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Flow of 3He-B through narrow channels

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of all three elements would be of considerable interest.

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Flow of ^{3}He-*B* through Narrow Channels

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The critical current J_c of superfluid ^{3}He-*B* through 0.8-μm-diam channels has been measured. For small currents the pressure difference $\Delta P = 0$ along the flow channels within the resolution, implying small or zero dissipation. ΔP grows rapidly with increasing current above J_c; a clear transition to dissipative flow is thus observed. The temperature dependence of J_c indicates that the superfluid density and the critical temperature are reduced inside the narrow flow channels.

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The most important feature of a simple superfluid is that it can sustain mass flow without friction. At some critical current J_c, however, the superfluid state becomes unstable, which leads to dissipation. This model was derived from experiments on He II; its validity in the case of ^{3}He-*B* is currently of considerable interest. Parpia and Reppy[1] have observed the onset of

excess dissipation in an 18-μm-diam hole and they relate this to a critical velocity. Similar experiments by Crooker, Hebral, and Reppy[2] indicate that even in 5-μm holes the depairing velocity has not been reached. Eisenstein, Swift, and Packard[3] and Dahm *et al.*[4] found dissipation in larger flow channels for all velocities they investigated; in these measurements, however, only the maximum sustainable current was observed.

We report in this Letter direct measurements of ΔP in ^{3}He-B along narrow flow channels as a function of the mass current density J_s. The data are consistent with zero dissipation at small currents and show, as the velocity is increased, a clear transition to dissipative superflow. Our experimental method enables us to extrapolate to $\Delta P = 0$ and thus to find the critical mass current associated with the onset of dissipation. In addition, our measurements of the superfluid transition in bulk liquid show that T_c is reduced inside the flow channels.

Our experimental silver cell, which was thermally connected to a copper nuclear stage,[5] is schematically illustrated in Fig. 1. An aluminized Mylar diaphragm, with capacitor plates on both sides, divides the cell into two compartments. The separate ^{3}He fill lines to each side were connected together at the mixing chamber of the precooling dilution refrigerator; the flow through the fill line is negligible because of the high viscosity of normal ^{3}He. By application of a biasing voltage U on one side of the capacitor, liquid was forced through the flow channels. The displacement of the diaphragm from equilibrium was monitored by measuring the capacitance of the other side.

The susceptibility of CLMN (cerium magnesium nitrate diluted to 3% molar solution by the corresponding lanthanum salt) and the nuclear susceptibility of platinum were employed as thermometers. Tabulated values[6] of T_c vs P were used for calibration of all three thermometers; T_c was detected with CLMN as a change in the slope of the temperature drift curves.

The superleak was a piece of Nuclepore filter[7] with etched particle-track holes, believed to be straight circular cylinders. The thickness of the filter is 10 μm and the nominal diameter of the channels is 0.8 μm. The electron-microscopically determined total area of the channels was 6.4 $\times 10^2$ μm^2.

In our experiment the drive voltage was typically swept from 0 to 100 V so that U^2, i.e., the force on the diaphragm, varied linearly with time. As a result, the response ΔC of the capacitance bridge (proportional to the displacement x) is also linear with time, provided that there is

