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Oscillations of the thermoelectric power of cadmium in magnetic breakdown

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The transverse thermoelectric power and the magnetoresistance were measured in cadmium of high purity, of orientation $[10\bar{1}0]$ in fields up to 150 kOe. Oscillations of the thermoelectric power were observed in a wide range of angles when **H** was rotated in the $(10\bar{1}0)$ plane. Coherent magnetic breakdown between the first and second bands of the Fermi surface is used to explain the results.

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Until recently, magnetic breakdown (MB) in cadmium was investigated mainly with the aid of the de Haas–van Alphen (dHvA) effect.[1,2] The studies of the Fermi surface of cadmium by Tsui and Stark[1] has shown that MB can occur between sheets of the Fermi surface of the first and second band through a gap of spin-orbit origin. Thus, the section of the monster in the ΓKM plane can take the form of single-, two-, and three-lobe figure in the case of MB near the point K. A unique "bridge" is provided in this case for the carrier by the sharp peak of the α-pocket in the first zone, which passes close to the K point but without touching it (Fig. 1). When H was rotated in the $(11\bar{2}0)$ plane around the direction of the opening of the monster, new extremal sections γ' were observed in Ref. 1. They result from MB in the AHL plane between the pocket of the first band and the corrugated cylinder of the second, and branch away on the angular diagram from the usual sections of the monster γ. The combined two-band region which is produced because the cylinder is bounded from above and from below by pockets, has the observed extremal sections γ'.

However, a study of the MB phenomena by the dHvA method is a far from simple problem because of the complex spectrum of the observed frequencies and of the difficulty of its interpretation. From this point of view, the thermoelectric-power method, which has recently yielded a number of interesting results,[3-5] is preferable. It is shown that the thermoelectric-power coefficient S is sensitive to a restructuring of the electron energy spectrum by the magnetic breakdown, and depends little on the various scattering process in strong magnetic fields H. Compared with the magnetoresistance, whose oscillations are not observed in MB that leads to a change from open to closed trajectories,[6] a measurement of $S(H)$ makes it possible to observe such configurations in experiment. In addition, both the thermoelectric power and the magnetoresistance are oscillating functions of the magnetic field as a result of the Shubnikov–de Haas effect. To our knowledge, no such Shubnikov oscillations of the thermoelectric powers have observed so far, and the observed oscillations have been convincingly attributed to MB.

Cadmium remains perhaps the only hexagonal metal for which no investigations of oscillatory quantum phenomena were made by the thermoelectric-power method.

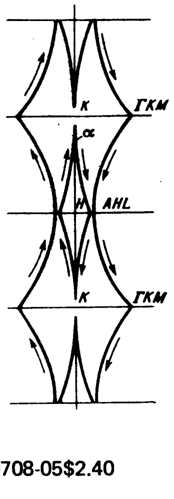

FIG. 1. Section of monster and pockets by the $(11\bar{2}0)$ plane along the KH line. The arrows show the direction of electron motion.

We report here observation of oscillations of the thermoelectric power of cadmium and present an analysis of a possible MB mechanism. Sufficiently detailed information on the singularities of its Fermi surface and the small number of orbits that are involved in the MB make their identification a rather simple matter.

EXPERIMENT

Cadmium samples with a resistivity ratio $\rho_{273\mathrm{K}}/\rho_{4.2\mathrm{K}} \approx 330\,00$[1)] were cut from x-ray-oriented single-crystal ingots. The crystal measured $2\times2\times15$ mm and their $[10\bar{1}0]$ axis was oriented in the direction of the applied temperature gradient. The mounting procedure and the method of measuring the coefficient S for the study of the effects connected with the MB are described in detail in Ref. 5. The potential electrodes welded to the sample could be used also to measure $\Delta\rho/\rho$; the current electrodes are in this case a differential thermocouple and one of the ends of the crystal connected with a common contact, such as the holder. The rotating unit in which the sample with the holder were placed made it possible to "rock" the sample through an angle $\varphi\sim30°$; this was necessary to reproduce a symmetrical angular diagram of S for all the samples.

