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STATIC SKIN EFFECT IN SINGLE-CRYSTAL SAMPLES OF CADMIUM

G. A. ZAĬTSEV

Kharkov State University

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THE following are the characteristic properties of the static skin effect [1] in metals with equal numbers of holes and electrons $(n_1 = n_2)$ in a strong oblique magnetic field: the current lines are concentrated near the surface in the case of cylindrical cross sections, or at the vertices in the case of polygonal cross sections of single-crystal samples; the depths of these regions of current concentration are of the order of the electron mean free path l. Obviously such a redistribution of the current density will alter the intrinsic inner $(\mathbf{H}_1)$ and outer $(\mathbf{H}_2)$ magnetic fields, and the phenomenon may be detected and investigated by measuring these fields.

For this purpose we used a ballistic method which is not sensitive to the constant external magnetic field **H** but which is selectively sensitive to the components $\mathbf{H}_1$ and $\mathbf{H}_2$. To detect the redistribution of current over the cross section in cylindrical single-crystal samples of cadmium, an internal cylindrical channel A (Fig. 1) was formed during growth and later a test coil K was placed in it. The plane of the coil windings coincided with the plane of the parallel axes O_1 and O_2 and therefore the ballistic "kick" on switching on the current through the sample was due to the component $\mathbf{H}_1$ perpendicular to O_2. If the current lines were concentrated in the layers I and II, then the change in the magnetic flux which governs the galvanometer kick was $\Delta\Phi = \Delta\Phi_{I} + \Delta\Phi_{II}$, where $\Delta\Phi_{I}$ and $\Delta\Phi_{II}$ are due to the magnetic field in the layers I and II respectively. When $H_1 \ll H$ we may assume that these magnetic fields are axially symmetric with respect to their axes. Therefore $\Delta\Phi_{II} = 0$ and $\Delta\Phi_{I}$ is, in accordance with the theorem on circulation, determined by the magnetic field of the current J_L flowing inside a force line of radius L. Consequently

$$\Delta\Phi = \Delta\Phi_{I} = C2J_L/L,$$

where C is a constant of the measuring circuit. Thus in the presence of the static skin effect we may expect the ballistic kick, $\Delta k \sim \Delta\Phi$, to decrease due to reduction of J_L.

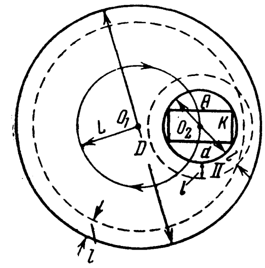

FIG. 1. Cross section of cylindrical cadmium samples Cd1, Cd2, Cd3.

Samples of 9—10 mm length and with D = 5.5—6 mm, d = 1.6 mm and L = 1.5 mm (Fig. 1) were cut from single-crystal cadmium with the resistance ratio $R(4.2°K)/R(293°K) \leq 1.6 \times 10^{-5}$; they were then treated chemically [1)].

The angle between the six-fold axis and the single-crystal axis was determined optically and amounted to ≈ 4°. In order to ensure a uniform distribution of the current density at the ends, the samples were soldered with Wood's alloy to the busbars of a sample holder made of niobium. The induction due to the magnetic field of the supply leads and ponderomotive forces were minimized by the special construction of the sample holder. Since the results of the measurements could have been affected by persistent eddy currents, their absence was checked by indpendent experiments. In all measurements the ballistic kick per unit current through the sample was recorded.

Figure 2 gives the results of measurements,

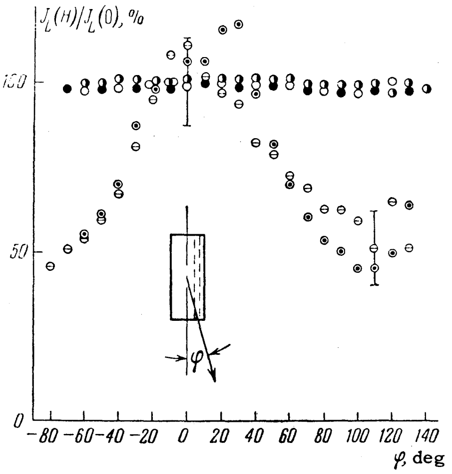

FIG. 2. Dependence of the current in the core of cylindrical cadmium samples on the direction of the external magnetic field: ●) Cd1, T = 78°, H = 1100 Oe, plane O_1O_2 horizontal; ○) Cd1, T = 13.5°K, H = 1100 Oe, plane O_1O_2 horizontal; ◑) Cd1, T = 4.2°K, H = 53 Oe, plane O_1O_2 horizontal; ⊙) Cd2, T = 4.2°K, H = 1100 Oe, plane O_1O_2 vertical; ⊖) Cd3, T = 4.2°K, H = 600 Oe, plane O_1O_2 horizontal.

at various temperatures, of the quantity $J_L(H)/J_L(0)$, which is proportional to the ratio of the corresponding ballistic kicks, as a function of the angle φ between the axis O_1 and the direction of **H**, where $J_L(0)$ is the current J_L at T = 4.2°K in the earth's magnetic field.

