Drop in the velocity of charges in ⁴He crystals in strong fields

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It is found that in perfect ^{4}He crystals, grown under a pressure of 31 atm, the velocity of positive charges in strong fields $E \geqslant 5 \times 10^4$ V/cm decreases as the field is increased.

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The first measurements of the motion of charges in solid helium were performed by Shal'nikov more than twenty years ago.[1] A number of papers have been published concerning experimental and theoretical investigations of the properties of charges of charged probe microparticles introduced into the lattice of a quantum crystal (see the reviews Refs. 2 and 3); however, the structure and mechanisms of motion of charges in solid helium have yet to be uniquely established.

As follows from experiments,[4] in bcc ^{3}He crystals grown under pressures $P \geqslant 35$ atm the dependence of the velocity on the temperature T and the applied electric field E in fields up to 10^5 V/cm can be described by expressions of the form

$$v(T, E) \sim \exp\left(-\frac{\Delta}{T}\right) \cdot \mathrm{sh}\,(eEb/kT),$$

where Δ and b are constants, i.e., thermally activated diffusion across a barrier $b \sim 10^{-8}$ cm) plays the main role. A stronger than linear dependence $v(E)$ has been observed in hcp ^{4}He specimens at pressures $P \geqslant 30$ atm,[5] but the range of measurements is limited to fields $E \leqslant 5 \times 10^4$ V/cm. The purpose of this work was to study the dependences $v(T,E)$ in ^{4}He crystals in a wide range of fields ($E = 10^3$–1.3×10^5 V/cm) and temperatures (up to 0.4 K).

The dependence of the velocities of positive v_+ and negative v_- charges on the applied voltage U in one of the perfect crystals, grown under a pressure of 31 atm, are shown below in Figs. 1 and 2. The construction of the apparatus and the measurement procedure are analogous to those used previously.[4] The source of charges (β active target) and the collector (6×35 mm plates) were situated inside a metallic ampoule with diameter ϕ 8 mm and length 60 mm. The source–collector gap in the present measurements was $d = 0.3$ mm. We grew the helium crystals by cooling the compressed liquid at constant pressure. We calculated the average velocity of the charges from the time of arrival of the charged-particle front at the collector, i.e., from the positions of the peaks on the $I(t)$ curves, which describe the time dependence of the collector current with a stepped voltage U. The average value of the accelerating field in such a diode is close to $E = U/d \approx 33\ U$ V/cm. The working pressure range was $U = 30$ V–4 kV. The saturation current of the target was $I_{\text{sat}} = 3 \times 10^{-8}$ A. The working currents in the experiments, $I = 10^{-9}$–10^{-13} A, were much lower than I_{sat}.

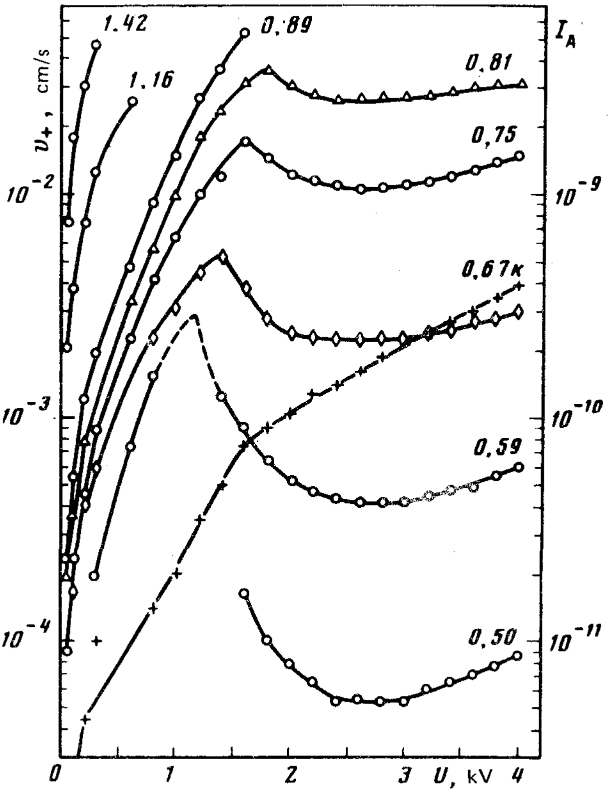

FIG. 1. Average velocity of a positive charge (Fig. 1) and a negative charge (Fig. 2) as a function of the potential difference applied to the diode electrodes U at different temperatures. The cross marks indicate the dependence $I(U)$ for one of the temperatures [$(I_+(U)$ at $T = 0.67$ K and $I_-(U)$ at $T = 0.81$ K].

