Motion of Ions Trapped on Vortices in He II†

R. M. Ostermeier and W. I. Glaberson
Department of Physics, Rutgers University, New Brunswick, New Jersey 08903
(Received 5 May 1975)

We have measured the drift velocity of ions trapped on vortex lines at temperatures down to 0.35 K. We observe several effects which cannot easily be explained in terms of existing theories, including the broadening of an ion pulse, a limiting velocity in high electric fields, and a zero-field mobility which increases, at lower temperatures, much more rapidly than expected. An attempt is made to explain qualitatively some of these effects.

Quantized vorticity in superfluid ^{4}He is impossible to probe effectively with any of the usual probes of condensed matter. The velocity field associated with a vortex line interacts only weakly with light or neutron beams, and there are thermodynamically insignificant numbers of vortices at experimentally accessible rotation speeds. Mechanical interaction with rotating helium and second-sound-attenuation experiments have proven to be useful techniques for observing the existence of quantized vorticity and its gross features.[1] Neither of these techniques, however, directly probe the most interesting part of a vortex line—the central-core region—where superfluidity breaks down and many-body effects become important. Ions interact with vortex lines and become trapped on their cores as a result of a hydrodynamic interaction suggested by Donnelly.[2] Measurements of the cross section for the capture of negative ions by vortex lines[3] and of the thermally activated escape rate from vortex lines of both positive[4] and negative[5] ions are consistent with this hydrodynamic interaction.

Measurements of the mobility of "trapped" negative ions along the vortex lines[6] showed that these ions experienced more drag in motion through the liquid than "free" ions. Glaberson *et al.*[7] attempted to explain this in terms of an excess normal-fluid density on the cores of the vortices associated with the Doppler-shifted excitation spectrum in the vortex velocity field, and Douglass[8] and Fetter and Iguchi[9] discussed the phenomenon in terms of scattering of thermally excited vortex waves. Using a rotating ^{3}He refrigerator, we have extended these earlier measurements to lower temperatures for both positive and negative ions, and we have observed several new features which cannot easily be explained in terms of either theoretical approach.

In our experiment, ions are produced by a ^{210}Po α source and are trapped on vortices in a trapping region of the experimental cell by means of a transverse beam of either ions or charged vortex rings. The source is then turned off for some delay time. The purpose of this is twofold: It allows time for any free ions or rings to be cleared from the trapping region and it also allows time for any hydrodynamical or electronic disturbances caused by the charging process to die down. At the end of this time, some of the remaining trapped ions, in the form of a thin charge cloud, are gated into a uniform electric field region by pulsing an appropriate grid. The ions then traverse this region along the vortex lines and currents are detected by a high-speed electrometer and signal averaged.

Two examples of the signal-averager output, taken under different experimental conditions, are shown in Fig. 1. The upper curve is for a relatively low temperature, 0.50 K, and high electric field, 57.6 V/cm. The most striking feature of the current pulses at low temperatures

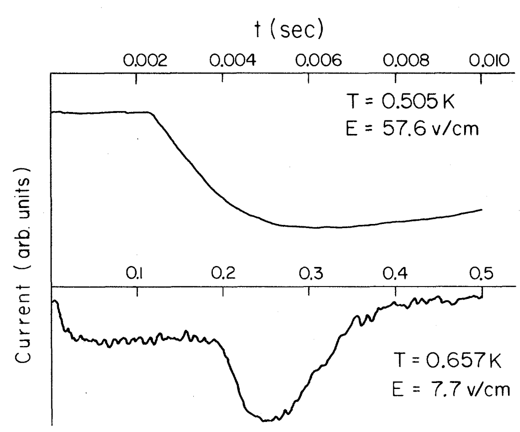

FIG. 1. Current-versus-time outputs of the signal averager. In both cases, the rotation speed was 10.6 rad/sec.

