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TO MEASURE THE NEUTRON ELECTRIC DIPOLE
MOMENT

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“SQUIDS as Detectors in a New Experiment to Measure the Neutron Electric Dipole Moment”

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Abstract— A new experiment has been proposed at Los Alamos National Laboratory to measure the neutron electric dipole moment (EDM) to 4×10^{-28} ecm, a factor of 250 times better than the current experimental limit. Such a measure of the neutron EDM would challenge the theories of supersymmetry and time reversal violation as the origin of the observed cosmological asymmetry in the ratio of baryons to antibaryons. One possible design for this new experiment includes the use of LTC SQUIDs coupled to large (~ 100 cm²) pick-up coils to measure the precession frequency of the spin-polarized ³He atoms that act as polarizer, spin analyzer, detector, and magnetometer for the ultra-cold neutrons used in the experiment. The method of directly measuring the ³He precession signal eliminates the need for very uniform magnetic fields (a major source of systematic error in these types of experiments). It is estimated that a flux of $\sim 2 \times 10^{-16}$ Tm² ($0.1 \Phi_0$) will be coupled into the pick-up coils. To achieve the required signal-to-noise ratio one must have a flux resolution of $d\Phi_{SQ} = 2 \times 10^{-6} \Phi_0 / \sqrt{\text{Hz}}$ at 10 Hz. While this is close to the sensitivity available in commercial devices, the effects of coupling to such a large pick-up coil and flux noise from other sources in the experiment still need to be understood. To determine the feasibility of using SQUIDs in such an application we designed and built a superconducting test cell, which simulates major features of the proposed EDM experiment, and we developed a two-SQUID readout system that will reduce SQUID noise in the experiment. We present an overview of the EDM experiment with SQUIDs, estimations of required SQUID parameters and experimental considerations. We also present the measured performance of a single magnetometer in the test cell as well as the performance of the two SQUID readout technique.

I. INTRODUCTION

A. Background

Despite nearly 50 years of experimental effort, to date nobody has been able to observe an electric dipole moment (EDM) of a neutron or any other elementary particle. If such an EDM could be shown to exist, it would be direct evidence for the violation of time-reversal, T, symmetry (as well as parity violation) in the interactions of particles. Understanding T-violation is fundamental to our picture of elementary particles and their interactions. For example, if one believes that at the time of the “big bang” there was no other asymmetry, the reason we observe much more matter than anti-matter in our universe may be the result of T-violation.

T invariance has been observed indirectly in the decay of the neutral kaon but its origin remains unexplained and it

Neutron EDM Measurement with SQUIDs

Fig. 1. Upper: Schematic drawing of the EDM experiment. The z-axis is into the page. The entire apparatus is contained inside a superconducting vessel (not shown) at a temperature of ~ 0.5 mK. Lower: Expected signal produced from ³He precession. The Larmor frequency for a 3 mG holding field, B, is ~ 10 Hz.

has never been observed in any other processes. Any model put forth to explain the elementary particles and the forces by which they interact must explain T-violation in neutral kaon decay and hence predict a neutron EDM. Some of these models, i.e. supersymmetry, predict a value for the neutron EDM that is within experimental reach. For reasons such as these, the quest to put better and better limits on the neutron EDM is considered more important than ever.

B. Experimental Overview

The reader is referred to the article by Golub and Lamoreaux[1] for a complete description of the proposed experiment to measure the neutron EDM. Here we present only a brief outline explaining the manner in which SQUIDs could be used.

The upper panel of Fig.1 shows a schematic of the proposed experimental set-up. The entire apparatus shown would be contained inside a superconducting vessel (not shown). Spin polarized ultra-cold neutrons (UCN) are produced and stored in this superconducting vessel that contains a bath of superfluid ⁴He and a small concentration ($\sim 10^{13}$ atoms/cm³) of polarized ³He. A 3 mG uniform static magnetic field, B, is oriented along the +z axis (into the page). A 5 kV/mm uniform static electric field, E, is oriented parallel to B for one half the measurements and

anti-parallel for the other half. If the neutron possesses an EDM, d_n , its precession frequency, ω_n , about the z-axis (after a pulse which aligns its spin in the x-y plane) will be slightly different between the two cases where B and E are parallel or anti-parallel. If we describe the UCN precession frequency as $\omega_n = B\gamma_n$ where B is the magnetic field and γ_n is the gyromagnetic ratio, then

$$\delta\omega_n = B(\delta\gamma_n) = -2\frac{d_n E}{\hbar}. \quad (1)$$

Due to the low concentrations of UCN in the experiment it is impossible to measure ω_n directly. However, a nuclear reaction that proceeds only when the UCN and ^3He spins are anti-parallel produces measurable scintillation rate in the ^4He ,

$$\phi(t) = 1 - p_3 p_n \cos[(\gamma_3 - \gamma_n)Bt + \Phi], \quad (2)$$

where p_3 and p_n are the polarization vectors for the ^3He and UCN, γ_3 and γ_n are the gyromagnetic ratios and Φ is an arbitrary phase.

