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MAGNETIC FLUX DISTRIBUTION ON A SPHERICAL SUPERCONDUCTING SHELL

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We report measurements of flux distributions on superconducting spherical shells in an ambient magnetic field of 0.2 ± 0.1 μG. The aim of these experiments is to minimize the number of flux lines trapped in the superconducting shells, an important requirement for the Gravity Probe B gyroscopes.

1. INTRODUCTION

When placed in a field small compared to the critical field, a high quality superconductor will expel magnetic flux lines due to the Meissner effect. In contrast, a sample of less quality will trap some flux lines. In this work we report observations of flux trapping for sputtered niobium films in low fields. The samples used in these experiments are gyroscopes developed for the Gravity Probe B program[1], and the purpose is to find an effective way to reduce the flux trapped in their superconducting coating.

2. EXPERIMENTAL SETUP

The samples are niobium films sputtered on either fused quartz spheres or single crystal silicon spheres of 38 mm in diameter. The thickness of the films is either 1.3 μm or 2.5 μm. Film thickness is controlled to about one percent, while typical grain size is about 0.5 μm. Details of sample preparation and film characterization are published elsewhere[2].

All experiments described here are carried out in a test system which provides 4.2 K ambient temperature in a field of less than 0.3 μG. Samples consisting of the electrostatically suspended gyroscopes are placed in a vacuum can and inserted into the low field region. Helium gas is used for cooling the samples, while heating is performed by using an infrared laser beam. The thermal conductivity of the supporting structure is relatively low, allowing the sample to be heated significantly above the sample transition temperature of about 9.2 K without boiling off much liquid helium. Sample cooling rates are controlled by the pressure of the helium gas in the vacuum can. These pressures are typically between 0.1 and 1000 μtorr. The gyroscope can be spun up to 50 Hz with a helium gas jet at temperatures below the transition temperature of the sample.

Three SQUID magnetometers are used to characterize the motion of the gyroscope and the magnetic field trapped in the niobium film. Two of the magnetometers are connected to two sets of orthogonal Helmholtz pick-up loops. Data from these two magnetometers allow us to determine the following quantities[3]: 1) the gyroscope rotation axis in the frame defined by the pick-up loops; 2) the dipole component of the trapped field; 3) the London moment associated with the rotation of the sample; 4) the angle between the rotation axis and the magnetic dipole. The third magnetometer, connected either to a circular loop around the equator of the sample or a loop sensitive mainly to the quadrupole of the trapped field, provides additional information about the trapped field.

3. RESULTS

In a typical experiment, the sample is heated to a temperature significantly above the transition temperature by the laser beam. After the laser beam is turned off, helium gas is introduced into the vacuum can to cool the sample. We will refer to this procedure as a thermal cycle. The measurements take place after the sample is cooled back to the ambient temperature. For measurement convenience, the sample is typically spun to a few Hz by a helium gas jet.

When a thermal cycle takes place in an applied field significantly above the ambient field, the applied field is found to be trapped by the sample. With a uniform field of 100 μG, the trapped field contains a dipole component of 100 μG, while the other harmonic components, measured by the third

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magnetometer, are typically two orders of magnitude smaller. Similarly, when the applied field has a dominant quadrupole component, the trapped field contains a large quadrupole. These type of measurements have been carried out with applied fields between 10 and 1000 μG and with cooling rates from 0.1 to 10 K/hr. The results are insensitive to the details of the thermal cycle. When a thermal cycle is performed in the ambient field of the facility, the dipole component of the trapped field varies from 0.2 to 5 μG, depending on the details of the thermal cycle such as cooling and heating rate. For a given sample and a well defined thermal cycle, the measured dipole amplitudes are repeatable within a factor of two.

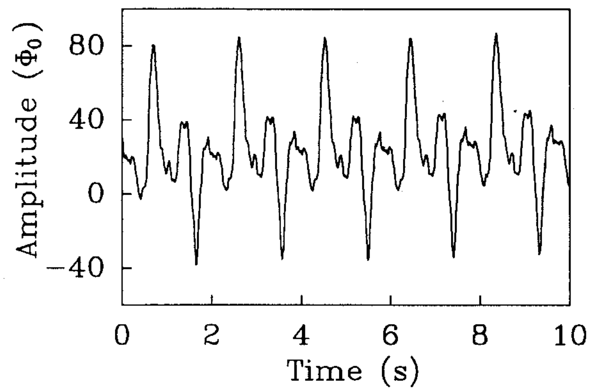

Figure 1. Difference between the number of flux lines trapped on the two hemispheres of the sample. The hemispheres are defined by the rotation of the sample at 0.5 Hz with respect to a fixed pick-up loop.

The data obtained from the circular loop which has a diameter only 1.6 mm larger than the sample diameter provides interesting details of the flux distribution on the sample. Since the gap between the pick-up loop and the sample surface is small, the amplitude of the signal is the difference of the number of flux lines between the two hemispheres of the sample surface, as defined by the plane of the pick-up loop. Since the sample is rotating at a constant rate of about 0.5 Hz, the rapid variation of the signal amplitude indicates that the flux lines on the surface are not uniformly distributed (see Fig. 1). The dipole component for this data is 0.5 μG. Because the rotation axis is not in the pick-up loop plane, the signal is not symmetrical.

4. DISCUSSION

Sputtered films contain a high density of defects, some of which will serve as pinning centers for trapped flux lines. Consequently, when the samples become superconducting the magnetic field lines, instead of being expelled by the Meissner effect, are more likely to be trapped by the pinning centers. The above scenario provides a plausible explanation for the results with an applied field significantly above the ambient field.

There are at least two possible explanations for the observation that the distribution of flux lines on the surface is not uniform and can be affected by the details of the thermal cycle. One explanation is that during the cooling process some areas of the film become superconducting earlier than other areas due to either non-uniform cooling or small differences in the transition temperature. The magnetic field generated by thermoelectric currents in the normal areas will then be trapped by the areas undergoing superconducting transitions. A second explanation depends on the supporting structure containing magnetic contaminants and/or thermoelectric currents. This would account for both the trapped flux asymmetry and the thermal cycling dependence. At this point, we are unable to determine which mechanism produces the non-uniform field observed in the experiments. By improving the sensitivity of the magnetometers we will be able to map out the location of individual flux lines on the superconducting shell in the near future. In this case it should be possible to correlate the distribution of flux lines on the surface with the thermal cycle procedure and gain better understanding of the trapping mechanisms.

In conclusion, we demonstrated that it is possible to reduce the field trapped in a relatively large superconducting device to below micro gauss levels. We believe that with a better understanding of the trapping mechanisms the trapped field can be reduced even further.

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