Transition from Dissipationless Superflow to Homogeneous Superfluid Turbulence

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The critical velocity has been measured at the transition from dissipationless superflow to homogeneous superfluid turbulence. The results do not agree well with the recent prediction of Schwarz based upon a topologically self-sustaining vortex tangle.

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The problem of turbulent flow in the superfluid phase of liquid ^{4}He has been clarified substantially by two recent developments. Experiments have shown that the turbulence associated with the flow of the superfluid component alone (the normal component being immobilized) is geometry independent,[1] and has a remarkably simple description in terms of a density L_0 of quantized vortex lines.[2] On the theoretical side, Schwarz[2] has succeeded in simulating the steady-state density of quantized vortex lines in homogeneous turbulence. The Schwarz model provides a prescription for calculating the time evolution of a random tangle of vortex line. Each element of line moves through the superfluid with its local self-induced velocity and in response to the force exerted by the normal fluid. It is assumed that when two vortex lines become sufficiently close they simply reconnect. These topology-changing reconnections are of central importance to the evolution of the self-sustaining steady state. By implementing these dynamical rules on a computer, Schwarz has simulated the steady-state line density for homogeneous superfluid turbulence. These results are in excellent agreement with the vortex line density measured in pure superflow.

In order to include the effect of boundaries on the vortex tangle, Schwarz has recently[4] supplemented the dynamical rules with the assumption that lines which approach sufficiently close to a boundary will undergo a line-surface reconnection. Calculation of the steady-state line density in this case reveals that there is now a critical velocity V_c below which the tangle ceases to be topologically self-sustaining and $L_0 \to 0$. The production of new vortex line by the reconnection process is insufficient to balance the destruction of line at the boundaries. The magnitude of the critical velocity is found to depend strongly on channel shape and on the exact nature of the surface reconnection. The temperature dependence of V_c is independent of these details and is entirely determined by the dynamical model used in the simulation. In this paper we report the first experiments to measure unequivocally the critical velocity at the transition from homogeneous superfluid turbulence to dissipationless superflow.

The apparatus is similar to one used previously[1,2] and is shown schematically in Fig. 1. Modifications have been incorporated to improve significantly the superfluid velocity measurement, the temperature regulation, and the thermometry. A fountain pump pulls superfluid from a reservoir through the flow tube at speed V_s. The flow tube is glass, 9.9 cm in length (l), and circular in cross section with an internal diameter (d) of 1.34×10^{-2} cm. The superfluid velocity V_s is computed from the rate at which fluid leaves the reservoir as indicated by a level-sensing capacitor.

Dissipation in the superflow gives rise to a temperature difference ΔT related to the steady-state vortex line density L_0 as [5]

$$\Delta T = (\rho_n \kappa B V_s l / 3\rho S) L_0. \qquad (1)$$

Here ρ_n/ρ is the normal fluid fraction, κ the quantum circulation, S the entropy density, and B the Hall-Vinen coefficient (related to the scattering of normal-fluid excitations from vortex lines). Measurements of ΔT are then used with Eq. (1) to determine the vortex-line density L_0 as a function of V_s and T. Our previous experi-

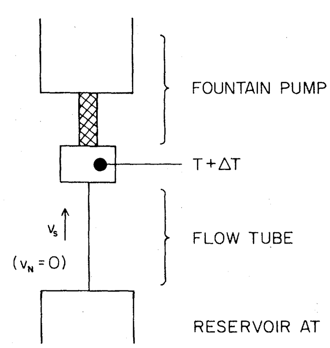

FIG. 1. Schematic diagram of the superflow apparatus.

ments at velocities greater than about 2 cm/sec gave the simple result

$$L_0 = \{\gamma(T) V_s\}^2. \quad (2)$$

The fundamental parameter $\gamma(\boldsymbol{T})$ was shown to be independent of flow-tube geometry and in good quantitative agreement with the values obtained in the Schwarz simulation of homogeneous superfluid turbulence.

