Persistent Currents and Dissipation in the *A* and *B* Phases of Liquid ^{3}He

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(Received 19 August 1985)

We report observations of long-lived persistent currents in both the *A* and *B* phases of ^{3}He. In this work we have exploited the relation between the dissipation of small-amplitude oscillatory superflow and the average relative velocity between the superfluid and normal-fluid components. This provides a new technique for the nondestructive determination of the superfluid velocity associated with persistent currents in liquid ^{3}He.

PACS numbers: 67.50.Fi

Recent experiments[1,2] utilizing an ac-gyroscope technique have been successful in demonstrating the existence of long-lived supercurrents in the *B* phase of liquid ^{3}He. Following the suggestions of Anderson and Toulouse,[3] it seemed likely that the critical velocity for *A*-phase persistent superflow would be very nearly zero since the superflow could be relaxed by textural motion without the creation of new singularities. However, if large-scale motion of the texture is suppressed, persistent currents can be stabilized. This Letter reports measurements of nonzero persistent currents in the *A* phase as well as in the *B* phase.

In the experiments presented here, a new technique has been employed for the detection of persistent currents in superfluid ^{3}He. The ^{3}He cell used in these experiments consists of a torus packed with 25-μm SiC powder mounted on an axial torsion rod. Small electrodes have been mounted on the cell for the excitation and detection of torsional oscillations at a frequency of 400 Hz about the axis of symmetry. In our cell the 25-μm powder provides sufficiently small channels for the normal component to be strongly locked to the cell at the frequency of the torsional oscillations. In addition, a fraction of the superfluid mass is also coupled to the cell as an induced mass effect associated with the potential flow through the porous medium.[4] The overall geometry is similar to that used for our ac-gyroscope measurements of *B*-phase persistent-current angular momentum.[1] Unfortunately, the sensitivity of the present gyroscope is not sufficient for the direct detection of persistent-current angular momentum in the *A* phase.

In the measurements reported here, we exploit instead a dependence of the damping of small-amplitude torsional oscillations of the cell on the magnitude of a persistent current circulating within the cell. This phenomenon is closely related to the *A*-phase "history-dependent dissipation state," first reported by Gay *et al.*[5] and can be understood in terms of orbital-relaxation effects. Since in our cell the normal fluid is well locked, the hydrodynamic viscous damping accounts for only a small part of the total dissipation while textural-relaxation effects are the prime contributor. The period shift of the torsional resonance, below T_c, is used to estimate the temperature and superfluid density in a manner analogous to that used in earlier experiments with Andronikashvilli-type oscillators.[6]

In Figs. 1 and 2 we illustrate the basic phenomena observed in the present experiment.[7] The quantity, Q^{-1}, proportional to the dissipation, is plotted against an imposed steady rotation rate, Ω, of the entire cryostat. In Fig. 1, the measurements start from initial states, indicated by the solid circles, that have been prepared by cooling slowly through the superfluid transition while maintaining the cryostat at rest. In this way, we have created initial states where the average superfluid velocity is zero ($\bar{v}_s=0$). If we then rotate

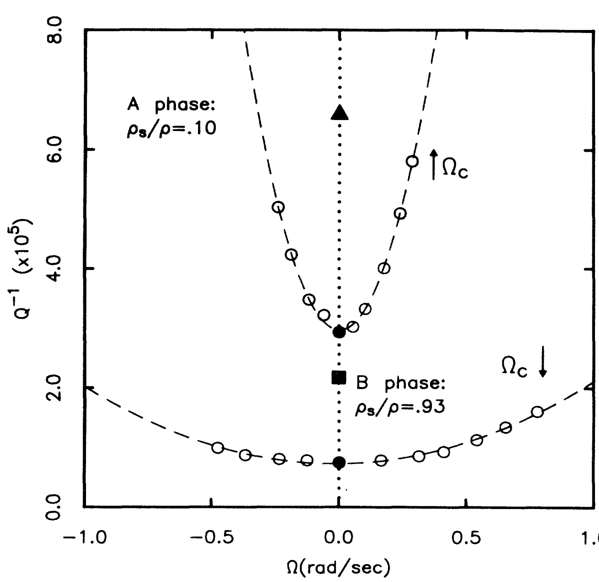

FIG. 1. A plot of dissipation, Q^{-1}, as a function of cryostat angular velocity, Ω, for initial states, filled circles, with $\bar{v}_s=0$. The angular velocity Ω_c indicates the limit on the range for reversible behavior. The filled triangle and filled square represent *A*- and *B*-phase dissipation states with large persistent currents present. The dashed lines are quadratic fits to the data.