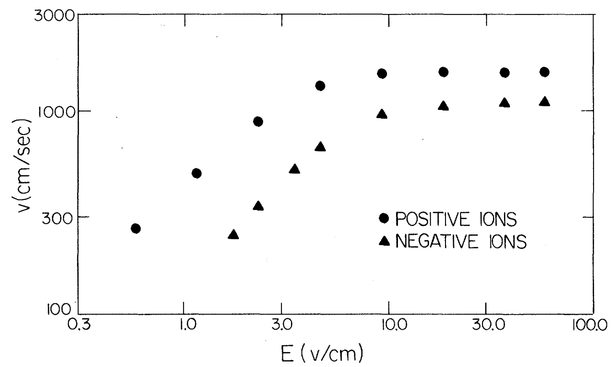

FIG. 2. Electric field dependence of the ion velocity, defined in terms of the leading edge of the ion pulse, at $T=0.41$ K.

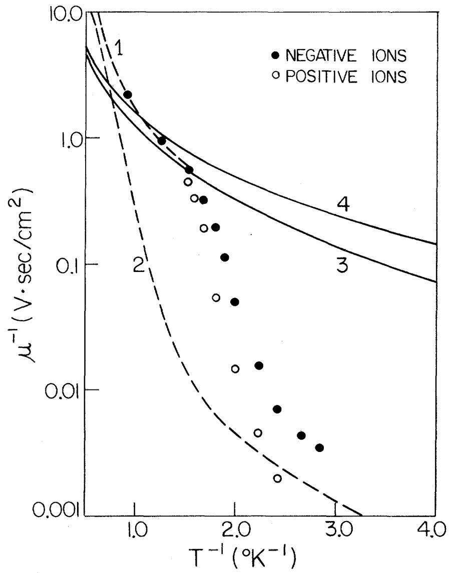

FIG. 3. Temperature dependence of the low-field mobility. Curves 1–4 are described in the text.

is their considerable time width. The gate, allowing charge into the uniform field region, is open for a time small compared to the transit time of the fastest ions across the cell, so that the broadening clearly occurs in the drift region. The leading edge of the pulse is relatively sharp, and a precise velocity can be determined. The trailing edge, on the other hand, is not nearly as well defined and can take up to an order of magnitude longer in time to arrive. The pulse width decreases, both absolutely and relative to the leading-edge arrival time, with increasing electric field. This implies that the pulse width cannot easily be associated with the propagation of free vortex rings. Further, a change of more than a factor of 2 in ion pulse amplitude produces no change in either the velocity or the pulse shape, so that ion-ion interactions appear not to be responsible for the broadening.

The lower curve in Fig. 1 shows a positive-ion current pulse for $T=0.66$ K, a temperature at which the thermal lifetime of positive ions in vortex lines is of the order of the transit time across the drift region.[10] The current plateau preceding the ion pulse is due to those ions which have escaped from the lines during transit. At these temperatures, the ion pulse width is much smaller relative to the leading-edge arrival time than at lower temperatures, but it is still considerably larger than the width of the gate pulse.

The electric field dependence of the positive- and negative-ion velocity, defined in terms of the leading edge of the current pulse, is shown in Fig. 2 for $T=0.41$ K. The ion velocity increases linearly with increasing electric field for small fields. For larger electric fields, the velocity levels off to some limiting value which is maintained up to the highest electric fields attempted. The limiting velocity is only a weak function of temperature, decreasing slightly as the temperature is raised, and is larger for positive ions than for negative ions. As seen in Fig. 2, the limiting velocity is about 15.5 m/sec for positive ions and about 11.0 m/sec for negative ions at $T=0.41$ K.

Our experimental values for the (inverse) low-field mobilities of trapped positive and negative ions are shown in Fig. 3. Curve 1 represents the experimental data of Ref. 7, in excellent agreement with our present results. Curve 2 is the experimental free-negative-ion data[11] and curves 3 and 4 are the theoretical predictions of Fetter and Iguchi[9] for trapped positive and negative ions, respectively. The normal-vortex-core approach of Glaberson, Strayer, and Donnelly[7] also yields a relatively weak temperature dependence at low temperatures. There is obviously poor agreement between our experimental results and the theoretical predictions. Inclusion of any additional drag mechanism would increase the disagreement.

