STRUCTURE OF THE DIMPLE LATTICE ON LIQUID ^4He

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Electrons on the surface of liquid ^4He become localized in macroscopic dimples when the electric field perpendicular to the surface exceeds a critical value. These dimples, each holding about 10^7 electrons, form a two-dimensional hexagonal lattice.

The free surface of liquid ^4He has proven to be quite a versatile experimental system. It has been studied as an example of an extremely clean and well-characterized surface, and most of its properties, like the surface tension and the spectrum of surface excitations, are well known [1]. In other experiments this surface has been used because of its unique features, e.g. as a particularly homogeneous and suitable substrate for a two-dimensional sheet of electrons [2].

Such a layer of electrons at the surface is not without influence on the surface itself. It has been predicted that the spectrum of surface excitations (ripples) will be modified because the electrons exert a pressure, which in effect reduces the contributions of surface tension and gravity in the dispersion relation [3,4]:

$$(\rho_l + \rho_g)\omega^2 = (\rho_l - \rho_g)gq + \sigma q^3 - E^2 q^2 / 2\pi. \quad (1)$$

Here ω and q are the frequency and wave vector of the ripples, q is the acceleration of gravity, σ the surface tension, ρ_l and ρ_g the density of liquid and gaseous helium and E the externally applied electric field $^{\dagger 1}$. According to eq. (1) it is expected that the ripplon frequencies will be reduced by the electric field, in particular for the "soft ripplon" at a wave vector $q = 1/a$, where $a = [\sigma/(\rho_l - \rho_g)g]^{1/2}$ is the capillary length. Eventually, at a critical field E_c the

frequency of the soft ripplon will have dropped to zero and the surface becomes unstable. It spontaneously deforms, and in an electrical break-through the charge disappears from the surface.

An instability of that kind has been observed recently at the charged interface of ^3He – ^4He mixtures [5], a system in many respects similar to the free helium surface. Somewhat surprisingly, however, not all the charge carriers – electron bubbles in this case – left the interface during the break-through; the remaining charge was no longer distributed homogeneously throughout the interface, but in a periodic array of groups of about 10^6 electron bubbles, giving rise to a strikingly regular pattern of interfacial indentations, the "dimple crystal".

Whereas there exist only few investigations of ions at the mixture interface, electrons at the free liquid surface have been studied extensively [2, 6–8]. Loss of the surface charge related to the predicted instability of the surface has been reported by several authors [9,10], and the development of this instability has been investigated in detail by Khaikin and coworkers [11]. A regular array of dimples, however, was never observed. Therefore the question arose whether the dimple crystal is a peculiarity of the mixture interface and for some not obvious reason cannot exist at the free surface.

In the experiment described here we found that the dimple crystal does indeed form and is stable also at the free helium surface. Besides, we have determined its structure, which appears to agree with that at the

$^{\dagger 1}$ In eq. (1) it is assumed that the discontinuity in the electric field at the surface due to the surface electron density n , $\Delta E = 4\pi ne$, is much smaller than the external field E , i.e. the surface is far from being charged to saturation.

mixture interface.

Comparing the ^4He surface at, say, 4.2 K with the interface of ^3He – ^4He mixtures at 0.57 K [5] more quantitatively, we expect the formation of dimples in these two systems to differ in several respects, mainly because the surface tension σ is considerably higher than the interfacial tension [1, 12]:

(i) Assuming low charge density, (see footnote 1), the critical field is given by

$$E_c = [16\pi^2\sigma(\rho_g - \rho_l)g]^{1/4}, \quad (2)$$

which yields an absolute value of $E_c = 1830$ V/cm at the surface, more than twice as high as at the interface ^{#2}.

(ii) In our earlier experiment [5], the lattice constant of the dimple crystal at the interface was found to be of the order of $2\pi a$. Since for the helium surface $a = 0.28$ nm, the dimple crystal there should have a lattice constant of about 2 nm, distinctly larger and hence even more readily observable than at the ^3He – ^4He interface. Likewise, also the size of the dimples

^{#2} For the other limiting case, namely a surface charged completely so that the field above the helium surface is zero, the critical field below the surface is $E_c\sqrt{2}$. See ref. [3].

and the number of charges in each dimple should be larger.

