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[10]The integral of Eq. (3) has been performed for the band modes over a mesh of sixteen bins for each $\bar{\Gamma}\bar{M}\bar{\Gamma}$ interval. The local-mode singular contributions have been calculated analytically from Eq. (6) and added. Because of quite long computer times needed in calculating Z_γ and ρ, I could not use a thicker mesh, which limits the accuracy of the present results. The possible water contamination of the surface would affect the experimental data [see, e.g., D. E. Houston and D. R. Frankl, Phys. Rev. Lett. 31, 298 (1973)], making the comparison with calculation questionable. However, a recent work by Wilsch *et al.* (unpublished) gives definitive evidence that the standard preparation procedure gives water-free surfaces.

Effect of ^{3}He Impurities on the Lifetime of Ions Trapped on Quantized Vortex Lines*

Gary A. Williams† and Richard E. Packard
University of California, Berkeley, California 94720
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The lifetimes of both positive and negative ions trapped on quantized vortex lines in rotating ^{3}He-^{4}He mixtures have been measured at temperatures down to 0.1 K. Evidence is found that the ^{3}He condenses at the vortex core, and possibly at the surface of the electron bubble.

This Letter briefly describes recent measurements of the trapped lifetimes of positive and negative ions bound to quantized vortex lines in ^{3}He-^{4}He mixtures.[1] The primary purpose of these measurements was to see if the trapped lifetime would exhibit effects attributable to ^{3}He condensing either in the vortex core[2,3] or on the surface of the ions.[4]

In pure liquid ^{4}He it is widely believed that the negative ion is an electron self-trapped in a bubble with radius of 17 Å.[5] The positive ion is thought to be a singly ionized He atom surrounded by an electrostrictively induced solid "snowball" with a radius of approximately 6 Å. When either of these ions is near a quantized vortex line they feel attracted to the line as a result of the Bernoulli pressure. The ion can become localized in a hydrodynamic potential well centered on the line. The average length of time for which the ion remains trapped (trapped lifetime) depends on a Boltzmann factor containing the well depth and on an attempt frequency which depends on the detailed motion of the ion in the well.[6] Thus the intrinsic trapped half-life $\tau_{1/2}$ can be written as

$$\tau_{1/2}=\tau_0 e^{U/kT}, \tag{1}$$

where U represents the well depth, k is Boltzmann's constant, T is the temperature, and τ_0^{-1} is the escape attempt frequency.

In addition to thermal escape, trapped ions can leave the fluid whenever a vortex line migrates to a wall and is destroyed, releasing its trapped charge.[7] This geometry-dependent mechanism determines the upper limit of the lifetime observed in a given experiment at low temperatures.

If ^{3}He is present in the superfluid it can profoundly influence the lifetime. If the ^{3}He condenses on the vortex core it will decrease the well depth U and may also change τ_0. Furthermore if the ^{3}He changes the size of the ion it will change both U and τ_0. Since $\tau_{1/2}$ depends strongly on U and τ_0, lifetime measurements provide a sensitive probe of these parameters.

Our measurements were made with a rotating dilution refrigerator.[8] The charge was trapped on vortex lines in a cylindrical region of rectangular cross section, with dimensions 1 cm by 2.2 cm and length 3.2 cm. The rotation axis ran through the cylinder axis. The sides of the container were split to allow the application of an electric field transverse to the vortex lines. The walls were coated with resistance paint which, when voltage biased, allowed the ions to be moved along the lines towards a collector at the top of the cell. No grids were within the cylinder although there was a grid lying perpendicular to the rotation axis placed immediately before the collector.

The ions were produced near a 0.1-Ci tritium source located outside of the cell. Bias potentials produced a beam of ions which entered the central region through a grid in one side wall and drifted perpendicular to the vortex lines. The trapped charge was detected by moving it along the lines to the metallic collector at the top of the cell. The resulting current pulse was detected with an electrometer and integrated to give the total charge. The order of magnitude of both positive and negative trapped charge was 10^{-11} C.

The ion-trapping lifetime was measured by charging the lines for a fixed time, and then switching off the charging current. The charge Q remained trapped for a variable delay time t, and was then collected and measured. Repeating this cycle for increasing delay times (automatically sequenced) gave the charge decay $Q(t)$ as a function of time. The lifetime $\tau_{1/2}$ was determined by computer, fitting the data by a simple exponential decay function with the lifetime an adjustable parameter. The data discussed in this paper represent a small portion of a total of 24 000 measurements of $Q(t)$ in ^{3}He-^{4}He mixtures with ^{3}He concentrations ranging between 0.01% and 4.8%. A more complete description of the experiment and data will be published elsewhere.[9]

Positive-ion lifetimes as a function of temperature and ^{3}He concentration are shown in Fig. 1. These data display the same general features as the lifetimes found[10] in pure ^{4}He. At temperatures below ~0.5 K the lifetime assumes a constant value (larger than that in pure ^{4}He) which is approximately the same as that found for the negative ion at low temperatures. At temperatures between 0.7 and 0.5 K, $\tau_{1/2}$ increases exponentially in T^{-1} indicating thermal excitation of the positive ions out of the Bernoulli potential well. The data displayed in Fig. 1 show that the lifetime in this thermal-ejection region shifts to lower temperatures as the ^{3}He concentration is increased.[11]

