proportional to the ^{3}He mole fraction, although it is somewhat less at low concentrations and somewhat greater at high concentrations. If possible concentration errors of up to ±0.5% are considered along with the estimated uncertainties in the determination of the temperatures at the minima, then the following formula may be used (for interpolation purposes only) to express the temperatures (T_{mixt}) of the volume minima as functions of the ^{3}He mole fraction and the temperatures of the volume minima of pure ^{4}He ($T_4{}^0$) and pure ^{3}He ($T_3{}^0$):

$$(T_4{}^0 - T_{mixt})/(T_4{}^0 - T_3{}^0) = x_3 - 0.027 \sin 2\pi x_3.$$

The only other direct measurements of the densities of mixtures, those of Ptukha,[3] are in good agreement with the present results at lower concentrations but give temperatures as much as 0.060°K higher for the density maxima. However, our own analysis of Ptukha's density-temperature data indicates that the density maximum for the 40% ^{3}He solution occurs within 0.005°K of the smooth curve through our data for the temperatures of the volume minima.

Thus it appears that, since the volume minimum follows an independent locus, the experimental determinations of the λ line are in reasonable agreement with each other. An exception is the visual experiment of Zinov'eva and Peshkov[4] which gave unusually high results for the λ temperatures, although their results for the stratification temperatures are in good agreement with the data of other investigations. Roberts and Sydoriak[1] have discussed several reasons why this type of experiment might give erroneous results as a consequence of large temperature and concentration gradients associated with the nature of the method. Such gradients might reasonably be enhanced by the existence of the density maximum just above the true λ temperature. As shown in Fig. 2, all but two of their data points fall within 0.030°K of the curve for the volume minima—an observation which suggests that their experiment may have been more sensitive to the density gradients than to the λ phenomenon.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1]References to most of the pre-1961 data on the λ line and the stratification region have been given by T. R. Roberts and S. G. Sydoriak, Proceedings of the Seventh International Conference on Low-Temperature Physics (University of Toronto Press, Toronto, Canada, 1961), p. 633; S. G. Sydoriak and T. R. Roberts, Phys. Rev. 118, 901 (1960).

[2]E. C. Kerr, Proceedings of the Fifth International Conference on Low-Temperature Physics and Chemistry, Madison, Wisconsin, 30 August 1957, edited by J. R. Dillinger (University of Wisconsin Press, Madison, 1958), p. 158.

[3]T. P. Ptukha, Zh. Eksperim. i Teor. Fiz. 34, 33 (1958) [translation: Soviet Phys.—JETP 7, 22 (1958)].

[4]K. N. Zinov'eva and V. P. Peshkov, Zh. Eksperim. i Teor. Fiz. 37, 33 (1959) [translation: Soviet Phys.—JETP 10, 22 (1959)].

[5]E. C. Kerr and R. D. Taylor, Proceedings of the Seventh International Conference on Low-Temperature Physics (University of Toronto Press, Toronto, Canada, 1961), p. 538; and (to be published).

[6]C. E. Chase, E. Maxwell, and W. E. Millett, Physica 27, 1129 (1961).

[7]D. M. Lee and H. A. Fairbank, Phys. Rev. 116, 1359 (1959); Phys. Fluids 2, 582 (1959).

[8]E. C. Kerr and R. D. Taylor, Ann. Phys. (N.Y.) 20, 450 (1962); Proceedings of the Seventh International Conference on Low-Temperature Physics (University of Toronto Press, Toronto, Canada, 1961), p. 605.

[9]R. H. Sherman, S. G. Sydoriak, and T. R. Roberts, Los Alamos Scientific Laboratory, Report No. LAMS-2701, 1962 (unpublished).

[10]R. de Bruyn Ouboter, K. W. Taconis, C. le Pair, and J. J. M. Beenakker, Physica 26, 853 (1960).

PERSISTENT CURRENTS IN SUPERFLUID HELIUM*

John D. Reppy and David Depatie
Department of Physics, Yale University, New Haven, Connecticut
(Received 22 January 1964)

The superconducting ring experiment, first performed by Kamerlingh Onnes, is one of the classic demonstrations in low-temperature physics. In this experiment an electric current is created in a ring of superconducting material. The lifetime of such a current is effectively infinite, provided that the ring remains in the superconducting state.

