Persistent Currents in Superfluid ^{3}He-B

P. L. Gammel, H. E. Hall,[a] and J. D. Reppy
Laboratory of Atomic and Solid State Physics and The Materials Science Center, Cornell University, Ithaca, New York 14853
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Observations of persistent currents in superfluid ^{3}He-B have been made with use of a recently developed ac gyroscope technique. The persistent currents are generated in a toroidal region filled with a fibrous material with average pore size of 10^{-2} cm. In this geometry, a mean critical velocity of 7×10^{-2} cm/sec was observed. To within experimental error, no decay of the currents was observed for periods of over one hour.

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We report in this Letter the first direct observation of persistent currents in superfluid ^{3}He. The observation of, and the study of the lifetimes of, superfluid persistent currents allows the most stringent bound to be placed on dissipation associated with flow of the superfluid component.[1-3] This is particularly important for ^{3}He-B where it has been suggested[4] on the basis of recent flow experiments that there may be an intrinsic damping mechanism which would preclude the existence of long-lived persistent currents.

The experiments we report here are restricted to the B phase of ^{3}He and were performed at a pressure of 29 bars. The apparatus used, an ac gyroscope,[5] combines many features of earlier ^{4}He gyroscopes[6,7] with the torsional oscillator techniques[8] developed at Cornell University in recent years. A schematic of this gyroscope is shown in Fig. 1. A toroidal flow channel is formed in a cylinder of epoxy (Stycast 1266). In order to lock the normal fluid, we have filled the open volume of the flow channel with a fibrous

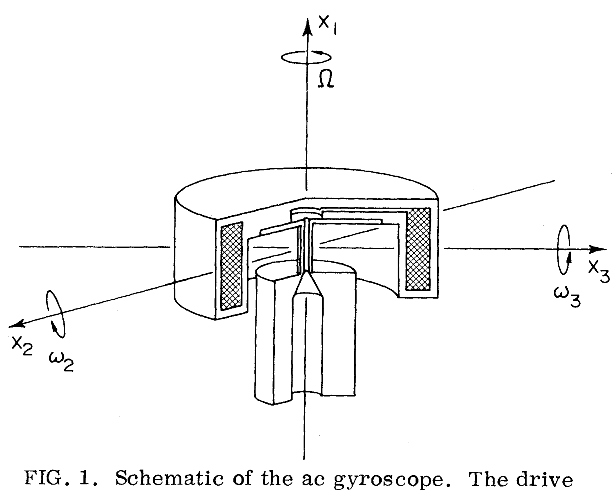

FIG. 1. Schematic of the ac gyroscope. The drive and detection electrodes are not shown. For a description, see text.

air-filter material. The filter material is compressed to fill 15% of the open volume and gives an average size on the order of 10^{-2} cm. The fibrous material may also serve to increase the critical velocity as would be the case for superfluid ^{4}He. We have chosen not to use even smaller pore sizes since we wish, in this first experiment, to avoid possible complications due to restricted-geometry effects.[9] The epoxy cell is mounted on a hollow beryllium-copper torsion rod, and is filled with ^{3}He through the torsion rod. The refrigeration is provided by a conventional $PrNi_5$ demagnetization cryostat, mounted on a platform capable of rotating at variable angular velocities up to 0.75 rad/sec. Thermometry was provided by a ^{3}He-melting-curve thermometer and a lanthanum-diluted cerium magnesium nitrate susceptibility thermometer. In addition, the hydrodynamic response of the gyroscope could be used to estimate the temperature and superfluid density in a manner analogous to that used in earlier experiments on Andronikashvilli-type oscillators.[8]

The three principal axes of oscillation are indicated in Fig. 1. Motion about the axis of cylindrical symmetry, X_1, is the usual torsional mode. We denote the moment of inertia of the cell about this axis by I_1, and that of the ^{3}He by I_f. In addition, there are two nearly degenerate tipping modes about the axes X_2 and X_3 with resonant angular frequencies ω_2 and ω_3. For the present cell, the moments of inertia about the tipping axes are nearly equal, i.e., $I_2 = I_3$. The cell is designed with the center of mass located at the midpoint of the torsion rod. Thus, to first order, the tipping motion corresponds to a simple rotation about the center of mass. The various motions of the cell are driven and detected by an array of capacitive electrodes.

