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THE CQ EXPERIMENT

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Abstract

It is expected on very general grounds that superflow will break down along a curve on the superfluid side of the Q (heat flux) - T (temperature) plane, and it has been shown that the heat capacity at constant Q, C_Q, should diverge along that same curve, which we refer to as $T_c(Q)$. The fundamental purpose of the CQ experiment is to measure C_Q as close as possible to $T_c(Q)$. Earthbound measurements to determine $T_c(Q)$ have given results that disagree with theory. Our own laboratory measurements of C_Q yield a much larger enhancement of the heat capacity than predicted by theory but, for a variety of gravity-related reasons, measurements could not be made close to $T_c(Q)$. The CQ experiment will make use of the microgravity environment to resolve both of these discrepancies between theory and experiment. It will be conducted as a guest experiment using the hardware that has been developed for the Critical Dynamics in Microgravity Experiment (DX), described in a separate paper in this session.

Introduction

One of the most important achievements in modern condensed matter physics is the development of the Renormalization Group Theory (RG)[1]. The ability to explain a vast number of static properties near different phase transitions within a unified theoretical framework is a success unseen since the development of quantum mechanics. The theory has survived the most stringent tests performed thus far. The most precise of these were performed in space[2,3], using the superfluid transition of ^{4}He as a model system because of a number of near ideal properties of liquid helium. ^{4}He can be made chemically pure[4], and is free of defects and grain boundaries that are inherent in solid-state materials. However, even without these imperfections, the properties of helium near the lambda transition temperature T_λ are still not perfect on Earth, due to an inhomogeneity resulting from hydrostatic pressure . In space, even this source of imperfection is removed, allowing this perfectly sharp transition to be studied to the limit offered by the best available high-resolution technologies. Much of these technologies were developed in previous space flights[2,3].

DX/CQ proposes to make use of this near perfect testing ground in space to study the dynamical and non-equilibrium properties of ^{4}He near T_λ, with the objective of testing the extension to the Renormalization Group theory that covers dynamical properties near phase transitions. One such extension is through the application of RG technique to solve the Model F flow equations of Hohenberg and Halperin[5]. This approach is thought to give accurate predictions of dynamical properties of ^{4}He near T_λ. Earlier ground based measurements of the thermal conductivity[6] above T_λ and second sound damping coefficients below T_λ appear to agree very well with the theory[7]. However, as mentioned earlier, more recent measurements of $T_c(Q)$[8] and C_Q[9] are at odd with the predictions of the theory. In the following, we will give a brief review of the thermodynamics, which leads to the prediction of the divergence of C_Q and the possibility of exciting new physics near $T_c(Q)$. We will discuss a possible explanation of the $T_c(Q)$ discrepancy, the technical difficulties of measuring C_Q on Earth, and how a Space flight experiment might elucidate the C_Q discrepancy.

The Divergence of C_Q

The divergence of C_Q at $T_c(Q)$ can be understood from very general thermodynamic principles[10]. In nature many materials exhibit interesting thermodynamic behavior due to the existence of a different degree of thermo-dynamical freedom. This degree of freedom manifest itself as a different way to do work on the system, and thus a different work term in the first law of thermodynamics. For example, magnetic materials exhibit a magnetic degree of freedom due to the ability to do work by magnetizing them. In a superfluid, a different way to do work exists; for example one can pull on a piece of porous material immersed in the superfluid. Because the normal fluid is dragged along, due to its viscosity, work is done on the normal component while the superfluid component passes through unaffected. Thus from a thermodynamic standpoint, the study of the static properties of superfluid helium under the condition of superfluid flow is analogous to the studies of magnetic properties of magnetic materials, or the thermodynamic properties of a gaseous system as a function of pressure P and volume V. Under the conditions of the CQ experiment one can, to an excellent approximation, write down the first law of thermodynamics in the laboratory frame as:

$$dE = Tds + J_s du_s \qquad (1)$$

where s is the entropy density, u_s is the superfluid velocity, $J_s = \rho_s u_s$ is the superfluid momentum density and ρ_s is the superfluid density. (Note, near T_λ under a heat current, the normal fluid velocity and its contribution to the free energy is negligible.) From this the free energy and thus the heat capacities at constant u_s or J_s can be calculated in a way similar to the calculation of the heat capacities at constant pressure and constant volume of a gaseous system[10], resulting in the following relation:

$$C_{J_s} = C_{u_s} + TV \frac{(\partial J_s/\partial T)_W^2}{(\partial J_s/\partial u_s)_T} \qquad (2)$$

