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Published in:
Physical Review B

DOI:
10.1103/PhysRevB.26.5233

Published: 01/01/1982

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Manninen, M. T., Pekola, J. P., Sharma, R. G., & Tagirov, M. S. (1982). Critical current of 3He-A in narrow channels. Physical Review B, 26(9), 5233-5236. https://doi.org/10.1103/PhysRevB.26.5233

Critical current of ^{3}He-A in narrow channels

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(Received 23 April 1982; revised manuscript received 5 August 1982)

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 $T_{BA}(\text{cyl})/T_{BA} = 0.92$ 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 $\hat{l}$ vector.[1,2] Measurements of v_c in channels with diameter large compared to the coherence lengh, $\xi_0 = 0.076$ μm at $P = 0$, have yielded values between 0.1 and 0.8 mm/s.[3–5] Even in a channel as small as 18 μm v_c was not more than 2 mm/s.[6] All these values are less than either the observed v_c in the B phase under similar conditions[6] or the predicted depairing critical velocity.[7,8] 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 $\hat{l}$ 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[10] 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 ΔP. 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.[11] 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 ΔC on the other side was monitored. The mass current was varied by employing different sweep rates of U^2. An average pressure difference ΔP_{av} was determined by integrating the instantaneous ΔP, obtained from the recorded U^2 and ΔC as functions of time, and an averaged supercurrent J_s was found from the slope of the ΔC 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 ΔP_{av} vs J_s by extrapolating J_s to $\Delta P_{\text{av}} = 0$. More details about our experimental techniques have been reported elsewhere.[9]

Considerable changes in the phase diagram of ^{3}He are anticipated when the fluid is confined in a restricted geometry,[12–14] e.g., in a channel with its radius R comparable to ξ_0. In our channels, with $R/\xi_0 \cong 23$ at the highest pressure $P = 27.4$ bars, we expect a 0.7% reduction in T_c at most.[13] The $B \rightarrow A$ transition, however, should be suppressed much more owing to the different surface energies in the A and B phases.[14] 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 in the B phase. This is clearly seen from Fig. 1,

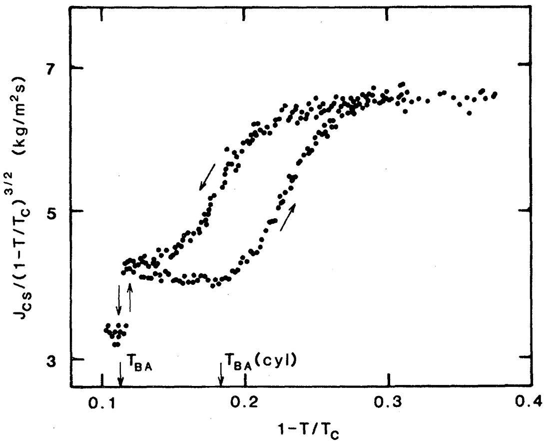

FIG. 1. The normalized average current J_{cs} at $P=27.4$ bars corresponding to $\Delta P_{av} \cong 16.7$ μbar, plotted as a function of the reduced temperature. The $B \rightarrow A$ transition in bulk liquid (at T_{BA}) and inside the flow channels [at T_{BA}(cyl)] are indicated by arrows.

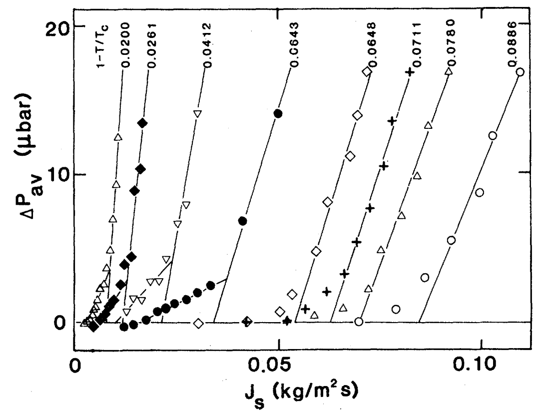

FIG. 2. The average pressure difference ΔP_{av} during the flow at $P=24.6$ bars, plotted as a function of the mass current J_s; the reduced temperatures for each set of points are shown. $1-T_{BA}/T_c=0.064$; because of supercooling, the points at $1-T/T_c=0.0643$ have been measured, however, with the bulk liquid outside the channels in the A phase. The straight lines illustrate extrapolations to $\Delta P_{av}=0$ for determining J_c.

where the average current J_{cs}, 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_{cs}, 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 $1-T_{BA}(\text{cyl})/T_c=0.18$. 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_{cs} 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 $1-T_{BA}(\text{cyl})/T_c=0.11$ 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[15] in a 4-μm parallel-plate geometry; Saunders *et al.*[16] have found $1-T_{BA}(\text{cyl})/T_c > 0.5$ 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 ΔP_{av} on J_s, measured at $P=24.6$ bars. Below T_{BA} the behavior is similar to that observed in the B phase at lower pressures.[9] Above T_{BA}, however, the onset of dissipation is markedly different. ΔP_{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 ΔP_{av} to zero.

