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Positive-Ion Trapping on Vortex Lines in Rotating He II*

Gary A. Williams, Keith DeConde, and Richard E. Packard
Department of Physics, University of California, Berkeley, California 94720

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The direct trapping of positive He ions on quantized vortex lines in rotating He II has been observed at temperatures below 0.7 K. Trapping lifetimes have been measured between 0.1 and 0.7 K, and agree with models of thermal escape and charge loss from vortex motion. An ion radius of 7.7±0.1 Å is found.

The trapping of ions on quantized vortices in superfluid helium has proven to be a very useful probe of the vortex properties and of the detailed structure of the ions.[1] The negative ion has been shown to be an electron which forms a bubble of radius[2] ~17 Å. The positive ion is thought to be a "snowball" structure in which electrostrictive pressures cause the He atoms to solidify around the positive charge to a radius[2] of 6–8 Å. The electron bubble is observed to become trapped on quantized vortex lines via a Bernoulli-pressure potential well.[3-5] This paper describes observations of *positive-ion* trapping on quantized vortex lines.[6,7]

The motivation for this work originates in the fact that ion trapping on vortex lines provides a very sensitive test of models describing both the size of the ion and the nature of the vortex core. It has been shown that trapped ions can leave the vortex via thermally activated processes.[3-5] This model predicts a trapping half-life $\tau_{1/2}$ which depends on temperature according to the relation

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

where k is Boltzmann's constant, T is the temperature, and τ_0 is a parameter which is determined mainly by the ion radius and mass. The depth U of the Bernoulli potential well depends on the ion radius. For negative ions, experiments[8] have shown that the temperature dependence of Eq. (1) is satisfied above 1.5 K with a binding energy U of 50 K. Below this temperature a lack of normal fluid damping allows the vortices to move more freely (presumably because of apparatus vibrations). The trapped charge is lost when a line encounters a boundary.[9,10]

Previous experiments[9,11] designed to observe positive-ion trapping on rectilinear vortices were unsuccessful. However, positive ions have been observed to be trapped on vortex rings and in strong electric fields the escape rate has been measured[12] and seems to agree with the thermal-activation model.[4] It was not expected that positive ions would be trapped at temperatures above 1 K because of the ion's small size.[3] Since the observed trapped lifetime is determined by the intrinsic ion-vortex interaction as well as line motion, it is desirable to observe both positive- and negative-ion trapping to help distinguish between the different charge loss processes.

Our measurements were made with a rotating dilution refrigerator.[13] The charge was trapped on vortex lines in a cylindrical region of rectangular cross section. The rotation axis runs through the cylinder axis. The sides of the container are split to allow the application of an electric field transverse to the vortex lines. No grids were placed within the cylinder. 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.

The ions are produced near a 0.1-Ci tritium source located outside of the cell. Bias poten-

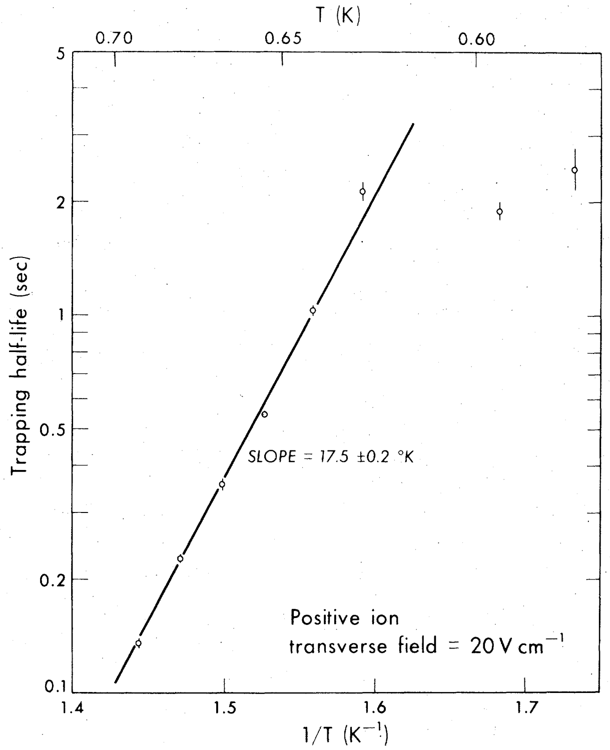

FIG. 1. The temperature dependence of the half-life of positive ions trapped on vortex lines. The rotation speed was 1.5 sec^{-1}.

tials produce a beam of charged vortex rings which enter the central region through a grid in one side wall and drift perpendicular to the vortex lines. The trapped charge is detected by moving it along the lines to a metallic collector at the top of the cell. The resulting current pulse is 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 remains trapped for a variable delay time, and is then collected and measured. Repeating this cycle for increasing delay times gives the charge decay as a function of time. Figure 1 shows some data taken at a rotation speed of 1.5 sec^{-1} and a transverse field of 20 V/cm. In a limited temperature region the lifetime increases exponentially with $1/T$. A computer analysis of the data yields a value of $U = 17.5 \pm 0.2$ K and $\tau_0 = 1.36 \times 10^{-12}$ sec. This is in good agreement with the thermal-activation model of Donnelly and Roberts.[5] With this value of U and a vortex core radius[4] of 1.47 Å, a fit with their model yields an ion radius $R_+ = 7.7 \pm 0.1$ Å. This agrees with the value of 7.9 Å deduced from the analysis of high-field escape from vortex rings.[4] This radius includes the length over which the superfluid density falls to zero at the ion surface. Subtracting a healing length of 1.5 Å gives a "hard-core" ion radius of 6.2 Å, which is close to the value of 6.1 Å determined in a resonance experiment.[2]

