Influence of an Axial Heat Current on Negative-Ion Trapping in Rotating Helium II*

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The trapping of negative ions by quantized vortex lines in rotating helium II is found to be strongly inhibited by a small thermal counterflow parallel to the axis of rotation.

A study has been made of the interaction of negative ions with an array of quantized vortex lines produced by rotation, in the presence of an axial thermal counterflow. We find that a small counterflow is effective in almost completely eliminating the negative-ion–vortex interaction. The results suggest that the axial normal-fluid flow drastically alters the trapping probability of a quantized vortex line for a negative ion.[1] The experimental apparatus and a series of important control experiments are described in the paragraphs below, followed by a description of the results and some discussion.

The interaction of ions with quantized vortex lines was first studied by Careri, McCormick, and Scaramuzzi.[2] There followed experimental work by Tanner[3] and Douglass[4] among others, and a theoretical description of the capture and excape of ions based on fluctuation theory by Donnelly and Roberts.[5]

One of our experimental arrangements is shown schematically in Fig. 1. It consists of a square channel, 1 cm × 1 cm, 7 cm in length. The channel is constructed of insulating material of thickness 2.5 mm, incorporating various sets of gold-plated electrodes. A thin layer of silver paint makes all channel walls available as electrodes. The thermal current can escape into the bath only at the top of the apparatus above $E1$. The apparatus is suspended on a long tube in a 3-in. liquid-helium Dewar. The heater at the bottom is wound from Evanohm with a resistance of 115 Ω. A thin metal plate on top of the heater (R in Fig. 1) ensures uniform heat flux into the channel and can be used as a repeller to reduce space charge by an axial electric field. The source in Fig. 1 is embedded in a sealed chamber so that grid SG forms one section of the channel wall. We call this the "7-cm apparatus." Much of the data for this experiment was taken in a simpler apparatus, similar to Fig. 1 except for the absence of grids SG and FG, flush mounting of source S, and a total length of 9.6 cm. We call this the "9.6-cm apparatus." Radial heat flow from the exit of the channel to the bath was minimized by mounting $C1$ 4 cm above the channel.

The temperature of the main bath is measured by a calibrated germanium resistor and controlled to within 2×10^{-4} °K for heat pulses in the channel up to 50 mW. The ion current is produced by a 60-μCi Am^{241} source plated on an electrode 8 mm × 15 mm. With a bias of − 5 V, the equilibrium current collected at $C2$ is about 1.5

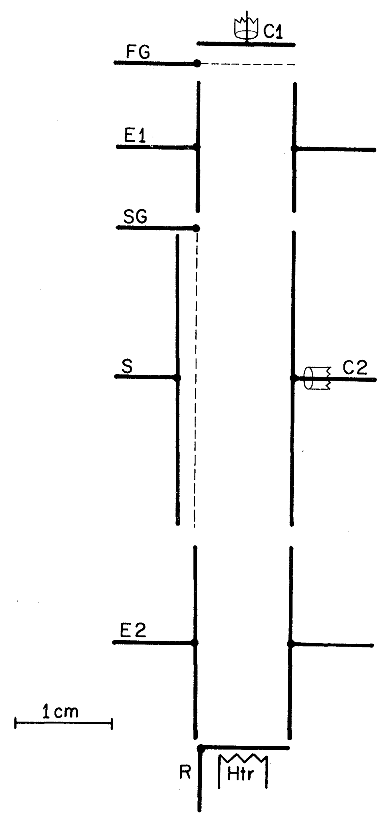

FIG. 1. Electrode arrangement for the 7-cm-long channel. The electrodes including grid SG are flush with the channel walls which are 1 cm × 1 cm × 7 cm. The region above $E1$ communicates freely with the surrounding bath. The thermometer is located near the channel exit. The 9.6-cm-long channel is similar except that the grids SG and FG are absent, source S is flush with the channel wall, and $C1$ is 4 cm above the channel exit.

