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TOPOLOGY OF FERMI SURFACES OF METALS (Reference Table)

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THE last fifteen years have seen exceptionally rapid progress in experimental methods of investigating the electronic properties of metals. Greatest attention has been paid in the experiments of these years to the energy spectrum of the conduction electrons of the metals - to the dependence of the energy of the electrons on their quasi-momentum $\epsilon = \epsilon(p)$.

One of the most important concepts of model electronic theory of metals is the "Fermi surface" ($\epsilon(p) = \epsilon_F = \text{const}$). The Fermi surface separates the states occupied by electrons from the free ones in quasi-momentum space. Knowledge of the geometry of the Fermi surface and its characteristics makes it possible to explain many macroscopic properties of a metal, for example the electric resistance in a magnetic field. On the other hand, an investigation of various properties of the metal makes it possible in turn to reconstruct the Fermi surface of the metal. Thus, most quantum effects contain quantitative information concerning the areas of the extremal sections of the Fermi surface, cyclotron resonance yields information on the effective masses of the electrons and the velocities on the Fermi surface, absorption of ultrasound in a magnetic field and the radio-frequency size effects make it possible to determine linear dimensions of the cross sections of the Fermi surface, etc.

By now, the Fermi surfaces of most metals have been investigated in sufficient detail. In particular, it is known whether this surface is closed or open, and the topological types of open Fermi surfaces have been determined. The dimensions of the Fermi surfaces of most metals have also been determined.

These data were obtained not only because of the development of the experimental methods, but also because of the development of theoretical concepts in this field of solid-state physics. The summaries of the theoretical and experimental investigations of the energy spectrum of metals were contained in the reviews of I. M. Lifshitz and M. I. Kaganov (Usp. Fiz. Nauk 69, 419 (1959); 78, 411 (1962); 87, 389 (1965) [Sov. Phys.-Usp. 2, 831 (1960); 5, 878 (1963); 8, 805 (1967)], M. Ya. Azbel' (Usp. Fiz. Nauk 98, 601 (1969) [Sov. Phys.-Usp. 12, 507 (1970)], and J. N. Ziman (Contemp. Phys. 3, 241 (1962); 3, 301 (1962); 3, 321 (1962); 4, 1 (1963); 4, 81 (1963)).

In these reviews, the experimental material served only as an illustration of the theory. The reviews contain no references to the majority of the original experimental and theoretical papers.

The present paper partly fills these gaps. In essence, it is by way of an appendix to the reviews of I. M. Lifshitz, M. I. Kaganov, M. Ya. Azbel', and J. N. Ziman, and yields most general information concerning the topology of the Fermi surfaces of metals and intermetallic compounds. This information has been obtained mostly from galvanomagnetic effects.

The article contains a table, diagrams of the main types of open Fermi surfaces observed experimentally,

Metal	Crystal lattice	Topological type and other information on the Fermi surface	Method of Fermi surface investigation						Remarks
			Galvanomagnetic effects	de Haas-van Alfven and Shubnikov–de Haas effects	Cyclotron resonance	Magnetoacoustic effect	Radio-frequency size effect	Calculation of the band structure and comparison with experiment	
Aluminum	FCC	$n_1 \neq n_2$; H < 30 kOe, closed; H > 30 kOe, magnetic breakdown.	1–4	5–8	9–13	14–17	18	19–21, 324	[314] (ASE)
Beryllium	HCP	$n_1 = n_2$, H < 50 kOe, closed; H > 50 kOe, magnetic breakdown in the basal plane, open; flat grid of corrugated cylinders along the axes ⟨1210⟩ and ⟨1010⟩.	23	23				24–26	[318, 319] (PA) (Fig. 1)
Vanadium	BCC	$n_1 \neq n_2$, open (?)	27, 28					29	In [27] it is found that the Fermi surface is closed
Bismuth	Rhombohedral	$n_1 = n_2$, closed	30	31–36	37, 38	39–42	43, 44	45–47	[315] (PA)
Tungsten	BCC	$n_1 = n_2$, closed	47, 48	49, 50	51, 52		53	29, 54	
Gadolinium	HCP							55–57	[320] (PA)
Gallium	Orthorhombic	$n_1 = n_2$, open corrugated cylinder along the c axis	58–60	61	62, 63	64	65	66, 325	
Graphite		Closed, self-intersection		67, 68	69, 70			71	
Iron	BCC	$n_1 = n_2$, open three-dimensional grid of corrugated cylinders along the axes ⟨001⟩	72–74	74				75–77	[321] (PA) (Fig. 2)
Gold	FCC	n_1 = 1 electron/atom, n_2 = 0, open three-dimensional grid of corrugated cylinders along the axes ⟨111⟩ (principal open direction) and the axes ⟨110⟩ and ⟨100⟩ (secondary open directional)	78, 79	80–82	83	84, 85		86, 326, 327	(Fig. 3)
Indium	Tetragonal	$n_1 = n_2$, closed	4, 87–89	90–92	93	94, 95	96	93, 97	

