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Observations of the Superfluid Circulation Around a Wire
in a Rotating Vessel Containing Liquid He-II

S. F. Kral and W. Zimmermann, Jr.

School of Physics and Astronomy, University of Minnesota
Minneapolis, Minnesota, U.S.A.

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Several years ago, observations in our laboratory of the superfluid circulation around a fine wire stretched along the axis of a cylindrical container filled with liquid He-II gave rather clear evidence of preferential metastability at quantum levels in the range from -3 to +3 quantum units.¹ The quantum unit of circulation is h/m , where h is Planck's constant and m is the mass of the He^4 atom. Thus those observations strengthened the evidence presented by Vinen a few years earlier for the existence of quantization of circulation in superfluid helium flow around a solid obstacle.² Our measurements at that time were all conducted with the wire and container at rest.

It seemed of considerable interest to us to extend those measurements to the case of the wire and container in rotation. We were interested in looking for circulations larger than those seen at rest, in studying the dependence of circulation upon angular velocity of rotation, and in comparing that dependence with the equilibrium predictions of the quantum vortex model for superfluid rotation. Therefore, in the present work we have made measurements of the circulation in rotation at angular velocities up to 4 rad sec^{-1} in magnitude, using a cell similar to the one used in our earlier work. These measurements were made at temperatures between 1.2 and 1.4 °K.

Figure 1 shows the experimental cell, consisting of a brass can containing the central wire, which is approximately 50 mm in length and from 0.066 to 0.083 mm in diameter, and a concentric quartz tube having a 5.0 mm inner diameter, which defines the outer boundary of the flow

space around the wire. The can is filled with liquid helium, and the entire cell can be put into rotation about its axis.

The apparent circulation κ around the wire is determined by measuring the difference $\Delta\omega_t$ between the angular frequencies of the two lowest transverse vibrational modes of the wire. With the wire and container in rotation at angular velocity ω_r , $\Delta\omega_t$ as observed in the rotating system is given to good accuracy by the expression

$$\Delta\omega_t = \sqrt{(\Delta\omega_k - \Delta\omega_r)^2 + (\Delta\omega_o)^2},$$

where $\Delta\omega_k = \kappa \rho_s / \mu$, $\Delta\omega_r = 2\omega_r$, and $\Delta\omega_o$ is the intrinsic angular frequency splitting of the wire due to asymmetries in the wire and its mounting. Here ρ_s is the superfluid density and μ is the effective mass of the wire per unit length. Hence a measurement of $\Delta\omega_t$ enables a determination of $\Delta\omega_k$ and thus of κ to be made.

In order to excite and observe the wire's vibration, the cell was situated in a transverse magnetic field which rotated with the cell. Measurements of $\Delta\omega_t$ were made recurrently at 5 or 6 sec intervals by passing an a.c. current pulse through the wire to excite its lowest modes of vibration. The emf induced along the wire as it then underwent damped free oscillation was detected. This emf took the form of a decaying beat pattern from which $\Delta\omega_t$ could be determined.

Circulation data were obtained using two main procedures. In the first, ω_r was varied in steplike fashion from one value to another, measurements of κ all being made at constant ω_r . Unlike our earlier

experiments, very little evidence for quantization of circulation was obtained in this type of run. Both at rest and in rotation κ showed considerable metastability at a wide variety of levels, far from as well as near to quantum levels. Various attempts to drive κ to any reproducible levels that might have been preferred by the system were unsuccessful. These attempts included rapping the apparatus, giving particularly large excitation pulses to the wire, and abrupt stopping and restarting of rotation.

Nevertheless, we observed that at each value of ω_r the values of κ measured appeared to lie within a restricted, ω_r -dependent range whose median increased with ω_r . This behavior is illustrated in Fig. 2, where the circles show data obtained after steplike changes in ω_r , both increasing and decreasing. We believe that these observations indicate the existence of a region in the κ versus ω_r plane inside of which κ is metastable or stable while outside it is unstable. Note that except for small values of ω_r the sense of κ always agrees with that of ω_r . Note also that for this wire, which had a diameter of 0.079 mm, the range of metastability at $\omega_r = 0$ runs from about -3 to +3 quantum units, in good agreement with the range of circulations observed in our earlier measurements at rest with wires of similar diameter.

