

Measurements of the Thermal Emissivity of a Superconducting Niobium Film

Robert Brumley, Saps Buchman, John Mester

W. W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305-4085, USA

The radiative exchange of heat between a superconducting Nb film at 4.2 K and a Ti film at 4.2 - 11 K has been measured. A Nb-coated quartz sphere was used as a bolometer to measure total heat absorbed, from which an effective emissivity was derived. Under these conditions the effective emissivity of the Nb film is about 3%.

1. INTRODUCTION

The Gravity Probe B Relativity Mission is a program designed to measure Geodetic and Frame Dragging effects using cryogenic gyroscopes in Earth orbit. The rotor of the gyroscope consists of a quartz sphere coated with a 2.5- μm niobium film, and the wall of the housing containing the sphere is coated with titanium and held at 2 K. The sphere is electrostatically levitated and spun to 170 Hz. The precession of the spin axis is determined by a precise measurement of the London Moment generated by the spinning superconductor.[1]

High-energy protons encountered on orbit will put an average of ~ 1 nW of heat into the gyroscope.[2] Gas pressure within the housing will be less than 10^{-9} Pa, providing less than 0.25 nW of cooling for a rotor at 6 K and a housing at 2 K. Radiative exchange of heat between the housing and the sphere must be sufficient to keep the rotor superconducting.

This experiment uses the gyroscope rotor as a bolometer in a direct measurement of total heat transfer between Nb and Ti films. The Nb coating was allowed to react with air in a clean room environment for several months. The reaction of Nb with air has a significant impact on the superconducting properties of the surface[3] and may therefore affect the total emissivity of the film. These measurements are indicative of what an experimenter will find when no special effort has been made to eliminate niobium's oxide coating.

2. EFFECTIVE EMISSIVITY

It is customary to define a coefficient of emissivity ϵ to relate the heat radiated by a body to its temperature. Emissivity is a function of both temperature T and wavelength λ . In general the net rate of heat exchange

between two bodies with spectral distributions $E_i(\lambda, T)$ and areas A_i is

$$\frac{dQ}{dt} = \int [F_2 E(\lambda, T_2) \epsilon_2(\lambda, T_2) - F_1 E(\lambda, T_1) \epsilon_1(\lambda, T_1)] d\lambda$$

where F_i is a form factor taking into account the system's geometry.[4] The Gravity Probe B rotor and gyroscope housing can be well modeled as two concentric spheres. Neglecting the temperature dependence of ϵ , the net heat transfer from the inner sphere to the housing becomes:

$$\frac{dQ}{dt} = \epsilon_{\text{eff}} A_1 \sigma (T_2^4 - T_1^4)$$

which defines an effective emissivity

$$\epsilon_{\text{eff}} = \frac{\epsilon_1 \epsilon_2}{A_2 \epsilon_2 + A_1 \epsilon_1 - A_1 \epsilon_1 \epsilon_2}$$

3. EXPERIMENTAL APPARATUS

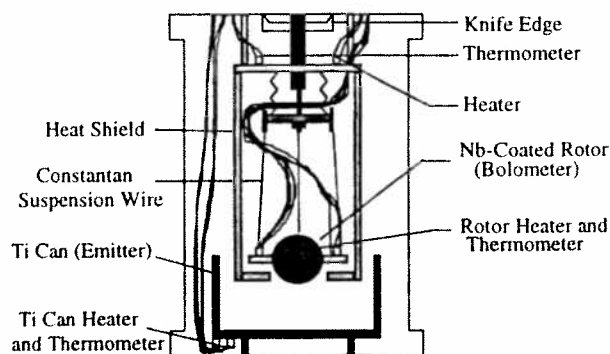


Figure 1. Experimental Apparatus

A 1.9-cm diameter fused quartz sphere with a 2.5 μm thick Nb coating was placed within a copper ring and suspended by three Constantan wires 50 μm in diameter. The temperature of this assembly was measured with a GRT and a heater was provided for calibration purposes. A heat shield completely surrounded the assembly, except for a hole in the bottom which allowed the sphere to view the titanium can. The heat shield was controlled to within 20 mK of the bolometer's temperature, which minimized heat transfer from the bolometer to other portions of the probe. The only non-radiative heat conduction path between the titanium can and the bolometer was through the outer vacuum can immersed in liquid Helium.

The pressure in the room-temperature portion of the probe was below the measuring threshold of the ionization gauge (less than 3.0×10^{-9} Pa) with the probe sealed and removed from the vacuum system. Further, the probe's cryogenic region could be isolated from the room-temperature region by using a mechanical feedthrough to press a copper knife edge against the top of the vacuum can. Thus the true pressure within the cryogenic region is thought to be several orders of magnitude lower than the gauge sensitivity. Heat conduction between the bolometer and the bottom can due to gas is calculated to be ~ 0.1 nW at 3.0×10^{-9} Pa.

3. CALIBRATION

The heat capacity of the bolometer was calibrated by observing its rise in temperature as a function of time in response to 10 μW of power input through a heater located on the bolometer. If the effective emissivity is less than 10%, then all other heat conduction paths to the bolometer have less than 0.2% the power of the calibration signal and can be safely neglected in a first-order analysis. Data indicates a total heat capacity for the bolometer of 0.02 J/K near 4 K. This is in good agreement with calculations given tabulated values for the heat capacity of fused quartz and copper.

Conduction to the bolometer through the wires was similarly calibrated by putting smaller amounts of heat into the bolometer and fitting the response to find the equilibrium temperature. The Ti can was kept at a temperature close to that of the bolometer to eliminate radiative coupling during this procedure. With all wires thermally grounded to the heat shield, conduction through the wires was less than 5 nW. The heat coupled into the bolometer through wires does not depend on the temperature of the Ti can and could be subtracted from the data.

4. EXPERIMENTAL RESULTS

To measure the effective emissivity, the temperature of the Ti can was alternated between 4.2 and 6.3 K. The bolometer, which was initially at ~ 4.4 K, was allowed to respond to the changing influx of heat. This allowed the separation of radiative coupling from conduction through wires. Figure 2 shows data from a typical run in which residual DC heating effects have been subtracted out. The data indicates approximately 5 nW of heat coupled into the bolometer, corresponding to an effective emissivity of $3 \pm 0.5\%$.

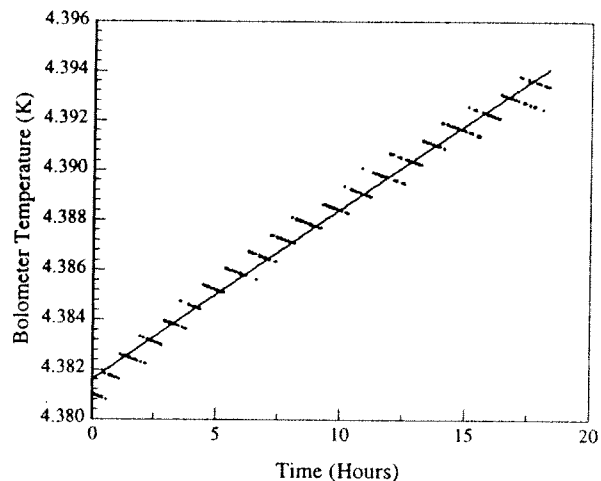


Figure 2. Bolometer Response to Radiative Heating

Currently, work is underway to extend these measurements with a more sensitive apparatus. This experiment will also seek to measure radiative heat exchange where the distance between the two interacting surfaces is small compared to the characteristic wavelength of the interaction.

5. REFERENCES

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