Evidence for Quantum Tunneling of Phase-Slip Vortices in Superfluid ^{4}He

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We have observed that at temperatures below 200 mK quantized vortices are created by a new process which is not described by the thermal activation theory of vortex nucleation. The critical flow velocity in a submicron orifice has been determined using two techniques. Down to about 200 mK the critical velocities rise linearly with falling temperature. Below this temperature the critical velocity stops rising and becomes almost temperature independent, indicating that a new process, possibly quantum tunneling, dominates the phase-slip nucleation.

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Superfluid ^{4}He is well described as a system of two interpenetrating fluids [1]. The "normal" component contains entropy and displays viscous dissipation. The "super" component is in the quantum mechanical ground state and flows as a perfect Eulerian fluid containing vortices of fixed circulation $\kappa = h/m_4$. At temperatures well below 1 K the normal component is absent but the fluid still exhibits flow dissipation. In this low-temperature limit the processes which extract energy from the flow involve the passage of quantized vortices across stream lines of the potential flow [2]. This basic picture of superfluid ^{4}He can describe almost all existing hydrodynamic experiments in superfluidity.

An outstanding question deals with the origin of these quantized vortices. At temperatures well below the transition temperature T_λ, it seems unlikely that vortices can appear spontaneously in the bulk fluid [3]. However, it is possible that vortices may be nucleated at surfaces or that vorticity evolves from preexisting remnant vortices, perpetually pinned to surface irregularities [4].

Recent experiments involving flow through submicron orifices have measured the critical velocities involved both in discrete phase-slip phenomenon [5,6] and in pressure-driven flow. The discrete phase slips refer to dissipation events characterized by a single vortex passing across the orifice. In pressure-driven flow the average fluid velocity in the orifice saturates (i.e., becomes almost independent of pressure) and phase slips occur at the Josephson frequency $f_J = \kappa \Delta P/\rho$ where ρ is the liquid density and ΔP is the pressure difference across the orifice [2].

Over a wide temperature range several investigators [4] have observed that the phase-slip critical velocity v_c displays a linear temperature dependence,

$$v_c = v_{c0}(1 - T/T_0) . \tag{1}$$

The parameters T_0 and v_{c0}, which may be characteristic of the microscopic surface structure in the orifice, vary slightly between various experiments being on the order of 3 K and 10 m/s, respectively. One can show that Eq. (1) is consistent with vortices being thermally activated over a velocity-dependent energy barrier [4] E_a of the form

$$E_a = E_0(1 - v/v_{c0}) . \tag{2}$$

Experiments suggest that E_0 is of the order 100 K [4].

The existence of velocity-dependent energy barriers has been shown, through specific calculation [7], to be a general feature of vortex-surface interactions. The energy of interest is the hydrodynamic energy associated with the combination of potential flow and a small vortex filament situated near a surface. Several authors have studied systems containing the elements of this situation. In each case one finds that for some range of velocities an energy barrier inhibits vortices from moving away from the boundary. The height of this barrier is a decreasing function of velocity. Thus the calculations yield a result in qualitative agreement with Eq. (2). The thermal activation theory, based on Eq. (2), seems to be the best explanation for the linear temperature dependence of v_c.

It is reasonable to ask if, at low enough temperatures, the thermal activation rate of the phase-slip process will be so low that some other process will dominate the vortex creation. Experiments on vortex nucleation around electron bubbles demonstrate [8] a temperature-independent critical velocity below about 200 mK which has been ascribed to quantum nucleation processes in that system. Furthermore a recent heuristic argument suggests that quantum processes might become apparent in aperture-flow critical velocities at temperatures as high as several hundred millikelvin [9].

The experiment described herein was conceived to check the latter possibility by measuring the temperature dependence of the phase-slip critical velocity down to 10 mK. The data presented in this paper show that below 200 mK the critical velocity becomes almost temperature independent. This suggests that the energy barrier of Eq. (2) is traversed by a nonthermal mechanism.

