# Effective mass of electrons localized over the surface of liquid helium

V. S. Édel'man

*Institute of Physics Problems, USSR Academy of Sciences*

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The effective mass $m$ and the relaxation time of electrons localized over the surface of liquid $^4$He were measured by the cyclotron-resonance method at a temperature 0.4°K. At clamping-field values $\leq 15$ V/cm the value obtained is $m = (1.0005 \pm 0.0004)m_0$, and decreases linearly when the field increases at a rate $\sim 2\times10^{-5}$ V$^{-1}$ cm at an electron density $3\times10^8$ cm$^{-2}$. The mobility in weak fields is equal to $(1.15\pm0.15)\times10^7$ cm$^2$/V-sec and decreases with increasing clamping field.

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In the investigation of electrons localized over the surface of liquid helium, great interest attaches to the study of their properties at temperatures below 1°K, when the collisions with the gas cease to play any role whatever because of the low vapor density. The interaction of the electrons with one another and with the oscillations of the liquid of the surface (electron-ripplon interaction), which appears under these conditions, has been the subject of a large number of theoretical papers (see the reviews[1,2]). A promising investigation is that of cyclotron resonance (CR), at $T<1$°K, in the system of surface electrons, previously observed by Grimes and Brown.[3] This is a direct and most accurate method of measuring the effective mass $m$. An investigation of the influence of external actions, for example of the clamping electric field $E$, the surface density of the carriers, etc. is important in connection with the problem of formation of electron-ripplon states[4] and Wigner crystallization of electrons.[5,6] From the width of the resonance line it is also possible to determine the relaxation time $\tau = H_p/\omega\delta H = mc/e\delta H$ ($H_p$ and $\omega$ are the resonant field and the angular frequency, $\delta H$ is the half-width of the CR line at half-height) and to calculate the mobility of the charges

$$\mu = e\tau/m = c/\delta H. \qquad (1)$$

We have measured the CR of electrons localized over the surface of liquid $^4$He at a frequency ~17 GHz and a temperature ~0.4°K. We measured the coefficient of reflection of a microwave from a cylindrical TM$_{011}$ resonator (diameter 19 mm, height $h=12$ mm). The $^4$He was condensed inside the resonator. The bottom of the resonator was electrically insulated from the housing, and a dc voltage $V=10$—300 V was applied between them and produced the confining field.

Electrons produced by striking a discharge located over the liquid landed on the surface of the helium at $T=1$°K. We did not succeed in producing a surface charge by this method at lower temperatures. It appears that with decreasing

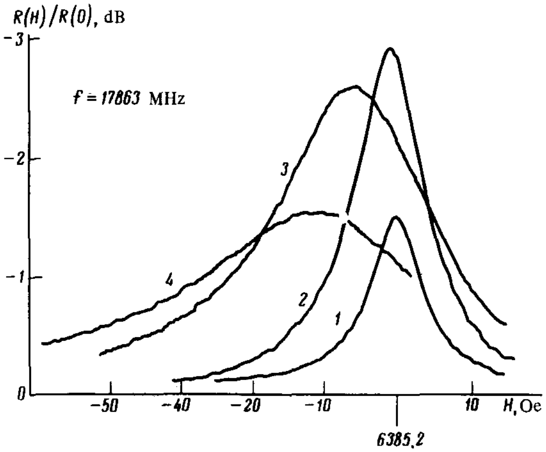

FIG. 1. Dependence of the coefficient of reflection from the resonator on the magnetic field: 1—$E = 15$ V/cm, $n = 7 \times 10^7$ cm$^{-2}$; 2—$E = 30$ V/cm, $n = 1.4 \times 10^8$ cm$^{-2}$; 3—$E = 120$ V/cm, $n = 3 \times 10^8$ cm$^{-2}$; 4—$E = 230$ V/cm, $n = 3 \times 10^8$ cm$^{-2}$.

vapor density the electrons with energies ~ 100 eV do not have time to slow down and penetrate into the liquid.

After the electrons have landed on the $^4$He surface, the apparatus was cooled to ~ 0.4 °K and the magnetic-field dependence of the coefficient of reflection of the microwave by the resonator was measured. The power dissipated in the resonator was $10^{-10}$—$10^{-11}$ W. Noticeable broadening of the resonance line and nonlinear effects were observed at a power ~ 10 times larger.

A magnetic field ~ 6 kOe produced by a superconducting solenoid was applied parallel to the normal **N** to the free surface of the $^4$He with accuracy ~ 5′. The direction $\mathbf{H} \parallel \mathbf{N}$ was determined from the minimum value of the CR field. Just as in[3], when the direction of **H** was varied (in the range ± 4°), an increase of $m$, close to the function $1/\cos(\sphericalangle \mathbf{H}, \mathbf{N})$ was observed; this confirms the two-dimensional character of the motion of the electrons taking part in the resonance. The magnetic field intensity was measured accurate to 0.03—0.04% with a Hall pickup located inside the solenoid.

