Crystallization waves in ⁴He

A. Ya. Parshin

S. I. Vavilov Institute of Physical Problems of the Academy of Sciences of the USSR Usp. Fiz. Nauk 135, 175-178 (September 1981)

PACS numbers: 67.80. - s, 64.70.Dv

According to the classical views (see, e.g., Ref. 1), a macroscopically homogeneous surface of a crystal existing in equilibrium with a liquid or vapor can be atomically smooth or atomically rough. A rough surface is characterized by a high concentration of different types of surface defects: steps, jogs, adatoms, etc. With a certain degree of arbitrariness, one can treat an atomically smooth surface as a two-dimensional crystal having a small concentration of defects. and an atomically rough surface as a two-dimensional liquid. At low enough temperatures such a liquid should freeze just like ordinary three-dimensional liquids. In other words, any classical crystal at absolute zero must have an atomically smooth surface without any defects. This statement stems directly from the fact that an atomically rough surface (in the classical sense) cannot exist as an equilibrium surface at absolute zero. since its entropy is not zero.

As Andreev and the author have shown,² quantum effects can alter the situation. Namely, if the amplitude of the zero-point vibrations is large enough, an atomically rough surface can remain in the "liquid" state down to absolute zero, just as ordinary liquid helium does at pressures below 25 atm. Of course, this state is no longer rough in the classical sense, but amounts to its quantum analog. At absolute zero all "roughnesses" in this state must be delocalized and collectivized, and their movement must be strictly coherent, just like the movement of particles of a superfluid liquid. In particular, this coherence implies that the growth and melting of a crystal with such a surface at absolute zero can occur in a strictly nondissipative manner without destroying phase equilibrium.

In order to convince ourselves that such a situation is actually possible, let us examine the following simple example. Let an isolated step with a jog exist on the atomically smooth surface of a quantum crystal [Fig. 1(a)] existing in equilibrium with the liquid phase. The jog can be treated as a point defect on the step. The energy of the jog does not vary when it is shifted by the



FIG.1.

translation vector of the crystal, since the transfer of material from one phase to the other that accompanies this shift does not contribute to the energy, owing to the equal chemical potentials of phases existing in equilibrium. Therefore, similarly to other point defects in a quantum crystal,³ the jog behaves like a delocalized quasiparticle whose state is defined by a quasimomentum. Let p_0 be the value of the quasimomentum corresponding to the bottom of the energy band [Fig. 1(b)]. At absolute zero this state for an isolated jog is stationary (and is the ground state). while the velocity of the jog is zero. The stationary states lying close in energy $(p - p_0)$ correspond to a nonzero velocity of the jog. Thus an isolated jog is an example of a system that has stationary states arbitrarily close in energy to the ground state, and which is characterized by a continuous flux of matter from one phase to the other. And this implies that crystallization (or melting) can occur in a strictly nondissipative manner. By analogy with superfluidity, such a process can be called "supercrystallization" (or "supermelting").

Of course, an actual quantum-rough surface is much more complex in structure than in the treated example; nevertheless, we can assume that a surface between liquid and solid helium can possess this property, at least when in certain orientations. If this is actually so, then the crystallization and melting of helium at low enough temperatures can possess many unusual features, of which the most interesting seems to be the existence of weakly damped oscillations of the surface caused by periodic melting and crystallization. These oscillations-crystallization waves-can have a macroscopic amplitude. In many ways they resemble the ordinary capillary waves at the surface of a liquid. The distinction consists in the fact that the movement of the boundary in the case of crystallization waves is totally due to periodic melting and crystallization, while the crystal remains completely motionless in bulk (in the long-wavelength limit, in which we can neglect the compressibility of the two phases). The spectrum of these waves, without account taken of the gravitational field and the damping, is given by the expression

$$\omega^2 = \left(\alpha + \frac{\partial^2 \alpha}{\partial \varphi_1^2}\right) \frac{\rho_2}{(\rho_1 - \rho_2)^2} k^3.$$
(1)

Here $\alpha(\varphi_1, \varphi_2)$ is the surface energy for a given orientation defined by the angles φ_1 and φ_2 , with φ_1 measured from the direction of **k**, and ρ_1 and ρ_2 are the densities of the crystal and of the liquid, respectively. The damping of the crystallization waves can also be cal-





culated.² Let us stress once again that these waves have no relation to ordinary surface elastic waves in crystals.

