ing to the reciprocity theorem, however, $f_{kk}=f_{-k,-k}$, so that $Z_k=Z_{-k}$ and consequently

$$\int w_{k'k}^{as}\delta(\varepsilon_k-\varepsilon_{k'})dk'+w_k^{p,as}=0. \tag{A.2}$$

If the scattering potential has no bound states, $I_k^r=0$, then (A.2) leads to (13). But if the center has an energy level, then radiative capture of an electron by the level is possible with a probability w_k^r. In this case (A.2) leads to relation (23).

For the model considered in the text (Sec. 2), the additional contribution to the collision integral is due to the quantum-electrodynamic process of virtual emission of a photon by the electron and the transition of the electron to the impurity level, the subsequent absorption of the photon, and the return of the electron to the band.

[1]The latter is determined from the condition.

$$\int (I_k^i-I_k^r)\,dk=0$$

[2]The macroscopic field produced by polarized impurities has no bearing on our problem. It is determined by the boundary conditions and can be set equal to zero.

[3]We note that the symmetric potential (unlike U^{as}) cannot be regarded as small, since it has a bound state.

[4]We assume that the amplitude of scattering by a symmetric potential is of the order of r_0.

[5]The reversal of the sign of the current as a function of the frequency and of the polarization of the light were observed in experiments.[3]

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Magnetic breakdown and thermoelectric power in niobium

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We measured the transverse magnetoresistance and thermoelectric power of a niobium sample with orientation [001] in fields up to 150 kOe. A large thermoelectric-power signal and its oscillations were observed at **H** ∥ [110]. Coherent magnetic breakdown in the region of the conical point contacts located on the Γ*P* symmetry lines, is invoked to explain the results.

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Experimental investigations of the influence of magnetic breakdown on the thermoelectric power of a number of simple metals yielded results that were so highly promising,[1–4] that it was proposed in[2] to use the thermoelectric power to study metals whose Fermi-metal topology impedes the onset of magnetic-breakdown resistance oscillations. This is precisely the situation in niobium, where the magnetic breakdown leads to a transition from open to closed trajectories,[5,6] and according to[7] this transition should not be accompanied by resistance oscillations.

We report here results of an investigation of the thermoelectric power of niobium in strong magnetic fields.

EXPERIMENT

The thermoelectric power and the magnetoresistance were measured on a niobium sample of orientation [001] with a resistance ratio $\rho_{300\,K}/\rho_{res}\approx 3000$. The mounting of the sample is shown in Fig. 1. Copper current leads were spark-welded through small nickel bushings. The potential leads of an alloy 70% Pb + 30% Sn, were spot-welded. The heater, with resistance ~20 Ω was bifilarly wound on a form and fastened with BF-2 adhesive, after which it was slipped over the "hot" end of the sample. To monitor the temperature gradient, a differential Cu–(Au + 0.07% Fe) thermocouple[8] was glued to the sample.

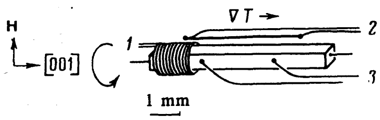

FIG. 1. Mounting of the sample for the measurement of the thermoelectric power and the magnetoresistance: 1—heater, 2—differential thermocouple, 3—potential leads.

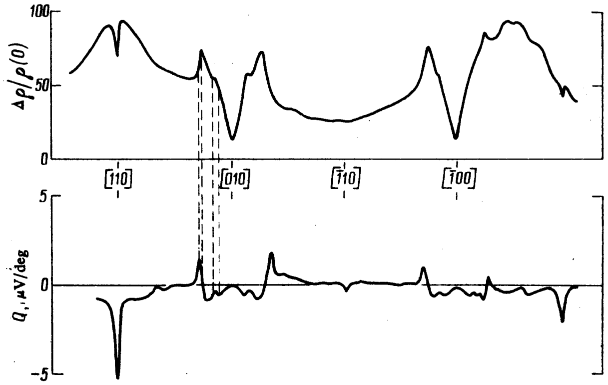

FIG. 2. Angular dependences of the magnetoresistivity ρ and of the thermoelectric power Q of niobium in a field 140 kOe at $T \approx 4.5$ K.