The scintillation signal is modulated by the difference in the ^3He and UCN precession frequencies or gyromagnetic ratios, where $\gamma_3/2\pi \sim -3.33 \text{ Hz/mG}$ and $\gamma_n/2\pi \sim -3 \text{ Hz/mG}$. The difference in the scintillation modulation between E along $+z$ or $-z$ is a signal for the neutron EDM. As implied by (1), if there is an EDM, γ_n will change slightly depending on the orientation of E (because of electron screening effects the ^3He have no EDM and γ_3 will not change). However, to extract the neutron EDM from the scintillation signal one must know the magnetic field B to high precision, a very difficult problem.

Presently magnetic systematic effects are limiting EDM experiments. The current experiments improve on measuring B directly, by using a technique called "atomic dressing". A RF field is applied to effectively make the ^3He and UCN gyromagnetic ratios identical, $\gamma_3 - \gamma_n = 0$. The difference in the required RF field between E and B parallel and anti-parallel is the signal for the neutron EDM. However, it is very difficult to keep a RF field with the required uniformity, and this again limits the precision of EDM experiments.

We propose a novel technique of measuring the precession frequency of the ^3He directly with SQUIDS coupled to large pick-up coils (see Fig. 1), and in this way remove B from the problem. This article describes an experimental program designed to determine whether or not this method will be feasible. Section II describes the requirements of SQUID sensitivity and magnetic noise levels from the rest of the experiment. Section III describes a superconducting test cell that was built to investigate the SQUID performance (and eventually noise sources) in an environment similar to the proposed EDM set-up and the tests performed thus far. Section IV describes tests performed with a two-SQUID readout technique, and Section V discusses the future directions of the EDM project.

II. EXPERIMENTAL REQUIREMENTS AND CONSIDERATIONS

A. SQUID Sensitivity

The EDM experimental cell will be roughly 20 cm in diameter and 10 cm high. The ^3He will be essentially 100 % polarized. If we assume a geometric coupling factor of $1/4$ for the 100 cm^2 pick-up loop this corresponds to an expected magnetization signal coupled to the SQUID of $S = 0.1 \Phi_0$. To obtain the desired experimental sensitivity we must reach a SQUID signal to noise ratio of at least $\text{SNR} = 24 \sqrt{\text{Hz}}$ where

$$\text{SNR} = \frac{S}{\sqrt{d\Phi_p^2 + d\Phi_e^2}}, \quad (3)$$

$d\Phi_p$ is the intrinsic flux sensitivity of the pick-up loop and $d\Phi_e$ is experimental flux noise coupled to the pick-up loop. This corresponds to requiring the denominator of (3) be $\sim 4.2 \text{ m}\Phi_0/\sqrt{\text{Hz}}$.

$$d\Phi_{SQ} = M \frac{d\Phi_p}{(L_p + L_i)}, \quad (4)$$

where M is the mutual inductance between the pick-up loop and the SQUID input coil, L_p is the inductance of the pick-up loop and L_i is the inductance of the input coil. Using "typical" values from a commercial LTS SQUID[2] where $d\Phi_{SQ} \sim 2 \mu\Phi_0/\sqrt{\text{Hz}}$, $M = 10 \text{ nH}$, $L_i = 600 \text{ nH}$, and the inductance of the 100 cm^2 pick-up loop $L_p = 1.4 \mu\text{H}$, we find $d\Phi_p$ is $\sim 0.4 \text{ m}\Phi_0/\sqrt{\text{Hz}}$.

If SQUID noise is proportional to $\sqrt{T}$, as one expects for white noise, we anticipate a factor of 3 improvement in $d\Phi_p$ during the real experiment at $\sim 0.5 \text{ K}$. There are, however, concerns about the performance of these SQUIDS when they are coupled to such a large pick-up coil with a high inductance.

