MOTION OF CHARGES IN LIQUID AND SOLID HELIUM

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The motion of charges in liquid and solid helium has been investigated over the temperature range between 4.2 and 1.5° K. A dependence of the currents in solid helium upon the quality of the crystals produced has been established.

THE nature of electric charges in liquid helium and the mechanism of their motion cannot as yet be regarded as completely explained, despite the fact that a considerable number of papers have already been devoted to this question.[1-8] In particular, the fundamental problem of the nature of the anomalously large effective masses, whose possible existence was pointed out in our first note,[6] still remains unsolved.

The polarization and conductivity hysteresis phenomena which we observed led us at that time to suggest that the current carriers consist principally of submicroscopic impurity particles carrying charges of both signs. If one accepts Atkins' hypothesis,[5] however, the polarization phenomena evidently find a satisfactory explanation within its framework without assuming the presence of impurities, which can, nevertheless, exert a strong influence upon the conditions of a real experiment.

We present here, briefly, the results of experiments on the motion of charges in liquid helium, under pressures ranging from equilibrium to the solidification point, which, it seems to us, can provide further data on the nature of the charge carriers.

We employed both all-glass and glass-metal systems (Fig. 1), whose construction permitted measurement of weak electrical currents in liquid and solid helium over a wide range in pressure, as well as visual observation of the helium solidification process.

The experimental volume containing the electrodes was connected through a glass or metal capillary, protected by a Dewar jacket, to a helium gasifier capable of producing and maintaining pressures up to 100 atm.* To one of the electrodes, made of stainless steel, there was attached a molybdenum disc (4 mm in diameter), covered with a layer of titanium tritide which served as a source, emitting electrons of 5.7 kev average energy. Another molybdenum disc—the electrometer electrode—was rigidly fastened to the first through a system consisting of two pairs of glass beads into which were sealed ferrochromium wires serving as guard electrodes.

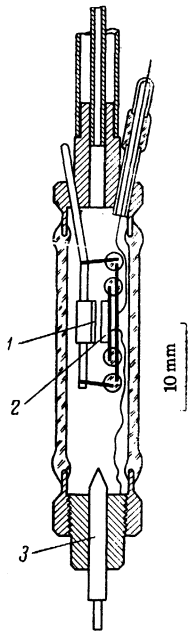

FIG. 1. Diagram of the apparatus: 1 – source, 2 – electrometer electrode, 3 – copper rod.

Prior to an experiment the experimental volume and the gasifier reservoir connected to it were filled with liquid helium, condensed from a glass gasholder and passed, before condensation, through a trap containing highly-purified activated charcoal at 90° K.

The current through the interelectrode gap was measured with an ÉMU electrometer. For the current measurements in solid helium an electrostatic screen, manipulated through the cover of the surrounding helium Dewar, was moved into place over the normally uncovered experimental chamber.

*Throughout this article, pressure is to be understood to mean relative (above atmospheric).

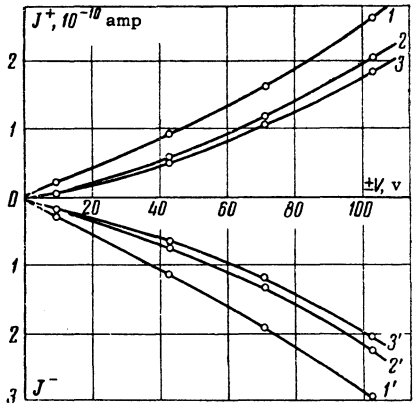

FIG. 2. Variation of current with field intensity in liquid helium: curves 1, 1′ – for 0 atm, 4.2 °K; curves 2, 2′ – for 5 atm, 1.65 °K; curves 3, 3′ – for 10 atm, 1.65 °K.

Voltage-current characteristics for one of our systems (with a source emitting 7.95×10^7 electrons/sec and an interelectrode spacing of 500 μ), at temperatures of 1.65 and 4.2° K and pressures of 0.5 and 10 atm, are shown in Fig. 2. As can be seen from the figure, the current in the liquid helium reaches 2.5×10^{-10} amp for an electric field intensity of ~ 2000 v/cm; this is only an order of magnitude less than the total saturation ion current of the source.

