D. SAVIGNAC, Technische Universität München, and J. BODENSOHN and P. LEIDERER, Universität Mainz, 6500 Mainz, West Germany.

When a liquid surface is charged, an electrohydrodynamic instability develops at high charge densities as a result of the coupling between the charges and interfacial excitations /1/. For an ordinary solid surface such an instability is not expected because its excitation spectrum is quite different from a liquid. Solid ^{4}He, in contrast, is unique in this respect because at the interface toward the superfluid phase rapid melting and freezing leads to interfacial waves characterized by a dispersion relation /2/

$$\omega^2 = \frac{\rho_l}{\rho_s - \rho_l} g\eta + \frac{\rho_l}{(\rho_s - \rho_l)^2} \bar{\alpha}\eta^3 - \frac{i\omega\eta\rho_s\rho_l}{m_4 K(\rho_s - \rho_l)^2} \qquad (1)$$

resembling surface waves on a liquid. (Here ρ_l and ρ_s are the densities of the liquid and solid phase, respectively, g is the gravitational acceleration, $\bar{\alpha}$ is the effective interfacial tension and m_4 the atomic mass of ^{4}He; the last rhs term represents the damping of the excitations arising from the finite growth coefficient K of the crystal.) As this interface is charged, e.g., with negative ions (= electron bubbles), the frequency of the interfacial excitations will be reduced by the wavevector-dependent electrostatic pressure to a value ω_E, given by /3/

$$\omega_E^2 = \omega^2 - \frac{\rho_l}{4\pi(\rho_s - \rho_l)^2} \eta^2(\varepsilon E^2) \qquad (2)$$

where ε and E are the dielectric constant and the electric field in the solid, and the interface for simplicity is assumed to be completely charged (i.e. in the liquid E = 0).

According to Eq. (2) a charge- induced instability ought to develop also at the He^4 solid-liquid interface when the electric field is increased above a critical value $E_c = [64\pi^2 g\bar{\alpha}\Delta\rho/\varepsilon^2]^{1/4}$, similar to the behavior of the charged free liquid ^{4}He surface /4/. There at the onset of the instability the initially homogenous charge distribution spontaneously breaks up into a spatially periodic state: a crystal-like regular array of charged dimples appears on the surface, which for $E = E_c$ has a lattice spacing equal to $2\pi a$ ($a = [\bar{\alpha}/g\Delta\rho]^{1/2}$ is the capillary length).

We have sought for the possible formation of regular dimple structures on solid He in a cylindrical sample cell (inner diameter d = 2 cm) with optical access from the top. Since d was comparable to $2\pi a$ (0.62 cm for hcp-superfluid ^{4}He at T = 1.35 K), a dimple lattice at $E = E_c$ (= 1850 V/cm) was not to be expected in this case. We have therefore studied the development of the charge-induced instability at fields somewhat above E_c, corresponding to a smaller characteristic wavelength of the instability /3/ . As Fig. 1 shows, a regular dimple pattern is indeed observed, although with an obvious influence of the cylindrical geometry. The anisotropy of the crystal surface manifests itself

Fig. 1: Charge-induced instability of an hcp-superfluid ^{4}He interface, as observed from above, at T = 1.35 K and $E \sim 1.2\ E_c$. The instability develops in the form of dimples on the interface - here appearing as dark spots - in which the ions accumulate. The diameter of the pattern is about 1.5 cm. The fringes result from the interference of light reflected at the bottom and the top plate of the sample cell.

in an elliptical deformation of the pattern. A more detailed study of the instability should allow to quantitatively determine the anisotropic properties of this surface.

In Fig. 2 examples for the development of the instability at fields well above E_c are given. The higher E the smaller is the characteristic distance of the dimples in the instability pattern. Furthermore a tendency toward a more chaotic behavior is apparent, resulting from - according to eq. 2 - an increasing band of unstable wave vectors. Again, the anisotropy of the instability pattern is due to the crystalline substrate of the electron system.

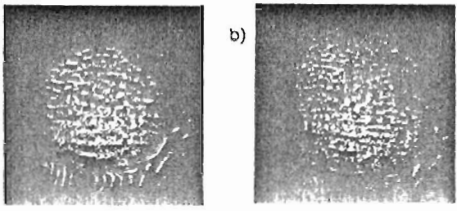

Fig. 2: Instability pattern of an hcp-superfluid ^{4}He interface at E/E_c = 2.6 (2a) and 2.9 (2b), respectively. The scale is the same as in Fig. 1.

It should be mentioned that the corrugations in Figs. 1 and 2 result from melting processes and not, as might be suspected, from a plastic deformation of the crystal. This is supported by the observation that in the course of the instability the dimples increase in depth, until charged liquid bubbles split off from the dimple tips and move through the crystal at a relatively high velocity of the order of 1 mm/sec. A typical bubble has a diameter of $D \sim 0.1$ mm and contains $N \sim 10^6$ electrons /5/; hence the electrostatic pressure $P_{el} = NeE/\pi D^2$ exerted by the charges on the solid in the direction of the electric field is only about 1 Pa at E = 2000 V/cm. This seems to be at variance with an experiment by Andreev et al. /6/, where a small magnetic sphere, pulled against solid He with a pressure as high as 5×10^4 Pa, moved at a velocity $v \lesssim 2 \times 10^{-7}$ cm/sec. The apparent contradiction is resolved when the presence of the solid-liquid interface in our experiment is taken into account. The electrostatic pressure gives rise to a difference in the chemical potential $\Delta\mu$ between the solid and the liquid phase, which leads to melting of the solid at the bubble front with a velocity $v = m_4 K \Delta\mu$, while at the opposite side solidification at the same rate takes place. Taking for the growth resistance $(m_4 K)^{-1}$ of the solid-liquid interface a value of 10 m/s at 1.35 K /7/, we obtain $v \sim 0.5$ mm/s, in quite satisfactory agreement with the observed bubble velocity.

We gratefully acknowledge financial support by the Deutsche Forschungsgemeinschaft.

References

/1/ See, e.g., V.B. Shikin and P. Leiderer, Zh.Eksp.Teor.Fiz. 81, 184 (1981) [Sov.Phys. JETP 54, 92 (1981)]
/2/ K.O. Keshishev, A.Ya. Parshin, and A.B. Babkin Zh.Eksp.Teor.Fiz. 80, 716 (1981) [Sov.Phys. JETP 53, 362 (1981)]
/3/ D. Savignac and P. Leiderer, Phys.Rev.Lett. 49, 1869 (1982)
/4/ P. Leiderer and M. Wanner, Phys.Lett. 73A, 189 (1979)
/5/ roughly estimated from the number of bubbles and the original charge density
/6/ A. Andreev, K. Keshishev, L. Mezhov-Deglin, and A. Shal'nikov, Pis'ma Zh.Eksp.Teor.Fiz. 9, 507 (1969) [JETP Lett. 9, 306 (1969)]
/7/ J. Bodensohn, P. Leiderer, and D. Savignac, to be published.