Galvanomagnetic and thermomagnetic properties of osmium in high magnetic fields

N. V. Volkenshteĭn, V. P. Dyakina, V. V. Dyakin, V. E. Startsev, A. N. Cherepanov,
V. M. Azhazha, V. A. Elenskiĭ, and G. P. Kovtun

Physicotechnical Institute, Academy of Sciences of the Ukrainian SSR

(Submitted 5 May 1983)
Zh. Eksp. Teor. Fiz. **86**, 580–589 (February 1984)

The magnetoresistance, Hall coefficient, and magnetothermopower of osmium single crystals with resistance ratios $\rho(273.2\text{ K})/\rho(4.2\text{ K})$ up to 2000 have been measured in magnetic fields up to 90 kOe at a temperature 4.2 K. Shubnikov type quantum oscillations of thermopower were observed and studied in fields above 50 kOe. It was found that in osmium, unlike its electron analog ruthenium, the Fermi surface does not have open directions along the hexagonal axis. The possibility of magnetic breakdown in this metal is discussed.

INTRODUCTION

Osmium is a 5*d* transition metal with a hexagonal close packed lattice and is one of the few metals for which the electron spectra and Fermi surface (FS) topology have not been reliably established. There are no experimental facts on the basis of which the following questions can be answered: what is the topology of the FS of osmium and is magnetic breakdown possible in osmium, similar to that found in its electron analog, ruthenium?[1]

According to the results of measurements of the de Haas–van Alphen (dHvA) effect,[2] the FS of osmium (see Fig. 1 of Ref. 3) consists of two closed electron sheets, centererd on point Γ (sheets $\Gamma 9e$ and $\Gamma 10e$) and of a closed hole ellipsoid[1)] ($LM7h$). Apart from the closed sheets, there is a hole sheet $KM8h$, multiply connected in the basal plane, which unlike the analogous sheet of the FS of ruthenium is not connected in the ⟨0001⟩ direction. On the other hand, the FS model proposed by Jepson *et al.*[4] on the basis of calculations by the augmented plane wave method in the relativistic approximation, is considerably different from that constructed experimentally from the cross-sections deduced from the dHvA effect. First, the calculation[4] gives two additional sheets of the FS—a closed hole $\Gamma 10h$ sheet and a hole $L7h$ lens; second, according to this calculation, the multiply connected $KM8h$ sheet should intersect the basal plane in the region of point L, forming an open direction along the ⟨0001⟩ axis. The possibility of such open directions existing was noted by Alekseevskiĭ *et al.*[5] who studied the magnetoresistance of osmium single crystals with resistance ratio $\rho(273.2\text{ K})/\rho(4.2\text{ K})\approx 100$.

The experimental and theoretical results thus do not agree and do not give a unique answer to the problem of the connectivity of the FS of osmium in the hexagonal direction. The necessity of studying the FS topology of osmium in the region of point L of the Brillouin zone is directly related to the question of the possibility of magnetic breakdown in this metal, since in its electron analog, ruthenium, it is just the existence of necks on the multiply connected $KM8h$ hole sheet and $L7h$ lens, separated by the spin-orbit gap, which brings this effect about.[1] The results of calculation[4] also indicate the possibility of breakdown in osmium. Since osmium has a higher atomic number than ruthenium, there are appreciable relativistic effects in the formation of its electronic spectrum, which could influence the nature of the appearance of breakdown in the kinetic properties or could lead to the formation of such a FS for which magnetic breakdown would not be possible. We have published preliminary results on the measurement of thermopower in osmium.[6] For the further study of breakdown in it we have undetaken measurements of its galvanomagnetic and thermomagnetic properties in high magnetic fields on the purest single crystals available at present with resistance ratio $\rho(273.2)/\rho(4.2\text{ K})\approx 2000$, grown as described by Azhazha *et al.*[7]

EXPERIMENTAL METHOD

Measurements of anisotropy and of the field dependences of magnetoresistance and magnetothermopower were made at $T=4.2$ K and in magnetic fields up to 90 kOe on single-crystal specimens with dimensions $1\times 1\times 12$ mm. The specimens were cut out along the chief crystallographic axes by the electrospark method. Specimen orientation was monitored by x-rays with an error of less than 2°. The specimens were mounted in such a way that magnetoresistance, magnetothermopower, and the Hall effect could be measured simultaneously. The conventional dc method was used to measure magnetoresistance. Magnetothermopower was measured in the manner described by Alekseevskiĭ *et al.*[8] The temperaure gradient, which was not more than 1.0 K/cm was measured by a differential thermocouple. The sign and magnitude of the thermopower were determined in the absence of a magnetic field, and NbTi superconducting wire connections were used for this. Copper thermocouple wire connections were used to measure the thermopower in a magnetic field. Measurement of the field dependences of magnetoresistance and magnetothermopower was carried out during a smooth sweep of the magnetic field of a UIS-1 superconducting solenoid at a rate not above 5 kOe/min. The specimen was rotated perpendicular to the solenoid axis by a turning mechanism for measurements of anisotropy. The dependence on field strength and direction was recorded on PDP-4 two-coordinate recorder with preamplification of the signal. The Hall coefficient was measured by the method described previously.[1]

