ON THE PROBLEM OF THE MOTION OF CHARGES IN LIQUID HELIUM II

R. G. ARKHIPOV and A. I. SHAL'NIKOV

Institute for Physical Problems, Academy of Sciences, U.S.S.R.

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The behavior of electrical charges produced in liquid helium with the aid of a β source has been investigated. An attempt has been made to observe "flushing" of the charges by a thermal current. The suggestion is advanced that the hysteresis effects observed arise from the presence of impurity particles suspended in the liquid helium.

THE behavior of charges in superfluid helium is of considerable theoretical interest. It can be assumed that due to the small polarizability of helium atoms an electron in liquid helium will interact weakly with the thermal excitations, and that its effective mass will be close to the mass of a free electron. In the case of positive charges two points of view are possible. It may turn out, for example, that positive charges in liquid helium move as "holes," and have, therefore, an effective mass close to that of negative charges. The possibility, however, cannot be excluded that, as a consequence of the appreciable binding energy of a positive charge, the helium ions may form about themselves "solvate" shells. In this case the interaction of the positive charges with the bulk of the superfluid liquid helium would naturally be considerably stronger. In particular, analogously to what occurs with a He^3 impurity, there should then be observed effects associated with the "flushing" of the charges by a thermal current.

In connection with the experimental investigations begun in 1954 by Shal'nikov to study the interaction of electrical charges with a thermal current in helium II, one of us[1] constructed a theory of the mobility of charged particles of small effective mass in superfluid helium. For the theory thus developed to be correct, in addition to the requirement of small effective mass $m^* \ll kT/S^2$, where S is the velocity of sound, the quasiclassicality conditions must be fulfilled — the impurity mean free path l must be much greater than the corresponding de Broglie wavelength ($l \gg \hbar/\sqrt{mkT} \sim 10^6$ cm), since in the alternative case it is impossible to write the kinetic equation for the problem, and the approach to the problem changes completely.

This quasiclassicality condition must absolutely be fulfilled for a sufficiently weak interaction of the impurities with the thermal excitations. However, the measurements published to date on the mobility of charged particles in superfluid helium sharply contradict the ideas presented above. The first publication on this problem was that of Williams,[2] who observed the current pulses arising in liquid helium in fields of 10 to 50 kV/cm under the action of a polonium source. The method employed by Williams, as is evident, is in practice quite unsuited to the measurement of ion mobility in the case of helium. In actuality, the ranges of the α particles in this low-density liquid are comparable with the distance between the electrodes of the pulse ionization chamber, the dimensions of which could not be further increased for a variety of reasons, which makes observation of even the pulses themselves impossible. Williams' results are insufficiently definitive, and not only by reason of the scatter in his experimental data; thus, for example, the mobility of the negative ions as determined in his experiments ($\mu^- = 2.0 \times 10^{-2}$ cm^2/v-sec) turned out to be less than the mobility of the positive ions ($\mu^+ = 8.8 \times 10^{-2}$ cm^2/v-sec), which seems to us in the highest degree improbable.

Unfortunately, we do not know all the details of the experiments of Careri et al. These authors also used an α -source, but the value of the mobility was obtained from the "flushing" of the charges by a thermal current. In a second communication by Careri et al.,[3] the agreement of their previous observations with Williams' results is confirmed.

In 1958, Meyer and Reif[4] published the results of mobility measurements obtained by them using the electric shutter method of Tyndall and Powell. They found that the mobility is independent of the magnitude of the electric field intensity for weak fields (50 - 200 v/cm), and confirmed again the closeness of the mobilities of the positive and negative carriers.

The results of Meyer and Reif seem to us surprising in the highest degree. Most astonishing is the number (10!) of successive current maxima observed on the curve showing the dependence of the current upon the frequency of the voltage applied between the grids. It is known that even in gaseous helium at low pressures, at densities a hundred times smaller than the density of liquid helium, it has proven impossible to observe maxima of such high orders, as a consequence of scattering effects. The equidistant spacing of the maxima in the work of Meyer and Reif indicates, moreover, that the charge carriers in liquid helium have one single effective mass.

Although the experiments we have undertaken have not led us to any wholly definite conclusions, we think it appropriate to report them briefly, in view of the general obscurity of the problem of the motion of charges in liquid helium.

