Abstract—A new experiment has been proposed at Los Alamos National Laboratory to measure the neutron electric dipole moment (EDM) to $4 \times 10^{-28}$ cm, 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 low temperature superconducting (LTS) SQUIDs coupled to large ($\sim 100$ cm$^2$) pick-up coils to measure the precession frequency of the spin-polarized $^3$He atoms that act as polarizer, spin analyzer, and detector for the ultra-cold neutrons used in the experiment. The method of directly measuring the $^3$He 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 $\sim 2 \times 10^{-16}$ Tm$^2$ ($0.1 \Phi_0$) will be coupled into the pick-up coils. To achieve the required signal-to-noise ratio one must have a flux resolution of $d\Phi_{SQ} \approx 5 \times 10^{-8} \Phi_0$/Hz$^{1/2}$ 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 symmetry, T, and parity violation in the interactions of elementary particles. Understanding T-violation is fundamental to our picture of the "big bang", the reason we observe much more matter than anti-matter in our universe may be the result of T-violation.

T-violation has been observed indirectly in the decay of the neutral kaon but its origin remains unexplained and it has never been observed in any other processes. Present models that 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 our experimental reach. For reasons such as these, the quest to put lower limits on the neutron EDM is considered of great scientific importance.

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 in this experiment.

The upper panel of Fig.1 shows a schematic of the proposed experimental set-up. The entire apparatus would be contained inside a superconducting vessel (not shown) at a temperature of -0.5 mK. Lower: Expected signal produced from $^3$He precession. The Larmor frequency for a 3 mG holding field, B, is $\sim 10$ Hz.

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 $^3$He precession. The Larmor frequency for a 3 mG holding field, B, is $\sim 10$ Hz.

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oriented along the +z axis (into the page in Fig. 1). A 5 kV/mm uniform static electric field, $E$, will be 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, $\omega_n$, about the z-axis 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 $\omega = B\gamma$, where $B$ is the magnetic field and $\gamma$ is the gyromagnetic ratio, then

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

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

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

where $p_3$ and $p_n$ are the polarization vectors for the $^3$He and UCN, $\gamma_3$ and $\gamma_n$ are the gyromagnetic ratios and $\Phi$ is an arbitrary phase.

The scintillation signal is modulated by the difference in the $^3$He and UCN precession frequencies or gyromagnetic ratios, where $\gamma_3/2\pi = -3.33 \text{ Hz/mG}$ and $\gamma_n/2\pi = -3 \text{ Hz/mG}$. The difference in the scintillation modulation between $E$ aligned along $+$z and $-$z is a signal for the neutron EDM. As implied by (1), if there is an EDM, $\gamma_n$ will change slightly depending on the orientation of $E$ (because of electron screening effects the $^3$He have no EDM and $\gamma_n$ 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.

All current neutron EDM experiments are limited by magnetic systematic effects. To eliminate these effects, we suggest a "dressed spin" technique that uses a RF magnetic field to make the $^3$He and neutron magnetic moments equal ($\gamma_n = \gamma_n$). As seen in (2), if the effective magnetic moments are equal there is no dependence of the relative spin angle on the magnetic field. Any difference in RF field required to keep the $^3$He and neutron magnetic moments equal between $B$ and $E$ parallel or anti-parallel is the signal for the EDM. However, this technique will require a very homogeneous and well-controlled RF field within the superconducting shield. This appears to be a difficult problem, and we are therefore exploring alternative possibilities to eliminate magnetic contributions to the neutron precession signal.

We propose a novel technique of directly measuring the precession frequency of the $^3$He with SQUIDs coupled to large pick-up coils (see Fig. 1), and using this information in conjunction with the scintillation measurement to extract any signal of the neutron EDM. This article describes an experimental program designed to determine whether or not this method is feasible.

