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MOTION OF CHARGES IN SOLID HELIUM

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The temperature dependence of a current (produced by a β source) in helium crystals grown at pressures between 25.3 and 154 atm is measured. It is found that the nature of the motion of electric charges in liquid helium (He I and He II) and in helium crystals is similar.

We have presented in an earlier communication[1] data on the influence of pressure on the character of motion of charges produced by a β source in liquid helium, and also the results of observation of the currents flowing in helium at the instant of its solidification or melting. It was established that during the phase transition the current depends essentially on the quality of the crystal in the interelectrode gap, and the current changes by more than one order of magnitude under crystallization conditions that ensure formation of a single crystal (or large crystalline blocks).

In the present investigation the procedure for obtaining solid helium was greatly improved and we were apparently successful in ensuring conditions for the production of single crystals with minimum defects and internal stresses.

Figure 1 shows schematically the vacuum chamber, which is located in the lower part of a helium Dewar and in which an ampoule was placed for growing the solid-helium crystal[1]. The cold source was a copper reservoir A, filled with liquid He^4 or He^3, the vapor of which could be pumped through tube B. Both the reservoir A and the upper cover of the ampoule were electrically insulated from the vacuum chamber by glass supports. The ampoule was connected to a gas generator, producing a pressure up to 200 atm.[2] by a capillary. A segment of the capillary, located inside the vacuum chamber, was cooled by a bulky copper cold duct C equipped with a heater D and a thermometer E. Two cylinders of crystalline quartz F were soldered to reservoir A with pure tin; the ground ends of the cylinders were silvered with paste. A heater G was wound on the upper quartz insulator, to which a carbon thermometer H was soldered.

The thermometer and heater were thus in good thermal contact with the reservoir A, and were at the same time highly insulated from it electrically. On the other quartz insulator J was fastened a carbon thermometer K, which measured the temperature of the upper end of the ampoule.

The ampoule was cooled by pumping off an external bath, and gaseous helium was fed into the ampoule under pressure from the gas generator, until it was completely filled with liquid, as determined by means of viewing tube L. By regulating the heating of the gas generator, the desired pressure was established in the ampoule, after which

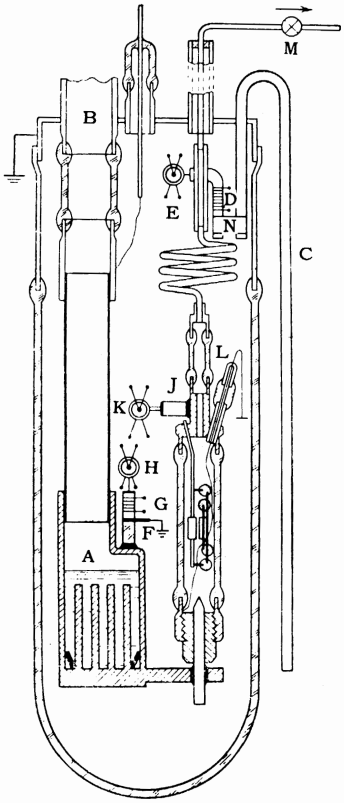


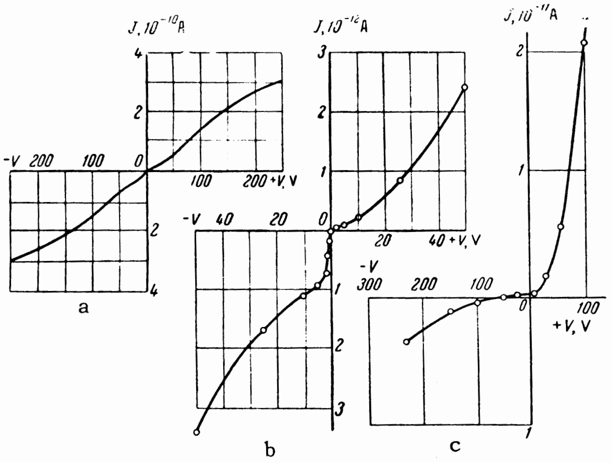
FIG. 1. Diagram of the experiment.

petcock M was closed and the crystal growth began. During the growth, the temperature of the section of the capillary connected with a heat conducting bridge N to the cold duct C was regulated by means of heater D and monitored by thermometer E.

The reservoir A, as indicated above, could be filled with liquid He^3 or He^4, and its temperature, and consequently also the temperature of the copper priming needle in the ampoule, could be lowered to 0.5° K¹⁾. By regulating in this manner the temperatures of the lower and upper ends of the ampoule, it was possible to vary over a wide range the rate with which the flat boundary of the growing crystal moved upward in the ampoule. The heater of the cold-duct bridge was turned off only after the crystal-liquid boundary passed through the sighting tube. The crystal temperature thus obtained could then be varied from 0.6° K up to the melting temperature.