In our first experimental arrangement we proposed to observe the interaction of currents produced with the aid of a radioactive source with a thermal or mechanical current in liquid helium II. As an ion source we used a thin layer of Zr or Tl ($\sim 0.5\mu$), treated with tritium to obtain a compound of the type AT_2, and applied to a polished tungsten plate. The dielectric layer thus obtained was covered, by evaporation or by cathode sputtering, with a thin film of metal (Pt, $\sim 0.1\mu$), providing a good electrical contact between the surface layer of the emitter and the material of the substratum. Such a source (dia. ~ 3 mm) emits β particles having a maximum path in liquid helium $\sim 5\mu$ and allows 4.4×10^9 ion pairs/sec to be obtained.

In Fig. 2 is presented the dependence of current upon distance between the electrodes of apparatus a, illustrated in Fig. 1, on one of which is located the β-particle source, for various values of field intensity; Fig. 3 shows the dependence of current upon field for separations of 40 and 640μ. In these first measurements we encountered hysteresis effects which, it would seem, should not occur at all under the conditions of our experiments, and which were completely absent in gaseous helium. These hysteresis effects were partially present even when the most careful measures were taken to purify the helium, and were the more strongly evident, the weaker the currents being measured. In Fig. 4 are presented two voltage-current characteristics obtained, under conditions of maximum purity within our system, successively within 1.5 hours. The displacement of the characteristics is quite evident even for a current $\sim 10^{-11}$ amp.

Despite these complicating circumstances we nevertheless made an attempt to observe "flushing" of the charges by a thermal current in liquid helium, in the apparatus depicted in Fig. 1b. The idea of this experiment consisted of observation of the displacement of the voltage-current characteristic by a thermal current flowing in the liquid helium from the heater through the screen electrode into the surrounding bath. In the event that the charge current flowing in the space between the electrodes of the chamber was being entrained by the thermal current, we should have observed an effect opposite to the well-known ion "wind" effect. The instability

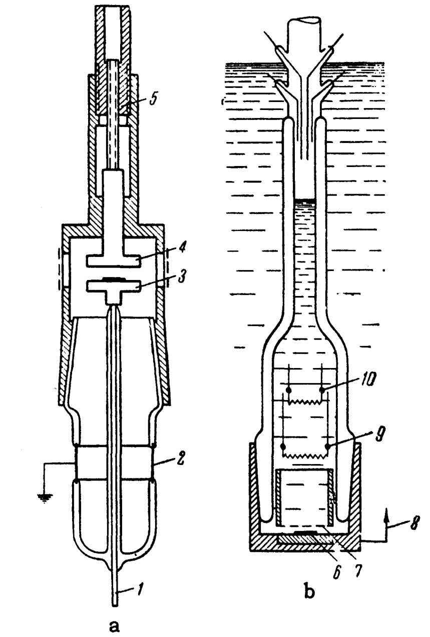

FIG. 1. Diagram of the apparatus: a) 1 – electrometer electrode, 2 – guard ring, 3 – electrode with β-particle source, 4 – electrode, 5 – differential screw; b) 6 – β source, 7 – grid electrode, 8 – electrometer electrode, 9, 10 – thermometer heaters.

