MAGNETIC BREAKDOWN IN BERYLLIUM

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We describe investigations of the resistance of single-crystal beryllium in a superconducting magnet. Oscillations were observed in the dependences of the resistance on both the magnitude and the direction of the magnetic field. The amplitude of the oscillations increases rapidly in fields H ~ 50 kOe. The largest amplitude is observed in the oscillations due to the occurrence, at **H** ∥ [0001], of open trajectories in the hexagonal plane, initiated by magnetic breakdown. We discuss the existence of oscillations in a wide interval of magnetic-field directions. The period of the oscillations for all directions of the magnetic field corresponds to the central section of the electron ellipsoids of the Fermi surface (the so-called cigars). The value of the energy gap between the second and third bands in the [11$\bar{2}$0] direction is approximately 6×10^{-3} Ry.

INVESTIGATIONS of galvanomagnetic properties yield extensive information on the electronic spectrum of metals with open Fermi surface. According to the theoretical data[1,2], beryllium has a closed Fermi surface. We have already shown[3] that in magnetic fields up to 30 kOe beryllium behaves in fact like a metal with a closed Fermi surface with $n_1 = n_2$. However, in stronger fields, a sharp increase of the anisotropy of the magnetoresistance is observed, thus indicating the appearance of open trajectories. We have advanced the hypothesis[3] that the open trajectories are the result of magnetic breakdown. This point of view was subsequently confirmed by the fact[4] that when the mean free path is reduced by 2.5 times (as a result of the increase of the temperature to 78°K), the kink in the ρ(H) dependence, i.e., the occurrence of open trajectories, occurs in the same region of magnetic fields as at 4.2°K. Thus, the point of inflection in the ρ(H) plot at **H** ∥ [0001] and **J** ⊥ **H**[1)] is determined not by the effective magnetic field ($H_{eff} = H\rho_{300^\circ}/\rho_T$), but by the intensity H of the external magnetic field.

As a result of magnetic breakdown, the electrons can go over from one closed orbit to another, forming by the same token open trajectories. The probability P of such a tunnelling of the electron under the potential barrier separating two closed orbits is given by the Blount formula[5]

$$P \sim \exp(-H_0/H),$$

where H is the external magnetic field and

$$H_0 = \frac{K\Delta^2 m^* c}{e\hbar\varepsilon_F} = \frac{K\Delta^2 m^*}{2\mu_B\varepsilon_F m_0}$$

is a parameter usually called the field breakdown, which is completely determined by the energy spectrum. (Here K is a normalization factor on the order of unity, Δ the energy gap, m^*/m_0 the ratio of the effective mass of the electron to the free mass, μ_B the Bohr magneton, and ϵ_F the Fermi energy.)

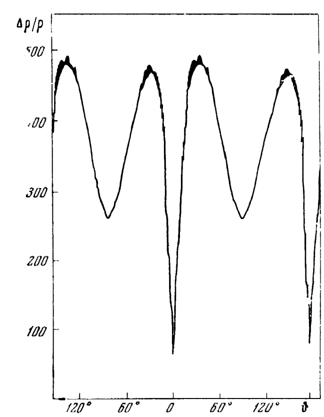

FIG. 1. Angular dependence of the magnetoresistance for a binary sample of Be (θ = 87°, φ = 15°, ρ(300°K)/ρ(4.2°K) = 130) in a superconducting magnet. **J** ⊥ **H**, T = 4.2°K, H = 75 kOe. The minima correspond to **H** ∥ [0001], ϑ – angle between the direction of **H** and the projection of the [0001] axis.

Falikov and Sievert[6][2)] considered theoretically the magnetoresistance under conditions of magnetic breakdown, and have shown, in particular, that when the free path increases, the magnetic field H_m, in which the change of ρ(H) takes place, decreases. However, this dependence is quite weak. Thus, for an hexagonal metal (see Fig. 16 in[6]), H_m decreases by less than three times when the relaxation time τ is increased by 30 times. Therefore, inasmuch as in our case τ changes only by 2.5 times, and also to a considerable degree owing to the fact that this change is due to increasing the sample temperature to 78°K, we cannot deduce from our data that an appreciable increase of H_m took place (according to[6]). To the contrary, owing to the thermal smearing of the energy levels, the occurrence of open trajectories due to a unique "thermal breakdown" was observed by us[4] at T = 78°K in somewhat weaker fields compared with T = 4.2°K. The possibility of a "thermal breakdown" of this kind was later considered theoretically by Kaganov et al.[8].

