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TRANSPORT MEASUREMENTS NEAR THE LAMBDA-POINT OF LIQUID HELIUM IN A REDUCED EFFECTIVE GRAVITY ENVIRONMENT ON THE GROUND

Ulf E. Israelsson and Melora Larson
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California

Abstract:

The study of properties of liquid helium very near the λ-point in the presence of a heat current has recently received increased experimental and theoretical attention. Traditional ground based experiments very near the k-point are limited by gravitationally induced pressure variations in the helium sample. In order to circumvent this difficulty we have developed a technique which utilizes the diamagnetic properties of liquid helium and a highly specialized magnetic field configuration to minimize these pressure effects. Using a superconducting magnet with a field-field gradient product of 21.0 T^2/cm *we can oppose gravitationally induced pressure variations over a limited volume in a helium sample down to a level of about 0.01g. We report on the operation of the large field gradient magnet and discuss the limitations of this technique. We also report on numerical simulations of the behavior of a sample of helium near the l-point in a reduced gravitational environment.*

1. Introduction

Recent experiments [1,2] on the influence of a heat current on the superfluid transition in ^{4}He revealed unexpected behavior. These experiments displayed noticeable disagreement with existing theoretical predictions.[3,4] These theories do not include the effects of gravity in their predictions; therefore, it is possible that by reducing the effective gravity on the sample the experiments might better reflect the theoretical calculations. Reducing the gravitational effects on a helium sample would have additional experimental benefits. If a column of helium is held sufficiently close to the lambda transition, the pressure dependence of the transition temperature allows superfluid and normal fluid phases to coexist in a finite gravity environment. With a reduction of the pressure gradients in the sample, the transition can be more closely approached before entering the two phase region. Also, by reducing the effects of gravity, the range of heat currents that can be applied to the cell will be expanded. For a fixed cell length, higher heat currents can be applied at lower effective gravity before the onset of convection in the normal fluid region occurs. Also, in a reduced gravitational environment, the range of heat currents where the transition is governed by the applied heat current instead of the gravitational field can be extended to smaller heat currents than those used in previous ground based experiments, For small heat currents in 1-g, properties like the width of the interface region and the nonlinearity of the thermal conductivity become dominated by gravitational effects. This limits experiments performed in a l-g environment to using heat currents larger than 4×10^{-8} W/en? to study the heat current dependent properties of the transition. Also, with the effects of gravity reduced, the width of the interface between the normal fluid and superfluid phases is predicted to become more macroscopic, possibly allowing the actual interface to be studied in detail.

We have recently acquired the necessary high field gradient magnet, and we report here on preliminary measurements with this magnet. We have also developed the capability to numerically simulate the behavior of a thermal conductivity cell of ^{4}He as it passes through the A-transition. By reducing the value of gravity used in the numerical simulations, we are able to predict the behavior of a sample cell in the magnetic low-gravity simulator. In the remainder of this paper we will discuss our ongoing work with both the low-gravity simulator and the numerical simulations.

2. Reducing the Effect of Gravity on the Ground

Ginzburg and Sobyanin proposed in the early 1980's that the gravitationally induced pressure variations in a column of helium could be counteracted by applying a suitably shaped static magnetic or electric field.[5] They showed that both fields couple to the chemical potential of liquid helium similar to the way pressure is coupled into the system. Since the superfluid transition is known to be similar at all applied pressures along the lambda line, applying such electromagnetic fields should not change the nature of the transition. The electric field densities necessary to create the desired gravity-cancelling profile over any reasonably sized cell volume are very large, and it is probable that excessive heating of the helium would occur using this method.[6] Therefore, we are building a low-gravity simulator by creating a suitably shaped magnetic field instead. To create a diamagnetic force that counteracts gravity in a column of liquid in the earth's gravitational field, a gradient in the square of the magnetic field of:

$$\partial(B^2)/\partial z = 2g\mu_0/(\partial\chi/\partial\rho) \qquad (1)$$

is needed, where g is the magnitude of the local gravitational field, μ_0 is the magnetic permeability of free space, χ is the magnetic susceptibility of the liquid, and p is the mass density of the liquid. For helium, the field profile necessary to balance the earth's gravity field is $\partial(B^2)/\partial z = -42\ (T^2/cm)$.

