APPLICATION OF A SUPERFLUID GYROSCOPE TO THE STUDY OF CRITICAL VELOCITIES IN LIQUID HELIUM NEAR THE λ TRANSITION*

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The nature of the λ transition in liquid helium remains one of the outstanding problems of low-temperature physics. A unique feature of the transition is the appearance of a single macroscopic quantum state, the superfluid, below the transition temperature. Most experimental work to date on liquid helium in the neighborhood of the transition has been dominated by the effects of the normal fluid. To complete the experimental description of the λ transition, it is desirable to have direct measurements of the behavior of the superfluid.

The present experiment is designed to obtain information on the stability of superfluid flow in the vicinity of the transition. The method is based on the results of an earlier study[1] of the properties of persistent currents in liquid helium. The angular momentum of a persistent current formed in an annular container was shown to be proportional to the superfluid density and to be a reversible function of temperature. This result agreed with the expectation that the superfluid has the properties of a single quantum state, since the velocity field of such a state remains fixed during an adiabatic variation in temperature, while the effective density, ρ_s, changes.

The temperature reversibility of the angular momentum is used to examine the stability of persistent current states within 10^{-5} °K of the transition. A persistent current is formed at a temperature well below the transition. The temperature is slowly raised to near the transition. After holding constant for about five minutes, the temperature is lowered, and the value of the angular momentum is measured. If the critical velocity for superfluid flow near the transition is less than the flow velocities of the persistent current, then dissipative processes would occur, and the angular momentum would be reduced.

In the previous experiment[1] no measurements were made closer than 15×10^{-3} °K from the transition because the sensitivity was low and a cumbersome technique which required the destruction of the current was used to determine angular momentum.

A new method[2] which allows repeated nondestructive measurements of the persistent current angular momentum has been developed. Mehl and Zimmerman[3] have recently reported on a somewhat similar technique. The apparatus is shown schematically in Fig. 1. The superfluid current is formed in an annular container. The walls of the container are thin magnesium, and the interior is filled with a fibrous foam to increase the critical velocity. This system constitutes a superfluid gyroscope, where the rotating element is frictionless superfluid. The persistent current angular-momentum vector, $\vec{L}_p$, is in the horizontal plane. The torque required to make $\vec{L}_p$ rotate at a constant angular velocity ω about the vertical axis is provided by a small deflection against a horizontal torsion fiber. The deflection is detected by a change in frequency of an oscillator. The λ temperature was determined by

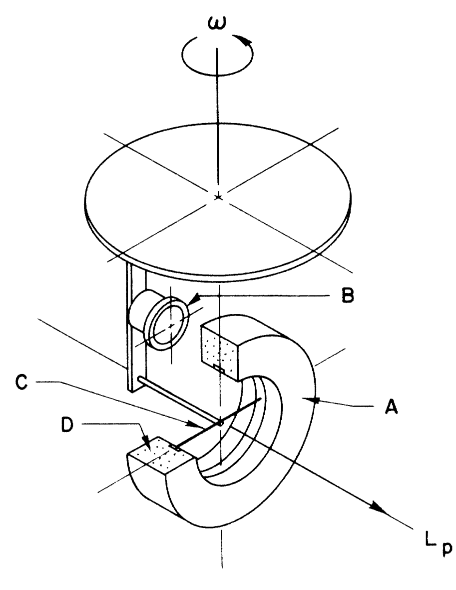

FIG. 1. Schematic of apparatus. The persistent current with angular momentum $\vec{L}_p$ is formed in the annular container A. The container dimensions are 5.0 cm o.d., 3.0 cm i.d., and 1.5 cm long. It is filled with fibrous foam, D. During rotation $\vec{\omega}$, about the vertical axis, the container deflects against a 2-mil tungsten fiber, C. This deflection is sensed by an oscillator tank coil, B.

the discontinuity of a resistance thermometer. A servo capable of holding the temperature constant to a few microdegrees was used.

