

Anisotropy of growth coefficient and surface hardness of the ${}^4\text{He}$ crystals

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This letter reports a continued study of the anisotropy of the equilibrium and kinetic properties of the surfaces of ${}^4\text{He}$ crystals having an hcp structure. The angular dependence of the surface hardness and that of the growth coefficient have been measured for several cross sections which pass through the basic symmetry elements of the crystal: the C_6 and C_2 axes.

The apparatus used in the present experiments made it possible to grow oriented samples, to study selected properties of a plane surface of the crystal in a known crystallographic orientation, and to change this orientation by rotating the test chamber. The construction of the apparatus and the experimental details were published previously.¹ To determine the surface hardness $\tilde{\alpha}$ and the growth coefficient K , we used a method of exciting and detecting crystallization waves,² which made it possible to measure the spectrum and attenuation of these waves. We recall that as a plane crystallization wave propagates along a surface, this method makes it possible to detect the configuration of the surface (over an arbitrary scale along the ordinate axis) at a certain instant and to thereby determine the wavelength λ and the attenuation. We might add that in a control experiment we independently measured the amplitude of the crystallization waves which we detected. The maximum amplitude was $1.5 \mu\text{m}$ in our case.

Using an expression for the spectrum of crystallization waves,³ and ignoring gravitation and attenuation in it, we find the following expression for an experimental determination of the surface hardness $\tilde{\alpha}$:

$$\tilde{\alpha} = \rho_l k^3 / (\rho_s - \rho_l)^2 \omega^2, \quad (1)$$

where ω is the wave frequency (in our experiments, $\omega \approx 1 \text{ kHz}$), $k = 2\pi/\lambda$ is the wave vector, and ρ_l and ρ_s are the densities of the liquid and the crystal. Incorporating gravitation and attenuation yields corrections to the surface hardness no greater than 5%.

Since the attenuation of the crystallization waves results primarily from the finite value of the growth coefficient, if we assume that the attenuation is slight, we find the following expression for the growth coefficient K for a surface of the given orientation³:

$$K = \frac{\rho_s \rho_l^{1/3} \omega^{1/3}}{\tilde{\alpha}^{2/3} (\rho_s - \rho_l)^{2/3}} \kappa^{-1}, \quad (2)$$

where κ^{-1} is the attenuation length of a crystallization wave.

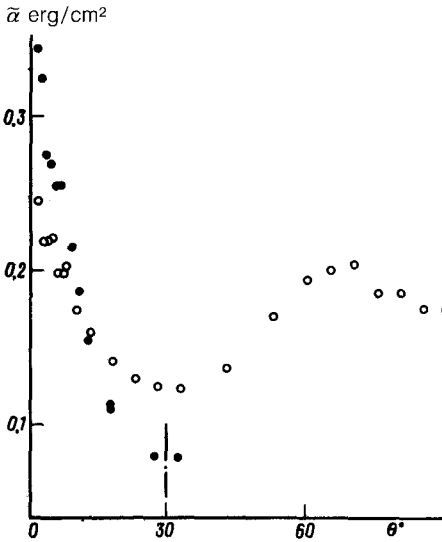


FIG. 1. Angular dependence of the surface hardness in two mutually perpendicular cross sections. \circ —Cross section 1; \bullet —cross section 2.

By measuring the length and the attenuation of the crystallization waves for each surface orientation, we find the surface hardness and the growth coefficient as functions of the angle in various cross sections of the crystal. It is important to note that the experimental chamber was rotated around an axis running perpendicular to the plane formed by the vector normal to the surface, \mathbf{n} , and the wave vector of the wave, \mathbf{k} . Consequently, the surface hardness found experimentally from expression (1) is expressed in terms of the surface energy α by $\bar{\alpha} = \alpha + \partial^2 \alpha / \partial \theta^2$. The angle θ lies in the (\mathbf{n}, \mathbf{k}) plane.

The measurements were carried out at the temperature $T = 0.4$ K. The roughening temperature of the (0001) basal plane is $T_{R1} = 1.3$ K, and that of the $(10\bar{1}0)$ plane is $T_{R2} = 0.9$ K (Refs. 2, 4, and 5).

Figure 1 shows experimental results on the surface hardness versus the angle in two mutually perpendicular cross sections. In cross section 1, the vectors normal to the surfaces under study lie in a plane passing through the C_6 axis, and θ is the angle which the surface makes with the (0001) plane. The orientation of this cross section with respect to the C_2 axis is arbitrary. By virtue of the symmetry of the crystal, the function $\bar{\alpha}(\theta)$ is symmetric with respect to the point $\theta = 90^\circ$. The point $\theta = 0$ is a singular point of the $\bar{\alpha}(\theta)$ dependence and corresponds to an atomically smooth (0001) face. The minimum angle at which we were able to determine $\bar{\alpha}$ is 2° . An increase in the attenuation prevented measurements at smaller angles. In cross section 2 the vectors normal to the surfaces under study are perpendicular to the C_6 axis, and θ is the angle made by the surface with the $(10\bar{1}0)$ plane. The $\bar{\alpha}(\theta)$ dependence in this cross section should obviously be symmetric with respect to the point $\theta = 30^\circ$. The closest we could come to the $(10\bar{1}0)$ face was an angle of 1.5° .

