MAGNETIC BREAKDOWN IN NIOBIUM IN STRONG MAGNETIC FIELDS

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We investigated the magnetoresistance of ultrapure niobium in fields up to 170 kOe. Magnetic breakdown, leading to a change of open trajectories into closed ones, has been observed. An analysis of the experimental results within the framework of the coherent model yields a breakdown field $H_0 \simeq 280$ kOe.

The Fermi surface of niobium has by now been investigated in sufficient detail both theoretically and experimentally. The first calculations of Mattheiss by the augmented plane wave (APW) method [1] have shown that this surface consists of deformed hole octahedra in the second zone, and that in the third zone there are hole ellipsoids and an open multiply-connected surface. The experimental results on magnetoresistance [2, 3] and also the results on the de Haas and Van Alphen effect [4] have confirmed this model and have made it possible to determine the geometric dimensions of some details of the niobium Fermi surface.

What is still unclear is the question of the distance between the hole octahedra of the second zone and the multiply connected open surface of the third. Theoretical models that do not take into account the spin orbit interaction result in tangency of these surfaces along the peripheries of the necks of the mutliply connected open surface. These tangencies were not observed in experiments.

We have investigated the transverse magnetoresistance of single-crystal niobium samples with different orientations, cut from ultrapure niobium [5]. The resistance ratio $\rho(300)/\rho(0°K)$ of the samples ranged from 2×10^4 to 6×10^4. The investigations were carried out in the helium temperature region in the field of a water-cooled E-150 copper solenoid of our Laboratory. The sample was rotated with a device similar to that described in [6]. The measurements were made in magnetic fields up to 170 kOe.

Figure 1 shows the angular dependences of the magnetoresistance of a niobium sample whose axis made a small angle with the [001] direction. The angular dependences were plotted in the two-dimensional region ofthe open directions (the stereographic projection of the open direction is given in [7]). With increasing field, dips are observed on the angular dependences of the magnetoresistance, located at 7.5° and 10° away from the [100] direction. The field dependences for different magnetic field directions are shown in Fig. 2. If the angle between the magnetic

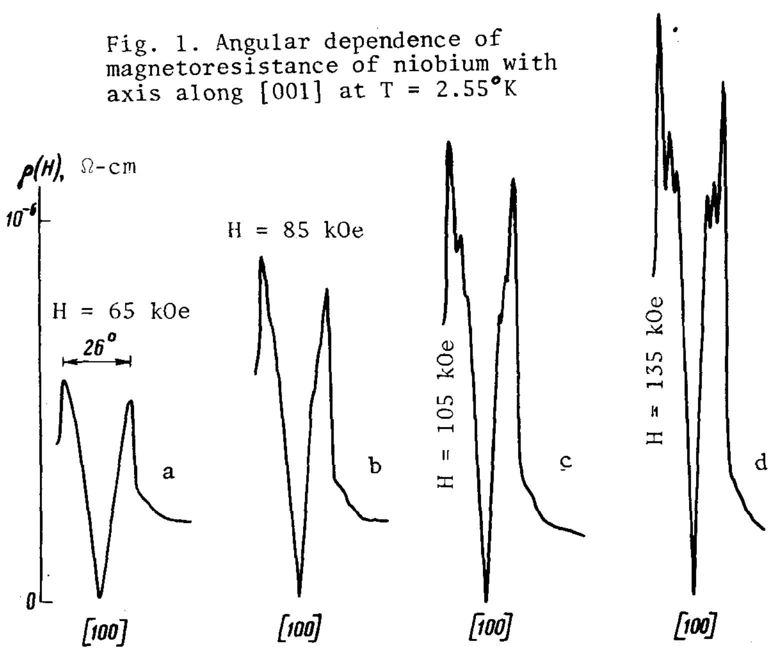

Fig. 1. Angular dependence of magnetoresistance of niobium with axis along [001] at T = 2.55°K

