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[12]If one accepts different values of C_0, namely $C_{0\text{I}}$ and $C_{0\text{II}}$, as found in reference 5, this implies latent heat at least in some regions along the λ line. It is, however, difficult to understand how $C_{0\text{I}}$ can exceed $C_{0\text{II}}$ as reported there.

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OBSERVATION OF STABLE SUPERFLUID CIRCULATION IN LIQUID-HELIUM II AT THE LEVEL OF ONE, TWO, AND THREE QUANTUM UNITS

S. C. Whitmore and W. Zimmermann, Jr.

School of Physics, University of Minnesota, Minneapolis, Minnesota

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It has been proposed that the circulation of the superfluid component of liquid-helium II is quantized in integral multiples of h/m, where h is Planck's constant and m is the mass of the helium atom.[1,2] One of the most direct attempts to verify this proposal has been Vinen's ingenious experiment in which the circulation around a fine wire immersed in superfluid helium was measured by means of the influence that the circulation exerts on the transverse vibrations of the wire.[3] We wish here to report a repetition and extension of Vinen's experiment which we believe has given new evidence in support of the hypothesis of quantization of circulation. A related aspect of the hypothesis, the existence of quantized free vortices in the superfluid, has recently been given strong support by the experiments of Rayfield and Reif[4] and of Richards and Anderson.[5]

The principle of the measurement can be understood by considering the case of a cylindrically symmetric wire. In the absence of circulation such a wire can be regarded as having as its lowest modes of transverse vibration two degenerate circularly polarized modes. With circulation κ around the wire, the degeneracy of these modes is removed by the "lift" force,[6] resulting in a splitting, $\Delta\omega_\kappa = \rho_s\kappa/\mu$, between the angular frequencies of the two modes. Here ρ_s is the superfluid density, and μ is the mass per unit length of the wire plus that of the fluid displaced. If the two modes are excited simultaneously with equal amplitude, the result is vibration of the wire in a plane which precesses with angular frequency $\Delta\omega_\kappa/2$ in the same sense as the fluid is circulating.

The wire can be set into vibration by passing a current pulse through it in the presence of a steady transverse magnetic field. The free, slowly damped vibrations which follow can then be observed by means of the oscillatory emf induced along the wire. As the plane of vibration precesses, the induced emf sweeps out a decaying beat pattern with beat period $2\pi/\Delta\omega_\kappa = 2\pi\mu/\rho_s\kappa$. Thus, for a cylindrically symmetric wire, the circulation around the wire can be determined simply by measuring the beat period once μ and ρ_s are known. More accurately, the quantity κ measured in this way is a weighted average of the circulation around the wire taken along the wire's length, a quantity we shall call the apparent circulation.

In practice, however, the lowest vibrational normal modes of a wire in the absence of circulation are rarely degenerate, presumably because of some inherent asymmetry in the wire or its mounting. In our case, as in Vinen's, these modes always appear to be plane polarized, with mutually perpendicular planes of polarization. In such a circumstance it can be shown that the effect of the circulation will be to produce elliptically polarized modes whose total angular frequency difference, $\Delta\omega_t$, is given by $(\Delta\omega_t)^2 = (\Delta\omega_\kappa)^2 + (\Delta\omega_0)^2$, where $\Delta\omega_0$ is the angular frequency difference in the absence of circulation. Since the measured beat period is now $2\pi/\Delta\omega_t$, it is necessary in practice to know $\Delta\omega_0$ as well as μ and ρ_s in order to determine κ. It is helpful that at the beginning of a run $\Delta\omega_0$ can be adjusted to a convenient value by twisting the wire.

The basic elements of the apparatus, all of which are immersed in the liquid-helium bath, are shown in Fig. 1. The "wire" is in fact a quartz fiber, from 10 to 75 μ in diameter and 5 cm in length, onto which a conducting layer of gold has been evaporated. The wire is fastened to a steel post at each end with an epoxy cement, and electrical contact is made using silver paint. The lower post is fixed, while the upper post can be moved up and down to control the tension in the wire and rotated to twist the wire. The wire is surrounded by a coaxial Pyrex tube with 3 mm i.d., within which the observed circulation takes place. A brass can encloses the tube and wire, and the whole assembly of can, tube, and wire can be put into steady rotation about a vertical axis at speeds up to 80 rad sec^{-1}. A stationary permanent magnet provides an average transverse field of 1350 G at the wire.

