Cyclotron resonance with surface electrons in liquid helium

V. B. Shikin

Institute of Solid State Physics, USSR Academy of Sciences
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It is shown that heating of a system of surface electrons by a high-frequency electromagnetic field under cyclotron-resonance conditions makes it possible to transfer, in controllable fashion, some of the electrons from negative deep levels to positive quasiclassical levels. The presence of quasifree electrons "evaporated" from the surface levels leads to the appearance of characteristic singularities on the cyclotron-resonance curve.

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A characteristic feature of the electrodynamics of a two-dimensional system of electrons localized on the surface of liquid helium is the relatively low thresholds for various effects that are nonlinear in the leading electric field $E_{\parallel}$, i.e., in the field along the helium surface (see[1]). One such effect should take place under conditions of cyclotron resonance in the presence of a weak clamping field $E_{\parallel}$. We have in mind the heating, by the resonant field $E_{\parallel}$, of a system of surface electrons situated in a magnetic field normal to the helium surface, and the transfer of the bulk of the surface electrons from discrete negative energy levels $\Delta_i^{(-)}$ ($\Delta_i^{(i)} - \Delta_{i\pm 1}^{(i)} \gg T$, T is the temperature of the liquid helium) to positive quasiclassical levels with $\Delta_i^{(+)} - \Delta_{i\pm 1}^{(+)} \ll T$. The produced electron system, which is smeared out over the helium surface in a layer of thick-

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ness $\lambda \approx T_e/eE_\perp \gg \lambda_0$ (T_e is the electron temperature, $T_e \gg T$, and λ_0 is the scale of the electron localization at the ground-state level) is no longer two-dimensional. In particular, the cyclotron frequency for such electrons should not depend on the angle between the magnetic field and the normal to the helium surface, as is the case for surface electrons.[2] Another distinguishing property of quasifree electrons is the weakness of their interaction with the helium at sufficiently low temperatures. The point is that the density of the helium gas can be made arbitrarily small, and the interaction of the quasifree electrons with the oscillating surface is considerably attenuated by the noticeable distance between them and the free boundary of the helium, compared with the surface electrons.

The purpose of the present study was to determine the characteristic cyclotron-resonance parameters that favor the onset of a system of quasifree electrons. Among the possible limiting cases we shall consider below is the simplest classical situation, in which the electron density n_s is low ($e^2 n_s^{1/2} \ll T_e$), the cyclotron frequency is $\Omega \ll T_e$, and the density of the gas over the helium surface is small in absolute magnitude, but still high enough to make the electron temperature governed predominantly by collisions between the electrons and the atoms of the helium gas.

In the absence of a magnetic and of an alternating electric field, the population of the electrons of the ground-state surface level of depth $\Delta \approx 8$ K is given by[1]

$$\frac{n_s^{(1)}}{n_s} = (1+\xi)^{-1}, \qquad \xi = \chi \exp\left(-\frac{\Delta}{T}\right), \qquad \chi = \frac{m^{1/2} T^{3/2}}{\sqrt{2\pi}\hbar e E_\perp} \tag{1}$$

e and m are charge and mass of the free electron, T is the temperature, and $n_s^{(1)}$ and n_s are the surface densities of the electrons at the ground level and the total surface density of the electrons. It is obvious that the ground level is quite well filled if $\xi \ll 1$. At temperatures $T \lesssim 1.0$ K and at $E_\perp \lesssim 1$ V/cm we have $\xi \approx 0.04$ and $n_s^{(1)}/n_s = 0.96$. The definitions (1) are valid if the following inequalities are satisfied

$$e^2 n_s^{1/2} \ll T, \qquad \exp\left(\frac{\Delta}{T}\right) \gg N, \qquad \chi \gg N, \tag{2}$$

where N is the number of negative levels in the spectrum of the surface electrons in the presence of a weak clamping field $E_\perp$

$$2\pi\hbar N \approx \sqrt{2m}\int_0^{z^*}\left(\frac{\Delta}{z} - eE_\perp z\right)^{1/2} dz, \qquad z^* = \left(\frac{\Lambda}{eE_\perp}\right)^{1/2}, \qquad \Lambda = \frac{e^2(\epsilon-1)}{4(\epsilon+1)} \tag{2a}$$

$\epsilon - 1 = 0.06$, ϵ is the dielectric constant of the liquid helium. For $E_\perp \lesssim 1$ V/cm we have $N \gtrsim 10$. As to χ, we have $\chi \approx 123$ at $T \lesssim 1°$. Thus, in the region $T < 1$ K and $E_\perp \lesssim 1$ V/cm the inequalities (2) are satisfied with adequate margin.

