APPLICATIONS OF SUPERCONDUCTIVITY TO GRAVITATIONAL EXPERIMENTS IN SPACE

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ABSTRACT

We discuss the superconductivity aspects of two space-based experiments — Gravity Probe B (GP-B) and the Satellite Test of the Equivalence Principle (STEP). GP-B is an experimental test of General Relativity using gyroscopes, while STEP uses differential accelerometers to test the Equivalence Principle. The readout of the GP-B gyroscopes is based on the London moment effect and uses state-of-the-art dc SQUIDs. We present experimental proof that the London moment is the quantum mechanical ground state of a superconducting system and we analyze the stability of the flux trapped in the gyroscopes and the flux flushing techniques being developed. We discuss the use of superconducting shielding techniques to achieve dc magnetic fields smaller than 10^{-7} G and an ac magnetic shielding factor of 10^{13}. SQUIDs with performance requirements similar to those for GP-B are also used for the STEP readout. Shielding for the STEP science instrument is provided by superconducting shells, while the STEP test masses are suspended in superconducting magnetic bearings.

I. INTRODUCTION

Low temperature techniques have been widely used in high precision experiments due to their advantages in reducing thermal and mechanical disturbances, and the opportunity to utilize the low temperature phenomena of superconductivity and superfluidity. Gravitational experiments have reached the stage at which both low temperature technology and ultra low gravity space environments are needed to meet the requirements for measurement precision. In this paper we present some of the applications of superconductivity to two space based gravitational experiments — Gravity Probe B1) (GP-B) and the Satellite Test of the Equivalence Principle2) (STEP).

General Relativity predicts the geodetic and frame dragging effects to be 6.6 arcsec/yr and 0.042 arcsec/yr in a 650 km polar orbit3). The GP-B experiment will measure these effects with an accuracy of at least 0.3 marcsec/yr, by determining the precession of the local frame, given by gyroscopes, with respect to the fixed frame of the stars, given by a telescope pointed to HR5110. Figure 1 shows the GP-B experimental concept.

GP-B uses superconductivity for the implementation of the London moment gyroscope readout4). The London moment is aligned with the angular momentum of the gyroscopes, and is measured using ultra low noise dc SQUIDs. Two techniques of flux reduction in superconducting films insure a minimal level of trapped vortexes. Superconducting shielding is used to achieve both low static magnetic fields and high attenuation of variable magnetic fields. The following sections discuss the London moment readout, trapped flux reduction, and superconducting magnetic shielding.

STEP is designed to improve the measurement of the Equivalence Principle from the present accuracy of 10^{-12} to about 10^{-17}. This cryogenic experiment uses differential accelerometers (with test masses of different materials) placed in a drag free satellite. Figure 2 shows the STEP experimental concept. The position of the test masses is sensed with SQUID magnetometers with 10^{-2} Å precision, while magnetic shielding is provided by superconducting enclosures; both adaptations of GP-B developed techniques. Radial suspension for the test masses is provided by superconducting magnetic bearings.