II. EXPERIMENTAL REQUIREMENTS AND CONSIDERATIONS

A. SQUID Sensitivity

The EDM experimental cell will be roughly 20 cm in diameter and 10 cm high. The $^3$He will be essentially 100% polarized. With this design geometry the magnetization signal expected at the 100 cm$^2$ pick-up is $5\times 10^{-15} \Phi_0$. To obtain the desired experimental sensitivity we must reach a SQUID signal-to-noise ratio of at least $SNR=24 \text{ Hz}^{1/2}$ [2] where

$$SNR = \frac{S}{\sqrt{d\Phi_p^2 + d\Phi_c^2}},$$

$d\Phi_p$ is the intrinsic flux sensitivity of the pick-up loop and $d\Phi_c$ is experimental flux noise coupled to the pick-up loop. This means the denominator of (3) is at most 4.2 m$\Phi_0$/Hz$^{1/2}$. The flux sensitivity of the SQUID is

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

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 [3] at 4 K where $d\Phi_{SQ}=5 \mu\Phi_0$/Hz$^{1/2}$, $M=10 \text{ nH}$, $L_i=600 \text{ nH}$, and the inductance of the 100 cm$^2$ pick-up loop $L_p=1.4 \mu\text{H}$, we find $d\Phi_p$ is $-1 \text{ m}\Phi_0$/Hz$^{1/2}$. This makes it an extremely sensitive device.

We anticipate a factor of 2.8 improvement in $d\Phi_p$ during the real experiment at -0.5 K if SQUID noise is proportional to $T^{1/2}$, as one expects for white noise. There are, however, concerns about the performance of these SQUIDs when they are coupled to a large pick-up coil with a high inductance.

B. Other Noise Sources

As shown above, sources of magnetic noise from the experiment, $d\Phi_c$, are limited to $-4.0 \text{ m}\Phi_0$/Hz$^{1/2}$. Sources of concern are vibrations of the SQUID pick-up loop in the $B$ field, the magnetic fields due to leakage current from the high voltage plates, 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 allow the pick-up loop wires inside of the can to be connected to the SQUIDs and allow liquid helium in. A secondary lid is mounted 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. A lead piece 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 pcSQUID™ electronics. Two different types of pick-up coils were investigated. Both had \(-100\, \text{cm}^2\) 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 a magnetically shielded can. The dewar was five feet tall (with the test cell at the bottom) and the shielded can was four feet deep such that the top of the dewar was not shielded.

The first pick-up coil was made of copper strip with lead solder flowed over the copper traces. The noise power spectrum at \(10\, \text{Hz}\) was \(-5 \times 10^{-3} \, \text{pT/Hz}^{1/2}\) or \(2.5 \, \text{m}\Phi_0/\text{Hz}^{1/2}\), 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 constructed entirely of lead wire provided much better performance. The noise at \(10\, \text{Hz}\) was \(-3 \times 10^{-4} \, \text{pT/Hz}^{1/2}\) or \(15 \, \text{m}\Phi_0/\text{Hz}^{1/2}\), as shown in the curve labeled Pb in Fig. 3a. From the full noise power spectrum (Fig. 3b) one can see that with the improved noise performance the SQUID does not show white noise behavior until frequencies above \(100\, \text{Hz}\). At frequencies above \(100\, \text{Hz}\) the levels are \(-2 \times 10^{-4} \, \text{pT/Hz}^{1/2}\) or \(10 \, \text{m}\Phi_0/\text{Hz}^{1/2}\), not the expected \(-5 \, \text{m}\Phi_0/\text{Hz}^{1/2}\).

At frequencies below \(100\, \text{Hz}\) we observe noise from vibrations and external sources in the laboratory. For example, a peak due to vibration of the dewar can be seen \(-30\, \text{Hz}\) in the Pb-wire noise spectrum shown in Fig. 3a. These noise levels correspond to magnetic fields on the order of \(10^{-16}\). This implies that extreme care will have to be taken to further shield penetrations into the lead can and the entire system.

The modulation technique of the 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.