In concept, the operation of the gyroscope is quite simple. There are two basic modes of operation, which are nearly equivalent. The choice between the two methods depends upon secondary considerations. In our work, we have successfully employed both modes of operation.

A persistent current can be generated in the flow channel by rotating the gyroscope about the symmetry axis, X_1, while cooling through the superfluid transition temperature, T_c. After reaching a temperature below T_c, the rotation is stopped and a persistent supercurrent is expected to remain circulating in the gyroscope. Another method, which is often more convenient, is to rotate while below T_c but well above any critical velocity.

The angular momentum associated with the persistent current may be detected by driving the resonant motion of one of the tipping modes, e.g., the one about the axis X_2 at an amplitude θ_2. The angular momentum, L, of the persistent current will perform a small oscillatory motion. The precessional torque associated with this motion,

$$\tau_p = i\,\omega_2\theta_2 L\,\exp(i\omega_2 t), \tag{1}$$

will produce a small motion of amplitude θ_3 about the axis X_3. We work in the limit $Q > \omega_2/\Delta\omega$, where $\Delta\omega = \omega_2 - \omega_3$ is the angular frequency splitting. We then have

$$\theta_3 = iL(2I_2\Delta\omega)^{-1}\theta_2. \tag{2}$$

In our case $\omega_2 \simeq 5000\ \text{sec}^{-1}$ and $\Delta\omega \simeq 10\ \text{sec}^{-1}$. For a drive torque τ_2 applied on resonance, $\theta_2 = i\tau_2 Q\,\omega_2^{-1}$ and

$$\theta_3 = -\tau_2 Q L(2I_2\omega_2\Delta\omega)^{-1}. \tag{3}$$

In the second mode of operation, the cell is driven about the X_2 axis, but at the resonant frequency ω_3. The precessional torque resulting from the motion of L is then at the proper frequency to produce resonant motion about X_3. For a drive torque, τ_2, the amplitude θ_3 is again given by Eq. (2). However, the total motion of the cell is much smaller in this method of operation and viscous heating effects are minimized.

Measurements can also be made while the cryostat is rotating which give an independent check on Eqs. (1)–(3) and serve as a calibration of the sensitivity of the gyroscope. In this case, there is an additional Coriolis torque coupling the two modes. In the rotating frame, we may again write Eqs. (1)–(3) with L replaced by an effective angular momentum

$$L_{\text{eff}} = L + (I_1 - I_2)\Omega, \tag{4}$$

where Ω denotes the angular velocity of the cryostat. The amplitude θ_3 may be written as

$$\theta_3 = \theta_L + \theta_C, \tag{5}$$

where θ_L is given by (2) and θ_C is

$$\theta_C = -\tau_2 Q\,\Omega(I_1 - I_2)(2I_2\omega_2\Delta\omega)^{-1}. \tag{6}$$

While rotating, $\theta_C \gg \theta_L$, and so we may take the measured θ_3 to be equal to θ_C. Almost all the temperature dependence of θ_C stems from the temperature dependence of Q, so that $\theta_C Q^{-1}$ should be independent of temperature for a given angular velocity. In Fig. 2 we plot $\theta_C Q^{-1}$ for the empty cell, as well as for the full cell above and below T_c.

A determination of the slope, $\alpha = \partial\theta_C/\partial\Omega$, from a linear fit to a set of Coriolis signals, $\theta_C(\Omega)$, at a fixed temperature serves as a calibration of the sensitivity of the gyroscope to angular momentum at that temperature. The persistent-current angular momentum in the nonrotating frame may then be expressed as

$$L = \theta_3\alpha^{-1}(I_1 - I_2) = (\rho_s/\rho)I_f\,\Omega_f, \tag{7}$$

where Ω_f is an effective angular velocity for the persistent current. The average persistent-current flow velocity, v_s, may then be expressed as $v_s = \bar{R}\Omega_f$, where $\bar{R} = 6.8$ mm is the average flow-channel radius.