To obtain lower densities in the same experiment, the crystal was fused and the pressure in the ampoule dropped slightly to a new value, after which the operation of crystal growth was repeated. In some cases heat-exchange helium was pumped on in the vacuum jacket in order to graduate the thermometers and to bring the sample in thermal contact with the external bath.

The β source (titanium-tritium target), which was fastened on one of the electrodes of the ampoule, emitted $\sim 6 \times 10^{17}$ electrons per second. The current through the interelectrode gap was measured with the aid of a Vibron electrometer, whose lead-in was thoroughly insulated and shielded, so that currents $\sim 10^{-14}$ A could be reliably measured.



a b c

FIG. 2. Current-voltage characteristics for helium: a – liquid HeII, p = 0.8 atm, T = 1.26°K; b – liquid HeI, p = 80 atm, T = 3.1°K; c – solid helium, p = 154 atm, T = 4.1°K.

It must be borne in mind that an appreciable role could be played in these measurements by polarization phenomena, which should be reflected in the time behavior of the currents flowing through the crystal, and in their dependence on the magnitude, polarity, and sequence of application of the voltage. Since the measurement-cell capacitance was such that the transient times were beyond the time-lag limit of the electrometer employed in the work, the question of the role of polarization in our experiments remains open and we have operated throughout with residual and not with initial values of the currents.²⁾

Figure 2 shows the current-voltage characteristics plotted in liquid and solid helium in fields up to ~7,000 V/cm. We see that these characteristics have an essentially different character; whereas in the liquid the current is practically symmetrical with respect to reversal of electrode polarity (if we disregard the singularity near the null point), the current in the solid helium is strongly asymmetrical—larger when positive voltage is applied to the electrode with the target.

The reason for this asymmetry is not sufficiently clear, but in first approximation the slopes of the positive and negative branches of the characteristics are probably related like the mobilities of the corresponding carriers.

Under the special conditions of our experiment, where the zone of "appearance" of the charges lies in the direct vicinity of one of the electrodes (within ~10 μ), this conclusion can apparently be made.

We do not have any current-voltage characteristics in which saturation was reached; however, from the appearance of the curves plotted for solid helium (Fig. 3) at different temperatures, we can state that near the melting temperature the saturation current in the helium crystal differs little from the limiting saturation current of the targets (measured in liquid and gaseous helium), and that consequently the charge recombination near the active electrode is not significant.

To determine the temperature dependence of the current, the voltage was chosen, on the one hand, to make the operation far from saturation,

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1⁾To stabilize the temperature of reservoir A when working with He^3, we placed in it a continuous source of ionization – titanium-tritium targets.

2⁾To resolve the question of the role of polarization it would be necessary to employ a vibrating-string electrometer, with the possibility that measurements could be made at its sensitivity limit.

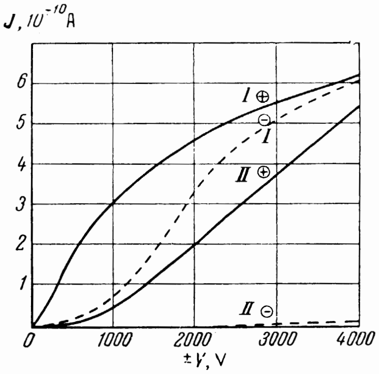

FIG. 3. Current-voltage characteristics for solid helium at a pressure of 154 atm: curves I – T = 4.29°K, II – T = 3.14°K (the symbols + and – denote positive and negative current).

and on the other, to make the currents flowing through the crystal obey approximately Ohm's law. The temperature relations obtained for the positive current are plotted in coordinates log J = f(1/T) in Fig. 4, where the points corresponding to the currents in liquid at a temperature close to the melting point are separately marked. Figure 5 shows a portion of the pT diagram of helium, showing the temperature regions in which the measurements were made for crystals grown at different pressures, from 25 to 154 atm.

