Nonlinear cyclotron resonance 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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An investigation of cyclotron resonance of electrons localized over the surface of liquid helium, at $T \simeq 0.4$ K, has revealed heating of electrons by radiation of frequency ~ 17.8 GHz and a power $\sim 10^{-10}$ W, causing them to go over from the ground state into the quasicontinuum. A narrow resonance line appeared, and its relative width reached $\sim 2 \times 10^{-5}$ in a field that corresponds to cyclotron resonance of the free electrons, and is independent of the angle between the magnetic field and the normal to the surface of the liquid.

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It was predicted in[1] that the conductivity of a two-dimensional system of electrons localized over the surface of liquid helium, under conditions when the electrons are scattered mainly by the surface oscillations (ripplons), becomes nonlinear in fields $\gtrsim 0.1$ mV/cm. The heating of the electrons and their transition to the excited state should lead in this case to an increase of the mobility, due to the increased average distance between the electrons and the surface of the liquid.

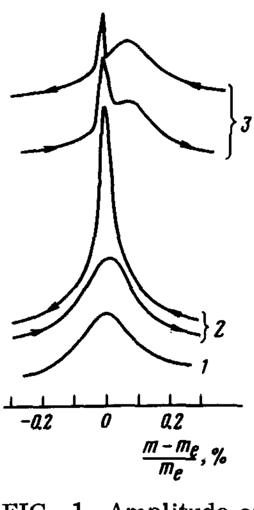

FIG. 1. Amplitude of a wave of frequency 17.80 GHz, reflected from a resonator, vs. the magnetic field: 1,2—H‖N, 3—$\angle$H,N = 2.5°. The microwave power fed to the resonator is ~ 1 dB larger for curves 2 and 3 than for curve 1. The electron surface density is $n = 2.3 \times 10^7$ cm^{-2} and the clamping field is $E = 20$ V/cm. The zero on the abscissa scale corresponds to $H = 6359$ Oe.

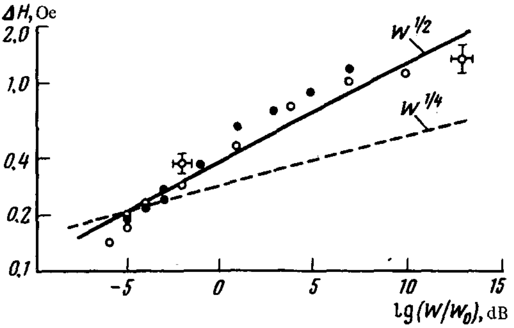

FIG. 2. Half-width at half-height of the cyclotron resonance line of the free electrons vs. the microwave power W scattered in the resonator: $W_0 \approx 10^{-10}$ W. ●—$n = 2\times10^7$ cm^{-2}, $E = 18$ V/cm;○—$n = 1.9\times10^7$ cm^{-2}, $E = 17$ V/cm.

The electron-ripplon interaction becomes predominant at $T \lesssim 0.7$ K. At $T = 0.4$ K, the frequency of these collisions with the ripplons is 10^3—10^4 times larger than with the helium-vapor atoms. [2] Cyclotron resonance at such temperatures, at a frequency ~17.8 GHz, and small amplitudes of the microwave field, was investigated by us earlier in[3]. The present paper describes experiments aimed at observing nonlinear phenomena that occur when the power fed to the electron system is increased. The experimental setup was perfectly analogous to that described in[3]. We measured the amplitude of the microwave reflected from a resonator partially filled with liquid helium as a function of the magnetic field. Electrons were deposited on the helium surface by turning on, for a short time, a discharge gap placed over the liquid. The electrons were kept over the surface by a constant electric field E applied between the insulated bottom of the resonator and its body.

Figure 1 shows plots of the signal reflected from the resonator against the magnetic field H expressed in relative units $(H - H_e)/H_e = (m - m_e)/m_e$ (H_e is the resonant field at m equal to the free-electron mass m_e). It is seen (curve 1) that at a small microwave power level W fed to the resonator, one peak is observed, as in[3], with a relative width ~10^{-3}. With increasing W, a second peak, narrower by one order of magnitude, appears against the background of the first peak. The microwave field amplitude corresponding to the appearance of the additional peak is ~1 mW/cm.