If Δf is the change in frequency between clockwise and counterclockwise values of ω, then

$$L_p = ks\Delta f/2\omega,$$

where $k = 1.0\times10^2$ dyne cm/rad is fiber constant, and $s = 1.5\times10^{-6}$ rad/cycle is the angular sensitivity of the oscillator.

The mean flow velocity of the superfluid may be estimated from the dimensions of the container and the values of L_p. In the present experiment the superfluid velocity is on the order of 2mm/sec, the exact value depending on the model assumed for the flow field.

The behavior of a superfluid current is illustrated in Fig. 2. Since the angular momentum, L_p, measured at temperature T, is proportional to the superfluid density, it is convenient to plot $\rho L_p/\rho_s$ against $T_\lambda - T$. The values of ρ_s/ρ are taken from the data of Dash and Taylor.[4] Values of $\rho L_p/\rho_s$ (open circles) were obtained in a sequence of measurements as the temperature was slowly raised from near 1°K towards T_λ. One would expect a constant value for $\rho L_p/\rho_s$ unless a transition occurs to a superfluid state with a different value of net angular momentum. Such a change is evident about a value of $T_\lambda - T = 2\times10^{-2}$ °K. This type of behavior was noted with several different currents and may be associated with some minor instabilities in the newly formed current Once such a change occurs the current appears to be more stable, and no further transitions of this type were observed.

As the λ point is approached, the scatter of $\rho L_p/\rho_s$ becomes larger because the value of L_p is decreasing. There is also considerable uncertainty in the values of ρ_s/ρ for temperatures near T_λ; therefore, direct measurements were not made for $T_\lambda - T < 1.5\times10^{-3}$ °K. The temperature reversibility of the angular momentum is used to avoid the difficulties of direct measurement. In Fig. 2 the current was cycled to within 5×10^{-4} °K of the transition temperature. When L_p was remeasured at lower temperatures (open triangles), the value of $\rho L_p/\rho_s$ was essentially unchanged.

This type of experiment was repeated for a number of persistent currents. Values of $\rho L_p/\rho_s$ obtained after each cycling to near the transition are plotted in Fig. 3 against $T_\lambda - T_{max}$, where T_{max} is the maximum temperature reached during the cycle. In several instances the temperature was raised slightly above T_λ for a brief period (50 to 100 seconds); the result was destruction of the persistent current. In the cases where the temperature was held below T_λ, there was no significant evidence of critical-velocity effects, even when the approach was to within less than 10 μdeg of the λ point. These results suggest that superfluid critical velocity may be discontinuous at the λ transition. This behavior is in contrast to that observed in superconductors where the critical velocity goes continuously to zero as the tran-

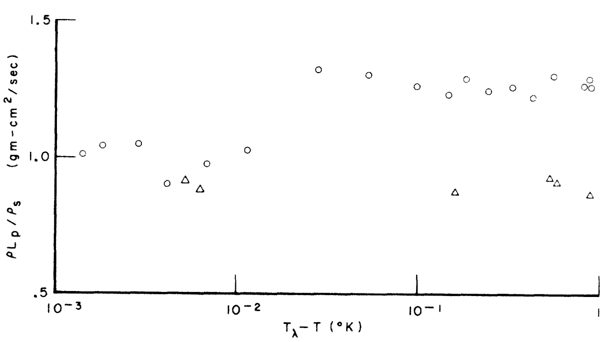

FIG. 2. The values of $\rho L_p/\rho_s$ are plotted against $T_\lambda - T$. The angular momentum L_p of the persistent current was measured at temperature T. The factor ρ/ρ_s removes the dependence of L_p on superfluid density ρ_s. Total density is ρ. The open circles are values obtained as the temperature was raised toward the transition temperature T_λ, and the open triangles are the values obtained when the temperature was reduced.

