Photoresonance and mobility of electrons localized over liquid helium

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The mobility of electrons localized over liquid ^{3}He and ^{4}He is investigated at a frequency ~20 MHz and a temperature 0.3–0.5 K. Upon irradiation of the system of electrons with a microwave signal of frequency $F \approx 70$–150 GHz, photoresonance was observed at holding-field values such that the difference between the natural frequencies of the electrons was equal to the frequency of the external radiation. The photoresonance is manifest in the variation of the electron mobility. For electrons localized over ^{3}He, both the mobility and the photoresonance line width are determined at $T \gtrsim 0.32$ K by collisions with the vapor atoms and vary in accord with the temperature variation of the saturated-vapor density. The absolute values of the relaxation times turn out to be half the theoretical ones. For the electrons over ^{4}He, in the investigated temperature region, the mobility is determined by the electron-ripplon interaction and amounted to 3.3×10^7 cm^2/V·sec at $T = 0.4$ K; this value agrees with the theoretical prediction. The half-width of the line of the observed photoresonance exceeded by one order of magnitude the theoretical value: it amounted to ~30 MHz and was determined by the field inhomogeniety caused apparently by the inhomogeniety of the work function along the electrodes. The width of the region in which the helium density changes from the density of the liquid to zero was determined from the difference between the natural frequencies of the transitions from the corresponding hydrogen levels. Assuming that the density in the transition region depends linearly on the coordinate, it is found that the width of the region is 8.2 and 6.1 Å for ^{3}He and ^{4}He, respectively.

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1. INTRODUCTION

In the investigation of the resonant properties of electrons localized over liquid helium, it was found that transitions between quantum levels—photoresonance—can be revealed by the change of the high-frequency mobility in a magnetic field.[1] An intriguing circumstance was the unexpectedly large photoresonance line width, exceeding by two orders of magnitude the value expected on the basis of the existing theory that takes into account scattering of electrons by vapor atoms and by thermal oscillations of the liquid surface (ripplons).[2] This has raised the question of a detailed investigation of photoresonance at low temperatures.

In Ref. 1, excitation of transitions between the levels was revealed by the change of amplitude of the cyclotron resonance, which was investigated at a frequency ~18.5 GHz. This method, besides the complexity of the organization of the experiment, has from the point of view of the study of photoresonance the shortcoming that in the microwave band, when cavity resonators are used, it is difficult to ensure high homogeneity of the holding field that determines the frequencies of the resonance transitions. With this in view, we have investigated the photoresonance by observing the nonlinearity of the high-frequency conductivity (at a frequency 10–20 MHz) with the electrons irradiated by microwaves of frequency 70–150 GHz. The first results of these investigations, dealing with the natural frequencies of the electrons localized over ^{3}He, were described in our preceding paper.[3]

We describe below our experiments: in Sec. 2 the experimental setup, in Sec. 3 the measurement results, and in Sec. 4 their discussion.

2. EXPERIMENTAL SETUP

We measured the Q of an LC circuit electrically connected to the electron layer of a charged liquid-helium surface. The circuit was connected to a receiver located outside the cryostat by a coaxial cable made up of thin-wall stainless steel tubes of 5 and 1 mm diameter, with the inner tube tinned; the length of the cable was ~1 m). A resonant-frequency signal from a Ch6-31 frequency synthesizer was applied to the upper part of the coaxial cable, located outside the cryostat, through a ~0.1 pF capacitor. Because of the high impedence of this capacitor compared with the resonant resistance referred to the input of the receiver, the amplitude of the received signal was proportional to the resonant resistance of the tank circuit, i.e., to its Q, which depends on the surface density of the electrons and their mobility.

To increase the relative contribution of the electrons to the losses, the tank circuit was constructed mainly of superconducting materials. The coil was a lead wire wound on a foamed-polystyrene form and surrounded by a lead screen. The capacitor was also superconducting (with the exception of the small part connected to the capacitance of the measuring cell). It was made of strips of tin foil interlined with kapron (nylon) cloth and rolled into a tube, so as to increase the rigidity and to decrease the microphone effect. The coaxial lead was connected to a tap of the coil of the tank circuit to form an autotransformer with a ratio ~1 : 20. This ensured a loaded Q ($Q_0 \approx 3 \times 10^3$–$10^4$) in the absence of electrons.

Because of the high Q of the tank circuit, the resonant resistance at the input of the receiver was of the

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order of several kΩ, so that the first stage was a broadband field-effect-transistor follower (the probe of the "Takeda Riken" *TR*-1180 frequency meter) with impedance 1 MΩ + 10 pF. The signal proceeded then to a tunable resonant amplifier with bandwidth ~100 kHz, a broadband amplifier UZ-33, and a detector using an inverted GI-401 diode and having a quadratic characteristic at an output signal $\lesssim$0.1 V. The drift of the output signal was determined mainly by the changes in the amplitude of the signal from the Ch6-31 synthesizer and by the microphone effect, and did not exceed ~1%. At an output signal 0.1 V, the amplitude of the electric voltage across the tank-circuit capacitor was 1 mV, corresponding to an effective field ~0.5 mV/cm acting on the electrons.