Figure 1 shows typical CR plots at different values of the clamping field and of the electron surface density. It was assumed that striking the discharge deposited

$$n = \frac{V}{2\pi e d} \tag{2}$$

charges on the surface ($d$ is the thickness of the liquid-helium layer), corresponding to the screening of the clamping field over the surface. With decreasing field, the density decreased correspondingly, leading to a proportional decrease of the area under the resonance curve. With subsequent increase of $V$, as in[7], the electron density again increased, but, as a rule, did not reach the maximum possible value (2). Whether $n$ varied or was constant could be determined from the area under the resonance curve. The inevitable electron

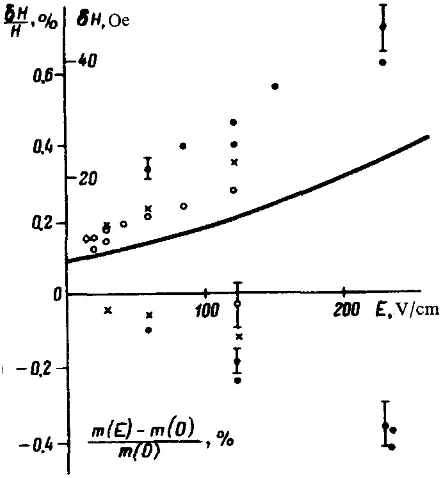

FIG. 2. Dependence of the width of the resonance curve $\delta H$ (top) and of the effective mass $m$ (bottom) on the clamping field: ●—$n = 3\times10^8$ cm$^{-2}$; x—$1.4\times10^8$ cm$^{-2}$; o—$7\times10^7$ cm$^{-2}$.

drain is apparently due to their gathering on the insulator of the discharge gap, which becomes charged when the discharge is ignited.

The results of the measurements of $\delta H(E, n)$ and $m(E, n)$ are shown in Fig. 2. The most interesting result is the proportionality of the change of the effective mass to the field; at $n = 3\times10^8$ cm$^{-2}$ in a field 230 V/cm this mass decreases by ~0.4% from the value $m = 1.00005 \pm 0.0004)m_0$, measured at $E = 14$ V/cm, where $m_0$ is the mass of the free electron. The presented value of $m$ is an average of four measurements. The error corresponds to the scatter of the measured values and agrees with the error in the measurement of the magnetic field intensity.

As seen from Fig. 2, the rate of change of $m$ depends on the electron concentration. At $n = 7\times10^7$ cm$^{-2}$ practically no shift of the resonance was observed. To be sure, it should be noted that owing to the strong broadening of the CR line and of the associated decrease of the signal amplitude to the noise level, measurements at small $n$ were possible also in a narrow range of variation of $E$, and their accuracy was much lower.

The electron mobility, calculated from formula (1) as $E \rightarrow 0$, was $\mu(0) = (1.15 \pm 0.15)\times10^7$ cm$^2$/V-sec, which agrees within the limits of errors with the value obtained by Grimes and Adams.[8] The $\mu(E)$ dependence is close to that obtained in[8] only at a low electron concentration $n = 7\times10^7$ cm$^{-2}$. At large concentrations, the values of $\delta H$ correspond to a much lower mobility (see Fig. 2). This may be due to variations of the electron concentration along the surface, which can be caused by the small (~1—2°) angle between the bottom of the resonator and the horizontal. Since $m$ depends on $n$, this may cause broadening of the observed resonance.

The results obtained in[8] at $T = 0.5$ °K were satisfactorily explained in[9], as being due to electron-ripplon interaction. At $T = 0.72$ °K, our measurements yielded $\mu = (5.6 \pm 0.6)\times10^6$ cm$^2$/V-sec, which is about half the value cited in[8]. It should be noted that Rybalko and Kovdrya have also observed, in the temperature range 0.7—0.4 °K, a doubling of the mobility, although the numerical values were smaller by an approximate factor of three. In accordance with the calculation[9], $\mu(0.7K)/\mu(0.4K) = 1.7$. Allowance for the collisions with the gases increases this ratio to ~2.1.

As to the $m(E, n)$ dependence, it can be due in principle to the increase of the electron-ripplon interaction with increasing field $E$.[4] In this case, however, the decrease of the effective mass should be proportional to $E^4$, should be independent of $n$, and should not exceed ~$10^{-4}$% in a field ~300 V/cm.

Another possibility is connected with the electron-electron interaction. According to the calculation given in[6], the natural frequency of the oscillations of the two-dimensional plasma coincides with the cyclotron frequency $\Omega$ only at the wave number $k = 0$. Since the resonator has finite dimensions, the oscillations take place with finite $k = 2\pi/\lambda$, $\lambda \approx 1$ cm, and their frequency is somewhat higher than $\Omega$. Substituting the numerical values of $n$ and $k$ in the formulas obtained in[6], we can estimate $[m(0) - m(n)]/m(0) \lesssim 10^{-4}$, i.e., it is 10—100 times smaller than the observed values. We note that in this case there is no $m(E)$ dependence.

Thus, the observed change of the effective mass cannot be explained at present on the basis of the existing theoretical papers.

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