Nuclear Instruments and Methods in Physics Research A 862 (2017) 36–48

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

# Cryogenic magnetic coil and superconducting magnetic shield for neutron electric dipole moment searches

S. Slutsky [a,*], C.M. Swank [a], A. Biswas [a], R. Carr [a], J. Escribano [a,b], B.W. Filippone [a], W.C. Griffith [a,c], M. Mendenhall [a,d], N. Nouri [e], C. Osthelder [a], A. Pérez Galván [a,f], R. Picker [a,g], B. Plaster [e]

[a] Department of Physics, Math and Astronomy, California Institute of Technology, Pasadena, CA 91125, USA
[b] Xamarin, San Francisco, CA 94111, USA
[c] Department of Physics and Astronomy, University of Sussex, Brighton BN1 9RH, United Kingdom
[d] Nuclear and Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[e] Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA
[f] Vertex Pharmaceuticals, 11010 Torreyana Rd., San Diego, CA 92121, USA
[g] TRIUMF, Vancouver, BC, Canada V6T 2A3

ARTICLE INFO

*Article history:*
Received 12 January 2017
Received in revised form
6 April 2017
Accepted 5 May 2017
Available online 5 May 2017

*Keywords:*
Electric dipole moment
Magnetic fields
Magnetic gradients
Cryogenic
Superconducting
Geometric phase

ABSTRACT

A magnetic coil operated at cryogenic temperatures is used to produce spatial, relative field gradients below 6 ppm/cm, stable for several hours. The apparatus is a prototype of the magnetic components for a neutron electric dipole moment (nEDM) search, which will take place at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory using ultra-cold neutrons (UCN). That search requires a uniform magnetic field to mitigate systematic effects and obtain long polarization lifetimes for neutron spin precession measurements. This paper details upgrades to a previously described apparatus [1], particularly the introduction of super-conducting magnetic shielding and the associated cryogenic apparatus. The magnetic gradients observed are sufficiently low for the nEDM search at SNS.

## 1. Introduction

The existence of a permanent electric-dipole-moment (EDM) on a subatomic scale would violate both parity (P) and time (T) symmetries, and would be a signature of physics beyond the Standard Model [2]. Additionally, with CPT symmetry, such an EDM would also violate the combined charge and parity (CP) symmetry. The amount of CP violation currently observed in meson decay cannot explain the baryonic matter/anti-matter asymmetry in the observed universe, within the Sakharov criteria [3]. Therefore, a larger source of CP violation is anticipated. With the expected precision of the next generation of competitive EDM searches, a positive or null measurement will have broad theoretical consequences [4–6].

Of the species available to probe EDMs, the neutron has several advantages. Relative to atoms or charged particles, the neutron can be considered simple to understand and manipulate. It has no electrons to shield or enhance the effect of an EDM, mitigating errors that can arise from theoretical predictions. Its trajectory is not affected by uniform electric fields, and it can be trapped in a material bottle and observed for periods only limited by its intrinsic lifetime. Currently, the most precise nEDM measurement was made using ultracold neutrons (UCN) by the Sussex/RAL/ILL nEDM experiment, setting a limit of $3.0 \times 10^{-26}$ e − cm [7]. Among the next generation of EDM experiments, the nEDM search at the SNS [8], based on the concepts discussed in [9], is possibly the most ambitious of all, with a design sensitivity of $d_n \lesssim 3 \times 10^{-28}$ e − cm.

While the Sussex/RAL/ILL experiment was statistically limited, the largest systematic uncertainty was due to the so-called "geometric phase" [10]. When a particle's spin precession frequency is measured in the presence of a magnetic field with a spatial gradient, there is a frequency shift proportional to both the linear magnetic field gradients and to the applied electric field; this can mimic the expected EDM signal. It is therefore critical to demonstrate that field gradients are under control and understand what materials constitute potential sources of magnetic field before designing a full-scale experiment. To that end, we constructed a prototype replicating the magnetic coils and shielding of the SNS

---

[*] Corresponding author.
*E-mail addresses:* sslutsky@caltech.edu, simonslutsky@gmail.com (S. Slutsky).

http://dx.doi.org/10.1016/j.nima.2017.05.005
0168-9002/

experiment at half-scale in each linear dimension, and we evaluated the magnetic fields inside.

## 2. Experimental apparatus

### 2.1. Summary of the nEDM apparatus at the SNS

In the SNS nEDM experiment, neutrons will be generated at the mercury spallation source and moderated to low temperatures, ~20–30 K. The cold neutrons will be spin-polarized with a supermirror polarizer and then guided into the cryogenic apparatus, where they will illuminate two cells filled with isotopically pure $^4$He. The two cells will be held at a temperature of ~450 mK by a large dilution refrigerator. Neutrons with a wavelength of 8.9 Angstroms can interact with the superfluid via phonon emission and down-scatter to an energy of ~0–200 neV [11,12]. These neutrons will be moving so slowly that they become trapped between the walls of the cell, which are coated with deuterated polystyrene. The neutrons that become trapped are considered UCN.

Trapped UCN will be subjected to a magnetic holding field, $B_0 \sim 3\ \mu\mathrm{T}$, to maintain polarization. A strong electric field, $E$, will be applied to probe the EDM, the direction of which can be reversed to control for systematics. A $\pi/2$ pulse will rotate the UCN spins perpendicular to the holding field. The UCN spins will then precess according to their Larmor frequency, $\omega_n$:

$$\omega_n = -2(\mu_n B_0 \pm d_n E)/\hbar \tag{1}$$

where $\mu_n$ and $d_n$ are the neutron magnetic and electric dipole moments, respectively, and $\hbar$ is Planck's constant. The sign of the EDM term depends on the direction of the applied field. Thus, a neutron spin-precession frequency shift proportional to $E$ indicates a non-zero nEDM.

