^{3}He Film Flow: Two-Dimensional Superfluidity

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(Received 7 May 1985)

^{3}He film flow has been observed. The maximum flow rate, at 0.7 mK, over a rim 0.9 mm above the ^{3}He level, was 1.2 mm^3/h corresponding to an approximate flow velocity of 0.2 mm/sec. A flow rate of 0.2 mm^3/h (~ 0.1 mm/sec) was measured with the rim 14 mm above the level. The transition to superflow occurred at 3.5 ± 0.5 mK for the 0.9-mm film and 2.0 ± 0.5 mK for the 14-mm film. This flow is in a regime where the film thickness is less than or comparable to the bulk superfluid ^{3}He coherence length (~ 1000 Å at 0.8 mK) and the temperature is higher than the bulk ^{3}He superfluid transition temperature (1.08 mK) and corresponds, we believe, to a two-dimensional superfluid phase of ^{3}He.

PACS numbers: 67.50.−b, 67.70.+n

The superfluid phases of liquid ^{3}He, discovered a decade ago, have proven a very rich field of physics.[1] Whereas the range of phenomena has been far more extensive than for superfluid liquid ^{4}He, film flow is one property which was expected to be unique to ^{4}He.[2] The reason for not expecting film flow in ^{3}He was that the coherence length is larger than the equilibrium thickness of the ^{3}He film on a vertical wall at a height of 100 μm or more above the meniscus of the free surface. This is demonstrated in Fig. 1 which compares film thickness (d), which varies with height (h), with the coherence length (ξ), in bulk ^{3}He at 0, 0.5, and 0.8 mK. The figure is schematic only; the coherence lengths are from BCS theory,[4] and the literature contains many warnings concerning estimates of helium film thickness.[3] We have taken $\xi(T) = 50(1 - T/T_c)^{-1/2}$ nm, and $d = 8 \times 10^{-9}/h^{1/3}$ m.

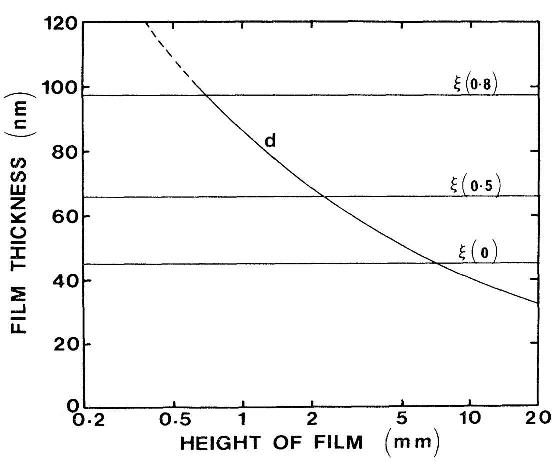

FIG. 1. Estimates of the coherence length in superfluid ^{3}He at 0, 0.5, and 0.8 mK, and of the thickness of a ^{3}He film on a metal substrate as a function of the height of the film above a free surface. The dashed line corresponds to the region where surface tension will cause a thickening of the film into a meniscus (Ref. 3).

This paper describes the results of what was originally an experimental search for the onset of film flow in the low-temperature, thick-film regime. Very soon after starting the experiment it was clear that there was ^{3}He film flow for films comparable to the coherence length, and at temperatures much higher than the bulk transition temperature (1.08 mK at saturated vapor pressure.[5]) We believe that these results are strong evidence for a two-dimensional superfluid phase of ^{3}He with a transition temperature of 3 ± 1 mK. A theoretical discussion of such a phase has been presented by several groups.[6]

Figure 2 shows the film-flow apparatus. It consisted of a copper chamber containing two stainless-steel coaxial capacitors, each one made of a 4.2-mm-i.d. outer tube and a 2.4-mm-o.d. inner tube; the level detector had a slot at the bottom and the film-flow detector had a slot (3.03 mm wide $\times 0.37$ mm high) near the top. This latter slot, cut with a diamond saw and the burr removed with No. 600 emery, is the rim for the film-flow experiment. The capacitors were sealed at the top and the bottom with Bakelite spacers and Stycast 2850 GT epoxy. The capacitors were measured separately with two General Radio capacitance bridges.[7] The sensitivity of each detector was 3.3-fF/mm ^{3}He, the limit of detectability was ~ 3 aF (1 μm), and the long-term stability was 0.1 fF (30 μm). There was a preliminary experiment with superfluid ^{4}He in a separate cryostat to test the film-flow cell and capacitance measurement system.