The measurements were made in a magnetic field of a superconducting solenoid of intensity up to 150 kOe. The average sample temperature in the measurement of the thermoelectric power was 4.7 K, and the temperature difference between the potential electrodes was ~1 K.

Measurement of the field dependences of $S(H)$ enabled us to determine the angle regions in which oscillations occurred, and the corresponding areas of the extremal orbits. However, the monotonic component of $S(H)$ can not describe the type of carrier trajectory. As shown by Blatt *et al.*,[7] the formula of Mott and Jones for the thermo-electric power can be transformed, for the change of S in a magnetic field, into

$$\Delta S(H,T) = -eLT\left(\frac{\Delta\rho/\rho}{1+\Delta\rho/\rho}\frac{\partial}{\partial\varepsilon}\ln\frac{\Delta\rho}{\rho}\right),$$

where e is the electron change, L is the Lorentz number, T is the temperature, and ε is the energy. This formula demonstrates that, in contrast to the magnetoresistance, the thermoelectric power $S(H)$ always tends to saturate, so that it was necessary, in the oscillation directions, to measure additionally the magnetoresistance $\Delta\rho/\rho$ as a function of H by the method described above.

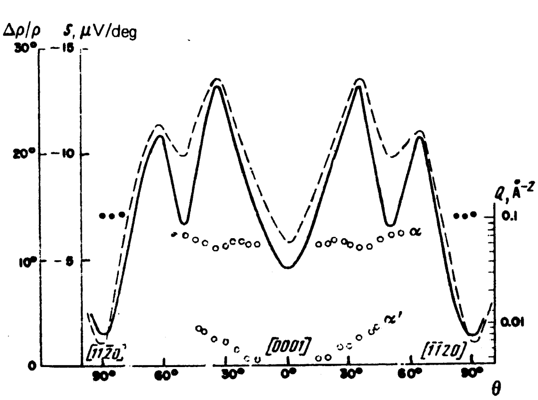

FIG. 2. Angular dependences of the thermoelectric power, of the magnetoresistance, and of the observable areas of the extremal sections of cadmium. The dark circles denote the sections obtained when H is rotated in the $(10\bar{1}0)$ plane, the light circles—when the sample is inclined by an angle $\varphi\sim3°$; solid curve—plot of $S(\theta)$, dashed—$\Delta\rho/\rho=f(\theta)$ at $H=100$ kOe.

MEASUREMENT RESULTS

Figure 2 shows a typical angular dependence of the magnetoresistance and thermo-electric power of Cd in the case when the field H rotates in the $(10\bar{1}0)$ plane and the temperature gradient is directed along the corresponding $[10\bar{1}0]$ axis. The singularities of the anisotropy of the thermoelectric power corresponds to the singularities of the magnetoresistane,[8] and the shape of the curve on the rotation diagram correlates with the shape of the Fermi surface in the second band.

The field dependences of S and $\Delta\rho/\rho$ were plotted in steps of 3–5° as the vector H was rotated from the [0001] to the $[11\bar{2}0]$ axis. In a small angle region ±10° about the $[11\bar{2}0]$ direction there are superimposed on the monotonic component of $S(H)$ oscillations of frequency 1.16×10^7 Oe, and these oscillators begin to differ from one another starting with fields $H\gtrsim75$ kOe (Fig. 3, curve 1). No such oscillations are observed on the field dependence of $\Delta\rho/\rho$ (curve 2).