Our experimental apparatus consists of a superfluid-filled chamber which is divided by a wall containing a metallized flexible diaphragm and a single submicron orifice. Fluid is driven through the orifice, from one side of the chamber to the other, by applying appropriate electric fields near the diaphragm. The flow is detected by monitoring the diaphragm's position using a SQUID-based displacement transducer [10] whose active element is a niobium film sputtered onto the diaphragm. The transducer noise is 5×10^{-15} m/Hz$^{1/2}$. The orifice was made using *e*-beam lithography on a silicon nitride membrane [11]. A scanning-electron-microscope (SEM) picture of the orifice shows an approximately square aperture of side 0.2 μm in a membrane about 0.1 μm thick. The surface of one side of the membrane appears rough in the SEM picture where the electron beam resist has been inadvertently baked on.

The complete cell is thermally connected to the mixing chamber of a dilution refrigerator. The apparatus is filled with superfluid helium through a pair of valves located on the mixing chamber, which isolates the cell from extraneous pressure fluctuations and one side of the diaphragm from the other. A platinum pulsed NMR thermometer, calibrated against a tungsten superconducting transition fixed point, is used to measure the temperature of the liquid up to 300 mK and to calibrate a carbon resistor in this range. The high-temperature end of the carbon resistor scale is calibrated against T_λ and the intermediate range is an interpolation.

We determine the phase-slip critical velocity by two methods. First, using methods similar to those of Avenel and Varoquaux the fluid is driven through the orifice in an oscillatory fashion at the Helmholtz frequency. The kinetic inductance of the flow path, which is determined by the orifice dimensions, couples to the restoring force of the diaphragm, to produce a characteristic Helmholtz frequency of a few hertz. At all temperatures up to 1.5 K we are able to observe quantized dissipation events which have been shown to be consistent with a single vortex line crossing the orifice. For this orifice, under noisy conditions, these phase slips are of size $2\pi n$, where n is an integer which is often greater than unity. However, in the conditions existing during the experiments reported here, the phase slips were usually of magnitude 2π. We will signify the velocity at which these events occur by v_c^{ac}.

In the second technique, fluid is driven by an impressed electrostatic pressure head through the orifice. The observed flow velocity, $\langle v\rangle$, is almost independent of pressure head and, assuming the dissipation arises from single vortices crossing the flow path, is related to the phase-slip critical velocity by [9]

$$v_c^{\mathrm{dc}}=\langle v\rangle+\langle n\rangle h/2m_4L\,. \tag{3}$$

Here L represents the effective length of the orifice, and $\langle n\rangle$ is the average phase-slip size in units of 2π. The magnitude of the second term in Eq. (3) is determined from the size of the phase slips observed in the ac experiment.

Figure 1(a) shows the temperature dependence of v_c^{ac}. It appears that for temperatures above 200 mK the critical velocity depends linearly on temperature as expected for a thermally activated transition over the velocity-dependent energy barrier of Eq. (2). However, below

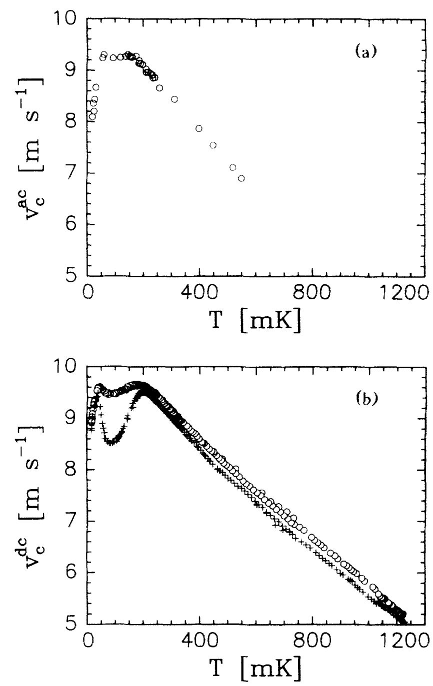

FIG. 1. (a) Critical velocity for single phase slips during oscillatory flow as a function of temperature. (b) Critical velocity for dc flow in two different directions (at an applied pressure of $\Delta P\approx0.5$ Pa) as a function of temperature. Circles represent $v_c^{\mathrm{dc}+}$ and crosses $v_c^{\mathrm{dc}-}$.