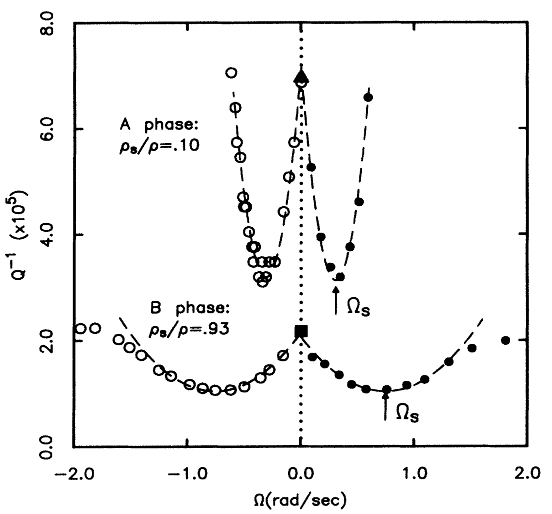

FIG. 2. A plot of A- and B-phase dissipation, Q^{-1}, as a function of cryostat angular velocity, Ω. The filled circles are for the case where the initial dissipation state contains a persistent current created by a positive rotation of the cryostat, while the open circles are for currents created by negative rotation. The dashed lines are quadratic fits to the data in the reversible regime.

the cryostat slowly, the superfluid remains essentially at rest except for the small potential flow induced by the porous medium,[4] while the dissipation is observed to increase. This change in dissipation is a reversible function of angular velocity provided that a critical velocity, Ω_c, is not exceeded. Thus, if the rotation is stopped without having exceeded Ω_c, the dissipation returns to its original value. For the reversible region, the dissipation increases as Ω^2 (indicated by the dashed lines). If, however, the critical velocity is exceeded, we find that the superfluid is irreversibly accelerated, and then, when the rotation is stopped, a circulating supercurrent remains with a dissipation that considerably exceeds the initial value. In the low temperature B phase, the existence of persistent currents, created in this manner has been verified by direct angular momentum measurements in the present cell. In Fig. 1 two such persistent-current states with higher dissipation, indicated by the filled triangle and the filled square, were created by rotation at angular velocities well in excess of $2\Omega_c$.

In Fig. 2 we illustrate the A- and B-phase dependences of the dissipation on rotation of the cryostat for persistent-current states of opposite signs.[8] When a circulating persistent current is present, we find that the dissipation can be reduced to a minimum value by rotating the cryostat at a rate, Ω_s, which is synchronous with the angular velocity of the persistent current. The dissipation is a reversible function of the cryostat angular velocity in the vicinity of the dissipation minimum at Ω_s and can be returned to its original value at $\Omega = 0$ provided that the rotation rate has not been raised to too large a value. Measurements such as those illustrated in Fig. 2 then permit the nondestructive observation of persistent currents for both the A and B phases of liquid ^{3}He. The average velocity, $\bar{v}_s$, of such a persistent current can then be estimated from $\bar{v}_s \cong R\,\Omega_s$, where R (7.0 mm) is the mean radius of the torus.

A more detailed understanding of the relation between the observed dissipation and the relative velocity between the normal and superfluid components can be achieved by a consideration of the orbital dynamics of the superfluid in the presence of oscillatory motion. We shall start with a consideration of the A-phase hydrodynamic equation for the motion of the $\hat{\mathbf{l}}$ vector,[9]

$$\mu\partial_t\hat{\mathbf{l}} = \mathbf{F}^{(2)}(\hat{\mathbf{l}}^0, \mathbf{v}_s^0)\cdot\delta\hat{\mathbf{l}} - 2\rho_0[(\mathbf{v}_n-\mathbf{v}_s)\cdot\hat{\mathbf{l}}]\delta\mathbf{v} - c_0(\hat{\mathbf{l}}\cdot\nabla\times\hat{\mathbf{l}})\delta\mathbf{v}, \tag{1}$$

where μ is the orbital damping coefficient, and $\mathbf{l}^0$ and $\mathbf{v}_s^0$ are the equilibrium texture and superfluid velocity for a given rotation rate, Ω. $\mathbf{F}^{(2)}$ is a matrix with positive eigenvalues describing the energy increase when the equilibrium texture is deformed, and $\delta\mathbf{v}$ is the velocity of the small torsional oscillations: $\delta v = R\theta\omega\cos(\omega t)$, where θ and ω are the angular amplitude and frequency of the torsional oscillation. A typical value of θ was 10^{-6} rad. Because of the $(\mathbf{v}_s\cdot\hat{\mathbf{l}})^2$ and $c_0(\hat{\mathbf{l}}\cdot\nabla\times\hat{\mathbf{l}})(\mathbf{v}_s\cdot\hat{\mathbf{l}})$ terms in the free energy,[10] the oscillatory motion generates a $(\mathbf{v}_s-\mathbf{v}_n)$-dependent force ($f$) and a $(\mathbf{v}_s-\mathbf{v}_n)$-independent force ($g$) in the fluid.