As shown by the measurements and as will be described below, the influence of the electrons on the Q of the tank circuit depends substantially on the geometry of the measurement cell. We have tested several versions located gap 6–8 mm above the lower flat electrode that produces the holding field; a cylindrical coil (a); a flat spiral coil (b); a system of three electrodes 30 mm long and 10 mm wide, separated by a gap of 1 mm, the outer ones grounded and the center one connected to the "hot" and of the tank circuit (c); the system (d) shown schematically in Fig. 1. In variant (a), in which the coupling with the electrons was via the alternating magnetic field, the measurement sensitivity turned out to be insufficient to observe the contribution from the electrons. The other three methods ensure comparable sensitivity. At the element dimensions indicated in Fig. 1, method (d) is less sensitive than the remaining two. However, the small dimensions of the region containing the high-frequency field, compared with the dimensions of the capacitor that produces the static field, ensured high homogeneity of the holding field in the working zone. The simple geometry of the cell made it possible to calculate the alternating electric field acting on the electrons, and by the same token determine from the magnitude of the observed effect the absolute value of the electron mobility.

The measuring cell was placed in an airtight container in which a specified amount of ^{3}He and ^{4}He was condensed during the time of the experiment in such a way that the helium level was between the lower and the upper electrodes. The container was in the thermal contact with a bath cooled by pumping off ^{3}He vapor. The temperature of the container was measured with a thermometer based on a "spare" resistor[D] whose resistance R in the temperature region 0.3–1 K satisfies the relation $1/T = a + b\log R$; the coefficients a and b were determined during the time of the experiment at $T > 0.4$ K, when measurement of the temperature by means of the vapor pressure of the ^{3}He in our cryostat ensured a measurement accuracy ~0.003 K.

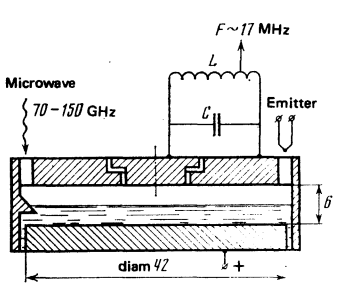

FIG. 1. Diagram of measuring cell.

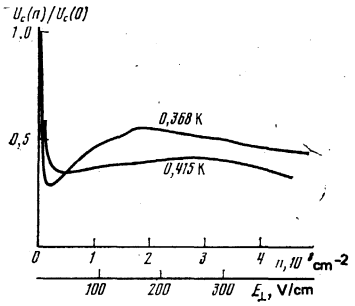

FIG. 2. Amplitude of HF tank-circuit oscillations vs the density of the electrons localized over ^{3}He.

The helium surface was charged by energizing for a short time the incandescent cathode (tungsten wire of 0.01 mm diameter). This produced a charge density n that ensured screening of the static field over the liquid surface. The density was determined from the condition

$$n = U/4\pi eh, \qquad (1)$$

where U is the dc voltage applied to the electrodes of the measurement cell, and h is the thickness of the helium layer. The appearance of the charge led to a change in the tank-circuit Q which was restored to the initial value by decreasing the voltage U to zero (Figs. 2 and 3).

To excite the photoresonance, the electrons were acted upon by a microwave signal of frequency 70–150 GHz generated by a backward-wave tube. The frequency of the generated signal was stabilized against a tunable reference resonator with accuracy ~10^{-4}. The microwave signal was modulated at a frequency 400–1000 Hz with the aid of a perforated rotating disk introduced into a slot 0.5 mm wide in the waveguide. A narrow-band amplifier and a synchronous detector separated accordingly from the megahertz detector signal a component at the modulation frequency, and the magnitude of the component was registered with an x-ray recorder as a function of the voltage that produced the holding field (Fig. 4).

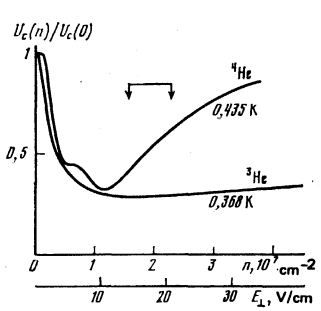

FIG. 3. Amplitude of HF tank-circuit oscillations vs the density of the electrons localized over ^{3}He and ^{4}He.

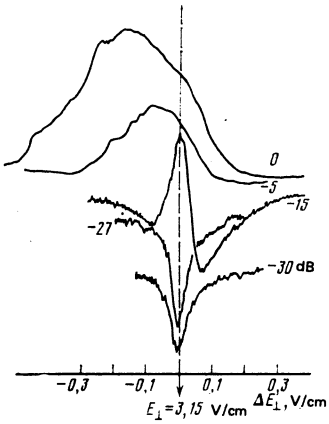

FIG. 4. Line shape of photoresonance signals for electrons localized over ^{3}He at the various microwave power levels marked on the right of the curves; $T = 0.35$, $\tilde{E}_t = 0.1$ mV/cm, $F = 72.93$ GHz.

