QUEST TO OBSERVE THE BULK SUPERFLUID BREAKDOWN IN A HEAT FLUX

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Abstract

A recent theory predicts that bulk superflow breaks down in a heat flux, Q, through an instability, where the fluctuations of the counterflow velocity diverge. In order to observe this interesting effect a number of obstacles must be overcome. First, it was recently suggested that in an ordinary thermal conductivity cell, the breakdown of superfluidity occurs initially at the hot end plate metal/liquid boundary, and not in the bulk superfluid. Second, the sample can become non-uniform due to a temperature gradient in the superfluid caused by vortices. Third, the sample may become non-uniform due to a pressure gradient induced by gravity. We will present analyses of these adverse effects in the Q-T plane and discuss ways to overcome them. The possibility of using the International Space Station to remove the gravity rounding effect will be elaborated.

Introduction

Due to the admirable success of the Renormalization Group theory[1] and its extension, the Dynamic Renormalization Group theory[2], much of static and dynamical phase transition phenomena have been explained to some degree of satisfaction. It is therefore quite surprising that under an applied heat current, the properties of ^{4}He on the superfluid side of the transition are found to be quite different from what is expected. For example, recent measurements of the heat capacity C_Q of ^{4}He in a constant applied heat flux Q showed that the change in the heat capacity due to Q is much larger than predicted[3]. Aside from this discrepancy, it has been predicted that near the bulk superfluid breakdown temperature $T_c(Q)$, C_Q is expected to diverge with a very different exponent[4].

At $T_c(Q)$, the fluctuations of the counterflow velocity are also expected to diverge. These predictions are based on very general thermodynamic grounds[4]. Therefore one would expect that near $T_c(Q)$ there is a region rich in interesting new physics. However, reaching $T_c(Q)$ has proven to be difficult. The reasons for these difficulties as well as ways to deal with them will be explored in the following sections.

Surface Breakdown of Superfluidity

$T_c(Q)$ is defined to be the bulk superfluid breakdown temperature under a heat flux. From the point of view of theory, this breakdown point arises from the optimization of the Ginsburg-Landau type free energy with $\nabla|\psi|$ set to zero (ψ is the order parameter). At $T_c(Q)$, one expects to observe an abrupt change from a uniform state ($\nabla|\psi|=0$) with no temperature gradient to a non-uniform state with a temperature gradient. However, what was observed on Earth is a gradual evolution of a non-uniform state near the hot end plate of a thermal conductivity cell, to another non-uniform state with a HeI-HeII interface inside the cell. In both of these non-uniform states, ψ changes from zero at the boundary or a HeI-HeII interface to a finite value far from the boundary. This change occurs over a distance of a few correlation lengths, resulting in a large $\nabla|\psi|$ value. Therefore the temperature at the HeI-HeII interface first measured by Duncan,, Ahlers and Steinberg[5] (DAS), $T_l(Q)$, can be interpreted as resulting from the Ginsburg-Landau type free energy with a dominant $\nabla|\psi|$ term. A temperature gradient in HeII adjacent to solid boundary where conversion of heat into counterflow occurs is generally associated with the singular Kapitza boundary resistance[6]. A model was put forth by Harter et al[3] suggesting that the singular Kapitza temperature profile at the hot endplate evolves into the HeI-HeII interface through an instability at the boundary. This model predicted a temperature that agrees with $T_i(Q)$ using measured values of the singular Kapitza resistance. This lends support to the idea that, in an ordinary thermal conductivity cell with a uniform cross sectional area, superfluidity breaks down at the hot boundary, not in the bulk, making $T_c(Q)$ inaccessible.

An obvious way to overcome this problem is to increase the surface area of the hot endplate relative to the cross section area of the cell. Figure 1 shows some concepts for implementing this with hills and valleys at the hot end plate, with a larger hot end plate, or a combination of both.

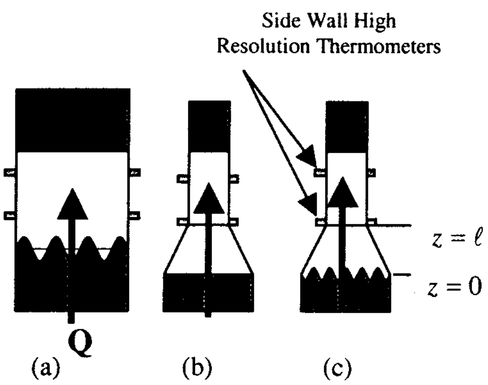

Figure 1: Three ways to increase the surface area for heat to get into the fluid.