In the measurements the helium surface was located between two parallel horizontal capacitor plates with a diameter of 80 mm and a spacing of 20 mm. The surface was charged with electrons emitted from a tiny filament close to the upper capacitor plate. When the voltage between the plates was increased above a critical value, the homogeneous depression of the helium surface due to the sheet of electrons [8] changed abruptly to a state of violent motion, and electrical break-through was observed as long as electrons were supplied by the filament. Only when the electron source was switched off the surface became calm again, and a steady dimple lattice appeared. The reason for this behaviour will be discussed below.

A photograph of the dimple crystal on liquid ^4He at a temperature of 4.2 K is shown in fig. 1. The picture was taken at an angle of 10° through the viewing slit of a conventional glass cryostat. The lattice structure in this photograph is obscured by the large distortion. Therefore, a rectified portion of the dimple lattice is drawn in fig. 2. Obviously the lattice has hexagonal symmetry. A structure of this type, which also seems to form at the ^3He – ^4He interface [5],

Fig. 1. Lattice of electron dimples at the free surface of liquid ^4He , photographed at an angle of 10° . The applied external field is 1820 V/cm, the temperature 4.2 K. The illumination was chosen such that deformations of the surface appear bright. The diameter of the lattice is about 4 cm. Arrows indicate the origin used in fig. 2.

Fig. 2. Rectified dimple positions as obtained from fig. 1. Circles represent the approximate dimple size. The hexagonal cell at the center is drawn for a lattice constant $d = 2\pi a$, corresponding to 1.76 mm. Apparent deviations from the ideal lattice are partly due to the poor optical quality of the glass Dewar walls.

has been suggested as being energetically most favourable [3].

The lattice spacing in fig. 1 is found to vary somewhat throughout the dimple crystal, but within 10% agrees with $2\pi a = 1.76$ mm, the wavelength calculated for the soft ripplon at the free surface [3]. Although one might imagine the dimple crystal to emerge from the increasing fluctuations, which develop close to instability as a result of the ripplon softening, a slight variation in the lattice parameter is not too surprising because in the dimple state the deformations are large and hence essentially all the charges are concentrated in the dimple minima. Therefore the assumption that the whole surface is at constant electrostatic potential — which is crucial for the derivation of the ripplon dispersion relation (1) — is no longer valid and non-linear effects come into play. Besides, the number of electrons in different dimples is not exactly the same, but depends on the formation process of the lattice in the early stages of the instability.

The dimple crystal could repeatedly be melted and recrystallized, with the phase transition always occurring at the same well-defined external critical field $E_c = 1790 \pm 40$ V/cm (independent of the height h for $0.2 < h < 1.9$ cm of the helium level above the lower capacitor plate). This field agrees well with the value expected for a surface charged to a density consider-

ably below the saturation value n_{sat} (see eq. (2)). From several observations we conclude that a surface in its dimpled state can hold only an average electron density of about

$$n_d \approx 0.2 n_{\text{sat}}. \quad (3)$$

If slowly more charges are added by carefully activating the electron source then dimples start breaking through and keep the surface in agitation. From eq. (3) together with the parameters for dimple formation given above it follows that there is a maximum charge per dimple of about 10^7 electrons. Such a value can also be estimated from calculations for the stability limit of a single, isolated dimple [13].

The forces acting on the dimples arise from the externally applied field, from the Coulomb repulsion between the individual dimples, and from the attractive interaction due to the deformation of the surface. The dimple crystal thus appears as a relatively simple and easy to survey model system for a two-dimensional solid which because of the predominant electrostatic interaction resembles a Wigner crystal [14]. Since the mobility of the charges at the free helium surface is very high and the viscosity of the substrate is small, at least for temperatures below the lambda point, this new system lends itself to study not only the crystal structure, but also dynamical phenomena, like longitudinal and transverse modes, in a macroscopic two-dimensional Coulomb lattice.

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