results, although the accuracy of these measurements was not high.

However, the details of the fluid dynamics in this experiment remain far from clear. Circulations as large as three quantum units have been seen in runs with a 75μ-diameter wire even when no steady rotation took place. The observations of circulation values intermediate to the quantum levels and of spontaneous changes in circulation also require explanation, and they suggest that an important role is played by free vorticity in the superfluid.[3,7]

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EXPERIMENTS ON THE CREATION OF CHARGED QUANTIZED VORTEX RINGS IN LIQUID HELIUM AT 1°K*

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Charged vortex rings of one quantum of circulation have been detected already by us at 1°K, and briefly reported,[1] following the investigations by Rayfield and Reif[2] at lower temperatures. In this Letter we investigate experimentally the origin of these charged rings at 1°K, and discuss these processes in the frame of the theory recently proposed by Huang and Olinto.[3]

The experiment consists of the determination of the drift velocity $\langle V_D \rangle$ of ions[4] in liquid helium at different field strength E, the temperature T and the pressure P being kept constant. The apparatus and the experimental technique used to measure the drift velocity are the same as the ones described in our previous work.[5,6] The electronics has been improved to extend the electric-field range and, therefore, to increase the temperature at which the phenomenon could be detected. An analysis of the experimental error involved in these measurements already has been done[6,7] and will not be repeated here. The experimental error is not shown in Fig. 1 for the sake of clarity, and it usually is ±3% for data taken in the same run.

In Fig. 1 we show the results of some runs as a plot of the drift velocity $\langle V_D \rangle$ versus the reduced field intensity $E(\rho/\rho_\gamma)$, where ρ is the total density and ρ_γ is the roton contribution to the normal fluid density. ρ_γ has been calculated as a function of the absolute temperature T and pressure P by the familiar Landau expression, using the neutron-scattering results.[8] Since we are interested in a rather small temperature range around 1°K, approximately $\rho_\gamma \simeq \text{constant} \times N_\rho$ where N_ρ is the roton density, this reduced field, $E(\rho/\rho_\gamma)$, has a simple intuitive meaning and is a useful quantity to correlate the data taken at different pressures and temperatures.

A glance at Fig. 1 shows that both positive and negative ions display two quite different hydrodynamical regimes, with a sharp transition in between. The first regime begins at low fields with a field-independent mobility, which is known[9] to be essentially proportional to N_ρ^{-1}, and therefore to ρ_γ^{-1} in our temperature range. Next, for higher fields, closer inspection[6,7] reveals the presence of small periodic discontinuities, the first one occurring at $\langle V_C \rangle = 5.2$ m/sec for positive ions. For still larger fields there is a more pronounced bending of the data partly due to the increase in the depth of the discontinuities. While all the runs taken in different days were

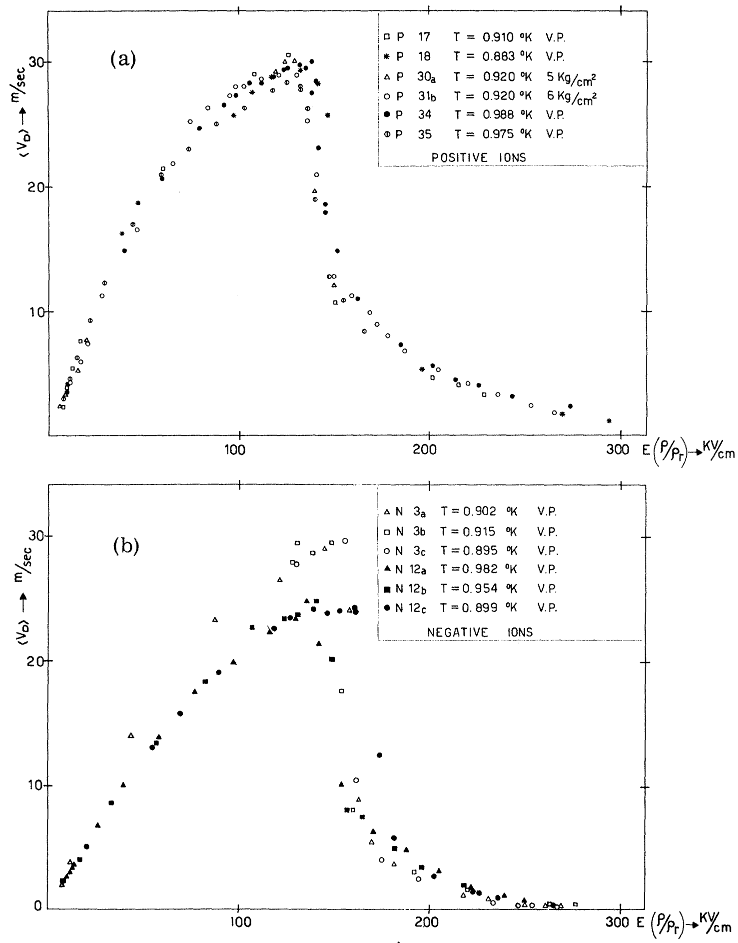

FIG. 1. The drift velocity $\langle V_D \rangle$ plotted versus the reduced electric field $E\,(\rho/\rho_\gamma)$ in different runs at the temperature and pressure indicated. (a) Positive ions, all runs taken in different days. (b) Negative ions, two sets of runs taken in two different days.