We recently purchased a magnet from Oxford Instruments capable of achieving a maximum $|\partial(B^2)/\partial z|$ of at least $46T^2/cm$. Oxford provided calculations of the field and the field profile for this magnet. In order to fully characterize the magnet, we performed our own measurements on the field both along the axis of the magnet and at a point 0.64cm off axis. Since only the z component of the magnetic field contributes to the force that opposes the force of gravity on the sample, only the z component of the field was measured. The field was measured using Hall probes on a moveable rod centered in the bore of the magnet. The magnet was energized to 6.8Tesla and placed in persistent mode before the data were taken. The magnet and the probes were in a helium bath at 4.2K.

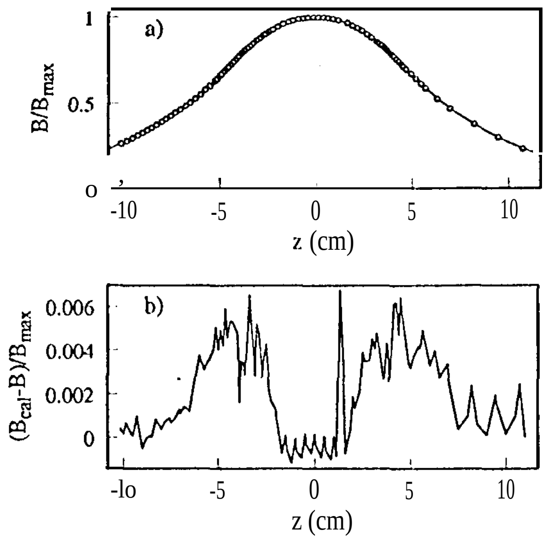

Figure 1:a) measured (symbols) and calculated (solid line) magnetic field versus axial distance from center of magnet along the axis of the magnet. b) difference of the calculated field versus the measured field along the axis,

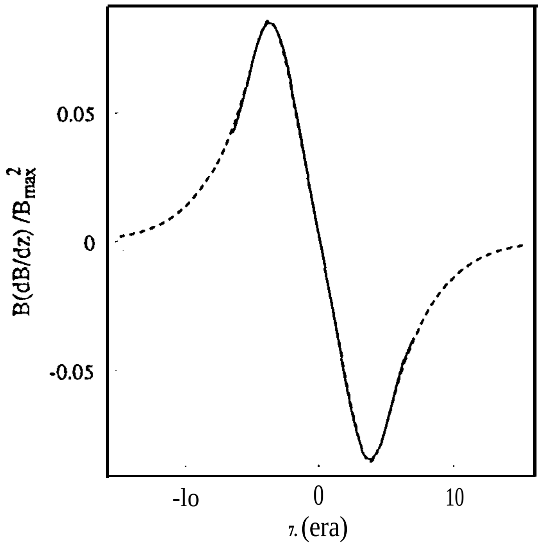

Figure 2: Magnetic field multiplied by the axial derivative of the field for the calculated field profile (dashed line) and for the fit to the measured field profile (solid line).

As can be seen from figure 1, the calculated field and the measured field were in close agreement. The plot of the difference between the calculated and measured fields in fig. 1b shows that the measured field was slightly larger away from the center of the magnet than was expected from the calculations.

For the low-gravity simulator, the relevant quantity is the field multiplied by the axial field gradient. As mentioned above, to be able to reduce the effects of gravity in a sample of liquid helium the gradient of the square of the magnetic field must be equal to $42T^2/cm$, or $B*(dB/dz) = 21\ T^2/cm$. To determine the actual

B *(dB/dz) of the magnet, the magnetic field data at r=0 were fit to a Legendre polynomial expansion in distance from the center of the magnet. By taking the derivative of the fit and multiplying it with the fit, B*(dB/dz) for the magnet can be determined, This measured profile and the calculated profile are shown in figure 2 normalized to a maximum field of 1Tesla. These values do differ slightly from each other as could be expected from the field profiles.