Metal	Crystal lattice	Topological type and other information on the Fermi surface	Method of Fermi surface investigation: Galvanomagnetic effects	de Haas-van Alfven and Shubnikov–de Haas effects	Cyclotron resonance	Magnetoacoustic effect	Radio-frequency size effect	Calculation of the band structure and comparison with experiment	Remarks
Ytterbium	FCC	Closed	98	99					In accordance with the model of free electrons, the Fermi surface should be open
Yttrium	HCP	Open (calculation						100, 101	
Cadmium	HCP	$n_1 = n_2$, open corrugated cylinder along the [0001] axis	102, 103	104–106	107, 108	109–112	113–117	118, 119	(Fig. 4)
Potassium	BCC	$n_1 = 1$ electron/atom, $n_2 = 0$; $H < 50$ kOe, closed sphere; $H > 50$ kOe, magnetic breakdown, open	120–122	123	124	125–128	129, 130	131–133, 328	
Calcium	FCC	Open (calculation), similar to the Fermi surface of lead		134				135, 329	
Cobalt	FCC							77	
Lithium	BCC	$n_1 \neq n_2$; closed	120					131, 132	
Magnesium	HCP	$n_1 = n_2$; $H > 5$ kOe, magnetic breakdown in the (0001) plane, open; flat grid of corrugated cylinders along the axes $\langle 1\bar{2}10\rangle$ and $\langle 10\bar{1}0\rangle$; *$H > 70$ kOe, magnetic* breakdown, open directions occur along the [0001] axis	136, 137	138–141	142	143–144		145–147	311 (ASE) (Fig. 1)
Copper	FCC	$n_1 = 1$ electron/atom, $n_2 = 0$; open; three-dimensional grid of corrugated cylinders along the $\langle 111\rangle$ axes, similar to the Fermi surface of gold	148–151	80, 82, 152–154	155, 156	85, 157, 158		86, 159, 326, 327	316 (ASE) (Fig. 3)
Molybdenum	BCC	$n_1 = n_2$; closed	47, 48, 160	49, 161	162	163, 164	165	166, 167	
Arsenic	Rhombohedral	$n_1 = n_2$, closed	168, 330	169–171, 336	172	173, 174		46, 175–177	
Sodium	BCC	$n_1 = 1$ electron/atom, $n_2 = 0$; closed	120, 178	179	124			131, 132, 328	
Nickel	FCC	$n_1 = n_2$; closed, three-dimensional grid of corrugated cylinders along the $\langle 111\rangle$ axes, similar to the Fermi surfaces of gold	180	181–184				185, 186	(Fig. 3)
Niobium	BCC	$n_1 \neq n_2$; magnetic breakdown, open; grid of corrugated cylinders along the axes $\langle 001\rangle$, $\langle 110\rangle$, and $\langle 111\rangle$	187–189	190				29, 187	(Fig. 5)
Tin	Tetragonal	$n_1 = n_2$; open; plane grid of corrugated cylinders along the axes $\langle 010\rangle$ and $\langle 110\rangle$; $H > 50$ kOe, magnetic breakdown	191–193	194–197	198–200	201	202, 203	196, 204, 205	317 (ASE) (Fig. 6) (see also figures in [196] and [197]).
Osmium	HCP	$n_1 = n_2$; closed; plane grid of corrugated cylinders parallel to the (0001) plane and to the [0001] *axis, magnetic breakdown*	206						
Palladium	FCC	$n_1 = n_2$; open; three-dimensional grid of corrugated cylinders along the $\langle 001\rangle$ axes	207	208–210				211, 331	(Fig. 7)
Platinum	FCC	$n_1 = n_2$; *open; three-dimensional* grid of corrugated cylinders along the $\langle 001\rangle$ axes; similar to the Fermi surface of palladium	136, 212	213–215		216		217	(Fig. 7)
Rhenium	HCP	$n_1 = n_2$; *$H < 30$ kOe, open:* corrugated cylinder along the [0001] axis; $H > 30$ kOe, magnetic breakdown, additional open directions appear along the axes [0001] and $[10\bar{1}0]$	218, 219	190, 220		221, 222		222, 223	(Fig. 8)
Rhodium	FCC	Closed (calculation		224, 225				224	
Mercury	Rhombohedral	$n_1 = n_2$; open, open directions parallel to the axes $\langle 100\rangle$ and $\langle 011\rangle$	226–228	229	230			231	322 (PA) (Fig. 9)
Rubidium	BCC	$n_1 = 1$ electron/atom, $n_2 = 0$; closed, sphere		123, 232				131–133, 328	
Ruthenium	HCP			233				233	
Lead	FCC	$n_1 = n_2$; open: three dimensional grid of corrugated cylinders along the $\langle 111\rangle$ axes	234, 235, 332	236–238	239, 240	95, 241		242, 243	(Fig. 10)
Silver	FCC	$n_1 = 1$ electron/atom, $n_2 = 0$; open; three-dimensional grid of corrugated cylinders along the [111] axes, similar to the Fermi surface of gold	244, 245	80, 82, 246	247	85, 248		86, 87, 249, 250, 327, 333	(Fig. 3)
Scandium	Polymorphic FCC, HCP	$n_1 \neq n_2$, closed	251					101, 252	According to calculation, the Fermi surface should be open
Strontium	Polymorphic	Open (calculation)						253	
Antimony	Rhombohedral	$n_1 = n_2$; closed	254	255–260	261	262–266		46, 267	
Thallium	HCP	$n_1 \neq n_2$; open; two corrugated planes (0001) connected by narrow necks along the [0001] axis; $H > 30$ kOe, magnetic breakdown	102, 268, 269, 270	271		272–274		275	(Fig. 11)

