Observations of a Critical Current in ^{3}He-B

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The flow of ^{3}He-B is studied in a U-tube geometry. The current is found to saturate at a critical value, $J_{s,c}$, which is independent of driving force. The current $J_{s,c}$ scales with temperature as $(1-T/T_c)^{3/2}$ in agreement with Ginzburg-Landau theory.

The very low-temperature phases of ^{3}He (i.e., ^{3}He-A and ^{3}He-B) are believed to be examples of anisotropic BCS-type "superfluids."[1] Such condensate systems should possess an effective superfluid density ρ_s which is a decreasing function of superfluid velocity v_s. This implies that the superfluid current, $\rho_s v_s$, exhibits a maximum value $J_{s,c}$ at some velocity above which the superfluid state is unstable.[2] This paper reports the first observation of $J_{s,c}$ and the determination of its characteristic temperature dependence.

Our apparatus permits the study of flow at saturated vapor pressure and thus we will restrict our discussion to the B phase of ^{3}He. Applying the Ginzburg-Landau free-energy expansion to this system (assuming weak-coupling BCS theory and no gradients in the magnitude of the order parameter) one gets the result[3,4]

$$J_{s,c}=2.15\,\rho\,\frac{k_B T_c}{p_F}[1-T/T_c]^{3/2},$$

where ρ is the fluid density, k_B is Boltzmann's constant, T_c is the transition temperature, and p_F is the Fermi momentum. The weak-coupling BCS theory should be quite accurate at zero pressure where, for example, the specific-heat jump (between the normal ^{3}He and the B phase) is found[5] to be quite close to the weak-coupling value.

Our experiment employs a U-tube geometry, shown in Fig. 1, to observe bulk superflow. The U tube is made up of two reservoirs connected by a capillary superleak. Since we measure the position of a free surface in the reservoirs we are necessarily operating at the saturated vapor pressure and hence, in the absence of a large magnetic field, in the B phase. The measurement of the velocity of the surface in the reservoirs provides a direct measure of the supercurrent in the superleak. Observing the response of the system to step forces of various amplitudes allows the determination of critical flow rates.

The body of the device is made from Stycast 1266 epoxy. The reservoirs are concentric cylinder capacitors, made of stainless steel. Each of these capacitors has a 0.020-cm gap, a 0.518-cm inner diameter, and a capacitance of about 7.5 pF. One of these serves as a liquid-level detector while the other is used to generate level differences.

The designed flow channel connecting these two capacitors is a cylinder 1 cm long and 0.25 mm in diameter. After our flow measurements were terminated, the cell was cut apart and an additional parallel channel (formed by a void in the epoxy) was discovered. By putting ink in the channel and observing through the transparent epoxy it was apparent that the channel had an irregular cross-sectional shape. Additional sectioning and measurement revealed that the region which appeared to have the smallest area was

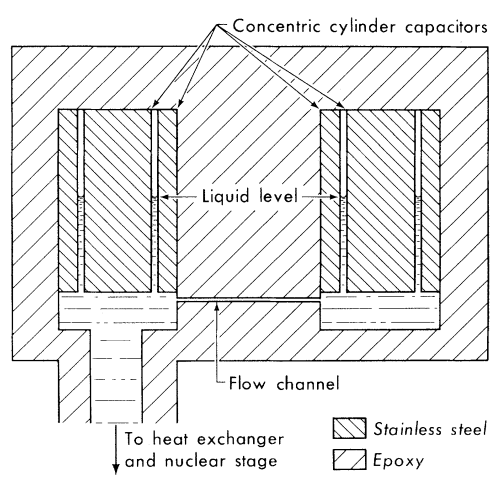

FIG. 1. Schematic diagram of the flow cell, not to scale. Heat exchanger and thermometer tower are not shown.

approximately rectangular in cross section with dimensions approximately 0.1 mm by 1 mm. Thus the region of smallest total cross section (and hence highest current density) had an area of approximately 1.5×10^{-3} cm^2.

The U tube is epoxied onto the lid of a sintered silver heat exchanger connected to a conventional nuclear demagnetization refrigerator.[6] This refrigerator is capable of cooling the ^{3}He to below 0.5 mK. The ^{3}He thermally relaxes to the nuclear stage in less than 3 min at 1 mK. The flow channel itself has a calculated thermal resistance of about 0.2 mK/nW at 1 mK and we estimate the heat flux along the channel to be less than 0.1 nW. The isolated side of the U tube will thermally relax to the heat exchanger side in about 20 sec at 1 mK.

