CAPTURE CROSS SECTIONS FOR NEGATIVE IONS IN ROTATING HELIUM II*

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Some preliminary experiments reported by the authors[1] demonstrated that negative ions trapped in quantized vortex lines in a rotating bucket are able to travel along the vortex lines parallel to the axis of rotation. Subsequently Douglass[2] was able to obtain an estimate of the velocity of the ions along the vortex lines and to show that under suitable field conditions ions could be contained in the vortex lines for considerable periods of time. An explanation for the observed trapping and lifetime effects has been advanced by Donnelly,[3] and it is the purpose of this note to present experimental measurements of capture cross section and compare them with the calculations.

Suppose a single vortex line presents a cross section (diameter) σ for the capture of a negative ion. Then a negative current propagated perpendicular to the axis of rotation will be attenuated according to the equation

$$I = I_0 \exp(-2\Omega m h^{-1} \sigma y), \tag{1}$$

where Ω is the angular velocity of the container, m is the mass of the helium atom, and y is the distance along the direction of the applied field. The quantity $2\Omega m h^{-1}$ is the number of vortex lines per cm^2.

The apparatus designed to measure σ is immersed in a special cryostat. The entire cryostat and low-level electronic cricuits are mounted on a five-foot-diameter turntable. The temperature is controlled by pumping through a 2-inch rotating seal, and electrical connections are made through mercury slip rings. Each electrode of the configuration, shown in Fig. 1, measures 6 cm by 3.5 cm. The α source (Am^{241}) is electroplated on a copper electrode 0.3 cm $\times$1.0 cm and is given a protective plating of gold. The strength of the source is approximately 200 μCi. The source is electrically guarded by a conducting shield. The collector C_1 is made of brass and is guarded by a rectangular shield C_2. The collector is larger than the source because it is known that the beam has an angular spread. The current reaching the collector is controlled by a grid G which is an 80-mesh screen located 2 mm from the source. All the electrodes are gold-plated to reduce stray potentials. The field E is taken to be the potential V between G and C_1 divided by the spacing (4.6 cm).

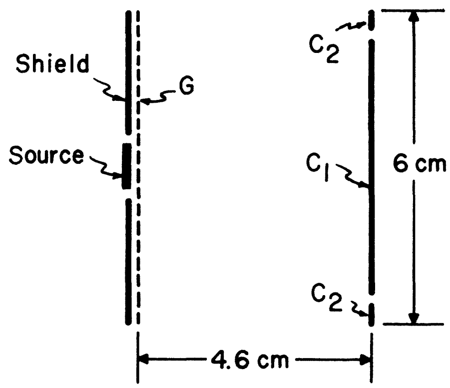

FIG. 1. Cell used to measure cross sections. The source measures 1 cm by 0.3 cm; the shield, grid G, and guard C_2 measure 6 cm by 3.5 cm.

The experiment consists of setting the temperature and field to the desired values, adjusting the current I_0 to a standard level, 1.5×10^{-12} A, and measuring I as a function of Ω. Results of such measurements are shown in Fig. 2. σ is deduced from the slope of the plot of $\ln I$ vs Ω. The time for the current to reach equilibrium after each change in angular velocity is typically of the order of 10 minutes. It is thought that this is a measure of the hydrodynamic relaxation time of the liquid helium.

The temperature dependence of the cross section at an applied voltage $V = 200$ V ($E = 43.5$ V/cm) is shown in Fig. 3(a). The uncertainties indicated by the vertical bars refer only to uncertainties in fitting lines such as in Fig. 2. There may be unknown systematic errors. The dashed curve refers to the theoretical cross section calculated by Donnelly[3] for a negative ion of radius 12.1 Å and mass 100 helium atomic masses, corrected as described below. The sharp cutoff at high temperatures is due to a rapidly increasing probability of escape, and the exact temperature of the cutoff is sensitive to the assumed mass and radius of the ion.

