

## Persistent-Current Experiments on Superfluid $^3\text{He-B}$ and $^3\text{He-A}$

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We have investigated persistent flow of superfluid  $^3\text{He}$  with an ac gyroscope filled with 20- $\mu\text{m}$  powder. In  $^3\text{He-B}$ , currents circulate undiminished for 48 h at least; this implies a viscosity 12 orders of magnitude lower than in the normal fluid. In  $^3\text{He-A}$ , the current does not persist. The observed critical velocity in  $^3\text{He-B}$  at  $P \leq 12$  bars is independent of temperature. At  $P > 12$  bars there are two regimes in the  $B$  phase: For example, at 29.3 bars the ultimate critical velocities are 5.4 and 7.8 mm/s, respectively.

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We present in this Letter results of persistent-current experiments in  $^3\text{He-B}$  and  $^3\text{He-A}$ ; we have obtained extensive data at eight different pressures. A comparison with the recent results of Gammel, Hall, and Reppy,<sup>1</sup> at  $P = 29$  bars, reveals several qualitative differences. For example, we see a reversible response of the superfluid to subcritical speeds of rotation and have observed two regions in the  $B$  phase with clearly different critical velocities; we have also extended persistent-current measurements from 1 to 48 h. By use of finer powder in the experimental cell, critical velocities became larger and the scatter of the data was thus considerably reduced over the results of Ref. 1.

Our experiments were carried out in a rotating nuclear refrigerator.<sup>2</sup> The basic measuring device, an ac gyroscope, is illustrated in Fig. 1. A metal torus, packed with 20- $\mu\text{m}$  plastic powder, forms a path for the circulating superfluid. This ring ( $R = 22$  mm,  $r = 3$  mm) is supported by two sets of mutually perpendicular hollow copper torsion tubes, also used as the filling capillaries for the  $^3\text{He}$  sample. Torsional modes about the tubes are determined by angles  $\theta$  and  $\phi$ . The device is ac-driven about  $\theta$  by a superconducting solenoid inside a niobium shield; capacitive detectors are used for monitoring the  $\phi$  motion.

When the ring is driven about  $\theta$  at the resonant frequency  $\omega_\phi/2\pi$  of the  $\phi$  mode, the response due to the angular momentum  $\vec{L} = \vec{z}L$  of the circulating superfluid is  $\phi_0 = Q_\phi L \theta_0 / I_\phi \omega_\phi$ ; here  $\theta_0$  is the amplitude of the drive motion and  $I_\phi$  and  $Q_\phi$  are respectively the moment of inertia of the torus and the quality factor of the resonance about the  $\phi$  axis. In our apparatus,  $Q_\phi = 20\,000$ ,  $I_\phi \approx 30$  g cm<sup>2</sup>, and  $\omega_\phi/2\pi = 69.8$  Hz; typically  $\theta_0 \approx 10^{-5}$  rad giving

$\phi_0 = 10^{-4}$  rad. In our mode of operation, with  $\omega_\theta \gg \omega_\phi$ ,  $\phi_0$  is insensitive to changes in the resonant frequencies. The response  $\phi_0$  is detected capacitively and the preamplifier output is fed back to a self-resonating drive circuit. This technique ensures a constant-amplitude drive, strictly at the resonant frequency of the  $\phi$  mode. The minimum observable change in  $L$  is 0.01 g cm<sup>2</sup>/s ( $\sim 10^{25}\hbar$ ) using 12-s integration time. Noise in the system is mostly of mechanical origin.

The  $L$  sensitivity of the device can be calibrated by means of the Coriolis effect: This force produces an additional torque about the  $\phi$  axis while

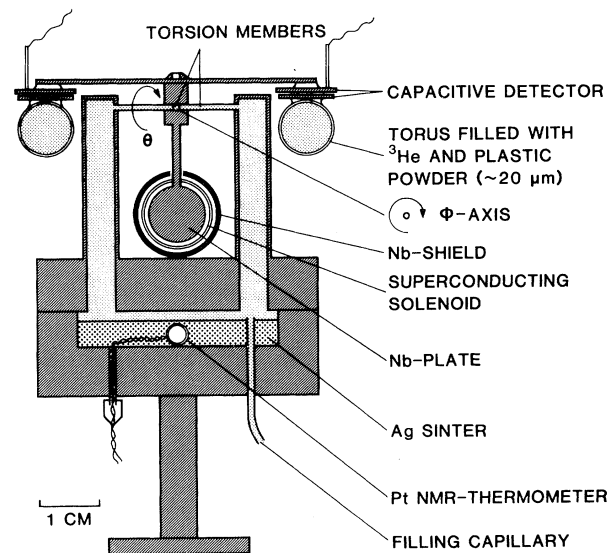


FIG. 1. The ac gyroscope. The foot is thermally connected to the nuclear refrigerator. For further explanations, see text.

the ring is being rotated. The Coriolis signal is  $\phi_C = \alpha \Omega$ , where  $\alpha$  is the calibration constant and  $\Omega$  is the cryostat's angular velocity. The signal due to persistent flow, with the cryostat at rest, is then  $\phi_L = \alpha L / (I_z - I_\theta)$ .