0038-5646/84/020338-06$04.00

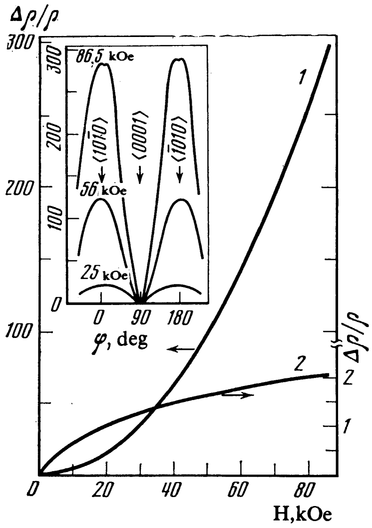

FIG. 1. Field dependences (1—**H**‖$\langle 10\bar{1}0\rangle$, 2—**H**‖$\langle 0001\rangle$) and anisotropy of magnetoresistance in magnetic fields 25 kOe, 56 kOe and 86.5 kOe in osmium, for **J**‖$\langle 1\bar{2}10\rangle$ and $T = 4.2$ K.

MAGNETORESISTANCE

Current orientations **J**‖$\langle 10\bar{1}0\rangle$ and **J**‖$\langle 1\bar{2}10\rangle$.

It can be established from the type of field dependences and anisotropy of the transverse magnetoresistance for specimens with this orientation whether the FS of osmium has open directions along the hexagonal axis,[4] which could be produced by the connection of the *KM* 8*h* sheets in the region of point *L*.

The anisotropy and field dependences of magnetoresistance for **J**‖$\langle 1\bar{2}10\rangle$ are shown in Fig. 1. These dependences are similar for a specimen with **J**‖$\langle 10\bar{1}0\rangle$. Deep, broad minima are observed on the $\Delta\rho/\rho(\varphi)$ curves for both specimens for the magnetic field along the $\langle 0001\rangle$ axis, and for these directions of **H** the magnetoresistance saturates. These facts are explained by the effect of geometrical decompensation:[2)] for **H**‖$\langle 0001\rangle$ a layer of orbits which is not of hole character, but electron, arises on the hole sheet *KM* 8*h*. On rotating the magnetic field from the $\langle 0001\rangle$ to the $\langle 10\bar{1}0\rangle$ or $\langle 1\bar{2}10\rangle$ axes, a monotonic growth in magnetoresistance is observed and is a maximum when the direction of **H** coincides with these axes. In both specimens the maximum of the magnetoresistance corresponds to its quadratic dependence on the magnitude of the magnetic field, which is a direct indication of the absence of open electron trajectories on the FS along the hexagonal axis. Shallow minima were observed[5] in the anisotropy of magnetoresistance for osmium with $\rho(273.2\ \mathrm{K})/\rho(4.2\ \mathrm{K}) \approx 100$ at these same directions of **H**, which the authors explained by the existence of open trajectories along the $\langle 0001\rangle$ axis. The results of measurements on purer single crystals and in larger effective magnetic fields, shown in Fig. 1, contradict those conclusions.[5]

It would be possible to attribute the magnetoresistance behavior typical of closed trajectories of electron orbits, to the occurrence of magnetic breakdown with restructuring of open trajectories along $\langle 0001\rangle$ into closed, as happens in ruthenium.[1] However, even in weak magnetic fields there are no signs of open trajectories: the $\Delta\rho/\rho = f(\varphi)$ dependences have the same form for different values of magnetic field (see Fig. 1). We note that for the same current orientations in ruthenium, closed magnetic-breakdown trajectories are realized, but in spite of this traces of prebreakdown open orbits are nevertheless revealed in the form of shallow minima on the $\Delta\rho/\rho = f(\varphi)$ curves (see Fig. 9 of Ref. 1). In additions, if it is, nevertheless, assumed that the absence of open trajectories along the $\langle 0001\rangle$ axis is due to magnetic breakdown, then it should be expected that a spatial network of breakdown trajectories should be realized for magnetic field directions intermediate between $\langle 0001\rangle$ and $\langle 10\bar{1}0\rangle$ or $\langle 1\bar{2}10\rangle$ (as in ruthenium). This should lead to the appearance of additional minima on the curves of magnetoresistance anisotropy. On the contrary, the existence of a spatial network would be impossible in osmium if the multiply connected hole *KM* 8*h* sheets are not open in the direction of the hexagonal axis. In osmium, unlike ruthenium, smooth $\Delta\rho/\rho = f(\varphi)$ dependences are observed, and features which could appear as a result of the existence of a spacial network of trajectories are absent.

