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MEASUREMENT OF THE SHUBNIKOV - DE HAAS EFFECT IN GRAPHITE AT PRESSURES UP TO 8 KBAR

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The electronic spectrum of graphite is usually described by the Slonczewski-Weiss model (SW). In this model, the dependence of the energy on the quasimomentum is expressed on the basis of general principles [1] in terms of parameters characterizing the conduction-electron interactions. The Brillouin zone for graphite is a hexagonal prism with a base-side length $2\pi/a_0$ and a height $2\pi/c_0$ (a_0 = 2.46 Å and c_0 = 4.70 Å). The Fermi surface of graphite occupies a small section of the Brillouin zone and is located along the vertical edges of the zone. In the SW model we can write for the dispersion law the simplified expressions:

$$E_{\pm} = 2\gamma_2 \cos^2\phi \pm \hbar^2\kappa^2/2m^*(\phi), \tag{1}$$

$$m^*(\phi) = {}^4/3\,(\hbar/a_0)^2\,(\gamma_1/\gamma_0^2)\cos\phi, \tag{2}$$

where $\phi = k_z c_0/2$, κ is reckoned from the edge of the Brillouin zone, γ_0 is the interaction energy of the conduction electrons in the plane of the layer, γ_1 the interaction energy of the conduction electrons of the neighboring layers, γ_2 is the same energy through the layer, and the + and - signs correspond to electrons and holes.

From this, recognizing that the Fermi energy $\epsilon_F = (4/3)\gamma_2$, we can readily obtain the value of the extremal section of the hole part of the Fermi surface of graphite, parallel to the (0001) plane,

$$S^h_{extr} = (4/3)^2\,\pi/a_0^2(\gamma_1\gamma_2/\gamma_0^2) = 0{,}923\gamma_1\gamma_2/\gamma_0^2\ \text{Å}^{-2}. \tag{3}$$

The expression for the analogous section of the electron surface differs only in the value of the coefficient preceding $\gamma_1\gamma_2/\gamma_0^2$. The SW model was experimentally confirmed in a number of recent papers [2-3].

In order to determine the deformation of the electron spectrum of graphite when the distance between layers is changed, it is necessary to measure the pressure dependence of all the parameters entering in Eq. (1). It is known from x-ray measurements of the compressibility of graphite up to 16 kbar [4] that the change in a_0 under pressure is negligible compared with the change of the interlayer distance c_0. We can therefore assume that γ_0 does not depend on the pressure in the pressure interval of interest to us.

To determine $\gamma_1(p)$ we must measure the pressure dependence of the effective mass m^* (see (2)), and $\gamma_1\gamma_2/\gamma_0 = f(P)$ can be obtained from the pressure dependence of any oscillation effect.

Arkhipov, Kechin, Likhter, and Pospelov (AKLP) [5] have shown that above room temperature m^* of graphite is determined by the dependence of the electric resistivity in the (0001) plane on the magnetic field H ‖ (0001). In particular, for the same extremal section as in (3) we get

$$m^* = 4/3\,(\pi/a_0)^2\gamma_1/\gamma_0^2 = \frac{\hbar^2 c_0 \pi^2}{(8\ln 2)\,ec}\,[T^2\rho_0^2(\frac{\Delta\rho_H}{\rho_0 H^2})_{H\to 0}]^{-1/2}. \quad (4)$$

AKLP determined $\gamma_1/\gamma_0^2 = f(P)$ up to 8.8 kbar by measuring the magnetoresistance of shavings of natural graphite in a field up to 5 kOe at temperatures from 20 to 90°C.

