ROTON EMISSION FROM NEGATIVE IONS IN HELIUM II

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This paper presents evidence that in He II under a pressure greater than about 12 atm and at low temperatures, the maximum velocity of negative ions is limited by roton emission. Below this pressure the maximum velocity is determined by the point at which vortex-ring creation occurs.

The mobility of both positive and negative ions in He II under pressure has been studied by Meyer and Reif.[1] During the course of this work they found an apparent "runaway phenomenon" for ions in high electric fields in He II at low temperatures. Although this effect was found to exist for positive ions at all pressures and for negative ions at low pressures, runaway did not seem to exist for negative ions at high pressures where there appeared instead a limiting velocity for negative ions.[2] Reif and Meyer[3] have suggested that the limiting velocity of negative ions was due to roton creation. Rayfield and Reif found the "runaway phenomenon" was due to the formation of quantized vortex rings.[4] A maximum velocity for negative ions has also been observed by Careri and co-workers at higher temperatures and zero pressure.[5] They suggested that this is the point at which vortex-ring creation takes place.

Figure 1 shows how the nature of the negative ions change with pressure. The quantity I_{vr}/I_i represents the ratio of ions able to penetrate a field-free region (vortex rings) to those that are not. In order to obtain this ratio, the grid arrangement shown in Fig. 2(a) is used. The current or number of ions injected into the 1-cm test region from the radioactive source is kept constant. The ratio of I_{vr} to I_i is obtained by observing the change in collector current with and without a sweeping electric field in the test region. Associated apparatus for the experiment is similar to that used earlier by Rayfield and Reif.[4]

In earlier work[4] it was observed that ions able to penetrate field-free regions were associated with quantized vortex rings. From the data shown in Fig. 1 it appears that above about 12 atm the negative ions either do not produce vortex rings or are unable to remain attached to them.

In order to explore these possibilities further, the grid arrangement shown in Fig. 2(b) was used to measure the velocity of the ions. A square-wave voltage V' is applied to both G_2 and G_3. The dc potentials of grids 1, 2, 3, 4, and source S are adjusted so that when V' is positive the electric field in the apparatus is uniform, except for "gate 3, 4" which has a negative electric field large enough to stop any charge carriers including vortex rings. When V' is negative, "gate 1, 2" is closed and "gate 3, 4" is open. In operation, the collector current I is monitored as the frequency f of the square wave is varied. If $\langle v\rangle$ is the mean velocity of the charge carriers over the length

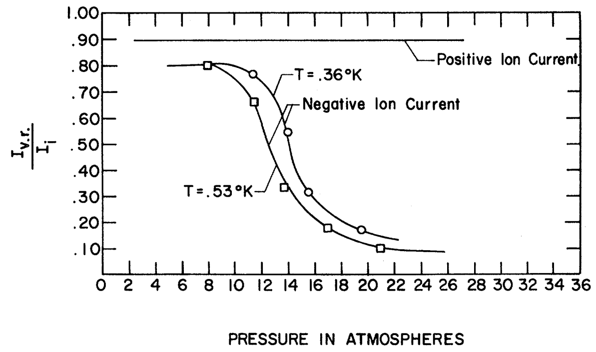

FIG. 1. Ratio of number of negative charges able to penetrate a field-free region to number that are not as a function of He II pressure.

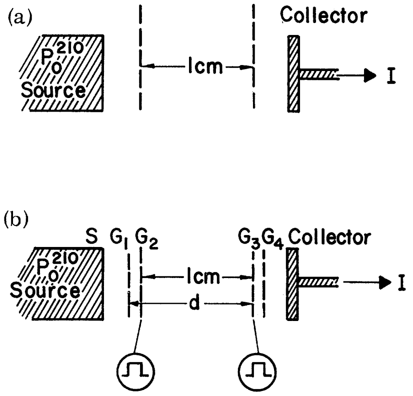

FIG. 2. Schematic arrangement of grids: (a) measurement of ionic current through field-free region, (b) velocity-measuring spectrometer.

d between 1 and 3, then when $f = n\langle v\rangle/2d$ where n is an odd integer, a peak in the collector current is observed.