In order to cancel the effects of gravity using the least possible field, the helium sample should be placed where B*(dB/dz) has its maximum negative value. From our measurements, we find that a field of 15.8T must be trapped in the center of the magnet to give | B*(dB/dz) | $=21T^2$/cm. Assuming a central field of 15.8T, the minimum in B*(dB/dz) is shown in figure 3 for both the calculated field profile and the measured profile. As can be seen from fig. 3, the measured B*(dB/dz) is within 1% of the required value for almost 1cm along the axis. This implies that gravity could be cancelled to within 0.01g along lcm of the axis. Off axis B*(dB/dz) grows with increasing r. From the calculations on the magnet combined with our measurements at r= 0.64cm, this implies a maximum sample volume of about 0.5cm long and 0.4 cm in diameter where the influence of gravity can be cancelled to within 1%.

After the magnetic field profile measurements were made, the bath was pumped below 2K and a field of 15.6T was trapped in the magnet. This field is over 9870 of the field needed to achieve the desired 1% cancellation of gravity,

3. Planned Uses for the Low-gravity Simulator

Initially, we plan to focus studies in the low-gravity simulator to look at the lambda transition in helium-4 under the influence of a heat current. For this purpose we have built a thermal conductivity cell composed of two copper end plugs separated by a thin stainless steel wall. The cell will have a heater on the bottom, and for most measurements, the temperature of the top of the cell will be slowly ramped through the λ-transition from both above and below. Several temperatures in the cell will be monitored using thermometry with 3nK resolution (helium-4 melting curve thermometers).[8] These thermometers should be negligibly effected by the large applied fields. Also, two temperature probes will be compressed against the walls of the cell to measure the temperature profile in the helium sample away from end effects.

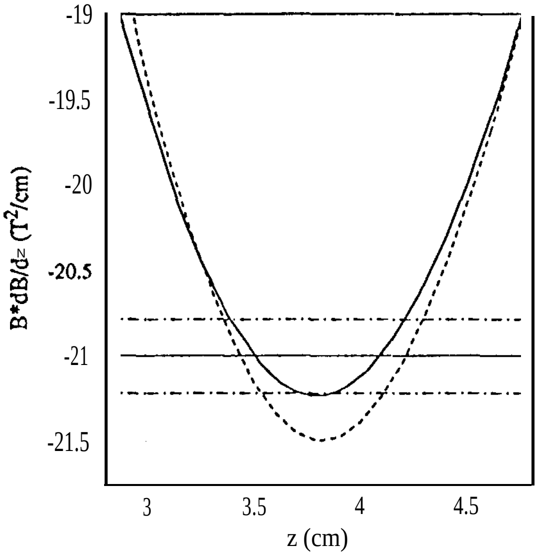

*Figure 3: Magnetic field multiplied by the axial derivative of the field with B=15.8T at the center of the magnet. Solid line is fit to measured field profile and dashed line is field calculations. Horizontal lines bracket gravity canceling region *1 %.*

After first confirming that the low-gravity simulator is effective in reducing the effects of gravity on the ground, we want to extend the range of measurements of the normal fluid conductivity closer to the transition temperature. By being able to approach the transition more closely without entering the two-phase region using our simulator, we expect to be able to observe and to map out the predicted heat current dependence of the normal fluid conductivity.[4]

Another focus of our investigations using the low-gravity simulator will be to look more closely at the heat current dependence of the transition temperature. Currently, the experimental observations of this dependence have shown a significantly stronger dependence on the heat current than can be explained within the available theoretical framework.* Since the theories do not include the effects of gravity or vortices, it is hoped that in the low-g simulator one will be able to use smaller heat currents than those used previously, therefore decreasing both the influence of induced vortices, and the influence of gravity. Hopefully the low-gravity simulator will more closely resemble the idealized system assumed in the theoretical calculations and provide a more thorough test of the theoretical calculations.

