

# Motion of charges in bcc $^4\text{He}$

A. I. Golov, V. B. Efimov, and L. P. Mezhev-Deglin

*Institute of Solid-State Physics, Academy of Sciences of the USSR*

(Submitted 6 August 1984)

Pis'ma Zh. Eksp. Teor. Fiz. **40**, No. 7, 293–296 (10 October 1984)

The mobilities of charges in samples of bcc  $^4\text{He}$  were measured. A comparison of the mobilities and the characteristic diffusion-activation energies of charges in samples of bcc and hcp  $^3\text{He}$  of approximately equal molar volume and also in samples of bcc  $^3\text{He}$  shows that the properties of charges in helium crystals grown at low pressures are primarily determined by the lattice structure of the samples.

In this letter we present the results of measurements of the mobilities of positive  $\mu_+$  and negative  $\mu_-$  charges and also the characteristic diffusion-activation energies of charges calculated from the temperature dependences  $\mu_-(T)$  and  $\mu_+(T)$ , in samples of bcc and hcp  $^4\text{He}$  of approximately equal molar volume. The idea that the structure of a crystal lattice strongly affects the properties of the charges introduced into solid helium was advanced a long time ago.<sup>1</sup> Observations of current surges in  $^3\text{He}$  (Ref. 1) or charge mobilities in  $^4\text{He}$  (Ref. 2) near the bcc–hcp phase-transition line have been reported in the literature. However, detailed studies of the motion of charges were performed only for hcp  $^4\text{He}$  (Ref. 3) or bcc  $^3\text{He}$  (Refs. 2 and 4) samples. We have measured for the first time the temperature dependences of charge mobilities in bcc  $^4\text{He}$ .

The experiments were performed using the setup described in Ref. 4. The measuring cell is a flat diode consisting of a charge source (a  $\beta$ -active target) and a  $6 \times 40\text{-mm}^2$  metallic collector. The cell is placed inside a cylindrical ampule, in which the helium crystals are grown. The source–collector gap is  $d = 0.3$  mm. The hcp-phase crystals were grown from a superfluid liquid under a pressure of  $\sim 26$  atm. The ratio of the molar volumes of the hcp and bcc phases of solid  $^4\text{He}$  to that of the liquid on the melting line is such that a slow heating of an hcp sample in a sealed ampule would nearly correspond to the hcp–bcc phase-transition line in the  $P$ – $T$  diagram.<sup>5</sup> This greatly extends the temperature range of the mobility measurements in the bcc phase. The temperatures of the hcp–bcc–hcp phase transitions, determined in our experiments from the current surges or the charge mobilities on the corresponding temperature curves, turned out to be approximately equal to the positions of the lower and upper triple points on the equilibrium  $P$ – $T$  diagram.<sup>5</sup>

The mobilities of the charges of both signs in the hcp phase, as well as of the positive charges in the bcc phase, were calculated, as in the previous case,<sup>4</sup> 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 dependence of the collector current on the time the voltage  $U$  was switched on stepwise. We performed the measurements in low fields of average intensity,  $E = U/d \leq 8 \times 10^3$  V/cm, where the transit time is inversely proportional to the field. However, the temporal resolution of this method turned out to be inadequate for measuring the mobility of negative charges in the bcc

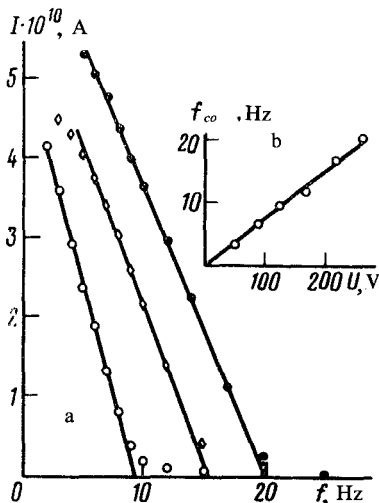


FIG. 1. (a) Dependence of the collector current on the repetition frequency of pulses with a  $\pm 260$ -V amplitude at the following temperatures:  $\circ$ —1.63 K,  $\diamond$ —1.63 K, and  $\bullet$ —1.72 K. Sample No. 179. The straight lines indicate the position of  $f_{co}$ . (b) Voltage dependence of the cutoff frequency at  $T = 1.72$  K.

phase: At the phase-transition point,  $\mu_-$  increases abruptly by a factor of  $\sim 30$  and then continues to increase with the temperature (the value of  $\mu_+$  decreases by a factor of 2–3 in the course of the transition).

Because of the large difference in the charge mobilities in the bcc phase ( $\mu_- \gg \mu_+$ ), we were able to use the modulation technique, which was used in the first measurements of charge mobilities in solid helium<sup>6</sup> in a cell with an intermediate control grid. We determined the time of flight of the negative charges across the source–collector baseline from the position of the cutoff point,  $f_{co}$ , on the plot of the collector current  $I_-$  versus the repetition frequency  $f$  of the square electric pulses applied to the source (a square-type meander with an amplitude of  $\pm U$ ). The curves  $I_-(f)$  for different temperatures are shown in Fig. 1 (the voltage is  $U = \pm 260$  V). The voltage dependence of  $f_{co}$  at  $T = 1.72$  K in the same sample No. 179 is shown separately. It is evident that within the error limits ( $\pm 5\%$ ) the quantity  $f_{co}$  increases in proportion to  $U$ , i.e., the mobility  $\mu_-$  does not depend on the field.