Metal	Crystal lattice	Topological type and other information on the Fermi surface	Method of Fermi surface investigation						Remarks
			Galvanomagnetic effects	de Haas-van Alfven and Shubnikov–de Haas effects	Cyclotron resonance	Magnetoacoustic effect	Radio-frequency size effect	Calculation of the band structure and comparison with experiment	
Tantalum	BCC	$n_1 \neq n_2$; magnetic breakdown, open; three-dimensional grid of corrugated cylinders along the ⟨001⟩ axes, similar to the Fermi surface of niobium	187	190, 276 277	278			29	(Fig. 5)
Titanium	HCP	$n_1 = n_2$; closed	279					101	According to calculation, the Fermi surface should be open
Thorium	Polymorphic			280, 281				282	
Chromium	BCC	$n_1 = n_2$; $H > 60$ kOe, magnetic breakdown, open	279, 283	284–286		287, 288		167, 289	(Fig. 12)
Cesium	BCC	$n_1 = 1$ electron/atom, $n_2 = 0$; closed, sphere		123, 290, 291				131, 132, 291	
Zinc	HCP	$n_1 = n_2$; $H < 2.5$ kOe, open; corrugated cylinder along the {0001} axis; $H > 2.5 >$ kOe; magnetic breakdown, open directions appear along the axes ⟨$1\bar{2}10$⟩ and ⟨$10\bar{1}0$⟩	102, 292–294	31, 295–297	298–301	111, 112 302–304		118, 119, 305	(Fig. 13)
Zirconium	BCC	Open (calculation)		306				307	323 (PA)
AuSn	Hexagonal	Open	308						
$AuAl_2$	FCC	Open, similar in topology to the Fermi surface of gold	309						(Fig. 3)
AgZn, CuZn PdIn	β-brass	Open (calculation)		310				311	
$AuGa_2$ $AuIn_2$	FCC	Open, analogous in topology to the Fermi surface of gold	309, 334	312				335	(Fig. 3)
$MgZn_2$	Hexagonal			313					