The flow cell was attached to one of four ports above the ^{3}He chamber of a standard $PrNi_5$ nuclear demagnetization cryostat.[8] The ^{3}He (about 10 cm^3, depending upon the level of the free surface) was thermally connected to the 1.4 moles of $PrNi_5$ refrigerant by 50 g of sintered silver powder ($RT \sim 30$ K^2/W; R is the thermal resistance and T the temperature) and

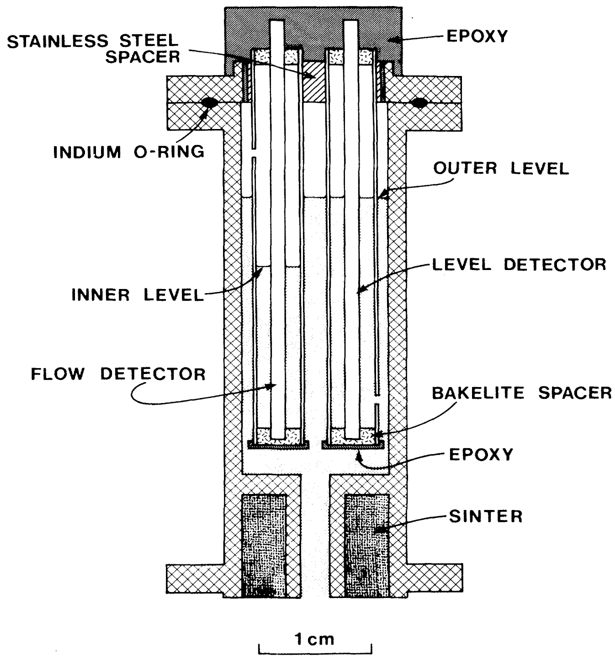

FIG. 2. The flow cell showing the coaxial-capacitor ^{3}He level and film-flow detectors. The flow cell is sealed onto the main ^{3}He chamber with an indium "O" ring.

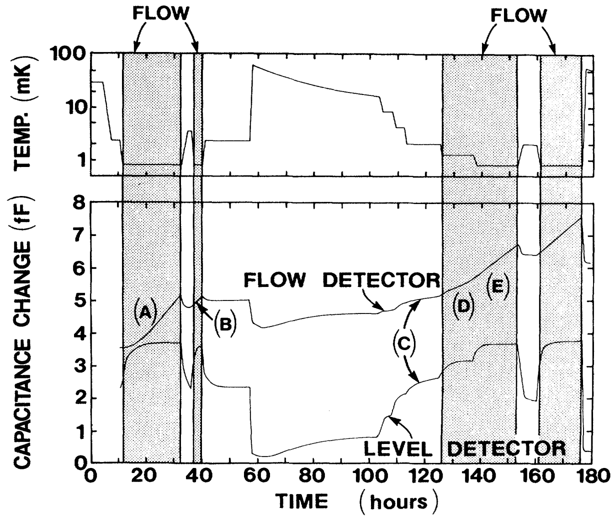

FIG. 3. A record of the changes of the level-detector and flow-detector capacitances following the first adiabatic demagnetization. Initially the ^{3}He level was 14 mm below the rim of the flow detector and the flow detector was empty. Both traces show reversible changes with temperature, but the flow detector also shows a net increase as a result of film flow.

72 annealed 1-mm-diam × 20-cm-long copper wires ($RT \sim 7$ K^2/W). The thermometry for these experiments was limited to a cerium-diluted lanthanum magnesium nitrate (LCMN) thermometer[9] and a germanium thermometer that had previously been calibrated above 40 mK. There were several consistency tests of our temperature scale.[10] These tests also showed that the total heat leak into the system was 20 nW, largely made up of an unidentified time-independent heat leak of 8 to 10 nW into a viscometer cell and about 10 nW of Joule heating from the capacitance bridges. Both of these heat leaks were into the metal chamber containing the liquid ^{3}He, rather than into the liquid ^{3}He, and were responsible for holding the chamber and liquid ^{3}He at about 0.7 mK ($\sim$ 0.3 mK above the temperature of the $PrNi_5$) following a demagnetization to the lowest temperature.[11] With the final field at 0.01 T, the ^{3}He and LCMN thermometer remained below 1 mK for 40 h.

