MULTIELECTRON DIMPLES ON THE SURFACE OF LIQUID ^4He

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We have investigated the self-trapping of electrons in macroscopic dimples on the surface of liquid ^4He . The existence of individual multielectron dimples is demonstrated.

I. INTRODUCTION

The Coulomb system formed by electrons on the surface of liquid helium has been studied extensively for about a decade/1/. In most of the experiments the liquid surface only was to serve as a nearly ideal flat substrate to confine the motion of the electrons to two dimensions; the coupling between the charges and the excitations of the surface generally could be neglected, except for the influence of the electron-ripplon scattering on the mobility of the electrons.

In some recent experiments, however, like the investigation of the microscopic two-dimensional electron crystal/2/ and the softening of ripples/3/ the interaction between the Coulomb system and the liquid surface is quite essential. The coupling increases as the applied electric field pulling the electrons towards the surface is raised, until finally, as a result of an electrohydrodynamic instability of the surface, the homogeneous charge distribution breaks up at a critical field E_c and a periodic array of macroscopic dimples, each containing a large number ($\sim 10^7$) of electrons, appears at the surface. Investigations of the properties of this dimple crystal close to the transition, i.e. for fields $(E-E_c)/E_c \ll 1$, have already been published/4/. Here we present results for dimples at fields well above E_c , and in particular deal with individual multielectron dimples.

II. THEORETICAL

The instability of a charged liquid helium surface in high electric fields has first been considered by Gorkov and Chernikova/5/, and in more detail by Ikezi/6/, who for $E \geq E_c$ obtained periodic deformations by including nonlinear terms in the equation of motion of the charged surface.

Extending these theories to fields distinctly larger than E_c , where the surface deformations become large, would require to take into account terms of still higher order. We have here chosen a different approach, considering the stability of a single macroscopic dimple. Both the deformation of the surface and the charge distribution in the dimple were determined by means of a self-consistent numerical calculation/7/. Starting from some fixed initial configuration of electrons, $n_0(r)$, and an external field E the local depression $z(r)$ of the liquid surface was

obtained by minimizing the total energy of the dimple, which consists of contributions from gravity, surface tension, and electrostatic energy:

$$W_{\text{tot}} = \int z \left[\frac{1}{2} \rho g z + \sigma (1+z'^2)^{1/2} + \frac{1}{8\pi\epsilon} ((\epsilon+1)4\pi n_0(r)eE - (\epsilon-1)(E^2 + (2\pi n_0(r)e)^2)) \right] 2\pi r dr$$

Here ρ is the density of the liquid (the density of the vapor is neglected), g is the acceleration of gravity, σ the surface tension and ϵ the dielectric constant. From the surface deformation found in this way a new electron configuration $n_1(r)$ was determined - using the condition of constant electrostatic potential within the charge distribution and keeping the total charge of the dimple $Q = e \int n(r) 2\pi r dr$ fixed - and then the procedure was repeated.

The stability of such a localized charge distribution on the surface of liquid helium depends on the applied electric field and the number of electrons in the dimple:

i) at high fields and large Q the charges become more concentrated at the center of the dimple in each iteration step, and the dimple depth increases indefinitely, leading to a break-through of the charges as expected.

Fig. 1: Calculated electron density $n(r)$ and surface profile $z(r)$ of a dimple containing 5×10^6 electrons in an electric field $E = 3400$ V/cm. The helium temperature is 2.5 K, the corresponding critical field $E_c = (16\pi^2 g \rho \sigma)^{1/4}$ is 2600 V/cm/4/.

ii) at low fields the charges spread out more and more, indicating the formation of a homogeneously distributed layer of electrons at the surface.

iii) for an intermediate range of fields above E_c a stable configuration can be obtained after several iterations if the charge in the dimple is below a limit $Q_c(E)$. An example for the surface profile and charge density of such an isolated dimple is given in Fig. 1. (Note that $n(r)$ in the center of the dimple is larger than the maximum attainable electron density of a homogeneously charged surface, which is $n_{\max} = 2.1 \times 10^9/\text{cm}^2$ at that temperature/4/.)

As Fig. 1 shows dimples can exist as isolated entities, with the electrons being completely confined to the center of the dimple. Since due to this self-trapping of the electrons the charge in each dimple is fixed, the interaction between individual dimples is dominated by Coulomb repulsion. An arrangement of such "deep" dimples at the surface of liquid helium can therefore be considered as a macroscopic two-dimensional Coulomb system; in contrast, for the "shallow" dimple lattice close to E_c , as calculated by Ikezi/6/, the electron density at the surface nowhere vanishes, but is only modulated and might thus be regarded as a charge density wave.

III. EXPERIMENTS

The existence of individual dimples was confirmed by measurements in a sample cell consisting of two horizontal capacitor plates (spacing 1.5 cm) and a cylindrical wall (diameter 8 cm). The lower capacitor plate was a gold mirror, the upper was a glass plate covered with a transparent conductive coating which allowed to observe the helium surface from above. Starting with an uncharged ^4He surface and an applied electric field $E > E_c$, a pulse of electrons was generated by momentarily heating a small filament located close to the circumference of the cell. The emitted electrons were pulled against the surface and then formed a dimple with a charge Q being determined by the emission of the source.

Fig. 2: Configurations of 2, 8 and 20 dimples (appearing as dark spots) in an external potential of cylindrical symmetry.

Fig. 3: Interferogram of a macroscopic dimple ($\sim 7 \times 10^6$ electrons, $E = 2700 \text{ V/cm}$, $T = 2.7 \text{ K}$). The fringe pattern is asymmetric because the two interferometer plates were slightly tilted. Consecutive fringes correspond to a difference in surface height of $11 \mu\text{m}$, the total dimple depth therefore is $80 \pm 10 \mu\text{m}$.

Since the negatively charged wall of the sample cell gives rise to a cylindrically symmetric potential, the dimple after being generated drifts to the potential minimum at the center of the cell. As more dimples are added they arrange themselves leading to configurations illustrated in Fig. 2. Upon increasing the number of constituents further a hexagonal lattice develops gradually which is also observed when the dimple state is produced from a homogeneous charge distribution by raising the electric field beyond the instability threshold/4/.

The deformations of the liquid surface near a dimple can be measured with high resolution, as is obvious in Fig. 3, which shows an interference pattern of a dimple obtained by the superposition of light reflected from the top and bottom capacitor plate. Although in this case for the number of electrons in the dimple only a rough estimate of about 7×10^6 exists, a more accurate determination of Q should allow a sensitive check of the calculations for the dimple state outlined above.

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