Crossover of Dissipation Mechanism in Flowing Superfluid ^{3}He-B Near the Tricritical Pressure

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dc flow of superfluid ^{3}He-B through a rectangular superleak exhibits two dissipative regimes and two critical currents with temperature dependence of the form $J_c = b(1 - T/T_c)^a$. At low pressures $a \simeq \frac{3}{2}$ and b increases with pressure. Around 21.5 bars a crossover occurs to a new dissipation regime with $a \simeq 2$ and the prefactor b then decreases with pressure.

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We report in this Letter a new result in experiments to investigate the systematics of superflow in liquid ^{3}He. In a previous Letter[1] we reported observations of low-frequency (~ 40 Hz) isothermal oscillations through a rectangular superleak 9.16 mm long and with cross section 48 μm by 2.86 mm, with a 98-G magnetic field perpendicular to the axis of the channel. They showed the existence in the B phase of three distinct flow regimes with low, medium, and high dissipation separated by sharply defined critical currents. Experiments in other laboratories[2–6] have also found differing flow regimes in superfluid ^{3}He-B with other types of superleak. The origins of the dissipation in the different regimes have not been identified, although we observed a limiting "saturation" current whose temperature dependence (at not too high pressures) and approximate magnitude corresponded with the theoretical so-called pair-breaking current,[7–9] $J_c \propto (1 - T/T_c)^{3/2}$, where T_c is the normal-superfluid transition temperature.

These measurements have now been extended to dc flow in the same apparatus, and, in general, give results consistent with the previous ones. They were designed, among other aims, to investigate in detail a single observation at 26 bars in our oscillation experiments which indicated a different power index in the temperature dependence of the critical current, and they have yielded an important new observation. There is a very striking and unexpected change in this temperature dependence over a narrow range (~ 2 bars) of pressure around 21.5 bars. This pressure, which is equal to the tricritical pressure p_3, has an obvious meaning at the tricritical temperature T_3 since $p > p_3$ and $p < p_3$ then correspond to the ^{3}He-A and ^{3}He-N phases which, of course, behave very differently. Our observation is, however, that even deep within the B phase, with $T < T_3$, there is a rather sharp change in behavior near p_3. There seems to be no obvious reason for this, which may be purely coincidental. The effect has now been carefully investigated as a function of pressure.

As previously described,[1,10] in our experiment fluid is driven through the superleak by means of an electrostatically operated gold-plated flexible circular membrane (Kapton). The quantities Δp (hydrostatic pressure difference across the membrane) and x (displacement of center of membrane) can be deduced from a knowledge of the electrostatic force applied to the membrane (proportional to V^2, where V is the applied potential difference between the membrane and a neighboring electrode) and a measurement of the capacitance C between the membrane and a second electrode on the other side. It can be shown simply that with a dc applied ramp voltage $d(V^2)/dt = \text{const}$ and the measured constant rate of change of C, $\dot{x}$ (and hence the flow current J) and $d(\Delta p)/dt$ can be deduced:

$$\dot{x} = \alpha \dot{C} - \beta d(V^2)/dt, \tag{1}$$

$$d(\Delta p)/dt = \gamma \dot{C} - \delta d(V^2)/dt, \tag{2}$$

where α, β, γ, and δ are constants (for a given cell) depending on geometry and the tension in the membrane. A voltage change from 50 to 500 V was always used, and the ramp rate was varied by changing the time of application from about 0.5 to 20 s. In all cases the observed flow current is constant, or very nearly so, for a given ramp rate ($x \propto t$) and in the supercritical cases the pressure difference also increases linearly. Hence the low current is *independent of the pressure head,* although it varies with the *rate of increase* of pressure difference, as shown in Fig. 1.