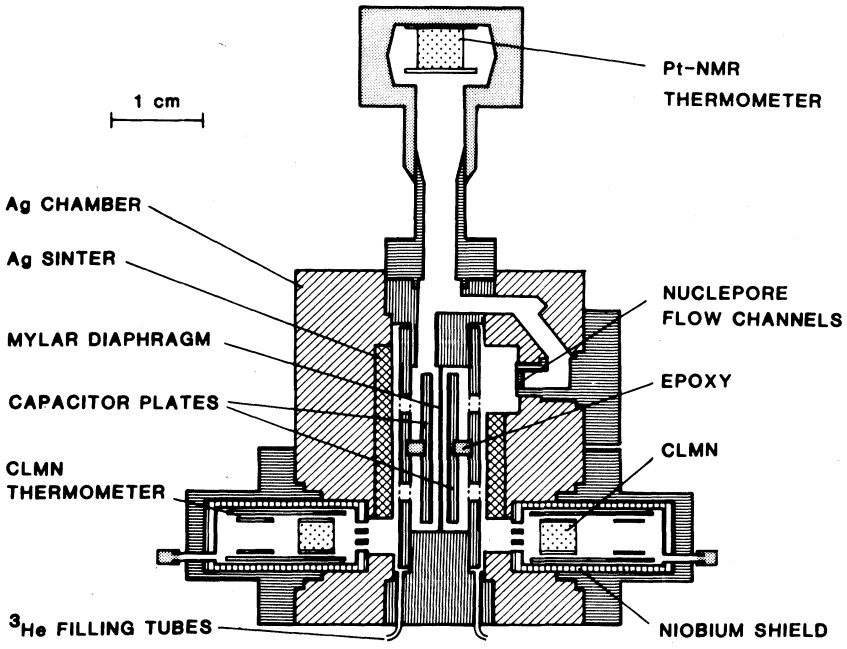

FIG. 1. Schematic diagram of the experimental cell.

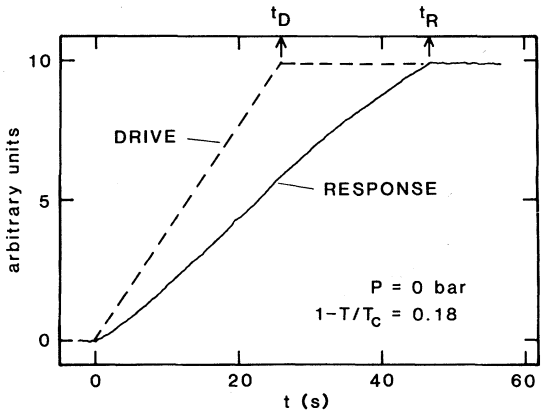

FIG. 2. The normalized response (λx) and drive (αU^2) vs time in a typical dissipative measurement.

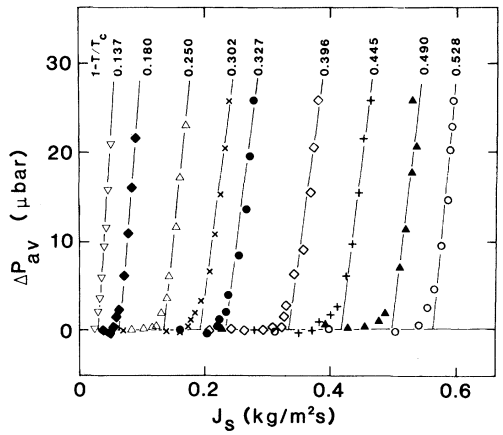

FIG. 3. The average pressure difference ΔP_{av} during mass flow, plotted as a function of the mass current density J_s at $P = 0$. Different symbols correspond to different measurements at constant temperatures; values of $1-T/T_c$ are indicated in the figure. The straight lines show the extrapolations to $\Delta P_{av} = 0$ for determination of J_c.

no dissipation. In this case the response time t_R, needed for ΔC to reach the new equilibrium value, is equal to the rise time of the drive voltage t_D.

Because the mass flow velocity is important only in the superleak, and even there is less than 10 cm/s, we may assume that there are no pressure gradients within the two ^{3}He volumes. If we neglect the small inertia of the membrane, the simple balance equation, $\alpha U^2 = \lambda x + \Delta P$, is valid also during the flow; here α is a geometrical parameter and λ depends on the tension of the diaphragm.

Above a certain value of $d(U^2)/dt$ a nonzero ΔP develops during the flow because the current cannot exceed the critical value J_c without dissipation. ΔP increases until $t = t_D$, after which it decreases while the flow continues and ΔC reaches the new equilibrium value at $t = t_R$ with $\Delta P = 0$. This is illustrated in Fig. 2; a typical measured response is shown together with the corresponding drive. The curvature of the response implies that the mass flow depends on ΔP.

It follows from the balance equation that the vertical difference between the two curves in Fig. 2 is equal to ΔP. Further, with neglect of a small term due to the nonzero compressibility of the liquid, the slope of the response curve is proportional to J_s. We have integrated ΔP from 0 to t_R to find an average pressure difference ΔP_{av}; the average current $J_s \propto 1/t_R$.

The results of our measurements at $P = 0$ are shown in Fig. 3. In analysis of the data a correction was made for the flow of the normal fluid by observing the response to a voltage step ($t_D = 0$) just above T_c and by reducing the $1/t_R$ values by an amount proportional to ΔP_{av}. This correction has little effect on the critical current because it is always negligible when $t_D \cong t_R$. Even with large ΔP_{av} and near T_c it is not more than 10%.

