1.9°K with pumping powers as low as 1 mW. Thus we are sure that 50-mW microwave power is sufficient for complete saturation of the "forbidden" transitions at this temperature.

POSITIVE IONS IN LIQUID HELIUM II. THE CRITICAL VELOCITY FOR CREATION OF VORTEX RINGS

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(Received 14 August 1968)

In this paper we report the results of experiments from which we have obtained the value of the critical velocity for quantized-vortex-ring creation by positive ions in liquid helium II. We have investigated the temperature range between 1.0 and 1.5°K. The critical velocity depends on temperature above 1.1°K.

Many experiments on quantized charged vortex rings have been made since the first evidence of their existence was obtained at low temperature,[1] and around 1°K.[2]

The velocity v_g and electric field E_g, at which the transition between ion and ion–vortex-ring regimes occurs, has been reported by Careri et al.[2] for the high-temperature range. Rayfield[3] has recently reported an analogous change of hydrodynamical regime in the low-temperature range. He concluded that at the transition one reaches the critical velocity for the creation of the vortex ring.

We have made experiments at temperatures and electric fields high enough to see directly the creation process, without the trapping of the ion by the vortex ring. In this way the analysis of the complex problem of the conditions for the trapping and initial stability of the ion–vortex-ring complex[4] is avoided. We have measured the drift velocity of positive ions in electric field up to 25 kV/cm and temperatures between 1.0 and 1.5°K. The idea of experiment is the following. The lifetime for positive ions in vortex rings[5] and negative ions in vortex lines[6] has been measured. It depends on both temperature and electric field. The negative ion is strongly bound to the vortex ring also at temperatures up to 1.8°K, while for the positive ion the escape probability is large already at temperatures about 1°K.[7] Therefore, if one works at temperatures and electric fields high enough, and if the creation probability is not strongly affected by temperature and electric field, one should reach a situation in which the ion creates vortex rings without being trapped. If this situation is reached, the drift velocity should be field independent for a relevant range of electric field.

We used three methods for the measurement of the drift velocity. The method (A) is that of Cunsolo.[8] In the method (B) we used three electrodes, i.e., a radioactive source S, a grid G, and a collector C. We applied between S and G an alternating, square-wave voltage V_1 and a dc positive voltage between G and the ground. The collector is grounded with a resistor R of value in the range between 200 kΩ and 1 MΩ. The drift space GC is periodically filled with charges by the alternating injecting voltage V_1. The voltage developed across R by the periodic current is amplified with low-noise electronics and detected with sampling techniques. The flight time is obtained from the filling or the emptying times. In the method (C) we used a source S, two grids G and G', and a collector C. We applied an alternating square-wave voltage V_1 of frequency ν between S and G, a dc positive voltage between G and G', and a gating square-wave voltage V_2 between G' and C, with the same frequency ν as V_1, but delayed with respect to V_1. From the measurement of the mean current at C as a function of the delay time, the flight time between G and G' is obtained. The details of the methods (B) and (C), which are suitable for high electric fields, will be published later. The three methods, when employed for positive ions, gave results with mutual agreement.

The experimental results for positive ions can be summarized as follows: (1) The velocity V_g of the giant discontinuity is temperature dependent for temperatures above 1°K. (2) Upon an increase in the electric field beyond E_g, the drift velocity decreases, goes through a minimum, and then increases. (3) The giant discontinuity becomes less and less deep and pronounced as one increases the temperature, until it disappears completely for temperatures around 1.4°K. In the place of the giant discontinuity one finds a large plateau where $\langle V_D \rangle$ is field independent.

