A new type of giant oscillations in the absorption of sound by metals due to coherent magnetic breakdown

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In this work we show the existence of a new type of "giant" oscillations in the absorption of longitudinal sound by metals due to coherent magnetic breakdown.

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The purpose of this work is to show experimentally and theoretically the existence of a new type of "giant" oscillation effect arising in the resonance (collision-free) absorption of longitudinal sound by metals under magnetic breakdown (MB) conditions.

1. The absorption of longitudinal sound ($\omega/2\pi = 150$ MHz) in tin with a relative residual resistance of 2×10^{-5} has been studied experimentally at temperatures of $T = 2$ and 4.2 K. The wave vector of sound $\mathbf{q}$ was parallel to the [001] axis to within $\pm 0.5°$. Quantum oscillations of the absorption coefficient of sound Γ in the magnetic field $H[\Gamma(H)]$, which became giant oscillations at $H \approx 50$–60 kOe (Fig. 1), were observed. The fundamental period of these oscillations $\Delta_0(1/H) = e\hbar/cS_0^{\min}$ corresponds to the area $S_0^{\min}$ of the minimum cross section of a small hollow on the Fermi surface located in the third Brillouin zone. A distinguishing feature of the giant oscillations is the anomalous sensitivity of their amplitude to small deviations of the magnetic field $\mathbf{H} = (0,0,H)$ from the axis of symmetry $\mathbf{n} = [001]$. According to Fig. 2, the relative oscillation amplitude $\Gamma(H)/\Gamma(0)$ reaches the maximum value 0.2 at the angle θ between $\mathbf{H}$ and $\mathbf{n}$ equal to 2° and decreases by an order of magnitude as θ increases to 4°. In the fields $H \lesssim 15$ kOe the value of $\Gamma(H)/\Gamma(0)$ is almost independent of θ (Fig. 2), indicating the absence of a sharp anisotropy of the energy of interaction of the electrons with the sound $\Lambda = \lambda_{ik}(p)u_{ik} = \lambda_{zz}u_{zz}$ (p is the momentum of the electron, λ_{ik} is the deformation-potential tensor, and u_{ik} is the deformation tensor).

A complete reconstruction of the angular dependence of $\Gamma(H)/\Gamma(0)$ in the region of $\theta = 4°$ as a result of the increase of H from 15 to 60 kOe led us to assume the existence of a new oscillation mechanism which is not related to the density oscillation of the number of states and, consequently, cannot be interpreted in the known quasi-classical terms.[1]

Since in the magnetic fields under study there is a developed MB between the small electron orbits of the third band and the "large" hole orbits of the fourth band,[2] it is natural to explain the observed effect in specific terms for MB. Neglecting the time the electron resides in the small orbits of the third band, they can be considered as effective MB centers in which quantum scattering of electrons occurs primarily in the large orbits of the fourth band. As a consequence of interference of the quasi-classical waves reflected from the "true" MB centers of a small orbit (see Fig. 3), the effective

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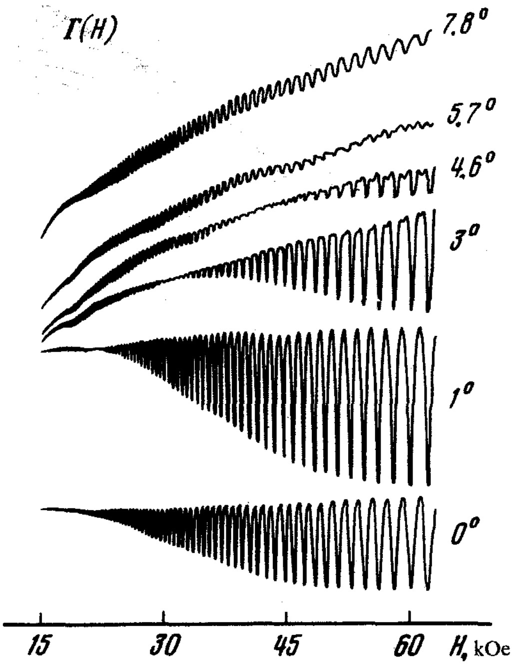

FIG. 1. $\Gamma(H)$ dependence at different angles θ.