The photoresonance line shape for the electrons over ^{3}He was substantially dependent on the microwave power fed into the measuring cell (Fig. 4). With increasing power, the signal reversed sign and the line became strongly broadened. A similar action was exerted by an increase of the amplitude of the alternating field applied to the tank circuit. In the line-width measurements the microwave power level was therefore chosen such that an increase or a decrease by 3–5 dB caused the signal amplitude to change in proportion to the power, and the waveform to remain unchanged. The voltage on the tank circuit was set at a value such that when it was changed by a factor 2–3, the shape of the photoresonance signal line remain unchanged. This took place at $\tilde{U} \lesssim 1$ mV.

Since the natural frequencies of the electrons depend on the holding field, a number of measures were taken to prevent the additional broadening due to the inhomogeneity of the field. A flexible suspension of the cryostat on springs reduced the vibrations and the oscillations of the liquid surface, and made it also possible to change the orientation of the instrument in space. This made it possible to maintain the charge surface of the liquid parallel to the lower flat electrode with accuracy ~1′ by minimizing the photoresonance line width (at $E_\perp = U/2h \approx 10$ V/cm, a tilt of ~10′ causes a broadening by an approximate factor of 2). The voltage that produced the holding field was fed to the electrodes through an RC filter having a time constant 1 msec and located in the cryostat next to the container with the measuring cell. The measured value of the components at the frequencies 50 and 100 Hz at the output of the holding-voltage source was < 1 mV. The combined action of the possible vibrations and of the alternating component of the voltage was estimated during the time of the experiment: the field value was set on the slope of the photoresonance line in such a way that the signal at the backward-wave tube modulation frequency was equal to half the maximum value. The noise spectrum was next plotted in the frequency range 1 Hz–100 kHz with the microwave power on and off. In the entire frequency range, no change was observed in this case in the spectral noise density, which did not exceed at all frequencies 10% of the amplitude of the modulation-frequency signal. Thus, the time varying parasitic component of the holding field does not exceed 10% of the line width, and its possible presence does not influence the experimental results.

To eliminate the parasitic fields connected with the contact potential differences, all the measuring-cell parts that form the static field acting on the electrons were covered with a gold film produced by thermal evaporation. Nonetheless, it could be noted in the experiments that even when the holding voltage source is turned off, an electric field exists between the electrodes and corresponds to a voltage U_{res} ranging from 0.1 to ~0.5 V and having opposite polarity. This field is revealed on the $Q(n)$ plot by the presence of a kink and of a plateau at small U (Fig. 3). Judging from the fact that in certain cases U_{res} changed noticeably during the course of one helium experiment, the appearance of this residual voltage can in part be attributed to electrization of the dust particles which are inevitably present on the lower electrode.

To eliminate this effect, experiments were performed with an improved charging procedure. At the instant when the cathode was turned on, the holding field was turned off. It was turned on again with a time constant ~1 msec after ~50 msec, when the cathode was already hot and certainly emitted electrons. As a result no accelerating fields were produced in the gap between the cathode and the helium surface, so that the electrons could not acquire the energy ~1 V necessary to overcome the surface barrier and charge the dust particles. The measurement results became in this case perfectly reproducible in the course of the experiment. However, even if the first charge was produced at $U < 1$ V, thereby guaranteeing the absence of fast electrons, a plateau at 0.1–0.15 V inevitably appeared. Its presence must thus apparently be attributed to the inhomogeneity of the work function along the electrodes.

The appearance of U_{res}, as shown by the experiments, leads to a holding-field inhomogeneity whose amplitude corresponds to ~0.1 U_{res}. This phenomenon greatly complicates the performance of the experiment, since small values $U_{res} \lesssim 0.1$ V could be obtained only in a relatively small number of experiments. It is not clear as yet, however, how to get rid of this unpleasant phenomenon. It can apparently be substantially weakened by greatly increasing the dimensions of the measuring cell, but this was impossible in our cryostat.

In the course of the work, some of the experiments were performed by the method in which cyclotron resonance is observed; the procedure employed is described in detail in Ref. 1.

3. MEASUREMENT RESULTS

Electron mobility. As seen from Figs. 2 and 3, the losses introduced into the tank circuit by the system of electrons depend in a complicated manner on the applied voltage or, more accurately, on the number of

electrons, which is determined by Eq. (1). After an initial linear decrease of the signal, due to the increase of the absorption, a minimum is observed, followed by a slow increase of the signal with increasing concentration. For electrons over ^{4}He, the picture is even more complicated. Variation of the temperature, which is accompanied by variation of the electron mobility, shifts the minimum with respect to the field in approximately inverse proportion to the slope of the initial section (Fig. 2).