To calculate how much the area needs to be increased in order to get to $T_c(Q)$, we use the theoretical critical heat flux by Haussmann and Dohm[7] $Q_c = Q_o t^{1/x}$ for bulk superfluid breakdown, and the experimental value of DAS[5] $Q_i = Q_{oi} t^{1/x_i}$ for breakdown at the boundary. Haussmann and Dohm predicted $Q_o = 7395\, W/cm^2$ and $x = 0.746$, while the measurement of DAS gave $Q_{oi} = 568 \pm 200\, W/cm^2$ and $x_i = 0.813$. From these values, we get $Q_c/Q_i = (Q_o/Q_{oi}) t_i^{1/x - 1/x_i} = 13 t_i^{0.11}$. For $Q = 0.01, 0.1, 1, 10\, \mu W/cm^2$ the surface breakdown reduced temperatures are $t_i = 1.8\times10^{-9}, 1.2\times10^{-8}, 7.6\times10^{-8}, 5.0\times10^{-7}$ and the area ratios are expected to be: $Q_c/Q_i = 1.4, 1.7, 2.1, 2.6$ respectively. This analysis neglects the effect of gravity on Earth. With gravity included, the area ratio would have to be much larger.

The Effect of Gravity

On Earth, inside a column of liquid helium, there exists a hydrostatic pressure, which varies with height. Because T_λ is a function of pressure, there is a height dependent transition temperature, with a T_λ shift of $\Delta T_\lambda = 1.27\, \mu K/cm$. Therefore, if the sample is uniform in temperature, the reduced temperature of the sample is different at different heights. The standard way to mitigate this effect on Earth is to make the sample thin, until one either reaches a practical limit related to cell construction or a fundamental limit set by the finite size effect. In the finite size limit, the correlation length ξ becomes comparable to the cell spacing, causing the properties of helium to deviate from those of the bulk. This sets the limit on Earth based experiments, that a uniform bulk sample cannot be studied at any temperatures closer than 10^{-8} K from the transition, for an optimal sample size of ~0.1 mm. Because of the singular Kapitza resistance, it is necessary to have a side wall thermometer to measure the helium temperature directly. It is very difficult to make a cell with height smaller than 2 mm. This sets a practical limit for T_λ-T of $0.25\ \mu K$. The horizontal line in Figure 2 shows this limit. The uniform region suitable for investigation is above this line. Below this line the sample in no longer sufficiently uniform.

For measurements of the static properties of helium, a standard technique for extracting data from the gravity-rounded region is to applied gravity correction to the data. This is possible because the static properties are well known. On the other hand, the properties under heat flux such as C_Q, are not as well established, the correction is not possible. microgravity is desirable for this type of investigation.

Temperature Gradient in Superfluid

Even with the limited temperature range for investigation, the static properties of liquid helium can be studied with small uncertainties under gravity. This is not the case for superfluid helium under the influence of a heat flux because of dissipative effects. Dissipation is thought to be due to mutual friction between the normal fluid and vortices. Recently, Baddar, Ahlers, Kuehn and Fu[8] reported measurements of the thermal resistivity R very close to T_λ in the superfluid phase. They showed that $R = t^{-2.8}(Q/Q_R)^{2.53}$ in units of $K-cm/W$, where $Q_R = 393\, W/cm^2$. Thus the temperature difference across a cell of thickness ℓ is given by:

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

This limits the range of investigation to $T_\lambda - T > \Delta T_R = T_\lambda \left[T_\lambda^{-1} Q\ell (Q / Q_R)^{2.53}\right]^{1/3.8}$, which is plotted (thin blue lines) in the Q-T plane in Figure 2 for cell heights of 1 and 0.2 cm. The region of investigation is above these lines. Below these lines, the sample is not sufficiently uniform due to the temperature gradient.