$\times 10^{-13}$ A and reproduces to within about 10% from run to run. The quiescent noise is around 5×10^{-15} A. We know from Tanner's work [cf. Ref. (3), Fig. 4] that a current of this magnitude avoids problems with space charge; our current density is about $\frac{1}{4}$ of Tanner's lowest.

First, experiments were carried out in the 9.6-cm channel to verify normal operation of the apparatus. If heat is applied without rotation, one finds attenuation of positive- and negative-ion currents to power levels of $\dot{q} = 40$ mW/cm^2 (as high as we have explored). This is apparently the result of flushing ions up the channel with the normal fluid, beyond the range of collector $C2$. At 1.5°K, the positive-ion attenuation is linear with $\dot{q}$, reaching ~4% at 18 mW/cm^2, after which it rises more rapidly. The negative-ion attenuation increases for $\dot{q} > 5$ mW/cm^2 more rapidly than can be accounted for by the ratio of ion mobilities, suggesting that some vortex tangle is being generated by the flow. This conclusion is strengthened by noting that at 1.9°K, positive and negative ions behave similarly when the difference in ion mobilities has been accounted for; 1.9°K is above the lifetime edge for negative ions.[4] These results can be compared with those described by Careri in a review of ion motion in helium II.[6]

Experiments in rotation without heat flow obeyed the usual rule, that $\ln[I(\Omega)/I(0)]$ is linear with Ω, I being the current collected at $C2$. The cross sections for capture were roughly those determined by Tanner.[3]

Experiments with combined heat flow and rotation produced the surprising result that modest heat currents *increased* the ion current reaching $C2$, that is, the attenuation due to the negative-ion–vortex interaction was *reduced.* A typical sequence of data taken at 1.5°K, $\Omega = 2.5$ rad/sec, and -5 V between source and $C2$ in the 9.6-cm channel shows a steady current before rotation. On starting rotation the noise level increases, and after some transients the current decreases to a level consistent with the expected cross section for negative-ion capture. The heater is switched on and the current at $C2$ increases, recovering its nonrotating value at $\dot{q} = 3.3$ mW/cm^2. The change in current is permanent; we find most of the change takes place in about 12 sec, and we typically allow 3–4 min to observe the new level. There is a tendency for attenuation to return again at heat currents about 1 order of magnitude greater.

The results are independent of whether the heat current or rotation is switched on first. The same experiment conducted with positive ions shows no effect due to rotation and no change in current due to heating for $\dot{q} < 5$ mW/cm^2. The results are strongly influenced neither by the rate of rotation, nor by changes in the field between S and $C2$, although we experienced difficulty in obtaining good results at higher fields where the capture cross section is smaller. The effect does not appear to be strongly influenced by the initial current on $C2$. We noted that the recovery of attenuation due to a heat flux was not complete in the 7-cm channel, where a grid (SG of Fig. 1) formed one wall of a section of the channel.

A decrease in trapping cross section could, of course, be associated with the destruction of the vortex lattice. To check this we installed a second-sound transmitter (an 80-Ω Nichrome plated resistor) and a receiver (Aquadag deposit carbon film with a resistance of 625 Ω at room temperature and 1650 Ω at 1.5°K) in the upper section of the 9.6-cm channel. A sine wave of 1.5 kHz applied at the transmitter was detected using a PAR model 124 lock-in on the receiver. We monitored the second-sound resonance simultaneously with the ion current at $C2$; both showed attenuation when the apparatus was rotated. Heat currents which were enough to eliminate the attenuation of ion current did not affect the second-sound resonance amplitude. We conclude that these small heat fluxes do not strongly disturb the vortex lattice.