reproducible for positive ions, this was not true for the negative ions, as already observed in the previous[7] study of the discontinuities.

The first regime terminates abruptly with a transition, where a giant fall downward occurs. The transition-point coordinates, $\langle V_g \rangle$ and E_g, are given in Fig. 2 for all our runs of positive ions; from these data one sees $\langle V_g \rangle$ to be independent of T and P with a value ranging around 29.5 ± 0.5 m/sec, while E_g varies linearly with ρ_γ/ρ. The velocity of the negative ions displays a considerable spread, and, on the average, their $\langle V_g \rangle$ and E_g seem to be, respectively, lower and higher than the corresponding quantities of the positive ones. Runs N12a, N12b, and N12c are particularly interesting; they have been taken in the same day and gave quite consistent results, with the exception of the transition of the run N12c which is "out of place," as if a kind of hysterisis has occurred.

For fields larger than E_g there is a second regime, where $\langle V_D \rangle$ decreases with increasing E, a behavior typical of a charged vortex ring when the electric force balances the dissipative forces. Since the ion–vortex-ring complex drifts in the roton gas, the dissipation is proportional to ρ_γ,[10] and, therefore, the quantity $E(\rho/\rho_\gamma)$ is still a useful reduced variable. We have already shown[1] for negative ions that this dissipation compares favorably with the Hall and Vinen constant D. Here we show in Fig. 3 that quantitative agreement is obtained with the function $\alpha(T)$, introduced in the recent paper by Rayfield and Reif,[11] if one writes this balance of forces as

$$eE = \alpha(T)(\eta - \tfrac{1}{4}), \qquad (1)$$

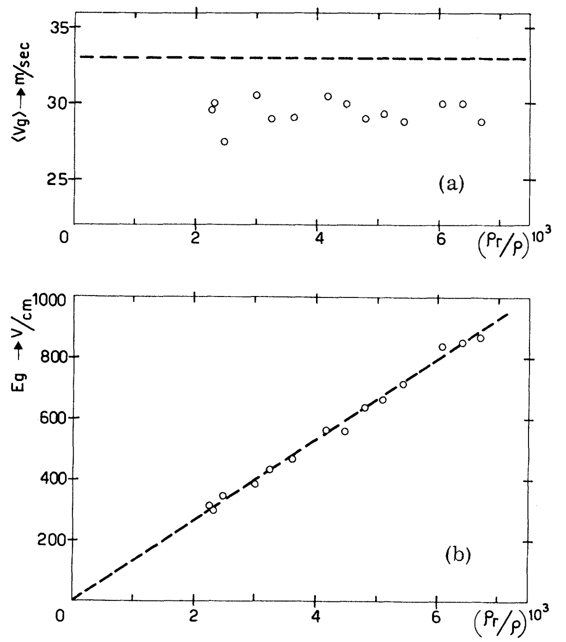

FIG. 2. Positive ions. (a) The drift velocity $\langle V_g \rangle$ and (b) the electric field E_g at which the giant discontinuity occurs, plotted versus the ratio ρ_r/ρ of the roton ρ_r part of normal fluid density to the total density ρ. Dashed lines are according to the theory of Huang and Olinto.[3]

where $\eta = \ln(8r/a_0)$, r and a_0 being the radius and the core radius of the vortex ring, respectively. Since the drift velocity of the vortex ring is

$$\langle V \rangle = (h/m)(4\pi r)^{\;1}(\eta - \tfrac{1}{4}), \qquad (2)$$

where h is Plank's constant and m is the helium mass, elimination of r between (1) and (2) gives

$$\ln\langle V \rangle / E = \ln[2he/\pi a_0 m \alpha(T)] + \tfrac{1}{4} - eE/\alpha(T). \qquad (3)$$

As shown in Fig. 3(a), Eq. (3) is satisfied only for fields somewhat larger than E_g.[12] In our experiments the radii of the vortex rings vary between 50 and about 1.000 Å. From this check the quantity $\alpha(T)$ has been derived, and is compared with the data obtained by Rayfield and Reif[11] at lower temperatures [Fig. 3(b)]. Quantitative agreement is obtained with the Rayfield and Reif data, particularly for the negative ions. The experimental point at $P = 8$ kG/cm^2 was taken at the temperature $T = 0.920$°K; however, in Fig. 3(b) it has been placed at $T = 0.960$°K, because at this temperature ρ_r at vapor pressure has the same value.