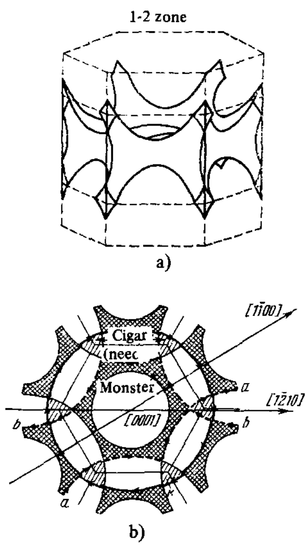

FIG. 1. a) Open Fermi surface ("monster") for beryllium and magnesium (without allowance for the spin-orbit interaction of the electrons) [118]; b) formation of open directions ⟨$1\bar{1}00$⟩ and ⟨$1\bar{2}10$⟩ as a result of magnetic breakdown between two parts of the Fermi surface—the "monster" and the "cigar" ("needle") for beryllium, magnesium, and zinc. The figure shows the section with the plane [0001], aa, and bb are open trajectories along [$1\bar{1}00$] and [$1\bar{2}10$].

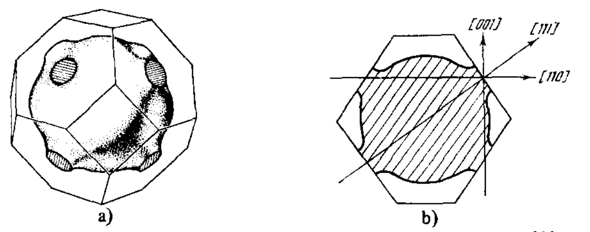

FIG. 3. a) Open Fermi surface of gold, copper, and silver [316]; b) intersection with the plane [110]. The existence of open directions [111], [110], and [001] is seen [244].

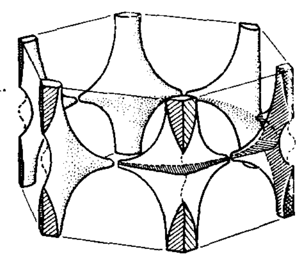

FIG. 4. Open surface of cadmium. There are discontinuities in the basal plane. As a result, no open directions are produced along the ⟨$1\bar{2}10$⟩ and ⟨$1\bar{1}00$⟩ axes (see Fig. 1b) [197].

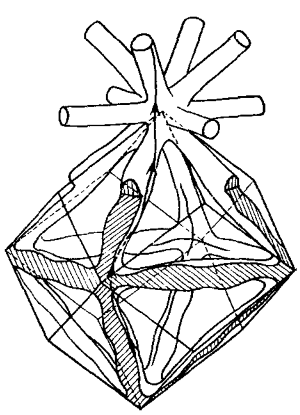

FIG. 2. One of the variants of the open Fermi surface of iron [75]. Curve with arrows—open trajectory along the [001] axis.

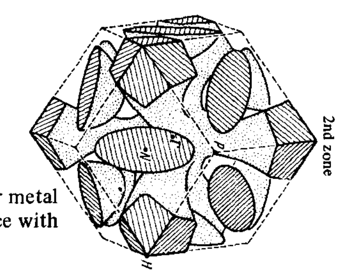

FIG. 5. Open Fermi surface for metal group VB (V, Nb, Ta) in accordance with the calculations of [187].

and a bibliography. Certain figures are drawn schematically and can give only a general idea concerning the topology of the open Fermi surface.

