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Critical current of $^3$He-$A$ in narrow channels

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The critical current $J_c$ of superfluid $^3$He-$A$ in 0.8-μm-diam channels has been measured by the observation of the pressure difference along the channels versus the mass current. During warming $J_c$ was found to decrease by about 30% at $T_{BA}$(cyl) and by another 30% at $T_{BA}$; $T_{BA}$(cyl) is the reduced $B \rightarrow A$ transition temperature in the narrow flow channels, with $T_{BA}$(cyl)/$T_{BA} = 0.92$ at 27.4 bars. Above $T_{BA}$ a second dissipative mechanism was observed at lower currents. These features are believed to be associated with the ends of the channels.

The $A$ phase of superfluid $^3$He, because of its anisotropic nature, is expected to possess unusual flow properties. For example, the critical velocity $v_c$ in a narrow flow channel should depend strongly on the texture formed by the $l$ vector. Measurements of $v_c$ in channels with diameter large compared to the coherence length, $\xi_0 = 0.076 \mu m$ at $P = 0$, have yielded values between 0.1 and 0.8 mm/s. Even in a channel as small as 18 μm $v_c$ was not more than 2 mm/s. All these values are less than either the observed $v_c$ in the $B$ phase under similar conditions or the predicted depairing critical velocity. The mechanisms responsible for the dissipation at these low velocities are not well understood.

In this work we have measured the critical mass current $J_c$ of $^3$He-$A$ through 0.8-μm-diam and 10-μm-long channels. Such a geometry should be suitable for observing the depairing current, because other dissipative mechanisms, like vortex movement, become ineffective when the channel diameter approaches the coherence length. The $l$ vector should also be effectively fixed by the boundary condition at the walls.

Our results show a number of new features not observed in experiments with larger flow channels. In particular, suppression of the $B \rightarrow A$ transition in the narrow channels permits us to measure $J_c$, with either $A$- or $B$-phase liquid outside the channels. The observed behavior of $J_c$ at the $B \rightarrow A$ phase transition temperatures, $T_{BA}$ in bulk liquid and $T_{BA}$(cyl) in the channels, suggests that the ends of the channels have a profound effect on the flow. Since we measure the pressure difference as a function of the current, we also obtain quantitative information about dissipation above $J_c$.

The experimental cell (cf. Fig. 1 in Ref. 9) consists of two $^3$He compartments, coupled through a superleak, which was made of Nuclepore filter; the total cross-sectional area of the flow channels is 0.015 mm$^2$. An aluminized Mylar diaphragm forms a flexible wall between the two compartments and was used, with capacitor plates on both sides, to induce a flow through the channels and to detect the pressure difference $\Delta P$. Temperatures were measured with two CLMN (cerium magnesium nitrate diluted to 3% molar solution by the corresponding lanthanum salt) thermometers, one on each side of the cell and both calibrated against tabulated values of $T_c$ versus pressure. $T_c$ and $T_{BA}$ were detected as a change in the slope and as a plateau region in the temperature versus time curve, respectively. All our measurements were performed in zero external magnetic field.

In our flow experiments a drive voltage $U$ was applied on one side of the capacitor, such that the force on the Mylar diaphragm, proportional to $U^2$, varied linearly with time. Simultaneously, the response of the capacitor $\Delta C$ on the other side was monitored. The mass current was varied by employing different sweep rates of $U^2$. An average pressure difference $\Delta P_{av}$ was determined by integrating the instantaneous $\Delta P$, obtained from the recorded $U^2$ and $\Delta C$ as functions of time, and an averaged supercurrent $J_s$ was found from the slope of the $\Delta C$ versus time curve. The uncertainty in converting the measured quantities to pressure and current is about 30%. The critical current was determined from a plot of $\Delta P_{av}$ vs $J_s$ by extrapolating $J_s$ to $\Delta P_{av} = 0$. More details about our experimental techniques have been reported elsewhere.

Considerable changes in the phase diagram of $^3$He are anticipated when the fluid is confined in a restricted geometry, e.g., in a channel with its radius $R$ comparable to $\xi_0$. In our channels, with $R/\xi_0 \approx 23$ at the highest pressure $P = 27.4$ bars, we expect a 0.7% reduction in $T_c$ at most. The $B \rightarrow A$ transition, however, should be suppressed much more owing to the different surface energies in the $A$ and $B$ phases. In our geometry, with relatively long channels and free liquid on both sides, we found that $J_c$ depends on whether the bulk liquid is in the $A$ or the $B$ phase. This is clearly seen from Fig. 1,
where the average current $J_a$, normalized with the expected temperature dependence $(1 - T/T_c)^{3/2}$ for the depairing current, has been plotted as a function of reduced temperature. $J_a$, produced by a voltage step $U = 100$ V applied on the driving capacitor, is about 30% larger than the extrapolated $J_c$, but it shows the general behavior of the critical current.

Three distinct regimes are evident from Fig. 1. Far below $T_c$ the bulk liquid as well as $^3$He in the channels are in the $B$ phase. Upon warming the $B \rightarrow A$ transition occurs first in the channels, at $1 - T_{BA}(cyl)/T_c = 0.18$. The observed broadening of this transition is probably caused by the distribution of the channel diameters; we found that 80% of the holes have a diameter between 0.8 ± 0.2 μm. Finally, the $B \rightarrow A$ transition in the bulk liquid is seen as a drop of $J_a$ to a lower value at $1 - T_{BA}/T_c = 0.109$. Temperature hysteresis due to supercooling is characteristic to both transitions.

