alous penetration should no longer properly apply.

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QUANTIZED VORTEX RINGS IN ROTATING HELIUM II †

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Experiments are described on the propagation of quantized vortex rings in He II across an array of quantized vortex lines. Both scattering and capture of the charge carriers are observed.

The use of ions in He II as microscopic probes has recently proved to be of great value in studying the vortex-line structure of the rotating superfluid,[1] and indeed, has shed light on the nature of the ions themselves.[2] This is primarily because of the large (~10^{-5} cm) effective width of a vortex line for trapping negative ions. We have discovered that a large interaction also exists between quantized vortex rings[3] and quantized vortex lines. This result is of intrinsic interest, since the details of the interaction are expected to provide insight into the effect of vortex lines on each other. The size of the effect also indicates that quantized vortex rings are very sensitive "vortex-line detectors," making them suitable probes for a number of problems in quantum hydrodynamics. Their free-flight characteristics and the great flexibility in their size should enhance their usefulness in this direction. The following paragraphs describe our measurements and their interpretation in brief.

The experiments were performed in a rotating He^3 refrigerator which will be described in a later paper. A top view of the experimental cell is shown in Fig. 1, where the axis of rotation is perpendicular to the page. Ions are produced by a 10-μCi Po^{210} source S (3 mm wide) which is surrounded by a guard to ensure a uniform electric field. A voltage V_1, applied to the 6-mm space between S and the grid $G1$, accelerates these ions to create quantized vortex rings of energy eV_1. A grid $G1$ passes a beam of width 3 mm, and the deflection plates D allow us to sweep this beam across the screen and slit $G2$ (which is 2 mm wide) in front of the collector C. The deflection plates were calibrated experimentally by measuring the voltage necessary to sweep the beam between two collectors. A back voltage can be applied between $G2$ and C to analyze the apparent energy distribution of the rings arriving there. The 2.1-cm drift space between $G1$ and $G2$ is completely surrounded by a metal shield connecting $G1$ and $G2$, so that it is free of stray electrical fields. Thus, only vortex rings can pass into this region of the apparatus.

The characteristics of the beam are obtained by scanning it across the narrow opening in front of the collector. Although general features are repeatable, the details vary from run to run. We ascribe this to varying accumulations of surface charge on the electrodes. The profile of the beam measured at the collector turned out to be surprisingly wide (>1 cm), although its outer edges were sharply defined. It seems that the shape of the beam is determined mainly by the collimating properties of the source

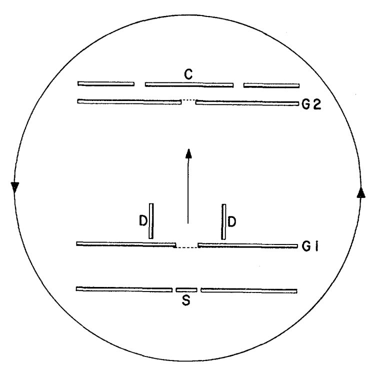

FIG. 1. Experimental cell. The region between $G1$ and $G2$ is shielded on four sides.

and first grid, although some space-charge spreading may also be present. The apparent energy of the rings in the beam as determined by measuring the current as a function of back voltage is distributed about a value E_0 which is typically about 60% of eV_1. The cause of this apparent deficit in energy is not known, although similar effects have been noted by other investigators.[3] It may be connected with the angle at which rings enter the analyzing region.

When the system is set into steady rotation, the shape of the beam is essentially unchanged, but its intensity is strongly decreased. According to a simple vortex-line model, the current should vary as

$$I = I_0 \exp\{-2\Omega l\sigma/\kappa\}, \tag{1}$$

where Ω is the speed of rotation in rad/sec, l is the length of the drift region, κ is the circulation of a quantized vortex line, and σ is the effective width for removal of a ring from the beam by interaction with a line. We do indeed find that, for a given ring energy, the current varies with rotation rate as predicted by this formula. Thus we can measure $\sigma(eV_1)$. The values obtained for positively charged rings are shown in Fig. 2 as a function of the ring radius R_0 corresponding to eV_1. The results show that σ is of the order of the ring diameter, which indicates that the cores of the line

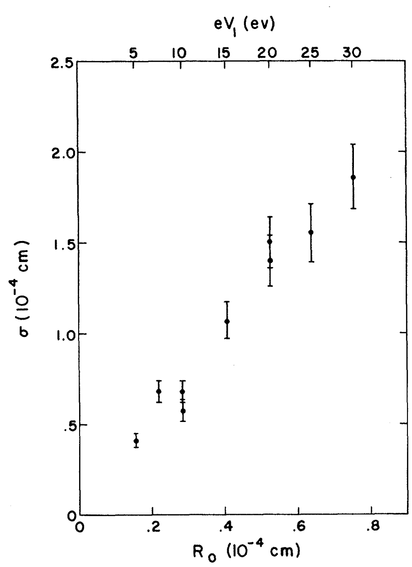

FIG. 2. Capture cross section for vortex rings incident on vortex lines as a function of the radius and energy of the rings.

and the ring have to be very nearly in contact for a strong interaction to take place. These values of σ are so large that for 20-eV rings a rotation rate of 1 rad/sec is enough to remove most of the rings in the beam. A few measurements of cross section for negatively charged rings showed the effect to be independent of charge, within the accuracy of our measurement. At temperatures below 0.5°K, the ring-line interaction was found to be completely insensitive to temperature variations, in marked contrast to the ion-line interaction observed at higher temperatures.

