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Sensitivity of fields generated within magnetically shielded volumes to changes in magnetic permeability

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ABSTRACT

Future experiments seeking to measure the neutron electric dipole moment (nEDM) require stable and homogeneous magnetic fields. Normally these experiments use a coil internal to a passively magnetically shielded volume to generate the magnetic field. The stability of the magnetic field generated by the coil within the magnetically shielded volume may be influenced by a number of factors. The factor studied here is the dependence of the internally generated field on the magnetic permeability μ of the shield material. We provide measurements of the temperature-dependence of the permeability of the material used in a set of prototype magnetic shields, using experimental parameters nearer to those of nEDM experiments than previously reported in the literature. Our measurements imply a range of $\frac{1}{\mu}\frac{d\mu}{dT}$ from 0–2.7%/K. Assuming typical nEDM experiment coil and shield parameters gives $\frac{\mu}{B_0}\frac{dB_0}{d\mu} = 0.01$, resulting in a temperature dependence of the magnetic field in a typical nEDM experiment of $\frac{dB_0}{dT} = 0 - 270$ pT/K for $B_0 = 1$ μT. The results are useful for estimating the necessary level of temperature control in nEDM experiments.

1. Introduction

The next generation of neutron electric dipole moment (nEDM) experiments aim to measure the nEDM d_n with proposed precision $\delta d_n \lesssim 10^{-27}e$ cm [1–8]. In the previous best experiment [9,10] which discovered $d_n < 3.0 \times 10^{-26}e$ cm (90% C.L), effects related to magnetic field homogeneity and instability were found to dominate the systematic error. A detailed understanding of passive and active magnetic shielding, magnetic field generation within shielded volumes, and precision magnetometry is expected to be crucial to achieve the systematic error goals for the next generation of experiments. Much of the research and development efforts for these experiments are focused on careful design and testing of various magnetic shield geometries with precision magnetometers [11–15].

In nEDM experiments, the spin-precession frequency ν of neutrons placed in static magnetic B_0 and electric E fields is measured. The measured frequencies for parallel ν_+ and antiparallel ν_- relative orientations of the fields is sensitive to the neutron electric dipole moment d_n

$$h\nu_{\pm} = 2\mu_n B_0 \pm 2d_n E \tag{1}$$

where μ_n is the magnetic moment of the neutron.

A problem in these experiments is that if the magnetic field B_0 drifts over the course of the measurement period, it degrades the statistical precision with which d_n can be determined. If the magnetic field over one measurement cycle is determined to $\delta B_0 = 10$ fT, it implies an additional statistical error of $\delta d_n \sim 10^{-26}e$ cm (assuming an electric field of $E = 10$ kV/cm which is reasonable for a neutron EDM experiment). Over 100 days of averaging, this would make a $\delta d_n \sim 10^{-27}e$ cm measurement possible. Unfortunately the magnetic field in the experiment is never stable to this level. For this reason, experiments use a comagnetometer and/or surrounding atomic magnetometers to measure and correct the magnetic field to this level [9,11,12]. Drifts of 1–10 pT in B_0 may be corrected using the comagnetometer technique, setting a goal magnetic stability for the B_0 field generation system in a typical nEDM experiment.

In such experiments, typically $B_0 = 1$ μT is used to provide the quantization axis for the ultracold neutrons. The B_0 magnetic field generation system typically includes a coil placed within a passively magnetically shielded volume. The passive magnetic shield is generally composed of a multi-layer shield formed from thin shells of material with high magnetic permeability (mu-metal). The outer layers of the

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shield are normally cylindrical [1,4] or form the walls of a magnetically shielded room [16,17]. The innermost magnetic shield is normally a specially shaped shield, where the design of the coil in relation to shield is carefully taken into account to achieve adequate homogeneity [3,5,9].

Mechanical and temperature changes of the passive magnetic shielding [18,19], and the degaussing procedure [17,19,20] (also known as demagnetization, equilibration, or idealization), affect the stability of the magnetic field within magnetically shielded rooms. Active stabilization of the background magnetic field surrounding magnetically shielded rooms can also improve the internal stability [12,18,21]. The current supplied to the B_0 coil is generated by an ultra-stable current source [11]. The coil must also be stabilized mechanically relative to the magnetic shielding.

One additional effect, which is the subject of this paper, relates to the fact that the B_0 coil in most nEDM experiments is magnetically coupled to the innermost magnetic shield. If the magnetic properties of the innermost magnetic shield change as a function of time, it then results in a source of instability of B_0. In the present work, we estimate this effect and characterize one possible source of instability: changes of the magnetic permeability μ of the material with temperature.

While the sensitivity of magnetic alloys to temperature variations has been characterized in the past [22,23], we sought to make these measurements in regimes closer to the operating parameters relevant to nEDM experiments. For these alloys, it is also known that the magnetic properties are set during the final annealing process [23–25]. In this spirit we performed our measurements on "witness" cylinders, which are small open-ended cylinders made of the same material and annealed at the same time as other larger shields are being annealed.

The paper proceeds in the following fashion:

- The dependence of the internal field on magnetic permeability of the innermost shielding layer for a typical nEDM experiment geometry is estimated using a combination of analytical and finite element analysis techniques. This sets a scale for the stability problem.
- New measurements of the temperature dependence of the magnetic permeability are presented. The measurements were done in two ways in order to study a variety of systematic effects that were encountered.
- Finally, the results of the calculations and measurements are combined to provide a range of temperature sensitivities that takes into account sample-to-sample and measurement-to-measurement variations.