Qualitatively similar behavior was found at $P = 22.7$ bars, with $1 - T_{BA}(cyl)/T_c = 0.11$ and $1 - T_{BA}/T_c = 0.021$.

The observed reductions in the $B \rightarrow A$ transition temperatures are comparable in magnitude to those reported by Ahonen, Krusius, and Paalanen in a 4-μm parallel-plate geometry; Saunders et al. have found $1 - T_{BA}(cyl)/T_c > 0.5$ in 2-μm-diam channels. The reduction of $T_{BA}$ in our experiments may be influenced by the relatively short length of our channels, compared with earlier static measurements, and by the $B$ liquid flowing into the channels.

Figure 2 illustrates the dependence of $\Delta P_{av}$ on $J_a$, measured at $P = 24.6$ bars. Below $T_{BA}$ the behavior is similar to that observed in the $B$ phase at lower pressures. Above $T_{BA}$, however, the onset of dissipation is markedly different. $\Delta P_{av}$ increases first with a relatively small slope and then faster with a slope similar to that observed below $T_{BA}$. We attribute these two distinct slopes to two different dissipative mechanisms which will be discussed below. Two critical currents are thus obtained from these two slopes by extrapolating the values of $\Delta P_{av}$ to zero.

The values of $d\Delta P_{av}/dJ_a$ are shown in Fig. 3 as functions of temperature. The steeper slopes taken above and below $T_{BA}$ lie on the same straight line (upper curve), suggesting that this slope in the $A$-phase region is due to the same dissipative mechanism which operates below $T_{BA}$. With large enough
\[ \Delta P, \] the current saturates to a value which is about 40% larger than the extrapolated \( J_c \).

The extrapolated critical current \( J_c \) is shown as a function of temperature in Fig. 4 at three different pressures. The uppermost points, joined by a curve, correspond to \( T_{BA}(cyl) < T < T_{BA} \); in this region \( J_c \) is approximately proportional to \((1 - T/T_c)^{3/2}\). The depairing current of the bulk \( A \) phase in the Ginzburg-Landau region is given by \[ 1.86(\Delta C_A/\Delta C_{BCS}) \times (\rho k_b T_c/\rho_f)(1 - T/T_c)^{3/2}. \]

Using the measured specific-heat jump it equals \[ 13.8(1 - T/T_c)^{3/2} \text{ kg/m}^2 \text{s} \text{ at } P = 27.4 \text{ bars}, \] which is about four times larger than our experimental \( J_c \). Above \( T_{BA} \) the magnitude of \( J_c \) is about 30% smaller (the middle set of points in Fig. 4) than below \( T_{BA} \) and the temperature dependence is slightly weaker.

The extrapolated current corresponding to the smaller slope in Fig. 2, as shown in Fig. 4, displays a similar behavior. Near \( T_c \) both currents tend to bend down owing to a reduction in \( T_c \); they extrapolate to zero at \( T/T_c = 0.994 \), in agreement with the theoretically expected decrease in \( T_c \) without flow. The change in \( J_c \) at \( T_{BA} \) and the existence of the second critical current must be caused by effects associated with the ends of the channels because the phase transition occurs only in the bulk liquid. The small value of \( J_c \) below \( T_{BA} \) may be due to the \( A-B \) interface present in this region. Figure 4 indicates that above \( T_{BA}(cyl) \) \( J_c \) is independent of pressure within the scatter of our data; below \( T_{BA}(cyl) \) \( J_c \) changes by 10% between 22.7 and 27.4 bars.

The effect of the ends of a cylindrical channel on the superflow has been considered by Thuneberg and Kurkijärvi. In particular, they show that the critical current through a long channel containing a disgyration texture vanishes, irrespective of the direction of the \( \vec{J} \) vectors at the two ends of the channel. With \( R = 0.4 \mu \text{m} \), a disgyration is energetically the most favorable texture. Further, in this case an applied pressure induces a current, which is determined by friction between the normal component and the \( \vec{J} \) texture. This current is given by \[ J_s = \left( \frac{m}{h} \right)^2 \times \left( \frac{\mu L_{eff}}{p} \right) \Delta P, \] where \( \mu \) is the Cross-Anderson viscosity coefficient and \( L_{eff} = 2R \) is the effective length of the end zones. After inserting typical values we obtain \[ d \Delta P/dJ_s = 0.4(1 - T/T_c)^{-3/2} \text{ m/s} \] which is close to our result in Fig. 3 (lower curve). The nonzero \( J_s \) can be qualitatively understood as arising from flow channels of noncylindrical symmetry, i.e., from channels having two or more holes touching each other. This model requires that the ratio of the critical currents corresponding to the steeper and smaller slopes is constant, depending only on the distribution of channels; this is not inconsistent with our data.

In conclusion, the critical mass current of \(^3\text{He}-A\) in narrow channels differs significantly from that measured in a more open geometry. At present there exists no theoretical calculations for the depairing current in a restricted geometry; in the bulk liquid the predicted value exceeds our measured \( J_c \) by a factor of 4. The results show that \( J_c \) and the nature of dissipation depend on the phase, \( A \) or \( B \), of the bulk liquid outside the flow channels. This suggests that dissipation is restricted to the end zones of the channels.

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