In the case of magnetic breakdown in beryllium, we can expect an increase in the amplitude of the resistance oscillations of the Shubnikov-de Haas type, due to the

1) In [3,4] we indicated incorrect azimuthal orientations for binary samples: the minimum of $\rho_H(\vartheta)$ is observed at **H** ∥ [0001] throughout, corresponding to open trajectories in the hexagonal plane.

2) The behavior of the resistance in strong magnetic fields under conditions of magnetic breakdown was considered also by Peschanskiĭ [7].

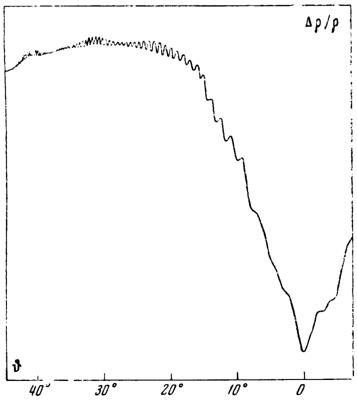

FIG. 2. Stretched-out plot of part of the angular diagram near the resistance minimum.

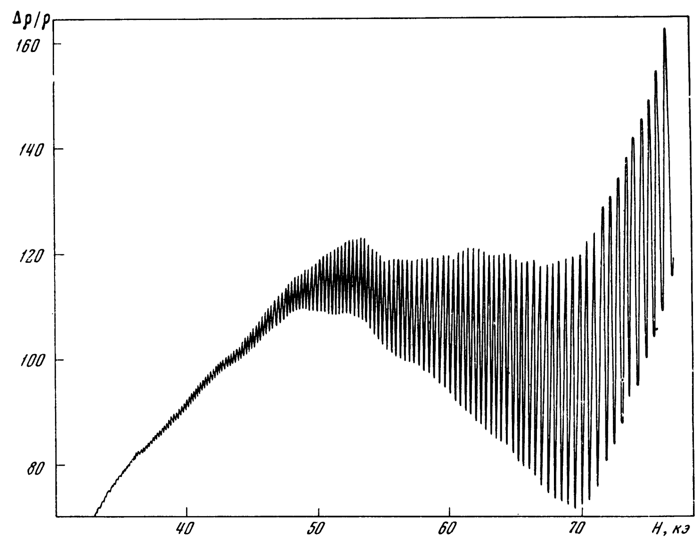

FIG. 3. Magnetoresistance of Be sample in the direction $\vartheta = 0°$.

passage of the Landau levels through the Fermi boundary. Oscillations of this kind were observed earlier in zinc[9,10] in weak fields. For beryllium, however, according to the published[1,2,11] dimensions of the details of the Fermi surface, the period of the oscillations should be quite small. In our earlier investigations[3,4], the possibility of observing oscillations with a small period was, naturally, excluded, first as the result of the use of an ac measurement procedure[12], and second as a result of the inhomogeneity of the magnetic field, which must not exceed 10^{-4} in order to observe a period $\sim 10^{-7}$ Oe^{-1} in a 50 kOe field. It was therefore of interest to perform the experiments with allowance for the indicated circumstances[3)].

In the present study we investigated the magnetoresistance in a single-crystal beryllium sample cut from a crystallite[4)] by the electric erosion method. The transverse dimensions of the sample, as usual, were 0.3×0.3 mm^2, and the length approximately 3 mm. The distance between the potential electrodes was ~ 0.5 mm. The magnetic field was produced by a superconducting magnet constituting a superconducting solenoid in which permendur concentrators were mounted, so that in a gap of 2 mm between them it was possible to obtain a magnetic field exceeding 80 kOe. The homogeneity of the magnetic field in the volume of the sample was not worse than 0.5×10^{-4}. The resistance of the sample was measured by the usual potentiometric method using a photoelectric amplifier. The angular rotation diagrams $\rho_H(\vartheta)$ at H = const were recorded with an ÉPP-09 potentiometer. The sample was rotated with the aid of a friction device at a rate of 360° in 22 minutes. The $\rho_\vartheta(H)$ plots at fixed directions of the magnetic field were recorded on an automatic two-coordinate plotter PDS-021. A signal from a Hall pickup[5)] was applied to the X coordinate. The rate of change of the magnetic field was ~ 4 kOe/min. The technique of measurements in the superconducting magnet was described in greater detail in[15].

