Proc. 18th Int. Conf. on Low Temperature Physics, Kyoto, 1987
Japanese Journal of Applied Physics, Vol. 26 (1987) Supplement 26-3

Suppression of the Superfluid Transition of ^{3}He in 350 nm Channels

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We have measured the suppresssion of the superfluid transition temperature due to confinement of the fluid by 350 nm diameter pores in Nuclepore filter. The experiments were carried out at several pressures between 0 bar and 29 bar, where the pressure variation allows us to vary the ratio of the coherence length to pore diameter by approximately a factor of five. The Nuclepore filter was mounted across an annular flow channel which formed part of the inertial bob of a torsional oscillator. Flow was induced by operating the device at its resonant frequency of 850 Hz at amplitudes between 50 pm and 10 nm. The measured suppression of the superfluid transition is less than that predicted by theory.

1. INTRODUCTION

For diffuse quasiparticle scattering it is expected that at least one component of the order parameter should be suppressed by the presence of walls. The spatial variation of the order parameter occurs over a distance of several correlation lengths, $\xi(T)$. Since the correlation length diverges at the superfluid transition suppression of the superfluid transition by confinement of ^{3}He results. It was with the aim of exploring this effect that we undertook the AC flow experiment described in this paper.

2. APPARATUS

The basic cell used in this experiment is similar to that used in the Andronikashvili torsion oscillator experiments, with the exception that instead of a disc shaped cavity for the ^{3}He we used an annular channel of dimensions 7.6mm radius x 0.25mm width x 1.25mm height, with a nuclepore filter (nominal 400nm pore diameter x 10μm thickness) placed across the channel. A fill line entered the annulus at a point diametrically opposite the nuclepore filter. The head was mounted on a beryllium copper torsion tube and had a resonant frequency of ~850 Hz which was excited and detected electrostatically. The cell is illustrated in Figure 1.

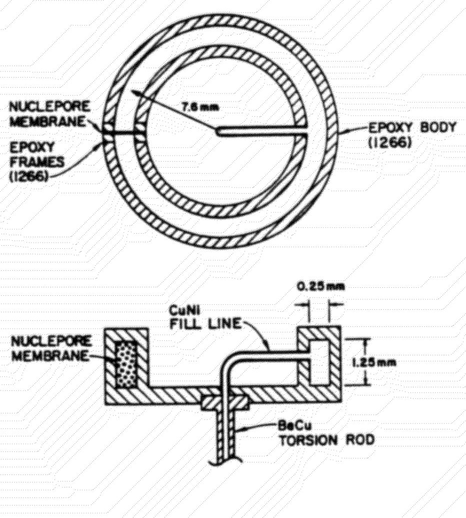

Fig. 1. A schematic view of the experimental cell, showing the dimensions.

The nuclepore filter was examined under an SEM. We were able to confirm that several of the pores appeared to cluster at the surface, giving the appearance of a large hole. However, in all cases we were able to discern discrete tracks diverging from the surface as a consequence of the angular dispersion of the nuclear particles used in the manufacturing process. The resulting pore size distribution is sharp with a mean diameter of 350nm.

The hydrodynamics of the cell is straightforward. Since the viscosity of the normal liquid ^{3}He is high at millikelvin temperatures, the viscous penetration depth greatly exceeds the pore diameter. Consequently, the liquid helium in the annulus is entirely locked to the oscillator because of the high impedance of the membrane to flow. When the ^{3}He in the pores is in the superfluid state, the impedance of the membrane becomes negligible allowing almost the entire superfluid mass in the annulus to decouple and lower the period of the oscillator. In practise we find that the transition from the low impedance to the high impedance state occurs over a finite width in temperature and depends on the impressed flow, which is proportional to the amplitude of oscillation. The cell has a high sensitivity to pressure differences across the membrane, and can produce exceedingly small flow velocities through the restricted geometry. A fuller account of the hydrodynamics is presented in reference 1.

3. RESULTS

3.1 Procedure

The experiment was carried out by cooling to temperatures on the order of $0.7T_c$, and then warming at a constant rate of 15-20μK/h. The cell was operated at a fixed amplitude until the bulk transition temperature was observed in the cell at which point the procedure was repeated at a different amplitude.

3.2 B Phase Results

The results for data taken at 20Bar are shown in Figure 2. We observe that there is an amplitude independent region below ~0.96 T_c, and another amplitude independent region at temperatures above the point marked II. We interpret these results as follows. The temperature II marks the onset of superfluidity in the pores. The various points marked I show the onset of dissipative superflow at which point the impedance of the membrane increases sharply.

