Anisotropy of magnetoresistance and the Shubnikov–de Haas oscillations in the organic metal β-$(ET)_2IBr_2$

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The field and angular dependences of the magnetoresistance of very high quality β-$(\mathrm{ET})_2\mathrm{IBr}_2$ single crystals in fields up to 150 kOe at $T = 1.45$–4.2 K have been studied. Two types of Shubnikov-de Haas oscillations have been detected. The Fermi surface is shown to be open at least in the cross section of the *ac** plane and it is noticeably bumpy near the c^* direction. The transverse magnetoresistance is found to be strongly anisotropic in the *ab* plane.

In the literature there are now no experimental data on the nature of the Fermi surface of class $(ET)_2X$ organic superconductors. The absence of such data is due primarily to the absence of single crystals of reasonably high quality which most methods of studying the Fermi surface require. Progress in the technique of growing such crystals has recently led to the discovery of slight Shubnikov oscillations of the β-$(\mathrm{ET})_2\mathrm{IBr}_2$ (Refs. 1 and 2), β-$(\mathrm{ET})_2\mathrm{I}_3$ (Ref. 2), and $(\mathrm{ET})_2\mathrm{Cu(SCN)}_2$ (Ref. 3) crystals in a field of $H \| c^*$. In the present letter we report the results of a detailed study of angular and field dependences of the magnetoresistance of high-quality β-$(\mathrm{ET})_2\mathrm{IBr}_2$ single crystals, in which we detected Shubnikov-de Haas oscillations of relative amplitude up to 2.5% at $T = 1.45$ K in $\sim$150-kOe fields.

The measurements were carried out with 11.7-Hz alternating current in a superconducting solenoid at the International Laboratory of Strong Magnetic Fields and Low Temperature (Wroclaw, Poland). The mehod of synthesizing the crystals and their principal parameters are described in Ref. 4. We measured the resistances of two samples: one along the *a* axis (R_a) and the other along the *c* axis (R_c). The first crystal rotated along the b' direction (the field is directed in the ac^* plane) and the second crystal rotated either along the b' direction or along the c^* direction (the field is directed in the *ab* plane).[2)] The error of the initial orientation of the crystals was no greater than $\pm 2°$.

Figure 1 is a plot of the resistances R_a (cure 1) and B_c (curve 2) versus the angle φ between the field and the c^* direction at $T = 1.45$ K and $H = 150$ kOe. In each case the $R(\varphi)$ curve is highly nonmonotonic. As the field is reduced, the curve flattens out, but the position of the local maxima and minima remains constant. The field dependences $R_a(H)$ tend to saturate at all angle and at angles near $H \| c^*$ we even see a slight decrease in the resitance at $H > 100$ kOe (Fig. 2). The $R_c(\varphi)$ curve has a sharp "tooth" near $H \| a$, near which $R \sim H^2$. This result suggests that the Fermi surface is open in the direction close to that of the c^* axis.

At $T < 4.2$ K and $H \gtrsim 70$ kOe the $R_a(H)$ and $R_c(H)$ curves reveal two types of Shubnikov-de Haas oscillations (Fig. 2): 1) slow oscillations with a frequency 0.5

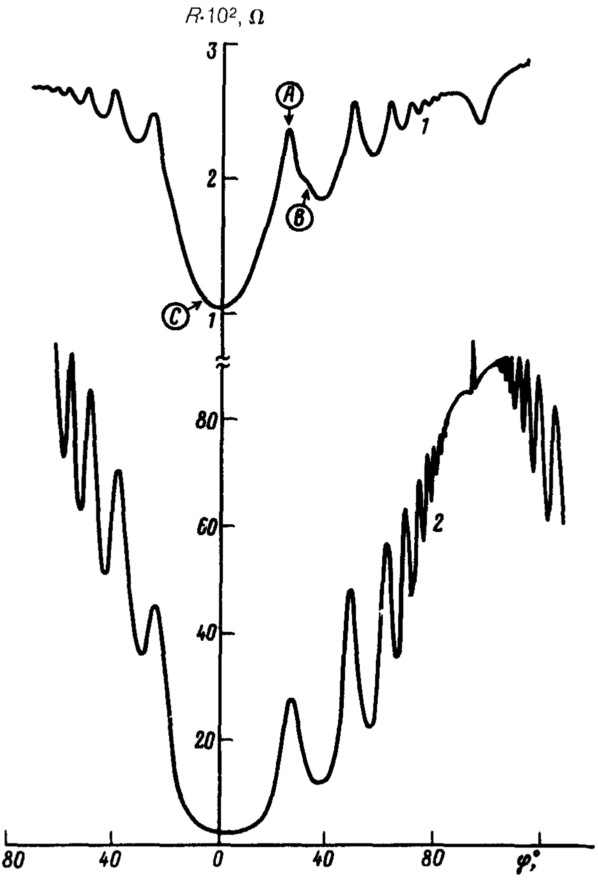

FIG. 1. Resistances R_a ($I \| a$, curve 1) and R_c ($I \| c^*$, curve 2) versus the angle φ between the field, lying in the ac^* plane, and the c^* axis. $H = 150$ kOe, $T = 1.45$ K.

