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A Preliminary Heat Capacity Measurement of ^{3}He in Aerogel near its Superfluid Transition

Jizhong He*†, A.D. Corwin*, G.M. Zassenhaus*, A.L. Woodcraft*, N. Mulders†‡, J.M. Parpia*, J.D. Reppy*, and M.H.W. Chan†

* *LASSP, Cornell University, Ithaca, NY 14853-2501*
† *Dept. of Physics, Penn State University, University Park, PA 16802-6300*
‡ *Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716*

We report simultaneous heat capacity and torsional oscillator measurement of ^{3}He in aerogel near the superfluid transition. The heat capacity has a peak at the temperature T_c where the torsional oscillator shows the onset of superfluid decoupling. The coincidence of these signatures suggests that ^{3}He in aerogel does undergo a true thermodynamic transition.

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1. INTRODUCTION

In spite of the random environment, ^{4}He entrained in aerogel exhibits an exceedingly sharp superfluid decoupling at a temperature T_c that lies slightly below the bulk lambda transition. The superfluid density below T_c is found to follow a power law dependence on the reduced temperature. The critical exponent characterizing the power law is distinctly different from that found in bulk ^{4}He.[1] The interpretation that ^{4}He in aerogel undergoes a genuine thermodynamic transition is not firmly established until a sharp heat capacity peak is found precisely at T_c defined by the superfluid measurements.[2] Recent torsional oscillator and NMR measurements of ^{3}He entrained in aerogel also found sharp signatures at a temperature that lies below the bulk superfluid transition temperature.[3–6] The nature of these signatures is a subject of considerable current interest.[7–9] These signatures have been interpreted as evidence that ^{3}He in aerogel, as ^{4}He in aerogel, does undergo a genuine phase transition.[3–9] The absence of a heat capacity peak at the transition temperature, however, renders such interpretations as

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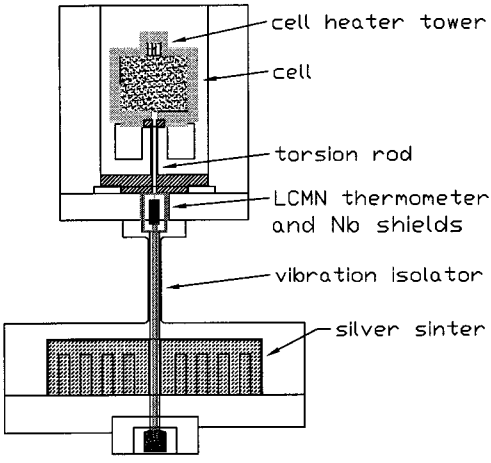

Fig. 1. Schematic drawing of the cell and torsional oscillator.

tentative.

In this paper, we report preliminary simultaneous torsional oscillator and heat capacity measurements of ^{3}He entrained in 98.5% porous aerogel. Our results indeed show a coincidence of the superfluid density and heat capacity signatures.

2. APPARATUS

We used a cylindrical aerogel sample with 98.5% porosity. The sample is $1.3cm$ in diameter and $1.5cm$ long. It is fitted within an epoxy cell (Stycast 1266.) The epoxy cell, mounted on top of a Be-Cu 25 torsion rod, is the head of a torsional oscillator of a conventional design.[10] Fig. 1 shows a schematic drawing of the cell and the torsional oscillator.

We opted to use a weak thermal link, instead of a heat switch, to achieve the thermal isolation and the cooling of the cell. ^{3}He inside the torsion rod and vibration isolation rod provides the weak thermal link between the cell and the silver sinter heat exchanger which is bolted to a $PrNi_5$ nuclear stage plate. The silver sinter has a volume of $2.5cm^3$ with a surface area of $\sim 10m^2$. The time constant of the cell is calculated to be $\sim$ 8 hours at $20mK$ and $\sim$ 5 minutes at $2mK$, using bulk values of normal ^{3}He heat capacity and thermal conductivity.

An LCMN salt pill, located in a superconducting single coil between the torsion rod and vibration isolator rod, is used as a dc susceptibility thermometer to measure the cell temperature.[11] The coil is enclosed inside

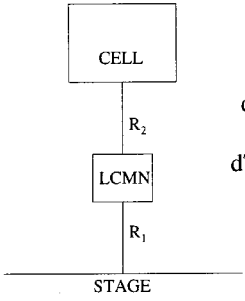

Fig. 2. A thermal model for the cell system. Here R_1 and R_2 are the thermal resistances from the LCMN thermometer to the stage and cell respectively. One the right are the relevant equations for the model, which are self explanatory.

a set of Nb shields (with small openings at both ends), which also provide a trapped static magnetic field of about $2G$. An ac SQUID setup, connected to the coil, is used to measure the magnetic flux change in the salt pill as a function of temperature. A melting curve thermometer located at the nuclear stage is used to measure the stage temperature and to calibrate the LCMN thermometer. A heater, made of $0.050mm$ diameter W-Ti wire and with a 50 Ω nominal resistance, is located in a small tower connected to the top of the cell.

3. DRIFT MEASUREMENT

We had planned to measure the heat capacity by using the conventional adiabatic calorimetry technique. Unfortunately, a short in the cell heater developed shortly after cool down. This forced us into adopting an alternative method.

The new method measures the temperature warmup rate of the cell $\dot{T}_c$, after a constant heat was applied to the stage. The constant heat input will develop a steady temperature difference across the weak link, thus a smoothly changing heat input into the cell. As a result, any feature in the cell heat capacity will show up in the temperature drift rate.