For the first flow experiment the ^{3}He chamber was filled slowly at about 100 mK, while the level detector was monitored. The ^{3}He contained $\sim$ 500-ppm ^{4}He but this was only enough for $\frac{1}{5}$-monolayer coverage of ^{4}He over the sinter in the ^{3}He chamber. The filling was stopped with the level about 15 mm below the open slot into the flow detector. The system was precooled to below 20 mK over a period of 40 h and the $PrNi_5$ demagnetized to 0.01 T. The resulting response of the level and flow detectors to this demagnetization and subsequent remagnetizations and demagnetizations is summarized in Fig. 3. At the time of this run there was no calibration of the LCMN thermometer and therefore, as described below, the magnetizing field was used as a guide to temperature. During the demagnetization (cooling) there was a reversible and reproducible change in both capacitances.[12] At the lowest temperature, the flow detector showed an additional linear change with time (region A in Fig. 3), which was not reversible upon magnetization (warming) to $\sim$ 2 mK, and thus was attributed to film flow. There followed a second demagnetization and more flow (B), a partial magnetization to 2 mK, and a full magnetization. After a further precool there was demagnetization in stages showing the temperature-dependent capacitance changes (C), the onset of flow at $\sim$ 2 mK (D), and the increase in flow with further reduction in temperature (E). Magnetization to above $\sim$ 2 mK inhibited flow and demagnetization restarted it. Finally, by remagnetization to full field and precooling, the flow detector was found to have gained 8 mm^3 of ^{3}He, corresponding to an average flow velocity of $\sim$ 0.1 mm/sec over the 34 h at the base temperature. Following the third precool, further demagnetizations (not shown) produced the same behavior. Although masked by the reversible changes in Fig. 3 there was an overall negative change in the level detector capacitance. From this first experiment we learned that there was ^{3}He film flow over a rim 14 mm above the free surface under a gravitational potential due to a 15-mm level difference of

^{3}He, that the transition temperature appeared to be 2.0 ± 0.5 mK, well above the bulk ^{3}He transition temperature, and that the flow was inhibited by sudden warming.

For the second experiment the free surface was raised to the slot in the flow detector. In fact, an excess of 0.1 cm^3 was added and spilled over to form a 14-mm column in the flow detector, which left a gravitational potential of 14-mm ^{3}He. The free surface probably settled to ~ 0.6 mm below the slot because of the height of the ^{3}He meniscus.[4] After demagnetization to below 1 mK the flow rate built up from an initial 0.35 to 2.3 mm^3/h, slowed, and then settled at 1.2 mm^3/h.

After a further cycle of magnetization to full field, a precooling to 18 mK, and demagnetization, the results shown in Fig. 4 were obtained. The flow rates were taken over 60 h as the system was slowly warmed by the 20-nW heat leak. There was a large uncertainty of the higher temperatures where the LCMN thermometer sensitivity was low. However, we confirmed that the flow started at 3.5 ± 0.5 mK by a subsequent demagnetization from 15 mK and full field. The rate of film flow, $\dot{V}$, is given by

$$\dot{V} = (\rho_s/\rho) p v_c d,$$

where ρ_s/ρ is the superfluid fraction, p is the effective perimeter of the rim, v_c is the critical velocity, and d is the film thickness at the rim. In bulk ^{3}He below T_c some experiments have shown a critical velocity that decreases with increase in temperature,[13] and such a possibility must be considered here. Therefore Fig. 4 cannot be used directly as a measure of the temperature dependence of ρ_s/ρ. If we assume that at the lowest temperatures $\rho_s/\rho \sim 1$ then the maximum flow rate corresponds to a critical velocity of 0.2 mm/sec. This is comparable to measured critical velocities in bulk ^{3}He-A.[14]

The third cooling cycle yielded a maximum flow rate, at the base temperature, of 1.0 mm^3/h. During the next, fourth, cooldown to the base temperature the levels equalized and the flow stopped. The small decrease from 1.2 to 1.0 mm^3/h over the first three runs occurred therefore despite the large drop in gravitational potential from 14-mm ^{3}He to almost zero. In fact, the decrease can probably be explained by the decrease in film thickness as the height of the film increased from 0.9 to 2.0 mm. Since flow stopped while cooling during the fourth run we were not able to separate gravitational-potential and temperature effects near the end point.