The measurements of charge mobilities in this sample in the hcp and bcc phases are shown in Fig. 2 (circles are for  $\mu_-$  and crosses are for  $\mu_+$ ). In the bcc phase, the systematic differences in the values of  $\mu_-$  and  $\mu_+$  in the course of thermal cycling (bcc–hcp–bcc transition) or in different samples (the crosses and  $\times$ 's in Fig. 2) were within  $\pm 20\%$ . A strong anisotropy of the hcp lattice was seen in the fact that the mobilities in the hcp phase differed systematically by more than a factor of two under the same conditions. Accordingly, a larger spread in the effective activation energies of the charges was observed from sample to sample in the hcp phase. The values of  $\Delta_+$  and  $\Delta_-$  were calculated from the slopes of the straight lines,  $\ln \mu = f(1/T)$ , drawn through the experimental points. The average values of the activation energies in the

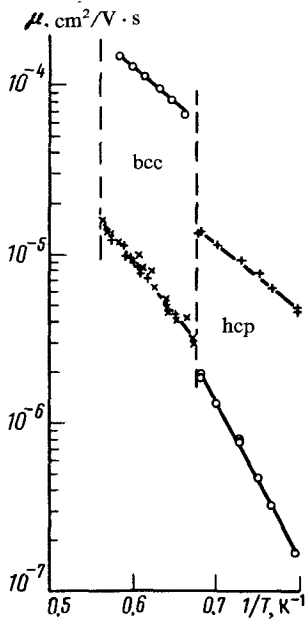


FIG. 2. Mobilities of positive (+) and negative (-) charges in sample No. 179 plotted as a function of the reciprocal temperature. The crosses represent positive charges in sample No. 176. The broken lines mark the region of existence of the bcc phase.

hcp phase,  $\Delta_+ = 9$  K and  $\Delta_- = 22.5$  K, coincide with those obtained in Ref. 3. In the bcc phase we have  $\Delta_+ = 15$  K and  $\Delta_- = 10$  K.

We recall that for measurements in the hcp phase the molar volume is constant,  $V_m = 20.9$  cm<sup>3</sup>/mole, whereas in the bcc phase  $V_m$  decreases from 21.1 to 20.8 cm<sup>3</sup>/mole with increasing temperature along the phase-transition curve.<sup>5</sup> In a qualitative analysis, however, this change can be ignored, since the relationship between the mobilities of charges of opposite signs and the corresponding activation energies of the hcp He<sup>4</sup> samples is opposite to that of the bcc He<sup>4</sup> samples of approximately equal molar volume: In hcp crystals  $\mu_+ \gg \mu_-$  and  $\Delta_+ < \Delta_-$ , whereas in bcc crystals  $\mu_+ \ll \mu_-$  and  $\Delta_+ > \Delta_-$ . This difference cannot be explained by an abrupt increase in the molar volume accompanying the hcp-bcc transition (from 20.9 to 21.1 cm<sup>3</sup>/mole at the lower triple point). According to the measurements in Ref. 3 and our data for low solidification pressures (for pressures lower than 30 atm we have  $V_m \geq 20.6$  cm<sup>3</sup>/mole), in the case of hcp <sup>4</sup>He, at constant temperature the difference between  $\mu_+$  and  $\mu_-$  and the activation energies increases with increasing  $V_m$ . For example, at  $V_m = 21$  cm<sup>3</sup>/mole we have  $\Delta_+ \approx 1/3 \Delta_-$ .

A comparison of these data with the measurements of the charge mobility in <sup>3</sup>He, using the same apparatus,<sup>4</sup> showed that the relationship between the charge mobilities and their activation energies in the bcc <sup>4</sup>He samples is analogous to that observed in the bcc <sup>3</sup>He samples at low pressures. The properties of charges in <sup>4</sup>He and <sup>3</sup>He crystals, grown under low pressures, are thus determined primarily by their crystal-

lattice structure. A change in the lattice structure changes significantly the mobility and the diffusion-activation energy of the charges in samples of approximately equal molar volume in the region of thermally activated motion. In contrast, this change, as indicated in Ref. 7, has virtually no effect on the activation energy of vacancies. The use of these results in theoretical studies may lead to a revision of the present conceptual understanding of the structure and mechanisms of diffusion of induced charges in quantum crystals.

<sup>1</sup>É. Ifft, L. P. Mezhov-Deglin, and A. I. Shal'nikov, Proceedings of the 10th International Conf. on Low-Temperature Physics, Moscow, 1967, Vol. I, p. 224.

<sup>2</sup>D. Marty and F. I. B. Williams, *J. Phys. (Paris)* **34**, 988 (1973).

<sup>3</sup>K. O. Keshishev, *Zh. Eksp. Teor. Fiz.* **72**, 521 (1977) [*Sov. Phys. JETP* **45**, 273 (1977)].

<sup>4</sup>V. B. Efimov and L. P. Mezhov-Deglin, *Fiz. Nizk. Temp.* **4**, 397 (1978) [*Sov. J. Low Temp. Phys.* **4**, 195 (1978)].

<sup>5</sup>E. R. Grilly, *J. Low Temp. Phys.* **11**, 33 (1973).

<sup>6</sup>K. O. Keshishev, L. P. Mezhov-Deglin, and A. I. Shal'nikov, *Pis'ma Zh. Eksp. Teor. Fiz.* **12**, 234 (1970) [*JETP Lett.* **12**, 160 (1970)].

<sup>7</sup>B. A. Fraass, S. M. Heald, and R. O. Simmons, Proc. Int. Quantum Crystals Conference, Colorado, 1977, p. 73.