Observation of Flow Dissipation in ^{3}He-*B*

J. P. Eisenstein[(a)] and R. E. Packard
Department of Physics, University of California, Berkeley, California 94720

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Anomalous dissipation is observed in ^{3}He-*B* flowing in a U-tube device. The dissipation is of unknown origin and persists to the lowest measured velocity. The position of this result in the framework of other ^{3}He-*B* flow experiments is discussed.

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The hydrodynamics of the *B* phase of superfluid ^{3}He has been the subject of several recent investigations.[1-5] Theory[6] suggests that the *B* phase should support dissipationless superflow, at least at low velocity. In contrast, several experiments have shown substantially larger losses in flow than can be accounted for. These include fourth-sound experiments[7] where observed Q factors are much too low, the experiments on flow in tubes which show anomalous damping in a U-tube oscillator,[2] and the conceptually similar membrane-driven flow measurements[4] which also show inexplicable damping. We present here new quantitative results on *B*-phase flow at saturated vapor pressure in a U-tube geometry where unexplained linear dissipation is found to persist to the lowest velocities observable. We also find a critical velocity above which the character of the dissipation changes, becoming nonlinear. These phenomena have been studied in several different-sized cylindrical-flow channels in a single device.

The U-tube device used in these measurements, shown in Fig. 1, consists of a central reservoir connected to four outer reservoirs by cylindrical flow channels of radii 102, 126, 177, and 227 μm, with lengths of 0.5, 0.5, 1.0, and 1.0 cm, respectively. At a given time only the central and one outer reservoir are partially filled with liquid while the others remain totally full. Thus we can study flow in each channel individually.[3] The fluid reservoirs are the annular gaps of concentric cylinder capacitors, each of length 1.0 cm, gap 0.020 cm, inner diameter 0.518 cm, and capacitance about 7.5 pF. Each capacitor is fitted into a cylindrical epoxy housing. The flow channels were constructed by potting steel wire in epoxy cylinders and then pulling the wire out after the epoxy had cured.[3] The resulting pieces were then expoxied at each end to the capacitor housings.

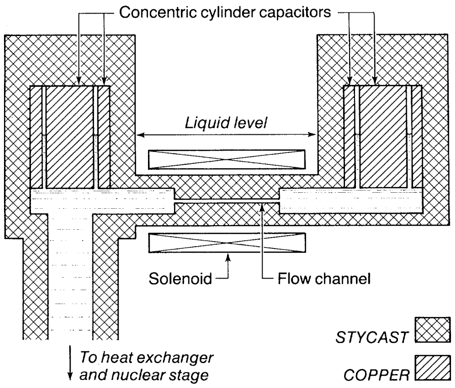

FIG. 1. Schematic of one arm of the U-tube device. The solenoid was not used in this experiment.

The single most striking observation made about *B*-phase flow in this geometry is that the U-tube system does not exhibit weakly damped oscillations of the liquid level. Instead, the system is almost always overdamped. Only at the lowest temperatures (about $T/T_c = 0.5$, $T_c \simeq 1$ mK) and in the two larger tubes does the liquid level even overshoot its equilibrium value. The basic datum recorded at each temperature is the entire digitized liquid-level transient resulting from a change in dc potential on one of the capacitors.

We have examined superfluid velocities (in the flow channel) over the range from about 7×10^{-4} to 1 cm/sec and can distinguish two distinct dissipation regimes. There is a well-defined critical velocity separating the two regimes, the determination of which is described below. The high-velocity regime is characterized by large and nonlinear dissipation. For sufficiently large applied forces (dc potential) the resulting initial mass current saturates, becoming very nearly independent of the applied force.[2] This maximal current, not to be confused with the critical velocity just mentioned, scales with temperature as $(1-T/T_c)^{3/2}$. Comparison with the simple depairing critical current shows the observed magnitude to be about 60% of the weak-coupling theoretical value[8] with little, if any, dependence on

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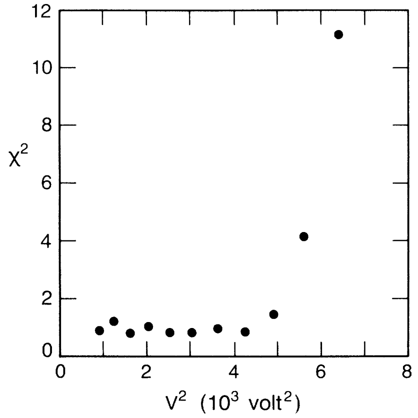

FIG. 2. Reduced χ^2 vs V^2 for a series of transients taken at $T/T_c = 0.921$ in the 102-μm-radius tube.