For temperatures near 0.5°K, fields on the order of 1 V/cm, and pressures below 12 atm, resonance peaks are observed which correspond to a velocity of several meters per second. As the electric field is increased these resonance peaks move to higher frequencies corresponding to higher velocities. Finally, as the electric field is increased further, the velocity reaches a plateau value of about 30 m/sec, which varies depending on the pressure and to a limited extent on the temperature. Low-frequency resonance peaks also appear which indicate a low velocity that is typical of charge-carrying vortex rings.[4] In particular, the velocity corresponding to this low-frequency spectrum decreases as the electric field is increased. At lower temperatures (0.36°K) the plateau value is reached at lower electric fields because the mobility of the negative ion increases. In addition, the plateau value is higher[6] and the ion vortex-ring transition region is much more abrupt. At even larger electric fields only the low-frequency vortex-ring spectrum exists. The measured vortex-ring velocities are in good agreement with the data of Rayfield and Reif at low temperature. If the pressure is increased above 12 atm, the high-frequency spectrum reappears and the low-frequency vortex-ring spectrum disappears. The plateau values for ion velocities found in He II under pressures greater than 12 atm at low temperatures are essentially independent of temperature.

Figure 3 shows the relationship between the plateau velocity and pressure, taken at temperatures of 0.36 and 0.48°K. The plateau velocity for vortex-ring creation is more easily measured at 0.48°K than at 0.36°K. Using results obtained from slow-neutron scattering data, Henshaw and Woods[7] have obtained the value of roton parameters in He II at zero pressure and at 25.3 atm pressure. From this data one obtains a Landau critical velocity ($v_c = \Delta/p_0$) of 60 m/sec at zero pressure and 45 m/sec at 25.3 atm. The dotted line in Fig. 3 is drawn between these two points. Note that above 12 atm the plateau velocity of the negative ions falls on this line. It would thus appear that negative ions under these conditions behave like bodies that have reached the Landau critical velocity and are losing the energy gained from the electric field by emission of rotons. A scaling error of about 4% in the data of Fig. 3 is possible.

In general, the Landau critical velocity holds only for macroscopic bodies of large mass. For an ion of effective mass m^* to create a roton of energy Δ and momentum p_0, it is required that $m^*(v_1 - v_2) = p_0$ and $(m^*/2)(v_1^2 - v_2^2) = \Delta$ where v_1 is the ion velocity just before emission of the roton and v_2 is the ion velocity immediately after emission.[8] Solving these equations one obtains

$$v_1 = \frac{\Delta}{p_0} + \frac{p_0}{2m^*}, \quad v_2 = \frac{\Delta}{p_0} - \frac{p_0}{2m^*}.$$

In an experiment such as this, one measures the average velocity of the particle $\langle v\rangle$. Neglecting collisions with quasiparticles in going from v_2 to v_1, we have $\langle v\rangle = \frac{1}{2}(v_1 + v_2) = \Delta/p_0$. If the bubble model[9,10] is used for the negative ion, then the effective mass would be something like 100 He^4 masses. The corresponding value of $p_0/2m^*$ is about 1.5 m/sec. A careful study of the manner in which the plateau is reached might be useful in estimating the effective mass. The change of drift velocity with electric field would be very rapid near $\langle v\rangle = v_c$ for a massive particle.

At lower pressures the plateau velocity is an increasing function of pressure. A decreasing bubble size would lead to an increase in

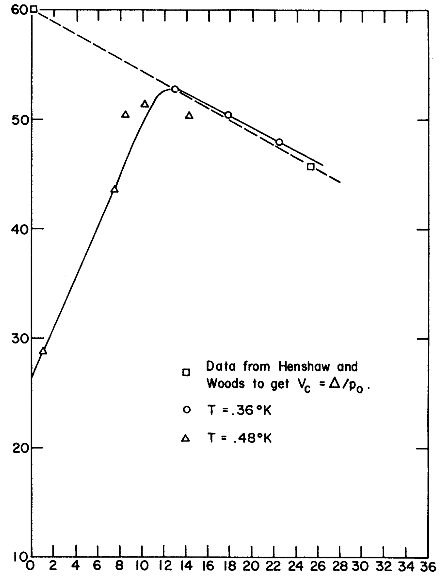

FIG. 3. Plateau velocities of negative ions in He II under pressure.

