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Tests of a SQUID-based ^{3}He Co-magnetometer Readout for a Neutron EDM Experiment

Young Jin Kim and Steven M. Clayton

***Abstract*—In a new experimental search for an electric dipole moment of the neutron, polarized ^{3}He will occupy the same volume as the neutrons under study to serve as co-magnetometer, enabling precise corrections for ambient magnetic field drifts that would otherwise severely limit the reach of the experiment. One of the two methods that will be built into the apparatus is to directly detect the ^{3}He magnetization signal using SQUID-based gradiometers. In a previous publication (*IEEE Trans. Appl. Supercond.*, 23 (2013), 2500104), we proposed a candidate design for a SQUID system consistent with experimental requirements and the planned nEDM apparatus. Because the ^{3}He precession signal is at approximately 100 Hz, signal contamination from low frequency magnetic noise could adversely affect the co-magnetometer readout precision; the addition of reference magnetometer channels to the SQUID system could mitigate this risk. In this paper, we present noise studies of the candidate SQUID system in a test apparatus and demonstrate effective ambient magnetic field noise cancellation with the implementation of reference channels. In addition, we report a demonstration of low-noise SQUID operation while a nearby photomultiplier tube and its high voltage power supply are operating.**

***Index Terms*—EDM, magnetic-resonance, ^{3}He co-magnetometer, SQUID, magnetic field noise, reference channel**

I. Introduction

An experiment to measure a permanent electric dipole moment (EDM) of the neutron could provide one of the most important low energy tests of the discrete symmetries beyond the Standard Model of particle physics [1]. Several world-wide efforts are underway to improve upon the present experimental neutron EDM limit of $|d_n| < 2.9 \times 10^{-26} e \cdot \mathrm{cm}$ (90% C.L.) [2]. The measurement principle is essentially nuclear magnetic resonance, in which a change in the precession frequency of the neutrons when a strong electric field is applied parallel versus anti-parallel to the magnetic holding field would indicate a non-zero neutron EDM.

One of the efforts [3], based on the concept presented in Ref. [4] and with the goal of two orders of magnitude improved sensitivity over the present limit, will employ a polarized ^{3}He magnetometer occupying the same volume as the (ultracold) neutrons under study, all in a cryogenic environment filled with superfluid ^{4}He at ≈400 mK. The ^{3}He co-magnetometer, which has negligible EDM, will be used to correct for magnetic field changes between measurement cycles that could otherwise mimic a neutron EDM. The ^{3}He also serves as neutron spin analyzer due to the highly spin-dependent cross section of neutron capture on ^{3}He, a process which, in the ambient ^{4}He, yields EUV scintillation light that will be down-converted to visible and subsequently detected by photomultiplier tubes (PMTs). Two methods to extract a neutron EDM measurement from this system will be built into the apparatus. One is based on the $n+{}^3$He capture scintillation signal of suitably "spin-dressed" neutrons and ^{3}He — in which the effective gyromagnetic ratios of the particles are matched by applying a relatively strong, non-resonant oscillating magnetic field — combined with a feedback/modulation scheme; this is discussed at length in Ref. [4]. The other method is to directly detect the few-femtotesla amplitude, freely-precessing ^{3}He magnetization signal with superconducting quantum interference device (SQUID)-based gradiometers, with the scintillation signal serving as the neutron spin analyzer as in the dressed-spin method.

In a previous publication [5], we discussed experimental requirements for a SQUID gradiometer system appropriate for the proposed nEDM apparatus and suggested a SQUID and pickup loop configuration consistent with these requirements. The candidate pickup loop is a thin-film first order planar gradiometer, consisting of two 3 cm×6 cm loops with center-to-center spacing of 9 cm, connected by 3.5-meter long, superconducting twisted-pair leads to the input loop of a high inductance SQUID (Star Cryoelectronics SQ2600). At the planned static magnetic field of 3 μT, the ^{3}He precession frequency is approximately 100 Hz, where signal contamination due to mechanical vibrations of the pickup loops or low-frequency external sources could adversely affect the measurement precision. In this paper, we present experimental tests of a mock-up of the proposed SQUID system, to which we have added reference channels [6]–[8] to enable suppression of low-frequency signal contamination. We also report a compatibility test with SQUIDs of a PMT and associated high voltage power supply, potential sources of RF interference that could adversely affect the SQUID measurements.