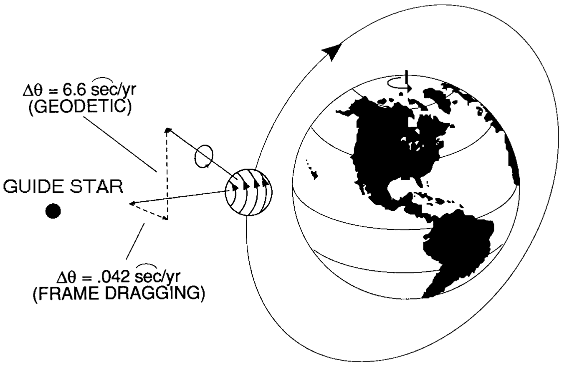

Figure 1. GP-B experimental concept

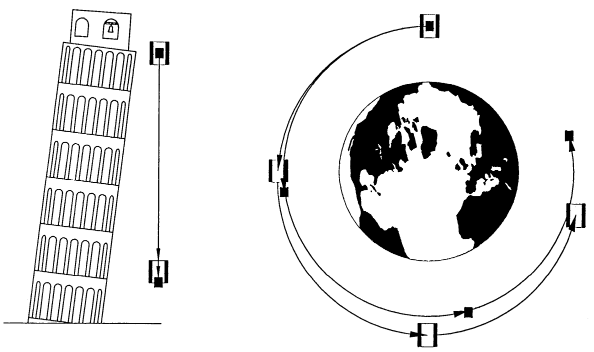

Figure 2. STEP experimental concept

II. THE LONDON MOMENT READOUT

The London moment is the effect by which a rotating superconductor produces throughout its volume a magnetic field $\boldsymbol{B}_L$ aligned with the instantaneous spin axis $\boldsymbol{\omega}_s$, which for a sphere of radius r results in a magnetic dipole moment $\boldsymbol{M}_L$ of magnitude:

$$\boldsymbol{M}_L = \frac{r^3 \boldsymbol{B}_L}{2} = -\frac{mc}{e} r^3 \boldsymbol{\omega}_s = -5.69 \times 10^{-8} r^3 \boldsymbol{\omega}_s \quad (\mathrm{G \cdot cm^3}) \tag{1}$$

where m and e are the mass and the charge of the electron, and c the speed of light.

The London moment can be understood in terms of a negatively charged frictionless fluid of electrons moving inside a lattice of positive ions fixed to the rotating body. The magnetic fields associated with the motion of the ion lattice produce electric fields that accelerate the electron fluid into moving almost exactly with the body. The London moment is due to the difference in the velocity of the surface layer of the electron fluid with respect to the ion lattice. This difference, a non-relativistic second order effect of a few parts in 10^7, produces a magnetic moment instantaneously aligned with the spin axis.

The angular momentum is the conserved quantity which represents the orientation of the local frame of reference, while the instantaneous spin axis cones around it. For a force free gyroscope with a small fractional difference in the principal moments of inertia $\Delta I/I$, the coning angle and frequency are given by $\Delta I/I$ and the spin speed ω_s respectively5). The GP-B gyroscopes have $\Delta I/I \leq 5 \times 10^{-6}$, causing the coning angle to be smaller than 1 arcsec, and to average to the level of 1 marcsec in less than 5 seconds. Thus the London magnetic dipole represents the angular momentum direction, independent of polhoding.

Figure 3 is a schematic of the London moment readout concept. Experiments conducted at GP-B6) have demonstrated that the London moment is the ground state of a superconducting rotating sphere. The same magnetic dipole is achieved independently of the thermal history of the process, that is cooling through the superconducting transition followed by spinning, or cooling after spinning. Note also that for films of above about 100 Å the London moment magnitude does not depend on the thickness.

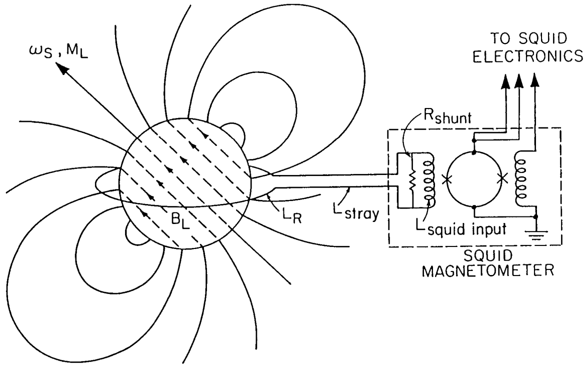

Figure 3. Schematic of the London moment readout sensing system.

III. TRAPPED FLUX REDUCTION

The Meissner effect predicts that a perfect superconductor will expel all magnetic flux when placed in a field small compared to the critical field. However, the 2.5 μm niobium film covering the 3.8 cm diameter quartz gyroscopes has enough defects to actually trap a density of flux lines roughly equivalent to low ambient fields in the range 10^{-3} G-10^{-7} G. The London moment read-out can be complicated by the polhoding induced motion of this trapped flux, therefore making it desirable to minimize the density of fluxons.