Crystallization waves in ⁴He have been observed experimentally.⁴ These experiments employed an optical cryostat having a design due to A. I. Shal'nikov,⁵ which permitted one to observe directly the process of growth of helium crystals at different temperatures down to 0.4 K. The ⁴He crystals were grown in a rectangular container with dimensions $12 \times 15 \times 28$ mm. At temperatures below 1 K, the growing crystal has a more or less clearly marked shape of a hexagonal prism, which gradually fills the entire lower part of the container (the crystal is somewhat heavier than the liquid). At equilibrium the surface of the crystal becomes rounded, owing to a decrease of the area of the faces of the growth prism, and it acquires the shape of a convex meniscus [Fig. 2(a)]. Oscillations of this surface at temperatures 0.4-0.6 K are easily excited, even by small vibrations of the cryostat [Fig. 2(b)]. Curiously, in direct visual observation these oscillations look just like the vibrations of the surface of ordinary liquids. Their amplitude can be as much as several millimeters. Here the monocrystallinity of the solid phase apparently does not at all suffer thereby: upon resumed growth of such a crystal, the orientation of the faces of the growth prism is fully restored.

The experimentally measured spectrum of the oscillations of the surface exactly corresponds to the theoretical spectrum, and essentially without any adjustable parameters. The sole previously unknown parameter $\alpha + \partial^2 \alpha / \partial \varphi^2$ that enters into (1) can be determined independently from the shape of the equilibrium meniscus,



FIG.3.

just as is done in studying the surface tension of liquids (however, in practice one can determine this parameter with greater accuracy, specifically from the spectrum of the surface waves). With increasing temperature, the damping of the surface oscillations rapidly increases, so that, even at 0.7 K, they practically cease to be excited. This fact fully agrees with the theory,² which predicts an exponential growth of the damping of crystallization waves in this temperature region.

The experimental facts presented here rather convincingly demonstrate the real existence of the special quantum state of a surface that had been postulated in Ref. 2. We note that this state is apparently realized for all orientations of the surface except for "special" orientations, namely those corresponding to the faces of the growth prism [thus, the base of the prism constitutes the face (0001). If the crystal is oriented with respect to the gravitational field so that one of the "special" faces is close to the horizontal plane, then the equilibrium meniscus will correspondingly contain an oriented plane region surrounded by a fully curved surface (Fig. 3). Here the crystallization waves are observed as before in the curved regions, while the "special" face remains completely motionless. That is, it behaves like a classical atomically smooth surface.

- ¹A. A. Chernov, Usp. Fiz. Nauk **73**, 277 (1961) [Sov. Phys. Usp. **4**, 116 (1961)].
- ²A. F. Andreev and A. Ya. Parshin, Zh. Eksp. Teor. Fiz. 75, 1511 (1978) [Sov. Phys. JETP 48, 763 (1978)].
- ³A. F. Andreev and I. M. Lifshits, Zh. Eksp. Teor. Fiz. 56, 2057 (1969) [Sov. Phys. JETP 29, 1107 (1969)].
- ⁴K. O. Keshishev, A. Ya. Parshin, and A. V. Babkin, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 63 (1979) [JETP Lett. **30**, 56 (1979)].
- ⁵A. I. Shal'nikov, Zh. Eksp. Teor. Fiz. **47**, 1727 (1964) [Sov. Phys. JETP **20**, 1161 (1965)].

Translated by M. V. King