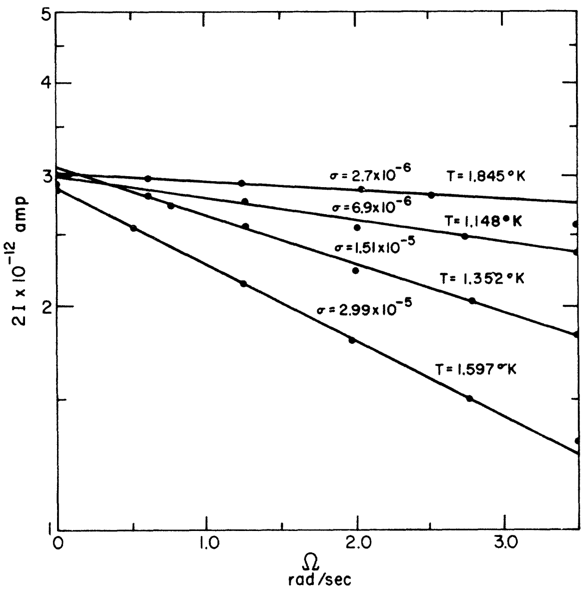

FIG. 2. Current I as a function of angular velocity Ω, measured by the cell shown in Fig. 1. The voltage V between G and C_1 is 200 V. The solid lines represent Eq. (1) for the cross sections shown.

This interpretation has been confirmed directly by lifetime measurements.[2]

The field dependence of the cross section at a temperature of 1.46°K is shown in Fig. 3(b). The experimental measurements show an apparent limiting cross section of approximately 10^{-5} cm at large V. This arises because absorption in the region between the source and the grid can dominate the absorption in the main drift space. The measured cross section is given by

$$\sigma = \sigma(E_2) + \sigma(E_1)y_1/y_2, \tag{2}$$

where E_1 is the field in the region of length y_1 between the source and the grid, and E_2 is the field in the region of length y_2 between the grid and the collector. Even though $y_1/y_2 = 0.043$, σ increases so rapidly at low fields that the contribution in the first region can dominate when $E_2 \gg E_1$. The dashed curve shows the theoretical result of Donnelly corrected for $E_1 = 0.5$ V/cm. The same correction was applied to the dashed curve in Fig. 3(a). The discrepancy in magnitude at low fields is thought to be due to the effects of space-charge limitation which give rise to a nonuniform field (and hence varying cross section) along the beam. At present we are not sufficiently sure