We now turn on a magnetic field normal to the surface of the helium, as well as an alternating electric field of the resonance frequency $\omega = \Omega$. Let the gas density over the helium surface be low enough to permit heating of the electron gas to an effective electron temperature $T_e > \Delta$. As a result, practically all the surface electrons should be evaporated from the deep negative levels and go over to the quasiclassical energy region, where there is only a weak clamping field $E_\perp$. The collisions of the near-surface electrons with the helium-gas atoms under weakly inhomogeneous conditions result in a new electron distribution function with an effective temperature T_e given by[3]

$$T_e = T + \frac{e^2 E_\parallel^2}{6m\delta\,[(\omega - \Omega)^2 + \chi^2]} \tag{3}$$

$E_\parallel$ and ω are the amplitude and frequency of the alternating electric field, δ is the average fraction of energy lost by an electron in one cóllision (for collision with a neutral atom we have $\delta = 2m/M$, where M is the mass of the He^4 atom), ν is the effective frequency of the collisions of the electrons with the helium gas atoms, $\nu = \pi a^2 n v_e$, a is the radius of the He^4 atom ($a \approx 0.62$ Å), v_e is the thermal velocity of the electrons ($v_e^2 \approx T_e/m$), and n is the volume density of the helium gas. The value of T_e determined in this manner is valid to the extent that the inequality $l \ll T_e/eE_\perp$, is satisfied, where l is the characteristic mean free path of the electrons. In addition, it is necessary that raising the electron-gas temperature to values $T_e \gg T$ must not lead to a noticeable heating of the helium gas (otherwise it is necessary to make allowance, in the determination of T_e, to the heat dissipation conditions, which in principle changes the volume density of the helium gas in the near-surface layer). It is easy to show that the customarily employed densities of the surface electrons $e^2 n_s^{1/2} \ll T$ do not lead to heating of the gas phase in the case of superheating up to $T_e \lesssim 10$ K.

Under conditions when the same electron temperature T_e is produced for all the electrons[1)] the population of the surface levels by the electrons is again described by expressions (1), in which the role of the temperature T is assumed by the electron temperature T_e. According to (1), the bulk of the electrons is in this case on quasiclassical levels if $\xi(T_e) \gg 1$. Consequently the requirement that delineates the region where a layer of quasi-free electrons exists is of the form $\xi(T_e) \gtrsim 1$, or, in expanded form, and under the assumption $T_e > \Delta$,

$$\frac{m^{1/2}}{(2\pi)^2 e\hbar\, E_\perp}\left(\frac{M^{1/2}\, e\, E_\parallel^*}{m^{1/2}\, n\, a^2}\right)^{3/2} \approx 1\ . \tag{4}$$

The numerical value of the threshold intensity $E_\parallel^*$ from (4) at $E_\perp \lesssim 1$ V/cm and $n \sim 10^{16}$ cm^{-3} is of the order of $E_\parallel^* \sim 10^{-8}$ cgs esu.

The feasibility of transferring a noticeable fraction of the surface electrons, under conditions of cyclotron resonance, to quasiclassical levels was demonstrated in Édel'man's experiments.[4] The appearance of quasi-free electrons with increasing intensity $E_\parallel$ leads in these experiments to the onset of a new relatively narrow resonant-field absorption line, whose position does not depend on the angle between H and the normal to the surface of the helium. From the quantitative point of view, however, the results of[4] pertain to an intermediate situation, when the bulk of the electrons is still on deep surface levels.

[1)]In the transition region of the parameters, when the electrons occupy positive and negative levels, the temperatures of the surface electrons and of the quasi-free electrons can differ.

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