A characteristic feature of the additional peak is that the corresponding resonant value of the magnetic field remains unchanged if the field is inclined relative to the normal **N** to the surface of the liquid. The wider peak, which is due to the resonance of electrons that are in the ground state[1)] and move only parallel to the surface, shifts in this case towards the stronger field (cf. curves 1, 2, and 3), as was indeed observed earlier in[3,4]. Thus, the narrow peak is due to cyclotron resonance with electrons that execute three-dimensional motion and consequently have a continuous or quasicontinuous spectrum with energy differences between quantum levels[1)] much smaller than the Landau splitting. For the sake of brevity we shall refer to these electrons as free.

The line width ΔH of the cyclotron resonance of the free electrons depends on W approximately like $\Delta H \propto W^{1/2}$ (Fig. 2) and is larger by two or three orders of magnitude than expected for scattering by helium vapor. This leads to the conclusion that the free electrons have a temperature T^* much higher than the temperature $T=0.4$ K of the liquid helium. An estimate of the collision frequency from the values of ΔH yields $\nu_{col} \approx 3\times10^6-3\times10^7$ sec^{-1}.

The energy absorbed by the electrons at resonance is proportional to W/ν_{col} and the rate of energy loss is proportional to $\epsilon(T^*)\nu_{col}$, where $\epsilon(T^*)$ is the energy lost by the electrons in each collision. From the energy balance it follows that

$$\epsilon(T^*) \propto W/\nu_{col}^2. \qquad (1)$$

The collision frequency can be determined, in principle, from plots of the type shown in Fig. 1. Unfortunately, it is difficult to obtain the exact value of ν_{col}, since T^* is obviously changed by the detuning from strict resonance, and this leads to a distortion and broadening of the line. However, recognizing that in the entire range of variation of W the line shape, which was close to a bell shape, remained practically constant, it can be assumed that its half-width is proportional to ν_{col}. Substituting in (1) the value $\nu_{col} \propto \Delta H \propto W^{1/2}$ (Fig. 2), we obtain

$$\epsilon(T^*) = \text{const}. \qquad (2)$$

The constancy of $\epsilon(T^*)$ means that the predominant contribution to the scattering is made by processes connected with the excitation of either plasma oscillations with wave vector $k \approx \pi\sqrt{n}$ (n is the surface density of the electrons)[5] or by the surface or volume oscillations of the liquid helium (for example, rotons) with wave vector $k \approx \pi/a \approx 1$ Å^{-1}, where a is the interatomic distance. Which of these processes predominate will apparently be determined once experiments are performed in which n and the clamping field E can be varied in a wide range.

Since the electron-scattering mechanism has not been uniquely identified, it is impossible for the time being to determine T^* from the observed resonance widths. It can only be stated that $T^* \ll 10^4$ K, since electrons with energy $\sim 10^4$ K ≈ 1 eV could overcome the energy barrier at the liquid—vapor boundary and go off to the lower electrode. As a result, no electrons would be left over the surface of the helium.

It can also be concluded from (2) that scattering by helium atoms for free electrons does not play a noticeable role, for in this case we should have $\epsilon(T^*) \propto T^*$. Since in collisions with atoms we have $\nu_{col} \propto \sqrt{T^*}$, in scattering by vapor we should obtain the relation $\Delta H \propto W^{1/4}$, which disagrees with experiment (Fig. 2). Numerical estimates show that even at $T \approx 10^4$ K the frequency of the collisions with atoms at $T=0.4$ K should be $\nu_{col} \lesssim 5\times10^5$ sec^{-1}, which is lower than the experimentally estimated value.

We note in conclusion that at microwave powers close to the threshold at which the free electrons appear, "hard" excitation of cylotron resonance with the free electrons is observed (Fig. 1). Thus, on curve 3, which corresponds to a decrease of the field, the appearance of the additional resonance is delayed, while on curve 2, with increasing field, there is no additional resonance at all. We consider a discusssion of the mechanism of this phenomena as premature.

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[1)]We have in mind quantization of the electron motion in a direction perpendicular to the surface of the liquid helium.

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