The nonmonotonic $Q(n)$ dependence can in principle be connected with the decrease of the mobility μ of the electrons with increasing holding field $E_\perp$. Its influence, however, becomes noticeable to any degree only $E_\perp \gtrsim 200$–300 V/cm.[1,2,4,5] From a comparison of the curves of Fig. 2 it is seen that in the field region $E_\perp \gtrsim 50$ V/cm the mobility decrease with increasing temperature is accompanied by a decrease of Q, i.e., by an increase of the absorption. Therefore the decrease of Q which takes place after a maximum is reached in a field ~200 V/cm must be attributed to a mobility decrease under the influence of the holding field. In still stronger fields $E_\perp \gtrsim 500$ V/cm, we observed an increase of the Q with increasing concentration, and this should take place at a considerable decrease of the mobility.

The complicated character of the $Q(n)$ dependence is connected with the fact that at high mobility and considerable density, the electrons manage to become distributed during one period of the HF field in such a way as to compensate for the alternating component tangent to the surface. This should lead to a decrease of the absorption. The process considered can be characterized by the dimensionless parameter $\beta = ne\mu/r\omega$, where r are the characteristic dimensions of the system. Substituting in the expression for β the dimension $r = 1$ cm and the values of μ determined below, we find that the maximum of the absorption is observed at ≈ 0.1. We note that the considered phenomenon depends on the configuration of the alternating field. Thus, in the measuring cell of type (c) no minimum of Q is observed.

Thus, without a calculation that takes into account the change of the configuration of the alternating electric field with increasing electron density, the mobility of the electrons can be determined only from the initial linear section of the $Q(n)$ dependence. For this region we can write

$$\frac{1}{Q} = \frac{1}{Q_0} + \frac{ne\mu}{\omega C\tilde{U}^2}\int E_t^2\, ds \frac{1}{1+(\omega\tau)^2}, \qquad (2)$$

where E_t is the tangential component of the alternating field on the helium surface in the absence of electron, and is proportional to the amplitude of $\tilde{U}$ of the alternating voltage on the tank circuit, C is the tank-circuit capacitance, and $\tau = m\mu/e$ is the relaxation time.

The values of for the electrons over ^{3}He, obtained from the plot of the type shown in Fig. 3 using formula (2), are shown in Fig. 5. The values of $\int_S (E_t/\tilde{U})^2 ds$ were calculated with a computer for the cell shown in Fig. 1, and this made it possible to establish the absolute scale of μ.

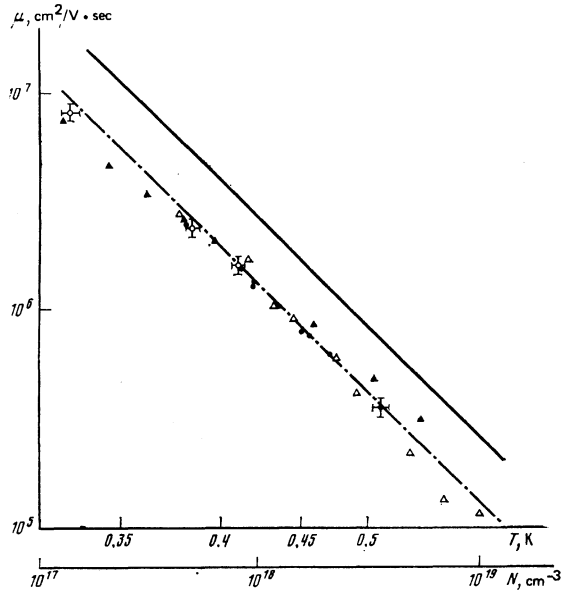

FIG. 5. Dependence of the mobility of the electrons over ^{3}He(○, ●, ▲) and ^{4}He (△) on the vapor density. The temperature scale refers to ^{3}He. For ^{4}He, the scale of the μ axis is changed by a factor 1.33, and the presented data are taken from Ref. 12. ○) measured in cell shown in Fig. 1; ●, ▲) various experiments with cell of type (c); the absolute values were established by comparison with ○ at $N \approx 10^{18}$ cm^{-3}. Solid line—theoretical calculation.

The appearance of an additional structure on the $Q(n)$ dependence for the electrons over ^{4}He is due to the spatial resonance of the longitudinal plasma waves, which takes place for symmetrical excitation under the condition $J_0(kr) = 0$, where J_0 is a Bessel function of zero order and r is the radius of the cell. In our case $\omega\tau \approx 1$ and only the fundamental mode of the resonance, corresponding to the first zero of the Bessel function, can be observed. Since the distance between the electrodes is much less than the cell diameter, the screening action of the electrodes influences substantially the spectrum of the waves. A simple expression connecting ω, n, and k for the case of solid electrodes was obtained in Ref. 6. The break in the upper electrode brings our situation closer to the case in which one of the electrodes is removed to infinity. The calculated values of the resonant fields for both types of boundary are indicated by arrows in Fig. 3. It is seen that the region of possible location of the resonance lies near the minimum of Q at $E_\perp \approx 10$ V/cm.