The superfluidity of liquid helium is, in many ways, analogous to the superconductivity of metals; therefore, it is reasonable to expect persistent currents in liquid helium. The detection of such currents in liquid helium presents certain difficulties. There is no external magnetic field such as exists in the superconducting case, so that any measurement must involve a direct mechanical interaction with the liquid helium. The experimental difficulties have been overcome, and a series of experiments[1-4] has established with increasing confidence that persistent currents can, indeed, exist in superfluid helium.

The primary aim of the present experiment is a study of the magnitude of the persistent currents as a function of temperature. The methods used are basically the same as those used in our earlier work,[4] but with certain improvements and simplifications of technique.

A cylindrical liquid helium container, Fig. 1, is suspended from a magnetic bearing so that it may rotate about its vertical axis with negligible drag. The interior of the container is divided into many annular regions by thin mica discs mounted, with spacers, on a central rod. The discs are spaced about 0.3 mm apart in order to increase the critical velocity.

The container is filled with liquid helium and sealed off. Exchange gas is used to maintain thermal contact between the container and a helium bath. The exchange gas is always removed before a measurement is made to avoid any spurious torques.

The persistent current is prepared by the following procedure. First, the container is rotated at a speed far above the critical velocity for the superfluid. Once the superfluid has absorbed angular momentum from the container,

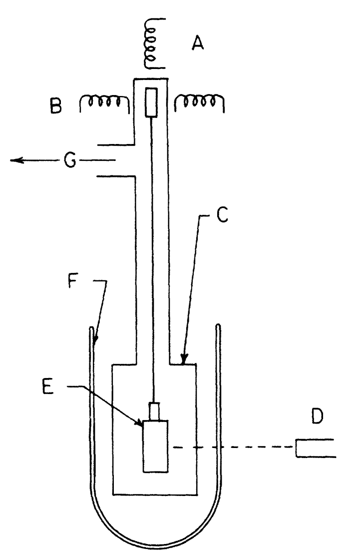

FIG. 1. Schematic of the apparatus. (A) Magnetic bearing; (B) brake and drive coils; (C) glass vacuum jacket; (D) lamp used for heating; (E) liquid container; (F) helium Dewar; (G) exchange gas source and diffusion pump.

the speed is slowly decreased until the container is finally brought to rest. The container is held at rest by a magnetic brake, for a given waiting period, before a measurement is made to investigate the presence of a persistent current. The length of this waiting period has been varied from five minutes to over 12 hours without any observable difference in the results.

After the waiting period, any exchange gas is removed and the magnetic brake released so that the container hangs free from the magnetic bearing. The presence of the persistent current is then detected by heating the container with an external light. If the liquid is heated to the λ point, the persistent current will be destroyed, and the container will start to rotate. Equilibrium takes place very rapidly, since the discs are spaced closely together, and the angular momentum of the persistent current will be shared by the container and the liquid. Since the method of heating exerts no torque, conservation of angular momentum holds, and the angular momentum of the persistent current, L_p, is given by $L_p = I\omega$, where I is the total moment of inertia of the rotating system, about 28 g cm^2, and ω is the equilibrium angular velocity of the container after the destruction of the persistent current.

In actual practice it was found that only the first half-second of heating is necessary to bring about equilibrium between the container and the superfluid. This first heat pulse triggers the destruction of the persistent current, and any further heating produces no observed effects other than an increase in the temperature of the liquid.

Two types of measurements were made. In the first instance, the persistent currents were measured at the temperature at which they were prepared, while in the second, the temperature was changed to another value before measurement.

The angular momentum of a number of persistent currents which were created and measured at the same temperature are plotted in Fig. 2 as a function of the temperature. The points are indicated by the squares. These results show the angular momentum of the persistent currents to have a strong temperature dependence very similar to that of the superfluid density. It should be noted that the values obtained by the present method probably represent, at each temperature, an approximate upper bound on the size of the persistent currents possible in this geometry.