some temperature T_i^{ac} which is about 200 mK, the critical velocity becomes temperature independent. This is a new feature, the existence of which indicates that some new mechanism is dominating the nucleation of phase slips and thus the critical velocity. Very similar effects have been seen in v_c^{ac} recently in Saclay [12]. At about 50 mK v_c^{ac} begins to decrease once again (to be discussed below).

Figure 1(b) shows the temperature dependence of v_c^{dc} (we have assumed that $\langle n\rangle=1$) for the two different flow directions ($v_c^{\mathrm{dc}+}$ and $v_c^{\mathrm{dc}-}$). In the thermal activation range v_c^{dc} again shows a linear temperature dependence down to T_i^{dc} at about 200 mK, and is very slightly different in the two different directions [13]. Thus v_c^{dc} is also as expected for a thermally activated transition. Below 200 mK, the critical velocity, although not completely independent of temperature, stops rising with falling temperature. For the positive flow direction, $v_c^{\mathrm{dc}+}$ is almost independent of temperature in the same range as v_c^{ac}. However, $v_c^{\mathrm{dc}-}$ decreases slightly and then increases again to the same maximum as before. Finally, at temperatures below 30 mK v_c^{dc} begins to decrease once again.

In the thermal activation region the differences between the dc and ac data can be understood by applying statistical analysis to the phase-slip process. For any stochastic phase-slip nucleation process involving transitions over or through a velocity-dependent barrier the average phase-slip velocity must depend on the fluid acceleration and hence on the pressure difference ΔP across the orifice. This dependence can be expressed by a parameter [9]

$$\alpha = \frac{1}{v_{c0}} \frac{d(v_c^{dc})}{d\ln(\Delta P)} . \tag{4}$$

A finite positive value of α implies that the observed critical velocity increases with the driving pressure. We find that v_c^{dc} does vary linearly with $\ln(\Delta P)$.

If the values of v_c^{dc} in Fig. 1(b), in the temperature-dependent regime, are scaled by the measured α, to the pressure (fluid acceleration) relevant to the driven oscillator measurements, we find that $v_c^{dc} = v_c^{ac}$ within the precision of the measurement of α. We therefore believe that the phase-slip processes are the same in both types of experiments.

Figure 2 shows the values of α, for the two directions of flow ($\alpha+$ and $\alpha-$) as measured in the pressure-driven experiments. At a temperature near T_i^{dc}, α drops and eventually becomes negative. This reduction in α may indicate that the phase-slip creation is no longer a stochastic process in this temperature range. Finally in the temperature range where the v_c^{dc} and v_c^{ac} begin to fall again $\alpha+$ and $\alpha-$ rise to large positive values.

One possible explanation of the temperature-independent critical velocity is that quantum tunneling processes are nucleating the phase slips at a faster rate than thermal processes. Although there is no complete theory of tunneling of vortices [14] there are several ways that one might estimate the temperature at which quantum processes become significant. For an interacting Bose gas the temperature T_Q at which density fluctuations due to quantum processes becomes comparable to those due to thermal excitations is given by [15]

$$T_Q = hc/2\pi k_B R , \tag{5}$$

where R is the length scale of the relevant volume and c is the speed of sound. The length of a vortex which has energy E_0 is approximately 4 nm which, when inserted into Eq. (5), gives $T_Q = 0.4$ K.

A second possible explanation for the maximum critical velocity for both the ac and dc experiments is that the Landau critical velocity for the production of rotons is being achieved in the flow near some surface irregularity. The fluid velocities measured here are in fact a velocity average over the area of the orifice and are a lower bound on the true velocity at the surface. Near surface irregularities the local velocity is higher than the average velocity by some geometrical factor. At temperatures above 200 mK the phase slips are created by thermal activation but below this temperature their creation may be assisted by a local breakdown of superfluidity caused by exceeding the Landau velocity. This latter process would be temperature independent.