Two methods for trapped flux reduction are used at GP-B. The first approach is based on the controlled thermal cycling of the superconductor, thus minimizing the thermally induced currents which generate the trapped flux. Using this method we achieve a dipole moment trapped in the sphere corresponding to a uniform field of about 0.2 μG, or a total of about 50 trapped fluxons6). The second method makes use of the fact that in a spherical shell the number of right-handed and left-handed flux vortices is equal. A normal spot, produced by an infrared laser beam, is used to trap and sweep the flux lines until they close on themselves7). The motion of the spot is produced by the slow rotation and precession of the gyroscope. Adjustable experimental parameters are the infrared power absorbed in the superconducting film (~0.3 mW), the pressure of the helium exchange gas (6×10^{-3} Pa), and the spin speed of the gyroscope (~0.5 Hz), resulting in a normal spot of about 50 μm radius. Using this technique the dipole moment corresponding to a field of 1 mG has been reduced to about 6% of its original level. Figure 4 shows the dipole moment component normal to the pickup loop, as a function of time, before and after the laser annealing. Further experiments, aimed at extending this technique to use in ultra low magnetic fields, are currently underway in an ambient field of 10^{-7} G.

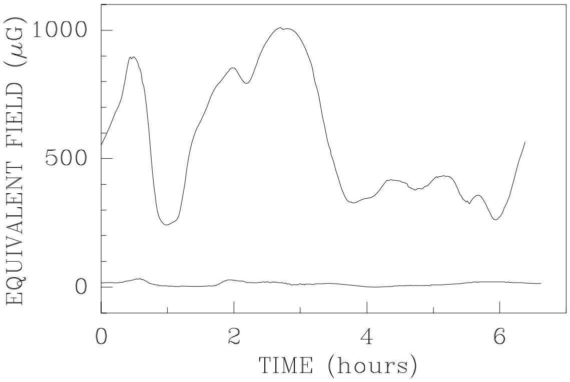

Figure 4. Evolution of trapped magnetic dipole moment before (upper trace) and after flux flushing (lower trace). Dipole magnitude expressed in units of equivalent uniform field in the sphere.

IV. MAGNETIC SHIELDING

The London moment based readout requires shielding from external ac magnetic fields by thirteen orders of magnitude, and a dc field of less than 10^{-7} G needed to insure low trapped flux in the gyroscopes. This level of shielding is achieved by using a system of superconducting magnetic shields, in conjunction with controlling the magnetic properties of the probe materials. A ferromagnetic shield provides a 10 mG magnetic field region within which the main field reduction is achieved by the expansions of superconducting lead foil cylinders. The foil cylinder, folded to minimize the cross-sectional area, is cooled through its superconducting transition temperature. Cooling rates are controlled in order to minimize thermal gradient induced currents. Once the lead cylinder is superconducting, it is mechanically unfolded to its maximum diameter. This operation reduces the magnetic flux in the cylinder by roughly the ratio of the folded to the expanded cross-sectional areas, a factor of about 20 in practice. Figure 5 represents schematically the expansion process. This process is repeated with additional lead cylinders being expanded one at a time inside the reduced field produced by the previous expansions. The lowest magnetic field values achieved are about 5×10^{-8} G; with further reduction prevented by thermoelectric effects in the lead foil8).

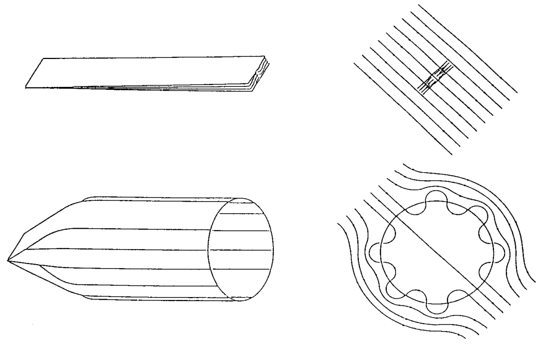

Figure 5. Lead cylinder expansion.

The ferromagnetic shield and lead foil superconducting cylinder provide an ac shielding factor of about 10^{9}, while a superconducting cylinder surrounding the gyroscope increases the shielding factor to 10^{12}. Finally, the superconducting gyroscope shields the readout loop from external fields by an additional factor of 10. The performance of the ac shielding scheme has been verified to the 2×10^{11} level, the limitation being the noise performance of the rf SQUID detectors used8). Measurements with improved resolution are currently being prepared.

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