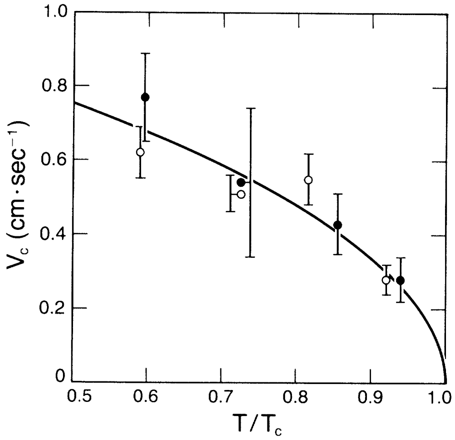

FIG. 3. Dissipation critical velocity. Solid line is a guide to the eye. Open dots, 126-μm-radius tube; solid dots, 227-μm-radius tube.

flow-tube radius.[9]

In this paper we wish to concentrate on the low-velocity regime which is consistent with a linear dissipation. To analyze the flow transients in this regime systematically we have modeled the system as a damped simple harmonic oscillator where the liquid displacement, x, in the reservoirs is assumed to follow the differential equation

$$\ddot{x} + 2L\dot{x} + \omega^2 x = 0. \quad (1)$$

The liquid-level transient resulting from a step force is fitted by a solution to Eq. (1) using a standard least-squares method. The results of the fit are a reduced-χ^2 goodness-of-fit parameter along with the fitted values of the damping and frequency parameters, L and ω, respectively. Figure 2 gives the results of such a fit at one temperature. Plotted is the value of χ^2 versus the square of the applied dc potential, V^2, for a sequence of flow transients. The parameter V^2 is proportional to the equilibrium liquid-level difference.[10] The χ^2 is seen to be near unity at low V^2 and then to rise sharply when the fit begins to fail. The fitted values of L and ω are found to be constant (to within error) over essentially the same range as that in which χ^2 is near unity. We interpret this as indicating the fit function to be statistically good and the losses at low velocities to be consistent with a *linear* dissipation. From the value of V^2 where the fit begins to fail, and the fitted values of L and ω in the linear regime, we can calculate the maximum flow-channel velocity in a transient at the upper limit of the linear range. This velocity represents a critical velocity separating two distinct dissipation regimes. We have examined the temperature and tube-size dependence of this dissipation critical velocity; the results are shown in Fig. 3. The observed velocities are all on the order of 0.5 cm/sec and appear independent of flow-channel radius.

The observation of a critical velocity in the B phase at which the character of the dissipation changes has been made by numerous workers.[1, 4, 5, 11, 12] While there is no way to be sure that the same mechanism is at work, it may be significant that two of the other reported values[1, 11] for this critical velocity are very near 0.5 cm/sec despite wide differences in flow geometry.

Figures 4 and 5 show the fitted values of ω and L, respectively, for representative flow transients from the linear regime, as a function of temperature. In Fig. 4 we have plotted ω/ω_0 vs T/T_c where ω_0 is the free oscillation frequency of the U tube.[9] This ratio should be independent of tube size; the data show this to be the case. The simplest two-fluid picture of U-tube flow gives $(\omega/\omega_0)^2$ very closely equal to ρ_s/ρ, the superfluid density fraction, on the assumption that the flow velocity is uniform across the channel. The solid line in Fig. 4 is this prediction[13]; the data lie substantially below it. The data on L, the dissipation parameter, shown in Fig. 5 show substantial scatter but it seems that L generally increases with increasing ω_0.

The magnitude and mechanism of the observed linear dissipation are unexplained. Using the two-fluid model we have examined several models[9] to explain the anomalous dissipation. These include losses due to temperature differences between

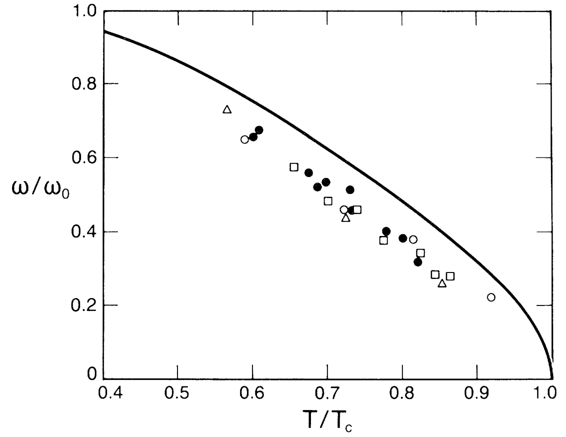

FIG. 4. Fitted values of ω/ω_0 vs. T/T_c. Solid circles, 102-μm-radius tube, $\omega_0 = 6.1\ \sec^{-1}$; open circles, 126-$\mu$m-radius tube, $\omega_0 = 7.6\ \sec^{-1}$; boxes, 177-$\mu$m-radius tube, $\omega_0 = 7.5\ \sec^{-1}$; triangles, 227-$\mu$m-radius tube, $\omega_0 = 9.6\ \sec^{-1}$.

