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The Stanford Relativity Gyroscope Experiment (D): Ultrahigh Vacuum Techniques for the Experiment

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1. INTRODUCTION

The gyro relativity experiment described in the preceding papers of this chapter makes use of a rotor spinning in a vacuum at a pressure of 10^{-10} torr or less to measure the very small precessions predicted by Einstein's general theory of relativity. The method to spin up the rotor, which uses a helium gas jet [1,2], leads to adsorption of helium on the gyroscope rotor and housing surfaces. This adsorbed helium yields a pressure above the required 10^{-10} torr during part of the gyro relativity flight experiment. This excessive helium gas pressure may lead to spurious gyro torques [3]. To keep the resulting spurious precession due to helium pressure below an acceptable level (about 0.3 m arc-sec) for most of the flight experiment duration, it is important that the time required for the helium pressure to reach 10^{-10} torr be short compared to the flight duration. It is possible to calculate this time if one has a knowledge of the adsorption properties of helium films for materials internal to the vacuum system in which the

gyroscopes are placed, along with knowledge of the temperature of these materials and the pumping speed for helium.

In this article, the description of an apparatus for measuring the adsorption properties of helium films on a substrate and the initial experimental results for a copper substrate are presented. Also, a low temperature bakeout procedure, which has been developed to quickly achieve the required pressure in the gyroscope housing while still maintaining the other required conditions of the experiment, is described; and the results of a bakeout cycle which approximately simulates this procedure are presented. The apparatus, which has been developed, can be extended to investigate other materials, such as fused quartz, which are to be used in the construction of the gyro relativity experiment.

2.   EXPERIMENTAL METHODS

The principal purpose of this work is to obtain helium pressure data for substrates of interest as a function of temperature and amount of adsorbed helium. For this reason the apparatus was designed to observe the properties of adsorbed helium films by measurement of the helium pressure in the volume rather than by measurement of the adsorption film specific heat. Although the direct measurements are of the pressure in the volume adjacent to the film, data from measurements can be used to infer some film properties since the chemical potential of the gas and the film are equal under the conditions of this experiment.

A schematic of the apparatus used in this work is shown in figure 1. The principal parts of the apparatus are the copper substrate; a helium supply coupled to the vacuum system by a variable leak; pressure measuring equipment including an ion gauge and a quadrupole mass analyzer; components for measurement and control of the substrate temperature; ion and turbo pumps; various vacuum lines and valves to connect the copper substrate to the pressure measuring equipment, helium supply and pumps; and a helium dewar.

The vacuum system is constructed using ultrahigh vacuum (UHV) techniques. The turbo pump is used for roughing the vacuum system and for pumping when the vacuum system is at higher pressures or at moderate partial pressures of helium. The ion pump, which is of the triode type and is capable of pumping helium, is used when the vacuum system is at lower pressures. Prior to an experimental run, the room temperature portion of the vacuum system is baked out at about 200° C and the low temperature portion at about 100° C. After bakeout the total pressure measured by the ion gauge is about 10^{-9} torr; however, after the low temperature portion is cooled down to 4.2 K, the total pressure drops to about 10^{-10} torr.
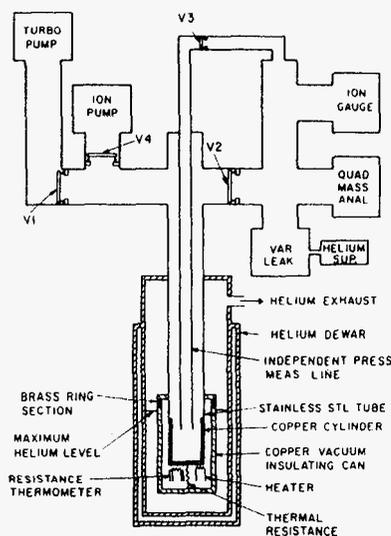
FIGURE 1. Schematic of apparatus to measure adsorption properties of helium.

