MOBILITY OF CHARGES IN LIQUID HELIUM UP TO SOLIDIFICATION

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The mobility of positive and negative ions in liquid He I is measured at pressures up to 115 atm in electric fields up to 10 kV/cm. The results of the experiments are compared with existing theoretical considerations.

ACCORDING to current representations,[1-4] positive charges in liquid helium form solid spheres of radius ~7 Å, while the negative charges form bubbles with radii ~17 Å. The study of the behavior of charges in liquid helium under pressures, which gives information on the physical nature of the carriers, thus allows us to obtain essential information on the nature of the carriers and the character of their motion.

The mobility of charges in He I and He^3 up to pressures of 30 atm and in fields up to 200 V/cm was studied in [5]. It was shown that with increase in pressure, the mobility of the positive charges decreases, while the mobility of the negative charges at first increases, and then, at pressures above 9 atm, also begins to decrease. Similar results were obtained in [6], where the behavior of the charges in liquid He^3 at pressures up to 15 atm were studied.

In the present work, the mobility of positive and negative charges was measured in liquid He I in the range of temperatures 2–4.2°K, at pressures up to 115 atm and in fields up to 10 kV/cm. The mobility of the carriers was measured by the time-of-flight method, similar to that applied in [7,8].

The measurement cell (Fig. 1) with an ivory shell consisted of the source of the charges, a collector, and five grids, with a transmission of about 75%, separated by mica layers. A titanium-tritium target served as the source,[9] radiating ~ 10^7 electrons/sec with mean energy 5.7 keV. The total distance between the source and the collector amounted to ≈ 3 mm, the distance between the shutters (drift space) was 800 microns, and the width of the shutters was 60 microns. The cell was placed inside a glass ampoule of 8 mm diameter, which withstood a pressure up to 130 atm. The system for obtaining the high pressure and the helium cryostat did not differ from that used earlier.[9]

The collector current of 10^{-10}–10^{-14} A was measured by an electrometer with a dynamic capacitor. In liquid helium, one could usually observe up to ten practically equivalent maxima on the plots of the frequency dependence of the ion current. The scatter of the location of the maxima from experiment to experiment did not exceed 5%.[3]

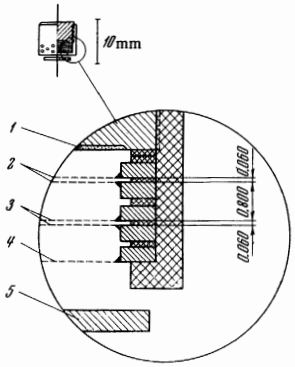

FIG. 1. Measurement cell; in the circle is shown the location of the grids in the cell and the distances between them (in mm) are given. 1 – target, 2,3 – grids of shutters, 4 – screen grid, 5 – collector.

Figure 2 shows the dependence of the mobility of the charges on the pressure in liquid helium, obtained by us for temperatures of 4.2, 2.63, and 2.07°K. It is seen that with increase in the pressure, the mobility of the carriers of positive charges decreases. For negative carriers at a pressure of the saturated vapor, the mobility is smaller by almost one-half; with increase in pressure, the mobility rises somewhat, and then begins to decrease smoothly. Beginning with some pressure, the mobilities of the positive and negative carriers are practically the same. As our measurements have shown, the mobility of the positive and negative charges up to fields of 10 kV/cm was virtually independent of the intensity of the field.

For the description of the motion of positive and negative charges (for temperatures above T_λ) one can use the well-known formulas[2] of the flow of a viscous fluid past a solid sphere or a bubble.[2] For positive carriers,

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[3] It should be noted that for each change in the voltage applied to the cell, the current of the collector, both in the static and in the dynamic regimes, was established within tens of minutes, which, however, did not affect the location of the maxima of the dependence of the current on the frequency, i.e., the value of the measured mobility. Upon reversal of the sign of the voltage, the sign of the current did not immediately follow that of the voltage, and the current reached the steady-state value, which was identical in sign with that of the voltage, only after several hours.

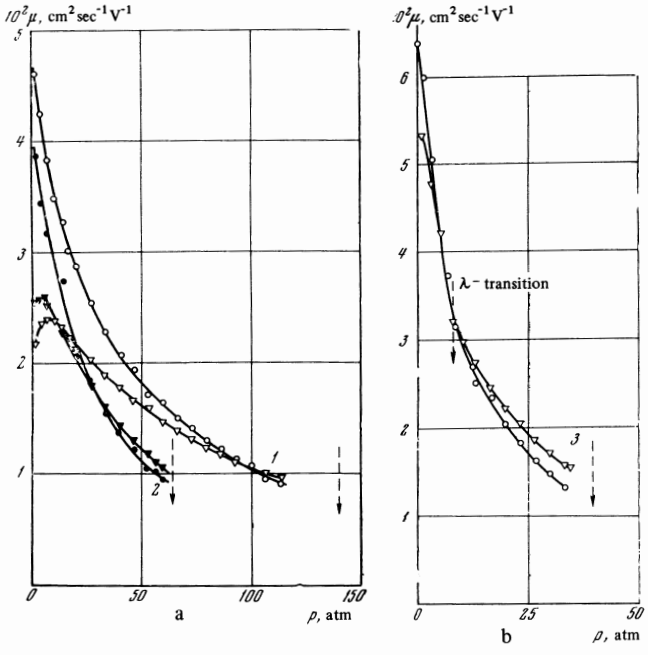

FIG. 2. Pressure dependence of the mobility of the charges in liquid helium. The circles correspond to positive charges, the triangles to negative ones. Curves 1 and 2 were obtained for temperatures of 4.2 and 2.63°,K, respectively, curves 3 were obtained for a temperature of 2.07°K. The arrows indicate the solidification pressure for a given temperature.