the critical velocity at which vorticity is produced. This is because quantization of circulation for the superfluid requires that $\oint \vec{v}_s \cdot d\vec{l} = h/m$. For a spherical object of radius R to give rise to quantized circulation, one would expect $Rv_c = \text{constant}$ where v_c is the velocity of the object at which creation of vorticity can occur. Hence $v_c \propto 1/R$ and one expects v_c to increase with pressure. A theory that explains the quantitative dependence of v_c on pressure is not yet available.

An interpretation of Fig. 3 may now be made. As the pressure of the He II is increased, the plateau velocity, determined by the velocity at which vortex-ring creation takes place, increases because the bubble size decreases. At about 12 atm, the plateau velocity for vortex-ring creation has reached a sufficiently high value for the negative ion to create rotons rather than vortex rings. The plateau velocity then decreases because the Landau critical velocity decreases. The data of Fig. 1 are explained by the same argument. Charge-carrying vortex rings are formed for pressure below about 12 atm and above this pressure the negative ions emit rotons.

The positive ions appear to create vortex rings at about 30 m/sec regardless of the pressure. Data on mobility[1] and on the binding energy of an ion to a vortex line[11] tend to indicate that the radius of the negative-ion bubble is larger than the radius of the positive-ion ball. Therefore it might seem that the negative-ion velocity for vortex-ring creation should be smaller than the corresponding velocity of the positive ion. However, the boundary conditions are quite different for a bubble and a solid ball and this could explain the difference in plateau velocities.

Using this experimental arrangement, a careful study of the conditions under which vortex rings are created can be made. It is hoped that these data will help explain the process of vortex-ring creation. So far the only charge carriers which have been observed are either singly quantized vortex rings or bare ions.

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[1] Lothar Meyer and F. Reif, Phys. Rev. 123, 727 (1961). Some data taken recently to check these results indicate that μ^- is equal to μ^+ only at pressures near 23 atm. Meyer and Reif find $\mu^- = \mu^+$ at all pressures above about 10 atm.

[2] 59 m/sec at 23.4 atm with $T = 0.550$°K and 52 m/sec at 15.3 atm with $T = 0.505$°K.

[3] F. Reif and Lothar Meyer, Phys. Rev. 119, 1164 (1960).

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

[5] G. Careri, S. Cunsolo, P. Mazzoldi, and M. Santini, in Proceedings of the Ninth International Conference on Low-Temperature Physics, Columbus, Ohio, 1964 (Plenum Press, New York, 1965).

[6] 37 m/sec at 1 atm with $T = 0.36$°K, compared with 29 m/sec at 1 atm with $T = 0.48$°K.

[7] D. G. Henshaw and A. D. B. Woods, in Proceedings of the Seventh International Conference on Low-Temperature Physics, Toronto, 1960, edited by G. M. Graham and A. C. Hollis Hallett (University of Toronto Press, Toronto, Canada, 1961), p. 64. Unfortunately, there is some temperature dependence of the roton parameters and no data are available below 1.1°K.

[8] It is assumed all rotons are created at the minimum in the quasiparticle spectrum of He^4.

[9] C. G. Kuper, in Proceedings of the International School of Physics, "Enrico Fermi," Course XXI, Varenna, July 3-15, 1961, Liquid Helium, edited by G. Careri (Academic Press, Inc., New York, 1963), p. 414.

[10] J. Jortner, N. R. Kestner, S. A. Rice, and H. Cohen, J. Chem. Phys. 43, 2614 (1965).

[11] Peter E. Parks and R. J. Donnelly, Phys. Rev. Letters 16, 45 (1966).