Mobility of charges in solid ^{3}He in strong fields

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The experimental dependence of the velocity at which charges of both signs move in bcc ^{3}He on the field $v(E)$ in fields up to 10^5 V/cm at different temperatures in the thermoactivated diffusion region can be described by a single law $v(E, T) \sim \exp(-\Delta T)\sinh(eEb/kT)$.

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The mobility of charges in solid helium was first observed by Shal'nikov.[1] In the same laboratory the temperature dependences of the currents through a diode were measured in ^{4}He and ^{3}He (Ref. 2) and the characteristic charge-activation energies were estimated from the slopes of the $I(T)$ curves; the I-V characteristics of a diode in helium in strong fields were investigated in Ref. 3, and the charge mobility in solid helium was measured for the first time in a three-electrode cell by using the time-of-flight method.[4]

Subsequent detailed studies of the dependence of the velocity of charge mobility in hep ^{4}He on the temperature and the applied electric field[5] showed that the velocity increases proportionally to the field only at small fields $E \leqslant 10^4$ V/cm. In large fields $E \geqslant 2 \times 10^4$ V/cm the velocity of charges ^{4}He, as a rule, increased faster than that according to the linear law. In Ref. 5 the experimental velocity dependences $v(E)$ in strong fields could be described by expressions such as $v(E) \sim (E + E_0)^3$, where the parameter E_0 changed drastically with the change in temperature, and the proportionality constant increased abruptly in fields $E > 3 \times 10^4$ V/cm. In the theory developed in Ref. 6, the transition from a linear dependence to a cubic dependence $v(E)$ was attributed to spontaneous emission of phonons by the moving charges when the energy acquired by a charge on moving a distance equal to the interatomic spacing exceeds the vacancy (delocalized vacancy) band width, and the break in the $v^{1/3}(E)$ curve in stronger fields was explained by the formation of bound vacancy states on the charges.

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The $v(E)$ dependences in strong fields in solid ^{3}He have not been reported in the literature, but it was known[3] that the I-V characteristics of a diode in ^{4}He and ^{3}He in strong fields are similar. However, theory[7] indicated that the properties of the vacancies of the vacancies in ^{4}He and ^{3}He at low pressures can differ drastically, for example, because of spin ordering of the atoms around a vacancy in solid ^{3}He. In addition, it was known[8] that at small fields $E \leqslant 10^4$ V/cm the activation energies of the motion of positive charges in bcc ^{3}He at all pressures and of the negative charges at least for $P \geqslant 60$ atm are considerably higher than the vacancy activation energies. If we assume, in accordance with modern theory,[9] that the motion of charges in helium in the thermoactivation region is caused by their interaction with vacancies, then the difference in activation energies can be explained by the formation of a charge image around the charge in ^{3}He, which prevents a direct site exchange between the charges and vacancies and which can be overcome by using the thermoactivation method (the polarization interaction between a charged particle and helium atoms can severely distort the crystal structure of the surrounding medium).

We have made a series of measurements of the velocity of charge mobility in ^{3}He crystals that were grown at pressures of 35-50 atm from technically pure ^{3}He (up to 0.2% ^{4}He impurity) in fields up to 10^5 V/cm, i.e., 5-7 times higher than those in our previous experiments.[8] The design of the device has been described in detail elsewhere.[8] The diode consisted of two rectangular molybdenum plates (a β-active source of charges and a collector) with typical dimensions of 6×35 mm, which were arranged inside an 8-mm-diam cylindrical ampoule in which the solid helium crystals were grown at a constant pressure. The source-to-collector gap was $d = 0.3$ mm. The average velocity was determined from the location of the maximum points on the time dependences $I(t)$ of the diode collector current in solid helium for a stepwise application of the voltage U. Control measurements in ^{4}He and the calculations of various authors[10,11] indicated that this method gives the same results as the time-of-flight measurements in a three-electrode cell[4,5] to within the accuracy of a coefficient close to unity. We have made supplementary calculations of the dependence of the arrival time τ of a charge front at the collector (the location of the maximum point) on the exponent n in the equation $v = \mu^* E^n$, which showed that for $n \leqslant 10$ the time τ decreases by no more than 18% as n increases, so that the average charge velocity v in a field $E_{avg} = U/d$ for $1 \leqslant n \leqslant 10$ can be determined from the relation $v = d/\tau \times (1.4 \pm 0.125)$.

