Superfluidity of ^{3}He Films

J. C. Davis, A. Amar, J. P. Pekola, and R. E. Packard
Department of Physics, University of California, Berkeley, California, 94720
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We have developed a new technique to study superfluidity in saturated liquid-^{3}He films. Using the enhanced sensitivity of this new method, we directly observe the suppression of the film's transition temperature T_c^F as the film thickness decreases. We also measure a well-defined maximum critical film current which scales with temperature as $(1-T/T_c^F)^a$, where $a=1.5\pm0.17$.

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Recently, much interest has been focused on the nature of superfluid ^{3}He confined to regions where one or more of the dimensions is of the order of the temperature-dependent coherence length. Theoretical work has concentrated on the prediction of the modifications to the superfluid properties caused by the confined geometry.[1-5] The experimental challenge has been to perform measurements in small geometries where the boundaries are simple enough to make rigorous comparisons to the theory. Already, qualitative comparisons to theory have been made from data on experiments in complex packed-powder systems and in multipore geometries.[6-10] However, little work has been reported based on simple geometry.[4]

A particularly simple geometry, which has been of interest for many years, is that consisting of an adsorbed liquid film. This film, which is common to both ^{4}He and ^{3}He, can consist of a liquid layer with thickness, δ, on the order of a few hundred angstroms, fortuitously comparable to the ^{3}He zero-temperature coherence length, ξ_0.

Because one expects superfluidity to be suppressed when confining dimensions are of the order of ξ_0, it was not surprising when early searches for ^{3}He superfluid films produced negative results.[11] However, it was very surprising when a recent paper not only described the detection of superfluidity in these films, but in addition reported a superfluid transition temperature much higher than in the bulk, unconfined liquid.[12] Subsequent reports[13,14] from this group do not confirm their early findings, but show film-flow effects similar to those reported here.

In order to study this phenomenon more thoroughly, we have developed a new technique which detects superfluid film currents at least 3 orders of magnitude smaller than in previous experiments.[12-14] As will be explained below, this technique confirms the observation that the ^{3}He films can exhibit superfluidity, but only at temperatures below the bulk transition temperature, in accord with the standard theoretical model.

Our experiment is shown schematically in Fig. 1.[15] A solid copper cylinder is partially immersed in a bath of liquid ^{3}He (which is cooled by a conventional nuclear demagnetization refrigerator). Although electrically isolated, this cylinder is in good thermal contact with the ^{3}He via a 10-m^2 silver-powder heat exchanger. The flat top surface of the cylinder protrudes a distance h above the bath. The top circular edge is rounded with a radium of curvature of about 0.5 mm. Slightly above this metal surface is positioned a flat metal disk which forms a capacitive pair with the top of the lower cylinder. Since the dielectric constant of the ^{3}He is greater than unity, the application of a dc voltage, V, produces a force which tends to pull the liquid into the capacitor gap. Since at low temperatures there is a negligible amount of vapor present, the only way liquid can move into the gap is through a superfluid film which covers the protruding end of the copper cylinder. The flow of normal liquid through the thin film is negligible because of the associated enormous flow impedance.

The amount of liquid in the gap is measured by our monitoring the interelectrode capacitance, which increases when ^{3}He arrives in the capacitor. The experiment consists of application of the potential V, and observation of the subsequent change in capacitance.

In the actual apparatus, the film-flow detector is surrounded by a pair of concentric metal cylinders whose measured capacitance serves as a detector of the liquid level in the bath.

