

Charge-Induced Deformation of the ^4He Solid-Superfluid Interface

J. Bodensohn and P. Leiderer, Fachbereich Physik, Johannes Gutenberg-Universität, 6500 Mainz, West Germany

and

D. Savignac, Technische Universität München, 8046 Garching, West Germany

The interface between solid and superfluid ^4He has revealed unusual dynamic properties. Characteristic of this quantum system are the very high thermal conductivity of the superfluid phase, and an extremely small heat of fusion below temperatures of about 1 K. As a result, equilibrium at the solid-superfluid ^4He interface is established quite rapidly, which gives rise, e.g., to melting - crystallization waves [1,2] - similar in appearance to surface waves on a free liquid surface - and to anomalous transmission of sound [3].

When a perturbation is acting on the solid-liquid interface, the response of the system is governed by two coupled equations which describe material and thermal transport. The kinetic coefficients characterizing these processes have been calculated from the density of thermally excited phonons and rotons by BOWLEY and EDWARDS [4]. Experimentally the relevant parameter for the motion of the interface, the kinetic growth coefficient K , has been derived from the damping of melting-freezing waves by KESHISHEV et al. for $T < 0.6$ K [2]. At higher temperatures the relaxation times for crystal growth were too long to be measured with this technique. Here we describe a method which is applicable also in the range of extremely long relaxation times, so that temperatures above 1 K, where the density of thermal excitations is high, become accessible, and in addition to the hcp phase of solid He also the bcc phase can be studied. As a by-product, also the interfacial tension of the solid-liquid boundary is obtained.

Our method is based on melting a thin layer of the helium crystal by the application of a small electrostatic pressure, and then recording the relaxation of the interface back to its original equilibrium position as the pressure is removed. For this purpose, the interface is charged with negative ions, which are generated in the superfluid by a field emission tip and drawn toward the solid by an electric field of the order of 1 kV/cm. The ground state energy of the ions in the crystal is about 18 meV higher than in the liquid [5], the charges therefore encounter an energy barrier high enough that they are prevented from penetrating into the solid and thus accumulate at the interface.

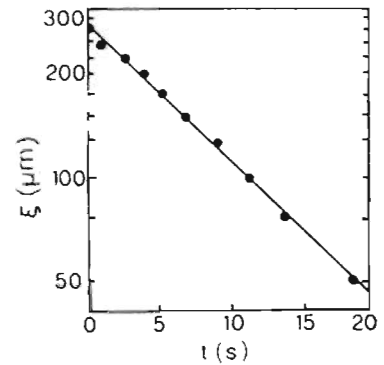
The pressure p_{el} which the space charge layer exerts upon the solid gives rise to a difference in chemical potential per unit mass, $\Delta\mu = p_{el}/\rho_s$, between the solid and the liquid phase, whose densities are ρ_s and ρ_l , respectively. As a result, the crystal melts in the charged area to such a depth ξ_0 that the electrostatic pressure is balanced by the gravitational pressure $p_g = (\rho_s - \rho_l) g \xi_0$. (Here we have assumed that the wave vector characterizing the deformation is small compared to the inverse capillary length a^{-1} [5] - 10 cm^{-1} for the hcp-superfluid interface - so that contributions from the interfacial tension are negligible; temperature differences are neglected as well.)

When the electric field is switched off, the crystal grows to its original shape with a velocity of the interface $v = m_4 K \Delta\mu(t)$, where m_4 is the ^4He atomic mass, and the chemical potential difference now is given by $\Delta\mu = \xi(t) g (\rho_s - \rho_l) / \rho_s$. Since $v = d\xi/dt$, the interfacial position varies in height as $\xi(t) = \xi_0 \exp(-t/\tau)$ with a relaxation time

$$\tau = \frac{\rho_s}{(\rho_s - \rho_l) g} \cdot (m_4 K)^{-1} \quad (1)$$

An example for the growth of an hcp ^4He crystal at 1.35 K after turning off the electric field is shown in Fig. 1. As expected, the position of

Fig. 1: Semilog plot of the relaxation of a ^4He hcp-superfluid interface at $T = 1.35\text{ K}$, after a crystal layer of $\xi_0 = 270\ \mu\text{m}$ had been melted by applying an electrostatic pressure $P_{el} = 4.5 \times 10^{-7}$ bar to the interface. The change in crystal thickness as P_{el} is turned off at $t = 0$ is measured with a resolution of $10\ \mu\text{m}$ by means of an interferometric technique [5].



the interface changes exponentially. The time constant here is 11 sec, corresponding to a growth resistance $(m_4 K)^{-1} = 9.6\ \text{m/s}$. One might suspect that by repeated melting and growth the crystal quality deteriorates, which could influence the kinetic processes at the interface. We found, however, that the reproducibility of the relaxation times was not affected as long as the applied electric field did not exceed a critical value E_c where the interface becomes unstable (see below).