An interesting result was obtained when the sample axis was inclined by an angle $\varphi\sim3°$, i.e., the vector H rotates at this angle to the $[10\bar{1}0]$ plane. This insignificant change in the experimental geometry is sufficient to upset the symmetry of the angular diagram of $S(\theta)$ and of $\Delta\rho/\rho=f(\theta)$ relative to the hexagonal axis. The measured $S(H)$ in an oblique field revealed an oscillatory component in a wide range of angles θ. Above all, when the direction of H is close to $[11\bar{2}0]$ the oscillations remain unchanged both in frequency and in amplitude. In the interval $15°\lesssim\theta\lesssim60°$, $S(H)$ contains a single harmonic of sufficiently large amplitude, with a frequency that ranges from 0.48×10^7 to 0.63×10^7 Oe. At $15°\lesssim\theta\lesssim43°$ there is superimposed on these oscillations a low-frequency modulating harmonic of noticeable amplitude (Fig. 4). The degree of modulation of the high-frequency oscillations at $H=150$ kOe reaches 80%.

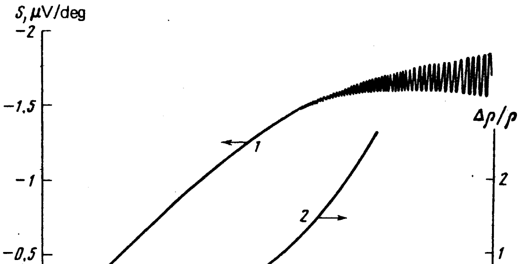

FIG. 3. Field dependences of the thermoelectric power and of the magnetoresistance of Cd at $H\parallel[11\bar{2}0]$ $(\theta=90°)$.

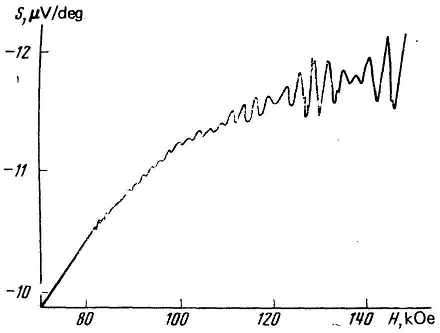

FIG. 4. Field dependence of the thermoelectric power of CdS at $\theta = 27°$.

The frequency of the slow modulating oscillations increases smoothly with increasing θ and reaches at $\theta = 43°$ a value $\alpha' \sim 10^6$ Oe. At a rotation angle $\theta \gtrsim 43°$ the modulation vanishes abruptly and thereafter only one component is observed on the field dependences of the thermoelectric power.

The field dependence of the magnetoresistance measured at H $\parallel [11\bar{2}0]$ and shown in Fig. 3 (curve 2) has a rather complicated shape. In fields above 15 kOe, following a quadratic increase, the dependence of $\Delta\rho/\rho$ on H tends to saturate, and at $H > 35$ kOe it regains its quadratic character. For all the remaining directions, both oscillating and nonoscillating, $\Delta\rho/\rho \propto H^{2\pm0.1}$.

DISCUSSION

The identification of the frequencies of the oscillations obtained at $\theta \sim 90°$ and of the high-frequency ones at $15° \lesssim \theta \lesssim 60°$ turned out to be relatively simple. The corresponding areas of the extremal sections (Fig. 2) are sections of the hole α pocket in the first band of the Fermi surface and agree well with the data first obtained by the dHvA method.[1] An essential difference between those results and our measurements is the angle range and the magnetic field values in which the oscillations are observed. According to Tsui and Stark[1] and the calculations of the band structure of cadmium,[8] the extremal orbits on the α pocket exist in the entire interval of rotation of H and are revealed by the dHvA method in fields ~30 kOe. Our experiments on the thermoelectric power yielded good agreement between the areas of the extremal sections of the pocket both with respect to the character of variation with changing θ, and in magnitude. The absence of oscillations near H$\parallel[0001]$ and in the range $60° \lesssim \theta \lesssim 80°$, where extended orbits exist, seems strange at first glance. This selectivity of the H directions at which oscillations from the pocket orbits are observed indicates that these oscillations are of magnetic breakdown origin. The angle range of their existence may then be limited by the singularities of second-band orbits that may become involved in the MB.