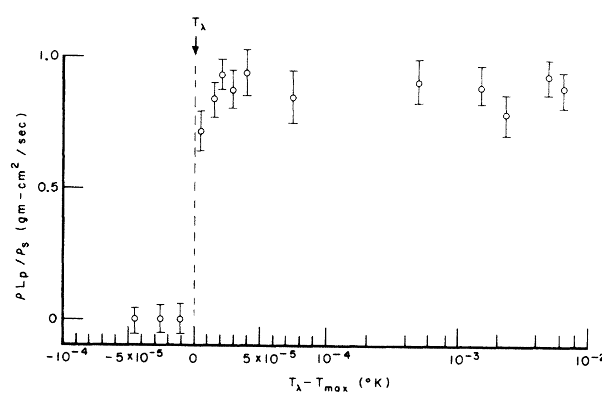

FIG. 3. The values of $\rho L_p/\rho_s$ obtained after the temperature was cycled to near the transition temperature are plotted against $T_\lambda - T_{max}$, where T_{max} is the maximum temperature reached during the cycle. Most of the points were obtained using different persistent currents; this may account for some of the scatter. The error bars represent the uncertainty in determining $\rho L_p/\rho_s$ for each current.

sition temperature is approached.

Future improvements in thermometry and temperature control should allow refinements of about an order of magnitude in this experiment. Eventually one is limited by the slope of the λ line which will produce a variation of T_λ over the dimensions of the container due to the hydrostatic head of liquid helium.

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STABILIZATION OF A CURRENT-CARRYING PLASMA BY WAVE-PARTICLE INTERACTION*

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The electron-velocity distribution in an electron-proton plasma subjected to a uniform static field E_0 was calculated by Spitzer and Harm (SH),[1] using the linearized Fokker-Planck equation in the Landau form, i.e., with static Debye shielding. Linearization of this equation is valid when E_0 is much less than the runaway field $E_{\mathrm{run}} \equiv n_e e a_e (\sigma_{\mathrm{SH}})^{-1}$. Here σ_{SH} is the linear conductivity obtained by SH, and a_e is the electron thermal speed.

Analysis of the stability of the current-carrying plasma, using the SH distribution, indicates that if the temperature ratio θ_e/θ_i is large, instability with respect to longitudinal ion waves occurs when E_0 exceeds a critical value E_{crit}, which is small compared to E_{run}.[2] As the field E_0 approaches the critical value, the fluctuation energy of those waves approaching instability increases.[3] This results from their excitation rate (due to spontaneous emission by particles) remaining approximately constant while their Landau damping (the net effect of absorption and induced emission by particles) approaches zero. There is thus an increase in the effect these electric-field fluctuations have upon the motion of electrons. This can also be described as an enhancement of the electron interaction due to wave exchange, i.e., due to wave emission and absorption. When the effect of wave-exchange interaction becomes significant relative to the statically shielded Coulomb interaction, the appropriate form of the Fokker-Planck equation is that of Lenard and Balescu (LB).[4] The LB equation incorporates wave exchange as a feature of dynamic shielding.

We expect that as E_0 approaches E_{crit}, the enhanced electron-electron interaction produces a change in the velocity distribution in such a direction as to make the plasma more stable, i.e., so as to increase the damping rates of those waves about to become unstable. As a result, E_0 can be increased beyond E_{crit}, without instability occurring. This expectation has been confirmed by an explicit numerical solution of the LB equation. For several values of θ_e/θ_i, the velocity distribution has been determined as a function of E_0. For $E_0 \ll E_{\mathrm{crit}}$, the distribution is nearly identical to that of SH. But as E_0 approaches E_{crit}, the enhanced wave exchange causes the electron distribution to become more isotropic in the ion frame, thereby preserving the plasma stability. In fact, as E_0 increases further, the distribution keeps adjusting itself so as to remain stable.

This effect is illustrated in Fig. 1, which shows the damping rate of that ion wave which would be the first to go unstable on the basis