All the measurements of the magnetoresistance of osmium on specimens with current oriented along the $\langle 1010\rangle$ and $\langle 1\bar{2}10\rangle$ axes and comparison of them with results on ruthenium thus show that the topology of the multiply connected *KM* 8*h* hole sheet is considerably different from the results of calculation:[4] there are, evidently, no open directions along the $\langle 0001\rangle$ axis on this sheet.

According to the results of calculation[4] and the results of magnetoresistance studies,[5] open trajectories may appear on the FS of osmium, perpendicular to the hexagonal axis, which could be found for a specimen with **J**‖$\langle 0001\rangle$.

Current Orientation **J**‖$\langle 0001\rangle$. The projection of the *KM* 8*h* sheet onto the basal plane is shown in Fig. 2, and the possible layer of open σ trajectories is shown shaded. The existence of such trajectories can be established using an experimental geometry with current orientation along the $\langle 0001\rangle$ axis, since the open direction in this case is perpendicular to the electric current.

The anisotropy and field dependence of the transverse

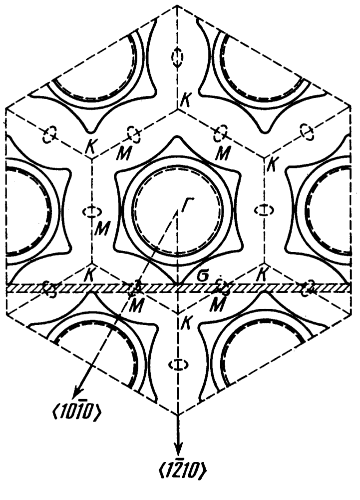

FIG. 2. Projection of the Fermi surface of osmium onto the $M\gamma K$ plane; the σ-layer of open trajectories along the $\langle 10\bar{1}0\rangle$ axis is shaded

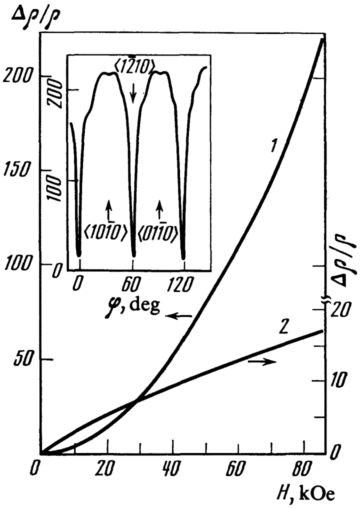

FIG. 3. Anisotropy for $H = 85$ kOe and field dependences of magnetoresistance of osmium for $\mathbf{J}\parallel\langle 0001\rangle$ and $T = 4.2$ K: 1—$\mathbf{H}\parallel\langle 10\bar{1}0\rangle$, 2—$\mathbf{H}\parallel\langle 1\bar{2}10\rangle$

magnetoresistance of a specimen with $\mathbf{J}\parallel\langle 0001\rangle$ are shown in Fig. 3. It can be seen from the inset, where the $\Delta\rho/\rho(\varphi)$ dependence is shown, that for $\mathbf{H}\parallel\langle 1\bar{2}10\rangle$ deep minima of magnetoresistance exist with half-width 7°. This indicates the existence of open trajectories along the $\langle 10\bar{1}0\rangle$ axis, which is also confirmed by the form of the field dependence of magnetoresistance (Fig. 3, curve 2) which tends to saturation at $\mathbf{H}\parallel\langle 1\bar{2}10\rangle$. A maximum in resistivity is observed in the $\Delta\rho/\rho(\varphi)$ dependence for the magnetic field direction along the $\langle 10\bar{1}0\rangle$ axis, while the field dependence is of the form $\Delta\rho/\rho \propto H^2$, which corresponds to closed configurations of the electron trajectories.

HALL EFFECT

Measurements of the Hall effect were carried out to confirm the conclusions about the topological features of the *KM* 8*h* sheet of the FS osmium, which follow from the results of measurements of magnetoresistance. It is just in compensated metals that the Hall coefficient R_h is sensitive to the onset of open trajectories for conduction electrons and to the effect of geometrical decompensation.