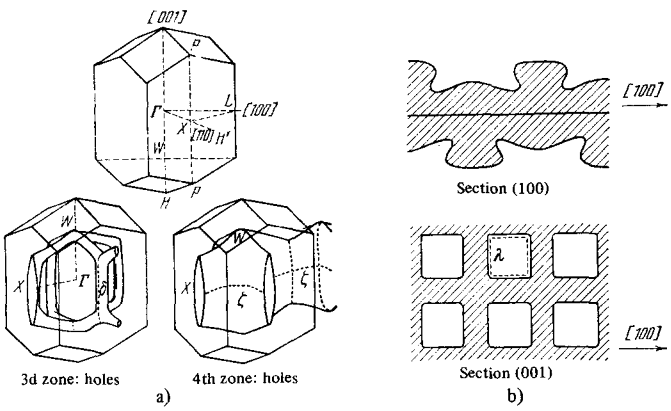

FIG. 6. Open Fermi surfaces for tin in accordance with calculations (their existence was confirmed in [191,194,196,198,202,203]). a) Open hole surfaces in the third and fourth zones [194] (concerning these surfaces see also the figures in [196,197]); b) sections of open electron surface in the fifth zone [205].

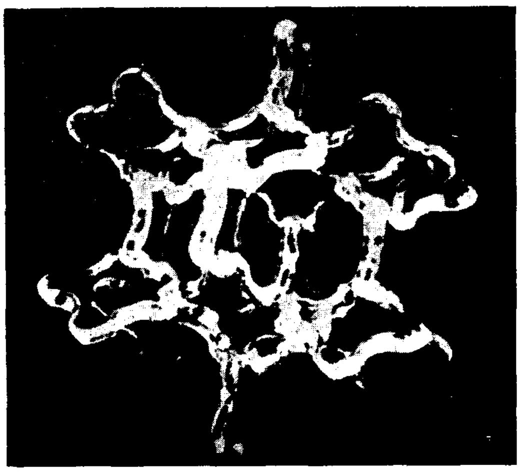

FIG. 7. Model of open Fermi surface of palladium and platinum [212].

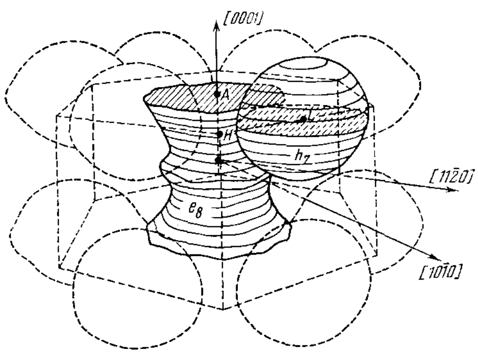

FIG. 8. Fermi surface of rhenium according to calculations [222]. e_8—electron surface open in the direction [0001] (zone 8); h_7—closed hole surface (zone 7). Magnetic breakdown between e_8 and h_7 leads to formation of open directions along the ⟨1100⟩ axes.

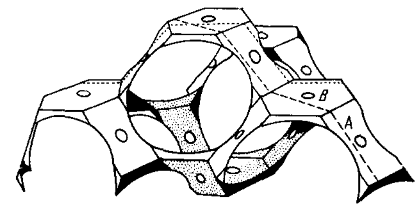

FIG. 9. Open hole Fermi surface of mercury in the first zone in accordance with calculations [231]. Dashed and dotted lines—open trajectories (see also the figures in [230]).

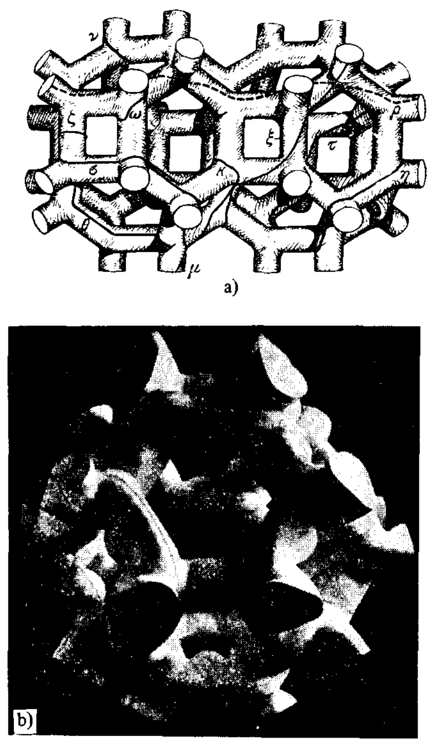

FIG. 10. Open electron Fermi surface of lead (third zone). a) Lines μ and ρ—open trajectories [236,237]; b) the same surface in one reciprocal-lattice cell, performed with conservation of the scale of all dimensions obtained experimentally (M. S. Khaĭkin and R. T. Mina).