We summarize our experimental data stressing that in the range of the reduced electric field studied we have observed and identified two hydrodynamical regimes: (a) at limiting low fields the motion of a bare ion in a rarified roton gas, and (b) at high fields the motion of a charged vortex ring in the same excitation gas. Therefore, there is no doubt that we should observe between these two regimes the formation of the charged vortex ring. These transition processes will be analyzed below, following the recent theory proposed by Huang and Olinto,[3] to explain in a phenomenological way both the periodic discontinuities and the giant fall observed in our experiments. Only the giant fall will be analyzed in the following discussion.

According to Huang and Olinto, vortex rings of one quantum of circulation are created by the ion at the critical velocity $\langle V_c \rangle = 5.2$ m/sec, but they are captured to form a stable charged vortex ring only if the electric field is such that $E \geq E_g$.[13] By using some parameters determined from previous experiments, this theory predicts for positive ions a temperature-independent critical velocity $\langle V_g \rangle = 33$ m/sec, and $E_g = 304 \exp[-\Delta/Tk + \Delta/0.889k]$ V/cm. Figure 3 shows that these predictions are well verified by our experimental data. (No predictions are made for negative ions by this theory.) For fields larger than E_g the theory predicts a behavior similar to the one observed in Fig. 3, the steep transition region which occurs for fields close to E_g probably being due to the presence of the dissipation force between the ion and the roton gas, a term not included in the balance of forces expressed by Eq. (1). Obviously this missing term is of importance only for the smaller rings, which are the ones that correspond to the highest velocities around $\langle V_g \rangle$. Finally, one must note that an even better quantitative agreement can be obtained in the frame of this theory, by better choice of the parameters to fit the experimental data presented here.

In our opinion the success of the Huang and Olinto theory to describe the giant discontinuity is due to its correct treatment of the stability conditions for the charged vortex ring, but we note that the nature of the creation process of the quantized rings could also be different than that postulated by this theory. For