The advantage of reference channels can be seen as follows. The output signal of a first order gradiometer, B_{g}, with baseline b and imbalance level α can be presented as

$$B_{\mathrm{g}} = B_{\mathrm{signal}} + \alpha B_{\mathrm{field}} + b G_{\mathrm{gradient}} \quad (1)$$

in a direction to which the gradiometer is sensitive (we neglect imbalance of the gradiometer in other directions for simplicity). Here, B_{signal} is a signal of interest, B_{field} is an ambient field noise, G_{gradient} is an ambient gradient field

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noise. The gradiometer's sensitivity to the field noise can be effectively counterbalanced by subtracting the output of an additional reference magnetometer channel, B_{refm}, from the gradiometer

$$a_1 B_{\text{refm}} \approx \alpha B_{\text{field}}, \tag{2}$$

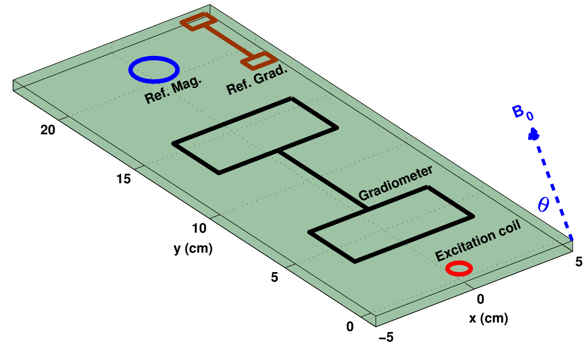
where a_1 is a scaling factor for most effective field noise cancellation, and the success of the noise cancellation depends on the degree of correlation between the reference and signal channels [7]. An additional reference gradiometer could be added to cancel gradient field noise (third term in Eq. 1).

As an example, a possibly significant source of field noise in the nEDM SQUID system is due to mechanical vibration of the pickups in the $B_0 = 3\ \mu$T magnetic field. An imperfectly-balanced gradiometer in a perfectly uniform B_0 field picks up magnetic flux $B_0 A_g \alpha \sin\theta$ if the pickup tilts by angle θ with respect to B_0 as shown in Fig. 1(a), where A_g is the area of the half-gradiometer loop. Similarly, the flux through the reference magnetometer pickup of area A_m, attached to the same rigid platform as the gradiometer pickup, is $B_0 A_m \sin\theta$. Then the vibration-induced signals in the gradiometer can be removed by subtracting the reference magnetometer signal scaled by a factor of $\alpha A_g/A_m$. The same argument holds (with the same scaling) to subtract a common-mode magnetic field noise fluctuation.

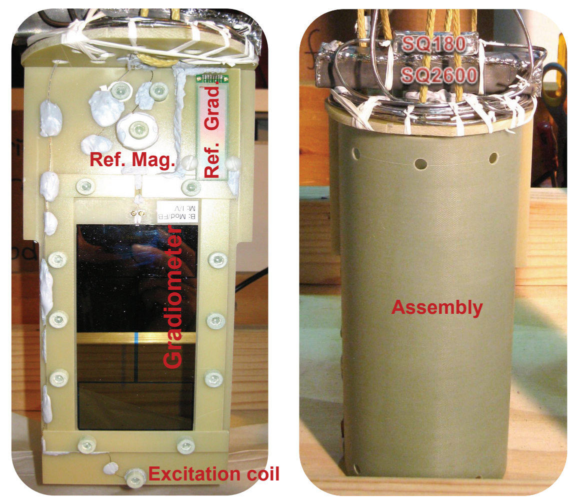
II. Tests with the Proposed SQUID Configuration