Also, the low gravity simulator will be used to search for the predicted change in the nature of the lambda transition from second order to first order under the influence of an applied heat current.[3] It is predicted that supercooling of the transition should occur with a magnitude similar to the transition temperature shift under the influence of a heat current:

$$T_s - T_\lambda = 4.43 \times 10^{-5}(Q^{0.744}) \qquad (2)$$

where Q is the heat current in mW/cm^2 and Ts is the shifted transition temperature and T_λ is the zero heat current transition temperature, both temperatures measured in Kelvins. This amount of supercooling can be related to the position where the interface initially appears between the normal fluid and superfluid phases in the cell. This position would be: $s=34.8xQ^{0.744}g/a$, where s is the position in centimeters from the top of the cell where the interface initially forms and a is the effective gravitational acceleration. This first-order effect was recently searched for but not observed in a 1-g ground-based experiment.[2]

In contrast to this previous experiment, we should be able to use much lower heat currents than the $37\mu W/cm^2$ used in the previous work, thus decreasing the heating of the normal fluid layer at the bottom of the cell. In the previous experiment, the normal fluid at the bottom of the cell had heated over 10mK above the transition temperature before the temperature of the top of the cell was ramped through T_λ. Perhaps these large temperature gradients in the cell affected the predicted supercooling. In a reduced gravity environment, it should be possible to use heat currents small enough to keep the overall temperature of the cell close to T_λ. By reducing the effective gravity to 0.01 g, as should be possible in the low-gravity simulator, a relatively modest heat current of $Q=10^{-8}W/cm^2$ should produce a supercooling size of 0.62cm, larger than our cell, without causing excessive heating in the normal fluid.

4, Numerical Simulations

To be better able to both plan and analyze our experiments with the low-gravity simulator, we have developed computer code to numerically simulate a one-dimensional thermal conductivity cell of helium. We used the basic time dependent heat flow equations and the known thermodynamic properties of helium at the superfluid transition.[9] The heat flow equations were simulated with finite difference equations using the Crank-Nicholson method. Additionally, the equations were transformed into terms of the local reduced temperature, instead of temperature, to more accurately reflect the physics, The effect of a finite boundary resistance at the ends of the cell was included. To match the numerical simulations with the physical experiment, the simulations assumed a boundary condition of constant heat flow at the bottom and a known, possibly time varying temperature for the copper top of the cell.

The simulations include the decrease in effective gravity acting on the cell by varying the spatial distribution of the local transition temperatures in the cell. In a finite gravitational environment, a pressure drop will exist from the bottom to the top of a column of liquid due to the hydrostatic pressure head. When the known pressure dependence of the superfluid transition is combined with the hydrostatic pressure head, one can relate the local transition temperature $T_\lambda(z)$ to the distance above the bottom of the cell and the local gravitational environment by:

$$T_\lambda = \left(1.273\frac{\mu K}{cm}\right) \times \frac{a}{g} \times z + T_\lambda(0) \qquad (3)$$

where z is the distance above the bottom of the cell and a is the magnitude of the local force acting on the fluid arising from the sum of gravity and the applied magnetic force.

We have performed preliminary work with the numerical simulations on the effect of reducing gravity on a thermal conductivity cell ramped through the superfluid transition. In figure 4, the effect of decreasing the effective gravity from 1 g to 0.1g is illustrated. The plots are for a 0.1cm long cell with a heat current of $0.25\mu W/cm^2$ passing through the cell from the bottom. For the 1g case, the transition temperature at the bottom of the cell is 127nK below the transition temperature at the top of the cell. In the 0.1g case, this difference reduces to only 12.7nK. The top temperature in both cases was ramped at a rate that would sweep the local superfluid to normal fluid transition from the bottom to the top of the cell in approximately 13 seconds, To achieve this, the top temperature in the 1g case was swept at 10nK/see, while in the 0.1 g case the top temperature was ramped at only 1 nK/sec. Both cases have with T_λ for the bottom of the cell at time equal to 0 seconds.