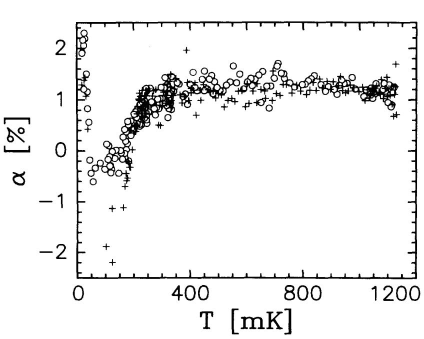

FIG. 2. Measured values of $\alpha+$ (circles) and $\alpha-$ (crosses) as a function of temperature.

A significant difference between the measurement of v_c^{dc} and that of v_c^{ac} is that the pressure difference across the orifice in the former case causes phase slips to occur at rates between 10^3 and 10^6 times faster. Whatever the mechanism for the production of phase slips below 200 mK, the results of the dc experiment show that it is perturbed by this higher phase-slip rate and that this perturbation depends on the direction of flow through the orifice. It may be that a vortex trapped near the nucleation site for the phase slips is excited into vibration (Kelvin mode [7]) or perhaps moved some distance by these high-frequency phase slips. This change in the condition of the nucleation site then manifests itself in the slight temperature dependence of the v_c^{dc} below T_i^{dc}, perhaps by causing the average phase-slip size $\langle n \rangle$ to increase. There is some evidence in the ac data that the average phase-slip size in this temperature range is in fact increased.

Both v_c^{dc} and v_c^{ac} turn sharply downward at lower temperatures. The downturn in v_c^{ac} confirms other earlier observations [5] of this same effect. These downturns are found empirically to depend on the concentration of ^{3}He impurities present in the sample. For instance, in early experiments the sample contained ^{3}He at the level of 10^3 ppm. For that sample the dc data exhibited a downturn in v_c^{dc} below 60 mK. For the data shown in Fig. 1 the sample was close to nominal purity, i.e., 0.2 ppm. For this level of ^{3}He the downturn in v_c^{dc} is shifted to below 30 mK, and v_c^{ac} turns downward at about 50 mK. Experiments performed with lower levels of ^{3}He show the same temperature behavior of both v_c^{ac} and v_c^{dc} except that the downturns are shifted to even lower temperatures.

Recent experiments performed in Saclay [12] show that ^{3}He concentration must be below a few parts in 10^9 before the downturn in v_c^{ac} falls below the lowest accessible temperatures.

Although the physics dictating the ^{3}He effects are not yet fully understood, one might suppose the phenomenon is associated with the condensation, at low enough temperature, of the ^{3}He on the vortex core [16]. Experimental and theoretical studies of the influence of ^{3}He on charged vortex ring nucleation rates in ion experiments [17] in superfluid ^{4}He may point the way towards understanding of the ^{3}He effects in the phase-slip process.

At the lowest temperature, at about the same point where the downturn in v_c occurs, α rises sharply. This would suggest that one effect of the ^{3}He is to let some stochastic activation again be more rapid than the process causing the temperature independence, perhaps by lowering the energy barrier E_0. At present we have no theoretical model explaining the effects of ^{3}He impurities.

In conclusion we have found that the critical velocities for observable single phase slips and that for dc flow (where the phase-slip rate can be 10^6 times faster) exhibit the same type of temperature dependence. In the thermally activated temperature range the quantitative relationship between v_c^{ac} and v_c^{dc} is outlined. At lower temperatures the measured temperature dependence of phase-slip critical velocity suggests a temperature-independent mechanism, possible quantum tunneling, for nucleation of the vortices. Here the relationship between v_c^{ac} and v_c^{dc} is less clear although the departures of v_c^{dc} from the simple temperature independence of v_c^{ac} may provide some clues as to the mechanism dominating the critical velocity in this temperature range.

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