By fitting the data above $T = 0.5$ K with Eq. (1) we can compute values of both U and τ_0 for each ^{3}He concentration. The binding energy U obtained from such a fit is shown in Fig. 2. U decreases approximately linearly with ^{3}He concentration. The parameter τ_0 is found to increase rapidly with concentation, from 7×10^{-10} sec in

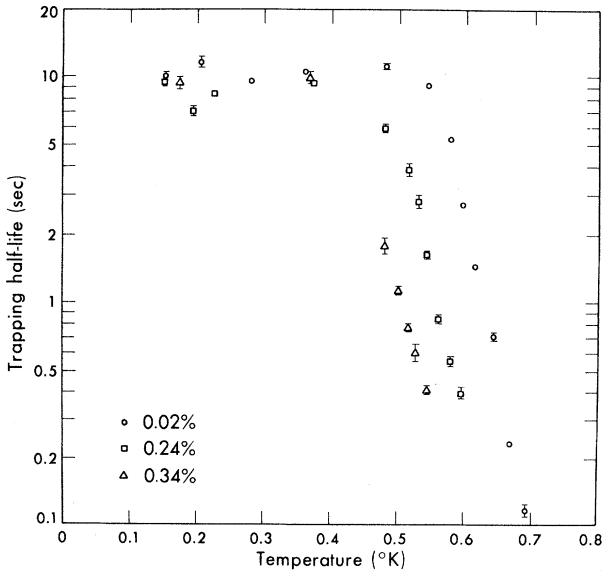

FIG. 1. Temperature dependence of the trapped lifetime of positive ions for three different ^{3}He concentrations. The rotation speed was 1.5 sec^{-1} and the transverse field was 20 V cm^{-1}.

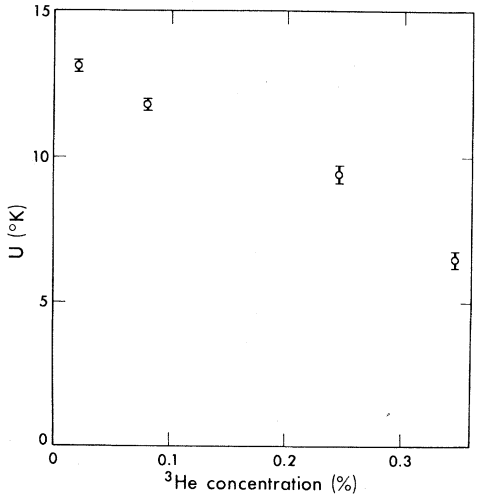

FIG. 2. Positive-ion binding energy U as a function of ^{3}He concentration.

the 0.02% solution to 2×10^{-6} sec in the 0.34% solution. These values for τ_0 are several orders of magnitude greater than would be calculated from the theory of Ref. 6. (Similar experiments in pure ^{4}He give good agreement with this theory.[10])

The data for positive ions indicate that U decreases with ^{3}He concentration. Since U is proportional to the superfluid density ρ_s near the vortex, an excess of ^{3}He near the vortex center can lower U by decreasing ρ_s. Furthermore phase separation may occur, increasing the size of the vortex core. Previous calculations do predict an increased core size in ^{3}He-^{4}He mixtures at sufficiently low temperatures.[2,3]

An additional effect which may influence $\tau_{1/2}$ is associated with the fact that there exists a repulsive polarization interaction between the positive ion and the ^{3}He atoms.[12] The repulsive energy of a ^{3}He atom sitting at the ion radius is approximately 1 K. If the ^{3}He atoms are bound to the vortex line with less than this energy then the distribution of ^{3}He near a trapped positive ion may be quite complex. In addition, the mobility and effective mass of the positive ion must depend on the ^{3}He which must move out of the way of the ion.

The observed behavior of the trapping lifetime for negative ions is more complex than for positive ions. Figure 3 shows the temperature dependence of $\tau_{1/2}$ for negative ions in a 0.8% mixture. This temperature dependence is typical of all concentrations tested. In the cell used for these measurements the lifetime above 1 K and below 0.25 K assumes a temperature-independent value of approximately 12 sec. In a previous experiment[7,8] using a cell with circular cross section (3.2 mm diam) the lifetimes in these regions were much larger—several hundred seconds at 1.3 K and greater than 10^3 sec below 0.2 K. We strongly suspect that this marked geometry dependence is characteristic of charge loss due to vortex motion[7] although we have no detailed model to explain the magnitudes of the lifetime.[13]

As seen in Fig. 3 the lifetime decreases below 1 K and reaches a temperature-independent plateau between 0.8 and 0.6 K.[14] This behavior is probably caused by the enhanced vortex motion allowed by the decreased line damping as the normal-fluid density ρ_n decreases with temperature.[7] The temperature-independent plateau is due to charge loss via vortex motion in the regime where ρ_n is determined solely by the ^{3}He concentration.[15] We find that the magnitude of the lifetime in this plateau increases monotonically with