The overall diagram of the pickup loops assembly including reference channels is shown in Fig. 1(a). The signal channel's pickup loop, a first order planar gradiometer, is rigidly attached to a plate, along with a reference magnetometer pickup loop, which is a single-turn circular niobium wire coil of diameter 1.89 cm placed about 6 cm above the nearest part of the signal gradiometer. An integrated SQUID gradiometer, a first order planar gradiometer comprising two 0.7 cm×1.2 cm pickup loops with 4.0 cm baseline, is mounted next to the reference magnetometer pickup. To simulate a 100 Hz ^{3}He precession signal, a circular loop of normally-conducting wire is located on the opposite side of the signal channel's pickup loop as the reference pickups, at a distance of about 3 cm between the nearest part of the gradiometer and the source loop.

Photographs of the test setup are in Fig. 1(b), showing the thin-film planar signal gradiometer fabricated on a Si wafer. Here, the gradiometer is wire bonded to screw terminals for testing purposes, creating significant imbalance between the top and bottom halves of the pickup. The signal gradiometer is connected to a high-inductance SQUID sensor (Star Cryoelectronics SQ2600) through 3.5 m long, 3 mil diameter, twisted-pair niobium leads as shown in the right photograph in Fig. 1(b). The SQUID is housed in a niobium enclosure and further shielded with a lead box. The long leads are run in hand-wrapped and soldered lead-foil conduit of ∼2 mm diameter for reduction of noise pickup along the leads. In a previous test of the signal channel only, in which the entire assembly was covered by a lead can, we confirmed that the intrinsic noise in the SQUID with the signal gradiometer connected through the long leads was the same as with a shunted input. Reference channels are attached to the same



(a)



(b)

Fig. 1. (a) Diagram of the pickups assembly in the reference channels method. A reference magnetometer and gradiometer are located above the signal gradiometer. An excitation coil which simulates the ^{3}He precession signal at ∼100 Hz is mounted 3 cm below the nearest part of the signal gradiometer. (b) Photograph of test setup showing a signal gradiometer fabricated on a Si wafer, and reference channels. The signal gradiometer and the reference magnetometer are connected to SQUIDs, housed in lead enclosures for stable operation, while the reference gradiometer is an integrated SQUID gradiometer.

G10 fiberglass plate as the signal gradiometer to minimize their relative vibrational motion. The reference magnetometer was coupled to a SQUID (Star Cryoelectronics SQ180) shielded in a lead box. Because the reference gradiometer is an integrated SQUID gradiometer, this SQUID cannot be shielded in a lead housing.

The test setup was immersed in a low noise, fiberglass 10-liter dewar containing liquid helium and positioned in the center of a two-layer magnetically shielded room (MSR). To reduce radio frequency (RF) interference, the dewar was wrapped in gold-coated mylar (90 nm gold) and its top was entirely covered with copper-coated polyester taffeta fabric. The residual field at the dewar location was measured to be ∼2 nT. The electronics for SQUID operation and data acquisition were powered by deep-cycle batteries and initially located inside the MSR, before being moved to an external RF-shielded cabinet connected to the MSR via RF-shielded conduit; no degradation of the field noise spectrum in the signal gradiometer was

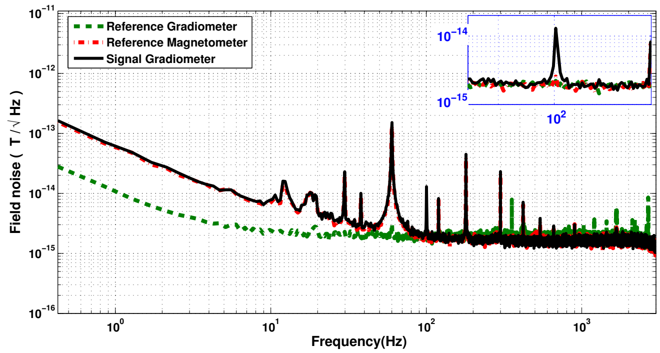


Fig. 2. Field noise spectra inside the MSR after 40 averages, with a 100 Hz signal applied using the excitation coil. The inset is an enlarged noise spectra around 100 Hz. Only the signal gradiometer significantly detected the 100 Hz signal. The magnetic field noise in the signal channel is 1.6 fT/$\sqrt{\text{Hz}}$ at 1 kHz.

