4.6×10^{11} sec^{-1}. Taking into account the very strong dependence of w_0 on the field intensity, the difference between the calculated and experimental values of w_0 is small and may be connected, in particular, with the error in the experimental determination of the absolute value of the threshold radiation-flux density.

It is interesting to note that under the conditions of our experiment the parameter γ introduced in [2] is close to unity, i.e., the case realized in the experiment is intermediate between multiquantum ionization and direct tunneling of the electrons in the field of the strong light wave.

The results obtained in this investigation offer evidence that the transition to picosecond pulse durations will make it possible to observe directly the photoionization that leads to breakdown, in the field of a strong electromagnetic wave, in the region of relatively high pressures of the investigated gases. The cascade breakdown mechanism is completely excluded in this case. It becomes possible to carry out the investigations both in the region of multiphoton ionization, and in the region of direct tunneling of the electron in the field of the strong electromagnetic wave.

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[1] F. V. Bunkin and A. M. Prokhorov, Zh. Eksp. Teor. Fiz. 46, 1090 (1964) [Sov. Phys.-JETP 19, 739 (1964)].
[2] L. V. Keldysh, ibid. 47, 1945 (1964) [20, 1307 (1965)].
[3] Ya. B. Zel'dovich and Yu. P. Raizer, ibid. 47, 1150 (1964) [20, 772 (1965)].
[4] F. V. Bunkin and A. M. Prokhorov, ibid. 52, 1610 (1967) [25, 1072 (1967)].
[5] I. K. Krasyuk, P. P. Pashinin, and A. M. Prokhorov, ZhETF Pis. Red. 7, 117 (1968) [JETP Lett. 7, 89 (1968)]
[6] W. K. Pendleton, A. H. Guenther, Rev. Scient Instrum. 36, 1546 (1965); S. D. Kaitmazov, M. S. Matyaev, A. A. Medvedev, and A. M. Prokhorov, Paper at Conference on Quantum Electronics, Erevan, 17 - 19 October 1967.
[7] S. D. Kaitmazov, I. K. Krasyuk, P. P. Pashinin, and A. M. Prokhorov, Dokl. Akad. Nauk SSSR 180, 1331 (1968) [Sov. Phys.-Dokl. 13, 591 (1968)].
[8] R. G. Tomlinson, E.K. Damon, and H. T. Buscher, Physics of Quantum Electronics, N. Y., 1966, p. 520.
[9] A. J. Alcock and M. C. Richardson, Phys. Rev. Lett. 21, 667 (1968).

SINGULARITIES IN THE BEHAVIOR OF SURFACE IMPEDANCE OF TIN UPON ESTABLISHMENT OF A STANDING SOUND WAVE AND QUANTUM OSCILLATIONS OF THE SPEED OF SOUND

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In astudy of electromagnetic excitation of sound [1] in tin situated in a magnetic field, we observed three interesting singularities having apparently a common nature.

The setup consisted of an ordinary radio-spectrometer with a Pound-Knight generator. It made it possible to study both the real and the imaginary part of the surface impedance of the samples. The samples were in the form of discs of 18 mm diameter and 0.5 - 1 mm thickness. The normals to the planes of the discs were parallel to the [010] axis of the crystal.

By varying the direction of polarization of the incident electromagnetic wave relative to the crystallographic axes it was possible to excite two transverse sound waves, either simultaneously or separately. A longitudinal sound wave was excited when the magnetic field was inclined to the normal to the sample surface.

The sample served as an acoustic resonator, and to study the shape of its resonance curves a quantity proportional to the derivative of the of the real part of the surface impedance, $\partial R/\partial f$, was plotted with an x-y plotter as a function of the frequency f at a fixed value of the magnetic field H. $\partial R/\partial f$ had a weak monotonic frequency dependence in the intervals between the resonance frequencies f_n (n = 1, 3, 5,...). In the resonance region, $\partial R/\partial f$ consititutes two approximately similar groups of peaks occupying a frequency interval Δf_n approximately equal to $10^{-2} f_n$. This interval is constant for different types of waves and does not depend on the value of H. The width of certain individual peaks in the groups is $2 \times 10^{-4} f_n$, i.e., the Q of the acoustic resonator is not worse than 5×10^3.

Each type of wave produces a characteristic system of resonance peaks, although the form of the system depends on the number of the resonance, n, and to a lesser degree on the value of H. With increasing n, the position of the most intense peak in each of the two groups becomes stabilized. At the same time, the number of peaks with lower intensity, having a characteristic M-shape, decreases. The described phenomena are observed most distinctly for longitudinal sound (Fig. 1). We note here that the inhomogeneity of the sample thickness and the synchronization of the various modes of the acoustic resonator do not explain fully the observed shapes of the resonance curves.