Figure 1 shows the rate of growth of dissipation, plotted as $d(\Delta p)/dt$, as a function of flow current J for a number of different temperatures at a pressure of 16.5 bars. Similar results are found at other pressures and temperatures. It is notable that in these experiments the dissipation is never observed to approach saturation over the time of application of the ramp. These dc flow results confirm strikingly the existence of sharply differing flow regimes

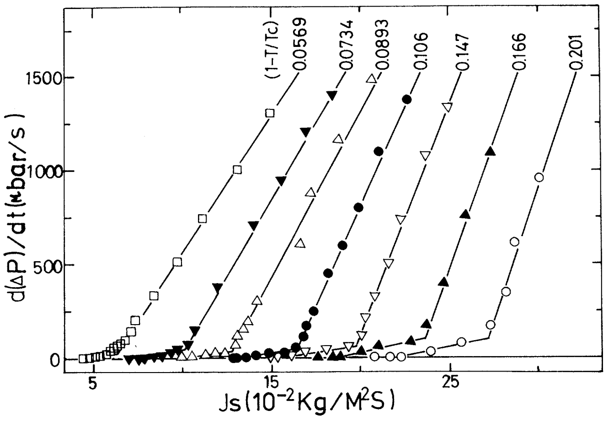

FIG. 1. Rate of growth of dissipation at 16.5 bars as a function of flow current, for various indicated temperatures ($T_c = 2.385$ mK).

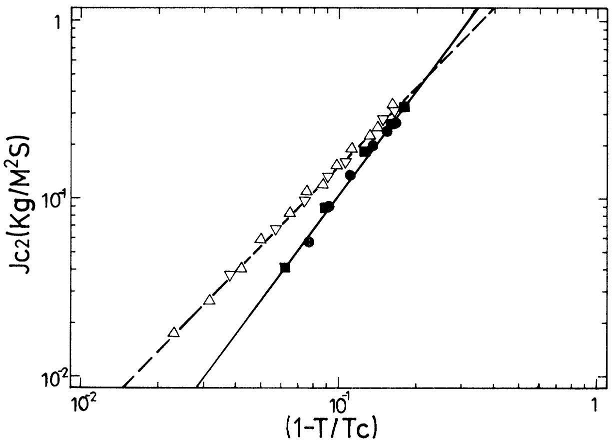

FIG. 2. Log-log plot of the upper critical current as a function of $1 - T/T_c$. Full line: $p = 24.5$ bars, $T_c = 2.630$ mK, slope $a = 1.95$. Dashed line: $p = 16.5$ bars, $T_c = 2.385$ mK, slope $a = 1.48$.

at a given pressure in this superleak. At the lowest currents, no dissipation is observable, although the sensitivity with which this can be determined is not so great as in the case of the oscillatory flow measurements as already pointed out[1,10] (the dc observations are sensitive to about 1 μbar, the oscillatory measurements to $\sim 10^{-3}$ μbar). Sharply defined critical currents J_{c1} divide this regime from a second where the rate of growth of dissipation with J is relatively slow. Equally sharply defined currents J_{c2} mark the onset of more rapidly increasing dissipation.

A number of other experiments,[2-6] in addition to our own previous oscillatory measurements, have also shown these different flow regimes in different types of superleaks, and it now seems firmly established that there are several distinct flow-dissipation processes possible in superfluid ^{3}He-B, with critical onset currents whose temperature and pressure dependence are obviously important. Both the lower ($J_c = J_{c1}$) and the upper ($J_c = J_{c2}$) critical currents fit with good precision a formula commonly used in fitting ^{3}He data, namely,

$$J_c = b(1 - T/T_c)^a, \qquad (3)$$

at all temperatures and pressures. This is the form predicted theoretically for the so-called "pair-breaking" current[7-9] with $a = 1.5$ (independent of pressure) and b a pressure-dependent quantity which depends on the detailed coupling coefficients. The present experiments confirm our previous oscillation results, and other work, that $a \simeq 1.5$ at lower pressures, for both J_{c1} and J_{c2}, though clearly not both critical currents can be "pair breaking," and in addition the current can be driven above the upper critical current J_{c2}, which it could not be for a true pair-breaking current. Specifically, for pressures below the tricritical pressure $a(J_{c1}) = 1.47 \pm 0.06$ and $a(J_{c2}) = 1.46 \pm 0.04$ in these experiments.