At H$\parallel[11\bar{2}0]$ one should expect for the field dependence of the magnetoresistance of cadmium a curve with saturation, as a result of the open orbits along [0001] in the second band. The obtained dependence of $\Delta\rho/\rho$ on H attests to the onset of MB in this direction. The transition from a quadratic growth to saturation at $H \sim 15$ kOe is determined by the condition $\omega_H\tau = 1(\omega_H$ is the cyclotron frequency and τ is the electron relaxation time). The field $H \sim 35$ kOe at which the plot again becomes quadratic can be regarded according to Peschanskii[9] as the breakdown field. The sheets of the first and second bands of the Fermi surface are separated by a spin-orbit gap. The plane of their closest approach is AHL, where the gap between the section of the pocket and the neck of the cylinder is ~0.07 eV. The picture of the cut of the plane $(11\bar{2}0)$ plane through the monster and the pockets along the KH line, shown in Fig. 1, illustrates the mechanism of the MB in the H$\parallel[11\bar{2}0]$ direction. The directions of motion of the carriers along the open cylinder and the closed pocket are identical.

In a strong magnetic field, on the AH line, at the point where they approach each other, the carriers can go over from one branch of open trajectories to another, owing to the "transparency" of the small α orbit. This transition leads to the formation of a closed trajectory and, as a consequence, to a relation $\Delta\rho/\rho\alpha H^2$. The possibility of observing the oscillation of S appears in the case of coherent MB, when the closed α orbit controls the motion along the open trajectories, leading to an increase of the amplitude by a factor $(\omega_H\tau)^2$. The field dependence of the magnetoresistance, as well as the estimate of Tsui and Stark,[1] yield a breakdown field value $H_0 \approx 33$ kOe, whereas in experiment the oscillations become discernible at $H \gtrsim 75$ kOe. This can apparently be attributed to the relatively high dislocation density in the crystals. Their large concentration leads to stochastization of the spectrum in fields lower than 75 kOe. Then the scattering of the electrons by the MB regions can be regarded as random motion along to parallel paired classical orbits in momentum space. The absence of oscillations connected with the extremal sections γ' of the two-band region is evidence that the MB is coherent over this length only at $H > 150$ kOe.

Thermoelectric-power oscillations that occur at $15° \lesssim \theta \lesssim 60°$ on the extremal sections of the pocket can also be explained within the MB framework. The angular selectivity of the oscillating directions suggests a sufficiently rigorous breakdown model. We note first that the extremal α sections, being the smallest among any of the previously observed sections of the Fermi surface of cadmium, are covered by larger extremal sections β corresponding to orbits on the neck of the monster. The region of existence of the extremal β orbit is limited in the plane $(10\bar{1}0)$ of rotation of H by the angle $\theta = 43.5°$ at which the plane containing the orbit becomes tangent to the surface of the corrugated cylinder. Above this limit, the extremal two-band β orbit appears only in the $(11\bar{2}0)$ plane of rotation of H at $42.5° \lesssim \theta \lesssim 60°$. The absence of such an orbit for our directions of H is attributed to the asymmetry of the cylinder in this plane, as a result of which the orbit is not extremal.

On the left side of Fig. 5 is shown the section of the

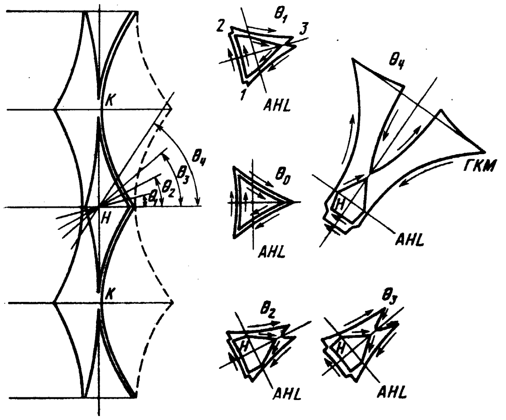

FIG. 5. Section of monster and pockets by the plane $(10\bar{1}0)$ along the line *KH*. On the left side of the figure are shown the traces of some planes containing extremal orbits, marked θ_0, $\theta_1, \ldots, \theta_4$; the corresponding sections for $\theta_0=0°$, $\theta_1=15°$, $\theta_2=27°$, $\theta_3=40°$, and $\theta_4=55°$ are shown in the right-hand side of the figure.

