QUANTUM OSCILLATIONS AT HIGH TEMPERATURES

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It is shown that, generally speaking, quantum oscillations that are not small exist on the single-parameter family of self-crossing trajectories at temperatures high compared with the distance between the Landau levels.

IT is well known that the usual quantum oscillations (the de Haas—van Alphen effect, the Shubnikov—de Haas effect, etc.) attenuate exponentially with increasing temperature T [1], so that to observe these oscillations we must have

$$T \lesssim \mu H/2\pi^2 k, \tag{1}$$

which for $H \sim 10^4$ Oe corresponds for the main bands to a temperature $T \sim 0.05°$K, and for anomalously small $T \sim 1$–$10°$K. In (1), H is the intensity of the magnetic field, $\mu = e\hbar/m^*c$ is the Bohr magneton, and m^* is the effective mass of the conduction electron on the extremal section of the plane p_z = const through the limiting Fermi surface $\epsilon(\mathbf{p}) = \epsilon_0$ ($z \parallel \mathbf{H}$, ϵ and $\mathbf{p}$ are the energy and quasimomentum of the electron). It is easy to understand that the effective mass defined in this manner cannot vanish.

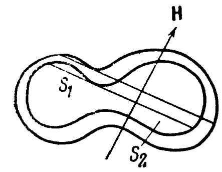
However, in addition to the oscillations connected with the extremal sections, there are oscillations due to self-crossing trajectories, where the role of m^* is assumed [2] by the quantity $m = (2\pi)^{-1}(dS_\epsilon/d\epsilon)_{\epsilon=\epsilon_0}$, where the area of the section on one side of the self-crossing [1)] (see the figure) is $S_\epsilon = S(\epsilon, p_z^0(\epsilon))$, with $p_z^0(\epsilon)$ determined from the relations

$$\varepsilon(p_x, p_y, p_z) = \varepsilon, \qquad \partial\varepsilon/\partial p_x = \partial\varepsilon/\partial p_y = 0.$$

Inasmuch as S_ϵ can both increase (S_2 in the figure) or decrease (S_1), m = 0 becomes possible. The condition

$$m(\mathbf{h}) = 0, \qquad \mathbf{h} = \mathbf{H}/H \tag{2}$$

determines, generally speaking, a one-parameter family of magnetic-field directions.



The calculations are analogous in this case to the calculations in the author's previous paper [2], and the oscillating part $\Delta\Omega$ of the thermodynamic potential Ω is equal to (the constant A is defined in the same way as in [2] and $f_0(\epsilon)$ is the equilibrium Fermi function)

$$\Delta\Omega = A\int_0^\infty d\varepsilon\, f_0(\varepsilon)\sin\left(\frac{cS_\varepsilon}{e\hbar H} - \frac{\pi}{4}\right).$$

Since $cS''_\epsilon(kT)^2/e\hbar H \ll 1$, we have

$$\Delta\Omega \approx A\left[\frac{\pi e\hbar H}{2c\,|S''_{\varepsilon_0}|}\right]^{1/2}\begin{cases}\sin(cS_0/e\hbar H), & S''_{\varepsilon_0} > 0\\ -\cos(cS_0/e\hbar H), & S''_{\varepsilon_0} < 0\end{cases}. \tag{3}$$

It is easy to see that the interval of the angles $\Delta\varphi$, which lead to (3) ($\Delta\varphi$—deviation of the direction where m = 0), is $\Delta\varphi \ll \mu'_{\Delta\varphi=0}H/4\pi kT$ if condition (1) for μ is not satisfied (with $\Delta\varphi \sim 1$), since $m(\Delta\varphi) \sim \Delta\varphi$. The amplitude of the oscillations is $\sim (cS_{\epsilon_0}/e\hbar H)^{1/2}$ times larger for m = 0 than for $\Delta\varphi \sim 1$, as follows from (2) and [2].

In this derivation we did not take account, however, of the finite mean free path l of the electrons, which "smears out" the Landau levels. This is justified so long as the electron has time to execute at least several revolutions between collisions, that is, so long as

$$r < l \tag{4}$$

[1)]We take this opportunity to note that in order to explain the periods of the oscillations in the presence of self intersection, we must use the quantization formulas from [3]. We cannot start from the approximate ordinary quantization rules, as proposed in [4] (such an approximation gives "parasitic" periods, which do not exist in reality). We emphasize also that m is far from equal to the effective mass m^*, which determines the period of revolution of the electron in the orbit and which becomes infinite when $p_z = p_z^0$.

(r is the Larmor radius). In the opposite case, in accordance with the probability of traversing a path $r > l$, the oscillations will attenuate exponentially with increasing r/l (see also [5].) [2)]

Condition (4) is much less stringent than (1) and enables us to observe near the indicated one-parameter family of directions quantum oscillations at temperatures which are high compared with (1), namely $T \lesssim 30°K$ for the main bands, and $T \lesssim 100°K$ for the anomalously small ones.

Apparently, it is convenient to detect these directions by noting the sharp increase in the amplitude of the oscillations as the magnetic field is rotated.

[2)]Calculation based not on the path but on the free-path time leads to an analogous result. Although the time to cover the self-crossing orbit becomes infinite, it does so logarithmically, and since the significant quantities are $[p_z - p_z^0(\epsilon)]/p_z^0(\epsilon) \sim e\hbar H/cS_{\epsilon_0}$, we obtain a condition which differs from (4) only by the minor factor $\ln(cS_{\epsilon_0}/e\hbar H)$.

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