of d_{e} of order $10^{-50}\,\mathrm{C\,m}$. Chin et al.[8] propose to trap $\sim 10^8$ Cs atoms in an optical lattice trap, to be observed for a time of $\sim 1\,\mathrm{s}$ set by the anticipated decoherence time of the atoms within the trapping laser fields. Gould[9] proposes to examine 3×10^8 atoms initially collected in a magneto-optical trap, to be observed for a time also of $\sim 1\,\mathrm{s}$ 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 examine $M_1 \rightarrow M_2$ 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 $10^{-50}\,\mathrm{C\,m}$ there corresponds from Eq. (2) a value of

$$D_{\mathrm{Cs}} = 0.38\,\mathrm{fT\,s}\ .$$

Values for the noise parameter D for slabs of a variety of materials and geometries are shown in Table II; the results greatly constrain the design of any experiment. In the following discussion references to soda lime glass, stainless steel, high-permeability metal (HPM), and MgZn ferrite are references to the specific, commercially available materials of Table II. We will take the ratio D/D_{Cs} for a slab as a rough estimate for 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 valid 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 $\lesssim 200\,\mathrm{nm}$. Materials exist whose resistivity at room temperature is low enough that 1 cm plates will function as electrodes but is high enough that their magnetic noise is negligible exist (e.g., doped silicon and silicon carbide), but no examples of the use of such materials as high-voltage electrodes is known to me. Electrodes made of heated glass[10, 11] are suitable; Gould[12] employed such plates made of soda lime glass (heated to 475 K to lower the electrical resistivity to $\sim 1 \times 10^4\,\mathrm{ohm\,m}$) to reverse electric fields of 35 MV/m. Such plates would generate noise roughly 2 orders of magnitude below the desired limit.

The noise from the wall of a standard 10 cm-radius stainless vacuum pipe (3 mm wall) is a factor of 20 above our limit. There must either be magnetic shielding inside the vacuum system[27], 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. *Set quis custodiet ipsos Custodes?*[28]. 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[13], 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.[3] and shown in Figure 1, would not be of order unity but the order of 10^{-4}. Lamoreaux' prediction is also in conflict with the measurements by Allred et al.[14], who found that the magnetic noise of metal plates of relative permeability 1 and of very high relative permeability matched the predictions of Nenonen et al.[3] to within the 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[15] of approximately $3b/(2\mu_{\rm rel}d)$. A 50-micron shield of HPM with radius 10 cm divides external magnetic fields by a factor of no more than 10. Because for a shield the 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 higher resistivity.

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

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[16–18] 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 ohm m, about a factor of 2×10^8 greater than that of HPM). A 10 cm-radius shell

3 mm thick would contribute magnetic noise a factor of 16 below our limit, while still reducing externally applied 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 putting a thick cylinder of ferrite inside a delicate onion of carefully annealed HPM shields is reducing the residual field to be as small as the ~ 1 nT achievable (before the use of trim coils) with the HPM alone. However the Curie temperature of ferrites is set by their composition; the particular ferrite modeled in Table II has a Curie temperature of $\approx 110\,^\circ$C, lower than the temperature to which a vacuum system is typically baked, which in turn is much lower than the $454\,^\circ$C Curie temperature of the 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 within only the tiny residual magnetic field provided by the HPM outer shields. The residual field left within the ferrite shell 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 suggests that within the innermost magnetic shield the noise from conducting materials in coils, support structures, 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 and spheres have not been done.

While is in principle possible to measure and subtract the contribution of the magnetic noise by including two kinds of atoms (or states) within each bunch that have different ratios of electric and magnetic dipole moments, one would still wish to keep the magnitude of the subtraction to be made small, and one would therefore still favor materials with a high electrical resistivity.