The gap in the film-flow detector is 62 μm which per-

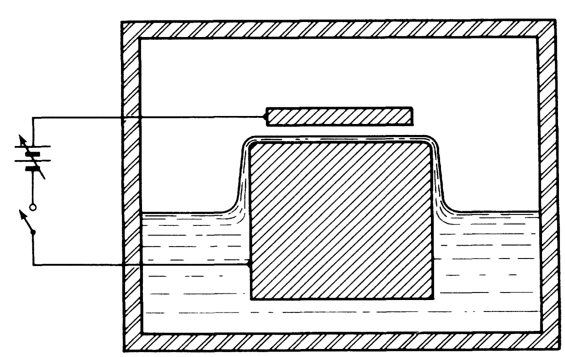

FIG. 1. A schematic diagram of the apparatus used to both generate and detect superfluid ^{3}He film flow.

mits us to detect film-thickness changes of about 1 Å in 1 s. The liquid-level detector has a annular gap of 500 μm and can resolve level changes of 1 μm. (There are surface-tension corrections which must be made to find the correct height h. These are included in the data shown below.) The central solid copper cylinder has a radium of 12 mm. The disk electrode above the cylinder has a radius of 9 mm. Overall, the film-flow detector can detect mass currents as small as 7×10^{-2} mm^3/h in 1 s. A typical superfluid current can be determined in about 10 s.

The static capacitance of the film-flow detector measures the total amount of ^{3}He in the gap. Since the copper surface is microscopically quite rough on the scale of the expected film thickness ($\simeq10^{-6}$ cm), we are unable to determine capacitively the actual filın thickness. However, on the basis of the total measured liquid in the gap, we know that $\delta < 5000$ Å. The actual value of δ may be much smaller.

Relatives values of δ are observed to increase as h decreases, as expected. However, on the basis of previous work, we do not consider it reliable to deduce δ from h. Hence, we choose to display measured film properties as a function of h rather than δ.[13,14]

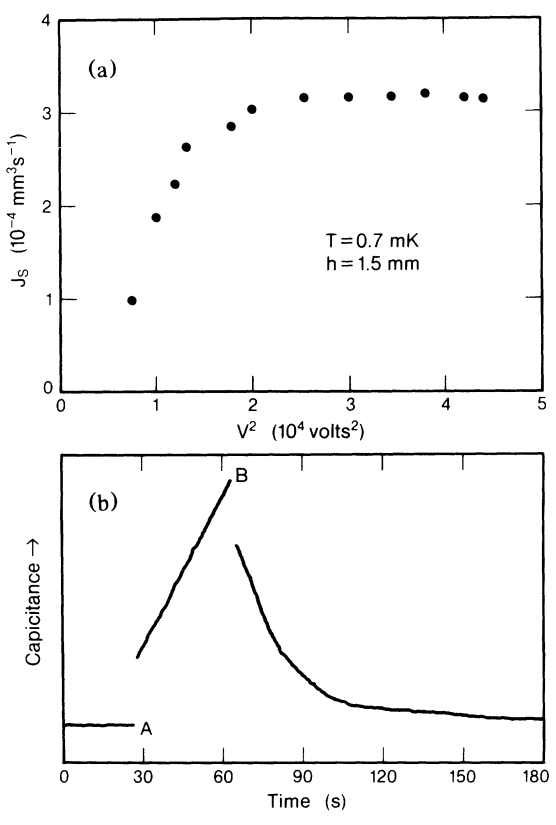

FIG. 2. (a) The rate of arrival of ^{3}He in the detector J_s as a function of V^2 (which is proportional to the driving pressure). (b) A data trace from a single measurement of the critical current J_c. See text for explanation.

The cell is filled slowly from the bottom at a temperature less than 100 mK until the free surface of the bulk liquid rises to a known distance h from the top of the film-flow detector. Since at these temperatures there is no appreciable vapor and the liquid is in its normal state, the film does not reach its equilibrium thickness nor does it respond to changes in h.

As the temperature is lowered through the bulk transition temperature T_c^B (which is detected with ^{3}He NMR), there is no observable change at the flow detector unless h is less than the capillary length ($\simeq$0.5 mm). After further cooling, the liquid abruptly begins to flow into the capacitor gap to permit the film to reach its equilibrium thickness. We identify this point as the film superfluid transition temperature T_c^F.

Once below T_c^F the film flow continues until the film thickness reaches its equilibrium value appropriate for the particular height h. Once this equilibrium is established, further decreases in temperature have no effect on film thickness.