A further series of experiments used the 7-cm channel with grids, as illustrated in Fig. 1. Grid SG was biased so that only negative ions could enter the heat channel. The potentials in the channel were arranged to move negative ions up the channel, but the Frisch grid FG was biased about 1 V positive with respect to the collector $C1$. This procedure completely stops free negative ions from reaching $C1$, but does not stop ions trapped on vortex lines which pass through the grid. We call this phenomenon, which evidently depends on trapped charge on the vortex cores, the "punch-through effect." When the apparatus was rotated with $\dot{q} = 0$, we observed that the current on $C2$ decreased with increasing rotation, whereas current was now observed on $C1$, increasing with increasing rotation. This is clearly trapped-ion current. On applying heat we observed an *increase* in current on $C2$, showing a decrease in trapping probability. Simultaneously the trapped-ion current on $C1$ decreased, verifying that the vortex lines were carrying less trapped current,

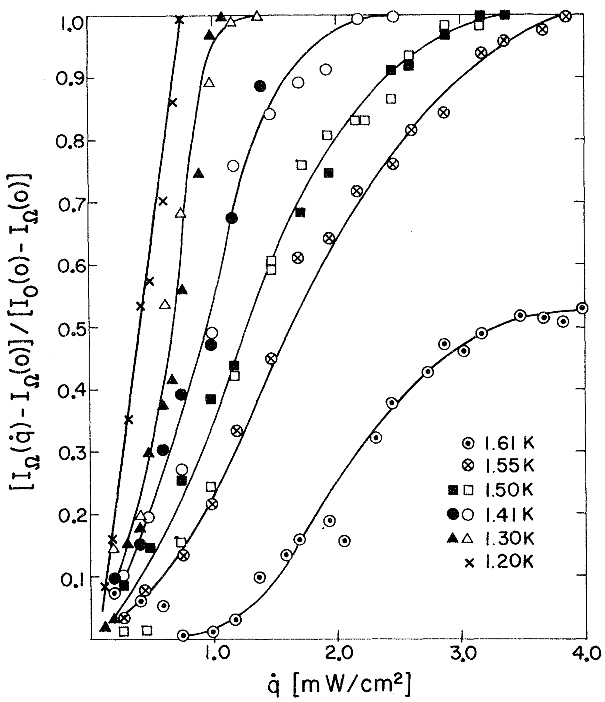

FIG. 2. Fractional recovery of the ion attenuation due to rotation as a function of heat current, and for a series of different temperatures. $\Omega = 2.5$ rad/sec, $E = -5$ V/cm. Open and closed circles were taken on different runs. Except for the points at $T = 1.61$°K, all data were taken at temperatures below the lifetime edge.

and with sufficient heat current, the trapped signal disappeared.

It was possible to arrange the fields in the apparatus of Fig. 1 to bottle and store trapped charge on the vortex lines. At temperatures below the lifetime edge where theory shows the lifetime to be long,[5] we were able to store trapped charge for considerable periods of time. If during the storage period we applied a pulse of heat current (for, say, 5 sec), we observed that, on release, the trapped charge was markedly decreased or eliminated.

The results of a systematic investigation in the 9.6-cm channel are shown in Fig. 2, where the vertical axis is scaled to show the fractional recovery of the attenuation $[I_0(0) - I_\Omega(0)]$ due to rotation alone, as a function of heat current, at a series of different temperatures, and for $E = -5$ V/cm and $\Omega = 2.5$ rad/sec. For three temperatures there are two sequences of experimental points, taken in runs about one week apart, to demonstrate the reproducibility of the results. Note that the results shown in Fig. 2 were obtained with an apparatus in a smooth hydrodynamic configuration containing no grids, incorporating electrodes flush with the channel walls, and with little obstruction at the top of the channel. Less favorable hydrodynamic configurations produced the same qualitative results, but with generally smaller recovery fractions.

TABLE I. Normal and superfluid velocities in the channel at $\dot{q} = 1$ mW/cm^2.