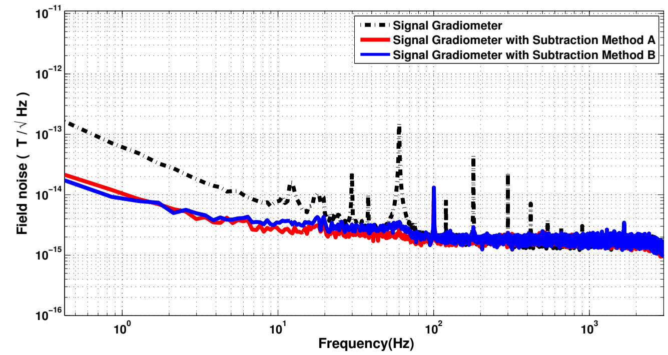


Fig. 3. Noise spectra of the signal gradiometer. The dashed line and solid lines represent spectra obtained without and with the subtraction method A and B. The 60 Hz and harmonics are nearly eliminated and lower frequency peaks are strongly suppressed, while the 100 Hz signal of interest remains.

observed after relocating the electronics to the external cabinet. All communication between the electronics and an external computer were by fiber optics to maintain the integrity of the Faraday shielding.

A. *Results without Applied Magnetic Field*

The field noise spectra in all the SQUID channels without an applied magnetic field are shown in Fig. 2. The data were acquired with a sampling rate of 21 kHz and a 3 kHz low-pass filter and 40-averaged. A 100 Hz signal simulating the ^{3}He precession signal was applied with the excitation coil indicated in Fig. 1. The inset in Fig. 2 is an enlarged noise spectra around 100 Hz showing that the reference channels do not significantly detect the 100 Hz signal.

Above about 100 Hz the field noise floor in the signal channel (referred to a half-gradiometer) and the reference channels is measured to be 1.6 fT/$\sqrt{\text{Hz}}$, comparable to the nEDM noise specification [3]. The peaks are consistent with 60 Hz facility power and harmonics. The increased noise floor below 100 Hz appears to be due to vibrations of the pickups with respect to the residual magnetic field inside the MSR and the limited shielding factor of the MSR to low-frequency external sources. The reference magnetometer and the signal gradiometer see nearly the same size signals in terms of B-field except the 100 Hz applied with the excitation coil. We speculate this could be attributable to the close proximity of superconducting shielding to the pickup loops, such that the B-field fluctuations at the reference magnetometer happen to be similar to the B-field difference between the two halves of the signal gradiometer.

Two subtraction methods, Method A and Method B, are employed to subtract the reference channels from the signal channel. In Method A, the reference magnetometer scaled by the ratio of the 60 Hz peak's amplitude in the signal gradiometer spectrum $S_{\text{g}}(60\text{Hz})$, to that in the reference magnetometer spectrum $S_{\text{refm}}(60\text{Hz})$, is subtracted from the signal gradiometer in the time domain, after which the reference gradiometer scaled in the same way is subtracted from the corrected signal $B_{\text{corr}}(t)$ in the time domain: $B_{\text{signal}}(t) \approx B_{\text{g}}(t) - \frac{S_{\text{g}}(60\text{Hz})}{S_{\text{refm}}(60\text{Hz})} B_{\text{refm}}(t) - \frac{S_{\text{corr}}(60\text{Hz})}{S_{\text{refg}}(60\text{Hz})} B_{\text{refg}}(t)$. In Method B, the time series of the reference magnetometer and reference gradiometer are added as $B_{\text{ref}}(t) = B_{\text{refm}}(t) + a \times B_{\text{refg}}(t)$, and then the balancing procedure in the frequency domain described in Ref. [7] is applied, in which a linear regression fit is performed in the frequency domain of the signal channel B_{g} with respect to the added reference channel B_{ref}. This method determines not a single scaling factor but a frequency dependent scaling vector. The coefficient a is chosen to have the smallest value of integration of the resulting spectrum. The noise spectrum of the reference gradiometer was flat above 70 Hz, and thus this channel cannot help cancel higher-frequency noise. Therefore, a 70 Hz butterworth low-pass filter was first applied to this channel before its use in either subtraction method, and the results were somewhat improved below this cutoff compared to ignoring the channel.