The presence of a standing-wave resonance indicates that for the electrons over ^{4}He we have $\omega\tau > 1$ in the investigated case. Taking this circumstance into account, and using the experimentally determined value of $\partial Q/\partial n$ for small n at $T = 0.42$ K in accordance with formula (2), we have obtained $\mu = (3.3 \pm 0.6) \times 10^7$ cm^2/V · sec.

Photoresonance. The complicated $Q(n)$ dependence leads also to a complicated picture of the photoresonance and, in particular, to a change of the sign of the effect when it is observed in different regions of the value of n. In the investigation of electrons localized

over ^{3}He it was established that at small microwave-field amplitudes the resonant excitation of the electrons corresponds to a decrease of the electron mobility. When the microwave-signal power is increased, the sign of the resonance is reversed (Fig. 4), i.e., the effective mobility at resonance increases.

For electrons over ^{4}He, an increase of the microwave-field amplitude does not lead to a change in the sign of the resonance, and only to its broadening. The excitation of the resonance, with allowance for the fact that $\omega\tau > 1$ under the experimental conditions, corresponded to an increase of the mobility (i.e., e.g., to a decrease of the absorption at small values of n). In all cases the excitation of photoresonance led to a rather small relative change of the Q of the tank circuit, not exceeding 1–2%.

The photoresonance detected by determining the change of the amplitude of cyclotron resonance in Ref. 1 and in the course of the present work had a somewhat larger amplitude, reaching 10–20%. For both ^{3}He and ^{4}He the photoresonance led in this case to an increase of the relaxation time, i.e., to an increase of the mobility (see Ref. 5, Figs. 25 and 26).

The dependence of the frequency of the resonant transitions (from the ground state 1 to the lth excited state) on the holding field for electrons over ^{3}He is shown in Figs. 6 and 7. This dependence was used by us to determine the width of the photoresonance line in the frequency scale. For the electrons over ^{4}He we used for this purpose the results of Grimes *et al.*[7]

The measured values of the half-width of the photoresonance line at half-height as a function of the temperature, at a holding field ~3 V/cm, are shown for electrons over ^{3}He in Fig. 8. In the same field region we have observed the transitions $1 \to 3$ and $1 \to 4$, the line width for which turned out to be ~20 mV/cm. Recognizing that the lines should have been much narrower at the considerably larger value of $\partial F/\partial E_\perp$ for the indicated transitions than for the transitions 1 and 2 (see Fig. 7) and that their width for the transitions $1 \to 3$ and $1 \to 4$ should be substantially different, we are inclined to attribute the value $\Delta E_0 = 20$ mV/cm to the

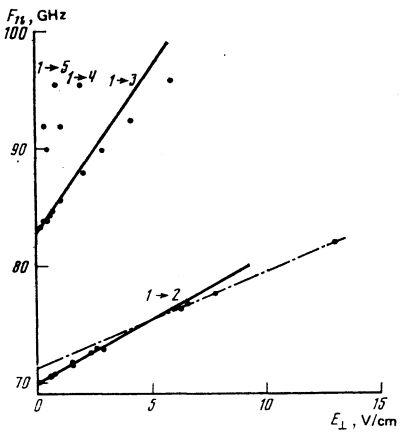

FIG. 6. Transition frequency in the spectrum of electrons localized over ^{3}He vs the holding field $E_\perp$.

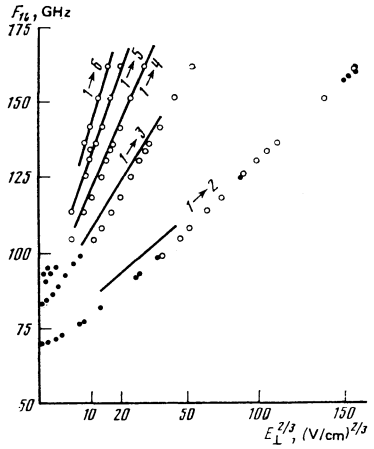

FIG. 7. The same as in Fig. 6 in a wide range of fields E. Solid lines—calculation with a potential of the form $eE_\perp z$ with account taken of the perturbation due to the image field and the field of the neighboring electrons. Since this approximation is not valid for the ground state, all the calculated frequencies are shifted by a constant amount, so as to make the calculation coincide with experiment for the $1 \to 5$ transition. Points: •) results based on measurement of the nonlinearity of the conductivity at 17 MHz, ○) measurements based on the nonlinearity of absorption at cyclotron resonance observed at 18.5 GHz.

inhomogeneity of the holding field. If we denote the natural line width by ΔE, then the observed width ΔE_{obs} should be close to the value $(\Delta E_0^2 + \Delta E^2)^{1/2}$. The plot of this formula under the assumption $\Delta E \propto N$ (N is the density of the vapor) describes satisfactorily the experimental results (Fig. 8). We note that at $N \approx 4 \times 10^{17}$ cm^{-3} the role of ΔE_0 turns out to be insignificant.

The area under the photoresonance peak, which is proportional to the product of the peak amplitude by the width, is inversely proportional to the vapor density (Fig. 8).