The quantum oscillations of the derivative of the real part of the surface impedance $\partial R/\partial H$ were investigated for H parallel to the [010] axis. Far from the resonant frequencies, three oscillation periods were observed, viz., when the hf field $\vec{E}$ was polarized along the [001] axis oscillations appeared with periods $P_1 = 2.3 \times 10^{-7}$ Oe^{-1} and $P_2 = 4.7 \times 10^{-8}$ Oe^{-1}. When E was parallel to [100], the periods were $P_1' = 2.3 \times 10^{-7}$ Oe^{-1} and $P_3 = 6.5 \times 10^{-8}$ Oe^{-1}. Although the oscillations with identical periods $P_1 = P_1'$ were observed at different polarizations, their amplitudes differ appreciably[1)]. The values of these periods agree well with data on the de Haas - van Alphen effect [3].

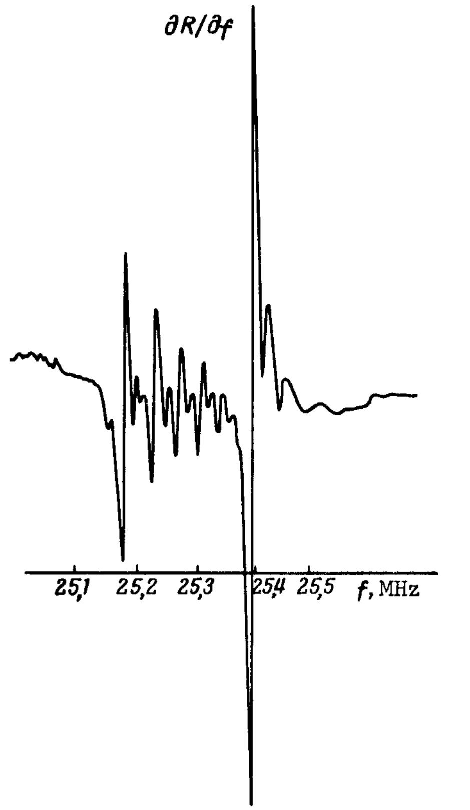

Fig. 1. Sample Sn-1. Derivative $\partial R/\partial f$ vs. frequency in the region where $f_n = nf_0$; n = 15, f_0 = 1.690 MHz. Sample thickness d = 1 mm; H = 40 kOe, T = 4.2°K, H parallel to [110]; hf current parallel to the [001] axis.

[1)]The manifestation of any particular carrier group in the surface impedance at a definite hf-field polarization is connected with the shape of the orbit of the extremal section of the corresponding part of the Fermi surface, and consequently with the different contributions of the electrons to the surface current [2].