In the second procedure for obtaining data, measurements of κ were made while rotation was being accelerated or decelerated in a slow and steady fashion. Data taken in this way are shown by the curves in Fig. 2. Starting at zero, ω_r was accelerated in the positive sense to

1.1 rad sec⁻¹, then in the negative sense to -1.1 rad sec⁻¹, and finally in the positive sense again to 1.0 rad sec⁻¹, the entire sequence having taken ~ 11 hours. The data are seen to trace out a form of hysteresis loop.

We believe that such a loop gives additional support for the existence of a metastable region. We suppose that the relationship between the loop and the region of metastability in Fig. 2 is as follows. As ω_r is increased from zero and κ starts to increase, the curve followed lies somewhere near the lower limit of metastability. Then as the acceleration is reversed and ω_r decreases, κ tends to remain relatively stable as the curve cuts back through the metastable region until the upper limit of metastability is reached. Then κ tends to decrease, following near to the upper limit until ω_r reaches its most negative value, and so forth. Similar data are shown by the continuous curves in Fig. 3 for another wire of similar diameter.

A particularly noteworthy feature of the hysteresis loops shown in Figs. 2 and 3 is that at large absolute values of ω_r , the circulation shows a marked preference to remain more or less constant as ω_r varies in either direction, sometimes changing from level to level in a rather steplike way. A number of these steps appear to be nearly one quantum unit in size, and some of the plateaus are very nearly at quantum levels, but there are many exceptions.

It is of considerable interest to compare the region of metastability observed for a given wire with the curve expressing the equilibrium

value of κ to be expected as a function of ω_r . If we apply minimum-free-energy considerations to the usual model for the rotation of the superfluid based on quantization of circulation and the existence of singly-quantized vortices, we expect a steplike curve for this function. As ω_r increases from zero, κ is first zero, then one quantum unit, then two units, and so forth, the transitions taking place at critical values of ω_r which depend upon the wire's diameter, the inner diameter of the quartz tube, and the vortex core parameter, and which reflect the details of the vortex distribution in the liquid.

Although a complete calculation of the equilibrium value of κ as a function of ω_r is difficult, it is easy to determine the values of ω_r at which κ should go from 0 to ± 1 .³ Further, in the limit of large ω_r one may use a simple continuum model similar to that of Stauffer and Fetter to evaluate the equilibrium behavior of κ .⁴ The results of these calculations are shown by the long-dashed curves in Fig. 3. The steps from $\kappa = 0$ to ± 1 occur at $\omega_r = \pm 0.011 \text{ rad sec}^{-1}$. Both the discrete and continuum portions of the curve seem to be well situated within the region of metastability that we would infer from the hysteresis loop.

Thus despite the absence of clear-cut direct evidence for quantization of circulation in the current experiment and the presence of a high degree of metastability, we believe that we have a good understanding of the average dependence of κ on ω_r based on a quantum vortex model for the rotation of the superfluid component. It continues to seem likely that non-quantum values of κ are associated with quantum vortices pinned to or near to the wire, but our experiment does not give us direct evidence on this matter.

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FIGURE CAPTIONS

Fig. 1. The experimental cell.

Fig. 2. Apparent circulation κ versus angular velocity of rotation ω_r for several runs with the same wire. The circles represent data taken after steplike changes in ω_r , while the curves represent data taken during nearly constant acceleration and deceleration having mean magnitude $(1.3) 10^{-4} \text{ rad sec}^{-2}$ at a temperature of 1.23°K . The wire's diameter was 0.079 mm.

Fig. 3. Apparent circulation κ versus angular velocity of rotation ω_r . The continuous curves show data taken during nearly constant acceleration and deceleration having mean magnitude $(1.1) 10^{-4} \text{ rad sec}^{-2}$ at a temperature of 1.27°K . The wire's diameter was 0.083 mm. The long-dashed curves show the predictions of equilibrium theory in the two limits discussed in the text.

EXPERIMENTAL CELL

Figure 1.

Figure 2.

Figure 3.