Dimensional analysis shows that the eigenvalues, E_n of $\mathbf{F}^{(2)}$, are of the order $\rho_s v_n(h/2mD)$, where D is the size of the pores. The characteristic reponse frequency of the texture, E_n/μ, is much smaller than the probing frequency, ω. It is easy to show that with this condition, the energy dissipation of the fluid is

$$\dot{E} = \mu\int \dot{l}^2 = \mu^{-1}\int(f+g)^2 \cong \mu^{-1}\int f^2 + \mu^{-1}\int g^2 \equiv \dot{E}_f + \dot{E}_g. \tag{2}$$

The $\int fg$ term has been dropped, since, in a porous geometry, the sign of $(\mathbf{v}_s\cdot\hat{\mathbf{l}})(\hat{\mathbf{l}}\cdot\nabla\times\hat{\mathbf{l}})$ will change rapidly rendering this integral negligible. We note that

$$\dot{E}_f = (1/2\mu)\int[2\rho_0(\hat{\mathbf{l}}\cdot\hat{\boldsymbol{\phi}})(\mathbf{v}_s-\mathbf{v}_n)^2](\theta R\omega)^2 = a(\rho_0^2/\mu)(\mathbf{v}_s-\mathbf{v}_n)^2(\theta R\omega)^2 V, \tag{3}$$

$$\dot{E}_g = (1/2\mu)\int[c_0(\hat{\mathbf{l}}\cdot\nabla\times\hat{\mathbf{l}})(\hat{\mathbf{l}}\cdot\hat{\boldsymbol{\phi}})]^2(\theta R\omega)^2 = b(c_0^2/\mu)(D^{-2})(\theta R\omega)V^2, \tag{4}$$

where a and b are constants characterizing the porous network with volume V. This results in a change in the dissipation:

$$\Delta Q^{-1} = Q^{-1} - Q_0^{-1} = \dot{E}/I_c(R\theta\omega)^2, \tag{5}$$

where Q_0^{-1} is the background dissipation of the cell and I_c is the cell moment of inertia. ΔQ is independent of the amplitude and frequency of the small torsional oscillations and has a quadratic dependence on $\bar{v}_s - \bar{v}_n$.

While we believe that the foregoing provides an adequate framework for the understanding of our experiment in the A phase, the picture for the B phase is somewhat less secure. Nevertheless, we would argue, following suggestions that the B-phase gap is deformed near a wall to assume an anisotropic A-phase-like character,[11] that, as in the A phase, orbital relaxation would lead to dissipation for small-amplitude oscillations. However, in the B phase the total dissipation is expected to be scaled down from the comparable A-phase value by the ratio of the volume of the anisotropic surface layer to that of the entire fluid. In the measurements at 29 bars, we find that the rate of increase with ρ_s/ρ of the maximum dissipation in the A phase is 25 times that of the B phase. With the use of an estimate for the surface area of our cell, this ratio would imply a thickness for the anisotropic layer of 5 to 10 times the coherence length.

In Fig. 3 we illustrate the temperature dependence of several different dissipation states as observed with the cryostat at rest ($\Omega = 0$). The lowest-lying curves in both the A and B phases correspond to states that have been prepared with $\bar{v}_s = 0$, while the higher-dissipation curves are for states where persistent currents are present. As would be expected at a first-order transition, we find that the memory of persistent currents is destroyed either by warming into the normal phase or by crossing the A-B transition. In our cell, a considerable hysteresis is observed in the temperature of the A-B transition. Although cooling either from the normal state into the A phase or from the A phase into the B phase produces a state with $v_s = 0$, warming across T_{AB} leads to a quite different result. In this case, the spontaneous generation of a small A-phase persistent current is always observed. In all cases studied thus far, these spontaneous A-phase currents, created by warming from the B phase, have a negative rotation sense with a typical value of -0.08 rad/sec and do not depend on either the magnitude or the direction of any B-phase persistent current that might have been present before warming.