B. Other Noise Sources

From the above calculations, sources of magnetic noise from the experiment, $d\Phi_e$, are limited to $\sim 4.18 \text{ m}\Phi_0/\sqrt{\text{Hz}}$. Sources of concern are vibrations of the SQUID pick-up loop in the B field, leakage current from the high voltage plates providing the large E field, Johnson noise from non-superconducting elements, magnetic noise leaking into the superconducting shield through penetrations, and non-uniformity in the B field. Many of these sources will be investigated inside the test cell described below.

III. SUPERCONDUCTING TEST CELL

Fig. 2 shows a photograph of a test cell built to resemble the EDM apparatus. The cell consists of an 8" diameter, 4" high lead can. The lid shown has recesses for up to four SQUID sensors. Penetrations in this lid bring the pick-up loop wires from the inside of the can to the SQUIDS and allow liquid helium in. A second lid sits on top (not shown) ensuring that the SQUIDS are totally surrounded by a superconductive shield during operation and that all penetrations into the cell make a 90° bend that limits the penetration of magnetic fields from the outside world. A

Fig. 2. Photo of 8" diameter lead can built to resemble the EDM apparatus. The lid shows recesses for up to four SQUID sensors. The pick-up coils are located inside the can. The actual EDM experiment would take place inside a superconducting can such as this.

lead piece that fits over the bottom of the can for the same purpose.

A Conductus 1020 SQUID was used for the experiments described below, operated with Conductus PC SQUID electronics. Two different types of pick-up coils were investigated. Both had $\sim 100 \text{ cm}^2$ area and were made of wire encapsulated on kapton film. The kapton film was wrapped around a phenolic support that fit snugly inside the lead can to minimize vibration. The entire system was cooled down with the dewar inside of a mu-metal can for further magnetic shielding. The dewar was five feet tall (with the test cell at the bottom) and the mu-metal can was four feet deep such that the top of the dewar was not shielded.

The first pick-up coil was made of copper wire with lead solder flowed over the copper traces so the pick-up coil would be superconductive. The noise power spectrum at 10 Hz was $\sim 5 \times 10^{-2} \text{ pT}/\sqrt{\text{Hz}}$ or $2.5 \text{ m}\Phi_0/\sqrt{\text{Hz}}$, as shown in the curve labeled Cu-Pb in Fig. 3a. The full spectrum (corresponding curve in Fig. 3b) shows that the SQUID never seems to exhibit white noise behavior. We believe the resistive copper connected in parallel with the lead caused this problem.

A second pick-up coil made entirely of lead wire gave much better performance. The noise at 10 Hz was $\sim 3 \times 10^{-4} \text{ pT}/\sqrt{\text{Hz}}$ or $15 \mu\Phi_0/\sqrt{\text{Hz}}$, as shown in the curve labeled Pb in Fig. 3a. From the full power noise spectrum (Fig. 3b) one can see that even with the improved noise performance the SQUID does not show white noise behavior until frequencies above 100 Hz. The levels are $\sim 2 \times 10^{-4} \text{ pT}/\sqrt{\text{Hz}}$ or $10 \mu\Phi_0/\sqrt{\text{Hz}}$, not the expected $\sim 2 \mu\Phi_0/\sqrt{\text{Hz}}$.

At frequencies less than 100 Hz we are seeing noise from vibrations and external sources in the laboratory. For example a peak due to vibration of the dewar can be seen $\sim 30 \text{ Hz}$ in the Pb noise spectrum shown in Fig. 3a. We need to do an even better job shielding all the penetrations into the lead can and cool the system down in a more shielded environment.

Fig 3a. Noise power spectra for 1020 SQUID with copper-lead pick-up coil (Cu-Pb) and lead only pick-up coil (Pb) from 0.1 – 100 Hz. Noise levels at 10 Hz were $\sim 5 \times 10^{-2} \text{ pT}/\sqrt{\text{Hz}}$ ($2.5 \text{ m}\Phi_0/\sqrt{\text{Hz}}$) and $\sim 3 \times 10^{-4} \text{ pT}/\sqrt{\text{Hz}}$ ($15 \mu\Phi_0/\sqrt{\text{Hz}}$) respectively.

Fig 3b. Same as 3a, from 100 – 10,000 Hz. There appears to be no white noise behavior for Cu-Pb coil. At frequencies above 100 Hz the Pb coil showed a white noise level of $\sim 2 \times 10^{-4} \text{ pT}/\sqrt{\text{Hz}}$ ($10 \mu\Phi_0/\sqrt{\text{Hz}}$).