For thermometry[6] we employ pulsed NMR in ^{195}Pt immersed in the ^{3}He. A Curie-law susceptibility is assumed and the calibration constant is determined with use of the Korringa relation for the spin-lattice relaxation time. In our magnetic field of approximately 200 G we assume a Korringa constant[7] of 29.8 mK sec. The thermometer is connected to the main ^{3}He reservoir and the temperature for the onset of superflow is found to be $T_c = 0.98$ mK. If our choice of the Korringa constant is wrong then the value of T_c correspondingly shifts. The values of T/T_c are, of course, independent of the calibration constant and rely only on Curie's law. The temperature resolution near 1 mK is somewhat less than 1%. The thermometer is contained in an epoxy tower attached to the heat exchanger. The tower is surrounded by a niobium tube used to trap the magnetic field for the NMR.

Level differences between the two reservoirs are established by applying a dc voltage V to one of the capacitors. Because of the dielectric constant of the ^{3}He, a level difference ΔH is induced given by

$$\Delta H = \alpha V^2,$$

where the geometry-dependent constant α is 5.6×10^{-7} cm/V^2. These height variations are measured by the opposite capacitor which is connected in an ac Wheatstone bridge circuit by use of a room-temperature reference capacitor. The changes in capacitance ΔC are related to the height variations Δx by

$$\Delta C = C_a(K-1)\Delta x/H_0,$$

where C_a is the active capacitance, K is the ^{3}He dielectric constant and H_0 is the overall capacitor height. With a bridge excitation of 0.2 V we can resolve level changes of 4×10^{-4} cm with a time constant of 1 sec.

When the ^{3}He is in the normal state, the liquid levels relax exponentially to their equilibrium value with a time constant proportional to the viscosity. For our apparatus $\tau \sim 10^4$ sec just above the transition temperature. Below T_c the relaxation time decreases dramatically and the characteristic curve of liquid height versus time is not exponential. A series of response curves is shown in Fig. 2. Note that there are no oscillations.[8] For sufficiently large V^2, the liquid levels initially relax linearly in time. This linear flow rate, which is the maximum current, is independent of the initial level difference (i.e., independent of driving force). We take this to be the characteristic signature of the critical current.

The maximum current in the superleak is given by $J_{s,c} = \rho \dot{x}_m A/\sigma$, where $\dot{x}_m$ is the maximum slope of the response curve and A/σ is the ratio of the capacitor cross-sectional area to the area of the flow channel. Since the flow channel had a varying cross section and relevant σ is the smallest area in the path. Our measurements of $\dot{x}_m$ are shown in Fig. 3. These results were obtained from several demagnetizations. The scatter is due mainly to the resolution of the NMR thermometer. The observed critical current evidently varies as $(1-T/T_c)^{3/2}$ at least down to $T/T_c \sim 0.5$. This is the behavior predicted.[3,4]

Using the somewhat imprecisely determined value of σ, we find the prefactor of $(1-T/T_c)^{3/2}$ is 0.3 g/cm^2 sec, which is close to the predicted value of 0.29 g/cm^2 sec. This close agreement may be fortuitous since, as stated earlier, the cross-sectional area σ is not known precisely. Further measurements are planned to make a

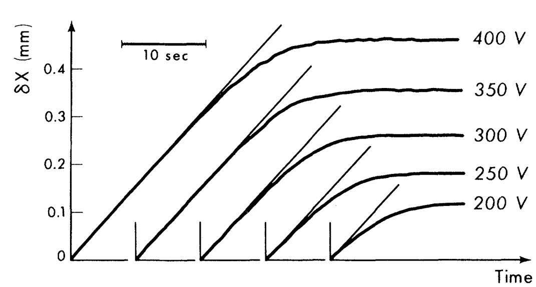

FIG. 2. A series of superfluid response curves taken at $T/T_c = 0.95$. These curves show the liquid-level difference after application of a dc bias to one capacitor. The diagonal lines are all parallel.