Below T_c^F, when a voltage is applied across the capacitor, the film flows into the gap to establish a new increased equilibrium thickness. The film current is determined by the rate of change of gap capacitance. As shown in Fig. 2(a), the mass current through the superfluid film, J_s, increases as a function of electrostatic driving force (proportional to V^2) until it saturates at a well-defined current. We identify this saturation current with the depairing critical current J_c. The fact that there are currents below J_c at finite values of V^2 implies that there are dissipation processes in the film flow which precede pair breaking.

A typical measurement is shown in Fig. 2(b). At point A, the voltage (200 V) is turned on and there is an abrupt increase in capacitance due to the direct motion of the two electrodes. Thereafter the capacitance in-

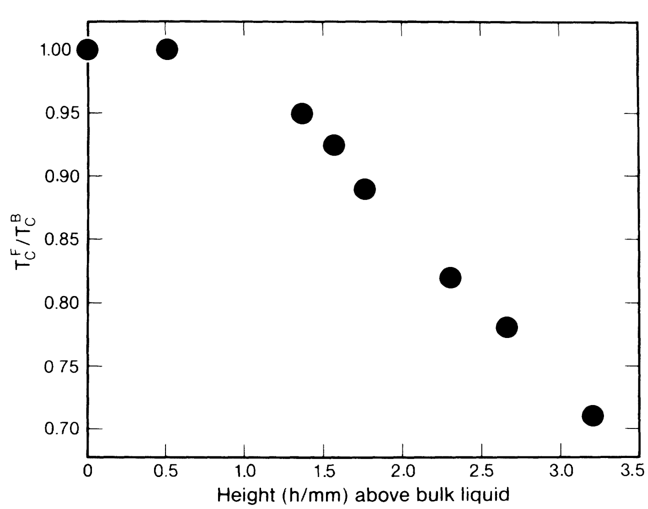

FIG. 3. The reduced critical temperature T_c^F/T_c^B for several values of h.

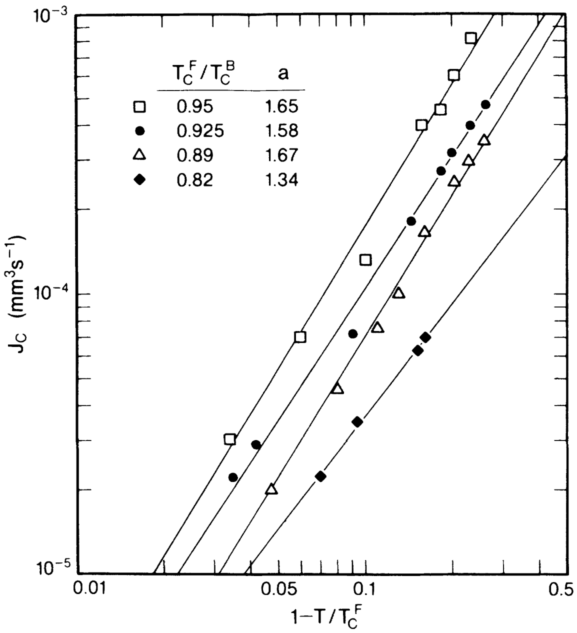

FIG. 4. The critical currents J_c for four different values of T_c^F as a function of $1-T/T_c^F$. The T_c^F's were measured as explained in the text. The solid lines are fits to the data and each has a slope a, as indicated in the legend.

creases linearly with time until at point B the voltage is switched to zero. At this instant the capacitance abruptly decreases as a result of the electrodes moving back to their original position. Subsequently the film flows out of the capacitor and relaxes back to the equilibrium thickness. The outgoing flow transient typically displays a constant slope, determined by the depairing critical current until very near equilibrium where the predepairing dissipation becomes evident.

During each of these measurements the film thickens by about 1%. For a fixed value of h, as the experiment slowly warms, a temperature is reached at which the current becomes zero. This is the film critical temperature T_c^F characteristic of the height h.