T (°K)	v_n (cm/sec)	v_s (cm/sec)
1.2	0.1076	0.0032
1.4	0.0362	0.0032
1.6	0.0148	0.0031

Let us now turn to a discussion of the results. The experiments show that we must seek an explanation involving the negative-ion–vortex interaction, since the existence of the vortex lattice, or distortion due to turbulence, is not in question. An examination of Fig. 2 points to a further significant result: At (say) $\dot{q} = 1$ mW/cm^2, the fractional current recovery decreases rapidly with increasing temperature. Now the average normal-fluid velocity upward is given by $v_n = \dot{q}/\rho ST$, where S is the entropy; the average returning superfluid velocity is $v_s = -(\rho_n/\rho_s)(\dot{q}/\rho ST)$. Values of these velocities at three temperatures are shown in Table I. We see that the superfluid velocity is essentially constant and that the effect of rising temperature is a rapidly decreasing v_n and a correspondingly weakened recovery fraction. Thus our attention is directed to the axial flow of the normal component.

It is difficult to see how the axial fluid pattern can prevent ions from coming into the influence of the vortex force. A simple way to see the problem is to note that the substitution energy for the ion in a flow of 1 cm/sec is only 10^{-7} °K. Instead it appears more likely that the normal flow somehow reduces the potential well for the ion around the vortex line. One speculation would be the excitation of vortex waves or ion oscillations of large amplitude which, in effect, "shake off" the ions. Douglass[7] has observed lower lifetimes for negative ions trapped at low temperatures than could be given by the calculated depth of the well. Perhaps these phenomena are related.

It will be important to ascertain whether the free ions flow homogeneously in the presence of an axial heat flow, or whether they actually avoid the vortex cores and flow in an inhomogeneous pattern which reflects the structure of the vortex lattice. Clearly, further investigation both experimentally and theoretically is warranted.

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Sideband Instability: Observations and Comparison with Theory*

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In the trapped-electron sideband instability of a nonlinear plasma wave of potential φ_0, initial enhanced damping occurs for a distance $\propto \varphi_0^{-1/2}$, beyond which signals grow at a rate scaling nearly linearly with φ_0. The growth remains exponential even in cases where the main wave is significantly damped. This behavior is more consistent with a quasilinear spectral development than with the commonly cited parametric bounce-frequency instability of a stationary Bernstein-Greene-Kruskal equilibrium.

The original observation by Wharton, Malmberg, and O'Neil[1] that satellite frequencies of a large-amplitude collisionless electron-plasma wave are unstable and grow with distance has stimulated a number of recent experimental and theoretical works. The frequency separation between the sideband peak and the "main" (large-amplitude) wave was found to be proportional to the bounce frequency

$$\Omega_b = k_0(e\varphi_0/m)^{1/2}, \qquad (1)$$

where φ_0 and k_0 are the main-wave electric potential and wave number, respectively. Since Ω_b is the frequency of oscillation of an electron trapped in the wave potential well, the instability was associated with the resonant electrons. No measurements of growth-rate dependence on external parameters were made in connection with this first observation.

Subsequent experiments have verified that the instability also occurs for ion-acoustic waves[2] and that it is possible to have a series of sidebands, with observed frequency separations given by the Doppler-shifted bounce frequency, growing from the background plasma noise.[3]

In this paper we describe new observations of the instability, designed specifically to test the various theories which have been advanced. To facilitate this approach we note that the theories may be classified generally according to which of two principal physical mechanisms is assumed responsible for sideband generation.

The first mechanism, originally proposed by Kruer, Dawson, and Sudan,[4] involves a parametric interaction between the main wave and the trapped electrons acting as Doppler-shifted harmonic oscillators. While these parametric sideband theories[4-7] differ in calculational detail, they share common features. In particular, (1) they test the stability of a Bernstein, Greene, and Kruskal[8] (BGK) state, which is a nonlinear stationary-wave equilibrium; and (2) they derive an instability growth rate $\gamma \propto \varphi_0^{1/2}$ (above a threshold,[7] in some cases).

The other class of theories[9,10] assumes that the main wave deforms the electron velocity distribution in the manner calculated (in one limit) by O'Neil.[11] Quasilinear theory may then, in princi-