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Characterisation of superconducting capillaries for magnetic shielding of twisted-wire pairs in a neutron electric dipole moment experiment

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ABSTRACT

The cryoEDM neutron electric dipole moment experiment requires a SQUID magnetometry system with pick-up loops inside a magnetically shielded volume connected to SQUID sensors by long (up to 2 m) twisted-wire pairs (TWPs). These wires run outside the main shield, and therefore must run through superconducting capillaries to screen unwanted magnetic pick-up. We show that the average measured transverse magnetic pick-up of a set of lengths of TWPs is equivalent to a loop area of 5.0×10^{-6} m^2/m, or 14 twists per metre. From this we set the requirement that the magnetic shielding factor of the superconducting capillaries used in the cryoEDM system must be greater than 8.0×10^4. The shielding factor—the ratio of the signal picked-up by an unshielded TWP to that induced in a shielded TWP—was measured for a selection of superconducting capillaries made from solder wire. We conclude the transverse shielding factor of a uniform capillary is greater than 10^7. The measured pick-up was equal to, or less than that due to direct coupling to the SQUID sensor (measured without any TWP attached). We show that discontinuities in the capillaries substantially impair the magnetic shielding, yet if suitably repaired, this can be restored to the shielding factor of an unbroken capillary. We have constructed shielding assemblies for cryoEDM made from lengths of single core and triple core solder capillaries, joined by a shielded Pb cylinder, incorporating a heater to heat the wires above the superconducting transition as required.

1. Introduction

Measurements of the electric dipole moment (EDM) of the neutron are one of the most significant experimental tests of T (and hence CP) violation, one of the factors required to explain the matter-antimatter asymmetry of the Universe. The current experimental limit of $|d_n| < 2.9 \times 10^{-26}$e cm set by the nEDM experiment [1] has already constrained, or ruled out, many theories. The next generation project, cryoEDM, aims to improve this limit by two orders of magnitude [2–5].

Magnetometry is an essential component of any neutron EDM experiment as the finite magnetic dipole moment of the neutron means magnetic field fluctuations between measurements of the precession frequency could mimic the frequency shift due to an electric dipole moment. To correct for this it is necessary to track changes in the magnetic field in the neutron cell between measurements to a precision of ~0.1 pT. The nEDM experiment did this using a co-magnetometer which determined the magnetic field from the precession frequency of mercury nuclei in the neutron cell [6,7]. As this will not work at the 0.5 K temperature required for cryoEDM, we have developed a SQUID magnetometer for this purpose [8].

Fig. 1 shows an overview of the cryoEDM apparatus. The neutron cells are located in the centre of a horizontal magnetic shield, made from multiple mu-metal layers and a superconducting Pb cylinder. The location of the SQUID sensors (outside the shield) and pick-up loops (close to the neutron cells) is shown. These must be separated by ~2 m due to the high electric field in the neutron cell (which could induce a large voltage across the SQUID input, leading to permanent damage) and the distortion of the magnetic field by the SQUID sensors (due to the influence of the cryoperm shielding around the sensors, or the field produced by readout currents). The connection between the pick-up loops and the sensors is made by long NbTi twisted-wire pairs (TWPs). These wires must be magnetically shielded as they pass outside the main magnetic shield and would otherwise pick-up magnetic field fluctuations, which would mask the signal from the neutron cells [9,10]. Similar issues are faced by the SNS neutron EDM experiment magnetometer, although that is a different design, using SQUID gradiometers to measure the magnetic field from the precession frequency of ^{3}He nuclei [11].

This paper describes a superconducting magnetic shield developed for this purpose. This is made from lengths of Pb–Sn solder,

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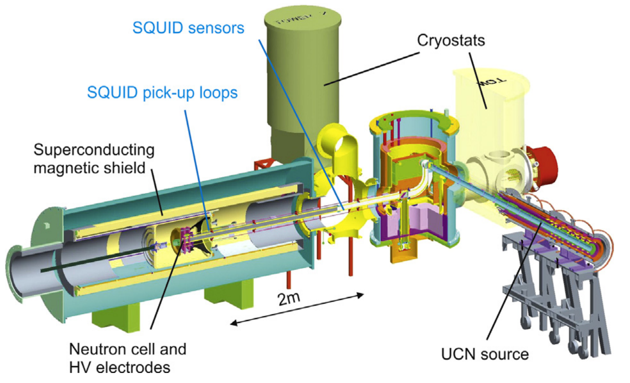

Fig. 1. An overview of the cryoEDM apparatus showing the main components and the location of the SQUID sensors and pick-up loops. The neutron beam from the ILL reactor enters from the right into the superthermal ultra-cold neutron (UCN) source. The neutrons are stored for the Larmor frequency measurement in neutron cells at the centre of the superconducting magnetic shield.

where the flux core has been removed creating a hollow capillary. The following sections describe the requirements for the experiment and the design of our system. Section 5 describes the production of the solder capillaries and Section 6 gives the details and results of experimental tests conducted to measure the pick-up of TWPs and the shielding factor of the capillaries. Section 7 shows frequency spectra recorded by shielded and unshielded TWPs and confirms that the capillaries can be used to reduce the noise from external magnetic field fluctuations to the intrinsic SQUID noise. Section 8 gives the results of tests of the heaters incorporated into the shielding assembly.

