New Factors Affecting the Measured Lifetime of Electrons Trapped on Vortex Lines in He II*

Keith DeConde, Gary A. Williams, and Richard E. Packard
Department of Physics, University of California, Berkeley, California 94720
(Received 22 July 1974)

The lifetime of trapped electrons measured at $T < 1.5$ K is found to be affected by factors which should not influence the intrinsic ion—vortex-line interaction. Observations indicate that the vortex lines move in the container, and the trapped charge escapes when the vortex lines interact with the container wall.

During the past fifteen years electrons have proven to be a powerful and versatile probe of the properties of superfluid helium.[1] Experiments have shown that the electron is self-trapped in a cavity (or bubble) whose radius is approximately 16 Å.[1] Using this model for the ion, Parks, Roberts, and Donnelly showed that this electron bubble should be attracted to, and trapped on, the core of a quantized vortex line. The ion should remain trapped in a Bernoulli potential well (depth ~ 50 K) until thermal fluctuations allow the ion to escape.[2] This model predicts a trapped lifetime τ which should *increase* rapidly with *decreasing* temperature. The model was supported by experiments in the range $1.59 < T < 1.82$ K.[3,4]

However, at lower temperatures ($0.6 < T < 1.1$ K) where the thermal-escape theory predicts $\tau > 10^{13}$ sec, it was found that the observed lifetime was orders of magnitude smaller than predicted, and it *decreased* with decreasing temperature.[5] The question raised was why does the thermal-escape theory not predict the lifetime observed at low temperatures? It is the purpose of this paper to attempt to answer this question.

We have measured the lifetime τ of electrons trapped on vortex lines in rotating He II over the temperature range $0.08 < T < 1.72$ K. The experimental results indicate that for temperature below 1.5 K the observed lifetime is not determined by the intrinsic properties of the ion-vortex interaction, but is instead a characteristic time for a vortex line to move to, and be destroyed at, the wall of the rotating container.

Our measurements of trapped-electron lifetimes were made in several different containers. Most of the containers have walls of high electrical resistivity so that voltages applied along the walls produce the electric fields necessary to manipulate the ions.[6] For a few of the measurements in the low-temperature range ($T < 0.5$ K) metal electrodes were used for the walls.[7] None of the buckets contained any grids in the liquid that might perturb the vortices. Although the manipulating voltages were applied axially, the resultant electric fields did have transverse fringe components in some regions. For temperatures above 1.2 K the container was in a superfluid-filled cell which was rotated in a stationary helium bath. For lower temperatures we used a rotating ^{3}He refrigerator or a rotating dilution refrigerator.

The lifetime measurements were made by using a procedure similar to that used in Ref. 3. Negative ions produced by a radioactive source (^{210}Po or tritium) are drawn into the liquid and become trapped on vortex lines during a fixed charging time (typically 5 to 10 sec). During a variable delay time no more charge is drawn from the source, and retaining fields prevent the trapped charge from escaping at the ends of the vortex lines. At the end of the delay time electric fields force the trapped charge along the vortex lines through the liquid surface to a collector in the vapor. For $T > 1.2$ K the collector is a proportional counter[6] and below 1.0 K the collector is a phosphor screen. The signal is amplified before passing through slip rings to instruments in the laboratory.

Figure 1 shows the temperature dependence of the measured half-life[8] τ observed in two cylindrical vessels of *different diameter*. The data indicate two regions in which τ has distinctly different temperature dependences. In the high-temperature range ($1.6 < T < 1.72$ K) τ is a rapidly increasing function of T^{-1} and our data are in good agreement with Refs. 3 and 4. Since the behavior of τ in this range is well explained by the theory of thermally assisted escape (represented by the solid line in Fig. 1) we call this the intrinsic lifetime. As expected from theory, we found that the intrinsic lifetime is independent of bucket size, angular velocity, and past rotation history, but τ does depend on the transverse electric field strength.