We made a simple model for the cell system as shown in Fig. 2. Based on the model, the heat capacity of the cell C can be deduced with the following formula:

$$C = \frac{T_{stage} - T_{cell}}{R\dot{T}_{cell}} \tag{1}$$

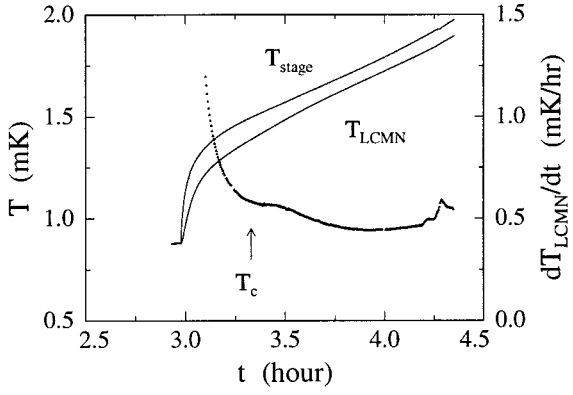

Fig. 3. Temperatures of the stage (upper line) and LCMN thermometer (lower line) during a drift measurement. The o is the drift rate of the LCMN thermometer. The aerogel transition temperature T_c, as indicated with the arrow, is determined from the period measurement (not shown).

here T_{stage} is the temperature of the stage measured by the melting curve thermometer, $R = R_1 + R_2$ is the total thermal resistance of the liquid ^{3}He column inside the torsion rod and vibration isolation rod. The thermal conduction due to the rods can be neglected at the temperature range of the experiments.

Because the thermal resistance of superfluid ^{3}He is not known exactly, we can only get the product of RC using Eqn. (1). But since there is no known singular feature in the thermal conductivity of the liquid ^{3}He column below the superfluid transition temperature, it is safe to treat R as a smooth function of T. As the result, the peak like feature in RC can be regarded as the feature of the heat capacity C.

4. RESULTS

Fig. 3 shows the temperatures of the stage and the LCMN thermometer as a function of time during a recent drift measurement. This is carried out at $10.8bar$ with $T_{c0} = 1.87mK$ and $T_c \sim 1.3mK$, where T_{c0} is the ^{3}He bulk superfluid transition temperature. The cell and the stage initially cooled down to about $0.9mK$ after demagnetization. The drift started with the application of a constant heat of about $0.2\mu W$ to the stage.

Also plotted in Fig. 3 is the drift rate of LCMN temperature $\dot{T}_{LCMN}$.

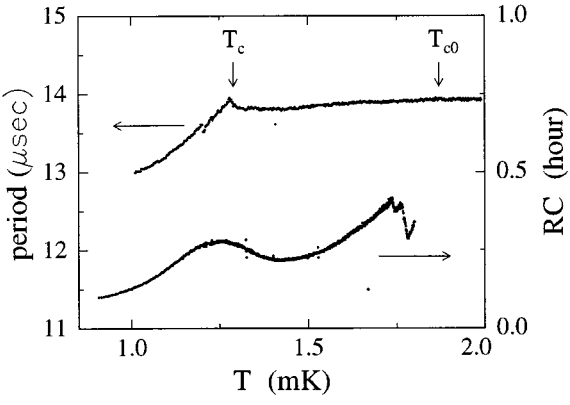

Fig. 4. Period and RC as a function of cell temperature. T_{c0} is determined from oscillator dissipation measurement (not shown).

A dip in $\dot{T}_{LCMN}$, indicating a peak in the heat capacity of the cell, is very visible. The feature at higher temperature is due to the bulk ^{3}He, surrounding the LCMN thermometer, undergoing a phase transition from superfluid to normal liquid. This gives a convenient temperature calibration point for the LCMN thermometer.

The values of RC and the oscillator period are plotted against the cell temperature T in Fig. 4. The peak in the heat capacity is centered around T_c with a rounding of about $0.3mK$. As a comparison, the period at T_c has a much sharper transition. The decreasing of the period indicates the decoupling of the superfluid to the torsional oscillator. The feature at around $1.7mK$ (cell temperature) is due to bulk ^{3}He phase transition surrounding the thermometer at $1.87mK$. Beyond this temperature, RC data from the drift measurement is meaningless and is omitted.

5. CONCLUSION

We have performed a drift measurement of the temperature of ^{3}He in 98.5% dilute aerogel under $10.8bar$. From the temperatures of the stage, the cell, and its time derivative, information on the cell heat capacity is extracted. Based on our preliminary analysis, we show that there is a peak centered at T_c, the temperature at which ^{3}He in aerogel decouples from the torsional oscillator. The half width of the peak is $\sim 0.2mK$, much smaller than the difference between T_{c0} and T_c ($\sim 0.6mK$), and this, we believe, is

the direct evidence that the superfluid transition of ^{3}He in aerogel is indeed a genuine phase transition.

Because we do not know the exact values of the thermal resistance R, and errors in determining the cell temperature from LCMN and stage temperatures, we can not determine the absolute value or the temperature dependence of the heat capacity of ^{3}He in aerogel. Conventional heat capacity measurements are currently in progress.

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10. *Experimental Techniques in Condensed Matter Physics at Low Temperatures*, R.C. Richardson and E.N. Smith, eds. (Addison-Wesley, Redwood City, 1988)
11. Due to the location, the LCMN thermometer actually samples both the cell and the stage temperatures, which equal when in thermal equilibrium. The cell temperature can be deduced from the LCMN and stage temperatures when the cell is not in thermal equilibrium with the stage.