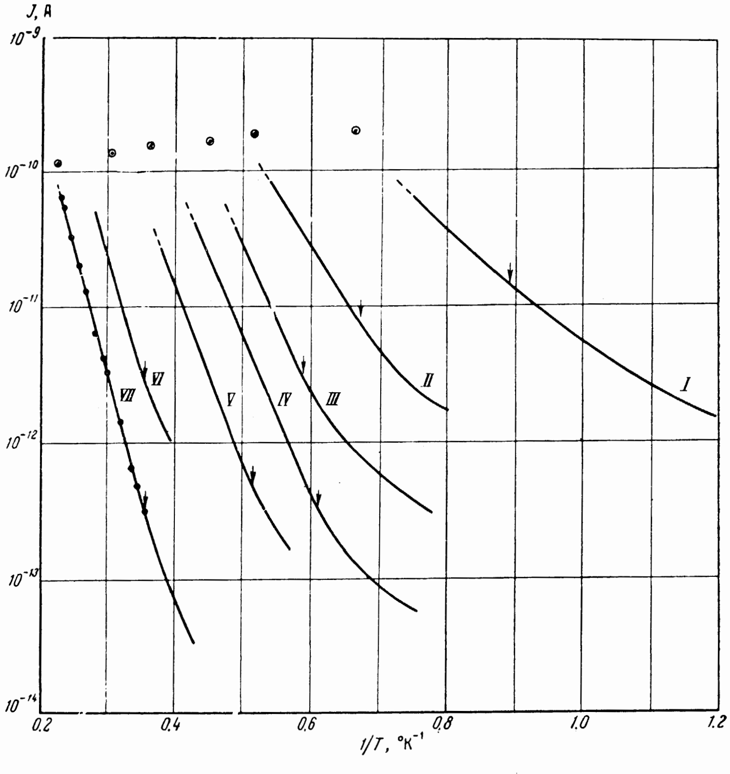

FIG. 4. Plot of J(1/T) in solid helium for different pressures. I – 26 atm, II – 33.5 atm, III – 49 atm, IV – 60 atm, V – 84 atm, VI – 118 atm, VII – 154 atm.

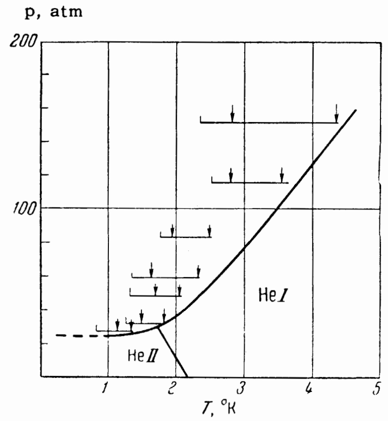

FIG. 5. pT diagram of helium. The arrows denote the temperature intervals for crystals of different densities, in which, however, a straight-line dependence is observed.

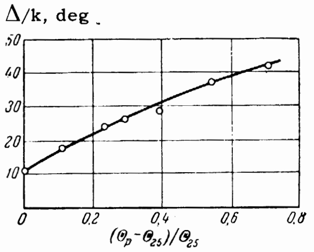

FIG. 6.

The argument of the exponential, calculated from the slopes of the linear sections of the curves of Fig. 4 at different pressures, is plotted in Fig. 6 against the Debye temperature Θ, the values of which for crystals with different densities were borrowed from [3].

It must be noted that the crystals grown in different experiments differ somewhat from one another. This is manifest in small changes in the slopes of the straight-line portions of the log J = f(1/T) curves and in the singularity of the variation of the temperature interval within which this law remains in force.

If the ampoule remains in vacuum, the temperature conditions are likewise subject to some uncertainty, since the thermal conductivity, depending on the pressure and on the temperature can vary over a very wide range and an appreciable temperature gradient can arise sometimes in the crystal. In the experiments where the temperature dependence of the current was measured while the crystal was gradually cooled or heated, we had to detect the onset of equilibrium by examining the variation of the current itself, which turned out to be much more sensitive to changes in temperature than the carbon thermometers we employed.

One must not forget also that the crystal near the active electrode (within ~ 10 μ) is subject during the entire time of the experiment to the action of electrons with maximum energy ~ 17 keV, but the bulk of its thickness ($\sim 300\,\mu$) remains undamaged.

How can we interpret our results? First, we call attention to the fact that when helium solidifies there is no appreciable change in the current, meaning that the mechanism of the transport of the bulk of the electric charges is apparently of the same nature in the liquid and solid states. And since the transport of charges can naturally not be accompanied by mass transport in the solid helium, it is reasonable to extend this conclusion also to the motion of charges in liquid He I and He II, and by the same token confirm our earlier conclusion[1] once more. Thus we can regard it as established that in liquid and solid helium it is the electrons and holes that move, and that in liquid helium in addition the charges connected with the unavoidable presence of solid contaminations also move. In helium crystals (which apparently are close to ideal[3)]) the mobility of the holes is appreciably higher than that of the electrons, and the exponential character of the temperature variation of the current indicates that the processes controlling the charge transport are of the activation type.

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[3)] According to measurements of Mezhov-Deglin (private communication), the thermal conductivity of helium crystals grown by the same method reaches the record value 30 W/cm-deg, indicating a high degree of their perfection.

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Translated by J. G. Adashko
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