The modulation technique of the PC SQUID electronics may also prevent reaching the intrinsic SQUID noise level. This method averages over many working points of the SQUID, not all of them optimal. To investigate this we developed the two-SQUID readout technique below.

IV. TWO-SQUID READOUT TECHNIQUE

We worked on developing a two SQUID read-out technique (pico-voltmeter) in parallel to the above experiments. Eventually the pico-voltmeter will be coupled to the large pick-up coil and placed in the test cell. For the experiments described below the system was developed in a smaller lead can with a niobium wire pick-up coil of roughly equivalent inductance ($\sim 0.9 \mu\text{H}$). Fig. 4 shows the pico-voltmeter probe described below.

Fig. 5 shows a schematic of the pico-voltmeter system. V_{in} is the voltage across the first or input SQUID. The second SQUID is operated in the conventional modulation technique and reads out voltage changes in the first SQUID. This method allows us to operate at the optimally quiet working point of the first SQUID.

The first SQUID was a Conductus 1020 connected in parallel with a 5.9Ω resistor. The second SQUID had a $0.6 \mu\text{H}$ input inductance, current resolution of $1 \mu\text{A}/\Phi_0$

Fig. 4a. Picture of Picovoltmeter probe, second SQUID is encased in lead at left, and matching electronics are at right on probe.

Fig. 4b. Opposite side of picovoltmeter probe shows first SQUID at right. This SQUID is inside a niobium cylinder. The entire probe is slipped inside a lead sleeve during testing.

($M=2$ nH), $R_0=1$ Ω , and was operated with Conductus PC SQUID electronics.

A was connected in parallel with the first SQUID. With this set-up we were able to measure a noise power spectrum with a white noise level of $3 \mu\Phi_0/\sqrt{\text{Hz}}$ down to frequencies ~ 1 Hz.

This is better than a factor of 3 improvement in the white noise level we were able to achieve with the conventional magnetometer in the lead test can. We were able to reach it at lower frequencies due to the better shielding of the probe and the smaller area of the pick-up coil.

It is our hope that with better shielding in the lead test can and the picovoltmeter, we can reach this white noise level at 10 Hz with the actual large pick-up coil.

V. FUTURE DIRECTIONS

A. Studies of Temperature Effects

The proposed EDM experiment will take place in a superfluid ^4He bath at ~ 0.5 K, which should lead to an improvement in the noise by a factor of $\sqrt{(4.2/0.5)}$ or ~ 3 . Previous studies of SQUID noise as a function of temperature show that the $\sqrt{T}$ behavior is seen with white noise[3] but with $1/f$ noise the behavior with temperature can be very unpredictable[4]. It is important that we know that we can achieve the white noise behavior as a function of temperature. We plan to test the picovoltmeter in a small dewar that can be pumped on to lower the temperature to ~ 1 K, where the effects of temperature on SQUID noise can be studied.

B. Tests in the Lead Can

After achieving the proper temperature behavior of the SQUID noise we will integrate the picovoltmeter into the lead test can. This will involve improved shielding of

Fig. 5. Schematic of the two-SQUID readout (picovoltmeter) system. Voltage changes across the first the first SQUID are measured by the second SQUID, operated by conventional modulation technique.

penetrations into the lead can as well as shielding during cooling of the system.

These tests have serious implications for the actual EDM experiment, where there will be many penetrations into the superconducting can. Knowledge of the level to which penetrations need to be shielded will be very important for the final experimental design, as will knowing what shielding is required during cooling of the superconductive can.

Once the SQUID system is in the lead test can we can investigate noise sources such as leakage current and Johnson noise from non-superconducting materials. It may also be possible to use the lead test can to study how to produce the uniform B field. Two ideas being investigated presently are trapping a current in the lead can as it goes superconducting, or using current carrying coils inside the lead can to produce the field. The 3 mG field must be uniform to ~ 0.1 %.

C. Tests in the Neutron Beam

The proposed EDM experiment was given beam time at the Los Alamos Neutron Scattering Center in 1997 that was used to investigate the scintillation of the neutron- ^3He reaction and our ability to collect that light. More beam time is scheduled for the fall of 1998, which will use a neutron beam to investigate the distribution of ^3He in a ^4He cell above and below the superfluid point.

We anticipate that SQUIDS will be incorporated in tests in the neutron beam to study the experimental noise and effects of radiation sometime in 1999. The full-fledged EDM experiment is expected to be on-line in ~ 2003 .

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