Figure 2 shows the experimental results on the growth coefficient as a function of

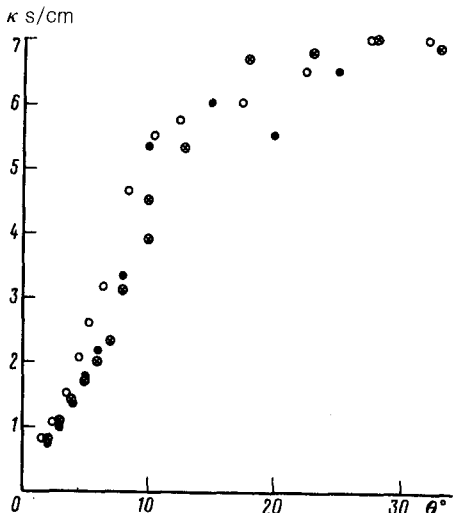


FIG. 2. Angular dependence of the growth coefficient of the crystal near special faces. ○, ●—Cross sections 3 and 4; ⊕—cross section 5.

the angle in three different cross sections of the crystal. Cross sections 3 and 4 run through the C_2 axis and differ in the orientation with respect to the C_6 axis. Cross section 5 passes through C_6 . In all three cases, the angle θ determines the deviation of the surface from the corresponding atomically smooth face.

In a theoretical paper, Nozieres and Uwaha⁶ derived the anisotropy of the growth coefficient of ^4He crystals near special faces through an analysis of the scattering of phonons of the liquid by surface defects of the crystal (jogs and steps). The qualitative $K(\theta)$ behavior which they predicted includes a linear behavior at small angles, a weak dependence on the angle far from the special faces, and an inflection point on the curve at intermediate angles. The experimental $K(\theta)$ curves in Fig. 2 demonstrate all three of these predicted properties. We cannot, however, assert that there is a complete agreement between experiment and theory in this regard. In the derivation of the linear function $K(\theta)$ at small angles, Nozieres and Uwaha leaned heavily on the condition that the steps forming a vicinal face were independent, i.e., that the width of the blurring of the steps was small in comparison with the distance between steps. Experimentally, a linear dependence is observed up to $\theta \approx 7^\circ$. It can be seen from the experimental curves of $\tilde{\alpha}(\theta)$ (Fig. 1), however, that the steps remain strongly interacting at least to an angle $\theta \approx 1.5^\circ$. The criterion for judging the weakness of the interaction of the steps is the surface hardness $\tilde{\alpha}$. Weakly interacting steps of a vicinal face should correspond to a low surface hardness (low in comparison with its value far from a special face). The large value of $\tilde{\alpha}$ observed at $\theta < 7^\circ$ in both cross sections (Fig. 1) implies a strong interaction of the steps in this angular interval. At $\theta \approx 7^\circ$, there is only a change in the power of the $\tilde{\alpha}(\theta)$ dependence (Fig. 3). At small angles we find $\tilde{\alpha} \propto \theta^{-1/5}$ to $\theta^{-1/6}$. At large angles, the dependence $\tilde{\alpha}(\theta)$ is different in the different cross sections and apparently corresponds to the natural anisotropy of the crystal. Also shown in Fig. 3 are experimental data of Babkin *et al.*,⁷ obtained through

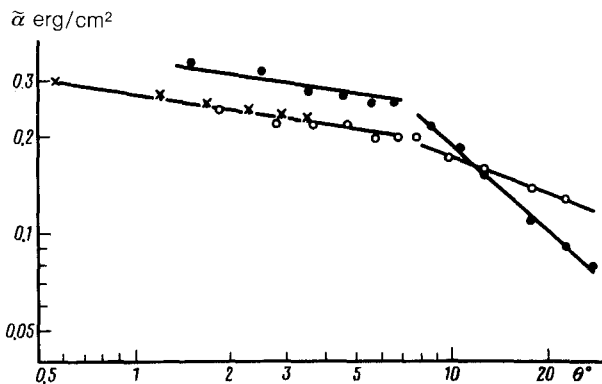


FIG. 3. Angular dependence of the surface hardness near special faces, in double logarithmic scale. ○—Near (0001) face; ●—near (10 $\bar{1}$ 0) face; ×—data of Ref. 7 near (0001) face.

an analysis of the equilibrium shape of the crystals at $T \approx 1.2$ K. The good agreement of the results shown here supports the assertion that there is no significant temperature dependence of the surface hardness over the temperature interval 0.4–1.2 K.

¹O. A. Andreeva and K. O. Keshishev, Pis'ma Zh. Eksp. Teor. Fiz. **46**, 160 (1987) [JETP Lett. **46**, 200 (1987)].

²K. O. Keshishev *et al.*, Zh. Eksp. Teor. Fiz. **80**, 716 (1981) [Sov. Phys. JETP **53**, 362 (1981)].

³A. F. Andreev and A. Ya. Pershin, Zh. Eksp. Teor. Fiz. **75**, 1511 (1978) [Sov. Phys. JETP **48**, 763 (1978)].

⁴J. E. Avron *et al.*, Phys. Rev. Lett. **45**, 814 (1980).

⁵S. Balibar and B. Castaing, J. Phys. (Paris), Lett. **41**, 329 (1980).

⁶P. Nozieres and M. Uwaha, J. Phys. (Paris) **48**, 389 (1987).

⁷A. V. Babkin *et al.*, Zh. Eksp. Teor. Fiz. **89**, 2288 (1985) [Sov. Phys. JETP **89**, 1322 (1985)].