Development of instability and bubblon production on a charged surface of liquid helium

A. P. Volodin, M. S. Khaĭkin, and V. S. Édel'man

Institute of Physics Problems, USSR Academy of Sciences

(Submitted 17 October 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 10, 707–711 (20 November 1977)

The onset and development of an instability on a liquid-helium surface charged by electrons localized over the surface are investigated. It is established that the electrons leave the surface by formation of bubblons (bubbles filled with electrons) containing 10^7–10^8 electrons and having dimensions 0.05–0.03 mm. Small-diameter bubblons are stable in a field of 1 cgs esu and move in the helium with a steady-state velocity $\sim 10^4$ cm/sec.

PACS numbers: 67.40.–w

A liquid-helium surface can be negatively electrically charged by electrons localized over th surface.[1] An equilibrium charged helium surface is produced in an electric field under t influence of gravitational, capillary, and electrostatic forces. There exist, however, critical values the electric field (or of the charge density) above which a flat surface becomes unstable. Gor'k and Chernikova have determined the conditions under which a charged helium surface becom unstable.[2,3] Owing to the instability, the attained surface-charge density has an upper bour $\sim 2\times 10^9$ electrons/cm^2, a value previously observed in experiment.[4,5]

In our article we describe experiments aimed at investigating the conditions for the appea ance of the instability, as well as the mechanism whereby the electrons leave the helium surfac The experiments were performed at $T\sim 1.3$ K in the assembly schematically shown in Fig. 1. T electron source was a incandescent tungsten filament 1. The voltage that produced the field whic retained the electrons on the helium surface 2 was applied to the electrodes of the capacitor. T lower, positively charged, plate 3 was surrounded by a screening ring 4. The upper grounded pla 5 was suspended on springs and could move in a vertical direction in the gap between it and t charged helium surface. The plate position was measured with a capacitive pickup 6 and served a measure of the field E_1. The level of the superfluid helium in the capacitor was regulated via t

0021-3640/77/2610-0543$00.60

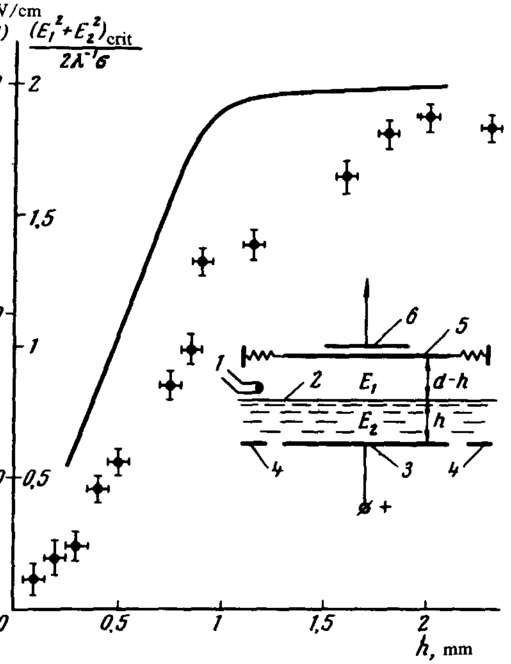

FIG. 1. Dependence of the critical parameter $(E_1^2+E_2^2)_{\text{crit}}$ at which a flat uniform surface of liquid helium becomes unstable, on the depth h of the helium in the capacitor. Points—experiment, curves—calculation.[3]

hermomechanical effect.[6] The capacitor plates, of 40 mm diameter, were positioned parallel to he helium surface with accuracy 30″ as determined by the maximum of the critical parameter (see elow). The distance d between the plates was set in the range 1–5 mm. The assembly was placed ı an optical cryostat fastened onto a platform suspended on soft shock absorbers. To investigate ıe dynamics of the phenomenon, we used high-speed (up to 4000 frames/sec) photography with n SKS-1M-16 camera.

At a certain initial position of the helium level h_0 and a voltage U_0 applied to the capacitor, lectrons were emitted from cathode 1, which was turned on for a time $\sim$0.1 sec. The appearance f the surface charge manifested itself in a complete screening of the field over the helium surface, e., $E_1=0$. The critical conditions for the charged helium surface were then attained either by owly lowering the helium level h in the instrument, or by increasing the voltage U. The field E_1 as recorded as a function of the varied parameter.

High-speed photographs were simultaneously taken of the surface and volume of the liquid elium.

The experiments have shown that when the critical conditions, determined in the general case y the parameters U_0, h_0, h, or U_0, h_0, U were reached, capillary-gravitational waves with amplitude 0.5 mm were excited on the helium surface after times 0.03–0.1 sec and the surface charge ınished after 0.1–0.3 sec. This is evidence of a "hard" regime of instability development.[7]

The measured dependence of the critical quantity $(E_1^2+E_2^2)_{\text{crit}}$ on the helium level height h is ıown in Fig. 1. In the figure are gathered points obtained at an experimental geometry close to at at which the quantity $(E_1^2+E_2^2)$ is a single-valued critical parameter, i.e., at $h=d/2$ or $\ll d-h$.[3] The experimental dependence (points) is in satisfactory agreement with the calculation Chernikova[3] (curve).