The line half-width for the transitions $1 \to 2$ and $1 \to 3$ for electrons over ^{4}He at $E \lesssim 3$ V/cm and $T = 0.4$ K agreed within ~10% and amounted to $\Delta E_0 \approx 40$ mV/cm. According to the same arguments that were advanced above, this quantity should be attributed to the inhomogeneity of the field. Recognizing that the measurement accuracy is ~5–10%, we obtain for the natural line width an upper bound $\Delta E < 0.5 \Delta E_0$, which corresponds to $\Delta F \lesssim 15$ MHz.

With increase of the holding field to $E_\perp \gtrsim 20$ V/cm, the line width is increased in approximate proportion

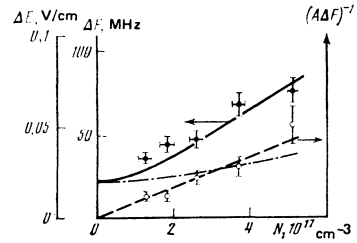

FIG. 8. Dependence of the half-width of the photoresonance (•) and of the area under the photoresonance (○) on the vapor density for electrons localized over ^{3}He.

to the field, so that $\Delta E_{obs}/E \approx 0.3-0.5\%$ for electrons both over ^{3}He and over ^{4}He. On this basis it can be assumed that the broadening is due to the inhomogeneity of the field. Calculation for an ideal cell in accordance with Fig. 1 yields, at a liquid-layer thickness 3 mm inside a circle of 10 mm diameter, in inhomogeneity ~0.01%. The much higher degree of inhomogeneity obtained in the experiment is apparently due to deviations exceeding ~0.01 mm of the surface of the lower electrode from planarity.

All the measurements were performed at a maximum charge of the liquid surface, ensuring the screening of the electric field over the electron layer. With decreasing electron density, the photoresonance line broadens considerably because of the worse homogeneity of the field, due to the slot in the upper electrode.

The photoresonance line widths measured in the present paper turn out to be several times smaller than those reported in Ref. 1. For this reason we have repeated the measurements in a magnetic field and established that the photoresonance line width can vary from experiment to experiment by several times. The minimum half-width of the line for the electrons over ^{3}He (at $F \approx 139$ GHz and $T = 0.38$ K) was ~0.5 V/cm for the transitions $1 \to 2$, $1 \to 3$, and $1 \to 4$ (respective fields 107, 34, and 18 V/cm). It appears that this quantity characterizes the field inhomogeneity due to random charges. Their role is more significant when the surface charge is produced by a cold discharge, in which electrons with higher energies are generated. They can accordingly overcome the energy barrier on the helium surface and produce a large parasitic charge. Unfortunately, the use of an incandescent cathode when working in a magnetic field is greatly hindered by the fact that it is destroyed by the current flow under the influence of ponderomotive forces.

Just as above, the natural width for the transition $1 \to 2$ can be estimated at $\Delta E \lesssim 0.25$ V/cm. When account is taken of the value of $\partial F_{1,2}/\partial E$, this yields $\Delta F \lesssim 110$ MHz. This value differs little from that given in Fig. 8 for the corresponding vapor density $N \approx 5 \times 10^{17}$ cm^{-3}.

4. DISCUSSION OF RESULTS

When a resonant quantum is absorbed, the electron acquires a considerable energy, amounting to ~3 K for the transition $1 \to 2$ in the case of ^{3}He. The lifetime in this excited state is relatively short, and at the dominant mechanism of scattering by the atoms of vapor of density N it is of order of magnitude $(6 \times 10^{-11} \cdot N)^{-1}$ sec, i.e., it amounts to ~10^{-7} sec at $N \approx 10^{17}$ cm^{-3} (Ref. 7). As a result of this scattering, the electron goes, with practically no change of energy, to the ground state, but with a large momentum parallel to the surface. Its further cooling is due mainly to two-ripplon collisions[8] within characteristic time intervals ~10^{-5} sec.[1] Collisions with the vapor atoms does not influence the energy relaxations, inasmuch as in each elastic collision its energy changes by $\sim m_e/m_{He} \approx 10^{-4}$, and a relative decrease of the energy by an amount on the order of unity calls for ~10^8 collisions. At the collision frequency 10^{+8}–10^{+9} sec^{-1}, which follows from the value of the mobility (Fig. 5), it follows that the energy relaxation due to this mechanism should occur after 0.1–1 sec.

These considerations confirm the experimental dependence of the photoresonance intensity on the vapor density. If the momentum scattering by the vapor atoms atoms is the dominant process, an equal heating of the electrons should lead obviously to a mobility change proportional to the mobility itself. This means that, in accordance with Fig. 5, the area under the resonance peak should be proportional to N^{-1}, which is in fact observed in experiment (Fig. 8). Thus, the change of the vapor density is not reflected in the energy relaxation, and consequently elastic collisions with helium atoms do not lead to cooling of the electrons.