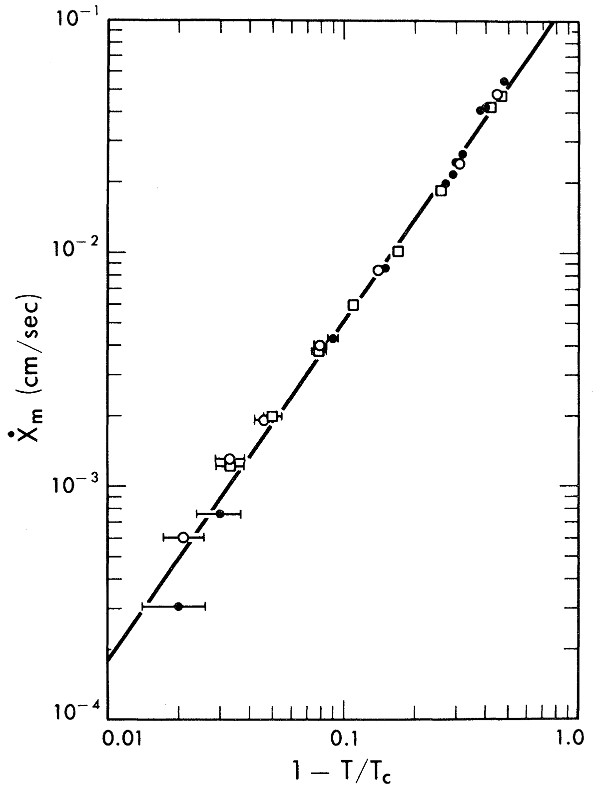

FIG. 3. Plot of the maximum fluid velocity in one of the capacitors, $\dot{x}_m$, vs temperature. The solid line has slope $\frac{3}{2}$ but is otherwise a guide to the eye. The different symbols refer to different demagnetizations.

meaningful comparison with theory.

It is important to realize that this critical current is not necessarily correlated with the onset of dissipation. It is entirely probable that some form of dissipation occurs at much lower velocities but the mechanisms are too weak to prevent the superfluid from attaining substantially higher velocities. Apparently this is the case as the system does not exhibit oscillations.

In conclusion, we have observed the saturation of driven superflow in ^{3}He-B. The maximum observed current exhibits the temperature dependence expected for the critical current computed in the Landau-Ginzburg regime.

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[1]For a review of the theoretical and experimental aspects of ^{3}He-A and ^{3}He-B, see the articles by A. J. Leggett and J. C. Wheatley in Rev. Mod. Phys. 47, 331 (1975), or the more recent articles in *The Physics of Liquid and Solid Helium Part II,* edited by K. H. Bennemann and J. B. Ketterson (Wiley, New York, 1978).

[2]The literature contains several discussions of these critical currents. For example, see J. Bardeen, Rev. Mod. Phys. 34, 667 (1962), or J. S. Langer and V. Ambegaokar, Phys. Rev. 164, 498 (1967).

[3]A. L. Fetter, in *Quantum Statistics and the Many Body Problem,* edited by S. B. Trickey, W. Kirk, and J. Dufty (Plenum, New York, 1975).

[4]Performing a microscopic calculation (but ignoring flow-induced gap distortion), D. Vollhardt and K. Maki [J. Low Temp. Phys. 31, 457 (1978)] compute $J_{s,c}$ at all temperatures, and find the $\frac{3}{2}$-power law extends to $T/T_c \approx 0.2$. A modification (K. Maki, private correspondence) which includes the flow-induced gap distortion agrees numerically with Ref. 3.

[5]T. A. Alvesalo, T. Haavasoja, P. C. Main, M. T. Manninen, J. Ray, and L. M. M. Rehn, Phys. Rev. Lett. 43, 1509 (1979).

[6]For a comprehensive description of the refrigeration and thermometry in the millikelvin regime see O. V. Lounasmaa, *Experimental Principles and Methods below 1K* (Academic, New York, 1974) or D. S. Betts, *Refrigeration and Thermometry below One Kelvin* (Sussex Univ. Press, Sussex, England, 1976).

[7]Systematic departures from Korringa's law have been reported by several groups. However, most of the measurements are unpublished.

[8]U-tube oscillators of this sort are subject to thermal losses as elucidates by J. E. Robinson, Phys. Rev. 82, 440 (1951). Calculations based on Robinson's model indicate our cell should exhibit only weakly damped oscillations. We intend to address the damping more thoroughly in future experiments.