As the experiment showed, in fields $E_{avg} \geqslant 2 \times 10^4$ V/cm the velocity of the charges in ^{3}He, just as in ^{4}He earlier,[5] usually increased faster than according to a linear or even,a cubic law, and the $v(E)$ dependence also could not be described by a single power law. This was especially obvious on the $v(E)$ curves for positive charges at low pressures. In contrast to the analysis methods used in Refs. 5 and 6, which assumed the existence of three different laws of motion, we attempted to find a single law suitable for describing the $v(E,T)$ dependences over a broad range of fields and temperatures. As indicated above, the difference in the activation energies of the charges and vacancies in ^{3}He may be attributed to the formation of a charge image around the charge, which prevents a direct exchange of sites between charges and vacancies and which increases the effective charge-motion activation energy, calculated from the experimental data, as compared with the vacancy-activation energy. In the simplest case of thermoactivated diffusion across the barrier, the drift probability of a charged particle along the applied field is $\sim \sinh(eEb/kT)$, where eEb is the energy acquired by a particle in the field E (b is a characteristic distance and e is the electron

charge; it is assumed that eEb is smaller than the height of the potential barrier around the charge). It was reasonable, therefore, to describe the experimental dependences of the velocity of charges of a given sign in a crystal at different temperatures by the following expression:

$$v(E, T) = A \exp(-\Delta/T) \sinh(eEb/kT), \quad (1)$$

where Δ is the effective activation energy, which was estimated from the slopes of the $v(T)$ curves at small fields in which the $v(E)$ dependence is close to linear. In general, the coefficient A may depend on the temperature, but not on E. If our assumptions are valid, then in the reduced coordinates $v^* = v/\exp(-\Delta/T)$ and $U^* = U/T$ the experimental $v^*(U^*)$ dependences at different temperatures must be described by similar curves, whose scale along the Y axis can vary with temperature proportionally to the change of the coefficient A. The $v^*(U^*)$ dependences for an ^{3}He crystal at a pressure of 46 atm are shown in Fig. 1 (A and B correspond to positive and negative charges). The values $\Delta_+ = 16$ K and $\Delta_- = 7$ K were determined from the slopes of the experimental $v(T)$ curves in small fields. The solid curves represent a calculation using Eq. (1), in which the parameter values were $A_+ = 5.2 \times 10^4$ cm/sec and $b_+ = 0.47 \times 10^{-8}$ cm for positive charges and $A_- = 78$ cm/sec and $b_- = 0.23 \times 10^{-8}$ cm for negative charges. The points along the curves are the experimental values, and the different symbols correspond to different temperatures. The agreement between calculation and experiment is reasonable; moreover, the experimental values of $v^*(U^*)$ lie fairly close on the graphs, i.e., the coefficient A is almost independent of temperature. There is another method of verifying the suitability of the proposed method of data analysis. For the condition $eEb > kT$ the quantity $\sinh(eEb/kT) \approx 1/2 \exp(eEb/$