2. Sensitivity of internally generated field to permeability of the shield $B_0(\mu)$

The presence of a coil inside the innermost passive shield turns the shield into a return yoke, and generally results in an increase in the magnitude of B_0. The ratio of this field inside the coil in the presence of the magnetic shield to that of the coil in free space is referred to as the reaction factor C, and can be calculated analytically for spherical and infinite cylindrical geometries [26,27]. The key issue of interest for this work is the dependence of the reaction factor on the permeability μ of the innermost shield. Although this dependence can be rather weak, the constraints on B_0 stability are very stringent. As a result, even a small change in the magnetic properties of the innermost shield can result in an unacceptably large change in B_0.

To illustrate, we consider here the model of a sine-theta surface current on a sphere of radius a, inside a spherical shell of inner radius R, thickness t, and linear permeability μ. The uniform internal field generated by this ideal spherical coil is augmented by the reaction factor in the presence of the shield, but is otherwise left undistorted. The general reaction factor for this model is given by Eq. (38) in Ref. [26].

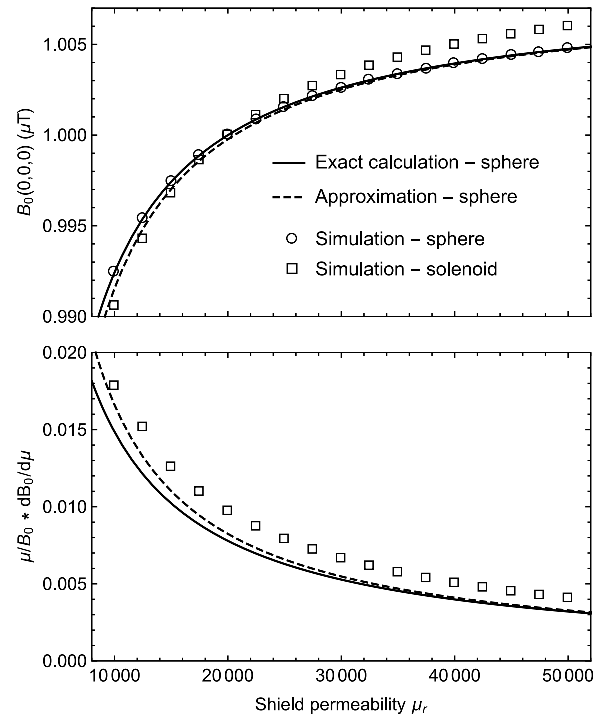

Fig. 1. Upper: Magnetic field at the coil center as a function of magnetic permeability of the surrounding magnetic shield for a geometry similar to the ILL nEDM experiment as discussed in the text. Lower: $\frac{\mu}{B_0}\frac{dB_0}{d\mu}$ vs. permeability. The solid curve is the exact calculation for the ideal spherical coil and shield from Ref. [26]; the dashed curve is the approximation of Eq. (2). The circles and squares are the FEMM-based simulations for the spherical and solenoidal geometries with discrete currents. Since the spherical simulation was in agreement with the calculation, it is omitted from the lower graph. For the exact calculation and the two simulations, currents were chosen to give $B_0 = 1$ μT at $\mu_r = 20{,}000$.

In the high-μ limit, with $t \ll R$, the reaction factor can be approximated as

$$C \simeq 1 + \frac{1}{2}\left(\frac{a}{R}\right)^3 \left(1 - \frac{3}{2}\frac{R}{t}\frac{\mu_0}{\mu}\right), \tag{2}$$

which highlights the dependence of B_0 on the relative permeability $\mu_r = \mu/\mu_0$ of the shield.

Fig. 1 (upper) shows a plot of B_0 vs. μ_r for coil and shield dimensions similar to the ILL nEDM experiment [9,28]: $a = 0.53$ m, $R = 0.57$ m, and $t = 1.5$ mm. In addition to analytic calculations, we also include the results of two axially symmetric simulations conducted using FEMM [29] to assess the effects of geometry and discretization of the surface current. The differences are small, suggesting that the ideal spherical model of Ref. [26] and the high-μ approximation of Eq. (2) provide valuable insight for the design and analysis of shield-coupled coils.

In the first simulation, the same spherical geometry was used as for the analytic calculations. However, the surface current was discretized to 50 individual current loops, inscribed onto a sphere, and equally spaced vertically (i.e. a discrete sine-theta coil). A square wire profile of side length 1 mm was used. As shown in Fig. 1, this simulation gave excellent agreement with the analytic calculations. In the second simulation, a solenoid coil and cylindrical shield (length/radius = 2) were used with the same dimensions as above. Similarly, the coil was modeled as 50 evenly spaced current loops, with the distance from an end loop to the inner face of the shield endcap being half the inter-loop spacing. In the limit of tight-packing (i.e., a continuous surface current) and infinite μ, the image currents in the end caps of the shield act as an infinite series of current loops, giving the ideal uniform field of an infinitely long solenoid [30,31]. As shown in Fig. 1, the result is similar to the spherical case, with differences of order one part per thousand and a somewhat steeper slope of $B_0(\mu_r)$.