The second type of measurement is suggested by the strong temperature dependence of L_p. If a persistent current were formed near the λ

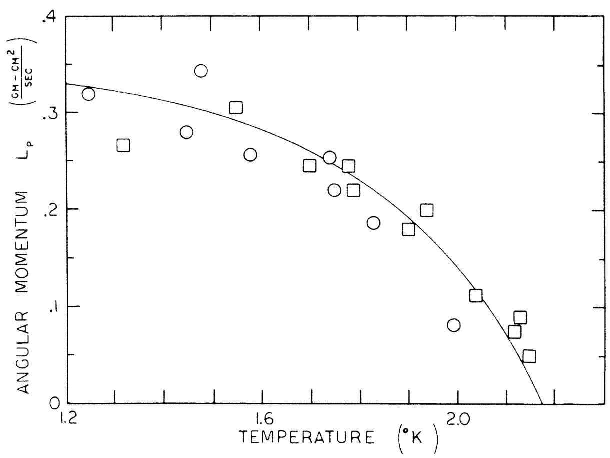

FIG. 2. Persistent current angular momentum, L_p, plotted against measurement temperature. The squares and circles indicate values obtained when the temperature, after formation of the current, was either held constant (squares) or lowered (circles) before measurement. The solid curve is the function $0.338\rho_s/\rho$ vs temperature.

point where the angular momentum of the currents is small, then one might expect that the angular momentum would remain constant if the liquid were cooled to a lower temperature. The two-fluid model, however, seems to predict a quite different result. The argument follows lines similar to Kelvin's well-known circulation theorem.

In the treatment of the two-fluid models given by Landau,[5] the condition curl $\vec{v}_s = 0$ is satisfied by the superfluid velocity. Under this condition, the superfluid obeys the hydrodynamic equation

$$\partial\vec{v}_s/\partial t = -\nabla[\Phi + \tfrac{1}{2}v_s^2 - (\rho_n/2\rho)(\vec{v}_n - \vec{v}_s)^2],$$

where Φ is the thermodynamic potential per gram of the stationary liquid, ρ_n and ρ the normal and total fluid density, and $\vec{v}_n$ the normal fluid velocity. Note that the potential function in the hydrodynamic equation is single-valued, even for nonsimply connected geometries. Consequently, an integral of the form $\oint \vec{v}_s \cdot d\vec{l}$ is constant in time for all motions of the superfluid consistent with the hydrodynamic equation.

When an isothermal condition holds throughout the container, the angular momentum of a persistent current can be expressed as an integral over the volume of the liquid in the following form:

$$L_p = \rho_s \iint r[\oint \vec{v}_s \cdot d\vec{l}]\,dr\,dz.$$

The circulation integral is taken over a circular path, radius r, centered on the axis of the container at a height z. Since the circulation integral over any fixed path is constant in time, then, for any given persistent current, the ratio L_p/ρ_s is a constant independent of the temperature.

It is essential in any experimental test of this result that variations in the temperature be made adiabatically in order that the flow velocities remain less than critical and that the hydrodynamic equation is obeyed at all times.

A number of persistent currents were formed at temperatures between 2.10°K and the λ point. During the waiting period, with the container at rest the temperature was slowly lowered to a new value before measuring the angular momentum. The results are plotted as circles in Fig. 2 as a function of the measurement temperature. The solid line is a curve proportional to the superfluid density which has been fitted to the data.

The experimental results bear out the prediction of the two-fluid model. The angular momentum of the persistent current is not conserved when the liquid is cooled, but rather grows in proportion to the superfluid density. One should note that there is no conflict with the general principle of conservation of angular momentum since the container is constrained during the cooling process.

The authors wish to acknowledge many instructive discussions with Professor C. T. Lane and Professor M. J. Stephen. We would also like to thank Mr. J. C. Weaver for technical assistance.

*Work supported by the Army Research Office (Durham) and the National Science Foundation.

[1]H. E. Hall, Phil. Trans. Roy. Soc. London A250, 980 (1957).

[2]W. F. Vinen, Proc. Roy. Soc. (London) A260, 218 (1961).

[3]Philip J. Bendt, Phys. Rev. 127, 1441 (1962).

[4]David Depatie, John D. Reppy, and C. T. Lane, Proceedings of the Eighth International Congress on Low-Temperature Physics, London 1962 (Butterworths Scientific Publications, Ltd., London, to be published).

[5]L. Landau, J. Phys. (U.S.S.R.) 5, 71 (1941).