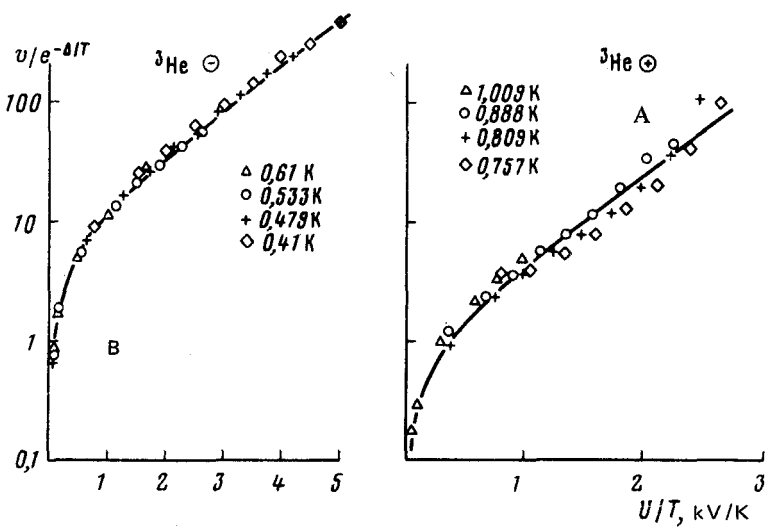

FIG. 1 Dependence of the velocity of charges in ^{3}He on the applied voltage in reduced coordinates. A and B represent the positive and negative charges. To determine the velocity in cm/sec, the numerical values plotted on the Y axis in Fig. 1(A) must be multiplied by the coefficient $6.7 \times 10^4 e^{-16/T}$ and those in Fig. 1(B) must be multiplied by $505\, e^{-7/T}$.

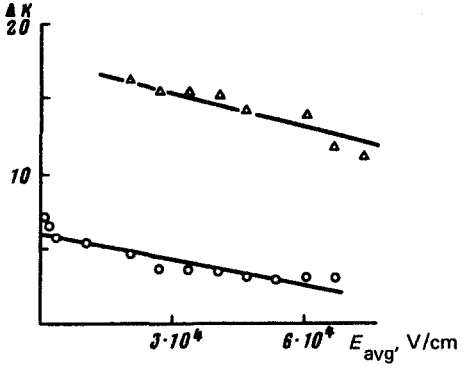

FIG. 2. Dependence of the effective activation energy Δ on the average electric field intensity. The triangles represent the positive charges and the circles denote the negative charges.

kT), so that in strong fields Eq. (1) can be written in the form $\nu(E,T) \sim \exp[-(\Delta - eEb/k)/T] = \exp(-\Delta_{\text{eff}}/T)$. The effective activation energy determined from the slopes of the $\nu(T)$ curves in strong fields must decrease linearly with increasing E_{avg}. The dependences of Δ_{eff} on E_{avg} for this crystal are shown in Fig. 2. We can see that Δ_{eff} decreases by 2–3 K with increasing field, i.e., the barrier height is $\geqslant 3$ K. Estimates of the parameter b from the $\Delta_{\text{eff}}(E)$ dependences give $b_+ = (0.7 \pm 0.1) \times 10^{-8}$ cm and $b_- = (0.5 \pm 0.1) \times 10^{-8}$ cm; these values agree well with those found earlier. The heating of the crystals during the current measurements in strong fields prevents a large increase in the fields.

We have attempted to analyze in a similar manner the results of experiments in ^{4}He. For a sample which was grown at 32 atm in our device, we obtained $\Delta_+ = 7$ K, $A_+ = 24$ cm/sec, $b_+ = 0.46 \times 10^{-8}$ cm, $\Delta_- = 13$ K, $A_- = 250$ cm/sec, and $b_- = 0.49 \times 10^{-8}$ cm. An analysis of the data in Fig. 2 from Ref. 6 for an ^{4}He crystal at 32.4 atm gave $A_+ = 98$ cm/sec and $b_+ = 1 \times 10^{-8}$ cm for $\Delta_+ = 11.2$ K. In Fig. 3 of this paper the graph of the $\nu(E)$ dependence for an ^{4}He sample at 40.5 atm was approximated by three different power functions. A calculation showed that the experimental $\nu(E)$ dependence can be described by a single curve, if it is assumed that $b_+ = 0.9 \times 10^{-8}$ cm and $A_+ \exp(-\Delta/T) = 3 \times 10^{-3}$ cm/sec, i.e., the $\nu(E)$ graphs in the literature can be described by a single dependence of the form (1); this is a significant advantage of the proposed data analysis method over that used in Refs. 5 and 6. It should be noted that the b values, which were calculated from the experimental curve (0.2–1.0) $\times 10^{-8}$ cm, are smaller than the interatomic spacing. A detailed theoretical study of this question would be of interest.

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