In the superfluid phases,  $\omega_\phi$  serves as a thermometer. The frequency change,  $\Delta\omega_\phi$ , is proportional to the superfluid fraction  $\rho_s/\rho$  which, in turn, is a known function of temperature<sup>3</sup> and independent of the velocity at the speeds involved in these experiments.  $T_c$  and the  $B$ - $A$  transition temperature  $T_{BA}$  serve as calibration points. Since the torus is filled with fine powder and since  $B_{\text{ext}} < 0.1$  mT, there is a spatially random distribution of the  $\hat{l}$  vector in  $^3\text{He-A}$ . Therefore, the  $\rho_s/\rho$  vs  $\Delta\omega_\phi$  calibrations coincide in both phases. An independent check of our temperature scale was provided at  $P = 29.3$  bars by the fact that  $\rho_s/\rho \rightarrow 1$  at the lowest temperatures. We have also measured the absolute temperature by reversible demagnetization-remagnetization cycles.

In our experiments we observe the angular momentum  $L = MR(\rho_s/\rho)v_s$  persisting in the torus; here  $M$  is the mass of  $^3\text{He}$  in the ring and  $v_s$  is the average velocity of the circulating superfluid. Figure 2 illustrates the increase of the persistent angular momentum in the ring as a function of  $\Omega_p$ , the preparation (=maximum) angular velocity at which the torus was rotated. The data were obtained well below  $T_c$  by first speeding up the cryostat to  $\Omega_p$ , and then slowing it down to rest where the measurement of  $L^{(+)}$  was made. The sequence was then repeated by rotating the apparatus in the opposite direction giving  $L^{(-)}$ . The difference,  $L = \frac{1}{2}[L^{(+)} - L^{(-)}]$ , is our basic datum. Precise

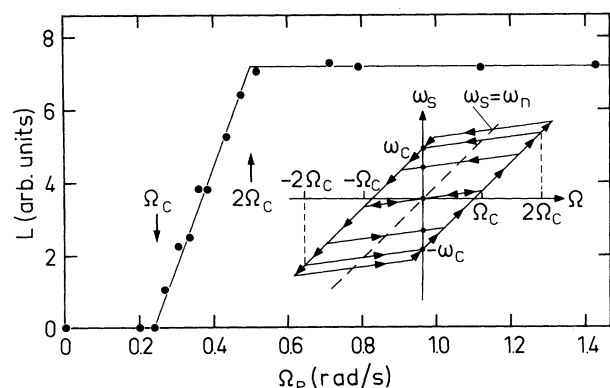


FIG. 2. Persistent angular momentum  $L$  vs the preparation angular velocity  $\Omega_p$  of the cryostat at  $P = 8$  bars. The inset shows the idealized hysteresis loop. For further explanations, see text.

measurements of  $L$  cannot be made while the cryostat is being rotated because the Coriolis momentum is  $\sim 100$  times larger than the superfluid effects.

We have made extensive measurements of the angular momentum at  $P = 3.0, 8.0, 12.0, 15.0, 18.0, 21.0, 23.0,$  and  $29.3$  bars from  $0.8$  mK to  $T_c$ . The experimental  $L$  vs  $\Omega_p$  curves separate into three regimes: (1) for  $\Omega_p < \Omega_c$ ,  $L = 0$ ; (2) for  $\Omega_c < \Omega_p < 2\Omega_c$ ,  $L = (L_c/\Omega_c)(\Omega_p - \Omega_c)$ ; and (3) for  $\Omega_p > 2\Omega_c$ ,  $L = L_c$ . The data in Fig. 2 demonstrate this behavior with  $\Omega_c = 0.23$  rad/s at  $P = 8$  bars. Here  $\Omega_c$  is the limit of the reversible region and  $L_c$  is the maximum persistent angular momentum.