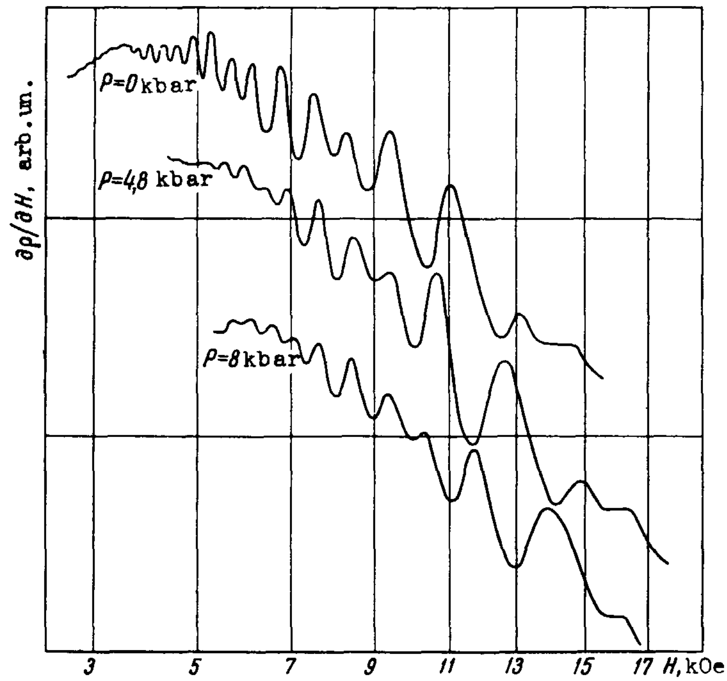
We measured the Shubnikov - de Haas effect in order to obtain the area of the extremal section of the Fermi surface of graphite parallel to the (0001) plane at various pressures. The measurements were made on single crystals of synthetic graphite in the form of plates measuring 12 x 2.5 x 0.2 mm parallel to the (0001) plane. The Shubnikov - de Haas was measured under pressure in a fixed-pressure bomb [6] by a modulation method which we used for the first time on bismuth [7]. We measured the quantum oscillations of the derivative $\partial\rho/\partial H$ in fields up to 16 kOe at 1.5°K.* The direction H ‖ (0001) was determined from the angular dependence of $\partial\rho/\partial H(\phi)$ at a constant field.

The figure shows plots of the electric resistivity oscillations in a magnetic field H ‖ (0001) at pressures p = 0, 4.8, and 8.0 kbar. The pressure was determined with a superconducting tin manometer. We also measured the oscillations at other angles between the direction H and the (0001) axis (up to ~50°). At p = 0, the data obtained agree well with the results of [2-3].

It is easy to determine from the obtained oscillations the periods pertaining to the hole part of the Fermi surface and the values of the periods $\Delta(1/H)$, namely 1.51×10^{-5}, 1.27×10^{-5}, and 1.15×10^{-5} Oe^{-1} at p = 0, 4.8, and 8.0 kbar respectively. Thus, as follows from the a priori reasoning, the volume of the Fermi surface increases with decreasing distance between layers. We used (3) to calculate $\gamma_1\gamma_2/\gamma_0^2$ for p = 0 and 8.0 kbar, and obtained $(\gamma_1\gamma_2/\gamma_0^2)_0 = 6.8 \times 10^{-4}$, $(\gamma_1\gamma_2/\gamma_0^2)_{8\text{ kbar}} = 9.0 \times 10^{-4}$, and $(\gamma_1\gamma_2)_{8\text{ kbar}}/(\gamma_1\gamma_2)_0 = 1.32$.

According to AKLP $(\gamma_1/\gamma_0^2)_{8\text{ kbar}} = 4.00 \times 10^{-2}$ eV at $(\gamma_1/\gamma_0^2)_0 = 3.46 \times 10^{-2}$ eV^{-1} (from McClure's data). It follows then from our measurements that $(\gamma_2)_0 = 0.0196$ eV (in agreement with the published data) and $(\gamma_2)_{8\text{ kbar}} = 0.0225$ eV, $(\epsilon_F)_0 = 0.026$ eV, and $(\epsilon_F)_{8\text{ kbar}} = 0.030$ eV.

AKLP calculated $\gamma_1\gamma_2/\gamma_0^2(p)$ under the assumption that $[(\gamma_1\gamma_2)p/(\gamma_1\gamma_2)_0] \approx (\gamma^*)^2 \exp\{-3[c(p) - c_0]/a^*\}$, $(\gamma_1 \approx \gamma^* \exp[-c(p)/a^*]$, and determined a* from $\gamma_1^0(p)/\gamma_0^2$. They obtained $[(\gamma_1\gamma_2)_{8\ \mathrm{kbar}}/(\gamma_1\gamma_2)_0] = 1.47$. The agreement is quite satisfactory, recognizing the errors in the theory, the differences in the measured quantities, and the possible experimental errors.



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* Measurements of the de Haas - van Alphen effect in graphite at pressures up to 2.5 kbar are reported in [8].

Article by E. S. Itskevich and L. M. Fisher, "Measurement of Shubnikov - de Haas Effect in Graphite at Pressures up to 8 kbar," (Vol. 5, No. 5, p. 115)

The name of the organization supplying the synthetic graphite (NIIGrafit - Graphite Reserach Institute) was left out of the article.