Curves showing the variation in current (for a field intensity of 3000 v/cm) with increasing pressure at temperatures between 2.0 and 4.2° K (obtained in an apparatus containing a source emitting 7.15 electrons/sec, with an electrode spacing of 340 μ), as well as the pressure dependence of the liquid density,[9] are presented in Figs. 3 and 4.

In our first systems, in which the electrodes were arranged horizontally, we were quite unable, by further increase in pressure, to cause crystallization to take place in such a way as to insure

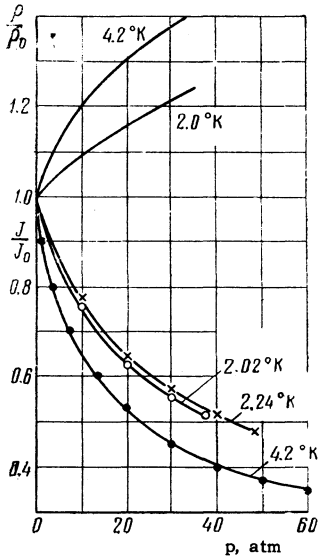

FIG. 3. Relative variation of current with pressure in liquid helium, and relative variation of liquid helium density with pressure.

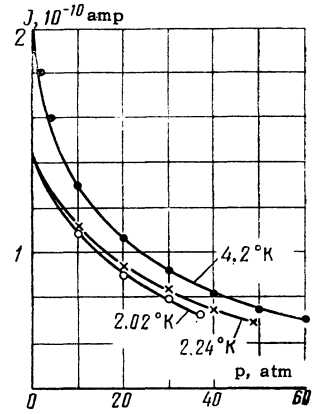

FIG. 4. Variation of current in liquid helium pressure.

that none of the liquid phase was blocked off in the space between the electrodes. We made use thereafter of systems in which the interelectrode region extended vertically, which considerably simplified the process.

As is evident from Figs. 5 and 6, the current changes discontinuously at the solidification point; the ratio of the currents before and after the discontinuity depends critically, however, upon the conditions under which crystallization occurs. Thus, besides the true decrease in the current resulting from the change in the character of the motion of the charges due to the transition of the helium into the crystalline solid state, discontinuities are very frequently observed whose magnitude is governed by partial freezing of the helium filling the space between the electrodes.

However, even the "true" discontinuity is found to depend upon the way in which the liquid helium crystallizes. When the helium solidifies into a finely-crystalline mass ("wet snow")[9] with subsequent compaction under pressure, the discontinuity is found to be most pronounced: the current falls by 30 — 50 times, while beyond the

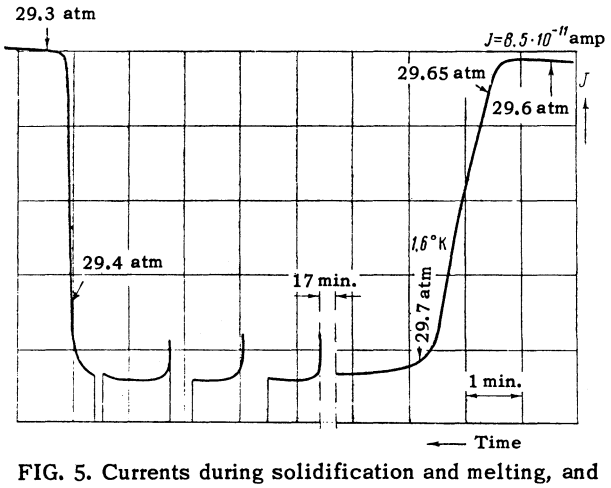

FIG. 5. Currents during solidification and melting, and currents in solid helium (pressure given at points indicated by arrows).