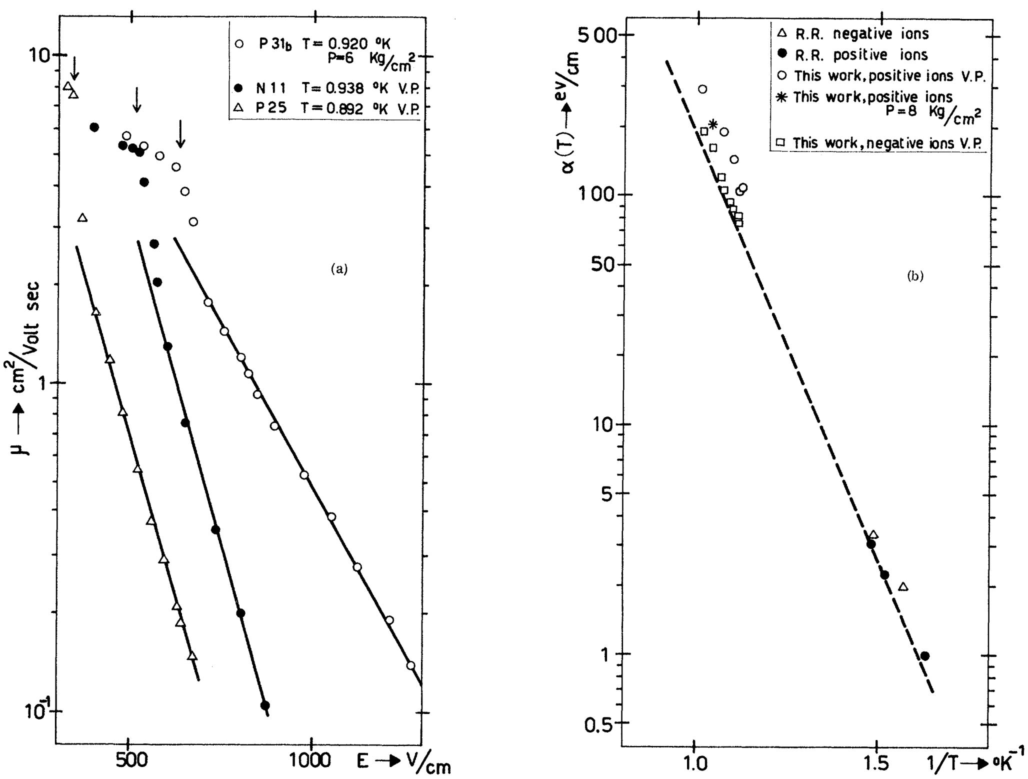

FIG. 3. (a) Plot of mobility μ versus the electric field E for three representative runs. The arrows indicate the field E_g at the transition for each run. From the slope of the solid lines, values of $\alpha(T)$ are determined according to Eq. (3). (b) The values of the function $\alpha(T)$ determined as above, plotted versus the reciprocal temperature. The data by Rayfield and Reif[11] are also included. The dashed line is the function assumed in the Huang-Olinto theory.

instance, one can also suppose some vorticity to exist already in the helium bath, and it is captured around the ion to form the charged vortex ring when suitable equilibrium conditions exist. Therefore, we conclude by saying that while the capture of the vortex ring by the ion to form the charged vortex ring is a process observed in the experiments reported here and well described by the theory of Huang and Olinto, the origin of the quantized vortex rings is still a matter of speculation.

Thanks are due to Professor K. Huang, Massachusetts Institute of Technology, for having sent us his paper[3] before publication.

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MOTION OF PLASMA AND LIFETIMES OF ENERGETIC IONS IN A TOROIDAL OCTUPOLE MAGNETIC FIELD*

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Simultaneous observations of the flow of plasma at numerous points in an octupole magnetic field have revealed processes responsible for the injection and trapping of a collimated plasma stream in the system of closed magnetic-field lines, the guiding of the plasma clouds around the toroid in both directions by the steering effect of the generated octupole electric field, phenomena occurring at the collision of the plasma clouds passing in opposite directions around the toroid, and the subsequent containment with no catastrophic depletion of electrons or ions to suggest instability of the plasma.

These observations were made in plasmas of density $n = 10^{12}$/cc near the injection port and in densities of ~10^9/cc after the plasma had filled the remote parts of the confinement region.

The electron temperature was 10 eV throughout the duration of the magnetic field (2.5×10^{-3} sec), and the ion or proton-energy distribution extended from 50 to ~300 eV.

The plasma, generated in a conical Z pinch gun, drifted 150 cm through a differential pumping region, and then passed through slots in the conducting wall of the chamber containing the octupole field. The field was formed by induced current in four copper hoops in the toroidal aluminum vacuum box[1] (Fig. 1). The magnetic field was zero on a circular line around the box approximately equidistant from each hoop. While the orbital magnetic moment of the particles is not invariant in this low field, there is absolute containment due to the invariance of the canonical angular momentum. However, the surrounding absolute containment zones in which the field is large have particles with invariant magnetic moments in addition to invariant angular momentum. Strong magnetohydrodynamic stability is provided by this magnetic field.[2]

For useful tests of multipole confinement mechanisms, the vacuum need not be better than ~10^{-6} Torr to avoid charge exchange loss, since ~100-eV ion energy was chosen. Tests with varying background pressure showed that ion lifetime was not affected noticeably until the pressure reached ~10^{-5} Torr (Fig. 2). In normal operation this pressure is reached 2×10^{-3} sec after plasma is injected. The ion component of the plasma was collisionless during the experiment. The mean lifetime of ions calculated from their thermal speed and from the geometry of the small hoop-supporting hangers which the plasma touches is 0.5×10^{-3} sec for 100-eV ions. The observed mean life is 0.4×10^{-3} sec–an order of magnitude longer than the duration of the large electrostatic potentials present during filling. In addition, the

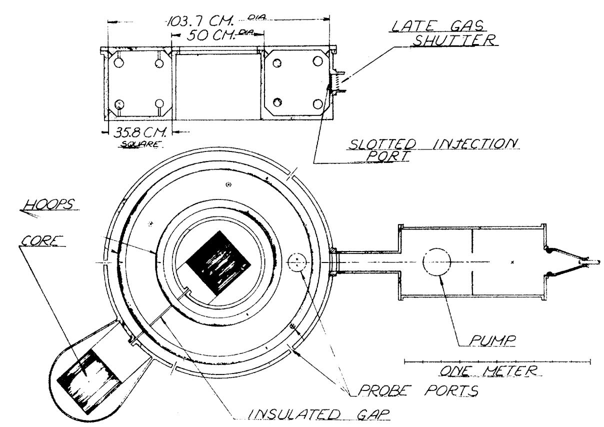

FIG. 1. Toroidal octupole apparatus. The plasma gun is at the right. The magnetic field is high near the wall and rods and zero near the center of the toroidal volume.