Figure 1 shows the angular dependence of the resistance of the investigated sample ($\theta = 87°$, $\varphi = 15°$, where θ and φ are the polar and azimuthal angles between the [0001] axis and the rotation axis), in a magnetic field of H = 70 kOe. On the whole, it is similar to the angular diagrams obtained earlier with binary samples. As in[3,4], deep sharp minima, corresponding to the appearance of open trajectories, are observed at **H** ∥ [0001][6)]. However, besides the ordinary relatively smooth dependence of the resistance on the angle, a superposition of unique oscillations is observed. In Fig. 2, the region of the angle diagram near **H** ∥ [0001] was plotted at a larger speed of the plotter chart, so that the resistance oscillations could be distinctly resolved. It is clearly seen here that the amplitude and the period of these oscillations vary with the angle, and that the positions of the oscillation minima and maxima is not connected with rational directions in the crystal.

The dependence of the resistance on the magnetic field at the minimum of the angle diagram also revealed oscillations (Fig. 3) of quite large amplitudes, and the monotonic part of the $\rho(H)$ plot is in good agreement with the earlier results. The oscillations of the resistance as a function of the reciprocal of the magnetic field have a constant period. The amplitude of the oscillations increases with the magnetic field. The start of the growth occurs approximately at the same magnitude of the magnetic field as the change of the dependence in the monotonic part, and corresponds to $H \sim 50$ kOe in accordance with the earlier work[3,4].

We then plotted $\rho_\vartheta(H)$ for different angles between the field and the hexagonal axis of the crystal. A number of such plots are shown in Figs. 4 and 5[7)]. As seen from the figure, the amplitude of the oscillations decreases sharply when the magnetic field deviates from the direction of the principal minimum. Following rotation through 4° in a field H = 65 kOe, the amplitude de-

3)Preliminary results were published in a brief note [13];

4)The initial Be crystallites were obtained by us from the Physicotechnical Institute of the Ukrainian Academy of Sciences.

5)The Hall pickup was an InSb crystal with increased electron density, kindly furnished by J. Hlasnik [14]. Such a pickup, while having a somewhat lower sensitivity, has on the other hand good linearity ($\sim 1\%$) up to fields H = 100 kOe.

6)We have in mind the projection of the [0001] axis on the plane of rotation of the magnetic field.

7)The plot was obtained at a lower sensitivity than in Fig. 3, since when $\vartheta \neq 0$ the $\rho(H)$ dependence has a large monotonic part. Consequently the oscillations of the resistance become noticeable at a larger value of the field.

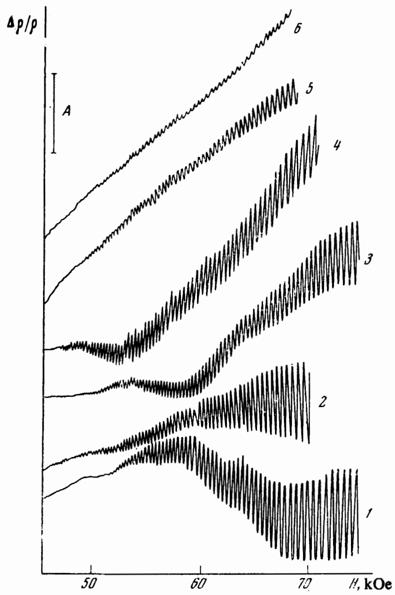

FIG. 4. Plot of $\rho\vartheta(H)$ in the region of the minimum resistance of the angle diagram of Fig. 2: 1 – $\vartheta = 0°$, 2 – $0° < \vartheta < 0.3°$; 3 – $\vartheta = 1°$, 4 – $\vartheta = 2°$; 5 – $\vartheta = 3°$; 6 – $\vartheta = 4°$. Scale A is the same for all curves, and the value of A coresponds to $\Delta\rho/\rho = 30$. The ordinates of all the curves are measured from different points.

creases to less than one tenth. In the region of angles ϑ near 10, 20, 30, and 40° (see Fig. 2) the amplitude of the oscillations increases somewhat, and, say for $\vartheta = 30°$, it amounts to approximately one third of the amplitude of the oscillations at the minimum (see Figs. 4 and 5).

With increasing angle ϑ, the period of the oscillations decreases. The results of the measurements of the period are shown in Fig. 6, which shows a plot of the quantity F, which is a reciprocal of the period, and which is proportional, in accordance with the Lifshitz-Onsager formula, to the area of the extremal section of the Fermi surface. When $\vartheta = 0$ this quantity corresponds to the central section of the electronic ellipsoids located

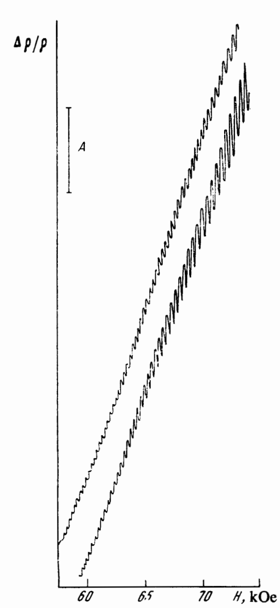

FIG. 5. Plot of $\rho\vartheta(H)$ in the region of the resistance minimum of Fig. 2: lower curve – $\vartheta = 30°$. upper curve – $\vartheta = 40°$.