The leads to the sample were cemented into a ribbon and the sample was potted in wax in a paper cartridge (the wax was removed from the "cold" end of the sample), and the cartridge was placed in the unit used to rotate the sample.

Measurements in magnetic fields up to 150 kOe were made in an Intermagnetics superconducting solenoid in the temperature range from 2 to 10 K. The signal from the sample was amplified with an Amplispot photoamplifier

The small loop made up of the potential leads produced a parasitic signal (up to 0.2 μV for rotation in a field of 150 kOe). This signal was eliminated by averaging diagrams plotted with the sample rotated clockwise and counterclockwise.

The thermoelectric power was measured mainly at a heater current 30 mA; the temperature difference between the potential leads was in this case 0.2–0.5 K. It should be noted that when the rotation diagrams of the thermoelectric power were plotted the readings of the control thermocouple were independent of the orientation of the sample relative to the magnetic field.

RESULTS

Figure 2 shows typical angular dependences of the magnetoresistivity and of the thermoelectric power. It is of the form typical of niobium samples of the given orientation: a broad maximum in the [010] direction and a narrow one along [110].[9,10] The fine structure of the broad minimum is connected with the magnetic breakdown.[6]

The singularities of the angular dependence of the thermoelectric power correspond to the singularities of the magnetoresistance: alternating-sign signals near the fourfold axes, as well as narrow peaks are observed against a common almost-zero background when the magnetic field is directed along the binary axis. These signals in a field close to 100 kOe at $T = 4.2$ K are larger by two orders of magnitude than the thermoelectric signal without a field. When the temperature is raised to 10 K no thermoelectric signal was observed in fields up to 150 kOe (the noise was 10 nV), although the angular

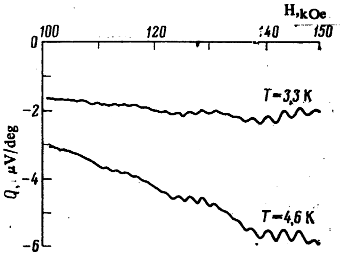

FIG. 3. Oscillations of the thermoelectric power of niobium at **H** ∥ [110].

singularities of the magnetoresistance still remained clearly pronounced.

The thermoelectric signal was as a rule more strongly dependent than the magnetoresistance on the magnetic field strength. At magnetic field directions other than the binary, this dependence can be represented by a power-law function with exponent 2.5–3. If the magnetic field is directed along the binary axis, then in fields stronger than 100 kOe oscillations were superimposed on the monotonic thermoelectric-power curve; the relative amplitude of the oscillations increased with decreasing temperature (Fig. 3). These oscillations have components with frequencies $F = (7.59 \pm 0.05) \cdot 10^6$ G and $f = (1.06 \pm 0.15) \cdot 10^6$ G. The component with the difference frequency $F - f$ has likewise a noticeable amplitude.

DISCUSSION

In the investigation of the thermoelectric power of niobium it could be assumed that its anomalies would correspond to the additional magnetic-breakdown resistance minima located near the fourfold axes.[6] The thermoelectric signal for these magnetic-field directions turned out to be, however, quite small (Fig. 2).

To the contrary, an unexpectedly large and narrow peak of the thermoelectric power was observed for the binary direction. Some time ago the minimum of the magnetoresistance in this direction was attributed[9] to the presence of two mutually perpendicular nonintersect-

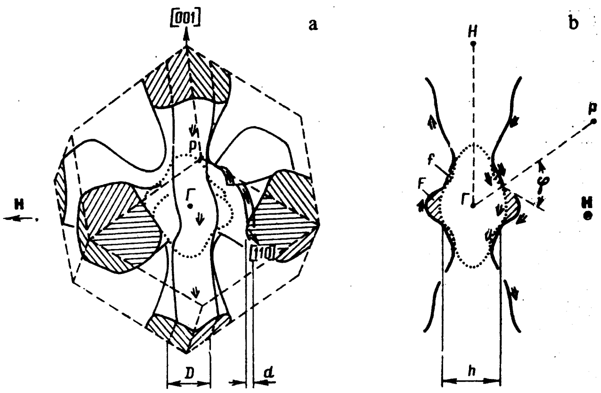

FIG. 4. a) Spatial arrangement of the layers of trajectories that are open along [001] (double arrows) and along [110] (single arrows). The points show the octahedron. b) Open trajectories of the central section (solid lines) and closed trajectories over the octahedron, when the field is directed along the binary axis.