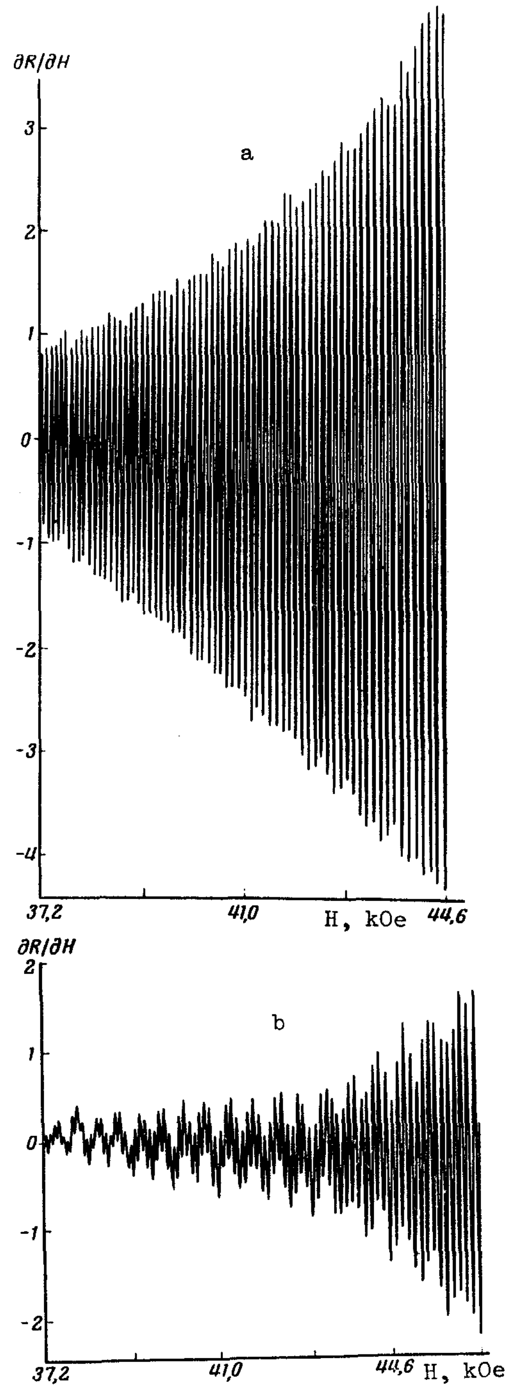

Fig. 2. Sample Sn-2. Dependence of the derivative ∂R/∂H on the magnetic field at two fixed frequencies and the same setup sensitivity: a - f = 5.428 MHz, b - f = 5.457 MHz. Sample thickness d = 0.55 mm; H parallel to [010], hf current parallel to [001]; T = 4.2°K.

When a standing sound wave is established in the sample, the amplitudes of the quantum oscillations increase appreciably (by approximately 100 times) [4], and two important singularities appear: first, the oscillations with periods P_1' and P_3 become stronger when $\vec{E}$ is parallel to [001], and those with periods P_1 and P_2 become stronger when $\vec{E}$ is parallel to [100]. This switch is evidence that the main contribution to the impedance is made inside the metal, and not in the skin layer, when the standing wave is established, inasmuch as inside the metal the field $\vec{E}$ connected with the sound is rotated through an angle $\pi/2$ relative to the field in the skin layer. Second, for a definite polarization of $\vec{E}$, within the limits of one resonance group, it is possible find close values of the frequency f such that oscillations of only one period become amplified. Figure 2 shows an example of such a selectivity.

To explain the nature of the amplification of the quantum oscillations, we measured in addition to $\partial R/\partial H$ also the derivatives of the imaginary part of the surface impedance $\partial X/\partial H$. Comparison of the plots of $\partial R/\partial H(H)$ and $\partial X/\partial H(H)$ makes it possible, as shown in [5, 6], to determine whether the absorption or the rate of excitation propagation is decisive in the formation of the quantum oscillations. The measurements have shown that the quantum oscillations observed upon excitation of a standing sound wave are connected with the oscillations of the speed of sound in the tin. When the speed oscillates, the amplitude of the oscillations of $\partial R/\partial H$ should be minimal at the maximum of the resonance curve of the surface impedance, and that of $\partial X/\partial H$ should be maximal. This is precisely what is observed in the experiment (Fig. 3). If the signal from the generator circuit is fed to an oscilloscope, then it is possible to observe directly the shape of the surface impedance resonance peaks if the depth of the frequency modulation is large enough. It is then possible to see periodic shifts of the individual peaks as the magnetic field is varied slowly. From these shifts it is possible to estimate the relative amplitude of the quantum oscillations of the speed of sound. Thus, in a field

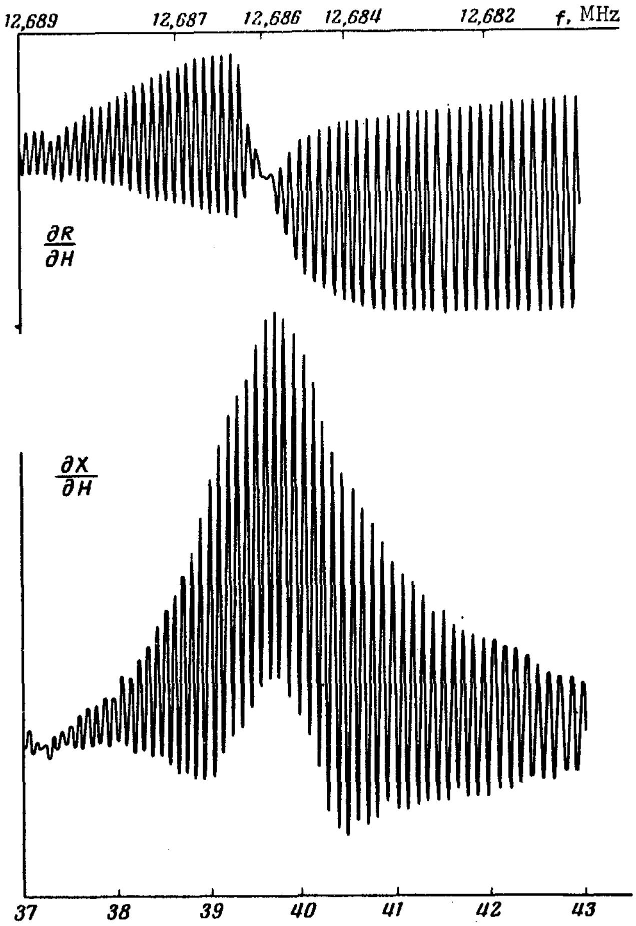

Fig. 3. Sample Sn-1. Field dependence of quantum-oscillation amplitude on going through resonance f_{res} = 12.686 MHz. The passage of the autodyne frequency through one of the resonance peaks in the group occurs simultaneously with the change of H; E parallel to [001], T = 4.2°K.