For circulation measurements the tension of the wire is usually adjusted so that the lowest vibrational frequencies of the wire lie at about 500 cps, and the wire is set into motion with a current pulse of 1-msec duration. The signal from the vibrating wire is passed through a narrow-band amplifier and displayed on the screen of an oscilloscope. The time interval between the occurrence of the pulse, which corresponds to a beat maximum, and the occurrence of the first beat minimum can be read

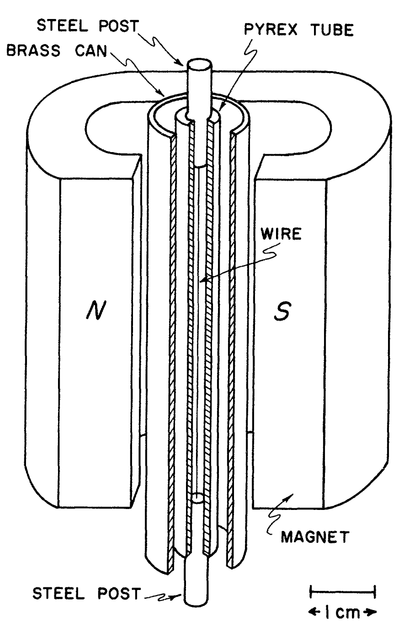

FIG. 1. Basic elements of the apparatus drawn to scale. Liquid helium surrounds these elements and fills the spaces between the can, tube, and wire.

directly from the oscilloscope and, after being corrected for a small time delay introduced by the amplifier, gives $\pi/\Delta\omega_t$.

The vibrations of the wire decay in time due to the viscous drag of the normal fluid. This damping rises rapidly with temperature and imposes an important limitation on the experiment, in so far as at least the first beat minimum must be visible before the signal decays into the noise. We have been able to make measurements in the range from 1.2 to 1.8°K, above which the damping becomes too great. Through-

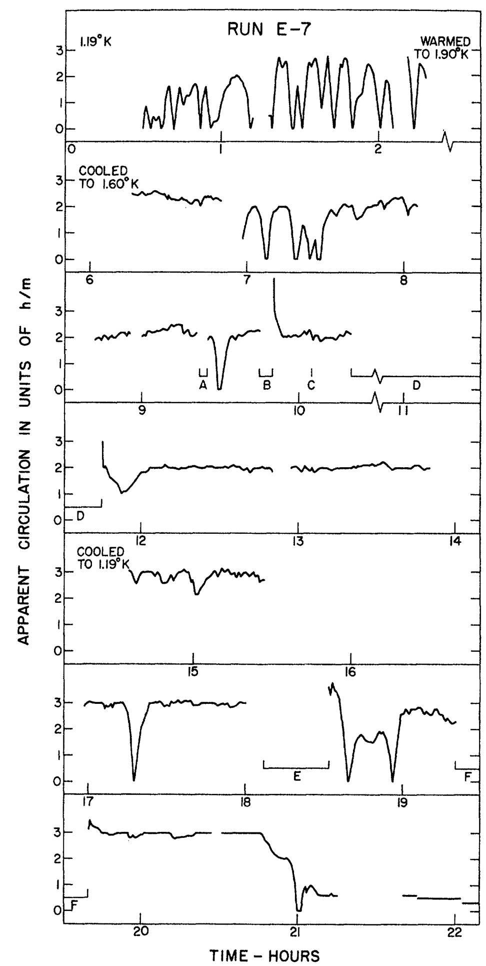

FIG. 2. Apparent circulation as a function of time during run E-7. Circulation measurements were made only during those periods for which the curve is shown. During those periods measurements were made every 5 sec using a 0.7-mA current pulse. Because of the compressed time scale, 60-sec averages of the measured circulations were used in making this plot. The lettered horizontal bars denote periods during which the wire was heated at the level of 3 mW by a direct current.

out this range of temperature the damping is rapid enough so that the wire can be pulsed and a measurement of κ made every 5 sec without interference between successive pulses.

Our work to date has yielded two principal results. The first of these is that motion of the superfluid can persist for long periods of time with the assembly carrying the tube and wire stationary. Moreover, this motion is not steady: Smooth changes in the apparent circulation are observed to take place spontaneously throughout a run. Examples of these effects are shown in Fig. 2, where the apparent circulation around the wire is plotted against time for a representative experimental run, E-7, made with a wire 75 μ in diameter. Previous to the beginning of this plot the apparatus was filled with liquid helium and the assembly carrying the tube and wire set into steady rotation at an angular speed of 2.9 rad sec^{-1} at a bath temperature above T_λ. While in rotation the apparatus was slowly cooled through T_λ to 1.19°K, where the rotation was brought to a stop. No further steady rotation was carried out during the run, which lasted until the helium-bath level fell to the top of the wire.

For each run the value of $\Delta\omega_0$ has been determined by making use of the fact that as changes in the $\Delta\omega_t$ take place during the run, $\Delta\omega_t$ is observed to return repeatedly to a consistent minimum value. It is this minimum value which has been taken to be $\Delta\omega_0$. In run E-7 $\Delta\omega_0$ was equal to 4.0 rad sec^{-1}.

Our second principal result is that the circulation around the wire tends to show markedly greater stability at the anticipated quantum levels than at other values. It can be seen in Fig. 2 that in run E-7 there were long periods of stability at the level of two and three quantum units. This stability is shown in another way in Fig. 3. In these histograms, for run E-7 and for an earlier run with the same wire, a plot is made of the total time the apparent circulation remained stable at each value of the circulation, the criterion for stability being roughly that for a period of at least 100 sec the circulation should not drift by more than ±5% of one quantum unit. For each of these runs the total time satisfying this criterion was about two-thirds of the time during which measurements were made. Whereas in run E-7 no evidence for stable circulation at the one-quantum level was seen, stable circulation at the level of one, two, and three quantum units was observed during run E-6.