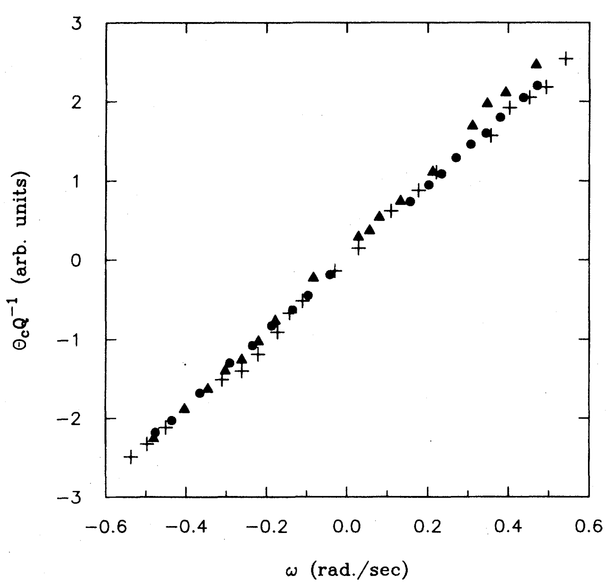

FIG. 2. The normalized Coriolis response. The data shown are for the B phase at $T/T_c = 0.64$ (circles), the normal Fermi liquid at 2.85 mK (plusses), and the empty cell (triangles), which has been corrected for the fluid moment of inertia. The data fall on the same line to within experimental error.

In Fig. 3, we show data for a sequence of persistent-current measurements. Before beginning such a sequence, the cell was allowed to cool from above T_c while at rest, giving zero initial superfluid angular momentum. The cryostat was then rotated at a preparation velocity ω_p. After stopping the cryostat, the remanent persistent-current signal, θ_L, was measured. A series of increasing preparation speeds is then used. The growth of a persistent-current signal is seen with saturation of its magnitude setting in at about 0.1 rad/sec (~ 0.7 mm/sec fluid velocity). The maximum residual signal likewise corresponds to a velocity of 0.7 mm/sec. The data show some remanent angular momentum even at the lowest preparation speeds as does ^{4}He data in a similar geometry, suggesting a distribution of critical velocities. In addition to data of the type shown in Fig. 3, we have also obtained data for currents created by cooling through T_c while rotating.

In Fig. 4, the temperature dependence of the saturated critical velocity, $v_{s,c}$, as determined by the maximum residual angular momentum signal, is shown. As compared to the noise in measuring a particular current, the data show quite a large scatter. This may be due in part to initial instabilities of the current as was observed in ^{4}He in a similar geometry.[1] Also, the resonant frequency of one of the tipping modes crossed a weak temperature-independent mode near $T/T_c = 0.57$, which greatly increased the noise level near this temperature.

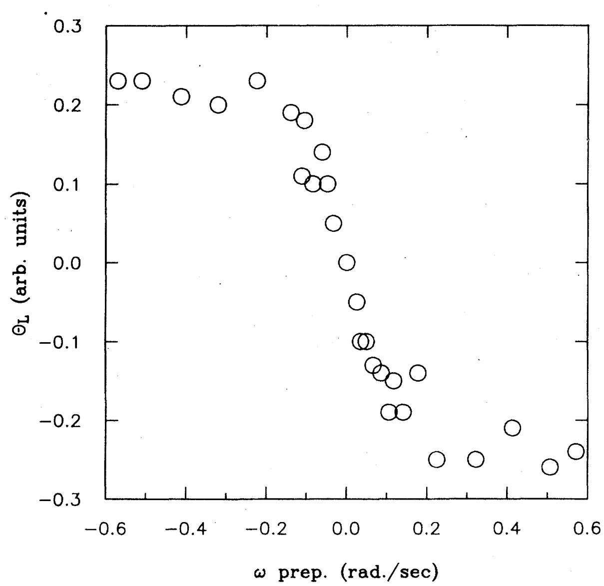

FIG. 3. The saturation curve for ^{3}He-B at $T/T_c = 0.64$. The maximum residual angular momentum corresponds to a fluid velocity of 0.1 rad/sec, as the knee in the saturation curve would indicate.

