;urface electronic states above a helium film

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

Institute of Physics Problems, USSR Academy of Sciences
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Experiments are described on the observation of surface electronic states above a superfluid helium that wets a dielectric or a metal. The mobility ($\sim 10^{-1}$ cm^2/V-sec) and the surface density ($\sim 10^{10}$ electrons/cm^2) are measured for the case of a metallic substrate.

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It is known that electronic states exist above the surface of liquid helium and ·e due to the ~1 eV barrier that prevents the penetration of the electron into e helium, as well as to the action of the electrostatic attraction forces.[1,2] [2,3] they predicted the existence of analogous states with a binding energy 4×10^{-2} eV above a helium film that wets the surface of a dielectric or a etal. The potential of the electrostatic attraction forces is due in this case

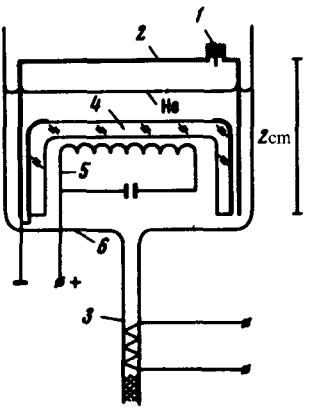

FIG. 1.

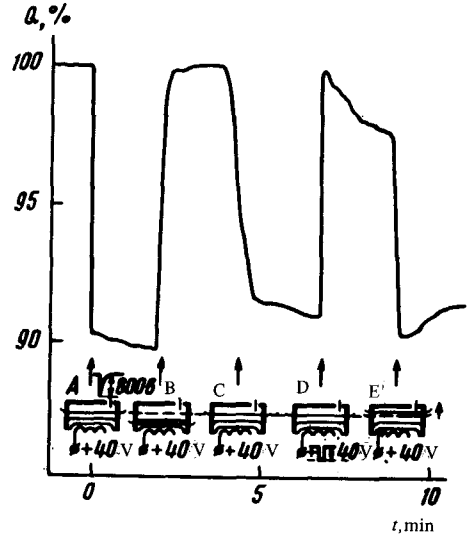

FIG. 2.

mainly to the substrate, and the effective holding field $E_\perp$ reaches $\sim 3\times 10^4$ V/cm.

Observation of cyclotron resonance with electrons above a helium film was mentioned earlier in[4]. The appearance of a charge on a free helium surface was reported in[5] and attributed there to the drift of the electrons along the film. The estimates of the mobility in the two cases ($\mu \sim 10^6$ cm^2/V-sec and $\mu \sim 10^{-6}$ cm/V-sec, respectively) differ by approximately 6 orders of magnitude from the value measured by us (see below). Thus, there is no assurance that the phenomena observed in the two studies are connected with electrons above the film.

We describe here experiments that establish the existence of surface states of electrons above a helium film. The measurements were performed with the apparatus schematically illustrated in Fig. 1. The electron source was an electron discharge in a gas near the tip of the discharge gap 1. The constant electric field $E_\perp$ that pushed the electrons towards the helium surface was applied between cylindrical copper vessel 2 and the flat spiral coil of the RF tank circuit 5. The tank circuit was covered with a cylindrical flat-bottom glass vessel 4, the outer surface of which (with the exception of an area 18 cm in diameter in the center of the bottom) was coated with an aluminum film. The measurement setup was contained in a glass vessel 6 placed in the cryostat above the liquid-helium level. The helium was fed to the vessel by the thermomechanical effect produced when the heater 3, placed in a capillary, was turned on. The position of the helium level was measured with a cathetometer and regulated by varying the power fed to the heater 3.

The experiment. After a short-duration (~ 0.1 sec) discharge produced by discharge gap 1, the quality factor of the measurement circuit (natural frequency of circuit 3.29 MHz, $Q \sim 300$) decreases because of the energy absorbed by the electrons localized near the surface of the liquid (Fig. 2A). The decrease

), at a fixed temperature, is proportional to the electron surface density deter-
nined by the value of the holding field (Fig. 2 was obtained at $E_\perp \sim 80$ V/cm),
nd can thus serve as a measure of the surface charge density.

Film above dielectric. When the liquid level drops below the glass surface of
essel 4, the Q of the circuit is restored to the value prior to turning on the
ischarge gap (Fig. 2B). Raising the liquid level in the chamber to its previous
eight led again to a decrease in the Q of the circuit, indicating that electrons
re present near the helium surface (Fig. 2C). (The difference between the
alues of Q following the experiments A and C in Fig. 2 is due to the small
~ 50 μ) difference between the positions of the helium level. Turning off the
olding field for a time ~ 10 min at a helium level below the glass did not lead
) a significant change in the Q after the level was brought back to its previous
alue.

If the superfluid-helium film is destroyed in the time interval between experi-
ients B and C by raising the temperature, the Q of the circuit remains high
fter the helium level in the apparatus is restored. The dielectric turns out to
e charge in this case, as is evidenced by the fact that the previous charge can
e restored above the surface only by applying double the maintaining voltage
) the discharge gap 1.