2. Twisted-wire pairs

Twisting two wires together is a well-established technique to minimise susceptibility to unwanted magnetic signals. The principle is that the magnetic flux through two adjacent loops created by the twisting will cancel, so there is no net magnetic pick-up. In this section we first calculate the signal induced in an ideal TWP in a uniform field, and a field with a constant gradient. As the measured pick-up is much larger than these values, we conclude that a real TWP deviates from a perfect twisting, and these imperfections are responsible for most of the pick-up.

2.1. Theoretical magnetic pick-up in uniform field

The current induced in a superconducting loop due to a change in the magnetic flux $\Delta\Phi$ is given by

$$\Delta i = \frac{\Delta\Phi}{L}$$

where L is the inductance of the circuit. In a SQUID magnetometer circuit

$$\Delta\Phi = \delta B_s A + \delta B_e \delta A$$

where δB_S is the magnetic field fluctuation at the neutron cell, which we wish to measure using a pick-up loop of area A. The additional loop area δA is formed by the readout wires between the SQUID input and the pick-up loop, which is exposed to magnetic fluctuations δB_e. In a well-designed system, we aim to make δA as small as possible.

In a simple model, a TWP is treated as a series of rectangular loops in a flat plane, oriented in alternating directions as shown in Fig. 2 [12]. Although a real TWP is not flat, this is a fair approximation of the area as seen from one direction. A perfect TWP exposed to a spatially uniform magnetic fluctuation δB_e will only give a signal if there are an odd number of loops. The signal in this case, on a calibrated magnetometer, is then

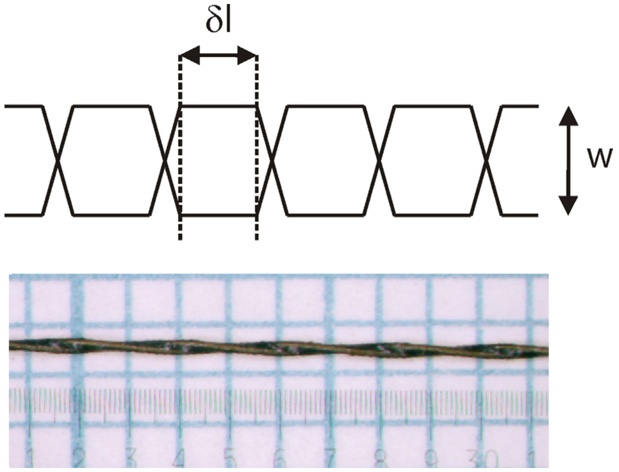

Fig. 2. A simple model of twisted-wire-pair geometry and a photograph of a TWP used for these tests (coated in Stycast after twisting). The average twist length was $\delta l = 2.7$ mm, and the wire diameter $w = 0.127$ mm.

$$\Delta S_e = \delta B_e \frac{\delta A}{A}$$

where δA is the area of a single twist. For wire of diameter $w = 0.127$ mm, and a twist length $\delta l = 2.7$ mm, we estimate a maximum loop area of $\delta A = w\delta l$. Thus for a 20 mm diameter pick-up loop (the smallest loop size used in the cryoEDM system), a magnetic fluctuation of $\delta B = 1$ μT along the TWP would give an error signal of 1090 pT.

2.2. Theoretical pick-up in field with finite gradient

A spatially uniform magnetic field fluctuation will give no net signal in a perfect TWP with an even number of twists. However if a magnetic signal has a finite gradient, then it will give a net pick-up as the flux through the loop formed by each twist will be slightly different from that through adjacent loops. This will be significant in the cryoEDM experiment where the TWPs run into the main magnetic shield, so the magnitude of field fluctuations will fall from their full external magnitude to close to zero along the length. For a magnetic field with a fixed gradient given by

$$B(x) = B_0 + \frac{dB}{dx}x$$

applied along a TWP with an even number of twists N, over length L, will give a net flux of

$$\begin{aligned}\Phi &= \sum_{i=1}^{N/2} B\left(\frac{2i+1}{N}L\right)\delta A - B\left(\frac{2i}{N}L\right)\delta A \\ &= \sum_{i=1}^{N/2}\left(\frac{dB}{dX}\right)\frac{L}{N}\delta A \\ &= \delta A\left(\frac{dB}{dX}\right)\frac{L}{2}\end{aligned}$$

We define a twist as a 180° rotation, exchanging the positions of the two wires. For a field gradient of 2 μT/m along 0.5 m, we estimate a maximum error signal due to this effect of magnitude 546 pT.

2.3. Magnetic pick-up of real twisted-wire pair

In this paper we will show that the measured pick-up in a twisted-wire pair exposed to a magnetic signal is greater than