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Fermi Dirac statistics for free electrons in uniform electric and magnetic fields

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Abstract

In this paper we study the De Haas - Van Alphen effect when an electric field is present. We prove that for sufficiently weak electric field, where the conditions are favorable for energy quantization, the free energy is a quasi - periodical function with respect to the fields. As a consequence we find, for the magnetic susceptibility, periodical expressions which are easily reduced to the known ones for the De Haas - Van Alphen effect when the electric field vanishes. In Fermi-Dirac statistics we calculate the free energy per unit volume from the relation $F - n\zeta = -2kT\sum_i \left(1 + e^{(\zeta-\epsilon_i)/kT}\right)$. We use the resulting formula to calculate the magnetic susceptibility in two interesting limited cases.

1. Stable states when $\sqrt{\alpha/\zeta} << 1$, $\alpha = \hbar^2 e^2(E_1^2 + E_2^2)/8m(\mu H)^2$. We prove that when the electric field, is very weak $E/H << 10^{-7}$, the contribution is limited to a small shifting in the arguement of the periodic terms. Over this value a new oscillating term is added, coming through the Bessel J_0 function, which is due to the interaction of the magnetic field with the crossed component of the electric field. Under certain conditions our colculations give the following magnetic susceptibility

$$\chi = \frac{m^{3/2}}{3\pi^2\hbar^3}\mu^2(2\zeta)^{1/2}\left\{1 - \frac{3\pi kT}{\mu H}\left(\frac{\zeta}{\mu H}\right)^{1/2}\sum_{r=1}^{\infty}\frac{(-1)^r}{r^{1/2}\sinh\left(r\pi^2\, kT/\mu H\right)}\times \left[J_0\left(\frac{2r\pi}{\mu H}\sqrt{\zeta\alpha}\right)\sin\left(\frac{\zeta+\alpha}{\mu H}r\pi - \frac{1}{4}\pi\right)\right]\right\}$$

For zero electric field, $\alpha \to 0$, we recover the known formula of De Haas - Van Alphen effect.

2. Unstable states when $\sqrt{\alpha/\zeta} >> 1$. When the fields become stronger, $\mu H >> kT$ and $v_F << c\sqrt{(E_1^2 + E_2^2)/H^2}$ where v_F is the Fermi velicity, the magnetic susceptibility becomes the difference of two quasi - periodical terms. Under certain conditions our colculations give now the following magnetic susceptibility

$$\chi = \frac{m^{3/2}}{3\pi^2\hbar^3}\mu^2(2\zeta)^{1/2}\left\{1 + \frac{9kT}{\mu H}\left(\frac{\alpha}{\zeta}\right)^{5/4}\sum_{r=1}^{\infty}\frac{(-1)^r}{r\sinh\left(r\pi^2\sqrt{\alpha/\zeta}\,kT/\mu H\right)}\times\right.$$
$$\left.\left[\cos\left((\sqrt{\zeta}+\sqrt{\alpha})^2\frac{r\pi}{\mu H}\right) - \sin\left((\sqrt{\zeta}-\sqrt{\alpha})^2\frac{r\pi}{\mu H}\right)\right]\right\}$$

The sums in the above formulas are rapidly convergent with respect to r.