At low microwave power, the state of the electron system is thus approximately the same as when the electrons are heated little by the measuring signals. This heating leads to a decrease of the mobility in scattering by vapor,[9] and to an increase of the mobility in scattering by ripplons.[1] In our case, in excitation of photoresonance, there is observed correspondingly a decrease of the mobility (for the electrons over ^{3}He) or an increase (for the electrons over ^{4}He).

If the electrons are significantly overheated, owing to population of the excited states in which the electrons move away significantly from the liquid surface, their mobility increases in both types of scattering.[5,10,11] In full accordance with this, the increase of the microwave power leads in all cases to an increase of the electron mobility.

Contradicting the described picture is the fact that for electrons over ^{3}He, investigations in a magnetic field ~6 kOe and at low excitation levels reveal an increase of the relaxation time, incidentally by not more than ~10% (Ref. 1). This contradiction can probably be reconciled by assuming that quantization imposes an additional limitation on the possible acts of scattering from state 2 to state 1, in which the energy and momentum would be conserved. The limitation should lead to an increase of the time that the electron stays in the excited state, so that the effective mobility can also increase. With further increase of the magnetic field, the increase of the mobility may turn out to be appreciable.

The mobility of the electrons over ^{3}He in the investigated temperature region 0.3–0.5 K is proportional to N^{-1}. The values of μ coincide with those measured for electrons over ^{4}He in Ref. 13, if in accord with the theory (e.g., Refs. 5 and 11) they are multiplied by the ratio of the effective charges $(\varepsilon - 1)e/4(\varepsilon + 1)$ which is equal[5] to 1.33 (Fig. 5). The electron mobility then turns out to be half the theoretical value. We note that besides in Ref. 12, the opposite value of the mobility in scattering by a gas was measured by the time-of-flight method in Ref. 10. According to Ref. 10 the values of μ are close to $N \approx 10^{19}$ cm^{-3} to the theoretical ones, and at $N \approx 10^{18}$ cm^{-3} they are close to the results of Ref. 12. It appears that they are not very accurate, as indicated by the considerable systematic deviation from the relation $\mu \propto N^{-1}$. The values obtained in investigations of

cyclotron resonance are smaller by a factor ~1.5 from the theoretical ones,[9] but their error is quite large.

The line width of the photoresonance of the electrons over ^{3}He is proportional to N (Fig. 8). However, in this case, too, the scattering turns out to be twice as effective as would follow from the theory.[2] We note that agreement with the theoretical calculation was established earlier[2] for the line width of the resonant transition for electrons over ^{4}He measured in Ref. 7. It was suggested in Ref. 5 that Ref. 7 contains an error since the authors cite in a later paper[13] a value twice as large which apparently should be regarded as correct. Our results confirm this opinion.

Thus, the experiments indicate that scattering by vapor atoms is twice as effective than follows from the theory. The cause of this discrepancy is not yet clear. It is possible that the discrepancy can be eliminated by taking into account the fluctuations of the gas density, in analogy with the procedure in Ref. 7.

In the region of the dominant electron-ripplon scattering, i.e., for electrons over ^{4}He, the mobility measured by us at $T=0.42$ K $(3.3\pm0.6)\times10^{-7}$ cm^2/V·sec, which agrees with the value 3.6×10^7 cm^2/V·sec calculated in Ref. 2 and is somewhat higher than the value 1.7×10^7 cm^2/V·sec obtained in Ref. 4 at 0.5 K. Rybalko *et al.*[14] obtained a value smaller by one order of magnitude. There is apparently no need to discuss this difference, inasmuch as in a recent paper by Esel'son, Rybalko, and Sokolov[15] the authors in fact refuted the results of Ref. 14, and reconciled numerically the measurement results with the theoretical value.

The mobility of the electrons over ^{4}He was measured also in Ref. 16. For the temperature region 0.4–0.5 K the value obtained there was $\mu\approx10^7$ cm^2/V·sec. This value, however, was determined for a holding field 100 V/cm. Furthermore, in that reference the quantities measured were not absolute but relative, and were tied in with values of μ measured by others in the region of scattering by vapor atoms.

As shown above, the large photoresonance line width observed in Ref. 1 is due to instrumental effects. In our present investigation of electrons over ^{4}He study we succeeded in observing lines that are narrower by an order of magnitude than in Ref. 1, and in estimating that the natural half-width of the line does not exceed 15 MHz. This value should be compared with the 2.7 MHz that follows from the calculation.[2] As is clear from this comparison, considerable methodological efforts must be made for a final assessment of the validity of the theory. Ways of solving this problem are not clear at present.

We consider now results pertaining to the spectrum of the natural frequencies of the electrons.