Before attempting an explanation of the pulse shape it would be useful to mention a few other relevant experimental observations. First, we found that the measured flight time decreased with increasing delay time (i.e., the time between source off and gate on) to some limiting value. This seems to indicate that the charging process creates some sort of disturbance in the vortex array, which, if not allowed to dissipate, increases the ion flight time. We also found that if, for a given delay time, the experimental repetition rate were too high, there again was a noticeable increase in the ion flight time. In order to eliminate this effect, a lower repetition rate was required at lower temperatures and lower angular velocities. This behavior suggests that the passage of an ion pulse along the vortex array also, in some way, disturbs that array and, if insufficient time is allowed, affects the passage of the following pulse. The data presented in Figs. 1–3 were taken with the necessary delay times and repetition rates so as to eliminate these effects.

In considering the effects discussed in the preceding paragraph it is reasonable to suggest that the large widths of the current pulses may be attributed to a perturbation of the vortex lines by the passage of ions along them. The first ions, corresponding to the leading edge of the current pulse, pass along relatively straight vortex lines. These ions generate deformations in the lines and subsequent ions in the same pulse take longer to arrive at the collector. That ions moving along the lines can perturb the vortex lines should not be too surprising since, for all experiments done so far, the ion motion is extremely supersonic with respect to vortex waves and, therefore, the lines are probably unstable with respect to deformation.[12] The high-field limiting velocity may also be associated with the generation of vortex deformations.

We have no simple explanation for the discrepancy that exists between our low-field mobility data and theory, but a number of observations can be made. Fetter and Iguchi[9] obtained the drag experienced by an ion as a result of the scattering of thermal vortex waves in the form

$$\frac{e}{\mu}=\frac{-2h}{\pi}\int_0^\infty dk\,k^2\frac{dn}{dk}|R(k)|^2,$$

where n is the Bose-Einstein distribution, k is the vortex wave number, and $|R(k)|^2$ is the reflection probability in the rest frame of the ion. $R(k)$ was calculated in the short- and long-wavelength limits and, assuming a rather long interpolation between these limits, they obtained curves 3 and 4 of Fig. 3. The most important wavelengths in the theory, however, are those for which $ka\approx 1$, where a is the ion radius. It is precisely these wave numbers that may contribute anomalously to the reflection coefficient and it is conceivable that the interpolation is responsible for the discrepancy between the Fetter-Iguchi theory and our data.

It is interesting to note that the theory is in relatively good agreement with the data at temperatures above about 0.7 K. This may indicate that at lower temperatures, instead of a breakdown in theory, a new phenomenon is occurring. One possibility is that the ion is not located at precisely the center of the vortex line. The ion might, for example, be kept off axis by the interaction between the flow fields produced by the moving ion and the vortex line (which, of course, moves in response to the off-axis ion). Once off axis, energy could be pumped into the resultant vortex deformation by the electric field. At higher temperatures, the vortex motion is strongly damped, and this process would not occur. An off-axis ion might then experience less drag in motion along the line and could give rise to the deformations referred to earlier in the paper. Suggestions of this sort are very speculative and serious consideration of them must await the results of very difficult hydrodynamic calculations.

We should like to acknowledge the help of E. Yarmchuk in obtaining the data.

†Work supported in part by a grant from the National Science Foundation.

[1]See, for example, R. J. Donnelly, *Experimental Superfluidity* (Univ. of Chicago Press, Chicago, Ill., 1967), Ch. 4.

[2]R. J. Donnelly, Phys. Rev. Lett. 14, 39 (1965).

[3]B. E. Springett, D. J. Tanner, and R. J. Donnelly, Phys. Rev. Lett. 14, 585 (1965); R. M. Ostermeier and W. I. Glaberson, J. Low Temp. Phys. 20, 159 (1975).

[4]R. M. Ostermeier and W. I. Glaberson, Phys. Lett. 51A, 348 (1975); G. A. Williams, K. DeConde, and R. E. Packard, Phys. Rev. Lett. 34, 924 (1975).

[5]R. L. Douglass, Phys. Rev. Lett. 13, 791 (1964).

[6]W. I. Glaberson, D. M. Strayer, and R. J. Donnelly, Phys. Rev. Lett 20, 1428 (1968); Douglass, Ref. 5.

[7]W. I. Glaberson, D. M. Strayer, and R. J. Donnelly, Phys. Rev. Lett. 21, 1740 (1968); W. I. Glaberson, J. Low Temp. Phys. 1, 289 (1969).

[8]R. L. Douglass, Phys. Rev. 174, 255 (1968).