MHz^{-1}, which are observed at angles ranging from 0 to ± 10° and which are consistent with those described in Ref. 1 and 2) fast oscillations which are observed over a wide range of angles and which experience characteristic beats at certain angles. If $H \| c^*$, the frequency of fast oscillations is $F \approx 39$ MHz^{-1}, which corresponds to the cross-sectional area of the Fermi surface $\sim 3.7 \times 10^{15}$ cm^{-2} ($\sim 50\%$ of the area of the intersection of the Brillouin zone with the ab plane). The beat frequency in this case is ~ 0.3 MHz^{-1}. This beat frequency probably is evidence that there are two Fermi surfaces with approximately equal extremal cross-sectional areas.

The amplitude of fast oscillations depends on φ nonmonotonically and reaches maximum values at the points of the local maxima and near the local minima of the $R_a(\varphi)$ and $R_c(\varphi)$ curves (points A and B and similar points in Fig. 1). There are no beats at these points. The absolute maximum of the amplitude, which is $\sim 2.6\%$ of the value of the resistance, is situated at point A. The frequency in this case is ~ 40MHz^{-1} and the carrier mass, estimated from the temperature dependence of the amplitude, is $\sim 5m_0$. The amplitude at the characteristic points similar to points A and B decreases rapidly with increasing $|\varphi|$. In the neighborhood of the points A, B, and C the fast

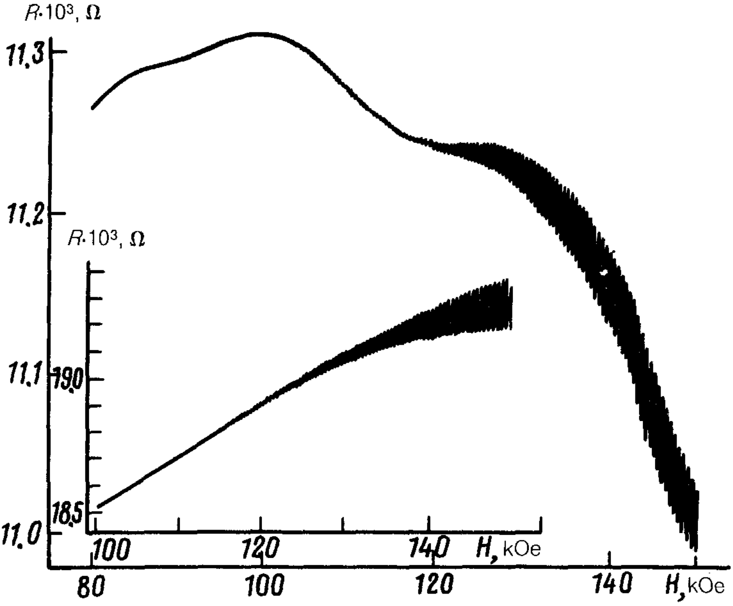

FIG. 2. The curve for R_a at point C in Fig. 1. The inset shows the coresponding curve for T (point B).

oscillations also occur in the angular dependences $R_a(\varphi)$ (they are hardly distinguishable on the scale in Fig. 1).

The angular dependence of the frequency F of fast oscillations is shown in polar coordinates in Fig. 3. The greater part of this dependence is approximated well by the straight line which corresponds to that field direction at which the tooth on curve 2 in Fig. 1 is observed. This result is consistent with the conclusion drawn above that the Fermi surface is open in the direction close to that of the c^* axis. The wavelike nature of the $F(\varphi)$ curve in its central part suggests that the Fermi surface is rippled. This rippling, on the other hand, accounts for the nonmonotonic nature of the angular dependence of the magnetoresistance of $R(\varphi)$ (Fig. 1).

At $T = 1.45$ K and $H = 150$ kOe, when the crystal rotates along the c^* direction (the field is directed in the ab plane), the resistance R_c varies by a factor of more than 10, suggesting that the anisotropy of the properties of β-$(\mathrm{ET})_2\mathrm{IBr}_2$ is highly pro-

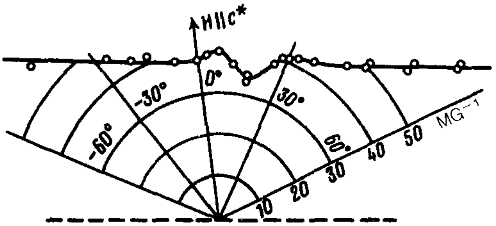

FIG. 3. Polar diagram of the dependence of the frequency F of fast Shubnikov oscillations on the angle φ between the field lying in the ac^* plane and the c^* axis. The dashed line is the direction correspond to the "tooth" on the $R_c(\varphi)$ curve (Fig. 1).

nounced in the *ab* plane. With such an orienttion, the $R_c(H)$ curves show no tendency toward saturation at any angle, nor do they display any oscillations. This behavior implies that the open Fermi surface along the c^* direction is seen in any cross section.

The $R_a(H)$ dependence was recently studied by Murata *et al.*[2] in >150-kOe fields with $H \| c^*$. They did not observe a tendency toward saturation of R_a to within 270 kOe, nor did they obsrve any Shubnikov-de Haas oscillations. The frequency of the fast oscillations, on the other hand, was rougly half that of our minimum frequency and the amplitude was nearly independent of the magnetic field. It is now unclear as to why our results differ so drastically from those obtained by Murata *et al.*[2] We should note that our conclusion concerning the existence of closed orbits at the Fermi surface in the *ab* plane, which extend across ~50% of the corresponding cross section of the Brillouin zone, is at variance with the results of the calculations of Kübler *et al.*[5]

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[2] $c^* \| [a \cdot b]$; $b' \| [a \cdot c^*]$.

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