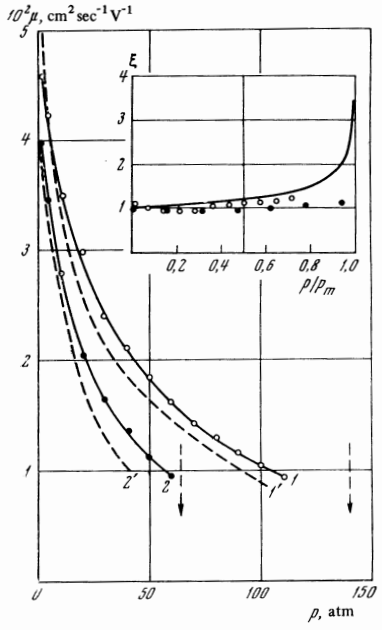

FIG. 3. Comparison of the measured mobilities of the positive charges with the computed values from Eqs. (1) and (2) (the dashed curves 1′and 2′). At the top are drawn the dependences of the dimensionless quanities $\xi = a + [2V\,pm / N\,\alpha\,e^2]^{1/4}$ on the relative pressure p/pm, computed from the Atkins model (solid curve), and the data of the experiment (O – T = 4.2°K, (O – T = 2.63°K, ● – T = 2.63°K).

$$\mu_+ = e / 6\pi\eta a_+, \qquad (1)$$

where a_+ is the effective radius of the carrier, e the ion charge, and η the coefficient of viscosity of the surrounding liquid. In the Atkins model,[1] the radius of the sphere is equal to

$$a_+ = (N\alpha e^2 / 2V(p_m - p)]^{1/4}, \qquad (2)$$

where $N\alpha$ is the molar polarizability, V the molar volume, p the pressure in the liquid, and p_m the solidification pressure.

The experimentally measured dependences of the mobility μ_+ on the pressure (solid curves 1 and 2) and those computed for the same temperatures (dashed curves 1′ and 2′) are shown in Fig. 3. Here the dependences of the dimensionless quantities $a_+[2Vp_m/N\alpha e^2]^{1/4}$ on the relative pressure p/p_m are shown. These were computed according to the data of the experiment and the Atkins model. The values of the viscosity of helium used for the computations were those measured by Tjerkstra.[10] As is seen from the drawing, the viscosity represented by the Atkins model $\mu_+(p)$ is close to the experimentally observed value at pressures sufficiently far removed from the solidification pressure. Close to the solidification pressure, the Atkins model is obviously inapplicable, inasmuch as the radius of the sphere becomes sufficiently large and it is necessary to take into account not only the motion of the sphere as a whole, but also the corresponding effects, in particular, for sufficiently high fields.

The maximum on the curve of the dependence of the mobility of the negative charges on the pressure can be explained by the fact that initially the radius of the bubble decreases with increase of pressure, and then, when the pressure on the boundary becomes equal to the solidification pressure (for a given temperature), a solid crust forms around the bubble.

Using the same apparatus, we made an attempt at the measurement of the mobilities in solid crystalline helium. For success, we needed entirely favorable circumstances, which, unfortunately, was not the case. It seems useful to discuss briefly the reasons for our failure. Earlier, by growing crystals of helium in a cylindrical glass tube, we succeeded in obtaining crystals of extraordinary perfection.[11] Fair crystals were also obtained by crystallization of the helium in a diode cell,[9] which was monitored by the size of the jump of induced electrical conductivity upon transition from liquid to crystal. In bad crystals, the current falls by a factor of several fold upon solidification; however, in carefully carried out crystallization, a change of current of at most several percent is observed. In the cell now used by us, in the interelectrode space in which five grids were located, the conditions for obtaining excellent crystals were much more complicated, which revealed itself first of all in the significant decrease in the currents between the electrodes of the cell (by a factor of 100).

However, the principal reason for the failure was the practical cessation of action of the shutters in the working regime. Both the significant decrease in the flows in the cell containing solid helium, and the disruption of the effect of the shutters, make their own contribution to the bad quality of the resultant crystals, the growth

of which in this case takes place simultaneously in an uncontrolled manner on many centers, and not on a single seed, as was the assured case in our previous experiments. The filling up of the cell with a finely crystalline mass leads to various polarization effects on the boundaries between the individual crystals and, as a consequence, to relaxation effects, the time constants of which evidently significantly exceed the working frequencies of the time-of-flight cell.

It is pertinent to make one more observation. The presence in the liquid helium of a source of charges would appear to give information of the conditions of its crystallization. Since the carriers in liquid helium represent spheres whose dimensions are determined by the value of the pressure in the liquid, while its concentration under our conditions can reach 10^9 cm^{-3}, the application of an electric field on the surface of the electrodes, should produce a "hail" of arbitrarily oriented centers. How we succeeded, under these conditions, in producing the growth of comparatively "excellent" crystals, is very surprising.

All these considerations lead us to the conclusion that the measurement of the mobility in crystals of helium by time-of-flight or any other similar method is scarcely possible. One should seek such methods in which charges produced by an external source can move in a crystal grown inside the container having no centers capable of serving as seeds of a new phase.

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