Effects on the Q-T Plane

On Earth the minimum practical cell height that incorporates at least one side wall thermometer is ~2mm, limiting the range of investigation to the region above the horizontal line shown in Figure 2 i.e. $T_\lambda - T > 0.25\,\mu K$. The surface instability temperature $T_i(Q)$ is also plotted (dashed line). If our hypothesis is correct, this is the closest one can get to $T_c(Q)$ in an ordinary thermal conductivity cell. In a special cell with hills and valleys on the hot endplate, it should be possible to exceed this limit. Also plotted is $T_\lambda - T_c(Q)$ (thick solid line). It can be seen that for $Q > 10\,\mu W / cm^2$, dissipation prevents $T_c(Q)$ from being reached. At $Q < 10\,\mu W / cm^2$, the data close to $T_c(Q)$ are degraded severely by gravity, making all measurements on Earth inaccurate. With gravity removed, the singularity near $T_c(Q)$ is available for investigation with very minimal rounding due to dissipation.

The two vertical dashed lines in Figure 2 represent two experimental paths of approaching the transition at constant *Q*. Path A is at 0.1 $\mu W/cm^2$ while path B is at 20 $\mu W/cm^2$. At 20 $\mu W/cm^2$, the surface instability limit is encountered first. If this limit is exceeded, the dissipation limit is then encountered and it is not possible to get near $T_c(Q)$. However, at 0.1 $\mu W/cm^2$, the first limit that is encountered is the gravity limit. If this limit is removed, then the approach to $T_c(Q)$ is limited only by the surface instability. Excceeding this limit will allow $T_c(Q)$ to be reached, with minimal rounding due to dissipation.

ISS Utilization and Conclusion

In the above discussion, we have shown that a major obstacle, which prevents $T_c(Q)$ from being reached on Earth, is gravity. The ISS together with the Low Temperature Microgravity Physics Experiment Facility (LTMPEF) will provide the ideal platform to overcome this obstacle. Other than a new cell designed to overcome the phenomenon of superfluid surface breakdown, all the hardware can be inherited from the first and second missions. This greatly reduces development cost and allows interesting new physics to be investigated on a fast turn around schedule. Meanwhile, ground based experiments will be conducted to improve our understanding on some of the hypotheses discussed in this paper.

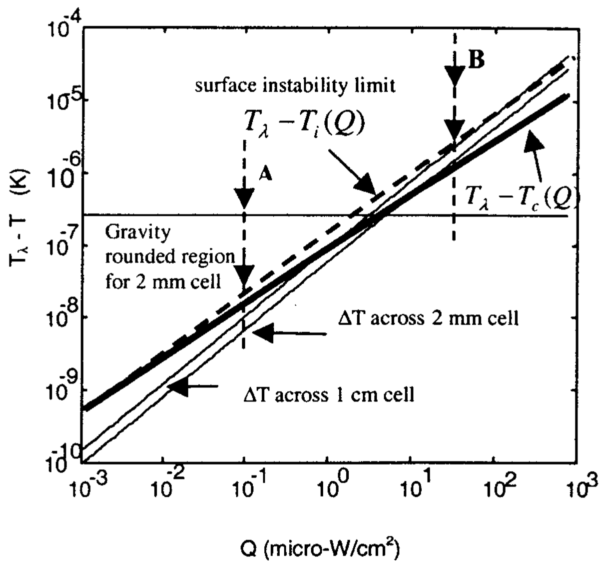

Figure 2: The effects of gravity, surface instability and temperature gradient due to dissipation in the sample plotted in the Q-T plan.

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References

1. K. W. Wilson, Phys. Rev. **B** 4, 3174 (1971).
2. P. C. Hohenberg and B. I. Halperin, Rev. Mod. Phys. **49**, 435 (1977). V. Dohm, *Z. Phys. B* **60**, 61 (1985).
3. A.W. Harter, R. A. M. Lee, A. Chatto, X. Wu, T.C.P. Chui, and D.L. Goodstein, Phys. Rev. Lett. **84**, 2195 (2000).
4. T. C. P. Chui, D. L. Goodstein, A. W. Harter, R. Mukhopadhyay, Phys. Rev. Lett. **77**, 1793 (1996).
5. R. V. Duncan, G. Ahlers, and V. Steinberg, Phys. Rev. Lett. **60**, 1552 (1988).
6. R. V. Duncan, G. Ahlers, and V. Steinberg, Phys. Rev. Lett. **58**, 377 (1987).
7. R. Hausemann and V. Dohm, Phys. Rev. **B** 46, 6361 (1992).
8. H. Baddar, G. Ahlers, K. Kuehn and H. Fu, , J. Low Temp. Phys., **119**, 1 (2000).