While each set of points in Fig. 3 was measured the temperature was constant within 5 μK. From observations of T_c with both CLMN thermometers we estimate that the thermal gradient between the two ^{3}He volumes was less than 1 μK. The uncertainty in converting the $1/t_R$ values to mass current is about 30% because of the poorly known total area of channels and the tension in the Mylar diaphragm. Flow measurements were performed both at 28 mT and at zero external fields, without noticeable differences in the results.

Figure 3 shows that ^{3}He-B exhibits a well-defined transition from a mass current with zero or very small friction to a dissipative superflow. Below J_c, $\Delta P_{av} = 0$ and, letting the scatter of our data define an upper limit for ΔP_{av}, we estimate that the effective flow resistance increases by at least 4 orders of magnitude in the critical region. We did not observe the oscillations seen by Dahm *et al.*[4]; the expected oscillation amplitude would be, because of our small channel area, at the limit of our resolution. J_c was found by extrapolating the experimental data points in the dissipative region with approximately parallel straight lines to $\Delta P_{av} = 0$, as shown in Fig. 3. The data at 3.5, 7, and 15 bars are qualitatively similar.

J_c is shown in Fig. 4(a) as a function of tem-

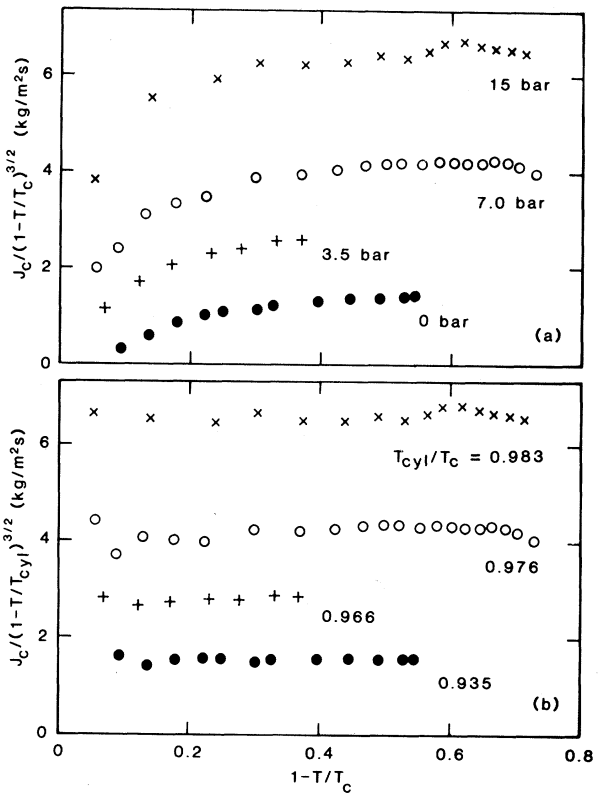

FIG. 4. (a) The temperature dependence of the critical mass current density J_c, suitably normalized, at four different pressures. (b) J_c normalized by $(1-T/T_{cyl})^{3/2}$.

perature at four different pressures. In our narrow channels we expect to observe the depairing critical current which, according to the weak-coupling theory,[8] behaves as $(1-T/T_c)^{3/2}$; this is used to normalize the measured J_c. The calculated values of $J_c/(1-T/T_c)^{3/2}$ are 3.06 kg/m² s at $P=0$ and 8.04 kg/m² s at $P=15$ bars. The deviation of our data from this prediction, both in magnitude and in the temperature dependence, can be explained, at least qualitatively, by a reduction of the superfluid density ρ_s inside the flow channels. The influence of their size depends on the ratio of the channel radius R to the coherence length $\xi_0 = 0.133\hbar v_F/k_B T_c$; $R/\xi_0 \cong 5$, 9, 11, and 17 for $P=0$, 3.5, 7, and 15 bars, respectively, if the values of m^*/m from Ref. 6 are used.