ing layers of open trajectories; one layer is open along [001], and the other along [110] (Fig. 4a). The thickness of the first layer is determined by the diameter of the neck of the open multiply connected surface $D \approx 0.21$ ΓH, the thickness of the second is $d \approx 0.07$ ΓH[10] (ΓH is the distance between the center and the top of the Brillouin zone).

In this treatment the angular dimension θ of the singularity is determined by the range of angles in which the trajectories can still be regarded as open. When the sample is rotated around the [001] axis the trajectories that are open along the [110] direction become elongated, and the angular dimension of the singularity can be obtained from the condition that the electron traverse the produced elongated trajectory once. According to[10],

$$\theta_1 \approx (c\hbar/eH)(d/2l),$$

where l is the mean free path.

This relation contradicts the experimental facts both qualitatively and quantitatively. First, the half-width of the minimum of the magnetoresistance does not decrease with increasing field; second, for our sample we have $l = \langle l\rho \rangle / \rho_{res} \approx 6.2 \times 10^{-4}$ cm and at $H = 140$ kOe we have $\theta_1 \approx 0.3^\circ$, much less than the value $\theta \approx 1.2^\circ$ obtained in the experiment.[1)]

From our point of view, the onset of a magnetoresistance minimum in the binary direction in strong field may may be due to magnetic breakdown for trajectories that are open along [001]. Indeed, according to the nonrelativistic Mattheis model[12] the open multiply connected surface of the third zone is in contact with the closed octahedra of the second zone on the necks of the multiply connected surface and along the ΓP symmetry lines (Fig. 4b). The degeneracy on the necks is accidental and is lifted by the spin-orbit interaction. The corresponding breakdown field is $H_0 \approx 280$ kOe.[6]

The degeneracy of the states along ΓP is due to the symmetry (Λ_3), and the spin-orbit interaction should not lift it.[13] If this is so, then the point contacts are conical points of the sheets of the niobium Fermi surface of the second and third bands. The peculiarity of the magnetic breakdown consists in this case of the fact that the breakdown field H_0^* depends on the distance to the conical point, namely: on the central section the electron trajectories of different zones touch each other and $H_0^* = 0$, while on sections located at a distance k_z from the central section ($\mathbf{H} \parallel z$) we have

$$H_0^* = (\pi\hbar c/e \operatorname{tg} \varphi) k_z^2$$

(the angle φ is indicated in Fig. 4b).

All the trajectories that are open along [001] pass through the necks of the multiply connected surface; magnetic breakdown on the octahedrons with formation of closed trajectories has in this case a probability that is determined by the breakdown field $H_0 \approx 280$ kOe. For sections close to the central one, an important role is played by the presence of point contacts, and for these the probability of formation of closed trajectories is much higher. Therefore the angular dimension of the singularity is determined by the thickness of the central layer, in which $H_0^* \leq H_0$:

$$\theta_2 \approx \frac{k_z(H_0)}{h} = \frac{1}{h}\left(\frac{eH_0 \operatorname{tg} \varphi}{\pi\hbar c}\right)^{1/2},$$

where $h \approx 0.33$ ΓH is the distance between opposite point contacts (Fig. 4b). According to this estimate, the half-width of the minimum of the magnetoresistance θ_2 turns out to be independent of the magnetic field and amounts at $\varphi \approx 60^\circ$ approximately 1.3°, which agrees well with experiment.

