M. S. Khaĭkin and A. P. Volodin. *Disturbance of stability of the charged liquid helium surface and formation of bubblons (film).* The density of the two-dimensional layer of electrons localized in a potential well on the surface of liquid helium cannot be increased beyond $\sim 2\cdot 10^9$ electrons/cm^2 (see Ref. 1). The limiting electron density at the surface of a film of superfluid helium on a metallic base may be an order of magnitude larger.[2] However, when an attempt is made to exceed this value, the charge vanishes completely from the helium surface. Theoretical analysis has shown that the plane surface of the liquid helium becomes unstable at a charge density exceeding the above limit.[3,4] This paper describes the results of an experimental study of the conditions under which the charged surface of liquid helium becomes unstable and the mechanism by which it loses electrons.[5]

The experiments were performed in a Dewar with optical windows for observation and filming with a high-speed camera. The interior of the instrument is shown in Fig. 1. The helium level h was adjusted (with a thermomechanical pump) between the horizontal plates of a capacitor with a diameter of 40 mm and a gap $d = 1$-5 mm. The field E_1 above the helium and, consequently, the charge density on the helium surface were determined from the displacement of the elastically suspended upper plate 1, which was measured by the capacitive transducer 2. The critical conditions for disturbance of the stability of the charged helium surface were reached by lowering the helium level h or by raising the voltage across the capacitor.

When critical conditions are reached at the helium surface, capillary-gravity waves with an amplitude of ~ 0.5 mm are generated for 0.03–0.1 sec, and the surface charge vanishes within 0.1–0.3 sec. Figure 2 shows a plot of the critical value $(E_1^2 + E_2^2)_{cr}$ against the helium level h; this quantity is a single-valued critical parameter under the conditions $h = d/2$ or $h \ll d - h$ that were maintained in the experiments. It is seen that the experimental results agree satisfactorily with the calculated relation indicated by the solid curve.[4] The change in the nature of the relation at $h = 1$–1.5 mm corresponds to the transition from instability with respect to waves with lengths $\lambda = 2$–3 cm at $h \lesssim 0.7$ mm to instability with respect to waves with lengths of the order of the capillary length $\lambda_c = 3.2$ mm at $h \lesssim 1.5$ mm. This pattern is clearly evident in the film.

The film showed the mechanism of electron escape from the helium surface. A quite stable helium surface appears in frame 1 (the top frame) of Fig. 3. Instability of the charged surface has begun to develop in frame 2; sharp depressions have appeared in the wave troughs. Bubbles (frame 3) with diameters of 0.05–0.3 mm form on these depressions and then dive into the helium (frame 4). On reaching the bottom—the capacitor's anode—the bubbles lose their charge; then the small bubbles with diameters around 0.05 mm collapse during a time $\lesssim 10^{-4}$ sec, while the large ones survive for $\sim 10^3$ sec and are able to float up. The observed phenomenon is explained by the fact that each bubble is a multiply charged (10^7–10^8 electrons) ion—a "bubblon" (bubble with electrons) in the superfluid helium. Equality of the internal electrostatic pressure to the capillary pressure yields an estimate for the bubblon radius: $r = \sqrt{n^2e^2/16\pi\sigma} \approx 8\cdot 10^{-3}$ cm, where e is the electron charge, σ is the surface tension of the liquid, and n is the number of electrons in the bubblon, determined from the total charge of the helium surface and the number of bubblons discharging it (20–100).

In a field $E = 1$ cgs esu, bubblons with small diameters around 0.05 mm move in the liquid helium at a velocity of 10^4 cm/sec, which corresponds to viscous Stokes motion. Their time to move to the bottom is $\sim 10^{-3}$ sec, which is much greater than the relaxation times of electrical and elastic inhomogeneities over the diameter of a bubblon. At the same time, the lower

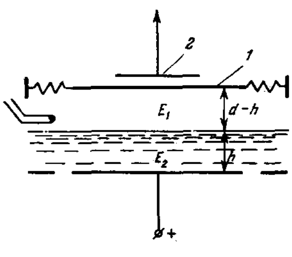

FIG. 1. Diagram of instrument. 1) Mobile cathode of capacitor suspended on springs; 2) electrode of capacitative transducer for indicating position of cathode 1.

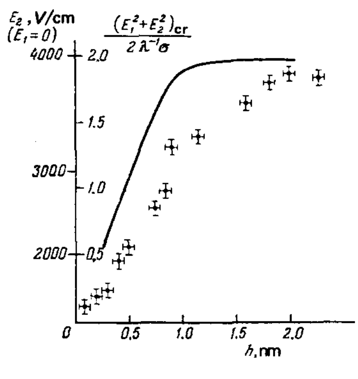

FIG. 2. Values of the critical parameter and of the field E_2 on reaching which a charged plane helium surface loses stability, plotted against depth h of helium in the capacitor.

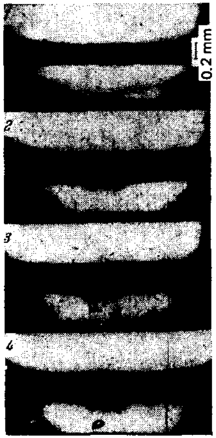

FIG. 3. Frames of film showing appearance of capillary waves on charged liquid helium surface and generation of bubblons that carry electrons from the surface into the interior of the helium. Frame 1 (top) shows the quiet charged helium surface (lower edge of dark band), which has been depressed by the field in the capacitor to 0.2 mm with respect to the helium surface outside of the capacitor (upper edge of dark band).

modes of the bubblon's natural vibrations have wavelengths of the order of its diameter, $\sim 10^{-2}\lambda_k$, which hardens the bubblon, and the more so the smaller its size. Moreover, decay of a small-diameter bubblon is energetically not favored (and tunneling escape of electrons even less so). Small bubblons should be regarded as stationary formations for these reasons.

As a result of electrostatic interaction, the electrons in a bubblon form a two-dimensional layer near the surface of the liquid. The electron density reaches $10^{11}-10^{12}/\text{cm}^2$—values so high that the layer can be treated as a plane layer, Wigner crystallization of which is highly probable.[6] At the same time, it is obvious that a bubblon with a small number of electrons should constitute a three-dimensional quantum system.

We mention in conclusion a highly interesting possibility that arises in the situation that is the geometric reverse of the above: the appearance of stationary "dielectric" electron levels around small helium droplets, and around dielectric particles in general.[7] The limiting case of this quantum system is well known: it is the negative ion. A calculation indicates that the dielectric-level spectrum ranges from optical frequencies (ions) to $10^{12}-10^{11}$ Hz (particle radii 10^{-6} to 10^{-5}/cm) and goes over into the spectrum of electrons above the flat surface as the surface radius of curvature increases. Such dielectric levels may exist around particles of cosmic dust and play a role in shaping the cosmic radiation in this range.

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

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

[3] L. P. Gor'kov and D. M. Chernikova, *ibid.* **18**, 119 (1973) [**18**, 68 (1973)].

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

[5] A. P. Volodin, M. S. Khaĭkin, and V. S. Édel'man, Pis'ma Zh. Eksp. Teor. Fiz. **26**, 707 (1977) [JETP Lett. **26**, 543 (1977)].

[6] R. S. Grandall, Surface Sci. **58**, 266 (1976).

[7] M. S. Khaĭkin, Pis'ma Zh. Eksp. Teor. Fiz. **27**, 706 (1978) [JETP Lett. **27**, 668 (1978)].