In the temperature range where τ decreases with increasing T^{-1} the lifetime is affected by

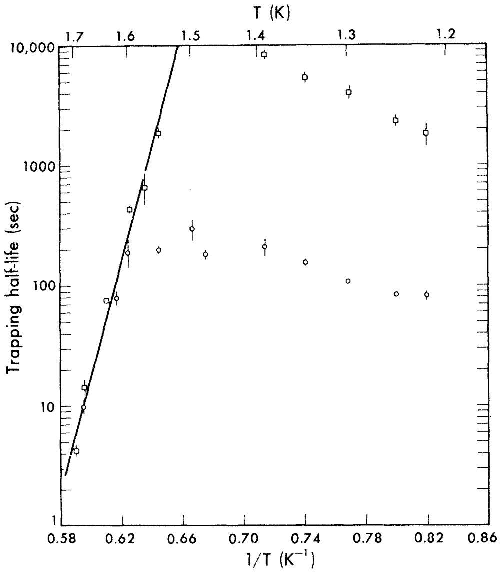

FIG. 1. Temperature dependence of the measured lifetime. The data were taken at $\omega = 3.9$ sec^{-1} in two circular buckets of different size. (The circles are for a 1.75-mm-diam vessel and the squares for a 3.17-mm-diam vessel.) The error bars represent 1 standard deviation. The solid line is the temperature dependence expected for the intrinsic lifetime with a well depth of ~ 55 K.

factors which do not affect the intrinsic lifetime. Most obviously from Fig. 1, the lifetime is much longer in a larger-size container. In this temperature range we found that the lifetime also increases with lower angular velocities, and is relatively insensitive to changes of the electric field strengths.

For temperatures lower than those shown in the figure the lifetime continued to decrease (in agreement with Ref. 5), finally becoming temperature independent below 0.8 K. In our 3.2-mm-diam bucket the low-temperature limit was $\tau \sim 3$ sec.

These observations indicate that there are two independent mechanisms by which trapped charge can leave the liquid. The observed escape rate (which is inversely proportional to the lifetime) is then the sum of two rates, one for each escape mechanism. In the high-temperature range the intrinsic ion escape rate is large, and dominates any other process. However, the intrinsic escape rate decreases so rapidly as the temperature is lowered that it soon becomes negligibly small compared to the escape rate due to another process.

Our results indicate that this other process involves the motion of charged vortex lines. We conjecture that a charged vortex line, in an array of vortex lines, moves with respect to the container. Eventually the vortex line will encounter the container wall and will be destroyed. The trapped charge is collected at the wall. To maintain the equilibrium line density another vortex will soon grow to replace the destroyed one, but the new line will be uncharged. If the characteristic time for a line to migrate to the container wall is short compared to the intrinsic lifetime, vortex motion will be the dominant mechanism of charge loss.

Therefore we believe that the lifetime observed at low temperatures is a measure of the characteristic time for a vortex line to traverse the container. This time should depend on the container size and on the effective velocity of the vortex line. The vortex velocity depends on several factors. For example, it should depend on the preparation or rotation history of the liquid, the angular velocity (which determines the mean spacing between lines), the amount of mechanical vibration of the container, and the amount of damping due to mutual friction with the normal fluid. We have observed that the lifetime is affected by all of the above factors. We believe that for $T < 1.5$ K the temperature dependence of the lifetime (which is qualitatively similar to the temperature dependence of the normal-fluid density ρ_n) is due to the reduced damping of vortex motion as ρ_n decreases. At sufficiently low temperatures ρ_n becomes negligible; then the vortex-line motion and lifetime is determined by the undamped vortex-line hydrodynamics, and τ should be independent of temperature, as we observed.

The above model of charge escape due to vortex-line motion is consistent with other qualitative observations. When only a few vortex lines are present, random destruction of vortex lines at the container wall should cause random fluctuations of the trapped-charge signal for a fixed delay time. Therefore, the size of relative fluctuations, $\Delta Q/Q$, provides a qualitative guide to the amount of vortex motion.[9] In the 1.75-mm bucket at 1.3 K, τ increased by a factor of 3 when the relative fluctuations decreased by a similar factor. Furthermore, when τ was shortest ($T < 0.5$ K) the fluctuations were ~100%.

In his original Letter[5] on low-temperature lifetimes, Douglass also presented results for lifetimes in a 2% ^{3}He mixture. The lifetime in the mixture was always longer than in pure ^{4}He, and

τ became independent of temperature below 0.8 K. We believe that this is because the ^{3}He impurities are part of the normal fluid, and they increase the damping of vortex motion. Below 0.8 K the damping due to elementary excitations becomes negligible compared to that due to the ^{3}He, and so the lifetime becomes independent of temperature.