Greatest interest attaches to the region of small values of $E_\perp$, in which the frequencies of the transitions F_{1l} depend linearly on $E_\perp$ (Fig. 6). Extrapolating $F_{1l}(E)$ to $E_\perp=0$, we obtain for ^{3}He the values $F_{12}(0)=69.9\pm0.1$ GHz and $F_{13}(0)=82.7\pm0.1$ GHz.[2)] Introducing, as in Ref. 3, a correction $(0.3\pm0.1)\%$ for the ^{4}He impurity in the employed ^{3}He, we obtain for pure ^{3}He the transition frequencies 69.8 ± 0.15 and 92.55 ± 0.2 GHz, respectively. These frequencies must be compared with the corresponding transitions between the hydrogenlike levels

$$\hbar\omega_l=-\frac{me^4}{2\hbar^2l^2}\left[\frac{\varepsilon-1}{4(\varepsilon+1)}\right]^2,\quad l=1,2,\ldots.$$

The calculated values $F_{12}(0)=67.6$ and $F_{13}(0)=80.1$ GHz are somewhat smaller than the measured ones. This difference allows us to estimate the width of the transition region from the liquid to the vacuum. In Refs. 7 and 3 they used for this purpose a perturbation-theory variant proposed in Ref. 17, with a model potential

$$V(z)=\begin{cases}-\Lambda/(z+\delta), & z>0\\ V_0 & z<0\end{cases}. \tag{3}$$

Here z is the coordinate along the normal to the liquid surface, $z>0$ above the liquid, V_0 is the energy barrier that hinders the penetration of the electron into the liquid, and $\Lambda=(\varepsilon-1)e^2/4(\varepsilon+1)$. A more realistic representation potential is

$$V(z)=\begin{cases}-\Lambda/(z+\delta), & z>0\\ -V_0z/2\delta, & z<0\end{cases}. \tag{4}$$

This form of $V(z)$ at $z<0$ was chosen under the assumption that the density varies linearly in the transition layer. According to calculations made in Ref. 18, the height of the barrier can be assumed with sufficient accuracy to the proportional to the density of the helium. The fact that $V(z)>V_0$ at $|z|>2\delta$ does not play any role, since the wave function manages to attenuate over a distance 2δ.

Corresponding to a potential of the form $V_0z/2\delta$ is a solution of the wave equation in the form of an Airy function. Neglecting the difference between the electron mass and zero compared with V_0, we obtain for the logarithmic derivative of the corresponding function ψ:

$$\psi'/\psi|_{z=0}=0.73(mV_0/\delta\hbar^2)^{1/3}.$$

Proceeding in analogy with Ref. 17, we obtain from this for the change of the self-energy

$$\Delta(\hbar\omega_l)=\frac{\hbar^2}{2m}[\psi_{l0}'(0)]^2\left[\delta-1.37\left(\frac{\delta\hbar^2}{mV_0}\right)^{1/3}\right], \tag{5}$$

where ψ'_{l0} is the derivative of the wave function that describes the lth hydrogenlike state. According to (5), $\Delta\omega_2=(1/8)\Delta\omega_1$ and $\Delta\omega_3=(1/27)\Delta\omega_1$. On this basis we can calculate, from the measured transition frequencies $F_{1l}=|\omega_1-\omega_l|/2\pi$ the energy shift of the ground state, which is equal to 2.52 ± 0.15 GHz for ^{3}He and 7.08 ± 0.2 GHz according to the data of Ref. 7 for ^{4}He. Substituting these values in (5), we obtain the transition-region widths $2\delta=8.2\pm0.15$ and 6.1 ± 0.1 Å for ^{3}He and ^{4}He, respectively. In the calculations for the barrier on the ^{3}He surface we have assumed $V_{03}=(V_{03}/V_{04})_{\text{theor}}V_{04\,\text{exp}}$, with the theoretical values corresponding to the calculations of Ref. 17, and $V_{04\,\text{exp}}=1.2\pm0.08$ eV.[19] We note that the transition-region width obtained by us for ^{4}He is close to that calculated in Ref. 20, where the potential used differs little from that assumed by us in accord with (4). The dimensions of the

transition region, expressed in fractions of the interatomic distance $a = v^{-1/3}$ in the liquid, where v is the volume per atom, amount to 2.08 ± 0.04 and 1.71 ± 0.02. Thus, both for ^{3}He and for ^{4}He the density decreases to zero over a distance equal to two interatomic distances.

In strong fields, the transition frequencies are determined mainly by the intensity of the holding field $E_\perp$, and vary the proportion to $E_\perp^{2/3}$ (Ref. 21). The experiment agrees qualitatively with this prediction (Fig. 7).

In conclusion, we wish to call attention to the following circumstance. As established in this paper, it is quite realistic to observe resonant transition in the spectrum of electrons localized over liquid helium, with a relative line width $\sim(1-3)\times10^{-4}$. This uncovers an unprecedented opportunity of measuring the dielectric constant averaged over a layer of thickness $\sim10^{-6}$–10^{-5} cm, accurate to $\sim10^{-5}$, and to study thus the impurity distribution near the surface in weak solutions of ^{3}He in ^{4}He and of ^{4}He in ^{3}He. This method can probably be extended also to the study of sorption, on a helium surface, of hydrogen atoms oriented on a helium surface by a magnetic field,[22] experiments on which has recently attracted increased interest.

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[2)]The value of F_{13} presented here is made more precise in comparison with Ref. 3.

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