The anisotropy $R_h(\varphi)$ and field dependences $R_h(H)$ for specimens with the orientations $\mathbf{J}\parallel\langle 0001\rangle$ and $\mathbf{J}\parallel\langle 1\bar{2}10\rangle$ are shown in Fig. 4. These dependences are similar to those shown in Fig. 4b for a specimen with $\mathbf{J}\parallel\langle 10\bar{1}0\rangle$. Values of the Hall coefficient of osmium for directions of **J** and **H** along the principal crystallographic directions ($H = 85$ kOe) are given in Table I. It can be seen first that as the **H** vector approaches the $\langle 0001\rangle$ axis, R_h increases appreciable, independently of the current orientation. This is explained by the geometrical decompensation due to the β-orbits of electron origin on the *KM* 8*h* hole sheet. The thickness of the β-layer, calculated from the measured values of Hall coefficient ($d = 4\pi^3/SR_h e$, where $S = 6.99$ Å^{-2} is the area of the intersection of the Brillouin zone with a plane normal to **H**, and e is thee electron charge), is $d = 0.76 \pm 0.07$ Å^{-1} and agrees with the size of the multiply connected hole sheet in the *HKH* direction (0.82 Å^{-1}) obtained from the dHvA effect.[2]

It can, secondly, be seen from Fig. 4a and Table I that the magnitude of R_h also increases for $\mathbf{H}\parallel\langle 1\bar{2}10\rangle$. It is just in this direction of the magnetic field that open trajectories arise in the basal plane. The anisotropy curves $R_h(\varphi)$ provide evidence that the open trajectories are not caused by magnetic breakdown: the form of the $R_h(\varphi)$ curves remains the same on increasing the magnetic field from 20 to 85 kOe and the ratio $R_h\langle 1\bar{2}10\rangle/R_h\langle 10\bar{1}0\rangle$ hardly changes. In ruthenium, however, where the open orbits are really produced by magnetic breakdown, the anisotropy of R_h increases severalfold[1] in just the same range of values of $\omega\tau$ and in just the same range of changes in magnetic field (here ω is the cyclotron frequency, τ is the relaxation time).

Thus in spite of the fact that there are a number of common features of the behavior of magnetoresistance and Hall effect in specimens of osmium and ruthenium with current directed along the $\langle 0001\rangle$ axis, there are facts which make it impossible to consider that the open σ-trajectories along the $\langle 10\bar{1}0\rangle$ axis in osmium are trajectories coming about by magnetic breakdown. First, there are no features characteristic of breakdown in the anisotropy and field dependences of the Hall coefficient of the osmium specimens studied, unlike ruthenium. Second, for the magnetic field directed along the $\langle 1\bar{2}10\rangle$ axis the power of H is less than unity over the whole magnetic field range used for $\omega\tau > 1$. The prebreak-

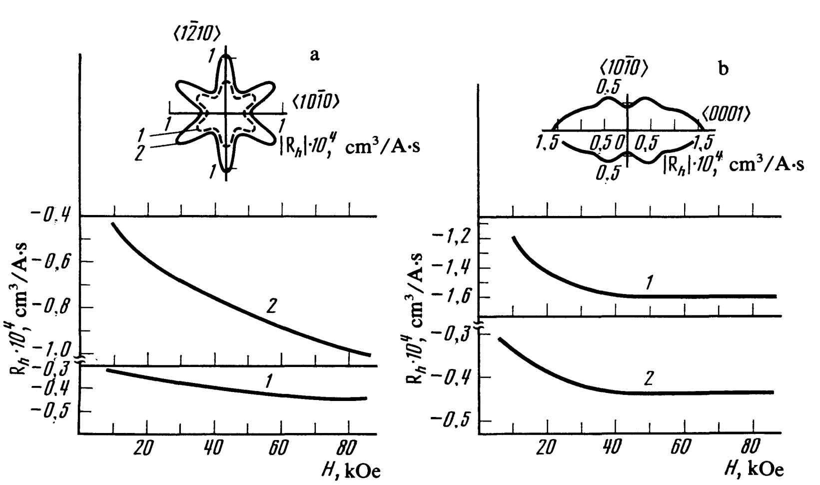

FIG. 4a. Anisotropy (1—$\mathbf{H} = 20$ kOe, 2—$\mathbf{H} = 85$ kOe) and field dependences of the Hall coefficient of osmium for $\mathbf{J}\parallel\langle 0001\rangle$ and $T = 4.2$ K (*1*-$\mathbf{H}\parallel\langle 1010\rangle$, 2—$\mathbf{H}\parallel\langle 1\bar{2}10\rangle$). b) Anisotropy for $H = 85$ kOe and field dependences of the Hall coefficient of osmium for $\mathbf{J}\parallel\langle 1\bar{2}19\rangle$ and $T = 4.2$ K (1∂$\mathbf{H}\parallel\langle 0001\rangle$, $\mathbf{H}\parallel\langle 10\bar{1}0\rangle$)