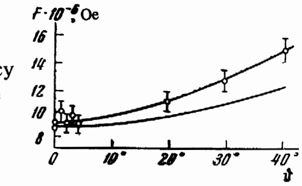

FIG. 6. Plot of magnetic frequency F against the angle ϑ. The lower curve corresponds to the data of [11].

at the corners of the Brillouin zone, the so-called cigars, in good agreement with the well known theoretical calculations[1,2] and the experimental data obtained in an investigation of the de Haas–van Alphen effect[11,16]. The lower curve corresponds to data on the de Haas–van Alphen effect obtained in[11]. The quantitative discrepancy in the values of F (~15%) exceeds the limits of the measurement errors, and cannot be explained satisfactorily at present. It is not excluded that under the conditions of magnetic breakdown the Lifshitz-Onsager quantization scheme may be violated and the electron motion, strictly speaking, will not be described by the orbits observed in the de Haas–van Alphen effect.

When the magnetic field deviates from the [0001] direction, the magnetic breakdown can lead to the appearance of elongated trajectories (Fig. 7) that connect two or three coronas through the cigar. Such orbits will encompass the central section of the cigar up to an angle $\vartheta \sim 50°$. The motion of the electrons along such trajectories, perpendicular to the current, can yield a noticeable contribution to the magnetoresistance, leading to oscillations of the latter. In the present experiments, the oscillations were observed (see Fig. 2) up to an angle $\vartheta = 42°$.

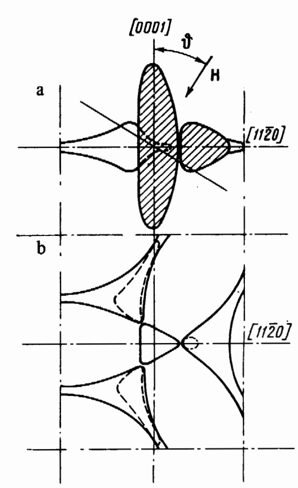

FIG. 7. Section through the Fermi surface of Be: a – by plane passing through the [0001] and [1120] axes (the dimensions are taken from [1]) and b – by hexagonal plane. The dashed lines show the approximate form of the "magnetic breakdown orbit" corresponding to the central section of the cigar.

On the basis of the obtained data, we can estimate the energy gap Δ in the [11$\bar{2}$0] direction. The magnetic field H_m at which the resistance goes through a maximum can be assumed equal to 50 kOe. The relation between this quantity and the breakdown parameter H_0, as shown in[6], depends on the relaxation time τ. If we use the calculation of[6]8) for the case of hexagonal metals (Fig. 16 in[6]), then, in accordance with our data on the change of the resistance with temperature, we can as-

8)Objections against the method of calculation used in [6] are raised in [17,18]. In this magnetic-field region, however, the results of [6] can be used.

sume $H_0/H_m \sim 3$. The ratio m_0/m^* in the [0001] direction for the cigar, as given in[11], is 5.9. To estimate the Fermi energy, we can use the quantity $\gamma = 0.4 \times 10^{-4}$ cal/mole-deg^2, obtained in[19] for measurements of the specific heat of very pure beryllium[9)]. Substituting these quantities in the Blount formula, we can obtain for the gap the value $\Delta \sim 6 \times 10^{-3}$ Ry[10)]. If we estimate the gap between the third and second bands in accordance with the data of[1], namely in accordance with the form of $\epsilon(k)$ in the third band in the [11$\bar{2}$0] direction (Fig. 9a of[1]) and in accordance with the distance between the corona and the cigar, given in Table IV of the same paper, then we get $\Delta \sim 5 \times 10^{-3}$ Ry, which is in good agreement with our result[11].

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[9)] The specific heat of beryllium is sensitive to impurities, so that the value of γ may turn out to be somewhat smaller.

[10)] A smaller value of the gap was obtained in [20], since a simplified model was used in the estimate.

[11)] The distance between the cigar and the corona is three times larger in [2] than in [1], and eight times larger in [11], whereas the discrepancy in the remaining dimensions does not exceed several percent. Therefore the magnetic breakdown, which yields the value of the gap Δ directly, has in this sense an advantage over methods of investigating the Fermi surface.

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