[9]A. L. Fetter and I. Iguchi, Phys. Rev. A 2, 2067 (1970).

[10]See Ref. 4. The transit times measured in our experiment are much shorter than, although conceivably related to, the "extrinsic" ion lifetimes first observed by R. L. Douglass, Phys. Lett. 28A, 560 (1969), and subsequently discussed by others: K. DeConde, G. A.

Williams, and R. E. Packard, Phys. Rev. Lett. 33, 689 (1974); Ostermeier and Glaberson, Ref. 3, and Phys. Lett. 51A, 403 (1975). "Extrinsic" lifetimes are further discussed by G. A. Williams and R. E. Packard, preceding Letter [Phys. Rev. Lett. 35, 237 (1975)].

[11]K. W. Schwarz, Phys. Rev. A 6, 837 (1972).

[12]W. I. Glaberson, W. W. Johnson, and R. M. Ostermeier, Phys. Rev. Lett. 33, 1197 (1974).

Phonon-Induced Enhancement of the Superconducting Energy Gap*

T. J. Tredwell and E. H. Jacobsen
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 12 May 1975)

We have observed large increases of the critical current in Josephson junctions under 10-GHz phonon excitation. Eliashberg has predicted that absorption of microwaves in a superconducting film will increase the energy gap by creating a nonthermal quasiparticle distribution. By modifying this theory to account for phonon absorption we obtain a good agreement with our results on the phonon-induced enhancement of the critical current. We conclude that absorption of phonons of frequency $\omega < 2\Delta(T)/\hbar$ increases the superconducting energy gap.

In 1970 Eliashberg[1] suggested that absorption of microwave electromagnetic radiation in a superconducting film would increase the energy gap of the superconductor through the creation of a nonthermal quasiparticle distribution. Ivlev, Lisitysyn, and Eliashberg (ILE)[2,3] later derived expressions from which the microwave-induced increase of the energy gap could be calculated. The enhancement of the energy gap would be observed at temperatures such that the applied radiation does not break Cooper pairs, i.e., $\hbar\omega < 2\Delta(T)$. Eliashberg suggested that if a Josephson junction were used as a probe of this new state, the critical current of the junction would be increased.

A number of investigators[4-7] have reported small increases in the critical current of microbridge Josephson junctions under low-power microwave electromagnetic excitation. There is wide variation in the reported magnitudes and temperature dependences of this enhancement of the critical current. Several authors have suggested the ILE mechanism as the explanation for their results. However, no detailed comparison has been made between the observed enhancement of the critical current and the enhancement calculated on the basis of the ILE theory. Such a comparison would be of questionable value because of the presence in these experiments of other effects which significantly influence the critical current of a Josephson junction. These effects include the microwave-induced suppression of fluctuations,[8-10] which increases the measured critical current, and the direct effect of rf on the Josephson junction,[11] which decreases the critical current and also produces current steps in the I-V characteristics.

We have conducted a series of experiments in which the response of both point-contact and microbridge Josephson junctions to pulsed 10-GHz microwave *phonons* has been investigated.[12] We have observed large increases in the critical current of both types of junctions under phonon excitation. This is the first time that a *phonon*-induced enhancement of the critical current has been observed. Because of the absence of other effects which influence the critical current of the Josephson junction, such as those mentioned above in connection with microwave excitation, a direct comparison between the observed enhancement of the critical current and that predicted on the basis of the ILE theory is possible for phonon excitation.

The experimental arrangement comprised an X-cut quartz rod (3 cm length, 0.4 cm diameter), one end of which was inserted into a re-entrant microwave cavity[13]; the opposite end contained either a point-contact or weak-link–microbridge Josephson junction (see inset in Fig. 1). The point-contact junctions comprised aluminum films of thicknesses 1200 to 6400 Å ($\lambda_{\text{sound}} = 6400$ Å) evaporated onto the end face of the quartz rod with an adjustable tin point mounted normal to the film. The weak-link bridges (1 μm $\times \frac{3}{4}$ μm) were fabricated from 1500–2000-Å aluminum films evaporated onto the rod end face by use of the technique of Gregers-Hansen and Levinsen.[5]

The response of the junctions to phonons was as follows. For $T - T_c < 0.005$°K the phonons caused the junctions to become normal. Abruptly at T/T_c