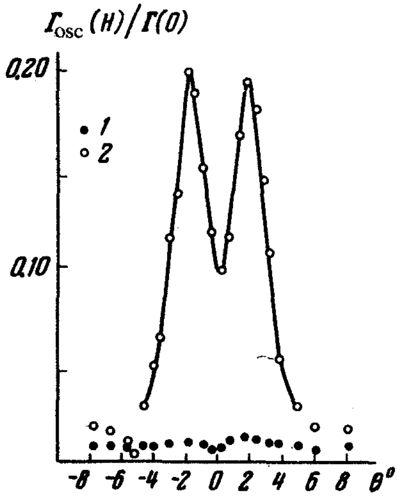

FIG. 2. Dependence of $\Gamma_{osc}(H)/\Gamma(0)$ on angle θ: curves: 1—$H = 13$ kOe, 2—$H = 60$ kOe.

MB probability w_{eff} characterizing the scattering by small orbits oscillates according to the quasi-classical phase $\phi_0 = cS_0(p_z,\epsilon_F)/ e\hbar H$ with a period of 2π (p_z is the projection of the momentum in the direction of **H** and ϵ_F is the Fermi energy). These oscillations in redistributing the electron density over the entire MB configuration (a system of large orbits bound by effective MB centers) lead to a periodicity of the matrix elements of the physical quantities in ϕ_0. All the earlier well-known MB oscillations of the kinetic coefficients are due to variation of the matrix elements of the

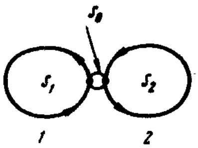

FIG. 3. MB-configuration model: 1,2—large orbits; S_1,S_2—areas of the large orbits; S_0—areas of the small orbit; ●—"true" MB centers with MB probability w.

Hamiltonian for the interaction of the electrons with the external field $\mathscr{H}_{\rm ext}$ [3-6] as a function of ϕ_0.

2. In the case of longitudinal sound $\mathscr{H}_{\rm ext} = \lambda_{zz}u_{zz}$ and $\theta \ll 1$, a fundamentally different oscillation mechanism is in effect. The point is that for $\theta \ll 1$, when large (and small) orbits of the MB configuration are nearly identical, the redistribution of electrons along the large orbits with an accuracy to values proportional to $\theta \ll 1$, $\theta_q = \widehat{\rm qH} \ll 1$ does not change the matrix elements of the operator $\lambda_{zz}u_{zz}$ responsible for absorption. It agrees approximately with the corresponding classical average over the large orbit (below Λ_0).

At first sight, there should be no gigantic MB oscillations in the absorption of sound under these conditions. However, this conclusion does not take into account the characteristic interference effects for MB, which lead to a significant reconstruction of the spatial-resonance frequencies $\omega_n^*(p_z) = q_z\, v_n(p_z)$ $v_n(p_z) \equiv \partial E_n/\partial p_z$ is the average steady-state velocity of the electronic magnetic-breakdown spectrum ("MB spectrum") with energy $E_n(p_z)$, and n is the number of the MB term.

This reconstruction becomes clear from an examination of the MB configuration in Fig. 3. The states of the MB spectrum in this case are characterized by two quantum amplitudes for the probability of finding the electron in the large orbits (C_1 and C_2). The velocity $v_n(p_z)$ is expressed through them as follows:

$$v_n(p_z) = \bar{v}_{\rm cl}(p_z) + \Delta v_{\rm quant}\,;\ \Delta v_{\rm quant} = (|C_1|^2 - |C_2|^2)(\bar{v}_1 - \bar{v}_2)/2\,, \qquad (1)$$

where $\bar{v}_{1,2}$ are the classical average velocities of the electron in the orbits 1 and 2, $|\bar{v}_1 - \bar{v}_2| \sim \theta v_0$ (v_0 is the characteristic Fermi velocity), and $\bar{v}_{cl}(p_z) = (\bar{v}_1 + \bar{v}_2)/2 \approx \bar{v}_{1/2}(p_z, \theta = 0)$. Since the electron experiences multiple coherent scattering by an effective MB center, the difference $|C_1|^2 - |C_2|^2$ depends not only on ϕ_0 but also on the difference $\Delta\phi$ of the quasi-classical phases $\phi_{1,2} = cS_{1,2}(p_z,\theta)/e\hbar H$ corresponding to different paths in the classical motion of the electron (along the orbits 1 and 2), a direct analog of interfering light rays in optics. It can be shown that