Thus, the described experiments demonstrate the existence of surface elec-
:onic states with low mobility above a helium film that wets the surface of
lass. From the limiting sensitivity of the system it can be estimated that the
iobility of such electrons is $\mu < 10^{-3}\ \mu_0$, where $\mu_0 = 0.5 \times 10^6$ cm^2/V-sec is the
iobility of the electrons above the surface of the liquid helium.[4]

Helium film on metallic substrate. The next experiment (Fig. 2D) indicates
ie existence of bound electronic states above a superfluid-helium film that
ets the surface of the metal. Turning-off $E_\perp$ for a short time (~ 0.5 sec) led
) a rapid escape of the electrons from the surface of the helium within
10^{-4} sec[1] and to a subsequent slow charging of the surface with a time con-
tant $\tau \sim 2$ mm. Raising the helium level by a small amount $l \sim 0.01$ cm re-
tores rapidly the surface charge (Fig. 2E).

The surface charge in experiments D and E can be attributed to the transfer
f the electrons from the region above the helium film that wets the internal
urface of the metallic vessel 2 to the surface of the liquid. The transfer takes
lace under the influence of the electric field component $E_\parallel$ along the film, and
nder the influence of their rapid "wiping out" when the level is raised. No
ther electron sources exist in the measuring apparatus when the discharge is
irned off. This is confirmed by an experiment with complete and irreversible
limination of the electrons from the instrument by removing from it the free
elium surface, for example, by raising the level above the bottom of the cop-
er vessel 2.

From the area of the lateral surface of the vessel and from the value of the
wiped off" discharge, in experiments similar to experiment E, we obtained
n estimate of the charge density above the metal surface, $N \sim (1-2) \times 10$ elec-
:ons/cm^2. This is 100-200 times larger than the density on the surface of the
quid at the employed fields $E_\perp \sim 100$ V/cm. The presence of a high-density
harge on the lateral surfaces of the vessel 2 is confirmed also by the observed

increase by 2—3 times, of the charge on the free helium surface when the holding potential is correspondingly increased, and by its rise to a height $l \sim 10\ \mu$ (to accelerate the process).

The rate of charging (section D—E) at a fixed level depends strongly on the prior history. If the level is dropped by an amount l immediately prior to turning-off the holding field, then the rate of charging decreases in proportion to l as a result of formation of a zone free of electrons along the metal. If, to the contrary, the level is raised definitely above the level at which the discharge gap was turned on, then the rate of restoration of the charge increases appreciably (by approximately one order of magnitude).

From the known time τ required for the charge to flow through an uncharged region of width l and from known component of the electric field intensity along the helium film ($E_{\parallel} \sim E_{\perp}(d/\tau)$, where $d = 4 \times 10^{-6}$ cm is the thickness of the helium film and $r = 1$ cm is the characteristic distance to the positive electrode, we can estimate the mobility of the electrons above the helium film, $\mu = l/\tau E_{\parallel} \sim 10^{-1}$ cm^2/V-sec. This estimate agrees with the theoretical assumption that bound states of electrons are produced with an attached mass $\sim 10^3$ helium-atom masses.[2]

The density $N \sim (1-2) \times 10^{10}$ electrons/cm^2 above the surface of the film that wets a metal does not depend, within the limits of experimental accuracy, on $E_{\perp}$ or on the lifetime of the discharge, during which $\sim 10^{14}$—10^{15} electron-ion pairs were produced. This allows us to assume that the density corresponds to the critical value, starting with which the homogeneous system becomes stable.[6] Replacing formally in the expression for the dispersion law of the surface oscillations[6] the gravitational potential by Van der Waals forces, which are determined numerically from the experimental data on the third-sound velocity v,[7] we obtain for the critical density an estimate $N_c \approx 8\rho v^2 d^2/3e^2 \sim 10^{11}$ (ρ is the helium density). Taking into account the possible change of the film parameters because of the absence of thermodynamic equilibrium, no special measures being taken to maintain this equilibrium, we can regard this estimate as in satisfactory agreement with experiment.

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[1] M. W. Cole, Red. Mod. Phys. **46**, 451 (1974).
[2] V. B. Shikin and Yu. P. Monarkha, Fiz. Nizk. Temp. **1**, 957 (1975) [Sov. J. Low Temp. Phys. **1**, 495].
[3] M. W. Cole, Phys. Rev. **B3**, 4418 (1971).
[4] T. R. Brown and C. C. Grimes, Phys. Rev. Lett. **29**, 1233 (1972).
[5] A. S. Rybalko and Yu. Z. Kovdrya, Fiz. Nizk. Temp. **1**, 1037 (1975) [Sov. J. Low Temp. Phys. **1**, 498].
[6] L. P. Gor'kov and D. M. Chernikova, Pis'ma Zh. Eksp. Teor. Fiz. **18**, 119 (1973) [JETP Lett. **18**, 68 (1973)].
[7] C. W. F. Everitt, K. R. Atkins, and A. Denentein, Phys. Rev. **136**, A1494 (1964).