Further evidence that ^{3}He increases the damping of vortex motion came from an experiment designed to photograph the positions of vortex lines in which we also measured the lifetime τ. In pure ^{4}He the lifetime was very short and the vortex lines did not produce a distinct image,[7] even though the apparatus had the necessary resolution. Adding 0.1% He^3 caused τ to increase substantially and then the distinct vortices were apparent in the photograph.[10]

One observation inconsistent with our model is Douglass's report that at temperatures below 1 K, positive ions seem to have a longer trapped lifetime than negative ions. If the lifetime is determined by vortex motion, both positive and negative ions should have the same lifetime at the lowest temperatures. However, Douglass stated that the positive-ion signal was "barely detectable" and so we feel his statements about the positive-ion lifetime are not conclusive. Although we have not yet had an apparatus which would favor observation of positive-ion trapping we hope to explore this further in the future.

Our observations concerning vortex-line motion may also be related to recent observations that electron trapping by vortex lines appears to be reduced in the presence of an axial heat current.[11] In that experiment electrons are drawn across a container filled with liquid helium, and the current reaching the other side is measured. When the container is rotated the current is attenuated because of charge trapping by the vortex lines. However, for small heat currents along the rotation axis, the attenuation disappears. Second-sound measurements in the same container indicate that the vorticity density is not changed by the heat flow. Unless the vortex lines are perfectly straight, mutual friction between the lines and the normal-fluid heat current should increase the motion of the lines. The increased rate of vortex destruction releases charge which gets pulled to the collector, thus reducing the attenuation of the current.

All of the observations discussed above are consistent with the model of charge loss due to vortex motion. The apparent fact that vortex lines do not form a stable, static array in an experimental chamber is not unexpected.[12] Calculations show that energy differences between possible regular arrays are very small.[13] Although it is not clear how to calculate energy barriers between different configurations, these barriers are probably not large compared with the random mechanical energy in the rotating system.

Although further measurements under a variety of conditions are necessary to conclusively verify our model, these measurements should provide much information on the stability and motion of vortex lines.

---

*This work was supported by the National Science Foundation.

[1] For a review of ions and vortices see R. J. Donnelly, *Experimental Superfluidity* (Univ. of Chicago Press, Chicago, Ill., 1967), Chap. 6. The most complete review is by A. L. Fetter, in *The Physics of Liquid and Solid Helium,* edited by K. H. Benneman and J. B. Ketterson (Wiley, New York, to be published).

[2] P. E. Parks and R. J. Donnelly, Phys. Rev. Lett. 16, 45 (1966); R. J. Donnelly and P. H. Roberts, Proc. Roy. Soc., Ser. A 312, 519 (1969).

[3] R. L. Douglass, Phys. Rev. Lett. 13, 791 (1965); W. P. Pratt, Jr., and W. Zimmermann, Jr., Phys. Rev. 177, 412 (1969); D. M. Sitton and F. Moss, Phys. Rev. Lett. 23, 1090 (1969).

[4] Another mechanism of charge loss which can occur in tangled vorticity is described by D. M. Sitton and F. E. Moss, Phys. Rev. Lett. 29, 542 (1972).

[5] R. L. Douglass, Phys. Lett. 28A, 560 (1969).

[6] This cell is similar to the one described in R. E. Packard and T. M. Sanders, Jr., Phys. Rev. A 6, 799 (1972).

[7] This cell is shown in R. E. Packard and G. A. Williams, in *Proceedings of the Thirteenth International Conference on Low Temperature Physics, Boulder, Colorado, 1972,* edited by W. J. O'Sullivan, K. D. Timmerhaus, and E. F. Hammel (Plenum, New York, 1973).

[8] In the temperature range $0.8 < T < 1.7$ K the charge appeared to decay exponentially but at lower temperatures the form of the decay curve was not as well established.

[9] The fluctuations $\Delta Q/Q$ depended on past rotation history, being larger for larger accelerations.

[10] Gary A. Williams and R. E. Packard, Phys. Rev. Lett. 33, 280 (1974).

[11] D. K. Cheng, M. W. Cromar, and R. J. Donnelly, Phys. Rev. Lett. 31, 433 (1973).

[12] See, for example, J. A. Northby and R. J. Donnelly, Phys. Rev. Lett. 25, 214 (1970); D. Stauffer and A. L. Fetter, Phys. Rev. 168, 156 (1968).

[13] Stauffer and Fetter, Ref. 12.