The upper limit of the resolution of the detecting apparatus was determined by the time constant of the electrometrical amplifier ($\geqslant 0.3$ s), and the lower limit was determined by the stability of its zero level when recording the curves $I(t)$ ($\leqslant 3 \times 10^3$ s). The recorded velocities ranged from 10^{-1} to 10^{-5} cm/s. We used an electronic stabilizer to maintain and control the temperature of the specimen, which permitted maintaining a given average temperature of the specimen to within *mK* when recording the curves $I(t)$. In the experiments, we recorded both the time of arrival of the front τ, and the stationary values of the current for $t \gg \tau$. This permitted judging the degree of perfection of the specimen. In specimens with defects, the fronts were not as steep, while the stationary values of the currents were several times lower than the peak value due to capture of charges by defects. In strong fields the current is unstable in such specimens. We shall discuss below the results of the measurements in perfect crystals only.

The most interesting and unexpected result of the measurements is the drop in the velocity of positive charges in a field above some critical value (Fig. 1): As the applied voltage is increased, the linear dependence $v_+(U)$ for $U \leqslant 300$ V is replaced by a nearly exponential dependence for $U \gtrsim 1$ kV [as also occurs in ^{3}He (Ref. 4)]. The velocity v_+

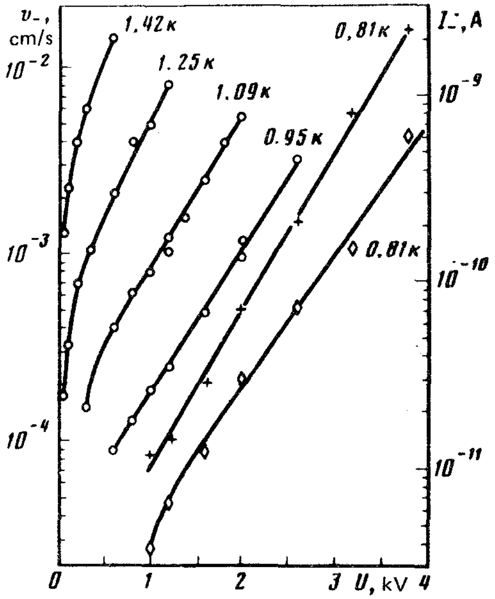

FIG. 2.

reaches a maximum at $U \approx 1.6$ kV and then decreases by a factor of 1.5–3 over a comparatively narrow range of fields and again gradually increases with voltages close to maximum voltage. As the temperature is lowered, the peak is displaced toward lower fields. It should be noted that the subsequent increases in the velocity v_+ could be partially due to overheating of the working region of the crystal between the plates of the diode due to Joule heating, since the average temperature of the specimen stabilizes during the measurements. The cross marks in Fig. 1 show the dependence of the stationary current on the field $I(U)$ at a temperature of 0.67 K (The ordinate scale is on the right). It is evident that the drop in the velocity changes only the slope of the curve $I(U)$. Similar results were reproduced in five specimens.

Figure 2 shows the field dependence of the velocity $v_-(U)$ and of the current $I_-(U)$ (at 0.81 K) in the same specimen. Because of the considerable difference between the characteristic activation energies for diffusion of positive $\Delta_+ \approx 9$ K and negative $\Delta_- \approx 16.4$ K charges, the velocities of the negative charges decrease rapidly with decreasing temperature, so that it was possible to perform the measurements only at temperatures $T \geqslant 0.8$ K. Measurements of v_- at low temperatures are also impeded by strong capture of negative charges by defects in the hcp crystals. In the range of fields and temperatures investigated, the velocity v_- increases monotonically with increasing fields.

The drop in the velocity of charges in solid helium with increasing field is observed for the first time. A similar effect was observed before in superfluid helium, where it is attributed to the creation of vortex rings in the fluid at a velocity above a critical velocity and capture of charges by these rings.[6] In analogy with liquid helium, we can assume that dislocation loops, which are capable of capturing the charge and moving together with it, form around a charge in solid helium in fields above some threshold value. The possibility of the appearance of such loops with moving charges was first pointed out by Nosanov and Titus,[7] who showed that the energies required to create vortex rings and loops with the same length have the same orders of magnitude. However, they have assumed that the mobility of dislocations is very low, so that large mechanical stresses must be applied in order to observe the motion of such a bound complex. The results of experiments performed recently in our laboratory[8] show that, in contrast to growth defects, freshly introduced dislocations in ^{4}He crystals have high mobility at $T \leqslant 1$ K whereas the characteristic activation energies of dislocations are close to the activation energies of point defects. This indicates that the proposed model is plausible.

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