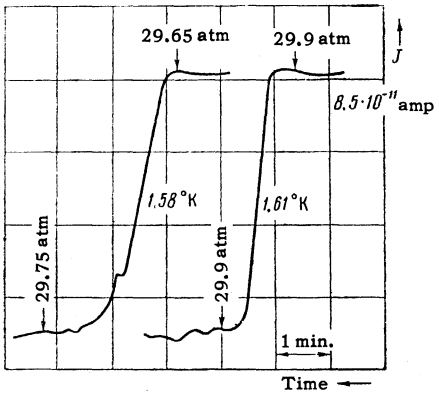

FIG. 6. Currents for two successive helium solidification runs.

discontinuity, even in the solid helium, there is observed a current variation of the type associated with polarization, as well as a general instability of the conductivity evidently connected with changes in the mechanical stresses and deformations.*

In certain cases, however, (Fig. 6), we succeeded in observing currents in solid helium (evidently monocrystalline or composed of coarse crystals) which differed in all by only a few times (≥ 3) from the currents in the liquid prior to its solidification. Figure 5 shows a current record during the solidification process, obtained with an ÉMU electrometer and a chart recorder. In this experiment the current in the solid helium fell by a factor of seven as compared with the current in the liquid at 29.6 atm, i.e., to 1.2×10^{-11} amp.†

It is evident from the curves showing the variation of current with time (Fig. 5), the measurement beginning within a fraction of a second after registering the capacitive surge, that as the pressure is removed and then reapplied, polarization and hysteresis effects are observed which are characteristic of a solid body in which charges of both signs are in motion.

An equilibrium value for the current is reached more rapidly when the charges moving in the region between the electrodes are predominantly negative in sign; when the polarity is reversed, equilibrium is established somewhat more slowly.

It must also be noted that reversible variations of current with pressure are observed only for good crystals, and only over that small pressure interval for which the boundary of the growing crystal is in direct contact with a sufficiently extensive liquid surface. Once the crystal has completely filled the experimental space, and the phase boundary has risen into the capillary, the pressure ceases for all practical purposes to be exerted throughout the whole volume of the crystal.

Although we performed many measurements over a broad temperature range from 4.2 to 1.3° K, disturbances associated with polarization made it hard nevertheless to secure reproducible results. It is difficult therefore to draw definite conclusions regarding the temperature dependence of the current-pressure relation below 2° K (where the effect of temperature is relatively slight), or the influence of the direction of the field within the interelectrode region upon the observed effects. It must be borne in mind that under our experimental conditions the measurements were performed over a period on the order of ten minutes, and if, for example, the current at the beginning of the measurement were higher by 15 — 20% for one polarity than for the other, then at the end of the experiment, the opposite pattern would usually be observed.

Nevertheless, on the basis of all of our observations we can draw the following definite conclusions:

1. The currents in solid helium are governed principally by the quality of the crystals obtained, and are near, in order of magnitude, to the currents in the liquid. The conclusion reached by Careri, Fasoli, and Gaeta [7] regarding the impossibility of observing the movement of charges in solid helium is, as follows from our experiments, in error.*

2. Inasmuch as charges of both signs may move in solid helium, we have no basis whatever for regarding their structure as different from that which they possess in the liquid.

3. Besides the charge carrier structure common to both liquid and solid helium, there are also present in the liquid charges whose structure is associated with the presence of impurities in the helium.

4. An increase in the density of liquid helium leads to a decrease in the mobility of carriers of both signs.

*This, clearly, is the situation encountered by Careri, Fasoli, and Gaeta, [7] who conclude that currents in solid helium cannot be measured at all.

†The slopes of the curves in Figs. 5 and 6 are determined by the ratio of the areas of the interelectrode regions occupied by the liquid and solid phases as the liquefaction or solidification proceeds.

*We have also performed a few exploratory experiments with He^3 which we propose to describe in more detail at some later date. We shall only mention here that the current in solid He^3 falls by only a small amount (~40%) as compared with that in the liquid. A substantial decrease in the current with a further, relatively slight, increase in pressure is also characteristic of solid He^3.

5. In liquid helium it is evident that charges are transported chiefly by carriers (of large effective mass) associated with the presence of impurities. At the same time, currents in liquid helium may also be carried by other kinds of charges (for example, electrons and holes), which, evidently, are responsible for currents in crystalline helium.

In conclusion, I wish to thank D. I. Vasil'ev for his aid in conducting the measurements.

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