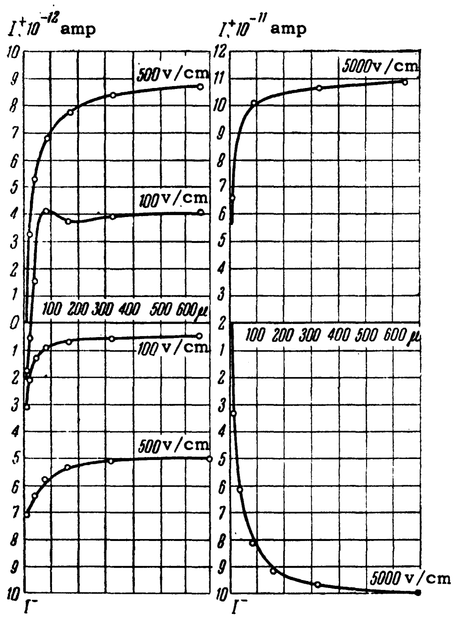

FIG. 2

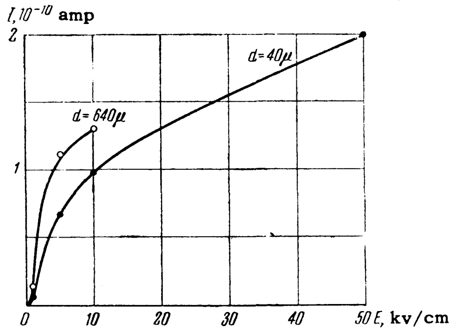

FIG. 3

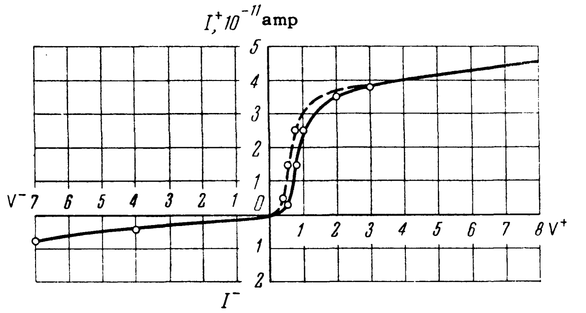

FIG. 4

of the characteristics of the system, however, arising from hysteresis in the region of limitingly small currents (for electric field intensities not exceeding tens of v/cm), prevented us from arriving at any definite conclusions.

Making use of the circumstance that in a sufficiently strong electric field, recombination of the ions virtually ceases at a certain distance from the emitting electrode (Fig. 2), we made yet another attempt to measure the mobility. For this purpose we placed in the apparatus 1a, at a distance of 300 μ from the emitting electrode, a grid, in the space beyond which we could work with a constant charge current of one or the other sign (depending upon the sign of the grid potential). From calculations,[1] the dependence of charge current upon field should be linear for small values of the electric field intensity, and then follow an $E^{1/2}$ law.

Plotting the dependence of the measured current upon field intensity on a log-log scale, it is possible to determine from the location of the break in the curve (field $E_0 \sim 3000$ v/cm), the quantity $1/m^{*1/2}{}'_2$, which, from our data, amounts to 10^5 both for positive and for negative charges and indicates that the premises of the theory are not fulfilled.*

In addition to the experiments described above in which a β-source served as a source of charges, we used the extraction of electrons from the electrode surface with the aid of light to obtain negative charges. Using a ~ 50-watt low-pressure mercury lamp we were able to obtain currents of the order of 10^{-13} amp from one square centimeter of the surface of a zinc electrode, which, however, proved insufficient for the measurements, in particular as a result of the strong influence of hysteresis effects. An attempt to obtain large currents with the aid of a pulsed light source (a quartz lamp filled with helium) completely submerged in the liquid helium was likewise unsuccessful.

All of the above-cited experiments have forced us to the conclusion that the task of studying the motion of charges in liquid helium meets with serious difficulties, evidently arising from the presence of the suspended charged particles of solidified gases invariably present in liquid helium. The movement of these charged particles in the electric field and their deposition upon the electrodes leads to a variety of polarization and hysteresis effects. The presence of suspended solids in the liquid helium appears to be, not merely possible, but, apparently, certain. Actually, helium, liquified and subjected to adsorptive purification on charcoal at liquid nitrogen temperature, can contain up to 10^{-7}% of impurities, which thereafter remain in the liquid principally in the form of submicroscopic particles. If the dimensions of these particles are $\sim 10^{-6}\,\mu^3$, then their concentration can reach $10^8 - 10^9$ particles per cubic centimeter.

We were able to reduce significantly the hysteresis effects by condensing the helium directly into the apparatus through specially treated charcoal at liquid nitrogen temperature and at the same time employing special ultrafilters. Unfortunately, however, we did not succeed completely in avoiding the harmful action of the suspended particles.

It is impossible to doubt that the presence in liquid helium of a suspension of solid impurities was also manifested in the most decisive fashion in the previously-published experimental results.

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*The conductivity of liquid helium is naturally negligibly small, even in fields close to the breakdown value, which from our measurements, amounted to 700 kv/cm over a 10μ gap.

[1] R. G. Arkhipov, JETP **33**, 397 (1957), Soviet Phys. JETP **6**, 307 (1958).

[2] R. L. Williams, Can. J. Phys. **35**, 134 (1957).

[3] Careri, Reuss, Scaramuzzi, and Thomson, Proc. Fifth Internat. Conf. on Low Temperature Physics and Chemistry, p. 155, 1955.

[4] L. Meyer and F. Reif, Phys. Rev. **110**, 279 (1958).

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