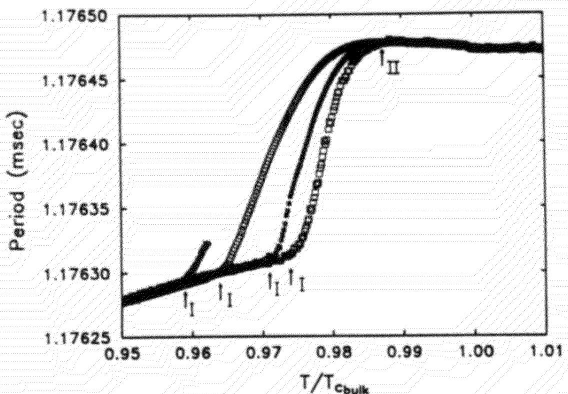

Fig. 2. The period shift for four different amplitudes. (from right to left 0.61Å, 1.9Å, 6.1Å, and 9.1Å. Feature II marks the onset of superfluidity, while feature I marks the onset of dissipative superflow at a particular amplitude.

3.3 Critical currents

The current through the pores may be inferred from the measured parameters and the bulk superfluid density. In order to determine the temperature at which the critical current vanishes we have plotted the inferred critical current $J_{sc}^{2/3}$ at which we observe the onset of dissipation vs (1-T/T_c). The data does not follow the expected power law dependence. We also find that within the precision of our measurements that the extrapolated value of the zero amplitude point of feature I does not coincide with the temperature of feature II. From this we infer that a novel dissipative state (similar to the intermediate state in superconductors) intervenes between T_c (I) and T_c (II). In addition, the critical currents are two orders of magnitude smaller than those previously observed.

3.4 A Phase Results

When the cell is operated at 23 and 29 Bar, it was observed that the critical currents were lower in the bulk A phase than in the B phase. This is illustrated in figure 3, where we show data taken at 3 amplitudes at 23 bar. It can be seen that while the ^{3}He is in the B phase, the membrane's impedance is in its "low" state. However upon entering the A phase, the liquid is observed to be in the dissipative superflow state. Thus we conclude that coincident with the bulk A B transition there is a change of state of the order parameter in the pores.

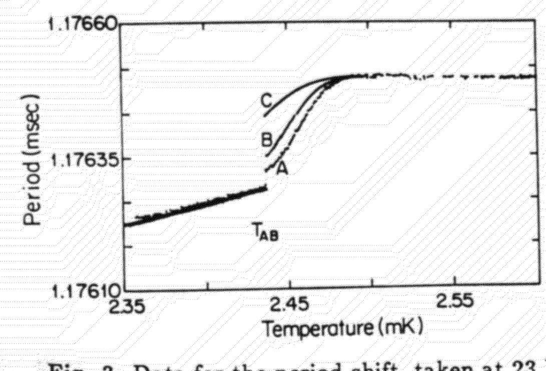

Fig. 3. Data for the period shift, taken at 23 Bar. The curves marked A,B,C, correspond to amplitudes of 0.61Å, 1.9Å and 6.1Å.

The pressure dependence of features I and II are in qualitative agreement with those of reference (2). However, the degree of suppression appears to be a factor of two smaller as can be seen from figure 4. In this figure, we plot the suppression of T_c for both the features, as well as the predicted suppression, together with lines through the data where we fit to the pore diameter.

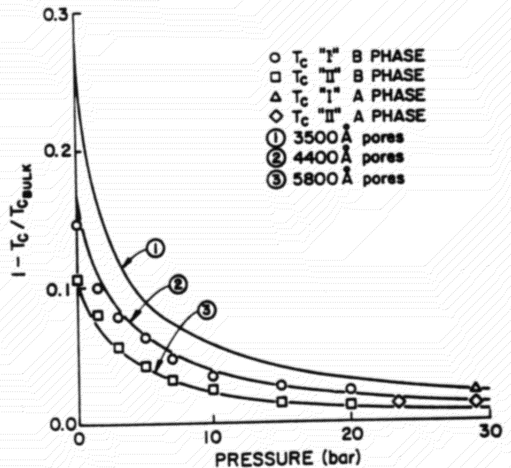

Fig. 4. Pressure dependence of features I and II. Shown for comparison are the results of reference 2, scaled to different pore sizes.

4. CONCLUSION

It is evident that there is qualitative agreement between our data and the theory of Kjaldman et. al (reference 2) . Our data show that an intermediate state exists where the impedance of the porous membrane is finite but not as great as in the normal state. Finally we conclude that the liquid in the pores shows a transition at the bulk A B transition temperature and has a smaller critical current in the A phase.

5. ACKNOWLEDGEMENTS

We acknowledge the support of the NSF through DMR 8696083 and the Cornell Materials Science Center through DMR 8516616.

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