For the next experiment, a series of demagnetizations from 50 mK and 7 T was then used to calibrate the level-detector capacitance as a secondary thermometer, by employment of the reproducible and reversible change with temperature when there was no

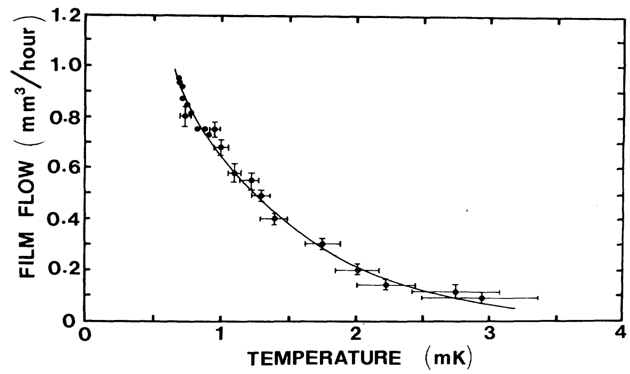

FIG. 4. A plot of film-flow rate as a function of temperature with the ^{3}He level 1.0 mm below the rim. The temperatures were derived from the LCMN thermometer as described in the text.

flow. This calibration was then used to estimate the precool temperature of the earlier experiments and, on the assumption of reversible demagnetizations, the temperatures at which flow started. This provided the temperature scale of Fig. 3 and the confirmation of the (3.5 ± 0.5)-mK transition temperature for the second experiment with the level ~ 1 mm below the rim.

For a final experiment, the film-flow cell was completely filled with ^{3}He. Subsequent demagnetization showed only the reversible changes in capacitance that we attribute to the epoxy insulation.

Over the total of 208 h of flow, following eight separate cooling cycles, the flow detector gained a total of 120 mm^3 or 12.5 mm in height and the level detector lost a total of 14.5 mm^3 or 1.5 mm in height with the ratio in agreement with the ratio of cross-sectional areas outside and inside the flow detector. The net superfluid film flow, 120 mm^3, was 1.2% of the total ^{3}He in the system.

The observation of film flow raises many interesting questions. Within the limitations of our thermometry it appeared that the transition temperature changed with film thickness, from 2.0 ± 0.5 mK for the 14-mm-high film to 3.5 ± 0.5 mK for the 1-mm-high film. There is also the question of continuity of flow at temperatures between 1 and 3 mK when the two-dimensional superfluid film is connected by presumably small regions of normal thick film to the two bulk helium reservoirs.[15]

This research has been supported by the Natural Sciences and Engineering Research Council, the Chief of Research and Development of the Canadian Department of National Defense, and a Killam Research Fellowship to one of us (J.P.H.). We would like to thank W. Ruesink and P. Zawadzki for their assistance, M. H. Edwards for his support, and our technical staff who constructed the cryostat.

Note added.—The apparatus has since been cycled to room temperature and the experiment repeated with 50-ppm ^{4}He impurity in the ^{3}He; all aspects of the experiment have been reproduced. The ^{4}He Atkins-resonance results with the same cell have now been analyzed. The interpretation is difficult because of the slot geometry but the best estimate is that the film cross section is 3 times the value calculated from the measured perimeter and the film thickness shown in Fig. 1, which suggests a rough surface.[16] This cross section was used to estimate the flow velocities given above. A separate run has also been made after the flow-detector slot was plugged with epoxy; over a 24-h period no flow was observed which eliminated the possibility of a leak at the bottom of the flow detector. In addition, a vibrating-wire "viscometer" provided a fixed point at the bulk ^{3}He superfluid transition and confirmed our minimum temperature of 0.7 mK.

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[10]These tests, along with more details of the flow experiments, will be described in full elsewhere.

[11]If the Joule heating had reached the coaxial capacitors the thermal resistance of the epoxy could have held the capacitor tubes at about 10 mK. Nevertheless, the high Kapitza resistance between stainless steel and the ^{3}He film, which is too thin to support bulk phonons below 50 mK, would have limited the heat input into the film to $\lesssim 5$ pW. In turn, on the assumption of specular scattering of ^{3}He quasiparticles at the film surface and hence the bulk ^{3}He conductivity for the film, the heating of the film could have caused up to 10% enhancement in film temperature at the slot.

[12]This has the familiar $\ln(T/T_0)$ dependence [see, for instance, S. Hunklinger and M. V. Schickfus, in *Amorphous Solids,* edited by W. A. Phillips (Springer-Verlag, New York, 1981), p. 81] and was attributed to the epoxy insulation. The flow detector showed a smaller reversible change that almost leveled off below 10 mK. However, this leveling temperature changed twice during the series of experiments, once (to 1.5 mK) soon after the levels equalized and again (to 5 mK) after the cell was completely filled with ^{3}He. Between these two changes the temperature dependence was quite reversible. The level detector showed no such change of behavior and the difference is attributed to the presence of a heater in the flow detector.

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