pockets and the monster along the line *KH* by the plane $(10\bar{1}0)$, on which the tracks of certain planes containing extremal orbits are marked by $\theta_0, \theta_1, \ldots \theta_4$. The corresponding extremal sections, shown on the right of Fig. 5, characterize the picture of the MB between the α orbit of the pocket and the β orbit of the monster, and account for the angle range of the oscillating directions. Thus, at $\mathbf{H} \| [000\bar{1}]$ in section θ_0 the monster and the pocket have the same configuration and are separated by a small gap. It is easily seen that there are no region favoring MB in this section, as is confirmed by the absence of oscillations of the thermoelectric power. This situation remains in force right up to angles $\theta \sim 15°$, starting with which the orbit plane of the monster will intercept the edges of the opened trefoil. This leads to formation of internal "teeth" at the corners of the triangular β orbit, which produce conditions for MB (see Fig. 5, section θ_1). When θ changes from 15° to the critical angle 43.5° for the existence of the β orbit, the sections of the pocket and of the cylinder vary but the conditions for the MB are preserved (Fig. 5, sections θ_2 and θ_3).

As noted above, in the H rotation plane $(10\bar{1}0)$ at $43.5° \leq \theta \leq 60°$ the orbit will not be extremal. Its form for $\theta = 55°$ is shown in Fig. 5 (section θ_4). The magnetic-breakdown situation is preserved also in this case: α oscillations are observed. The non-extremal character of the β sections can cause the corresponding oscillations to be unobservable. However, the non-extremal behavior is not the decisive cause of the absence of β oscillations—they are likewise not observed in experiment in the region of extremal sections.

Slow modulating oscillations of frequency $\alpha' \sim 10^6$ Oe occur in the region of existence of a one-band β orbit. They appear simultaneously with the α oscillations and vanish when a two-band β orbit is formed. This connection between the low-frequency oscillations and the MB orbits suggests that they are determined apparently by some difference area. According to our estimates, a corresponding area is possessed by the region between the sections of the pocket and the monster, and is made in MB at the points 1 and 2 (see Fig. 5, θ_1). The character of its variation with θ correlates well with the obtained experimental sections.

The reason for the vanishing of the modulations at $\theta \sim 43°$ may be the violation of the coherence of the electron waves when the two-band β orbit is produced (see Fig. 5, θ_4), although an orbit as small as α' will, of course, be coherent. Another possible explanation of the appearance of α' oscillations follows from the geometric singularities of the experiment. The pockets of the first band of the Fermi surface, which are elongated along the edges of the Brillouin zone along the line *KH*, make an angle 60° with each other. When the vector H rotates in the $(10\bar{1}0)$ plane, the areas of the pocket sections are equal. When H is inclined at a certain angle φ, the spatial disorientation of the α pockets leads to formation of two groups of sections, and the difference between their areas corresponds to the modulating harmonic. This model, too, has shortcomings. The angle range of observation of the α' oscillations should coincide with the angle interval in which the α oscillations appear, i.e., with the interval $15° \leq \theta \leq 60°$. Therefore the absence of α' oscillations at $\theta \gtrsim 43°$ can not be easily explained within the framework of such a representation.