The copper substrate is largely made of OFHC copper which, after machining and cleaning, was fired in dry hydrogen at about 1000° C to braze it to the stainless steel pumping line. The total surface area of the copper substrate is 210 cm². Nine percent of the copper substrate area is chromium-copper alloy (1% Cr).

Metered quantities of helium are inserted into the vacuum system by utilizing a constant volume of 45.9 cm³, a capacitance pressure gauge to measure the helium pressure in the constant volume, and a variable leak to allow a portion of the helium to be transferred to the vacuum system. The constant volume and variable leak are baked out to remove contamination. Pure helium gas is then inserted into the constant volume after it has passed through a liquid helium cryotrap to remove impurities. The pressure in the constant volume is typically brought to 1 torr. The error in the amount of helium inserted into the vacuum system is about 1% plus 2×10^{15} atoms.

The helium pressure in the vacuum system is measured by two means: an ion gauge and a quadrupole mass analyzer. The ion gauge is calibrated by inserting a measured amount of helium into the vacuum system and noting the ion gauge reading. The helium pressure for this reading is determined from the ratio of the vacuum system volume to the constant volume and from the pressure change in the constant volume. This calibration is accurate to a few percent, and it has proved to be stable. At lower pressures where the total pressure is not dominated by helium, a quadrupole mass analyzer is used to measure the partial pressure of helium. The quadrupole

mass analyzer is calibrated at intermediate pressures by transferring the ion gauge calibration to the quadrupole mass analyzer. This pressure measuring instrumentation allows the pressure to be observed in the range of 10^{-12} to 10^{-4} torr. The pressures, which are measured at room temperature usually through the 12 mm diameter line with valves V_2 closed and V_3 open, are corrected for the thermomolecular effect.

As shown in figure 1, the copper substrate is located in a vacuum-insulating can so the substrate can be maintained at a temperature different from that of the liquid helium. The temperature of the substrate is measured with a calibrated germanium resistance thermometer which has an error of a few millikelvin for temperatures in the range of 4 to 10 K. The temperature, which is determined by the liquid helium temperature, the thermal resistance and the power applied to the heater, is regulated by a servo loop using the resistance thermometer as a sensing element and the heater as a control element.

The copper substrate forms a volume which is connected to room temperature by a 41 mm diameter stainless steel line for pumping, and by a smaller 12 mm diameter stainless steel line for pressure measurement. Helium adsorption on the surface of these stainless steel lines can produce a large uncertainty in the helium surface coverage for the copper substrate. To reduce this uncertainty, the two stainless steel lines are kept at a higher temperature than the copper substrate. The larger stainless steel line is kept at a higher temperature with a combination of the brass ring section (see figure 1), heaters and insulation; its temperature is monitored with resistance thermometers. For this system to function correctly, it is necessarry that the maximum helium level be kept below the brass ring section. The smaller stainless steel tube is warmer since it is located in the vacuum system and is connected only at the room temperature end.

3.   ADSORPTION DATA FOR COPPER

The measurements shown in figure 2 were made as follows. Both valves V_1 and V_4 were closed, which left the vacuum system without pumping. First, the amount of helium corresponding to curve A in figure 2 was inserted into the probe vacuum system (0.327 atoms/nm^2). The copper substrate was then raised in temperature to the highest temperature shown for the curve, 9.5 K for curve A. At this temperature the pressure and related adsorption coverage came to equilibrium in a few seconds. Measurements at lower temperature were then made by stepping the temperature downward through the rest of the points on the curve. The next curve to the right was then made by inserting an additional known amount of helium and then repeating the above measurement process.