In Fig. 1 we have plotted the results obtained at 1.41 and 1.50°K. At these temperatures the drift velocity $\langle V_D \rangle$ is constant, within experimental errors, for an electric field range of about 10 kV/cm. This behavior is typical of the creation processes. The gradual change of the giant discontinuity into a plateau when the temperature is raised suggests that at the plateau the ion continuously creates vortex rings without being trapped. The increase of the electric field increases the rate of creation of vortex rings. We identify the plateau value of the drift velocity as the creation velocity V_γ at the temperature investigated. At lower temperatures, at which the escape probability is not so high, we observe a situation as the one shown in Fig. 2, where we show results obtained at 1.18 and 1.30°K. The behavior for $E > E_g$ can be explained qualitatively assuming that the ion is trapped by a ring for a mean time τ, escapes from it, creates another ring, and so on. The lifetime τ decreases when one increases the electric field, and so the mean velocity increases with electric field. At 1.3°K we were able to make measurements up to 25 kV/cm. At the highest fields the drift velocity tends to be field independent to a value which is the same, within the errors, as the V_g of the giant discontinuity. The creation process at this temperature is not so evident as at higher temperatures. For this reason we performed the following experiment at $T = 0.9$°K. The drift space was filled with charges in an electric field $E > E_g$, and the emptying time was measured in a field $E < E_g$. We observed that the ion-ring complex created in the filling stage is stable also at $E < E_g$.[9] This result, together with that obtained at 1.3°K, suggests that at the giant discontinuity, for positive ions, and in the investigated temperature range, one reaches the creation velocity and not the stability condition. We think that this result is not in conflict with the idea of Huang and Olinto[4] about the existence of a stability field. It merely means, in our opinion, that when one increases the electric field one reaches the stability field before the vortex ring has been created. Concerning the small periodic discontinuities of the mobility,[10] this result implies that they are not due the creation of vortex rings. This fact is in agreement with the results of our work on this subject.[11] On the other hand, we think that the periodic discontinuities should be due to some hydrodynamical process, involving the superfluid velocity field. Indeed the creation velocity V_γ for the vortex ring and the critical velocity V_c of the periodical discontinuities depend on the temperature in analogous way. Both V_γ and V_c start to decrease at the same temperature and are linear functions with the same slope of the normal-to-total density ratio ρ_n/ρ, as one can see in Fig. 3.

For the negative ions we cannot observe directly the creation process as we can for the positive one. The negative ion was found to be strongly bound to the vortex also at high temperatures

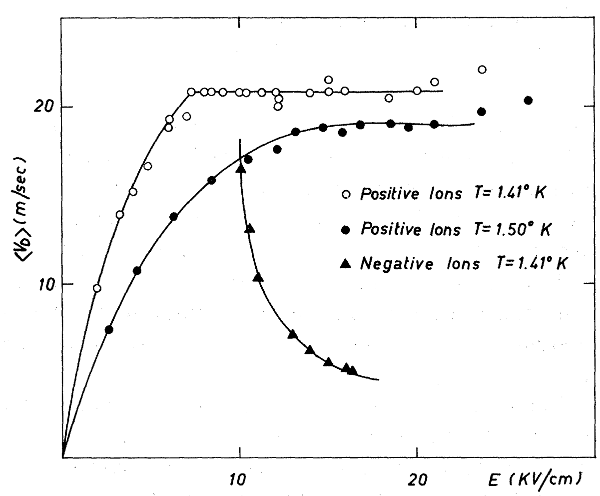

FIG. 1. Drift velocity $\langle V_D \rangle$ of ions as a function of electric field at high temperatures. As we can see, the positive and negative ions behave in a different manner.

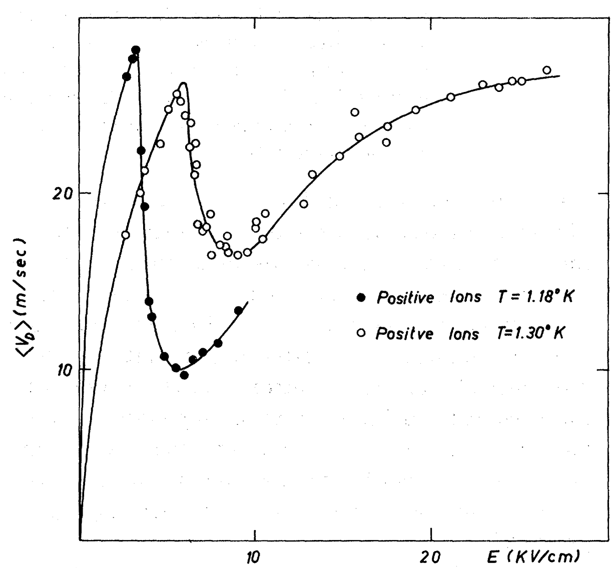

FIG. 2. Drift velocity $\langle V_D \rangle$ of positive ions as a function of the electric field. At the two temperatures indicated the ion-vortex complex begins to be unstable.

