Heat capacity measurements of ^{4}He at constant heat flux near T$_\lambda$

Alexa W. Harter [a,1], Richard A.M. Lee [b], Talso C.P. Chui [b], David L. Goodstein [a]
[a] *Condensed Matter Physics 114-36, California Institute of Technology, Pasadena, California 91125, USA*
[b] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA*

Abstract

The heat capacity, C_Q, of superfluid ^{4}He in the presence of a constant heat flux, Q, is expected to diverge at a depressed transition temperature, $T_c(Q)$. We have taken preliminary measurements of C_Q at various heat flux values in the range $1\ \mu\mathrm{W/cm}^2 \leq Q \leq 4\ \mu\mathrm{W/cm}^2$. We observe that at sufficiently small reduced temperatures, C_Q is enhanced as a function of Q, and that the enhancement is larger than theoretical predictions [1,2].

Keywords: Helium; heat capacity; phase transition

1. Introduction

Applying a constant heat flux, Q, to superfluid ^{4}He is predicted to depress the transition temperature [3,4], and to have a significant effect on its thermodynamic properties. The heat capacity was originally predicted to diverge [1,2] at the transition temperature, $T_c(Q)$, although a recent theory [5] that includes both gravity and vortex production predicts that it will, instead, exhibit a strong maximum.

A number of experiments have investigated the physics in the vicinity of this transition. An experiment by Duncan, Alhers, and Steinberg [6] (DAS) observed that dissipation entered the cell at a temperature, $T_{\mathrm{DAS}}(Q)$, that lies below the theoretical value of $T_c(Q)$.

2. Experiment

Measurements were taken in a cell constructed of two 6.985 cm diameter annealed oxygen-free high conductivity copper endplates connected by a 0.640 mm high stainless-steel sidewall. (See the inset to Fig. 1.) The cell was filled with ultra-pure ^{4}He (having a ^{3}He concentration of 0.07 ppb) and then sealed with a mechanical valve. A bubble filling 0.5% of the volume was trapped during this procedure, ensuring that heat capacity measurements would be taken at saturated vapor pressure. The helium temperature was measured with two high resolution paramagnetic salt thermometers [7] (HRTs) located on the top and bottom of the calorimeter.

The cell was mounted on a three stage thermal isolation system. The third stage consisted of a radiation shield that surrounded the calorimeter. During the experiment, the temperature of the

---

[1] Corresponding author. E-mail: awh@caltech.edu

shield stage was controlled to $\pm 0.2\ \mu$K with a third HRT. A constant heat flux, Q, was applied with a wire heater wound around the bottom of the calorimeter.

Heat capacity measurements, C_Q, were taken at constant heat flux values in the range $1\ \mu\mathrm{W/cm}^2 \leq Q \leq 4\ \mu\mathrm{W/cm}^2$. A series of heat pulses, $\Delta Q_{pulse} \sim 0.7\ \mu$J, were applied using a second wire heater also located at the bottom of the cell.

The temperature of the helium was inferred by averaging the measurements of the top and bottom thermometers, and then subtracting off a term to correct for the asymmetry between the top and bottom singular boundary resistances, using the data of Fu, Baddar, Kuehn, and Ahlers [8]. In order to confirm the consistency of our analysis, we also derived measurements of the helium temperature by independently correcting the top and bottom temperatures for their respective boundary resistances. We then used these measurements to obtain the heat capacity. All three measurements gave consistent results.

The data in Fig. 1 are terminated when the heat capacity measured by the thermometer on the bottom no longer agrees with the heat capacity as measured by the one on top. This point occurs when the bottom Kapitza resistance suddenly increases, which we attribute to a decrease in the effective bottom surface area when the correlation length of the sample is of the same magnitude as the surface roughness of the bottom wall.

3. Results

We found that at sufficiently small reduced temperatures, C_Q is enhanced as a function of Q (see Fig. 1), and that the enhancement is larger than theoretical predictions. Our measurements indicate that there is new and interesting physics to be explored in the vicinity of this transition. We are presently building a new cell that will allow us to measure C_Q with a penetrating sidewall thermometer.

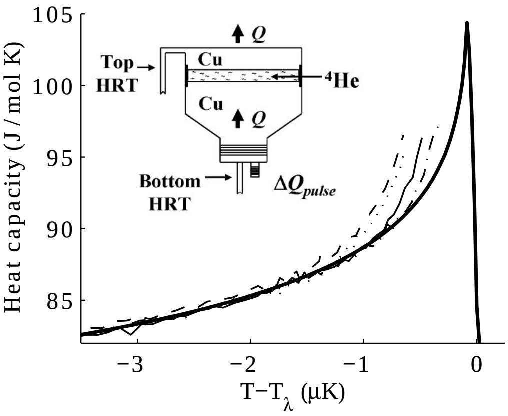

Fig. 1. Thick solid line: $Q = 0$ (rounded by gravity), dashed-dotted line: $Q = 1.51\ \mu\mathrm{W/cm}^2$, thin solid line: $Q = 2.01\ \mu\mathrm{W/cm}^2$, dotted line: $Q = 3.01\ \mu\mathrm{W/cm}^2$, dashed line: $Q = 3.51\ \mu\mathrm{W/cm}^2$. Inset: Schematic diagram of the cell.

Acknowledgement

We are grateful to G. Ahlers for providing us with his measurements of the singular boundary resistance, and to Xinkai Wu for his assistance. This research was carried out in a collaboration between the Jet Propulsion Laboratory and the Physics Department of the California Institute of Technology under a contract with National Aeronautics and Space Administration.

References

[1] T . C. P. Chui, D. L. Goodstein, A. W. Harter, and R. Mukhopadhyay, Phys. Rev. Lett. **77**, 1793 (1996).

[2] R. Haussmann and V. Dohm, Phys. Rev. Lett., **77**, 980 (1996).

[3] A. Onuki, J. Low Temp. Phys., **55**, 309 (1984).

[4] R. Haussmann and V. Dohm, Phys. Rev. Lett. **67**, 3404 (1991).

[5] R. Haussmann, preprint

[6] R. V. Duncan, G. Ahlers, and V. Steinberg, Phys. Rev. Lett. **60**, 1522 (1988).

[7] R. A. M. Lee, A. W. Harter, and T. C. P. Chui, *ICEC 17*, ed. D. Dew-Hughes, R.G. Scurlock, J.H.P. Watson, (Inst. of Physics Publishing, Bristol and Philadelphia, 1998), p. 817.

[8] H. Fu, H. Baddar, K. Kuehn, and G. Ahlers, Low Temp. Physics, **24** 69 (1998).