The superfluid transition temperature T_{cyl} in a cylindrical channel has been calculated by Kjäldman, Kurkijärvi, and Rainer.[9] Their results for T_{cyl}/T_c are 0.930, 0.955, 0.974, and 0.988, corresponding to the above four values of R/ξ_0, respectively. Our $P=0$ data only can be reliably extrapolated to $J_c=0$; we then find $T_{cyl}/T_c = 0.94$, which is in agreement with this prediction. We have also found at each pressure the value of T_{cyl} which gives the best fit of the form $J_c \propto (1-T/T_{cyl})^{3/2}$ to our data, as illustrated in Fig. 4(b). This analysis yields $T_{cyl}/T_c = 0.935$, 0.966, 0.976, and 0.983 at $P=0$, 3.5, 7, and 15 bars, respectively; the agreement with the calculations in Ref. 9 is good. Measurements of the superfluid density in packed powders by Chainer, Morii, and Kojima[10] have also shown suppression of transition temperature in agreement with Ref. 9.

The pressure variation of J_c found by us is inconsistent with the results of Hutchins *et al.*,[11] who observed a saturation current such that $J_c/(1-T/T_c)^{3/2}$ was almost independent of P. The flow channel used was 50 μm × 3 mm in cross section and 9 mm long. According to our results, the current density increases with pressure in 0.8-μm-diam channels more than would be expected from the weak-coupling theory, but the magnitude of the current is smaller than the depairing current predicted by this theory, especially at low pressures. This behavior is consistent with the suppression of superfluidity because ξ_0 decreases with increasing pressure. The magnitude of our J_c at $P=0$ is close to the saturation current observed by Eisenstein, Swift, and Packard[3] in a 354-μm-diam channel; this agreement, however, may be accidental in view of the suppression of ρ_s in our measurements.

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Shock Compression of Liquid Xenon to 130 GPa (1.3 Mbar)

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New data are reported for liquid xenon shock compressed to a pressure of 130 GPa (1.3 Mbar), a molar volume of 13.7 cm^3/mole, and a calculated temperature of 29 000 K. The data are consistent with the theory of Ross and McMahan, which indicates that xenon undergoes an insulator-to-metal transition at 9 cm^3/mole at about 130 GPa or greater at 0 K. The minimum molar volume achieved in these experiments corresponds to a pressure of 60 GPa on the 0-K isotherm.

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Xenon is the simplest material studied to understand the insulator-to-metal transition at high pressure. This material has been compressed statically to measure the 85-K pressure-volume isotherm up to 11 GPa (110 kbar) and 21 cm^3/mole,[1] and to measure electrical conduction at 32 K which indicates an insulator-to-metal transition at about 33 GPa.[2] The Hugoniot or shock-compression curve of liquid xenon has been measured previously up to a pressure of 50 GPa and a molar volume of 18 cm^3/mole.[3] Recent theoretical results are in agreement with the shock-wave data[4] but place the insulator-to-metal transition at 130 GPa or greater at 0 K.[4,5] Thus, theoretical predictions[4,5] of the transition pressure differ by a factor of 4 from the only reported experimental observation.[2]

We have measured the Hugoniot of liquid xenon to a pressure of 130 GPa and a molar volume of 13.7 cm^3/mole in order to estimate the density dependence of the narrowing of the conduction electron energy gap. Since rare-gas solids and fluids are extremely similar in their electronic structure, which is dominated by tight-binding character, these results for the fluid are expected to be representative of the solid as well. The estimate of the energy gap follows from the excellent agreement of the data with the theory of Ross and McMahan[4] which takes into account the density dependence of the electronic energy gap in xenon. The sensitivity of the data to the energy gap arises because strongly shocked xenon is heated to temperatures comparable to the gap energy; that is, xenon is a liquid semiconductor in our experiments. The heating is caused by the thermodynamically irreversible nature of the shock-compression process. A sufficient number of electrons are thermally excited so that the shock pressure is reduced by up to a factor of 3 from what it would be without electronic excitation. The reason is that the irreversible shock energy can be distributed in only two ways in a simple fluid like xenon: thermal motion and electronic excitation. If energy is absorbed internally by electronic excitation, the shock pressure will be smaller than if no excitation occurs because less energy is available for thermal pressure. Thus, the high shock temperature is a very useful probe of the electronic structure at high density and pressure.[6]

Shock waves were generated by accelerating a planar projectile to a velocity in the range 2.6–6.6 km/s with a two-stage light-gas gun[7] and impacting the projectile onto a target containing liquid xenon. The experiment is based on the Rankine-Hugoniot relations which relate measured kinematic parameters to thermodynamic variables. Diagnostic, cryogenic, and data-reduction techniques were as described earlier,[8,9] except that a cold N_2 gas system was used to cool the target assemblies and control sample temperature to 0.1 K.[10] Xenon gas was condensed until