The values of $d\Delta P_{av}/dJ_s$ 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

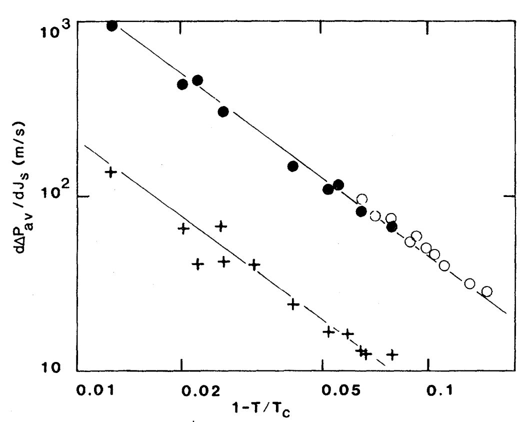

FIG. 3. The slope $d\Delta P_{av}/dJ_s$ vs temperature for $P=24.6$ bars. Circles represent the steeper slope in Fig. 2; filled circles correspond to $T > T_{BA}$. The smaller slope in Fig. 2 is drawn with crosses. The solid lines have the slope of $(1-T/T_c)^{3/2}$.

ΔP, 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 $T_{BA}(\text{cyl}) < T < T_{BA}$; 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 $1.86(\Delta C_A/\Delta C_{\text{BCS}}) \times (\rho k_B T_c/p_F)(1-T/T_c)^{3/2}$.[8] Using the measured specific-heat jump[11] this equals $13.8(1-T/T_c)^{3/2}$ kg/m^{2}s at $P=27.4$ 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 $T/T_c \cong 0.994$, in agreement with the theoretically expected decrease in T_c without flow.[13] 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 $T_{BA}(\text{cyl})$ J_c is independent of pressure within the scatter of our data; below $T_{BA}(\text{cyl})$ 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.[2] In particular, they show that the critical current through a long channel containing a disgyration texture vanishes, irrespective of the direction of the $\hat{l}$ vectors at the two ends of the channel. With $R=0.4$ μm, a disgyration is energetically the most favorable texture.[17] Further, in this case an applied pressure induces a current, which is determined by friction between the normal component and the $\hat{l}$ texture.[2] This current is given by $J_s=(m/\hbar)^2 \times (\mu L_{\text{eff}}/\rho)\Delta P$, where μ is the Cross-Anderson viscosity coefficient[18] and $L_{\text{eff}} \cong 2R$ is the effective length of the end zones. After inserting typical values we obtain $d\Delta P/dJ_s = 0.4(1-T/T_c)^{-3/2}$ m/s which is close to our result in Fig. 3 (lower curve). The nonzero J_c 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.

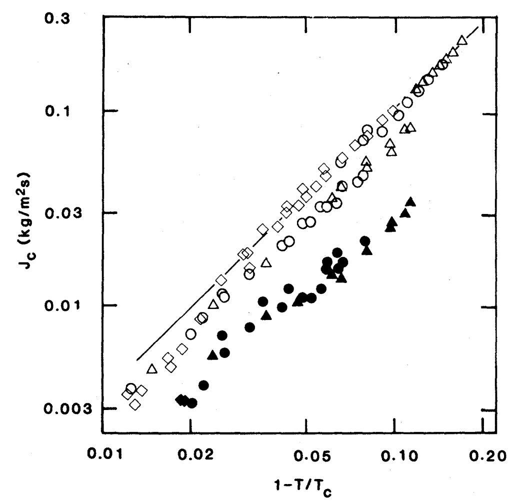

FIG. 4. The extrapolated critical current J_c as a function of temperature. Diamonds correspond to $P=22.7$ bars, circles to 24.6 bars, and triangles to 27.4 bars. Filled symbols represent extrapolations of the smaller slope above T_{BA}. The solid line has the slope of $(1-T/T_c)^{3/2}$.

In conclusion, the critical mass current of ^{3}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.

ACKNOWLEDGMENTS

We are indebted to S. A. Nenonen for help during the measurements and wish to acknowledge useful discussions with O. V. Lounasmaa, H. Smith, and E. V. Thuneberg. This work was financially supported by the Academy of Finland and by the Emil Aaltonen Foundation.

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