Our results can be interpreted in terms of the idealized hysteresis loop, shown as an inset in Fig. 2 and based on the premise that the relative velocity  $|v_n - v_s| = R|\omega_n - \omega_s|$  never exceeds the critical velocity  $v_c$ . We also assume that  $\Omega \equiv \omega_n$  because the fine powder in the torus clamps the normal fluid completely. The parallelogram path is bounded at the top and bottom by reversible regions in which the superfluid component exhibits potential flow, induced by the Kelvin drag between the powder particles and the ideal superfluid. Because of this,  $\omega_n - \omega_s$  differs from  $\Omega$ , even when  $\Omega < \Omega_c$ , and the true  $v_c \equiv R\omega_c$  deviates to some extent from the measured  $R\Omega_c$ . The sides of the loop have unit slope and correspond to generation of superflow by irreversible vortex creation processes. The hysteresis arises because the vortices become pinned to the powder particles. A similar hysteresis loop was seen by Rudnick *et al.*<sup>4</sup> in  $^4\text{He}$ . Our result is in marked contrast with the measurements of Gammel, Hall, and Reppy<sup>1</sup>; in their data (see Fig. 3 of Ref. 1) the elastic regime is absent.

In Fig. 3,  $v_c = L_c/[MR(\rho_s/\rho)]$  is illustrated as a function of the reduced temperature  $T/T_c$  at  $P = 12.0$  and  $15.0$  bars. The data were obtained in a manner similar to those in Fig. 2, but at fixed angular velocity  $\Omega_p > 2\Omega_c$ . The data of Gammel, Hall, and Reppy<sup>1</sup> are included for comparison. Our results show that  $v_c$  is independent of temperature within about 10%. In previous work the signal-to-noise ratio was insufficient to demonstrate the temperature independence of  $v_c$ .

A careful check for possible weak dissipation was made in  $^3\text{He-B}$  at  $P = 8$  bars. In these experiments the maximum angular momentum was first created in the ring by rotating the cryostat at  $\Omega_p > 2\Omega_c$ . The apparatus was then brought to rest and  $L$  was measured. After the cryostat had been kept in the

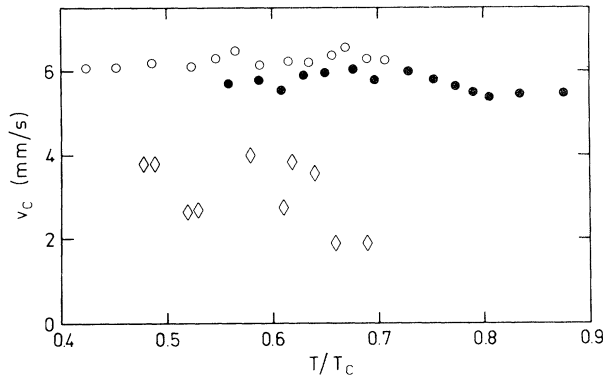


FIG. 3. Critical velocity  $v_c$  at  $P = 15.0$  bars (open circles) and  $12.0$  bars (filled circles) as a function of the reduced temperature  $T/T_c$ . Lozenges are the data of Gammel, Hall, and Reppy (Ref. 1) at  $P = 29$  bars, multiplied by 5, the ratio of the pore sizes  $[(100 \mu\text{m})/(20 \mu\text{m})]$ ; this reduction factor is only approximate because of different types of geometries involved.

$B$  phase continuously for 48 h,  $L$  was again measured. This value was then compared with that obtained after the cryostat was again rotated at the same velocity as before and then stopped. Within our experimental accuracy of 10% there was no decay in the signal. This gives for  $\tau$ , the relaxation time of the superflow, a value in excess of 450 h and implies in the  $B$  phase an effective viscosity,  $\eta_{\text{eff}} = \rho d^2/\tau$ , which is at least 12 orders of magnitude smaller than for the normal liquid at the same temperature. Here  $d \approx 20 \mu\text{m}$  is the average size of the interstitial pores.

Measurements of  $L$  made after thermal cycling in the region below  $T = 0.98T_c$  showed that the angular momentum is a reversible function of temperature. In addition to the fact that  $v_c$  is independent of temperature, this demonstrates that, because of macroscopic quantization, circulation is conserved in  ${}^3\text{He-B}$  as in He II.<sup>5</sup> The temperature reversibility was used to study the stability of persistent currents in the immediate vicinity of  $T_c$ . These experiments showed that above  $T = 0.98T_c$  the critical velocity decreases markedly; at  $T = 0.989T_c$ , for example,  $v_c$  is  $(50 \pm 5)\%$  of its low-temperature value.

Figure 4 shows a plot of  $L_c$  vs  $\rho_s/\rho$  at 29.3 and 12.0 bars. The slope of the linear regime between  $T_v = 0.56T_c$  and  $T_{BA}$  in the 29.3-bar data corresponds to  $v_c = 7.8$  mm/s. The critical velocity is different below  $T_v$ ; at low temperatures  $v_c \rightarrow 5.4$  mm/s. This value is close to that measured at  $P \leq 12$  bars. The change in  $v_c$  at  $T_v$  was not seen by Gammel, Hall, and Reppy<sup>1</sup> because an experimental artifact prevented accurate observations near  $T = 0.57T_c$ .