TABLE I

Current orientation	$R_h \cdot 10^4$, cm^2/A.sec		
	H ∥ $\langle 0001\rangle$	**H** ∥ $\langle 10\bar{1}0\rangle$]	**H** ∥ $\langle 1\bar{2}10\rangle$
$\langle 0001\rangle$	–	0.44	1,03
$\langle 1\bar{2}10\rangle$	1,61	0.45	–
$\langle 10\bar{1}0\rangle$	1.62	–	0.81

down quadratic-increase section of the field dependence of magnetoresistance is absent for osmium. Third, the existence of magnetic breakdown oscillations of magnetoresistance could be evidence of magnetic-breakdown production of open σ trajectories in osmium, but for **H**∥$\langle 1\bar{2}10\rangle$ no oscillatory contribution was observed within the sensitivity of the apparatus.

Since the thermomagnetic properties of metals are extremely sensitive to magnetic-breakdown oscillatory effects, measurements of magnetothermopower in high magnetic fields were carried out.

MAGNETOTHERMOPOWER

Anisotropy and field dependences of magnetothermopower. The results of measurements of magnetothermopower for the temperature gradient ∇T directed along the $\langle 1\bar{2}10\rangle$ axis are shown in Fig. 5. The appearances of these dependences are similar for $\nabla T \parallel \langle 10\bar{1}0\rangle$. It is possible to observed quantum magnetic-breakdown thermopower oscillations for such directions of the temperature gradient ∇T in the case when magnetic-breakdown restructuring of trajectories is realized, similar to the restructuring of open into closed trajectories along the $\langle 0001\rangle$ axis. The field dependence of thermopower $\alpha(H)$ for **H**∥$\langle 0001\rangle$ tends to saturation (Fig. 5), while a deep and broad minimum is observed on the anisotropy curve $\alpha(\varphi)$, the reason for which, as in the magnetoresistance, is geometrical decompensation. A maximum in thermopower is observed in the $\alpha(\varphi)$ curve for **H**∥$\langle 10\bar{1}0\rangle$, while the $\alpha(H)$ dependence is close to linear in the region $\omega\tau > 1$. Such a behavior of the thermopower, according to Bychkov *et al.*,[9] indicates the formation of closed orbits for the given magnetic field direction.

A similar anisotropy dependence and field dependences of magnetothermopower were also observed for $\nabla T \parallel \langle 10\bar{1}0\rangle$, which also indicates the absence of open electron trajectories along the hexagonal axis.

The anisotropy and field dependences of magnetothermopower of a specimen with $\nabla T \parallel \langle 0001\rangle$ are shown in Fig. 6. It can be seen that for such a direction of magnetic field (**H**∥$\langle 1\bar{2}10\rangle$) open σ trajectories are achieved along the $\langle 10\bar{1}0\rangle$ axis, a minimum appears on the $\alpha(\varphi)$ curve, while the sign of the thermopower is opposite to that for the other directions of **H**. However, it should be noted that for **H**∥$\langle 1\bar{2}10\rangle$, contrary to the conclusions of Bychkov *et al.*,[9] there is no saturation of the field dependence of thermopower (curve 2 of Fig. 6). In spite of this, the anomaly in the anisotropy of magnetothermopower near the $\langle 1\bar{2}10\rangle$ axis can evidently be associated with the existence of open σ trajectories. As in specimens[3)] with orientation along the $\langle 10\bar{1}0\rangle$ and $\langle 1\bar{2}10\rangle$ axis, a weak oscillatory contribution is observed for **H**∥$\langle 1\bar{2}10\rangle$ in a specimen cut along the $\langle 0001\rangle$ axis. The relative amplitude of the oscillations is less than 1% for $H \approx 80$ kOe. The amplitude of this oscillatory contribution is more than two orders of magnitude less than the amplitude of magnetic breakdown oscillations for open σ trajectories in ruthenium under equivalent conditions in $\omega\tau$ and $2\pi^2 K(T + T_D)/\hbar\omega$ (T_D is the Dingle temperature).

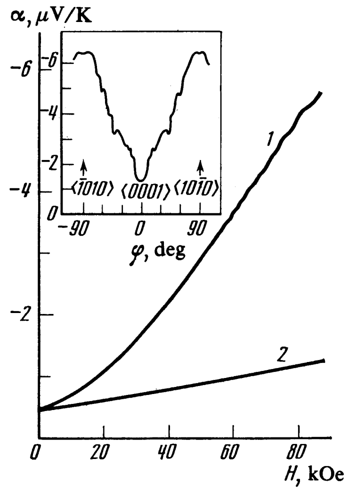

FIG. 5. Anisotropy at $H = 85$ kOe and field dependences of magnetothermopower of osmium for $\nabla T \parallel \langle 1\bar{2}10\rangle$ and $T = 4.2$ K (1—**H**∥$\langle 10\bar{1}0\rangle$, 2—**H**∥$\langle 0001\rangle$)