The frequency shift will be extracted by the spin-dependent interaction with $^3$He [13]. Polarized $^3$He will be injected at the time of measurement, will be subjected to a $\pi/2$ pulse to align the spins with those of the UCN, and will diffuse throughout the cell to cohabit with the neutrons. The $^3$He atomic EDM is known to be negligible compared to the neutron EDM, so the $^3$He spin can be considered to not precess under the applied electric field [14]. A neutron and $^3$He in proximity and with opposing spins can react to form a proton and triton with 764 keV. Charged decay products will cause the superfluid helium-II to scintillate, and the scintillations are observed to form the signal. This signal will oscillate in time as the neutron spins precess from aligned to anti-aligned with the $^3$He, and it will be maximized if the neutron and $^3$He spins remain in the same plane. Thus, a uniform magnetic field, particularly in the directions perpendicular to $B_0$ [34], is necessary to maximize the neutron and $^3$He transverse coherence time $T_2^*$. The polarized $^3$He can also be used as a comagnetometer to measure changes in the magnetic field. SQUIDS will be used to independently monitor the precession of the $^3$He magnetization; the neutron density will be too low compared to the $^3$He to affect this signal. The SQUID response can then be used to implement a time-dependent correction for background magnetic field shifts.

An undesired shift in the neutron spin precession frequency arises due to the coupling of magnetic field gradients and the motional magnetic field seen by the neutron motion in an electric field, $\vec{B}_m = -\vec{v} \times \vec{E}/c^2$. This frequency shift is linearly dependent on the electric field, $E$, so it will appear as a "false" EDM term, $d_f$, in Eq. (1):

$$\omega_n = -2(\mu_n B_0 \pm (d_n + d_f)E)/\hbar \tag{2}$$

This shift $\delta\omega_\mathrm{n}$ in $\omega_n$ due to $d_f$ is predicted for a rectangular cell with a linear magnetic gradient by [15]:

$$\delta\omega_n(\omega_0) = -\gamma^2\frac{E}{c^2}\left(\omega_0 \mathrm{Im}\left[G_y S_{yy}(\omega_0) + G_z S_{zz}(\omega_0)\right] + G_y\frac{L_y^2}{12} + G_z\frac{L_z^2}{12}\right), \tag{3}$$

where $\gamma$ is the gyromagnetic ratio of the neutron, $\omega_0 = \gamma B_0$ is the precession frequency of the neutrons under the holding field, $S_{yy}$ and $S_{zz}$ are the spectra of the position correlation functions found in reference [16], $G_y$ and $G_z$ are the linear magnetic field gradients, and $c$ is the speed of light. The coordinate system is defined such that the magnetic holding field is in the $x$-direction; the $y$- and $z$-directions are perpendicular to $x$, with $z$ along the axis of the cylindrical $\cos(\theta)$ magnet. $L_y$ and $L_z$ are the lengths of the cell in those directions. Given the geometry of the SNS nEDM design, we typically require linear gradients to be $G \le 3 \times 10^{-6} B_0/\mathrm{cm}$, or a false EDM $d_f \le 1 \times 10^{-28}$ e − cm.

Novel techniques are needed to maintain magnetic uniformity in such a low-temperature environment. Use of magnetic components must be minimized, and those that are used must be placed as far from the cells as possible. The cells must be magnetically shielded. Additionally, temperature fluctuations in the cryogens are transferred to metal components, which generates magnetic fluctuations via Seebeck effect currents (thermoelectric effect). On the other hand, the cryogenic nature of the experiment offers the possibility of using a superconducting shield to exclude external fields via the Meissner effect.

### 2.2. $\frac{1}{2}$-scale magnet prototype apparatus

As previously described in [1], a prototype magnet has been created at $\frac{1}{2}$− scale of the nEDM at SNS magnet design in order to understand the level of magnetic uniformities achievable. That work described the field uniformity of the prototype magnet as measured at room temperature. We now describe a series of upgrades to that apparatus, including a helium cryostat and a lead shield, which when cooled below 7.2 K becomes a superconductor, shielding external magnetic fields.

A central magnet, referred to as the "$B_0$" coil and seen in Fig. 1, is used to produce a uniform magnetic field, typically 3 μT, using ~50 mA current. The magnet follows a "cos($\theta$)" design, which uses a cylindrical geometry with currents running on the surface parallel to the axis according to a cosine distribution. This design is known to generate throughout the cylinder a uniform field perpendicular to the axis of the coil [17]. The center of the $B_0$ coil determines the nominal origin for coordinates mentioned throughout the paper.

The $B_0$ coil approximates the ideal cos($\theta$) design using copper wires strung along a cylindrical surface with spacing determined by a modified cosine distribution, the details of which can be found in [1]. The coil used is 2.13 m tall, 0.61 m in diameter, and has 60 axial wires, which pair off into 30 coil windings. The wires are wrapped on spring-tensioned pegs to maintain straightness. The pegs are mounted in acrylic holding rings and project slightly past the rings, so the $B_0$ coil and trim coils sit at a diameter of 0.65 m. The holding rings are supported by vertical rods made of alternating segments of G10 and nylon, with the ratio of the lengths of the G10 and nylon segments designed so that the thermal contraction of the entire rod will match the contraction of the copper wire. Finally, the entire structure is supported on a cylindrical acrylic frame, which has vertical grooves allowing the acrylic rings to slide.

Trim coils are used to compensate for field non-uniformities arising from local magnetic impurities or from the fact that the coil is discrete and not an ideal cos($\theta$) design. It was found that three pairs of trim coils were necessary to cancel ambient gradients, as shown schematically in Fig. 2: a cos($\theta$) coil with 12 wires (6 windings) to trim the field in the $B_0$ direction; a