As can be seen from figure 4, the two cases display noticeably different behavior. Because the helium in the 0.1 g case is on average much closer to the transition temperature, the 0.1 g case displayed noticeably slower dynamics than in lg. This is observable in the slower increase of the temperature in time for the 0.1g cell versus the 1g cell. The 1g cell fills with normal fluid at a rate over twice as fast as that for the 0.1 g cell, As shown in the figure, *when* the gravity acting on the cell is decreased, more of the heat put into the bottom of the cell leaves the cell at the top. The decrease in the amount of heat leaving the cell is caused by heating the normal fluid under non-equilibrium conditions. This implies that the 0.1g case more closely achieves a quasi-static experimental condition.

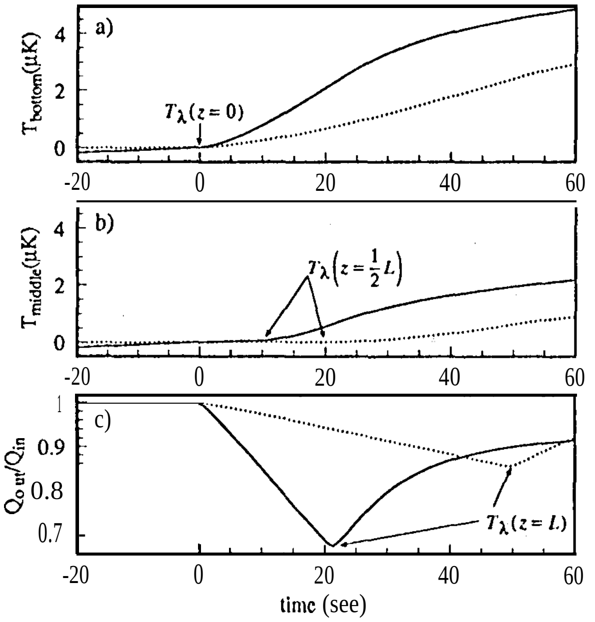

Figure 4: Numerical results from simulating a helium thermal conductivity cell at 1g (solid lines) and at 0.1g (dotted lines). a) The temperature at the bottom of the cell b) the temperature of the helium in the middle of the cell, and c) the difference between the heat entering the cell and the heat leaving the cell, as a function of time while the temperature of the top of the cell was steadily increased (see text).

The first goal of the magnetic low gravity simulator will be to show that gravity can be cancel led to 1% on the ground. If applying a suitable magnetic force counteracts gravity, the range of transition temperatures in a helium conductivity cell will decrease proportional to the effective forces acting on the cell. As can be seen from these numerical simulations, there are simple markers for when the helium at the bottom and top of the cell pass through the superfluid transition. When the bottom of the cell becomes normal, the temperature at the bottom of the cell increases dramatically. Similarly, after the top of the cell becomes normal, the amount of heat leaving the cell begins to increase sharply. Therefore, these numerical simulations show how to experimentally verify that gravitational effects are being decreased in our low-gravity simulator.

5. Cocclusions

Significant progress has been made in realizing a ground based low-gravity simulator. A magnet capable of achieving the necessary large gradient in the square of the field has been purchased and tested. A current of approximately 98% of the actual current needed to cancel gravity has been successfully trapped in the magnet, and the field profile of the magnet also been measured. The actual profile of the magnet has been found to be in close agreement with the calculated field profile and within the necessary requirements to cancel gravity of a reasonable sized volume of helium.

Additionally, the behavior of a thermal conductivity cell of helium has been numerically simulated. These numerical simulations provide insight into appropriate markers that can be used to confirm the success of the low-gravity simulator.

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