The precision with which the power index a can be determined is illustrated in Fig. 2, which is a log-log plot of J_{c2} against $1 - T/T_c$ for two pressures, 16.5 and 24.5 bars. It shows a clear difference in temperature dependence at these two pressures, where least-squares fits give $a = 1.48$ and 1.95, respectively. A striking feature of the present series of measurements is the change of a within a narrow pressure range (~ 2 bars) around the tricritical pressure, $p_3 = 21.5$ bars, even at temperatures well below the tricritical temperature. From a series of graphs similar in precision to those of Fig. 2 we obtain the pressure dependence of the power index a shown in Fig. 3 which shows the rapid change in a for both J_{c1} and J_{c2}. At the higher pressures, $a(J_{c1}) = 2.01 \pm 0.1$ and $a(J_{c2}) = 1.95 \pm 0.04$.

In trying to identify the origin of the critical currents, i.e., the crossover from one dissipative regime to another, the pressure dependence of their magnitude is clearly important. To examine this, we compare in Fig. 4 the magnitude of the prefactor b for J_{c2} with results of Manninen and Pekola[6] at different pressures below p_3. Their experiment was very similar to ours except that their superleak was a piece of Nuclepore filter consisting of many circular channels, each of much smaller cross section (diameter ~ 0.8 μm) than our single channel. They reported only one critical current, corresponding to our J_{c2}, although some of their results do in-

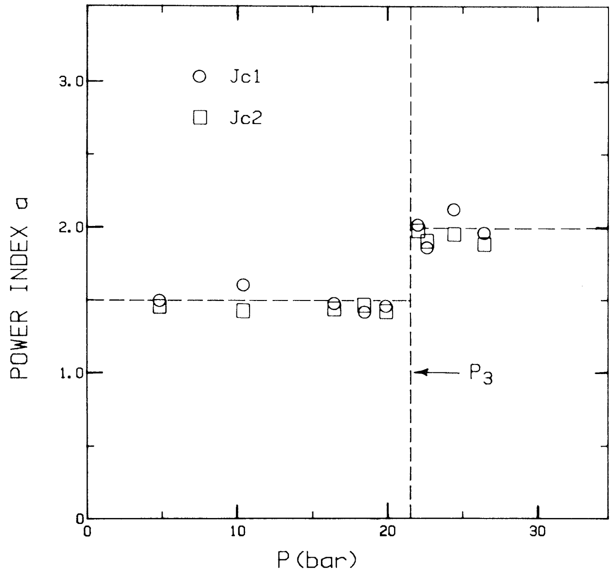

FIG. 3. Exponent a from Eq. (3) plotted as a function of pressure.

dicate the existence of lower critical currents. Because of the small size of their channels they expect their transition temperature to be reduced, and their results are consequently calculated by replacing T_c in Eq. (3) with this reduced temperature T_{cy1}, obtained from their own observations at the lowest pressure and by application of the theory of Kjäldman, Kurkijärvi, and Rainer[11] at higher pressures. Agreement between the two sets of measurements is extremely good, and implies that J_{c2} has negligible dependence on the cross section of the channel (except when it is small enough to reduce T_c significantly). The mechanism for J_{c2} is thus probably different from that for critical velocities in He II, which are strongly size dependent. Other experimental critical currents[1,3,5] are in rough agreement with those in Fig. 4 at low pressures, but as already reported, our oscillatory measurements in the same superleak[1] give an almost pressure-independent saturation current, which must be due to the different way in which the measurements are made.