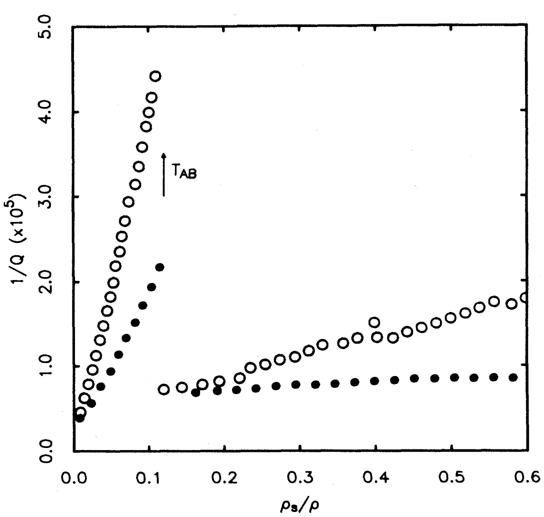

FIG. 3. The dissipation, Q^{-1}, with cryostat at rest ($\Omega = 0$) as a function of the average superfluid fraction, ρ_s/ρ. The closed points represent the minimum value of dissipation that occurs with the superfluid at rest ($\bar{v}_s = 0$). The A-phase data with open circles were obtained with a single persistent current present while the B-phase persistent-current data, open circles, consist of a number of different currents.

In addition to the two curves shown in Fig. 3, it is possible to gain access to a continuum of dissipation levels between a maximum value (not shown) and the minimum-dissipation state achieved by cooling slowly from above T_c. The temperature variation of the dissipation states shown in Fig. 3 for the A phase is essentially the same as that observed in the earlier Manchester experiment of Gay *et al.*[5] Although dissipation states corresponding to persistent currents with flow velocities somewhat below the maximum possible values show considerable stability over long periods of time even with temperature cycling, states with the maximum flow velocity do show signs of slow decay (on the order of 1% per day).

In the study of the temperature dependence of the critical velocity, we have created a series of maximal persistent currents. The values of Ω_s were determined for each by the method illustrated in Fig. 2. In Fig. 4 we show the critical superfluid velocities, $\bar{v}_{s,c} = R\,\Omega_s$, obtained as a function of temperature. In this plot we show data for 15 and 29 bars.

The A-phase and the 15-bar B-phase critical-velocity data show the usual decrease with increasing temperature near T_c, while the low-temperature B-phase data show a tendency to increase with increasing temperature. This remarkable behavior is most clearly seen in the 29-bar data where the critical velocity increases by almost 30% as the temperature ranges from the lowest values to T_{AB}. The temperature dependence of the B-phase critical velocities obtained from angular momentum measurements by Pekola *et al.*[2] also showed this increase with increasing temperature.

While our B-phase results are in good agreement with the critical velocities derived from the angular momentum measurements of Ref. 2, our A-phase results are fundamentally different. Pekola *et al.*[2]

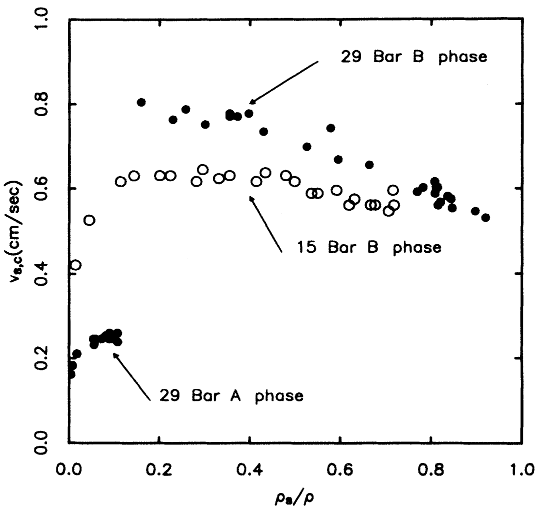

FIG. 4. The temperature dependence of the A- and B-phase critical velocities. The filled circles are 29-bar data while the open circles are data obtained at 15 bars.

found no evidence for persistent currents in the A phase. They suggest an upper limit of 0.5 mm/sec for the A-phase critical velocity for flow through a 20-μm packed powder. In contrast, we find clear evidence for long-lived A-phase flow states with critical velocities as large as 2.5 mm/sec. These critical velocities for superflow through 25-μm-diam powder lie in the range as the earlier A-phase measurements of Parpia and Reppy[12] for oscillatory flow through a single 18-μm-diam orifice. There is a clear discrepancy between our results and those of Ref. 2. It may be important that the method employed for the present experiment does not suffer a loss of sensitivity near T_c as is the case for angular momentum measurements.

In summary, we have established a new technique for the study of superflow in liquid ^{3}He. These measurements provide the first clear evidence for the existence of persistent currents in superfluid ^{3}He-A.

We wish to acknowledge the assistance of K. I. Blum and D. P. McQueeney. One of us (T.-L.H.) would like to acknowledge receipt of an Albert Sloan Foundation fellowship. This work has been supported by the National Science Foundation through Grant No. DMR-8119847 and by the Materials Science Center through National Science Foundation Grant No. DMR-8217227A-01.

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