VI. CONCLUSIONS

Magnetic noise from Johnson currents in conductors impose severe constraints on the design of atomic or molecular experiments to measure the electric dipole moment of the electron, if the precision of the experiment is to be limited by shot noise; experiments on

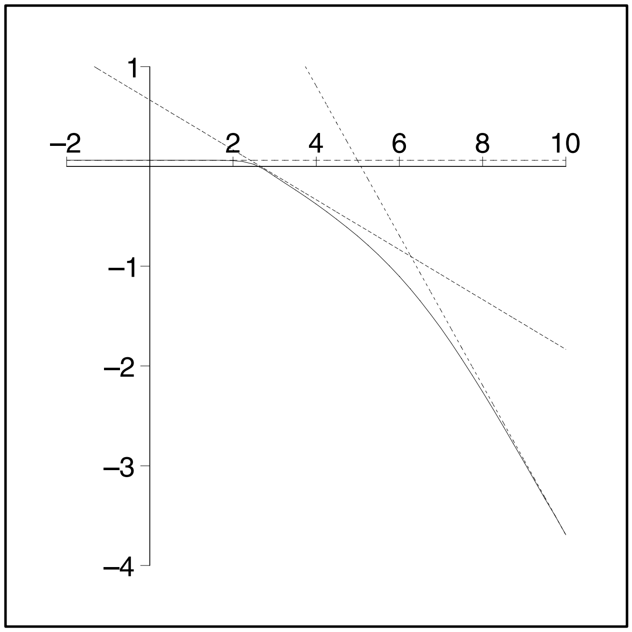

FIG. 1: Log-log plot (base 10) of θ as a function of ν, for a slab of MgZn ferrite ($\mu_{rel} = 1.0 \times 10^4$ and $\rho = 1 \times 10^{-1}$ ohm m) that is 3 mm thick and 10 cm away. The solid line curve is θ; the dotted, dashed, and dot-dashed curves are respectively the approximations numbered 2,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

polar diatomic molecules are less sensitive. Electric field plates made of metal are precluded. Magnetic noise from the walls of a vacuum system must either be screened or else the walls must be made a high-resistivity material. Standard high-permeability, metallic magnetic shields generate magnetic noise comparable to ordinary metals, and it is suggested the innermost of a set of shields be made of ferrite or some other material that combines magnetic permeability and low coercivity with high electrical resistivity.

Acknowledgments

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

#	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	$\frac{2+\tau}{\tau}\mu_{\rm rel}^2\frac{3\sqrt{2}}{\zeta^3}$	for $e^{-\zeta\tau} \ll 1$ and $\zeta \gg 1$ and $\zeta/\mu_{\rm rel} \gg 1$
5	$\frac{2+\tau}{\tau}\frac{2\sqrt{2}}{\zeta}$	for $e^{-\zeta\tau} \ll 1$ and $\zeta \gg 1$ and $\zeta/\mu_{\rm rel} \ll 1$

TABLE II: Values of D, the time integral of magnetic noise, from various slabs under different conditions, from a numerical integration of Eq. (4), and values of the ratio $D/D_{\rm Cs}$. For infinite slabs, and for the noise measured by a single atom or a cluster of atoms of negligible extent, the values of D are accurate to the number of significant figures given.

Material	ρ [ohm m]	$\mu_{\rm rel}$	d [m]	z [m]	T_0 [K]	D [fT s]	$D/D_{\rm Cs}$
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]	$1.0\times10^{+4}$	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 varies between 5×10^{-5} ohm m to 5×10^{-4} ohm m, depending on the degree of oxidation.

[c] Corning 0800.

[d] fully annealed CO-NETIC AA™, Magnetic Shield Corporation, shields@magnetic-shield.com.

[e] Eq. (5) predicts inaccurately 3.95×10^{0}.

[f] MgZn, product 10000HM™ of the Ferrite Domen Co, www.domen.ru.

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[25] For a discussion of known cancellations of contributions to d_{e} within the Standard Model, see ref. [19]. For the estimate that results see eq. (3.1) of ref. [20]; for the updated experimental

value of the parameter J in that equation see ref [2], p. 134. Upper bounds on the neutrino masses require[20] bound the contribution to d_e from from the CP-violation within a neutrino-analog of the CKM matrix to be no more than $\sim 10^{-58}\,\mathrm{C\,m}$.

[26] By this convention, standard in nuclear physics[21] and used in the 2000 CODATA Recommended Values of the Fundamental Constants[22], 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. See for example the Particle Data Book[2], p. 33 and p. 408, or [23], or the 1986 CODATA set of constants[24].

[27] Type 304 stainless steel, while nominally non-magnetic, has trace magnetism, and so could probably be used as a vacuum wall if some magnetic shielding is inside. Titanium alloy 6Al4V is indeed non-magnetic; however its greater strength and higher resistivity only lower the noise by a factor of roughly 2, compared to the same diameter stainless pipe.

[28] "Who will guard the guardians themselves?"—Juvenal, *Satires*, vi, 337.