In a superfluid, the application of a heat flux (Q) generates a counter flow between the normal fluid and the superfluid. The two-fluid model gives the relation that $Q = -\rho_s u_s ST$, where S is the entropy per unit mass, which is not a divergent quantity and is approximately a constant near T_λ. Thus, holding Q constant is the same as holding $J_s = \rho_s u_s$ constant, and hence $C_Q = C_{J_s}$. C_Q is linked to Model F through the theoretical prediction of how ρ_s changes with u_s. This theory predicts that under a uniform heat flux, ρ_s is decreased sufficiently by u_s, that a maximum occurs in J_s at a critical superfluid velocity u_c. Above u_c, $(\partial J_s/\partial u_s)_T < 0$ and the system is unstable against fluctuations, due to the violation of Le Chatelier's principle, resulting in the breakdown of superfluidity. (Note, this is a direct analogue of a gaseous system, where thermodynamic stability requires that $(\partial P/\partial V)_T < 0$.) At u_c and the corresponding Q_c, $(\partial J_s/\partial u_s)_T = 0$ leading to a divergence in C_Q as required by Equation (2) above. Fluctuations in u_s also diverge at this point, suggesting that there may be a region rich in interesting new physics close to $T_c(Q)$. For example the exponents of the singularity of a static quantity, like C_Q, is expected to be quite different from that at the lambda point.

Possible Explanation of the $T_c(Q)$ Discrepancy

Early reports showed that there were discrepancies between the measurements of superfluid breakdown temperature and $T_c(Q)$. Haussmann and Dohm[11] predicted that $t_c = (T_\lambda - T_c)/T_\lambda = (Q/Q_o)^x$, where $x = 1/2\nu = 0.746$, and $Q_o = 7395\ W/cm^2$, while the measurements of Duncan, Ahlers and Steinberg (DAS) resulted in fitting values of $Q_o = 568 \pm 200\ W/cm^2$, and $x = 0.813 \pm 0.012$. This discrepancy may now have been resolved. It was noticed that the theoretical prediction was made for the breakdown of superfluidity under uniform superfluid flow, while the experiment of DAS was not conducted under these conditions[9]. DAS observed a HeI/HeII interface that developed at the bottom and hot endplate of their thermal conductivity cell. This interface then propagated upwards into the cell as the temperature was raised. It is known that near a HeII-solid interface or a HeI/HeII interface, J_s changes from zero to the value given by the two-fluid model over the distance of a few correlation lengths. Thus the flow field is extremely non-uniform.

At the hot endplate, in the vicinity of the HeII-solid interface, transformation from diffusive flow to counterflow occurs over a thin layer. A temperature gradient ΔT_b can occur due to the remnant diffusive flow, as postulated by Landau[12]. The resulting surface thermal resistance is known as the singular Kapitza boundary resistance R_b, because, as the measurements by DAS[13] indicated, its value appears to diverge with a weak singularity at T_λ. A Model F solution for the singular Kapitza resistance was reported by Frank and Dohm[14], and is in good agreement with the measurements. Using experimental values of R_b, Harter et al showed that as the temperature of the superfluid T_{SF} is raised towards T_λ at constant Q, the slope $d\Delta T_b/dT_{SF}$ diverges when T_{SF} reaches a temperature T_i. At this point, presumably, the HeI/HeII interface leaves the surface and propagates into the cell. $T_i(Q)$ has the same functional form as $T_c(Q)$, but the parameters derived from measurements of R_b are $x = 0.8163 \pm 0.0023$ and $Q_o = 813 \pm 9$ W/cm^2. These values are very close to the measured values of DAS, suggesting that their measured breakdown temperature may be a result of breakdown at the surface, and not in the bulk superfluid.

There is another explanation proposed by Haussmann[15] that the discrepancy may be due to the presence of gravity. But there is not as yet any strong evidence supporting this interpretation.

C_Q Measurements on Earth and the Effects of Gravity

Measurements of C_Q have been made on Earth in the range 1 to 4 μW/cm^2; Figure 1 shows a scaled plot of the change in the heat capacity as a function of Q/Q_c [9]. As expected from the theory, measurements at different values of Q follow the same scaled-curve. But the magnitude of the observed effect is much larger than theoretical predictions. Aside from the problem related to inhomogeneity caused by hydrostatic pressure differences in the sample, there are other technical problems due to gravity. These problems are discussed below.

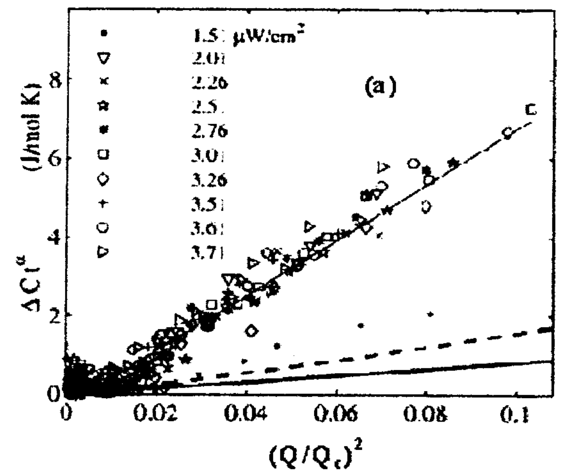

Figure 1: Scaled plot of the enhanced heat capacity. The thin solid line is a fit to the data. The thick solid line is from the theories of Chui et al[10]. The dashed line is from a later theory of Haussmann[15].