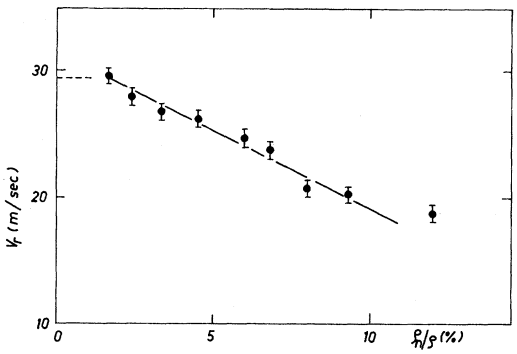

FIG. 3. The critical velocity V_r for production of vortex rings by positive ions as a function of the normal-to-total density ratio ρ_n/ρ. The dotted line summarizes the results at low temperatures (Ref. 2), where V_r is constant. The solid line is drawn with the same slope of that representing the critical velocity of the periodic discontinuities of positive ions as a function of ρ_n/ρ (Ref. 10).

and fields. A typical result, obtained at 1.41°K with the method (B), is plotted in Fig. 1. The drift velocity is a decreasing function of the electric field, and follows the dynamics of the charged vortex ring.

[1]G. W. Rayfield and F. Reif, Phys. Rev. 136, A1194 (1964).

[2]G. Careri, S. Cunsolo, P. Mazzoldi, and M. Santini, in the Proceedings of the Ninth International Conference on Low Temperature Physics, Columbus, Ohio, 1964, edited by J. Daunt (Plenum Press, New York, 1965), p. 335, and Phys. Rev. Letters 15, 392 (1965).

[3]G. W. Rayfield, Phys. Rev. Letters 19, 1371 (1967), and Phys. Rev. 168, 203 (1968).

[4]See, for example, K. Huang and A. C. Olinto, Phys. Rev. 139, A1441 (1965).

[5]A. G. Cade, Phys. Rev. Letters 15, 238 (1965).

[6]R. L. Douglass, Phys. Rev. Letters 13, 791 (1964).

[7]R. J. Donnelly, Experimental Superfluidity (University of Chicago Press, Chicago, Ill., 1967).

[8]S. Cunsolo, Nuovo Cimento 21, 76 (1961).

[9]This experiment is analogous to that performed by Rayfield (Ref. 3) at $T < 0.7$°K. In our temperature range, owing to the high value of the viscous force, the vortex rings cannot be injected in the drift space through a grid, but must be created in the drift space itself.

[10]G. Careri, S. Cunsolo, and P. Mazzoldi, Phys. Rev. 136, A303 (1964).

[11]L. Bruschi, P. Mazzoldi, and M. Santini, Phys. Rev. 167, 1 (1968).

MODEL FOR THE CORE OF A QUANTIZED VORTEX LINE IN HELIUM II*

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We propose that a quantized vortex line in helium II has a central core of normal fluid extending over a distance of a few angstroms. Surrounding this core is a "tail," a region of excess density of rotons whose momenta are predominantly aligned oppositely to the direction of circulation of the superfluid. This model is used to calculate the drag on a negative ion trapped on a vortex line, and appears to account for experimental results satisfactorily.

Perhaps the least satisfactory aspect of the classical theory of vortices is the treatment of the core. Now that vortices in liquid helium have provided fresh impetus for such studies, it is not surprising that there should be considerable interest in sorting out effects associated with the core structure. This Letter reports a model for the structure of the core with emphasis on the behavior of the excitations comprising the normal component. Models for the superfluid based on the behavior of a condensate have already appeared.[1]

Studies of ion motion in liquid helium have included three classes of experiment which shed light on vortex structure. The motion of large vortex rings demonstrates the quantization of circulation and gives a measure of vortex strength.[2] The trapping and escape of ions from vortices are sensitive to the distribution of superfluid near the core.[3] The motion of ions along quantized vortex lines is sensitive to excitations localized about the core.[4] We shall be concerned with the interpretation of such experiments by recourse to the Landau model applied to the vortex lines.

The dominant excitations at the relatively high temperatures of our experiments are rotons. Their excitation spectrum is approximated near the roton minimum by the familiar relation

$$\epsilon(p) = \Delta + (p - p_0)^2/2\mu_0, \tag{1}$$

where ϵ is the energy, p the momentum, Δ the