IV. TWO-SQUID READOUT TECHNIQUE

To improve the noise performance of our system, we developed a two SQUID read-out technique in parallel with the above experiments. A two-SQUID readout technique, which uses one SQUID as a picovoltmeter, allows us to operate at the optimally quiet working point of the SQUID. Eventually the picovoltmeter will be coupled to the large pick-up coil and placed in the test cell. For the experiments described in this section the system was developed in a smaller lead can with a niobium wire pick-up coil of roughly equivalent inductance (\(-0.9\, \text{yH}\)). Fig. 4 shows the picovoltmeter probe described here.

Figure 5 is a schematic of the picovoltmeter system. The second SQUID is operated in the conventional modulation technique, with Conductus pcSQUID™ electronics, and reads out voltage changes across the first. The first SQUID is a Conductus 1020 connected in parallel with a 5.9 \, \Omega resistor. The second SQUID is a non-commercial device optimized for this application. One can also think of the picovoltmeter as a very low-noise amplifier with a gain proportional to \(R_a/R_0\) or \(10^5\) (see Fig. 5).

We measured a noise power spectrum with a white noise level of \(3 \, \text{m}\Phi_0/\text{Hz}^{1/2}\) down to frequencies \(-1\, \text{Hz}\). This is better than a factor of 3 improvement in the white noise level we
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.

were able to achieve with the conventional magnetometer in the lead test can. This white noise level was achieved at lower frequencies due to the better shielding of the probe and the smaller area of the pick-up coil. However, we believe that with better shielding in the lead test can and the picovoltmeter, we can reach this white noise level at 10 Hz with the large area pick-up coil.

V. FUTURE DIRECTIONS

A. Studies of Temperature Effects

The proposed EDM experiment will be conducted in a superfluid 4He bath at -0.5 K. This should lead to an improvement in the noise by a factor of \((4.2/0.5)^{1/2}\) or 2.8. Previous studies of SQUID noise as a function of temperature report that white noise scales as \(T^{\alpha}\) [4], but with 1/f noise the behavior with temperature can be very unpredictable [5]. Because of the importance of achieving the predicted white noise behavior, we will test the picovoltmeter at temperatures below 1 K where the effects of temperature on SQUID noise can be studied.

B. Tests in the Lead Can

After achieving the required temperature behavior of the SQUID noise, we will integrate the picovoltmeter into the lead test can. Shielding of penetrations into the lead can will be improved, as will shielding during cooling of the lead can through the superconducting transition.

These tests have serious implications for the EDM experiment, where many penetrations into the superconducting can are required. Knowledge of the required shielding of penetrations will be crucial for final experimental design, as will knowing what shielding is required during cooling through the superconducting transition.

Once the SQUID system is in the lead test can we can investigate noise sources such as leakage current. It may also

be possible to use the lead test can to study how to produce the required uniform \(B\) field. Two ideas being considered 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. The time was used to investigate the scintillation of the neutron-\(^3\)He reaction and our ability to collect that light. More beam time is scheduled for late 1998, which will use a neutron beam to investigate the distribution of \(^3\)He in a \(^4\)He 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 EDM experiment is expected to be on-line by 2003.

VI. CONCLUSION

We built a lead can to simulate features of the neutron EDM experiment. Flux resolution, \(d\Phi_{Qx}\), at 4.2 K was \(-15\,\mu\Phi_0/\sqrt{\text{Hz}}\) at 10 Hz using 100 cm\(^2\) lead pick-up coils. The experimental requirement is \(5\,\mu\Phi_0/\sqrt{\text{Hz}}\). A two-SQUID readout technique using a similar inductance pick-up coil of smaller area gave \(d\Phi_{Qx}\approx-3\,\mu\Phi_0/\sqrt{\text{Hz}}\) at -1 Hz. Integration of the two-SQUID technique with the large pick-up coils and tests of flux resolution as a function of temperature remain to be done. Based on this work we are very optimistic SQUIDs can be a vital part of this experiment.

REFERENCES