Fig. 3 shows the improved noise spectra of the signal gradiometer (solid lines) obtained by the two subtraction methods. Both methods result in the desired flat noise spectrum in which the 60 Hz and harmonics are sufficiently eliminated and low frequency structure such as the 30 Hz and 40 Hz peaks and $1/f$ noise are suppressed. Only the 100 Hz signal peak of interest remains clearly in the spectra, as we desire. The Methods A and B provide 35 dB and 33 dB attenuation, respectively, of the 60 Hz peak and 19 dB and 17 dB attenuation of the 30 Hz peak. SNR of the 100 Hz peak in the signal gradiometer, here defined as (amplitude of 100 Hz peak)/(standard deviation of 67 data points from 70.4 Hz to 98.56 Hz), is 61 without subtraction and maximally improved to 84 by Method B.

B. *Results with Applied Magnetic Field*

We further investigated the reference channels method by applying a constant 3 μT magnetic field parallel to the pickup loops as in the planned nEDM apparatus. Here, a 74-cm diameter Helmholtz coil with 15 turns of AWG 15 Litz copper wire (37.5 μT/A) on a G10 frame was positioned symmetrically around the signal gradiometer, as shown in Fig. 4. Current through the coil was supplied by a 12 V battery inside the MSR with a series resistor to set the current.

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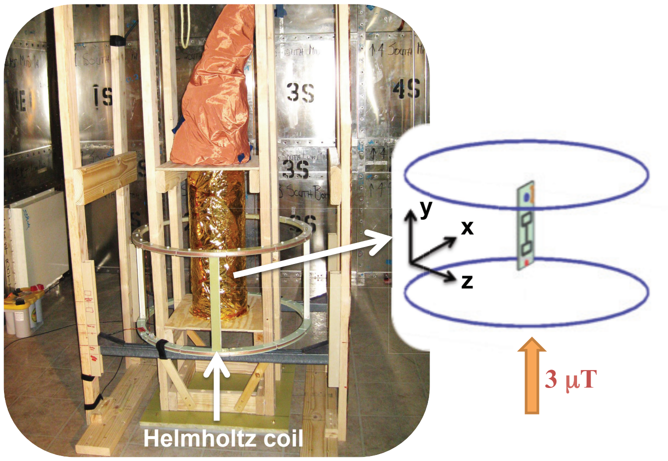

Fig. 4. The test setup with a Helmholtz coil to apply a constant 3 μT field.

Fig. 5(a) shows the field noise spectra in all the SQUID channels with the 3 μT magnetic field applied. We confirmed that the magnetic field application does not increase the field noise floor. Compared with Fig. 2, suppression of 60 Hz and harmonics was achieved by moving computers further away from the MSR. At low frequencies, the noise in the reference magnetometer increased by a factor of about 40 and that in the reference gradiometer by a factor of 10 when the coil was energized. Note that in the planned nEDM apparatus, the magnetic field will be very uniform from an optimized superconducting cosine-theta magnet coil [3].

To subtract undesired signals in the signal gradiometer, we tried the two subtraction methods described above. Both methods completely eliminate the 60 Hz and harmonics, however the degree of low frequency noise rejection is different. While the subtraction method A attenuates the 20 Hz peak by only 12 dB, the subtraction method B does by 35 dB. In the more complicated environment with the 3 μT field, the subtraction method B performs better. SNR of the 100 Hz peak is improved from 45 to 53 and 55 by method A and B, respectively. The improvement in SNR is due to moving the $1/f$ corner from slightly above to well below the 100 Hz signal frequency.