The temperature dependence of the relaxation time for crystal growth is plotted in Fig. 2. The data are compatible with a dependence

$$\tau \propto \exp(-\Delta/k_B T) \quad (2)$$

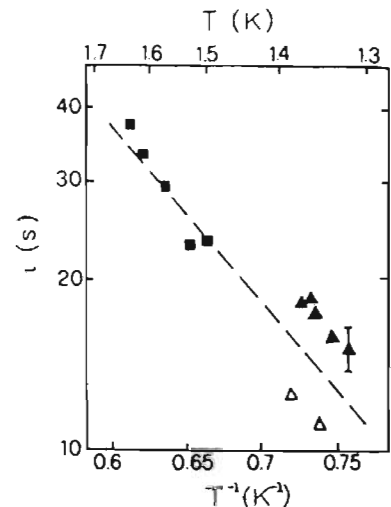


Fig. 2: Relaxation times for the growth of a bcc (squares) and two hcp (open and full triangles) crystals of ^4He in contact with the superfluid phase. The dashed line represents a temperature dependence $\tau \propto \exp(-\Delta/k_B T)$, with $\Delta/k_B = 7.2\ \text{K}$. A typical error bar is indicated.

where Δ is the roton energy, suggesting that - as supposed earlier [2] - the thermal excitations in the liquid phase dominate the crystallization rate. The crystal structure apparently is not relevant because the same relation is found for both the hcp- and the bcc-superfluid interface within the scatter observed for various crystal orientations. The data for τ , when extrapolated according to (2) to $T < 0.6$ K, are in remarkably good agreement with the results of KESHISHEV et al. [2] regarding that the extrapolation extends over 4 orders of magnitude.

As already indicated, the interface becomes unstable at high electric holding fields E , a phenomenon to be understood in terms of the dispersion relation for melting - freezing waves in the presence of charges [5]

$$\omega^3 = \frac{\rho_l}{\rho_s - \rho_l} gq + \frac{\rho_l}{(\rho_s - \rho_l)^2} \bar{\alpha} q^3 - \frac{i\omega q \rho_s \rho_l}{in_4 K (\rho_s - \rho_l)^2} - \frac{\rho_l}{4\pi(\rho_s - \rho_l)^2} q^2 \epsilon E^2 \quad (3)$$

Here again the subscripts s and l refer to the solid and the liquid phase, respectively; ϵ is the dielectric constant, and the effective interfacial tension in the form $\bar{\alpha} = \alpha + \partial^2 \alpha / \partial \varphi^2$ includes the dependence of α on the orientation of the surface with respect to the crystal axes. Although in the temperature range $T > 1.3$ K investigated here these waves are normally overdamped (i.e., the third rhs term predominates), equation (3) predicts that for E above a critical field E_c a band of modes around a wave vector

$$q_c = [g(\rho_s - \rho_l) / \bar{\alpha}]^{1/2} \quad (4)$$

will grow instead of decay in time and therefore lead to an instability of the interface. For electric fields near E_c this range of unstable modes is given by $|q - q_c| \leq 2q_c [(E - E_c) / E_c]^{1/2}$.

We have observed the growth of these modes by the same interferometric method as the stationary deformations at lower fields. As E is raised above E_c , corrugations spontaneously develop at the interface, whose preferential orientation is governed by the anisotropic surface properties of the helium crystal. For $(E - E_c) / E_c \ll 1$ the wave vector of these deformations approaches the critical wave vector q_c . Using (4) this provides a new method to obtain the interfacial tension between the liquid and the solid phase. Preliminary measurements for an hcp-superfluid interface (orientation not determined) at 1.35 K yield $\bar{\alpha} = 0.12 \pm 0.01$ erg/cm², in good agreement with earlier results [6].

We appreciate valuable discussions with Prof. D.O. Edwards. This work was supported by the Deutsche Forschungsgemeinschaft.

References

1. A.F. Andreev and A.Y. Parshin, Zh.Eksp.Teor.Fiz. 75, 1511 (1978) [Sov.Phys. JETP 48, 763 (1978)]
2. K.O. Keshishev, A.Y. Parshin, and A.B. Babkin, Zh.Eksp.Teor.Fiz. 80, 716 (1981) [Sov.Phys. JETP 53, 362 (1981)]
3. B. Castaing, S. Batībar, and C. Laroche, J.Physique 41, 897 (1980)
4. R.M. Bowley and D.O. Edwards, J. Physique 44, 723 (1983)
5. D. Savignac and P. Leiderer, Phys.Rev.Lett. 49, 1869 (1982)
6. J. Landau, S.G. Lipson, L.M. Määttänen, L.S. Balfour, and D.O. Edwards, Phys.Rev.Lett. 45, 31 (1980)