FIG. 2. Motion-picture frames showing the onset of capillary waves and of bubblons that carry away electrons from the charged helium surface when the latter becomes unstable.

The change in the character of the dependence at $h\approx 1$–1.5 mm corresponds to a transitio from instability with respect to long-wave perturbations to instability with characteristic oscillatio wavelengths of the order of the capillary wavelength $\lambda=3.2$ mm. This is confirmed by an analysi of the photograph frames: at $h\lesssim 0.6$–0.7 mm waves of length 2–3 cm, i.e., on the order of th dimensions of the capacitor plates, are excited on the helium surface, whereas at $h\gtrsim 1.5$ mm th excited waves are 2–5 mm long.

Motion picture photography has made it possible to trace the departure of the electrons fro the helium surface. Figure 2 shows four frames of the film. The first on the top shows a unifor stable surface. The flat uniformly charged helium surface is lowered by the electrostatic forces i the capacitor to 0.2 mm below the helium level in the cryostat; both levels are shown on the fram When instability sets in and surface waves build up, sharp dips are observed in valleys (Fig. second frame). At the tips of the dips are produced bubbles (frame 3) with dimensions from 0. to 0.3 mm; these bubbles then penetrate into the helium (fourth frame). After reaching t bottom—the anode of the capacitor—the bubble either vanishes or floats upwards, depending o its size: bubbles with 0.5 mm diameter collapse at the bottom within a time $\tau\lesssim 10^{-4}$ sec, while t larger have a lifetime 10^{-3} sec long enough to float upwards.

The cause of the observed phenomenon is that each bubble constitutes a multiply charge (10^7–10^8 electrons) negative ion—bubblon—in the superfluid helium. The bubblon moves toward ıe anode, where it is discharged upon contact; the remaining bubble with the gas collapses. From ıe condition that the electrostatic pressure from inside the bubble be equal to the capillary ressure we obtain for the bubblon radius an estimate $r \sim \sqrt[3]{n^2e^2/16\pi\sigma} \sim 8\times10^{-3}$ cm, where e is ıe electron charge, σ is the surface tension of the liquid helium, and n is the number of electrons in ıe bubblon and is determined from the total charge of the surface and the number of bubblons ıat discharge the surface (20–100).

It appears that the entire charge is carried away from the helium surface by the bubblons, in as ıuch as such a process is energywise more favored than the departure of individual electrons into ıe liquid helium. The electrons could in principle depart via the tunnel effect, but theoretical ;timates show that the probability of this effect is negligibly small,[1] and in experiment at $E_1^2+E_2^2) < (E_1^2+E_2^2)_{\text{crit}}$ the electrons remain over the helium surface for hours.

Bubblons with small diameter, 0.05 mm, move in the liquid helium in a field $E=1$ cgs esu ·ith velocity 10^4 cm/sec, which corresponds to Stokes viscous motion. The time to move to the ɔttom is $\sim 10^{-3}$ sec, which is much longer than the relaxation times of the electric and other ıhomogeneities over their dimensions. At the same time, the lower modes of the natural oscillaons of the bubblons should have wavelengths of the order of the bubblon dimensions, i.e., smaller y a factor of 10^2 than the capillary wavelength λ, thus ensuring a relative stability of the bubblon. mall-diameter bubblons should therefore be regarded as stationary formations.

As the result of electrostatic interaction, the electrons in the bubblon form a two-dimensional .yer near the surface of the liquid. The electron density is 10^{11}–10^{12} cm^{-2}—so high, that the layer ın be regarded as flat and its Wigner crystallization seems quite probable.[1] It must be emphazed in conclusion that bubblons are an interesting subject of study as perfectly new physical bjects.

The authors thank P.L. Kapitza for interest in the work, L.P. Gor'kov and V.P. Shikin for a iscussion of the results, and G.S. Chernyshev for technical help.

/.B. Shikin and Yu.P. Monarkha, Fiz. Nizk. Temp. **1**, 957 (1975) [Sov. J. Low Temp. Phys. **1**, ·59 (1975)].

.P. Gor'kov and D.M. Chernikova, Pis'ma Zh. Eksp. Teor. Fiz. **18**, 119 (1973) [JETP Lett. **18**, ı8 (1973)].

).M. Chernikova, Fiz. Nizk. Temp. **2**, 1374 (1976) [Sov. J. Low Temp. Phys. **2**, 669 (1976)].

.R. Brown and C.C. Grimes, Phys. Rev. Lett. **29**, 1235 (1972).

\.S. Rybalko and Yu.Z. Kovdrya, Fiz. Nizk. Temp. **1**, 1037 (1975) [Sov. J. Low Temp. Phys. **1**, ·98 (1975)].

\.P. Volodin, M.S. Khaĭkin, and V.S. Edel'man, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 524 (1976) JETP Lett. **23**, 478 (1976)].

.P. Gor'kov and D.M. Chernikova, Dokl. Akad. Nauk SSSR **228**, 829 (1976) [Sov. Phys. Dokl. **1**, 328 (1976)].