$$|C_1|^2 - |C_2|^2 = -2\sqrt{1-w}\,\sin\frac{\phi_0}{2}\,\sin\frac{\Delta\phi}{2}\left[4(1-w)\sin^2\frac{\phi_0}{2}\sin^2\frac{\Delta\phi}{2} + w^2\right]^{-1/2}, \qquad (2)$$

where $w = w(H)$ is the "true" MB probability, $\Delta\phi = \phi_1 - \phi_2 \sim (\theta p_z/\kappa p_0)$ [$p_z = 0$ is the extremal point of $S_{1,2}$ $(p_z, \theta = 0)$], and $\kappa = e\hbar H/cp_0$ is the quasi-classical parameter ($\kappa \sim 10^{-4} - 10^{-5}$) ($p_0$ is the characteristic Fermi momentum).

The dependence of the small correction $\Delta v_{\rm quant}$ [see Eq. (1)] on the phase $\Delta\phi$, which has large values at small angles θ and small p_z/p_0, makes it basically necessary to take it into account in the calculation of the collision-free absorption of sound energy $\dot{E}$. This is essentially the new oscillation effect examined by us. In fact, according to the general formula for $\dot{E}$ we have

$$\dot{E} \sim |\Lambda_0|^2 \sum_n \int dp_z \, df_0(E_n(p_z))/dE \; \delta(w_n^*(p_z) - \omega)$$
$$\sim 1/q_z \sum_{p_{res}} df_0(E_n(p_z))/dE \; |\partial(\bar{v}_{cl}(p_z) + \Delta v_{quant})/\partial p_z|^{-1}, \qquad (3)$$

where f_0 is the Fermi function and the summation is taken over all the resonance values that satisfy the condition $v_n(p_z) = s$ (s is the speed of sound) and, according to Eq. (1), are localized in the region $|p_z| \sim \theta p_0$ [for $p_z = 0$ the classical averages are $v_{1,2}$ ($p_z = 0$, $\theta = 0$) $= 0$]. It can be seen from Eqs. (1) – (3) that in the resonance region $|\partial \Delta v_{quant}/\partial p_z| \sim \theta^2/\kappa\,(|\partial v_{cl}/\partial p_z|)$ and, consequently, the contribution of the small quantum correction Δv_{quant} to $\dot{E}$ is equal to the classical one at $\theta^2 \sim \kappa(\theta \sim 1°)$. Since Δv_{quant} is periodic with respect to ϕ_0 and the number of resonance points in Eq. (3) is $N_{res} \sim \theta^2/\kappa$, the "giant" oscillations $\dot{E}$ in the region of angles $\theta^2 \sim \kappa$ ($N_{res} \sim 1$) should occur with the relative amplitude of ~ 1 and period $\Delta_0\,(1/H)$ (see above). In the range $\theta^2 \gg \kappa$ ($N_{res} \gg 1$) the correction Δv_{quant} oscillates rapidly with respect to p_z and, as the analysis shows, the oscillation contributions of all the p_{res} in Eq. (3) cancel each other with great accuracy, i.e., the oscillations are attenuated with increasing θ. The giant oscillations in $\dot{E}$ [see Eq. (1)] are absent when $\theta \to 0$. The fact that they vanish [see Eq. (2)] in the quasi-classical limit $w \to 0$, $w \to 1$ emphasizes their quantum-interference nature.

All the aforementioned points can be generalized for the examined MB configuration with an arbitrary number (N) of identical large orbits (for $\theta = 0$). It turns out that at $\theta^2 \gg \kappa$ the oscillation amplitude decreases as $(\kappa/\theta)(N - \frac{1}{2})$. When tin is used in the MB configuration, this means that giant oscillations exist only in a narrow region of angels θ (compare with Fig. 2).

It should be emphasized that small-angle scattering by extended defects (dislocations) may destroy the coherent interference of quasi-classical electron waves in the large orbits (see above), which produces a peculiar stochasticity in the MB dynamics of the electron.[8] In this case the examined oscillation effect is absent.

Thus, the observed effect is a reliable indicator of coherent MB. The $\Gamma(H)$ oscillations also have other peculiarities attributable to coherent MB, such as the presence of a node in the $\Gamma(H)$ dependence (Fig. 1), whose position depends on θ and H. A detailed analysis of this problem will be performed in a separate report.

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