The curves shown in figure 2 have a range of coverage from about 0.03 to 1.5 of a monolayer. Some care needs to be exercised in using the pressure range shown in the figure. At the highest pressures, a large fraction of the helium gas is found in the volume of the vacuum system. For each curve, the pressure at which 10% of the helium is found in the volume has been estimated. These estimates are indicated by the dashed curve in the figure. Above and to the left of this dashed line more than 10% of the helium is in the vacuum system volume. At the lowest pressures shown in the figure, there is an experimental difficulty. The pressure is beginning to approach a residual value, as seen by the curvature, rather than continuing an exponential decrease with $1/T$. This is thought, but not proved, to be due to the way that gas is inserted into the vacuum system. As the apparatus is currently used, the helium gas is inserted down the independent pressure measuring line. Although the helium gas is rather pure, there may be contamination which condenses on the lower and cold end of this line. This contamination may provide sites on which the helium can be adsorbed. At higher pressures helium is adsorbed at these sites, and at lower pressures the desorption of helium looks like a virtual leak in the pressure measuring line. Evidence indicates that this explanation may be correct since the residual pressure does slowly decrease with time.
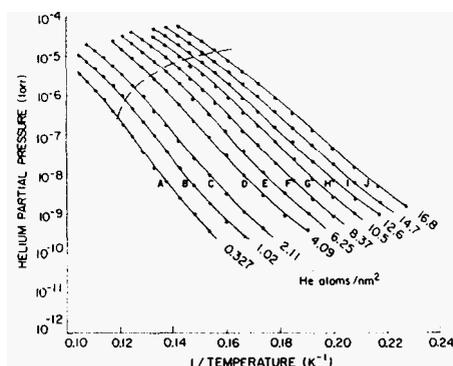
FIGURE 2. Helium pressure as a function of inverse temperature and surface coverage for a copper substrate.

The data shown in figure 2 are used to determine the parameters of an appropriate expression which characterizes the adsorption properties. This expression can be used together with known pumping and temperature conditions to calculate the pressure in a copper structure as a function of time. The following equation, which assumes the ideal condition that the binding energy for helium, ϵ_0, is uniform over the substrate, is the starting

point for such an expression:

$$P = (2\pi m/h^2)^{3/2}(kT)^{5/2}[x/(1-x)] \exp(-\epsilon_0/kT) \quad , \tag{1}$$

where the factor in brackets is the Langmuir isotherm factor which is dependent on x, the fraction of monolayer coverage [4]. Since the binding energy is not expected to be uniform over the copper substrate and the coverage exceeds one monolayer, equation (1) is modified to the following equation by allowing the Langmuir isotherm factor and ϵ_0 to become arbitrary functions of x:

$$P = (2\pi m/h^2)^{3/2}(kT)^{5/2}a(x) \exp(-\epsilon(x)/kT) \quad . \tag{2}$$

Equation (2) is fit to the set of data below the dashed curve in figure 2. Before fitting, the residual pressures are removed from the data. Figure 3 is a plot of the resulting $a(x)$ and $\epsilon(x)/k$ as a function of surface coverage.
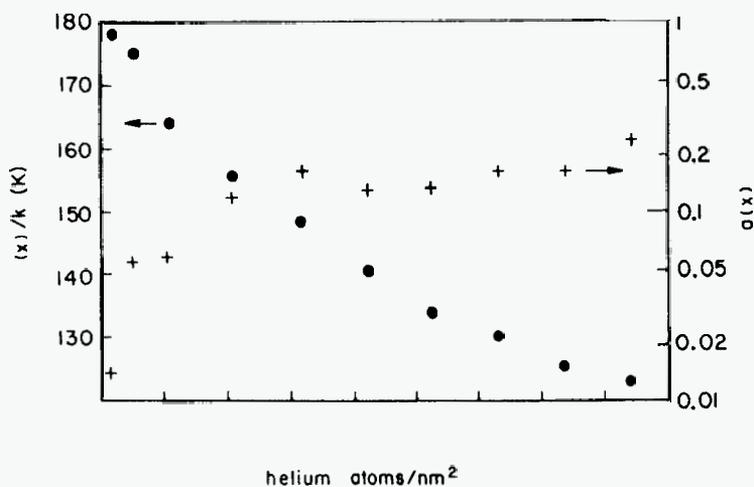

FIGURE 3. $\epsilon(x)/k$ (represented by •) and $a(x)$ (represented by +) as a function of surface coverage for a copper substrate.