Thus, a qualitative consideration of the obtained experimental dependences of S and $\Delta\rho/\rho$ on the field, jointly with the topological singularities of the Fermi surface of cadmium in the first and second bands, has made it possible to observe MB between closed and open trajectories and between closed trajectories in a wide range of angles. From the point of view of the feasibility of its observation, the thermoelectric power is in this case perhaps the only method. Thus, Tsui and Stark,[1] using the dHvA method, could detect MB by the formation of a two-band configuration only near open directions of the corrugated cylinder. Other kinetic coefficients are much less sensitive to the quantum-oscillation effects. Nonetheless, the study of the field dependences of the magnetoresistance supplement greatly the oscillatory characteristics of the thermoelectric power in the study of MB.

In conclusion, the authors thank N. E. Alekseevskiĭ, A. A. Slutskin, V. I. Nizhankovskiĭ for a discussion of the results and E. F. Golov for supplying the cadmium single crystals.

[1)] Single crystals of such high purity were grown in the Solid State Physics Institute of the USSR Academy of Sciences (Chernogolovka).

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Translated by J. G. Adashko

Effect of plastic deformation on charge motion in solid He^4

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The mobility of the charges in undeformed He^4 crystals with molar volumes 19.67 and 20.55 cm^3 was determined by two procedures: reduction of the diode current-voltage characteristics, and from the diode transient-current curves following application of a dc voltage. To justify the last procedure, the electrodynamic problem of the motion of the charge front in a plane-parallel diode is solved. The mobilities determined by the two methods differed by not more than 15%. Solid helium was plastically deformed in a gap between electrodes at three temperatures. Measurements of the time of flight in the deformed crystals have shown that the mobility changes by not more than 10%. The current-voltage characteristics are substantially altered: at low voltages the current is not proportional to the square of the voltage. The density of the immobile charge is estimated under the assumption that the change of the current is due to the pinning of the charges by the dislocations.

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Carrier mobility in crystalline helium had been investigated up to now in samples grown under the most favorable conditions: constant pressure and small temperature gradients. Keshishev[1] investigated the mobilities of positive and negative charges in such crystals (with molar volumes $V_{mol} = 19.5 - 20.9$ cm^3). The results obtained with crystals having the same molar volume were very well reproducible (see Ref. 1, Fig. 10). The observed nonlinear dependence of the ion velocity v on the electric field strength E was used to explain the deviation of the current-voltage characteristics from the relation $I \propto U^2$. The calculated current-voltage characteristics agreed well with the experimental data.

A different point of view was held by Dahm,[2] who assumed that the deviation from the $I \propto U^2$ law is due to partial release of the ions from the traps by a strong electromagnetic field. The traps can be formed by various crystal-structure defects, and in particular by dislocations. This effect was calculated by Murgatroyd.[3]

X-ray structure investigations show that samples grown at constant pressure and at a low rate have a high degree of monocrystallinity (see, e.g., Ref. 4). One cannot exclude, however, the presence of a large number of dislocations that are produced in the course of the crystal growth, as well as produced later when the crystal temperature is changed. There are presently no known direct measurements of the dislocation concentration Λ in He^4 crystals. Wanner, Iwasa, and Wales[5] cite an estimate $\Lambda \sim 3 \times 10^5$ cm^{-2} obtained indirectly from measurements of sound-velocity anomalies. This number of dislocations can produce, in principle, a large number of traps for the charges and influence significantly the current in solid helium.

We report here an experimental investigation of the effect of plastic deformation on the currents and charge mobility in solid helium.

EXPERIMENTAL PROCEDURE

Figure 1 shows the construction of the ampoule used in our experiments.

The crystal was grown at constant pressure at rates $(1-5) \times 10^{-4}$ cm/sec. It was first formed on the cold finger and then, as it grew, it filled the entire ampoule. The crystal growth procedure was described in detail by Shal'nikov.[6] In the present case the crystals were grown at two pressures, 32 atm ($V_{mol} = 20.55$ cm^3) and 49 atm ($V_{mol} = 19.67$ cm^3).

Plane-parallel electrodes 2 and 6, of 4 mm diameter and separated by $L = 0.28$ mm, formed the measuring diode cell. A molybdenum disk with a diameter 3 mm was pressed into the lower electrode and its outer sur-