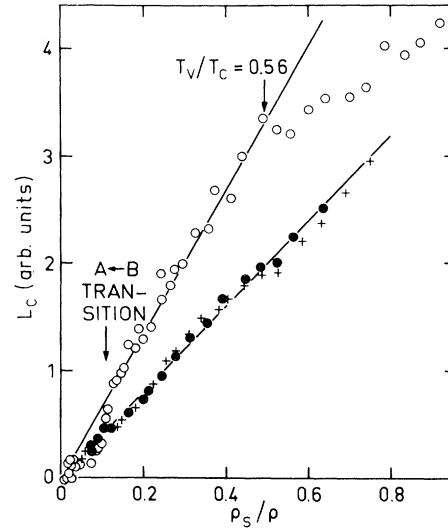


FIG. 4. Saturated angular momentum  $L_c$  as a function of  $\rho_s/\rho$  at  $P = 29.3$  bars (open circles) and  $P = 12.0$  bars (filled circles, crosses, two different experiments). The straight line corresponds to  $v_c = 7.8$  and  $5.6$  mm/s for the 29.3- and 12.0-bar data, respectively (to compare the two critical velocities one should divide the slopes by the density of  ${}^3\text{He}$  at each pressure). The nonzero  $L_c$  in  $A$  phase is an experimental artifact that was removed in later runs (see Fig. 5).

Experiments are in progress to test the possible relation of the change in  $v_c$  at  $T = 0.56T_c$  with the vortex-core transition observed in NMR experiments at  $T = 0.6T_c$ .<sup>6</sup>

Data in Fig. 5 illustrate that currents in  ${}^3\text{He-A}$  do not persist, at least under zero magnetic field. This conclusion is supported by an experiment in which the maximum  $L = L_c$  was first created and measured in  ${}^3\text{He-B}$ , whereafter the torus was thermally cycled to the  $A$  phase and then back to the  $B$  liquid again: The signal had completely disappeared during this sequence. The upper limit for the superflow decay in  ${}^3\text{He-A}$  is less than 1 min, which was the transient time for the signal to recover from the Coriolis shift after the cryostat had been stopped. Because of the anisotropic nature of  ${}^3\text{He-A}$ , the supercurrent might persist in some geometry different from our packed powder.

Critical velocities of the order of a few millimeters per second seem to be associated with vorticity in confined geometries from 10 to  $100 \mu\text{m}$ . For the emission of a vortex ring with diameter  $d_0$ ,  $v_c \sim (\hbar/m_3 d_0) \ln(d_0/\xi_0)$ , where  $m_3$  is the bare mass of the  ${}^3\text{He}$  atom and  $\xi_0 = 20$  nm is the coherence length.<sup>7</sup> If the vortex rings have a diameter equal to the pore size, the calculated critical velocity is 7

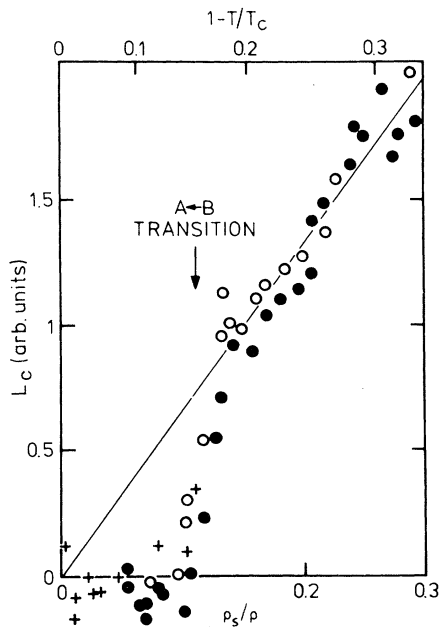


FIG. 5.  $L_c$  vs  $\rho_s/\rho$  around the  $B \rightarrow A$  transition at  $P = 29.3$  bars. Different symbols correspond to different preparation angular velocities: open circles,  $\Omega_p = 1.16$  rad/s; filled circles, 0.86 rad/s; pluses, 0.57 rad/s. Note that the reduced temperature scale at the top is non-linear.

mm/s in our experimental setup, quite close to the observed values 4.7–7.8 mm/s. Additional confirmation of this model is provided by the temperature independence of the measured  $v_c$ . The weak

pressure dependence is due to  $\xi_0$  in the logarithmic factor.

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