Discontinuities in the Drift Velocity of Ions in Liquid Helium

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The purpose of this short paper is to call attention to some experiments recently carried out by our group (*1*, *2*). First, we shall briefly recall their relevant experimental features, and then we shall propose a tentative explanation which should be substantiated by a proper theoretical treatment.

We have investigated the behavior of the drift velocity V_d of electric elementary charges (here called simply "ions") (*3*) in liquid helium at about 1°K as a function of the applied electric field E. Two experimental method were employed using two quite different techniques, and they gave quite consistent results. In the first method the time of flight of the ions between fixed electrodes was measured in different experimental conditions by AC electronics, while in the second one the drag suffered by an ionic beam in the normal fluid current was measured (heat-flush method).

In summary, the main results were as follows.

(a) The drift velocity of ions moving in liquid helium no longer increases linearly with the increasing field but suffers a sharp discontinuity. While the value of this critical field E_c depends on the temperature, the corresponding critical velocity V_c is a temperature-independent quantity.

(b) Increasing the applied field, other discontinuities of the drift velocity are found at values which are larger integers of the first one, indicating a periodical multiplicity of the phenomenon.

(c) The first discontinuity for positive ions is found at $V_c = 5.2 \pm 0.2$ meters/sec in a temperature range where the mobility $\mu = V_d/E$ changes by a factor of 3. The relative change of the mobility at the discontinuity $\Delta\mu/\mu$, ranges from 5 to 10%.

(d) The negative ions also show discontinuities at drift velocities which are multiples of 3.5 meters/sec. It is more difficult to observe sharp transitions for this kind of ions.

(e) Bath disturbances induced by vibrations and temperature fluctuations cause these discontinuities to disappear. What at one time was thought to be a kind of hysteresis which could sometimes prevent the transition at V_c, is now believed to be the effect of uncontrolled bath disturbances.

(f) The value of V_c is not affected by a change of a factor 20 in the ionic density of the beam and by big changes of its geometry, and within the experimental error is the same in both the experimental methods.

(g) A proper analysis of the heat-flush process indicates that the new interaction, which set in at V_c, is due to the normal fluid and not to the superfluid component.

So far the experimental results. We believe that from (f) one can derive the conclusion that this phenomenon is not due to a cooperative effect in the ionic beam, but to a process which involves only single ions. The numerical value of V_c rules out the direct production of rotons or phonons by the well known Landau criterion. The sharpness of the transition indicates that the process involves a time scale large in comparison with the ion-roton collision time, which is responsible for the mobility value before the first discontinuity. Therefore, we must look for a process in which a single ion can suffer periodical increases of interaction with the normal fluid.

We will now put forward a tentative explanation which requires concepts already familiar in the actual picture of liquid helium. We think the essential feature of the strange behavior of the ions to be due to the formation of a quantized vortex ring in the superfluid, at a value of the drift velocity consistent with the Landau criterion, and that this vortex ring remains closely bound to the ion in motion while interacting with the roton sea, so giving rise to a new source of dissipation. This picture will be qualitatively discussed in the following paragraphs.

The occurrence of quantized vortex rings in superfluid helium has been predicted by Onsager (*4*) and Feynman (*5*), and the energy and momentum expressions suggested by Feynman are such to allow a critical velocity of the order of magnitude observed by us if the radius of the ring is about 10^{-6} cm, which is the expected size if the ring must be close to the complex entity which we simply called the "ion." From the multiplicity of the quantized circulation the periodicity in the discontinuity of the drift velocity follows at once. However, the Feynman expressions are valid for free vortices and may not be for vortical rings close to a wall. The motion of a classical vortex ring close to a sphere at rest was investigated by Lewis (*6*) long ago. He found a range of stability, and we hope this holds true also for a sphere in motion, provided a convenient change in the radius of the ring is made. To approximate the ions as a sphere should not change the main result, owing to the small polarizability of the helium atoms.

The interaction of a vortex line with the roton sea is suggested by Hall and Vinen (*7*) to be responsible for the Gorter and Mellink force, the mutual-friction force which acts between the normal and the superfluid component above the critical velocity. If one uses the Lifshitz and Pitaevskii (*8*) expressions for this force acting on a filament of 10^{-6} cm length, one can get an interaction of the order of magnitude observed in the mobility change at the discontinuity. It is also realized that the higher circulation quantum numbers give rise to correspondingly higher dissipations. This multiplicity is not observed in capillaries or slits probably because in these cases the vortex filaments or the large rings are not stable and they soon generate a tangled mass of vortical lines, generally described as superfluid turbulence. The ion instead, owing to its spherical geometry and to its small dimensions, can permit a stable quantum vortex to live safely for a long period and in different quantum numbers.

The creation of a vortex ring close to the ion is a process still obscure to us, but it is certainly not more obscure than the creation of a large vortex ring in a capillary; also in this case a long relaxation time must be assumed (*9*). Notice that a backflow of superfluid must always exist around an ion in motion, and this flow has the same dipolar character as the one generated by a small vortex ring placed in the center of the sphere. This fact may help in the building-up process.

In conclusion the picture suggested here uses the same kind of arguments as the ones used currently to provide a possible explanation for the critical velocities observed in capillaries or slits. These arguments are not too firmly grounded to theory *(10)*. For instance, our picture suffers from the lack of proper theoretical treatment of the behavior of a small quantum vortex ring close to a sphere. What is the creation process, what are the correct energy and momentum expressions for the ring, what are its stability conditions? These questions are left to theoreticians. We point out the interest of these questions in order to prove the correctness of our picture and therefore of the multiplicity of the quantized circulation, which plays an essential role in it. So far this multiplicity has not been proved experimentally, the Vinen *(11)* vibrating wire experiment being indicative of the existence of the first quantum of circulation only; this experiment is not yet generally accepted theoretically *(10)*.

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