Experimental detection of crystallization waves in He^4

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We observe slightly damped oscillations of the interface between liquid and solid He^4 at 0.4–0.6 K due to periodic melting and crystallization. The spectrum of these oscillations is measured.

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Unusual properties of the surface of helium crystals were first noted by Shal'nikov and coworkers.[1] In their experiments they observed an anomalously rapid "healing" of a depression produced by an indentor at the interface between two phases. Andreev and Parshin[2] made an assumption according to which the equilibrium boundary between liquid and solid helium could occur in a special state which is the quantum analog of an atomically-rough surface. It follows from this assumption, in particular, that at temperatures significantly lower than the λ-point, slightly-damped oscillations caused by periodic melting and crystallization—crystallization waves—may occur on this surface. This phenomenon is discussed in the present paper.

The construction of the He^3 cryostat and the instrument in which the crystals were grown is identical to that used previously for studying the properties of solid helium.[1,3] Four pairs of plane-parallel windows were provided in the cryostat for visual control and optical measurements. The He^4 crystals were grown in a metallic container having a 12×15 mm cross section with two plane glass walls 12×28 mm^2 which allowed the crystallization process to be observed in the entire volume of the container. The crystal growth occured at a constant temperature (0.4–0.9 K), pressure (25 atm), and controlled flow of helium inside the container whose size determined the rate of cyrstallization. A capacitor designed to excite surface oscillations was mounted on one of the metallic walls inside the container, consisting of two copper wires in a capron insulator $\phi = 30\,\mu$m doubly wound (150 turns) on a textolite plate. The maximum field intensity between neighboring coils was $\sim 10^6$ V/cm.

It turned out, however, that even a small vibration of the instrument was enough to excite visible oscillations. By tapping on the outer door of the cryostat, the amplitude of the interphase boundary oscillation reached 1–2 mm^2. Figure 1 shows a motion picture sequence of the excitation and damping of oscillations. The first frame shows the calm boundary between the solid (located below) and liquid phases. The subsequent frames demonstrate the behavior of the boundary after a sharp blow on the outer wall of the cryostat. Boundary oscillations were clearly observed in the 0.4–0.6 K temperature range. The amplitude of the oscillations decreases rapidly with increasing temperature, and is nearly absent even at 0.8 K. This fact is in good agreement with the concept developed in Ref. 2, according to which the damping of the crystallization waves should rapidly increase with increasing temperature.

Diffraction of light from a He–Ne laser on the surface wave[4] was used to measure the oscillation spectrum. By applying a variable voltage to the capacitor, it turned out

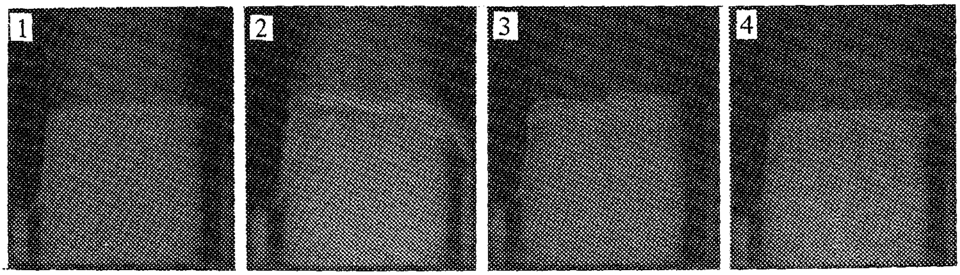

FIG. 1. Motion picture frames of the excitation and decay of crystallization waves at 0.5 K. The capacitor can be seen in the left side of the frames.

