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# SURFACE MAGNETIC SUSCEPTIBILITY OF METALS

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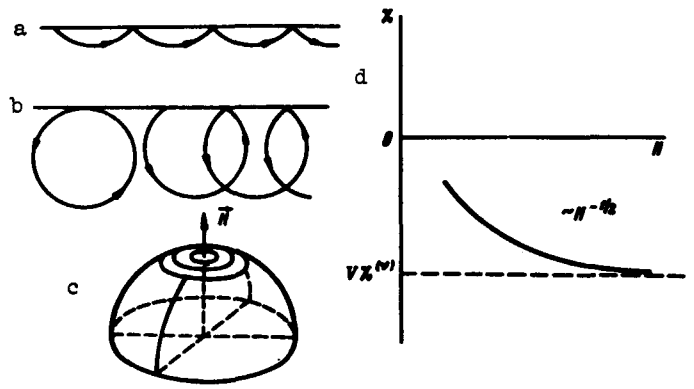
1. It is known [1] that the energy spectrum of the conduction electrons in a metallic plate placed in a parallel magnetic field $\vec{H}$ differs significantly from the energy spectrum of the bulky sample. Besides the magnetic Landau levels, there exist [2] magnetic surface levels due to the electrons skipping along the surface of the metal (see Fig. a). The dependence of the magnetic surface levels on H exhibits characteristic features, but these turn out to be inessential [3, 4] when the thermodynamic properties of metals are considered. (A more detailed analysis of the literature [3, 5 - 7] concerning this question can be found in [4].)

When considering the contribution of the magnetic surface levels to the thermodynamic quantities, it is necessary, as demonstrated in [3], to take into account the deviation of the magnetic surface levels from their quasiclassical values. The surface part of the magnetic moment $M^{(s)}$ is written in the quasiclassical approximation in the form

$$M^{(s)} = a^{(1)}_{\text{quas}} H^{-1/3} + a^{(2)}_{\text{quas}} H^{1/3} + \dots . \qquad (1)$$

Calculations [4] using the exact values for the magnetic surface levels have shown that $\alpha^{(1)} = 0$. Analogously, the author calculated the next term in the expansion (1), and it turned out that $\alpha^{(2)} = 0$. Thus, the electrons skipping over the surface of the metal (Fig. a) make no essential contribution to the thermodynamic properties of the metals. As will be shown below, an appreciable contribution to the thermodynamic quantities is made by electrons that are tangent to the surface of the metal (see Fig. b).




2. Assuming a quadratic isotropic dispersion law $\varepsilon = p^2/2m$ of the conduction electrons in the plate we obtain for the thermodynamic potential $\Omega(H, T)$ in the temperature region $T \ll \varepsilon_F$

$$\Omega(H, T) = \Omega(0, T) + \frac{1}{12\pi^2}\frac{V}{\hbar}\sqrt{\frac{\varepsilon_F}{2m}}\left(\frac{eH}{c}\right)^2 \times \times \left[1 - \frac{1}{24}\left(\frac{\pi T}{\varepsilon_F}\right)^2\right]\left[1 - (4\pi)^2\beta\frac{S\ell_H}{V}\right] + \Omega_{osc}(H, T), \quad (2)$$

where $\varepsilon_F$ is the Fermi level, e the electron charge, S the area of the surface bounding the volume of the plate V, $\ell_H = \sqrt{\hbar c/eH}$ is the characteristic magnetic length determining the region of the localization of the wave function of the electron in the magnetic field,

$$\beta = \frac{3}{8\pi^4}\left[\frac{2^{3/2}-1}{4}\zeta\left(\frac{5}{2}\right) + \pi^{1/6}\left(\frac{2}{3}\right)^{1/3}\Gamma\left(\frac{2}{3}\right)\Gamma\left(\frac{5}{6}\right) \times \times \sum_{k=1}^{\infty}\frac{1}{k^{5/2}}\sin\left(\frac{\pi k}{2} + \frac{\pi}{12}\right)\right] = 0{,}78 \cdot 10^{-2}, \quad (3)$$

and $\Omega_{osc}(H, T)$ is the part of the thermodynamic potential that oscillates with changing H.