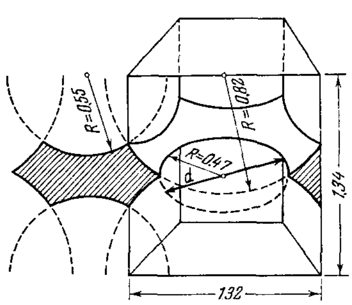

FIG. 11. Intersection of the plane (10$\bar{1}$0) with the open hole Fermi surface of thallium in accordance with the Harrison model [118,102]. According to the experiments, the diameter d is much larger than the calculated diameter: $d_{exp} = 0.1$ (all the values of the dimensions are given in units of $b = 1.16(2\pi/a)$, $a = 3.45$Å).

The table lists: 1) information on the topological type of the Fermi surface, the relation between the number of electrons n_1 and holes n_2, and 2) references to the principal experimental and theoretical papers in which the band structure of the metals and alloys was investigated.

In connection with the discovery of the phenomenon of magnetic breakdown, the concepts of open and closed Fermi surfaces have become arbitrary: in a magnetic field a closed surface may become open and vice-versa. Therefore the table indicates (approxi-

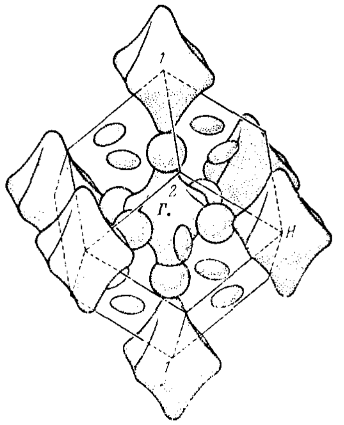

FIG. 12. Fermi surface of metals of the chromium type [29]. The open directions arise along the ⟨001⟩ axis as a result of magnetic breakdown between the closed surfaces 1 and 2.

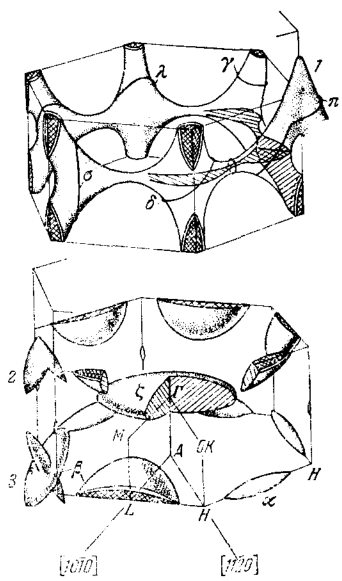

FIG. 13. Schematic representation of the completely determined Fermi surface of zinc [118, 297]. 1—Open hole surface (second zone), unlike Cd, there is no discontinuity in the surface on the basal plane, and therefore magnetic breakdown leads to the formation of open directions along the axes [1$\bar{2}$10] and [1$\bar{1}$00] (see Fig. 1b); 2—closed parts of the surface, located in different zones, with allowance for the magnetic breakdown between the surfaces α and β ("cigar" and "butterfly"); 3—the same without allowance for magnetic breakdown between the "cigar" and the "butterfly."

mately) the value of the magnetic field up to which it can still be assumed that the surface is practically closed or open.

In the appendix there are no references to experimental methods that are either themselves the subject of research or do not give additional information compared with the simpler methods. Nor are there references to the methods that have not gained wide acceptance and with the aid of which only modest information has been obtained so far.

The few investigations of the anomalous skin effect (ASE) and positron annihilation (PA) are placed at the end of the bibliography and corresponding references to them are given in the table in the "Remarks" column. On the whole, although the bibliography is not all inclusive, it represents sufficiently fully the main work done on the investigation of Fermi surfaces of metals.

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