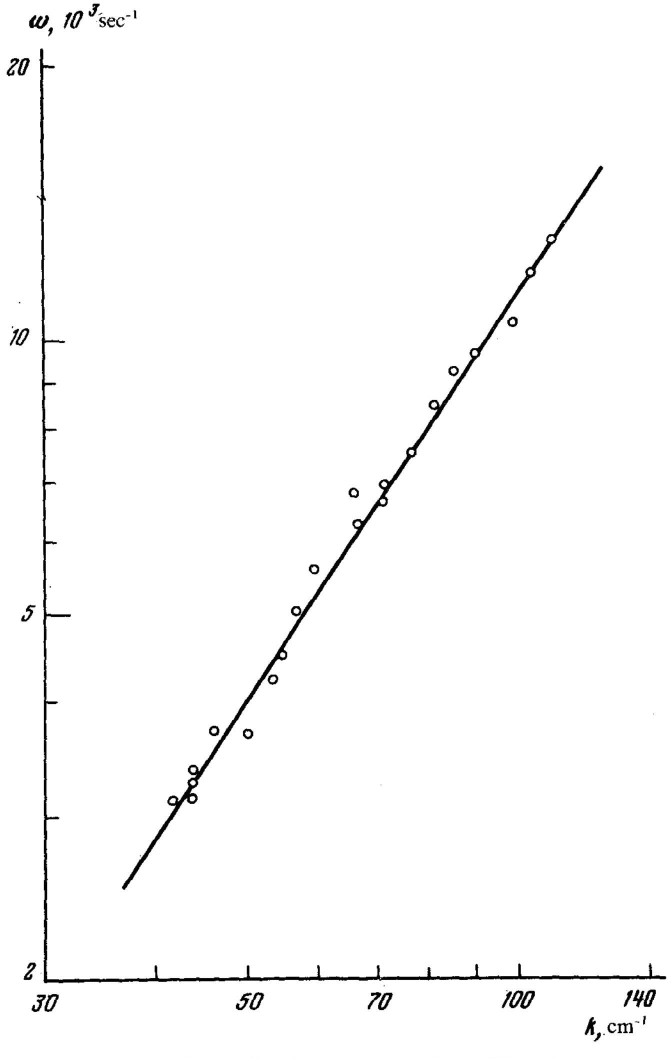

FIG. 2. Spectrum of crystallization waves at 0.43 K. The solid line is $\omega \sim k^{2}$.

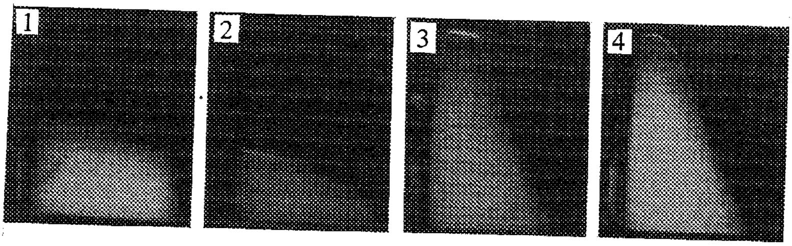

FIG. 3. Different stages in the growth of one of the crystals at 0.5 K.

to be possible to excite a "plane" wave (with an accuracy up to the surface curvature) and to study the oscillation spectrum $\omega(k)$. Results of the measurments at 0.43 K are shown in Fig. 2. Clearly, the predicted[2] dependence for crystallization waves $\omega \sim k^{3/2}$ is well satisfied. In the range of frequencies investigated the effect of gravity and compressibility of both phases may be neglected. The value of the surface tension α computed from these data (neglecting anisotropy) turns out to be 0.23 ± 0.04 erg/cm^2. It should be noted that plane waves could be observed only for certain, apparently monocrystalline, samples (see below). This fact may be explained by the anisotropy of α in a most natural way. We also note that vibrations of the cyrostat and the significant curvature of the meniscus (see Fig. 1) substantially complicate measurements by means of the technique being used.

From Fig. 1 it can be seen that the surface of the crystal forms a convex meniscus. In other words, solid helium poorly wets the solid walls (ferrochromium, glass, and the capron insulator of the capacitor leads). This condition had already been noted.[5,6] The observed values for the meniscus height and contact angle lead to a value for the surface tension at the interphase boundary $\alpha = 0.2$–0.3 erg/cm^2 over the entire temperature range from 0.45 to 1.2 K. This value as well as the preceding one are based on neglecting the anisotropy of α.

We conducted a large number of observations of the growth process for He^4 crystals. Crystallization was begun at a single random point, and we succeeded in following the growth of the crystal from the moment when the size of the nucleus had already reached 2–3 mm^2. The nucleus is usually limited at some stage. For further growth the orientation of the facets is maintained, while their degree of curvature depends on the rate of growth: the faster the rate the sharper the facets. In our experiments the growth rate varied from 0.01 mm/sec to 1–2 mm/sec. A similar dependence of the shape of a growing crystal on the growth rate has been observed previously.[6] Figure 3 shows motion picture frames demonstrating various stages in the growth of one of the crystals. It is curious to note that during the growth process the coexistence of plane and rounded surface regions is often observed. Thus, at sufficiently low temperatures such oscillations are clearly observed in the rounded regions (and only in them) as in the stationary boundary. After growth stops the crystal always assumes a rounded shape. If the developed crystal partially melts and then renews its growth process, the orientation of the growing faces is completely preserved. We did not always succeed in growing a monocrystal which occupied a significant part of the container volume; usually, the sample consisted of several units. As a rule, the unit samples had an undulating surface. After the termination of growth, the surface acquired the shape of an ideal meniscus apparently only for certain monocrystalline samples.

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