Cyclotron resonance at optical frequency in bismuth in an ultrastrong magnetic field

V. V. Druzhinin, A. I. Pavlovskiĭ, O. M. Tatsenko, M. I. Dolotenko, A. I. Bykov, and N. P. Kolokol'chikov
Moscow Engineering-Physics Institute

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The absorption coefficient was investigated in a polycrystalline bismuth film in fields to 10 MG at a wavelength of 0.633 μm. The peculiar behavior of the absorption at fields greater than 1.5 MG is interpreted as cyclotron resonance at an optical frequency.

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Cyclotron resonance at frequencies $\omega_c = eBn/m^*c$, where m^* is the cyclotron mass, is usually observed in semiconductors, semimetals, and metals at low temperatures. In this situation, fields up to 100 kG are used, and the frequencies are equal to $\approx 10^{11}$ Hz. The availability of ultrastrong fields[1] of $\approx 10^7$ G makes it possible to increase ω_c for $m^* \approx m_e$ to values of 1.6×10^{14} rad/sec, which lies in the near-infrared region, and to observe the cyclotron resonance at room temperatures and in samples with a small relaxation time. A question in this case arises concerning the applicability of the effective-mass method, which in the two-band approximation requires that the

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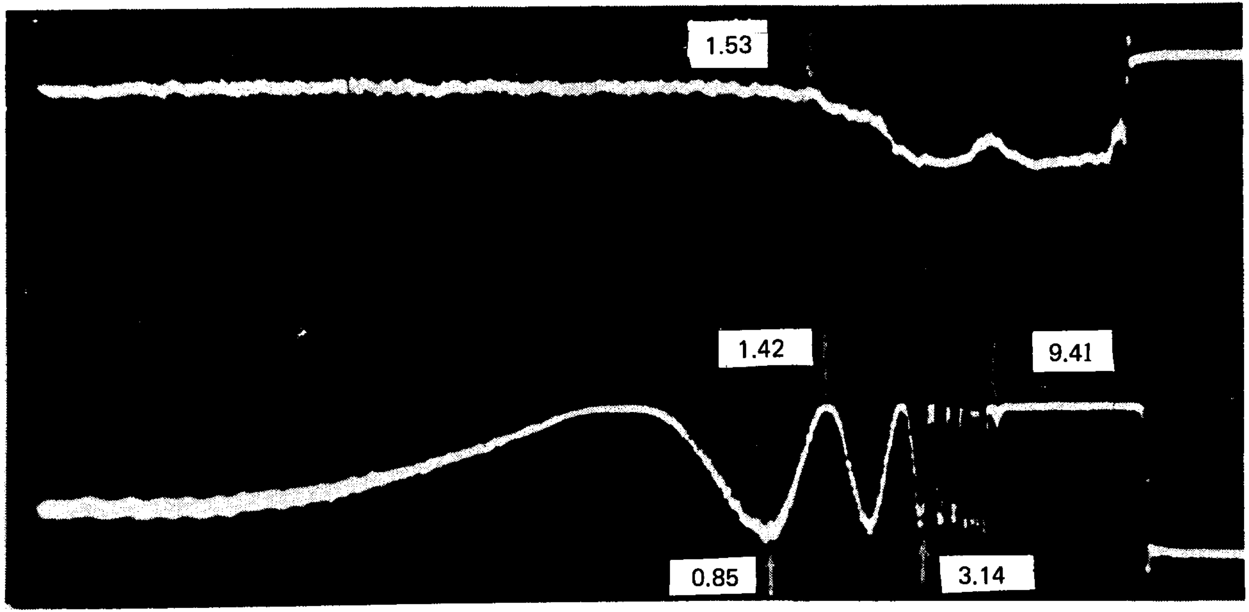

FIG. 1. Field dependence (upper trace) of the intensity of the radiation transmitted through bismuth and the Faraday oscillogram ($l = 0.207$ mm, TF-5, and $V = 0.0457$ min/cm·G) (lower trace). The numbers represent the field in MG.