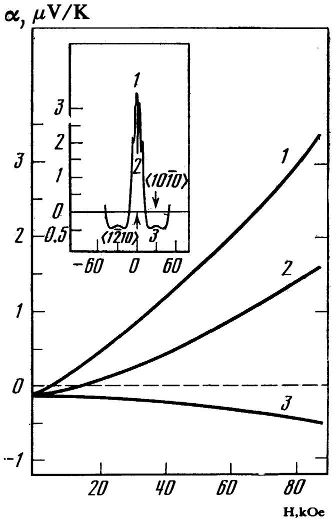

FIG. 6. Anisotropy at $H = 85$ kOe and field dependences of magnetothermopower of osmium for $\nabla T \parallel \langle 0001\rangle$ and $T = 4.2$ K (1—**H**∥$\langle 1\bar{2}10\rangle$, 2—**H**∥$\langle 1\bar{2}10\rangle$ + 0.5°, 3—**H**∥$\langle 10\bar{1}0\rangle$

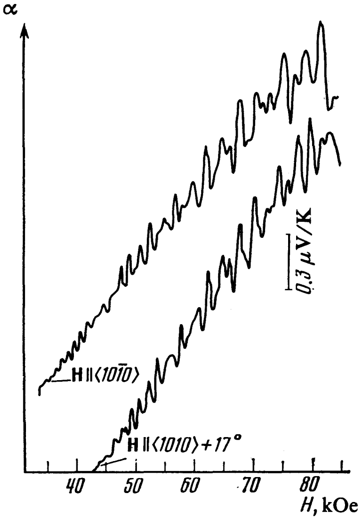

FIG. 7. Typical traces of oscillations of magnetothermopower of osmium for $\nabla T\langle 1210\rangle$ and $T = 4.2$ K

As can be seen, the results of measurements of thermopower are in agreement with results on magnetoresistance and confirm the conclusion about the absence of open directions along the $\langle 0001\rangle$ axis on the multiply connected $KM\,8h$ hole sheet of the osmium FS. However, it is necessary to elucidate the reason for the appearance of quantum oscillations of magnetothermopower.

Quantum thermopower oscillations. The oscillatory contribution to the magnetothermopower of osmium is relatively small (see Fig. 5). The oscillating part could be recorded in a form accessible to analysis by increasing the sensitivity of the apparatus. Typical traces of the oscillatory dependences of thermopower for $\nabla T \parallel \langle 1\bar{2}10\rangle$ are shown in Fig. 7. As can be seen, an oscillatory contribution is not only found for magnetic field orientations along the principal crystallographic axes. For all three specimens it is observed over a fairly wide range of magnetic field directions. For example, it exceeds the noise level up to an inclination of the magnetic field vector to the $\langle 10\bar{1}0\rangle$ axis at an angle $\varphi \approx 70°$ for a specimen with $\nabla T \parallel \langle 1\bar{2}10\rangle$. Magnetothermopower oscillations were not observed near the $\langle 0001\rangle$ axis.

It can be seen from Fig. 7 that the oscillatory component has a fairly complicated appearance, which indicates the presence of several frequencies. A Fourier analysis (see Appendix) showed that the spectrum of magnetothermopower oscillations of specimens with $\nabla T \parallel \langle 1\bar{2}10\rangle$ and $\nabla T \parallel \langle 10\bar{1}0\rangle$ contains two fundamentals and two second harmonics. The values of the fundamental oscillation frequencies, obtained from measurements of thermopower and the dHvA effect,[2] are given in Table II for the principal crystallographic directions.

TABLE II

Magnetic field orientation	Thermopower osccillation frequencies, 10^{-6} Oe	dHvA oscillation frequencies (sheet $LM\,7h$), 10^{-6} Oe
$\langle 10\bar{1}0\rangle$	1,44±0,03	1,43±0.01
$\langle 10\bar{1}0\rangle$	1,92±0,04	1,93
$\langle 1\bar{2}10\rangle$	1,53±0,03	1,55±0,01
$\langle 1\bar{2}10\rangle$	2,22±0.05	2,24±0,02
$\langle 0001\rangle$	Not observed	2,99±0,02

Comparison of the measured thermopower oscillation frequencies with the results of studying the dHvA effect in osmium[2] shows that they coincide to within an accuracy of 2% with the dHvA α frequencies from the $LM\,7h$ hole ellipsoids, situated between points L and M of the Brillouin zone. The complete correspondence between the anisotropy of thermopower oscillations and of the dHvA frequencies confirms this. The existence of two fundamental frequencies in the spectrum of oscillations on rotating the magnetic field from the $\langle 0001\rangle$ axis to the $\langle 10\bar{1}0\rangle$ andd $\langle 1\bar{2}10\rangle$ axes, and of three on rotating from the $\langle 1\bar{2}10\rangle$ to the $\langle 10\bar{1}0\rangle$ axis, corresponds to the symmetry of the position of the $LM\,7h$ ellipsoids in the Brillouin zone. It should be remarked that only frequencies associated with the $LM\,7h$ sheet were observed in the frequency spectrum of the thermopower oscillations studied.