During the last hour of each of these runs rather stable circulation values were measured which have been plotted in Fig. 3 as open bars. Such slowly drifting stability is often seen when the bath level is within 1 cm of the top of the wire and seems not to be related to the stability at the quantum levels.

An additional significant result of our work is that as the wire diameter has been increased, the maximum value of stable circulation observed has also increased. With a wire of 25μ diameter stable circulations larger than one quantum unit were rarely observed, and with a wire of 38μ diameter stable circulations larger than two units were rarely observed. These observations are consistent with the fact that Vinen, using a wire 25 μ in diameter, saw stable circulation only at the one-quantum level.[3]

Several subsidiary observations help support the conclusion that we are observing the effects of quantized circulation. Stable circulations at the quantum levels have been seen using different values of $\Delta\omega_0$ with the same wire and using wires of different diameter and mass per unit length. Furthermore, the levels of stable circulation appear at the anticipated quantum values over a range of temperature from 1.2 to 1.8°K. This is to say that $\Delta\omega_K$ for the respective stable levels depends linearly on ρ_S as expected, as ρ_S/ρ varies from 0.97 to 0.69. Here ρ is the total liquid density. Finally, on two occasions we have measured the ellipticity of the normal modes of the wire with circulation present and found the expected

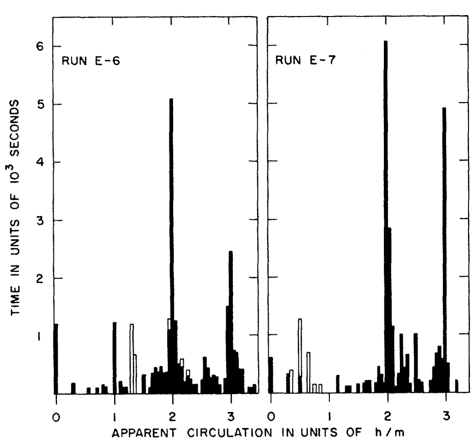

FIG. 3. Total times during which the apparent circulation remained stable at various values for two runs with the same wire. The open bars represent stable circulation levels during the last hour of each run.

results, although the accuracy of these measurements was not high.

However, the details of the fluid dynamics in this experiment remain far from clear. Circulations as large as three quantum units have been seen in runs with a 75μ-diameter wire even when no steady rotation took place. The observations of circulation values intermediate to the quantum levels and of spontaneous changes in circulation also require explanation, and they suggest that an important role is played by free vorticity in the superfluid.[3,7]

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EXPERIMENTS ON THE CREATION OF CHARGED QUANTIZED VORTEX RINGS IN LIQUID HELIUM AT 1°K*

G. Careri, S. Cunsolo, P. Mazzoldi, and M. Santini

Istituto di Fisica, Università di Roma, Rome, Italy
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Charged vortex rings of one quantum of circulation have been detected already by us at 1°K, and briefly reported,[1] following the investigations by Rayfield and Reif[2] at lower temperatures. In this Letter we investigate experimentally the origin of these charged rings at 1°K, and discuss these processes in the frame of the theory recently proposed by Huang and Olinto.[3]

The experiment consists of the determination of the drift velocity $\langle V_D \rangle$ of ions[4] in liquid helium at different field strength E, the temperature T and the pressure P being kept constant. The apparatus and the experimental technique used to measure the drift velocity are the same as the ones described in our previous work.[5,6] The electronics has been improved to extend the electric-field range and, therefore, to increase the temperature at which the phenomenon could be detected. An analysis of the experimental error involved in these measurements already has been done[6,7] and will not be repeated here. The experimental error is not shown in Fig. 1 for the sake of clarity, and it usually is ±3 % for data taken in the same run.

In Fig. 1 we show the results of some runs as a plot of the drift velocity $\langle V_D \rangle$ versus the reduced field intensity $E(\rho/\rho_\gamma)$, where ρ is the total density and ρ_γ is the roton contribution to the normal fluid density. ρ_γ has been calculated as a function of the absolute temperature T and pressure P by the familiar Landau expression, using the neutron-scattering results.[8] Since we are interested in a rather small temperature range around 1°K, approximately $\rho_\gamma \simeq \text{constant} \times N_\rho$ where N_ρ is the roton density, this reduced field, $E(\rho/\rho_\gamma)$, has a simple intuitive meaning and is a useful quantity to correlate the data taken at different pressures and temperatures.

A glance at Fig. 1 shows that both positive and negative ions display two quite different hydrodynamical regimes, with a sharp transition in between. The first regime begins at low fields with a field-independent mobility, which is known[9] to be essentially proportional to N_ρ^{-1}, and therefore to ρ_γ^{-1} in our temperature range. Next, for higher fields, closer inspection[6,7] reveals the presence of small periodic discontinuities, the first one occurring at $\langle V_C \rangle = 5.2$ m/sec for positive ions. For still larger fields there is a more pronounced bending of the data partly due to the increase in the depth of the discontinuities. While all the runs taken in different days were