The present experiments are intended to explore the domain of small V_s and small line density. The results given in Fig. 2 show clearly that there is a critical velocity V_c below which the vortex-line density vanishes abruptly. Although there have been previous reports of a critical velocity in pure superflow, the present results are the first to demonstrate unambiguously the transition from homogeneous superfluid turbulence (the solid lines in Fig. 2) to completely dissipationless superflow. The vortex-line density is given in Fig. 2 as the dimensionless quantity $L_0^{1/2}d$. Since the scale of a random tangle of vortex line (the average separation and the average radius of curvature) is $1/L_0^{1/2}$, the quantity $L_0^{1/2}d$ can be regarded as the ratio of external and internal scales. Since $L_0^{1/2}d$ is about 4 at V_c, it follows that the vortex lines are in a very loose and open structure at the transition. The results in Fig. 2 also show that the sharpness of the transition increases at lower temperatures. In Schwarz's computer simulation, L_0 goes to zero discontinuously at V_c and this possibility is certainly not contradicted by our data. If the transition is discontinuous, it should be possible to exceed V_c in the dissipationless state if the accidental nucleation of vorticity can be avoided. To examine this possibility we performed the following "saturation" experiment at 1.6 K: The velocity V_s was held steady at a subcritical value for a period of about 2 h. The velocity was then very slowly increased and the dissipation was monitored continuously. An abrupt transition from the dissipationless state to the turbulent state occurred at a velocity well above V_c. The metastable state ($L_0 = 0$, $V_s > V_c$) is very easily destroyed, and we have only succeeded in observing it twice.

The critical velocity, defined as the minimum velocity at which any dissipation was observed, is shown as a function of temperature in Fig. 3. The tube diameter d and the quantum of circulation κ are used to render V_c dimensionless. Quite remarkably, the critical velocity appears to be virtually independent of temperature. The

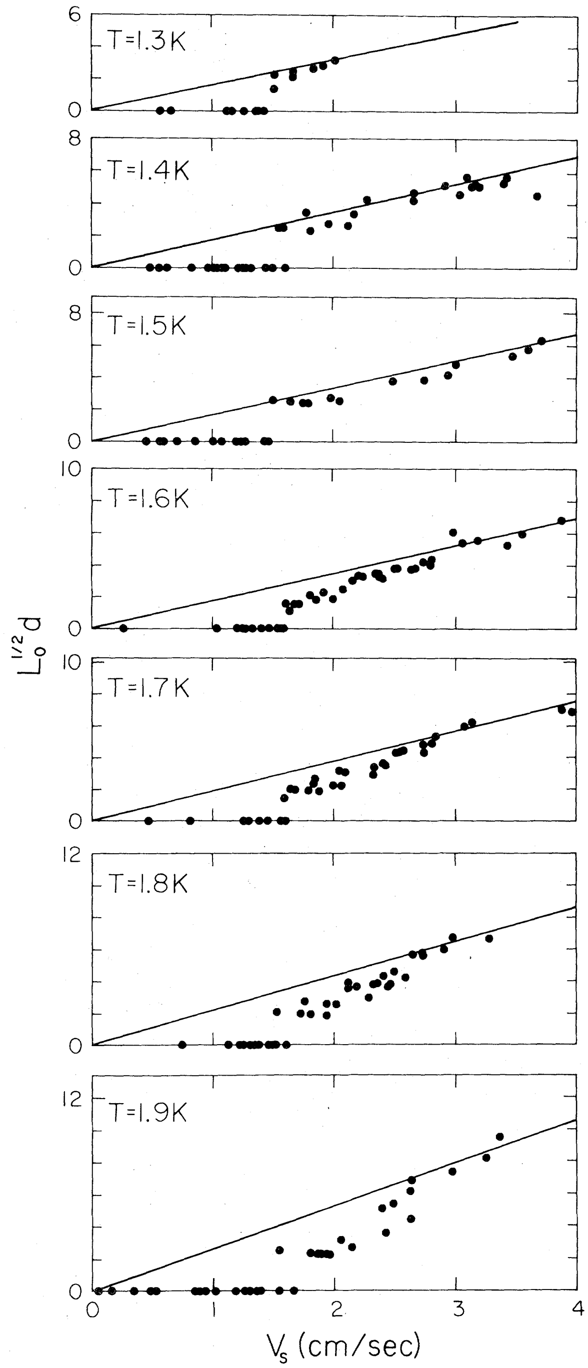

FIG. 2. The dimensionless vortex-line density $L_0^{1/2}d$ as a function of the superfluid velocity V_s showing the transition to dissipationless flow over a range of temperatures. The straight lines represent homogeneous superfluid turbulence as given by Eq. (2).