From the results of studies of magnetothermopower oscillations it can be concluded that they are not of origin. The basis for this is as follows. First, unlike ruthenium, there is no anomaly in the oscillation-amplitude anisotropy, which would indicate the existence of a magnetic-breakdown restructuring of the trajectories. Second, the magnetothermopower oscillation amplitude in osmium is an order of magnitude less for most magnetic field orientations, two orders of magnitude less and for **H** close to the $\langle 1\bar{2}10\rangle$ axis, than in ruthenium[10] at similar values of $\omega\tau$. Third, the observed oscillation frequencies are not produced by the $L\,7h$ lenses (as they are for ruthenium), but correspond to the extremal sections of the $LM\,7h$ hole ellipsoids, which according to Refs. 2 and 4 are considerably remote from the multiply connected $KM\,8h$ hole surface and conseuently cannot take part in magnetic breakdown (see Fig. 8). The magnetothermopower oscillations in osmium can therefore be attributed to the group of oscillatory effects of the Shubnikov–de Haas type.

The absence of thermopower oscillations with frequencies which could be produced by lighter hole carriers on the $L\,7h$ sheet shows that, contrary to calculation,[4] this sheet of the Fermi surface is completely absent. The Fermi surface of osmium in the region of the point L of the Brillouin zone has the geometry shown by the solid line in Fig. 8.

All the measurments made of magnetoresistance, Hall effect, and magnetothermopower, when compared with the results of studies of the de Haas–van Alphen effect,[2] point to the fact that the Fermi surface of osmium, unlike its theoretical construction,[4] does not have open directions along the hexagonal axis and does not contain a $L\,7h$ sheet. Contrary to what is expected, therefore, magnetic breakdown between the 7th and 8th energy zones, similar to the magnetic break-

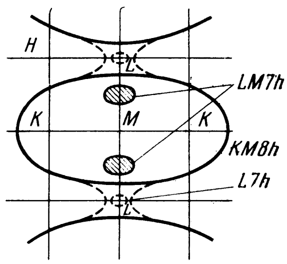

FIG. 8. Section of the Fermi surface of osmium by the *LMK* plane in the neighborhood of point *L*: dashed—Ref. 4, full line—Ref. 2

down in ruthenium, is not possible. Open trajectories of nonomagnetic breakdown origin in osmium come about on the multiply connected *KM* 7*h* hole sheet in the basal plane along the $\langle 10\bar{1}0\rangle$ direction. As regards the closed Γ 10*h* closed hole sheet, which follows from the calculation,[4] neither in the present work nor in that of Kamm and Anderson[2] were quantum oscillations observed to indicate its existence.

Quantum oscillations of magnetothermopower in osmium are not produced by magnetic breakdown, but are analogous to the Shubnikov–de Haas effect in magnetoresistance. Comparison of the results of studying quantum oscillations of magnetothermopower under conditions of magnetic breakdown in the electronic analog of osmium, ruthenium, shows that magnetic breadkown oscillations exceed Shubnikov oscillations by more than an order of magnitude.

The authors thank Yu. P. Gaĭdukov and G. A. Bolotin for discussion of the results, V. A. Sazanova for the x-ray determination of specimen orientation and V. Ya. Raevskiĭ for help in carrying out the analysis of the frequency spectrum of the oscillations.

APPENDIX

We shall indicate the main aspects of the mathematical analysis of the experimental measurements of the $\alpha(H)$ field dependences for determining the frequency spectrum of the quantum thermopower oscillations. Since the experimental $\alpha(H)$ dependences in high magnetic fields (see Figs. 6 and 8) are described by the superposition of a linear ($\alpha_1 = a + bH$) and an oscillatory contribution, the first step in the analysis is the deduction of the monotonic part $\alpha_1(H)$ from the measured $\alpha(H)$, the coefficients a and b of which are determined by least squares. The problem is then to deduce the modulus $I(\omega)$ of a Fourier-type table of results $\alpha - \alpha_1 = f(Z_j)$, where $Z_j = I/H_j$.