In earlier work, Parpia and Reppy[10] and Crooker, Hebral, and Reppy[11] studied the critical velocities for flow through orifices of well-known size. They observed a size dependence which could be written approximately as $v_{s,c} d = 6.5\times10^{-4}$ cm^2/sec, only weakly dependent on temperature. In Fig. 4 we show their results for 5- and 18-μm orifices scaled in this way to our $d = 10^{-2}$ cm.

Following Feynman[12] we may argue that the critical velocity for the instability of a single vortex line pinned at two points a distance d apart is

$$v_{s,c} = (h/2md)\ln(d/2a), \tag{8}$$

where m is the bare ^{3}He mass and we take the vortex core size a to be equal to the coherence length $\xi = (100\ \text{Å})(1 - T/T_c)^{-1/2}$. This function is shown by the dashed line in Fig. 4.

The AB transition indicated by the dotted vertical line of Fig. 4 is clearly marked by the dissipation in our gyroscope. No persistent currents were seen in the A phase to within our signal-to-noise ratio. If the critical velocity were the same

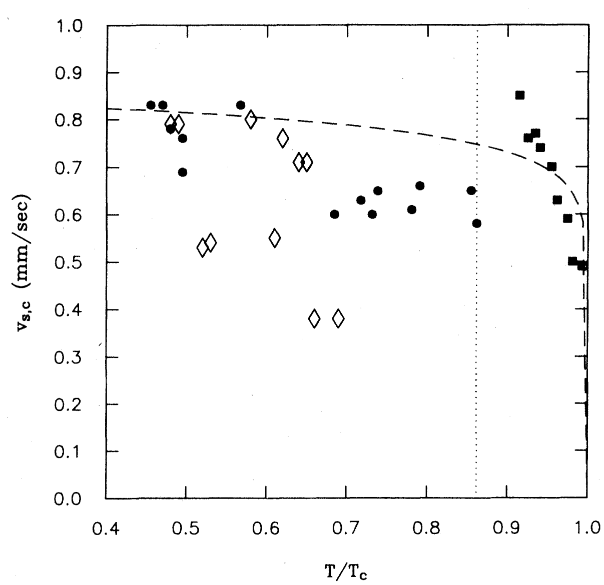

FIG. 4. The temperature dependence of the saturation critical velocity in ^{3}He-B. Points determined by the ac gyroscope are shown as lozenges. Also given is the critical velocity observed by Crooker, Hebral, and Reppy (Ref. 11) (circles) in 5-μm orifices at 21 bars and Parpia and Reppy (Ref. 10) (squares) in 18-μm orifices at 20.8 bars scaled by $d/(100\ \mu\text{m})$. The dotted vertical line is T_{AB} as determined by the hydrodynamic response of the ac gyroscope. The dashed line is the vortex critical velocity.

as in the B phase, we would not expect to see any currents, because of the small superfluid density. However, in the rotating frame, shifts in the period and dissipation of the cell were observed, suggesting some effects of textural alignment.

In the present experiments we have not made extensive studies of the lifetimes of ^{3}He persistent currents. However, in our experiments we have noted no observable persistent-current decay for periods of at least one hour. If we take as a conservative estimate 10^4 sec as the minimum lifetime of a ^{3}He persistent current, we may obtain an upper bound for an effective viscosity of the superfluid. The viscous relaxation time, τ, for undriven flow of a fluid in a channel of diameter d, is on the order of $\tau \approx \rho d^2 \eta^{-1}$, where ρ is the fluid density and η the viscosity. Taking $\tau = 10^4$ sec and $d = 10^{-2}$ cm, we obtain an upper bound for an effective superfluid viscosity which is 10^{-8} times smaller than the normal-component viscosity at the same temperature.

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[a]Permanent address: Physics Department, Manchester University, M13 9P1, United Kingdom.

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