As shown in the figure, $\epsilon(x)/k$ varies from 178 K at low coverage to 123 K at high coverage (x about 1.5). This dependence on coverage is usual for inhomogeneous substrates since the binding energy associated with defects on the substrate is typically larger than that for the rest of the substrate [5]. Further evidences of inhomogeneity of the substrate are the absence of any marked behavior in the data at the expected monolayer completion (about 11 atoms/nm^2) and the large departure of $a(x)$ from the Langmuir isotherm factor.
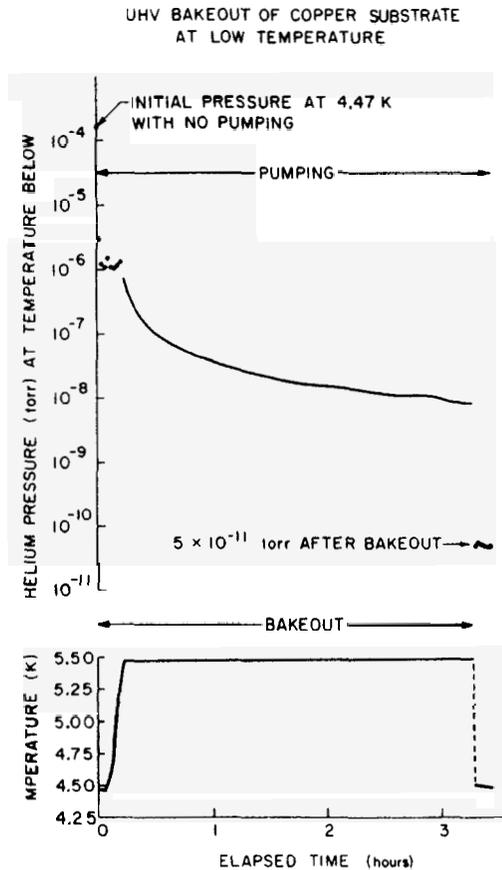
4. LOW TEMPERATURE BAKEOUT

A low temperature bakeout has been developed which should quickly bring the gyroscope vacuum to 10^{-10} torr. A low temperature bakeout can be illustrated using the data shown in figure 2. For example, if a (copper) gyroscope is spun up and subsequently pumped while at 4.7 K, it will eventually reach a pressure of 10^{-8} torr (as illustrated on curve J of the figure). If, when it reaches this pressure, the temperature is increased to 6 K, the pressure will increase to about 2×10^{-6} torr allowing the helium to be pumped 200 times faster. When the pressure again reaches 10^{-8} torr, the coverage will be that corresponding to curve D of the figure. Upon cooling the gyroscope back to 4.7 K, the pressure will drop to about 10^{-11} torr (requires extrapolation of curve D). After cooling, the rotor portion of the gyroscope will not quickly cool back to lower temperature since the thermal conduction due to the very low pressure helium and to radiation is very small. A higher temperature for the rotor and the correspondingly larger flux of helium atoms leaving the rotor is acceptable, however, since on the average helium leaving the surface of the rotor does not significantly change the direction of the rotor angular momentum. The helium flux leaving the rotor is pumped by the cooler housing.

The apparatus developed to measure the adsorption properties of helium films was used to simulate low temperature bakeout. Figure 4 illustrates the results of such an experiment. This figure shows both the pressure and the copper substrate temperature as a function of time. Initially the vacuum system is isolated from any pumping, and then helium is inserted into the vacuum system until it reaches a pressure of 2×10^{-4} torr, while the copper substrate is at about 4.5 K. Valve V_1 is then opened to allow pumping by the turbo pump. The pressure drops in about 1 minute to a pressure of 1×10^{-6} torr. Then the temperature of the copper substrate is slowly increased to 5.5 K in about 10 minutes. The helium pressure remains nearly constant during this time because of the increasing temperature. During the next three hours the pressure slowly drops while the temperature is held constant, and at the end of this period the pressure is about 10^{-8} torr. After the three-hour period, the temperature of the substrate is again decreased to the initial 4.5 K and the pressure drops to 5×10^{-11} torr which meets the residual helium pressure requirement for the gyroscopes.

Acknowledgments

FIGURE 4. UHV bakeout of copper substrate with a helium film at low temperature.

References

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