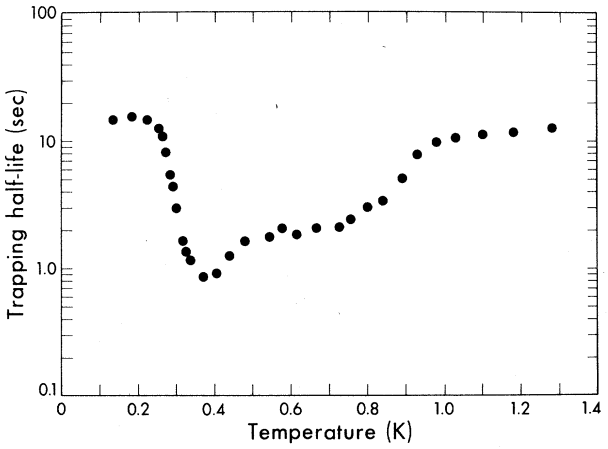

FIG. 3. Temperature dependence of the trapped lifetime of negative ions in a 0.8% ^{3}He-^{4}He mixture. The transverse field was 20 V cm^{-1}.

^{3}He concentration.

The most striking feature of the negative-ion lifetimes is the decrease below ~0.6 K and the rapid increase near 0.3 K. At *lower* concentrations the decrease is *more* pronounced and is evident at *higher* temperatures (~0.7 K for a 0.01% solution). The decreased lifetime is correlated with a decrease in the trapped-ion mobility along the vortex lines which occurs between 0.6 and 0.7 K.[8,9,16] These effects are most likely related to the condensation of the ^{3}He onto the vortex lines at these temperatures. Such condensation would increase the drag on the electron bubble (thus decreasing the mobility) and also lower its binding to the vortex.

The rapid increase in lifetime below 0.3 K is perhaps due to condensation of the ^{3}He onto the bubble surface. ^{3}He condensing on the electron bubble decreases the surface tension, allowing the bubble to increase in size. The free-ion mobility in mixtures[2] shows structure at 0.3 K which has been interpreted as the point where such a radius increase occurs.[4] With a larger radius the binding energy of the electron bubble to the vortex would be substantially increased, possibly leading to the increased lifetime which is observed.

An apparent inconsistency in this interpretation of the data is the fact that the positive ion has a much longer lifetime than the negative ion in the temperature range between 0.3 and 0.5 K. If excess ^{3}He at the vortex core lowers the negative-ion binding energy sufficiently to produce the short lifetime observed, the presumably smaller[17] positive ion would not be expected to be

bound to the vortex lines at all in this region.

It would seem that in order to explain the larger lifetime for positive ions between 0.3 and 0.5 K one might have to invoke either an extra binding energy for positive ions which is unimportant for negative ions, or a mechanism which gives the positive ions a much lower attempt frequency than the negative ones. We did make a rough measurement of the mobility along the line of the positive ion relative to the negative ion. We found the surprising result that the positive ions move ~50% slower than the negative ions. This might indicate an enhanced interaction of the positive ion with the ^{3}He.

In summary, it appears that ^{3}He atoms condense on the vortex lines below about 0.6 K and may condense on the electron bubble below ~0.3 K. There is still a great deal of work to be done to explain the details of the lifetime's temperature dependence. Studies of the ion trapping under pressure might be useful in separating the different effects which are observed.

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†Present address: Physics Department, University of California, Los Angeles, Calif. 90024.

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[5]For a review of ions and vortices in superfluid helium see R. J. Donnelly, *Experimental Superfluidity* (Univ. of Chicago Press, Chicago, Ill., 1967).

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[11]At the higher ^{3}He concentrations it was found necessary to increase the charging-current bias voltages to fairly high values (100–200 V) in order to trap a sufficient amount of charge on the lines. For concentrations greater than 0.34% we could not trap positive ions.

[12]R. M. Bowley and J. Lekner, J. Phys. C: Proc. Phys. Soc., London 3, L127 (1970); B. N. Esel'son, Yu. Z. Kovdrya, and V. B. Shikin, Zh. Eksp. Teor. Fiz. 59, 64 (1970) [Sov. Phys. JETP 32, 37 (1971)].

[13]In the regions where the lifetime appears to be geometry limited $Q(t)$ at first decays roughly exponentially, but at longer times the charge decrease is much slower than the initial time constant. The trapped lifetime is taken to be the initial decay time, which is probably only a lower limit for the complicated decay process.

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

[15]It is not clear why the lifetime between 0.8 and 0.6 K is shorter than the lifetime below 0.2 K, if both are determined by line motion. A possible explanation might be that the mutual friction forces are increased as a result of the excess ^{3}He condensing at the vortex cores below 0.6 K. This point is also discussed in the second paper of Ref. 1.

[16]Trapped negative-ion mobilities in mixtures at temperatures above 1 K have previously been measured by W. I. Glaberson, J. Low Temp. Phys. 1, 289 (1969).

[17]We would not expect the positive-ion size to be affected by the ^{3}He. The ^{3}He atoms are lighter and have a higher zero-point energy, making it unfavorable for them to solidify in the "snowball" structure.