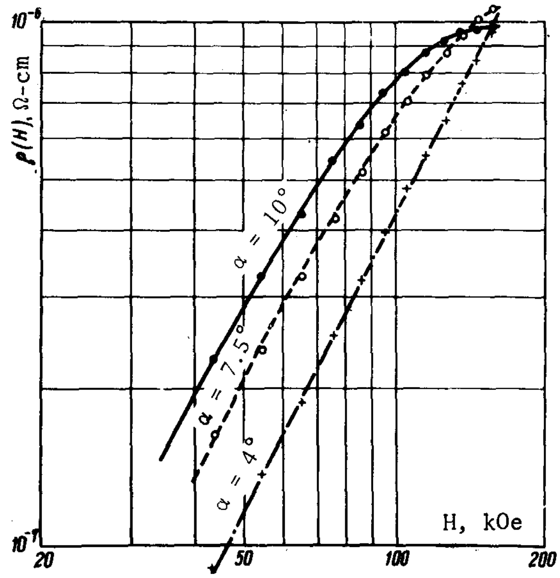

Fig. 2. Magnetoresistance vs.field of niobium along [001] at different angles α between field and [100]

field and the [100] axis is $\alpha < 6°$, then the magnetoresistance depends quadratically on the field; if $\alpha = 7.5°$, then a minimum appears on the $\rho_H(\alpha)$ plot, and a tendency to saturation is observed at this minimum. When $\alpha = 10°$, the magnetoresistance is fully saturated in a field of 155 kOe.

Analogous singularities of the angular dependences were observed for samples with other orientations ([011]; 8° from [001] to [111]; 10° from [011] to [111] in fields exceeding 100 kOe). Lowering the temperature enhanced the singularities, i.e., increased the depths of the minima on the angular dependence diagrams.

The singularities observed by us in the angular dependences of the magnetoresistance of niobium cannot be connected with the formation of elongated trajectories, since only ordinary closed and open trajectories can exist within the two-dimensional region of the open directions. The most probable cause of the observed singularities is the magnetic breakdown between the open multiply-connected surface of the third zone and the hole octahedra of the second.

If this explanation is valid, then we can estimate the breakdown field H_0. To this end it is necessary to analyze the possible electron trajectories. When the angle between the magnetic field and the fourfold axis is $\alpha \geq 7.5°$, there is one closed trajectory (over the octahedron) between two open trajectories (over the multiply-connected surface) with opposite directions. It is obvious that the magnetoresistance is given in this case by $\rho \sim H^2 W_{open}$, where W_{open} is the porbability of electron motion along a given open trajectory without transfering to a trajectory with opposite direction of motion..

Since the samples employed by us were of high perfection [5] (the impurity concentration did not exceed 5 ppm, the dislocation density was less than 10^4 cm^{-2}), it was natural to attempt to find W_{open} by using the coherent model of magnetic breakdown [8]. An estimate based on an analysis of the experimental data yielded for the breakdown field $H_0 \approx 280$ kOe.

From the formula obtained by Blount [9] we can estimate the energy barrier, namely $\Delta \approx 0.09$ eV. It should be noted that this value practically coincides with the spin-orbit interaction energy obtained by a spectroscopy method for the Nb^{+++} ions [10].

This coincidence is quite interesting. It would be desirable to perform similar studies on other metals, particularly vanadium, in which the spin-orbit interaction should be smaller by one order of magnitude. In this case there should probably be either no magnetic breakdown at all, are it should be observed in much weaker fields.

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[1] L. F. Mattheiss, Phys. Rev. 139, A1893 (1965).
[2] N. E. Alekseevskii, K-H. Bertel, A. V. Dubrovin, and G. E. Karstens, ZhETF Pis. Red. 6, 637 (1967) [JETP Lett. 6, 132 (1967)].
[3] E. Fawcett, W. A. Reed, and R. R. Soden, Phys. Rev. 159, 553 (1967).
[4] G. B. Scott and M. Springford, Proc. Roy. Soc. (London), A320, 115 (1970).
[5] I. Bartel, K.-H. Bertel, et al., Fiz. Met. Metallov. 35, 921 (1973).
[6] N. E. Alekseevskii, A. V. Dubrovin, G. E. Karstens, and N. N. Mikhailov, Zh. Eksp. Teor. Fiz. 54, 350(1968) [Sov. Phys.-JETP 27, 188 (1968)].
[7] N. E. Alekseevskii, K.-H. Bertel, and A. V. Dubrovin, ZhETF Pis. Red. 10, 116 (1969) [JETP Lett. 10, 74 (1969)].
[8] A. B. Pippard, Phil. Trans. Roy. Soc. (London), 256, 317 (1964).
[9] E. J. Blount, Phys. Rev. 126, 1636 (1962).
[10] W. Gordy, W. V. Smith, and R. F. Trambarulo, Microwave Spectroscopy, Wiley, 1952.