On examining the vortex-ring beam in rotation, we find that the apparent energy distribution of the remaining rings and the shape of the beam are not materially affected by the rotation. This suggests that these rings have not interacted strongly with the vortex-line structure. We observe, however, a deflection of the beam as a whole which is opposite to the direction of rotation, i.e., the deflection is to the right of the long arrow in Fig. 1. Since the same deflection seems to occur for all of the rings which pass through the fluid, we interpret it as a uniform curving of the path of each ring. We find experimentally that

$$\frac{d\Theta}{dl} = \alpha\frac{\Omega}{v_0}, \tag{2}$$

where $d\Theta/dl$ is the angular change in direction per unit path length, $\alpha = 4.0 \pm 0.4$, Ω is the rate of rotation, and v_0 is the ring velocity associated with eV_1. If the rings were moving in a straight line in the laboratory frame of reference, an effect like this would occur because of the movement of the collector. However, a simple calculation shows that this would only give $\alpha = 1$. Hence, even when viewed from a stationary system of reference, the rings are deflected as in Eq. (2), but with $\alpha = 3.0 \pm 0.4$.

The results above suggest that vortex rings which are removed from the beam by rotation are not scattered in the horizontal plane. Adding another collector at the top of our cell and a repeller at the bottom (but within the shielded region), we found that the missing charge moves vertically, in the direction of the vortex lines. A coarse grid (25 lines per inch) placed 6 mm below the upward collector made it impossible to observe this vertical current. A ring current is not affected in this way by a screen. Rather, the behavior is characteristic of charges trapped on lines, the lines preferring to terminate on the grid wires rather than pass close by them. Hence, it seems that those rings which disappear from the beam are destroyed by interacting strongly with a line, and the charge given up by the ring has good probability of being trapped by the line. It is worth noting that this is the first observation of significant trapping of positive charges by quantized vortex lines, an effect predicted to occur at low temperatures by Donnelly.[2]

The results described show that vortex-ring motion in rotating He II is a fascinating phenomenon: Indeed less has been done in the corresponding classical problem.[4] Taking a semiclassical approach to the theory, one finds that a quantitative treatment of the effect of a vortex-line velocity field on the motion of a ring is difficult. Qualitatively, one can see that a counterclockwise vortex line will deflect any approaching ring to the right, the effect being greater as the ring passes closer to the line. It appears that the large well-defined deflection of the beam which has been observed represents an average over a number of small deflections as the ring traverses the vortex-line array. If a ring passes through a region where the change in fluid velocity across the ring is on the order of the ring velocity itself, it will be violently deformed and possibly destroyed. Since the velocity field of a line is $1.58\times10^{-4}/r$ cm/sec and typical values of v_0 for the rings are 10-100 cm/sec, our measured effective widths for removal of the rings from the beam are eminently reasonable from this point of view. A more detailed theoretical interpretation of the experimental results is being formulated.

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MAGNETOABSORPTION IN SINGLE-CRYSTAL SEMICONDUCTING FERROMAGNETIC SPINELS

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Chalcogenide spinels of the type ACr_2X_4, where A = Cd or Hg and X = S or Se, have been found to be both electrically semiconducting and ferromagnetic.[1-3] We report herein absorption-edge measurements and optical effects associated with both the spontaneous magnetization and an externally applied magnetic field in single crystal $CdCr_2Se_4$ and $CdCr_2S_4$. Somewhat similar effects have been observed before only in diffuse reflectance spectra of powered ferro- and antiferromagnetic europium chalcogenides[4] or by transmission measurements on single-crystal EuSe.[5]

Crystals of $CdCr_2S_4$ were grown by closed-tube vapor transport[6,7] with Cl_2 as the carrier gas. Transport occurred across a gradient of about 50°C with the cooler growth end at temperatures of about 775°C. Numerous small (0.2-0.6 mm across) well-formed octahedra and plates normal to the (111) plane were obtained after 60-80 h. $CdCr_2Se_4$ crystals were grown by slow cooling (2-5°C/h) of a solution of $CdCr_2Se_4$ in anhydrous molten $CdCl_2$. The crystals were in the shape of rounded octahedra with an average diameter of about 1 mm. Powder x-ray diffractograms of selected crushed crystals showed that the material was single-phase cubic spinel with $a = 10.244$ Å for the sulfide and $a = 10.745$ Å for the selenide.[1] By chemical analysis of some of the $CdCr_2Se_4$ crystals