C. PMT and HV Power Supply Interference Test

Since PMTs are necessarily operating during the measurement cycle along with the SQUIDs, we performed a test of SQUID compatibility with PMT operation by observing the SQUID noise spectrum with and without an adjacent, operating PMT. We employed a custom, low-noise, battery-powered HV power supply [9] developed for the nEDM experiment to operate a Hamamatsu R7725 PMT. The PMT was at room temperature and positioned next to the plastic dewar housing SQUIDs in the same configuration as the tests described above. Light flashes were applied to the PMT photocathode by either an alpha-source/scintillator mounted directly on the PMT or a fast LED pulser [10] outside the MSR coupled to a plastic optical fiber. The anode signal from the PMT was terminated by a 50 Ω resistor via a $\sim$1 m coaxial cable. A range of PMT gains and light intensities were studied, with

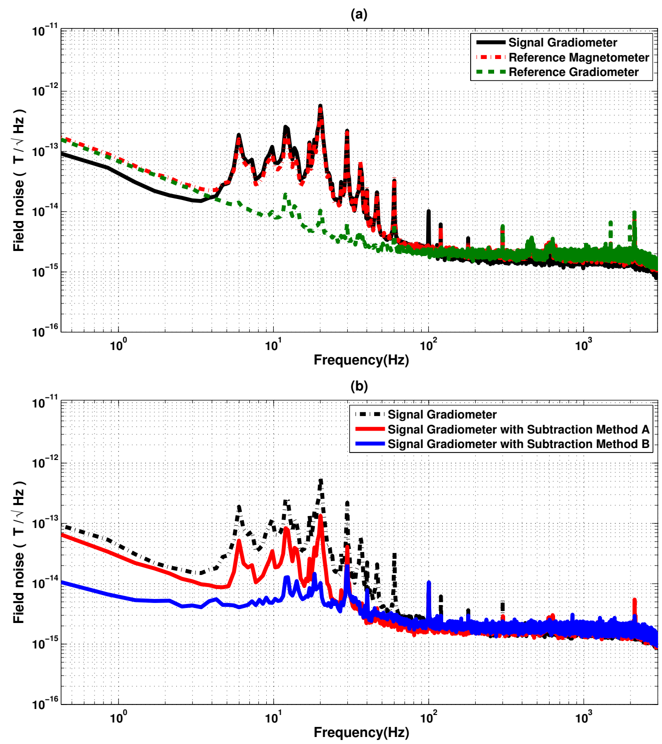

Fig. 5. (a) Field noise spectra in all the SQUID channels with the 3 μT field applied across the pickup loops. (b) Noise spectra of the signal gradiometer after noise cancellation with subtraction method A and B. The 60 Hz and harmonics are sufficiently eliminated in both methods without affecting the 100 Hz signal of interest, but method B better suppresses low frequencies.

maximum output pulse height of about 400 mV and typical pulse width $<$10 ns. Comparing the SQUID noise spectrum in the signal gradiometer with PMT/HV power supply off versus on and detecting light pulses, we did not see an increase of the SQUID noise floor or $1/f$ noise due to the operation of the PMT/HV power supply, except when the HV supply was operated below about 1300 V and became unstable. This is near the lower limit of its designed output capability and well below the nominal $\approx$1800 V appropriate for this PMT in our application. Different locations of the PMT gave the same null result, as did removing the gold-coated mylar from the dewar. We conclude that the PMT and HV power supply operation does not degrade SQUID performance.

III. Conclusion

We demonstrated that the proposed SQUID configuration for the ^{3}He co-magnetometer readout has sufficient signal-to-noise in a mock-up configuration, and that adding a reference magnetometer can be effective at suppressing unwanted signals. We also demonstrated that a candidate PMT and custom HV power supply are compatible with low-noise SQUID operation.

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