inequality $a/L \ll 1$ be satisfied, where a is the lattice constant and $L \approx (he/cB)^{1/2}$ is the magnetic length.[2] In a field of 10^7 G,$L \approx 9$ Å, which is comparable to a. We can go to the optical region of the spectrum and still use the effective-mass method by choosing a material with small cyclotron masses. Bismuth, in which the mass of the light electrons is $m^* \approx 10^{-2} m_e$, satisfies this requirement, i.e., the optical resonance between the nearest Landau levels in realized at $B \approx 10^6$ G. In this case, $L \approx 20$ Å and $a = 4.7$Å, i.e., the effective-mass approximation is apparently still valid. We note that the condition $\omega_c \tau \gg 1$, which is necessary for observing the cyclotron resonance, is satisfied with a large margin of safety just as the condition $kT \ll \omega_c \hbar$ at $T = 300$ K, $\omega_c = 3 \times 10^{15}$ rad/sec, and $\tau \approx 10^{-9}$–10^{-12} sec.

To verify these arguments, we designed an experiment, in which the absorption was measured in a polycrystalline-bismuth film on a glass substrate at the frequency of the helium-neon laser 3×10^{15} rad/sec. The field, oriented perpendicularly to the sample surface, had a pulsed value of 10 MG. The experiment was repeated twice. An oscillogram of the field dependence of the transmitted radiation intensity I is shown in Fig. 1. At zero field 75% of the incident light is transmitted. We can see from Fig. 1 that the absorption coefficient is independent of the field up to values $B = 1.5$ MG, after which it starts to increase. The increase stops in a field of ≈ 7 MG, and the absorption coefficient slowly decreases in the range 7–10 MG. We attribute this peculiar behavior to the cyclotron resonance at an optical frequency.

The Fermi surface of bismuth consists of three, highly elongated, electron ellipsoids and a hole ellipsoid of rotation. The smallest cross section can be obtained by orienting the field along the major axis of the electron ellipsoid $S_1 = 1.3 \times 10^{-42} \text{g}^2.\text{cm}^2/\text{sec}^2$; this gives a cyclotron mass $m^* = (0.82–0.9) \times 10^{-2} m_e$.[3] The ultra quantum limit in this case is realized[3] in the fields $B > 26$ kG. The transition frequency between the ground level and the first Landau level $\omega_c = eB/m_1^* c$ is equal to 3×10^{15} sec^{-1} in a field of 1.53–1.7 MG for $m_1^* = (0.82–0.9) \times 10^{-2} m_e$, i.e., it coincides with the probing frequency. We therefore, attribute to the resonance the onset of strong absorption in the 1.5-MG field. The absence of other resonances at weaker fields with a period $\Delta B^{-1} = 0.65$ MG^{-1} (in particular in a 0.75-MG field) can be explained by the fact that as the quantum number n increases, the amplitude of the resonance peaks decreases. The constant absorption (i.e., the absence of characteristic resonance surges) at a field $B > 1.53$ MG is due to the polycrystalline nature of the sample. It is known that for an arbitrary field orientation the cyclotron frequency is described by the equation

$$\omega_c = \frac{eB}{c} \left(\frac{a_1^2}{m_1^{*2}} + \frac{a_2^2}{m_2^{*2}} + \frac{a_3^2}{m_3^{*2}} \right)^{1/2},$$

where α are the direction cosines and m_i^* are the cyclotron masses equal to 0.82–0.9, 11.9, and 8.8 in units of $10^{-2} m_e$. Thus, a continuous resonance occurs at fields greater than 1.5 MG in all the cross sections of the Fermi surface of the electrons and holes. The width of this band, plotted as a function of B, extends to 24 MG, i.e., absorption exists up to the 10-MG fields attained in the experiment. The nonmonotonic dependence of the absorption coefficient is attributable to the unique features of the density of cyclotron resonances and to other transitions.

In one experiment we also measured the Faraday effect, which gave a nonlinear dependence on B of the rotation angle θ of the polarization plane in fields up to 1.7 MG. The sign of θ and the nonlinearity correspond to the dependence $\theta \sim \omega_c/(\omega^2 - \omega_c^2)$, which determines the Faraday effect in the cyclotron resonance region.

It was pointed out[4] that the fields of $\approx 10^8$–10^9 G are necessary for a significant change of the dispersion, i.e., change of the effective electron masses in metals. Investigation of light absorption in bismuth in an ultrastrong magnetic field had confirmed this hypothesis.

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