Temperature Gradient Effect

Even in superfluid helium a heat flux can generate a small temperature gradient that is proportional to Q due to vortices. At higher heat flux a temperature gradient of the form $\nabla T \propto Q^3$ is developed, due to mutual friction between the vortices and the normal fluid. Using measurements of ∇T near T_λ by Badder et al[16] the temperature difference across a cell of height ℓ can be estimated as:

$$\Delta T_R = R\ell Q = \ell t^{-2.8} (Q/Q_R)^{2.53} Q \,. \tag{3}$$

One can set the criteria that this temperature difference must be smaller than $T_\lambda - T$ so that the sample is uniform enough in temperature for meaningful investigation. This sets a limit on how close one can approach T_λ for a given Q. But, for the same Q, one also needs to get close enough to $T_c(Q)$ so that there is a large enough heat capacity difference to be studied. We showed that if Q is larger than 4 or 5 $\mu W/cm^2$ these two conflicting requirements cannot be met simultaneously. This limits all investigations both on Earth and in space to $Q < 5$ μW/cm^2. Such small Q means that any heat capacity deviations must be investigated very near to the lambda point, where gravity rounding due to a hydrostatic pressure gradient degrades the quality of the data. In fact it is fortuitous that there is a small parameter-space on Earth where this effect can be observed. To be within this parameter-space, a very thin cell is needed to avoid gravity rounding. The data shown in Figure 1 is measured in a cell that is only 0.64 mm high.

Non-Ideal Cell Design

The ideal cell design should have a high-resolution thermometer mounted on the side-wall of the thermal conductivity cell. This would allow the temperature of the bulk helium to be measured directly. But accommodating a side-wall thermometer requires the cell to be made at least 2 mm high. This would cause the data to be severely affected by gravity. The choice of a very thin cell without a side-wall thermometer has an important drawback. The temperatures read at the top and bottom endplates are not the temperatures of the bulk helium, but the temperature of the helium plus the temperature jump across the solid-liquid boundary due to the Kapitza boundary resistance and the singular Kapitza boundary resistance. Although the data can be corrected for these effects in a self-consistent way using the singular Kapitza resistance data of Fu et al[17], the accuracy of this correction is still a major uncertainty.

Space Experiment

By performing the experiment in Space, it is possible to use a thicker cell with multiple side-wall thermometers as shown in Figure 2. By removing gravitational rounding, it will be possible to use even smaller Q and therefore perform the experiment closer to T_λ. Since $\nabla T \propto Q^3$, smaller Q's will make the sample very uniform in temperature, and may have another advantage as well. At high Q, as mentioned earlier, the breakdown in superfluidity may occur at the hot boundary due to a surface instability. If this were true, then a space experiment would still be prevented from reaching $T_c(Q)$. But current data suggest that $T_c(Q)$ is much closer to the surface instability temperature $T_i(Q)$ at lower Q, and may even be higher than $T_i(Q)$ at the lowest Q. This would allow a much closer approach to $T_c(Q)$ in space, and perhaps may even allow it to be reached at the lowest Q.

NASA has already funded the development of the cell shown in Figure 2 as part of the DX flight development. DX plans to measure the temperature profile above $T_c(Q)$ to test the Model F RG prediction in the non-linear conductivity region[18] close to T_λ. CQ will use the same equipment, without any modification, on the same flight as a guest experiment. DX anticipates using less than one month of the 4.5-month mission, and so there should be more than enough time to do both DX and CQ.

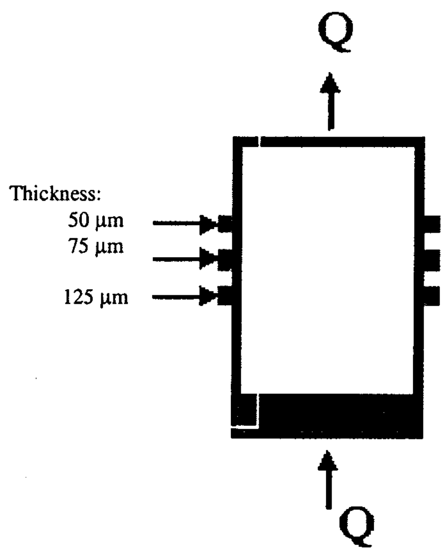

Figure 2: The DX cell with side-wall thermometers.

Conclusion

The DX/CQ experiment will make use of the low temperatures, microgravity and long duration capabilities offered by LTMPEF and the ISS to perform interesting investigations into the dynamical and non-equilibrium properties of liquid helium near the superfluid phase transition. The CQ experiment will help elucidate or resolve a major discrepancy between experiment and theory in the ongoing development of a comprehensive understanding of dynamical critical phenomena.

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