The solid line in Fig. 4 represents the variation of the pair-breaking critical current with pressure according to weak-coupling theory. As previously noted,[12] there is a serious discrepancy in magnitude between theory and experiment. Manninen and Pekola[6] have calculated the modification to weak-coupling theory when account is taken of the reduction in T_c due to small channel size. This gives a curve which is in better agreement with their experiments, but not in such good agreement as that between the two sets of experimental results, and may therefore be fortuitous.

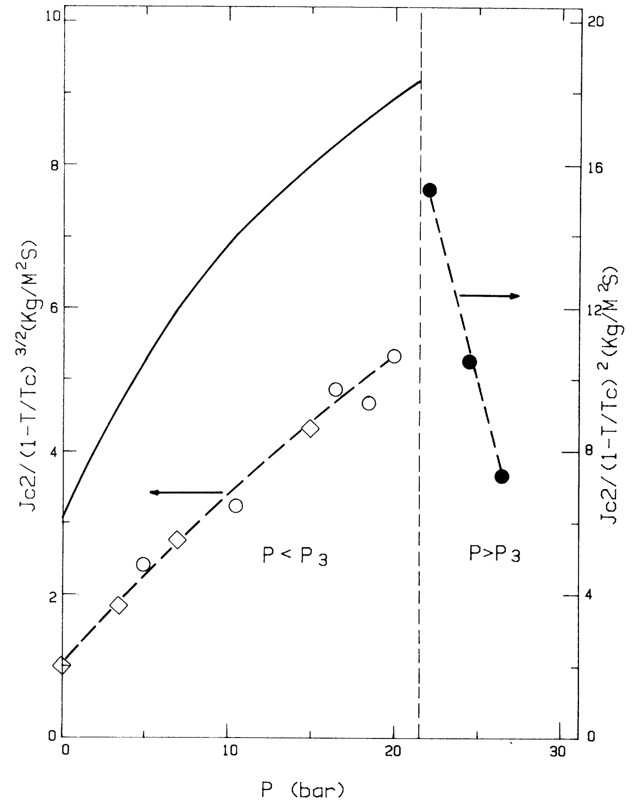

FIG. 4. Prefactor b from Eq. (3) plotted as a function of pressure for the data of Maninnen and Pekola (Ref. 6) (diamonds) and the present experiments (open and filled circles). The left ordinate relates to pressures below p_3, where $a \simeq \frac{3}{2}$, and the right ordinate to pressures above p_3, where $a \simeq 2$.

The power-index change around 21.5 bars, shown most clearly in Fig. 3, implies that as the pressure is increased in flowing ^{3}He-B a rapid change in the dissipation process takes place over a pressure range of at most 2 bars. Fetter[7] has shown that there is a critical current where ^{3}He-B makes a transition into the A phase. However, within the A phase, critical currents for onset of dissipation[6,13,14] do not have the temperature dependence observed by us here at $p < p_3$, implying that the different dissipation process at higher pressures is not due to the presence of ^{3}He-A in flowing ^{3}He-B in this case. In our high-pressure regime, the prefactor b in the expression $J_{c2} = b(1 - T/T_c)^2$ is a strongly decreasing function of pressure, as shown in Fig. 4.

We should, however, point out an experimental effect which may have some general bearing on the observation of dynamic equilibrium observations in both superfluid ^{3}He and ^{4}He. All of the above reported observations were made after considerable periods (≥ 5 h) had elapsed during which thermometric observations indicated the existence of thermal equilibrium. We had discovered that, after a nuclear demagnetization lasting ~ 10 h, temperature equilibrium was indicated but critical current observations were time dependent for further periods amounting to 5 h or more. We therefore adopted a standard procedure of waiting for at least this period of apparent thermal equilibrium, and then testing for reproducibility, before regarding our observations as reliable. This observation of long-lived dissipative structures may be related to the recent report by Awschalom and Schwarz[15] of an equilibrium remanent vorticity in superfluid ^{4}He, and may provide an indication of the origin of some of the dissipation we observe, if not of its pressure dependence.

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