According to Moshchalkov,[11] the positions of ω_j for the peaks of the curves

$$I(\omega) = \left| \int_{Z_0}^{Z_N} \exp(i\omega Z) f(Z)\, dZ \right| \tag{A.1]}$$

are related to the extremal frequencies, which are proportional to the extremal sections of the FS. The function $f(Z)$ is specified on some network $\{Z_j\}$ within an error δ, and the interval (Z_0, Z_N) is determined by the experiment itself.

First of all the function $f(Z)$ is determined for all values of Z from (Z_0, Z_N) by quadratic interpolation, so that the integral of Eq. (A.1) is evaluated analytically. The accuracy of the interpolation is estimated from mathematical experiments with an analytical function $F(Z)$, close to $f(Z)$, and amounts to about 1–2%.

For deducing the reliability in determining the frequencies ω_j, mathematical trials with the functions

$$F(Z_j) = f(Z_j) + \delta\theta(Z_j),$$

were used, where $\theta(Z_j)$ are random numbers from the range $(-1, 1)$, and values from 1 to 8 were taken for δ. In addition, the values of Z_N were also varied with $N = 150$, 170, and 200. (The values of ω_j are little sensitive to the value $N \approx 300$.) It turned out that a number of frequencies ω_j behaved rather stably, changing within the limits of 1–2%. It is just to these frequencies that the physical meaning of extremal frequencies is ascribed. Finally, a model function $F(Z)$ close to $f(Z)$ was constructed according to the stable frequencies found and the corresponding intensities, and the whole process, starting with the quadratic interpolation, was applied to this. The final discussion of the reliability in the determination of extremal frequencies is comprised in the results of this experiment.

[1] The first letter in the designation o the sheets indicates the symmetry point of the Brillouin zone on which the sheet is centered (two letters give the direction in the zone), the number corresponds to the number of the energy band to which the given sheet belongs, the letters *e* and *h* characterize respectively an electro and hole type of sheet.

[2] A similar effect occurs in ruthenium: its influence on the falvanomagnetic properties has been discussed.[1]

[3] The oscillation amplitude at $H \approx 80$ kOe for specimens with this orientatio is about 4%.

---

[1] V. E. Startsev, A. V. Cherepanov, V. P. Dyakina, N. V. Volkenshteĭn, G. P. Kovtun, V. A. Elenskiĭ, and V. M. Azhazha, Zh. Eksp. Teor. Fiz. **77**, 193 (1979) [Sov. Phys. JETP **50**, 98 (1979)].

[2] G. H. Kamm and J. R. Anderson, Phys. Rev. **B2**, 2944 (1970).

[3] N. V. Volkenshteĭn, V. P. Dyakina, V. V. Dyakin, V. E. Startsev, V. I. Cherepanov, V. M. Azhazha, G. P> Kovtun, andd V. A. Elenskiĭ, Fiz. Nizk. Temp. **7**, 1156 (1981) [Sov. J. Low. Temp. Phys. **7**, 561 (1981)].

[4] O. Jepson, O. K. Andersen, and A. R. Makintosh, Phys. Rev. **B12**, 3083 (1975).

[5] N. E. Alekseevskiĭ, A. V. Dubrovin, G. É. Karstens, and N. I. Mikhaĭlov, Zh. Eksp. Teor. Fiz. **54**, 350 (1968) [Sov. Phys. JETP **27**, 188 (1968)].

[6] N. V. Volkensteĭn, V. E. Startsev, and A. N. Cherepanov, Pis'ma Zh. Eksp. Teor. Fiz. **31**, 678 (1980) [JETP Lett. **31**, 639 (1980)].

[7] V. M. Azhazha, G. P. Kovtun, and V. I. Makarov, Izv. Akad. Nauk SSSR Met. No. 6, 165 (1976).

[8] N. E. Alekseevskiĭ, K. H. Bertel, V. I. Nizhankovskiĭ, M. Glin'skiĭ and G. Fuchs, Zh. Eksp. Teor. Fiz. **73**, 700 (1977) [Sov. Phys. JETP **46**, 366 (1977)].

[9] Yu. A. Bychkov, L. É. Gurevich, and G. M. Nedlin, Zh. Eksp. Teor. Fiz. **37**, 534 (1959) [Sov. Phys. JETP **10**, 377 (1960)].

[10] V. E. Startsev, A. N. Cherepanov, V. P. Dyakina, N. V. Volkensteĭn, G. P. Kovtun, V. A. Elenskiĭ, and V. M. Azhazha, Fiz. Met. Metalloved. **48**, 780 (1979) [Phys. Met. and Metallogr. (GB) **48**, No. 4, 91 (1979)].

[11] V. V. Moshchalkov, Izv. Vyssh. Uchebn. Zaved. Fiz. No. 1, 58 (1978).

Translated by R. Berman