The proposed model makes it also possible to explain the oscillations of the thermoelectric power. As seen from Fig. 4b, the directions of motion of the electrons along the multiply connected surface and over the octahedron are identical, and on the necks of the multiply connected surface and in the regions of the conical point contacts the electrons can go over from one sheet of the Fermi surface to another. A similar but simpler situation was considered by Stark and Friedberg.[14] They have shown that if the magnetic breakdown takes place in coherent fashion, then the chain of such orbits move in parallel and are coupled by magnetic breakdown becomes a "quantum interferometer" of sorts, the "base" of which are the sections located between the trajectories (shown shaded in Fig. 4b). The areas of these "base" sections could be estimated from the figure shown in[12]. The corresponding frequencies turned out to equal $F \approx 6 \times 10^6$ G (for a section located between point contacts) and $f \approx 1 \times 10^6$ G (for a section located between a point contact and a neck of a multiply connected surface), which is in reasonable agreement with the experimental values.

We next calculated, by a method similar to that of[14], the possible spectral composition of the oscillations. It turned out that the oscillations can contain components with frequencies

$$F, f, F-f, F+f, 2f, F-2f, F+2f,$$

and their amplitudes are determined by the ratio of the probabilities W_1 and W_2 of magnetic breakdown on the neck and in the region of the point contact, respectively. If W_1 and W_2 are of the same order, then the amplitudes of all the components are also approximately equal. In the experiment, however, there were observed only the first three components, and this is possible only if $W_1 \ll W_2$, i.e., if the contact on the ΓP line is indeed a point contact.

Since there is at present no rigorous theory of the behavior of the thermoelectric power in a magnetic field, it is difficult to offer a nonequivocal explanation of the vanishing of the thermoelectric-power signal when the temperature is raised to 10 K. It should be noted, however, that at this temperature we have even in the strongest fields $\hbar\omega_c \lesssim kT$.

Thus, the experimental facts presented in the present paper favor the assumption that the symmetry-induced degeneracy of the states along the ΓP line in niobium is apparently not lifted by spin-orbit interaction. In the region of the resultant degeneracy of the conical point contacts, magnetic breakdown can account for both the behavior of the magnetoresistance and of the thermoelectric power. If this explanation is valid, then the results above are the first observation of magnetic breakdown of this type.

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Conductivity of disordered one-dimensional metal with half-filled band

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The density correlator, the conductivity, and the dielectric constants are calculated for an impurity-containing one-dimensional metal with half-filled band. If the Fermi level coincides exactly with the center of the band, and the amplitude for forward scattering by an individual impurity is equal to zero, then at zero temperature the localization length is infinite. In the frequency region $T<\omega<1/\tau$ (T is the temperature and τ is the free-path time) the conductivity is constant and the dielectric constant increases with decreasing frequency like $(|\omega|\ln^2|\omega|)^{-1}$. When the Fermi level does not coincide with the center of the band, the static conductivity is equal to zero and the dielectric constant increases in the region $\epsilon<1/\tau$ in proportion to $|\epsilon|^{-1}$, where ϵ is the distance from the Fermi level to the center of the band.

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1. INTRODUCTION

Theoretical investigations of disordered one-dimensional systems have by now reached a level such that many properties of real crystals with one dimensional spectra can be explained.[1] We point out, in particular, the electronic-state localization that leads to the vanishing of static conductivity,[2,3] and to the change in the character of this localization when account is taken of the interaction with the phonons.[4,5] These studies make use of continual models that do not take into account the periodicity of real crystals. Dyson[6] has shown that such a characteristic as the density of states in a one-dimensional disordered harmonic chain has singularities in special points of the Brillouin zone. Analogous singularities should take place also in the electron spectrum. The appearance of a singularity in the state density near the center of the zone was observed by Weissman and Cohan,[7] who considered a model with nondiagonal disorder. As shown by Bush[8] the localization length of such a model becomes infinite when the center of the band is approached.

Gor'kov and Dorokhov[9] considered a model in which impurities with fixed potential were randomly distributed over the sites of a one-dimensional lattice with a period a. In the Born approximation, the potential of an individual impurity is characterized by two amplitudes corresponding to forward and backward scattering. It was shown that the electronic-state density becomes infinite at the center of the band only if the forward scattering amplitude is equal to zero. Gor'kov and Dorokhov had demonstrated the possibility of satisfying this condition using as examples TCNQ salts with asymmetric cations.[1]

The appearance of singularities in the state density and in the localization length should lead to a nontrivial behavior of the kinetic characteristics near the center