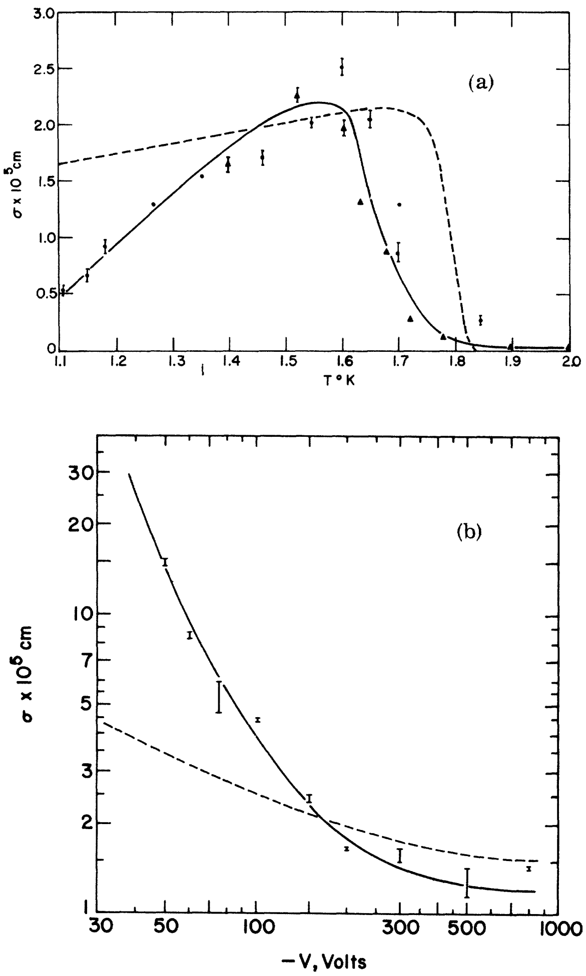

FIG. 3. (a) Cross section as a function of temperature for $V = 200$ V. The solid circle and solid triangle refer to measurements made at widely separated times. (b) Cross section as a function of V at a temperature of 1.46°K. The continuous curves indicate only the experimental relationships. The dashed curves represent the theoretical cross sections corrected according to Eq. (2).

of this correction to attempt a direct calculation.

The experimental existence of a well-defined capture cross section for ions in rotating helium II is striking support for the existence of a grainy structure such as is postulated on the quantized vortex-line model. We are now refining our experimental techniques in an effort to obtain more complete data, and we are looking for positive-ion absorption in the region below 1°K in accordance with the predictions of reference 3. We plan also to investigate the effects of pressure on cross sections.

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ROTATIONAL INSTABILITY IN A PENNING-TYPE DISCHARGE*

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The study of "anomalous diffusion" or enhanced loss of plasma across a magnetic field has been the object of many theories and experiments in a wide variety of discharges for many years (excellent reviews are given by Hoh,[1] Lehnert,[2] and Boeschoten[3]). In spite of the variety of plasma sources used, there are many telltale signs suggesting that this loss is of the same nature generally. In particular, the ratio of the ion current collected by a probe at the wall to that at the center decreases with increasing magnetic field in a characteristic manner until the critical field is reached, after which it increases. At this critical field there is an increase in low- and high-frequency noise. Also, the power needed by the plasma to maintain a constant density decreases until the critical field is reached and increases thereafter.

In searching for a unifying feature one is led to consider the effect of the radial electric field which is always present. Theories by Hoh,[4] Guest and Simon,[5] and Bingham[6] show that the $E\times B$ rotation can be unstable to fluting in the $m=1$ mode even in the absence of a directed discharge current for rather modest values of electric field (a few V/cm) when the field is inward. The theory of Kadomtsev and Nedospasov[7] adequately explains these phenomena in terms of an unstable $E\times B$ helical rotation in discharges with directed currents (positive column, arcs, etc.) as shown by the experiments of Paulikas and Pyle.[8] (A similar rotation was found in an arc discharge by Morse.[9]) In Penning-type discharges, however, one cannot appeal to this theory since there is no directed current. Using his theory Hoh was able to find agreement between his calculated critical fields and those observed by Chen and Cooper[10] and by Briffod and co-workers[11-13] at Saclay. In the cold-cathode experiments by the group at Saclay no rotation was found and, on the strength of the noise they observed,[13] they attributed the loss to some high-frequency microinstability. Using a hot-cathode, Penning-type discharge, Chen and Cooper apparently found a low-frequency oscillation, which they attributed to an asymmetric rotation due to the radial electric field, superimposed on incoherent hash. However, they examined the incoherent hash for longitudinal correlations since they felt the coherent rotation could not cause enhanced diffusion.

It is the purpose of this Letter to present the results of an investigation in a low-pressure, hot-cathode, Penning-type discharge which show a strong relation between this rotation and the effects normally considered to indicate anomalous diffusion.

The hydrogen discharge is 66 cm long and ~4.1 cm in diameter. There is one hot cathode, a hollow cylinder about an inch in diameter causing a slightly hollow discharge, and one cold cathode, a solid aluminum cylinder. The cylindrical anodes just in front of the cathodes are only a few centimeters long and so do not extend the length of the tube. In the center of the discharge tube (made of glass) were placed four probes separated radially by 90°, 90°, and 60°, and extending a centimeter into the discharge. The floating potentials of these