In the previous negative-ion trapping experiments[8] the ion radius determined from the measured parameter U gave a value for the parameter τ_0 which was several orders of magnitude different from the observed value. In contrast, using our deduced radius of 7.7 Å and an ion mass of 43 helium atoms[2] we compute a value for τ_0 which agrees within 15% with our measured value.

The lifetime was weakly dependent on the transverse electric field; at $T = 0.655$ K the half-life increased from 0.52 to 0.61 sec as the field increased from 10 to 40 V/cm. This is a weaker field dependence than given by Ref. 4.

At temperatures below 0.63 K the positive-ion lifetime deviates from that predicted by the thermal-activation theory. The lifetime assumes a roughly constant value of several seconds in the range between 0.1 and 0.5 K. In this temperature range the charge decay is at first exponential but at long times decreases with a slow, nonexponential tail. This behavior is also observed for negative ions over the same temperature range, and is thought to be due to vortex motion.[10]

An additional observation is that although negative ions on lines passed through the free surface, we were unable to detect any trapped positive ions emerging through the surface.

We also found that in a 0.8% ^{3}He:^{4}He mixture positive ions were not observed to be trapped down to 0.1 K, while trapped negative ions were observed.[13] This may be caused by ^{3}He atoms concentrating near the vortex center and producing a larger effective core.[14] We plan to investigate this further.

In summary, we have observed positive-ion trapped lifetimes longer than 0.1 sec for $T < 0.7$ K. In pure ^{4}He below 0.5 K the trapped lifetimes of both positive and negative ions are the same, in agreement with expectations of recent models of vortex motion.[10,15]

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Observation of Plasma-Density Modulations Produced by Ruby-Laser Light Mixing

G. G. Albach and J. Meyer
Department of Physics, The University of British Columbia, Vancouver, British Columbia, Canada

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The effect of mixing two high-power ruby-laser beams in a plasma has been investigated by means of light scattering. Coherently scattered light has been observed with intensities of up to 30 times that scattered by incoherent thermal fluctuations. As indicated by the wave-vector distribution, the nonlinear electromotive forces of the mixed electromagnetic waves produce a stationary electron-density wave in the plasma.

Large perturbations in plasma density fluctuations may be caused by the nonlinear forces of two intense electromagnetic waves acting on plasma electrons.[1] Since the scattering form factor $S(\vec{k},\omega)\propto\langle|n(\vec{k},\omega)|^2\rangle$, the light-scattering properties of the plasma will be changed. In plasma atmospheres in front of solid targets where incident and specularly reflected waves mix, this effect may strongly influence the backscattering of laser light and thus may be of importance in laser-fusion experiments. It has been shown previously that two laser beams of different frequencies, when mixed in a plasma, can enhance the density-fluctuation intensity if the difference frequency coincides with the plasma resonance frequency.[2] A similar effect may be expected if the difference frequency coincides with the ion resonance. In this Letter we would like to show that even for zero frequency difference of the mixed laser beams a strong modification of the density fluctuations takes place, the nonlinear electromotive forces setting up a stationary density wave.

It can be shown[1,3] that two plane monochromatic electromagnetic waves of the same frequency induce coherent fluctuations in a plasma of the form

$$\langle|n(\vec{k})|^2\rangle = Vn_0^2\beta^2\,\frac{1+Z\alpha^2}{1+\alpha^2(1+Z)}\,\delta(\vec{k}_0-\vec{k}). \qquad (1)$$

Here

$$\beta=\frac{e^2\vec{E}_1\cdot\vec{E}_2}{2m\omega^2KT},\quad \alpha^2=\frac{n_0e^2}{\epsilon_0KTk_0^2},\quad \vec{k}_0=\pm(\vec{k}_1-\vec{k}_2),$$

$\vec{k}_{1,2}$ are the wave vectors, ω the frequency, $\vec{E}_{1,2}$ the electric field amplitudes of the mixed waves, and V the mixing volume. (The functions F_e and F_i in Ref. 1 are equal to unity for $\omega\to 0$.)

In the present experiment two ruby-laser beams of equal power (up to 250 MW within a spectral linewidth of 0.03 Å) are mixed in a plasma in opposite directions. The beams are focused to a volume of 0.3 mm diam inside the plasma. A third beam of frequency-doubled ruby-laser light of about 4 MW is used for light-scattering diagnostics, being focused into the focal volume at an angle of 60° with respect to one mixing beam and 120° with respect to the other. In order to satisfy both the wave-vector conditions of Eq. (1) and the scattering condition that requires $\vec{k}$ to equal the