We have determined the film transition temperature T_c^F as a function of the height h. The data, shown in Fig. 3, demonstrate that T_c^F is a decreasing function of film thickness, as expected. Under no circumstances have we detected film flow at temperatures above T_c^B. Since we do not have a reliable determination of the film thickness, it is impossible to make a strong comparison of our data to existing theory. However, it seems reasonable that film thicknesses of the order of 10^3 Å should lead to suppressions of T_c comparable to those which are observed.

We have also measured the variation of saturation critical current as a function of temperature for several different film thicknesses. (The measurements were made with an applied voltage of 200 V.) The data shown in Fig. 4 demonstrate that J_c varies with temperature as $(1-T/T_c^F)^a$ where a is between 1.34 and 1.67. The temperature dependence predicted in several calculations on depairing currents in confined geometries[2] is $(1-T/T_c^F)^{1.5}$.

Also apparent in Fig. 4 is the fact that the saturation current J_c is smaller at a given reduced temperature as the film thickness decreases (with increasing h).

Studies of superfluid ^{3}He film flow have also been reported in a double-beaker experiment.[12–14] If the data from those experiments are analyzed in terms of the height h, which is the directly measured quantity in both types of experiment, there is agreement to about 15% in both the critical currents and the T_c suppression.[16]

In summary, it is clear that superfluidity in ^{3}He films can be achieved and that the resultant phenomena can probably be understood in terms of existing theoretical models. It appears as if the ^{3}He superfluid film system can be an interesting testing place for current ideas of quantum liquids. We hope to continue this research using a flow apparatus whose walls are smooth on a scale much less than ξ_0.

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[1]L. H. Kjaldman, J. Kurkijärvi, and D. Rainer, J. Low Temp. Phys. **33**, 577 (1978).

[2]K. W. Jacobsen and H. Smith, J. Low Temp. Phys. **67**, 83 (1987).

[3]A. L. Fetter and S. Ullah, to be published, and Jpn. J. Appl. Phys. **26**, 149 (1987).

[4]J. P. Pekola, J. C. Davis, Zhu Yu-Qun, R. Spohr, P. B. Price, and R. E. Packard, J. Low Temp. Phys. **67**, 47 (1987).

[5]J. Hook, Jpn. J. Appl. Phys. **26**, 159 (1987).

[6]T. Chainer, Y. Morii, and H. Kojima, J. Low Temp. Phys. **55**, 353 (1984).

[7]V. Kotsubo, J. Ditusa, T. Hall, R. Mihailovich, and J. M. Parpia, Jpn. J. Appl. Phys. **26**, 143 (1987).

[8]K. Ichikawa, S. Yamasaki, H. Akimoto, T. Kodama, and T. Shigi, Phys. Rev. Lett. **58**, 1949 (1987).

[9]M. T. Manninen and J. P. Pekola, Phys. Rev. Lett. **48**, 812, 1369(E) (1982), and J. Low Temp. Phys. **52**, 497 (1983).

[10]V. Kotsubo, K. D. Hahn, and J. M. Parpia, Phys. Rev. Lett. **58**, 804 (1987).

[11]D. D. Osheroff, unpublished.

[12]A. Sachrajda, R. F. Harris-Lowe, J. P. Harrison, R. R. Turkington, and J. G. Daunt, Phys. Rev. Lett. **55**, 1602 (1985).

[13]J. G. Daunt, R. F. Harris-Lowe, J. P. Harrison, A. Sachrajda, T. Seeto, S. C. Steel, R. R. Turkington, and P. Zawadzki, Jpn. J. Appl. Phys. **26**, 145 (1987).

[14]J. G. Daunt, R. F. Harris-Lowe, J. P. Harrison, A. Sachrajda, S. Steel, R. R. Turkington, and P. Zawadzki, to be published.

[15]A more detailed view of the apparatus is shown in a preliminary report of this work, J. D. Davis *et al.*, Jpn. J. Appl. Phys. **26**, 147 (1987).

[16]S. Steel, private communication.