$H \sim 50 - 60$ kOe its value for the period P_3 is approximately 2×10^{-4}, i.e., it is comparable with the width of the peak itself. This explains the tremendous amplification of the quantum oscillations when a standing sound wave is established.

We explain the described phenomena as follows: The tin sample constitutes two coupled systems, viz., an acoustic resonator with properties specified by its shape and elastic moduli, and the conduction electrons. The interaction of these two systems leads to a splitting of the modes of the acoustic resonator. This splitting can be connected, in particular, with the shape of the orbits and with the masses of the individual groups of the conduction electrons. For example, the shape of the electron orbit in the magnetic field may influence the angle of rotation of the vector $\vec{E}$ of the hf field inside the sample. As a result, different values of the speed of sound are connected with different electron groups. Thus, the regularities observed upon excitation of standing sound waves in tin can be employed for the study of individual groups of carriers in a metal.

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[1] V. F. Gantmakher and V. D. Dolgopolov, Proc. 10th Internat. Conf. on Low-temperature Physics, Moscow, LT-10, 3, 133 (1967).
[2] E. P. Vol'skii, Zh. Eksp. Teor. Fiz. 46, 123 (1964) [Sov. Phys.-JETP 19, 89 (1964)].
[3] M. D. Staflen and A. R. de Vroomen, Phys. stat. solidi 23, 675 (1967).

[4] Yu. P. Gaidukov and A. P. Perov, ZhETF Pis. Red. 8, 666 (1968) [JETP Lett. 8,412(1968)].
[5] E. A. Kaner and V. G. Skobov, Usp. Fiz. Nauk 89, 367 (1966) [Sov. Phys.-Usp. 9, 480 (1967)].
[6] I. P. Krylov, ZhETF Pis. Red. 8, 3 (1968) [JETP Lett. 8, 1 (1968)].

ACOUSTIC BIREFRINGENCE IN ANTIFERROMAGNETIC $MnCO_3$

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An oscillatory dependence on the magnetic field was observed in the intensity of transverse hypersound passing through an antiferromagnetic $MnCO_3$ crystal.

Below 32°K, $MnCO_3$ is an antiferromagnet with weak ferromagnetism. The spins lie in the basal plane perpendicular to the threefold axis. As a result of the interaction of the low-frequency oscillations of the electronic antiferromagnetic system with the nuclear magnetic system, the two branches of the electron-nuclear resonance, which were investigated in [1, 2], are observed.

The presence of low-frequency electron-nuclear branches with a strong field dependence was reason for hoping to observe the influence of a magnetic field on the passage of sound at frequencies 100 MHz and higher. We investigated the passage of transverse hypersound of frequency 104 and 204 MHz through single-crystal $MnCO_3$. The samples were plates (1 - 10 mm^3) whose plane coincided with the basal plane. The $MnCO_3$ crystals were grown by N. Yu. Ikornikova at the USSR Academy Crystallography Institute by a hydrothermal method.[1)]

The sound propagated in the sample along the threefold axis. The sound was generated and received by U-cut quartz plates with natural frequency 5 MHz. A continuous procedure was used. An aluminum foil 15 microns thick was used to screen against direct passage of the electromagnetic wave.

When an external magnetic field is applied in the basal plane, oscillations are observed in the intensity of the transmitted hypersound as a function of the magnetic field (Fig. 1). The period of the oscillations increased very rapidly with the field and the sound intensity is practically independent of the field in fields stronger than 4 kOe. When the magnetic field is inclined to the basal plane, the curve stretch into the region of strong fields and coincide with one another if the abscissas represent the field projection on the basal plane. Similar oscillations were observed in [3] following the passage of hypersound through iron garnets.

This phenomenon is attributed to the presence in the garnets of acoustic birefringence

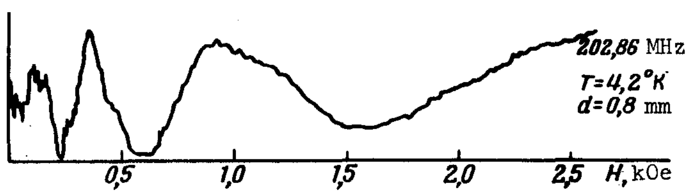

Fig. 1

[1)]I am grateful to N. Yu. Ikornikova for kindly supplying the crystals.