liquid-helium literature is filled with observations of critical superfluid velocities, several of which[6,7] are also temperature independent. There is a fundamental difference between these obser-

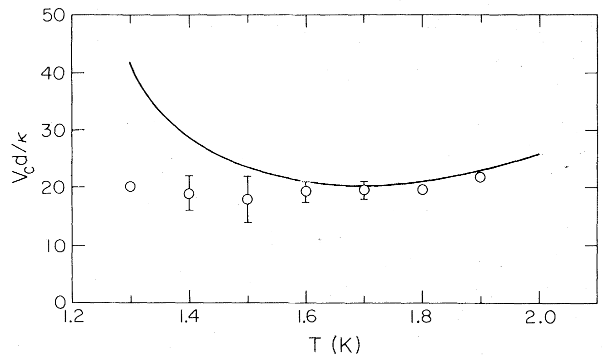

FIG. 3. The dimensionless critical superfluid velocity measured at various temperatures. The temperature dependence determined by the Schwarz model is shown by the solid line.

vations and the results of the present experiment, however. In the previous work the helium was *constrained to be isothermal* and the observed dissipation was very weak. This dissipation is not presently understood, but it is certainly not the result of the self-sustaining vortex tangle of homogeneous superfluid turbulence. To our knowledge there is only one previous measurement of a critical superfluid velocity that may be associated with the collapse of the homogeneous vortex tangle. Using a tube 0.385 cm in diameter and a sensitive second-sound attenuation technique to measure dissipation, Peshkov and Stryukov[8] found (dimensionless) critical velocities of approximately 10 at 1.44 K and 12 at 1.32 K. The experimental uncertainties are such to make these values quite comparable with our data shown in Fig. 3. The critical velocity recently computed by Schwarz on the basis of his model of homogeneous turbulence is both larger in magnitude and more temperature dependent than the present data. Since the magnitude of V_c depends strongly on shape and surface effects, we have normalized the predicted values to our data at high temperature. The results shown by the solid line in Fig. 3 indicate that the temperature dependence of V_c determined by the Schwarz model is too strong.

It is instructive to compare the transition to turbulence in pure superflow and in thermal counterflow. Here the normal and superfluid components flow in opposite directions at relative velocity V. There is a clearly observed critical value of V below which the vortex-line density drops to zero.[5] At the transition $L_0^{1/2}d$ is about 2 or 3, and as for pure superflow, the transition can be "saturated" ($L_0 = 0$ persists as a metastable state for $V > V_c$). The physics of the Schwarz model indicates that this critical relative velocity should be identical with V_c in pure superflow (neglecting the complications of spatial inhomogeneities). In fact the Schwarz calculation of V_c fits the thermal counterflow data extremely well, both in magnitude and temperature dependence.

The situation is paradoxical. The Schwarz model, which should be appropriate to the homogeneous turbulence in pure superflow, instead gives the highly temperature-dependent critical velocity observed in counterflow. Schwarz[9] has suggested that the experimental results could be consistent with a low level of pinned vortex lines in the flow tube. Experimental determination of such a remnant vorticity density has recently been announced.[10] A modification of the computer simulation of V_c to include this effect would be very interesting.

In summary, we have succeeded in observing the transition from homogeneous superfluid turbulence to dissipationless superflow and have measured the critical velocity V_c as a function of temperature. The results do not agree well with the critical velocity for a topologically self-sustaining vortex tangle based on the Schwarz dynamical model. The temperature independence of V_c could be consistent with a transition dominated by residual vorticity in the flow tube rather than a simple line-wall reconnection process.

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