Confining ourselves to an examination of the smooth part in the dependence of the thermodynamic quantities on H (for an analysis of the oscillations of the thermodynamic quantities see [3, 1]), it is convenient to write the magnetic susceptibility $\chi$ in the form

$$\chi = V\chi^{(v)} + S\chi^{(s)}. \quad (4)$$

Since $\chi = -\partial^2\Omega/\partial H^2$, we obtain from (2) and (4)

$$\chi^{(v)} = -\frac{1}{6\pi^2}\frac{e^2}{\hbar c^2}\sqrt{\frac{\varepsilon_F}{2m}} \quad (5)$$

and

$$\chi^{(s)} = \beta\left(\frac{e}{c}\right)^{3/2}\sqrt{\frac{\varepsilon_F}{2m\hbar}}H^{-1/2}, \quad (6)$$

where $\chi^{(v)}$ is the Landau diamagnetic susceptibility [8] in the case of a bulky metal and $\chi^{(s)}$ is the surface part of the magnetic susceptibility. Analogous expressions are obtained from (2) for the specific heat $C = -T\partial^2\Omega/\partial T^2$.

The foregoing formulas (2) - (6) hold in magnetic fields $H \gg H_c$, where $H_c = hc/eL^2$ is the intensity of the field at which $\ell_H = L$. For plates of thickness $L \sim 10^{-3}$ cm we have $H_c \sim 0.1$ Oe. In weak fields $H \tilde{<} H_c$, the magnetic susceptibility $\chi$ has a more complicated dependence on L and it cannot be represented in the form of two terms proportional to the volume V and the area S of the boundary surface, respectively.

The surface part of the magnetic susceptibility $\chi^{(s)}$ is determined mainly by the electrons tangent to the boundary surface of the metal and located near the limiting points on the Fermi surface (Fig. c). Since the distance between

the quantum energy levels is $\Delta\varepsilon_H \ll \varepsilon_F$, large quantum numbers become significant, so that we can use in the calculation the quasiclassical approximation for the energy spectrum. The quantum energy spectrum of the conduction electrons is determined under the assumption that the electrons are specularly reflected from the boundary of the sample. The specular-reflection condition is sufficiently effective, since the main contribution to the effect under consideration is made by electrons that are tangent to the surface of the metal and thus have a sufficiently large wavelength, corresponding to the motion of the electron along the normal to the surface of the metal.

The values $\chi^{(s)}$ obtained in this paper describes the contribution of the boundary surface of the metal to the Landau diamagnetism (see Fig. d). Whereas in the calculation of the diamagnetic susceptibility of metals the presence of the metal boundary leads to the appearance of additional terms of the order of $\lambda\!\!\!^{-}_F/L$ (see [9], $\lambda\!\!\!^{-}_F$ is the Fermi wavelength of the electron), in the case of Landau diamagnetism the influence of the boundary is more significant and causes the appearance of additional terms of the order of

$$S\chi^{(s)}/V\chi^{(v)} \sim (H_c/H)^{1/2}.$$

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## PURELY ROTATIONAL SPECTRA OF NONPOLAR MOLECULES IN THE VIBRATIONAL GROUND STATE

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Fox [1] has shown recently that in spite of the fact that the methane molecule (point group $T_d$) has no dipole moment in the ground electron-vibrational state, this molecule can have a rotational spectrum of dipole transitions in the ground state as the result of vibrational-rotational interaction; the intensity of the strongest line of such a spectrum can be, under certain conditions, much higher than the intensity of the collision-induced rotational spectrum of methane. It is shown in the present communication that as a result of the effect of first-order centrifugal distortion, purely rotational spectra of dipole molecules in the ground state can be possessed not only by methane [1], but also by all nonpolar molecules belonging to the point groups $D_n$, $D_{2d}$, $D_{3h}$, $S_4$, T, and $T_d$.