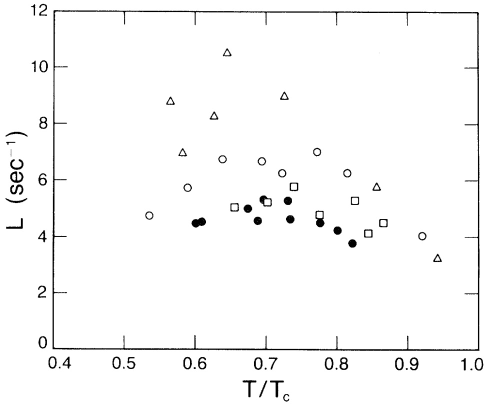

FIG. 5. Fitted values of L vs. T/T_c. Symbols as in Fig. 4.

the reservoirs as discussed by Robinson,[14] as well as similar losses from thermomechanical temperature gradients along the capacitor gap forming each reservoir. Also investigated were the frictional losses associated with possible normal-fluid motion in both the reservoirs and flow channel. None of these models produces Q factors below 100 for reasonable estimates[15] of the physical parameters involved.

We emphasize that our data present no direct evidence that the dissipation is intrinsic to the superfluid or that it is necessarily occurring in the flow channel. The apparent increase of L with ω_0 may point to a loss mechanism occurring within the reservoirs.[9]

It would be very useful if a direct comparison of our experiment to other B-phase flow experiments could be made. This is very difficult in the light of wide differences in flow geometry and requires substantive assumptions about the dissipation mechanism. Such a comparison may therefore be very misleading. Nevertheless, we have attempted a comparison with the two experiments which are most suggestive of friction-free flow. To do this we model the losses as arising from an internal friction opposing the relative flow of normal and super components. Quantitatively, we take the force per unit volume on the superfluid to be $2L\rho_s(v_n - v_s)$ with L identified as the dissipation parameter discussed above. This *assumes* L to be an intrinsic parameter and not to depend on the flow geometry. We have applied this model to the experiments of Parpia and Reppy[1] and Manninen and Pekola.[5]

In the work of Parpia and Reppy[1] an ac flow is driven through an 18-μm-diam, 10-μm-long orifice by a torsional oscillator. Using the above model and details[1,16] of the torsion cell, one can calculate the losses due to oscillatory superflow through the orifice. These losses are to be compared with the known "nuisance" Q of the device, presumably due to the torsion member, along with values for the stored torsional energy. The calculated flow losses come out 10 to 100 times smaller than the nuisance losses and therefore may have escaped notice. Similar measurements by Crooker, Hebral, and Reppy[12] show no change in the dissipation critical velocity when the torsional oscillator is uniformly rotated. This may mean that the expected persistent current does not exist and that the superfluid is rotating along with the oscillator.

Manninen and Pekola[5] have performed a dc flow experiment where ^{3}He-B is driven through a parallel array of some 1300 0.8-μm-diam, 10-μm-long channels. Dissipation is detected via the induced pressure drop across the channels. At sufficiently low velocities no pressure head greater than about 10^{-6} bar is detected. The intrinsic friction model above would have steady pressure drops accompanying dc superflow through the channels. Calculation shows that such pressure drops are several orders of magnitude less than 10^{-6} bar and would thus not have been detected.

We emphasize that this model is purely speculative and is meant only to provide a basis for comparing distinctly different experiments. Our data present no way of proving this model to be correct.

In conclusion, we have found excess linear dissipation in B-phase flow at saturated vapor pressure persisting to the lowest measured velocities. The mechanism of the dissipation is unknown. Although some purely classical effect could be the cause, a review of past flow measurements reveals no convincing evidence of dissipationless B-phase flow. The basic nature of the question this raises about our understanding of superfluid ^{3}He suggests further effort, both theoretical and experimental.

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[a] Present address: Department of Physics and Astronomy, Williams College, Williamstown, Mass. 01267.

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Low-Energy Ion Scattering from the Si(001) Surface

M. Aono, Y. Hou, C. Oshima, and Y. Ishizawa
National Institute for Research in Inorganic Materials, Namiki 1-1, Sakura, Kurakake, Ibaraki 305, Japan

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The structure of a clean Si(001) surface has been studied by a specialized technique in low-energy ion scattering spectroscopy. It has been found that (1) the surface is dimerized, and (2) the intradimer atomic distance parallel to the surface is 2.4± 0.1 Å.

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The clean annealed Si(001) surface is reconstructed into a (2×1) structure[1-4] with substantial subsurface strain,[5] although a $c(4\times2)$ structure coexists in a small proportion.[6-8] Concerning this surface reconstruction, many models, e.g., vacancy models,[7,9,10] conjugated-chain-type models,[4,11] and dimer models,[1,2,12-14] have been proposed, but comparisons of calculated surface electronic structures[14-16] for the various models with photoemission data[17,18] suggest that the dimer models are the most favorable. In this Letter, we report that (1) the surface is certainly dimerized, and (2) the intradimer atomic distance parallel to the surface is 2.4± 0.1 Å. These results have been obtained by a specialized technique[19] in low-energy (of order kiloelectronvolts) ion scattering spectroscopy (ISS),[20] which we call impact-collision ion scattering spectroscopy (ICISS).[19] The specialization used in ICISS is to take the experimental scattering angle θ_L at 180° (or close to 180°) so as to observe such scattered ions as have made head-on collision (or impact collision) against target atoms with zero (or nearly zero) impact parameter b. Despite its simplicity, this specialization yields useful new aspects as described elsewhere.[19]

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