At 78 and 13.5°K in fields **H** up to several thousand oersted no redistribution of the current density was observed, while at helium temperature an oblique field of several hundred oersted directed close to $\varphi = 90°$ reduced the ratio $J_L(H)/J_L(0)$ by $\approx 50\%$. The effect was independent of the rotation of the plane containing O_1 and O_2 about the horizontal axis, and was independent of the reversal of the direction of **H** and the magnitude of the current through the sample. The dependence of the ratio $J_L(H)/J_L(0)$ on H at the minimum and maximum is shown in Fig. 3. If it is assumed that the static skin effect begins to appear at $r \approx l^3/D^2$ [1] (where r is the Larmor radius), then the calculated threshold intensity is in good agreement with that deduced from our graph.

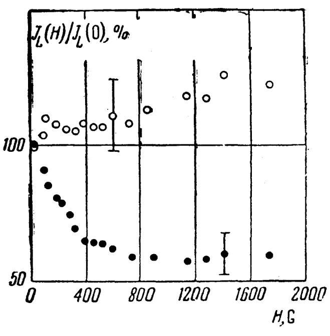

FIG. 3. Dependence of the current in the core of cylindrical cadmium samples on the value of the external magnetic field; Cd3, T = 4.2°K; ○) at a maximum, ●) at a minimum.

The redistribution of the current density is complete in fields of up to 800 Oe and the subsequent constancy of $J_L(H)/J_L(0)$ is due to the large value of $l \approx 3$ mm, [2] which is responsible for the fact that a large fraction of $J_L(0)$ remains inside the force line of radius L. The slight rise of $J_L(H)/J_L(0)$ above 100% at the maximum, which is particularly clear after the niobium busbars of the sample holder lose their superconductivity at H > 800 Oe, is due to the focusing action of the magnetic field on the current lines which are not parallel to the axes O_1 and O_2.

We also measured the field $\mathbf{H}_2$ near a sample which had a "droplike" cross section (Fig. 4).

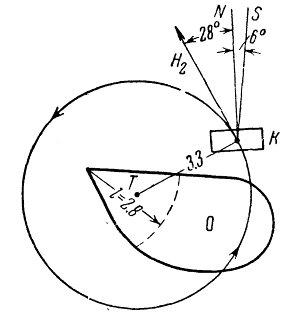

FIG. 4. Cross section of "droplike" Cd4 sample; S is perpendicular to the plane part of the sample surface, N is the normal to the test coil K (dimensions in mm).

When the sample and the coil K were positioned as shown in Fig. 4 and the current was concentrated in the tip of the "drop," the value of $\Delta\Phi(H)/\Delta\Phi(0)$ increased because of the increase of the angle between $\mathbf{H}_2$ and the plane of the coil K; here $\Delta\Phi(0)$ is the change of the magnetic flux of $\mathbf{H}_2$ on switching on the current through the sample at T = 4.2°K in the earth's magnetic field.

The plot of $\Delta\Phi(H)/\Delta\Phi(0)$ against the angle φ between the generators of the sample and **H** (for H = 600 Oe and T = 4.2°K) shows maxima and minima in full accordance with Azbel's theory. The dependence of $\Delta\Phi(H)/\Delta\Phi(0)$ on H at a minimum and a maximum is shown in Fig. 5. It is evi-

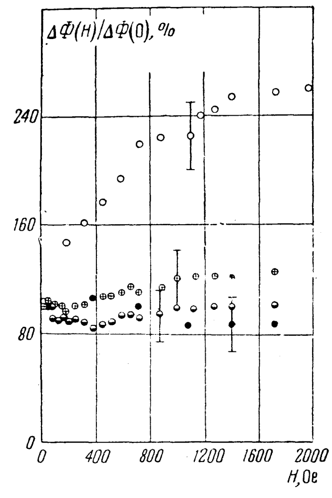

FIG. 5. Dependence of the intrinsic outer magnetic field in the sample Cd4 on H; ○) sample with a smooth surface, maximum; ●) sample with a smooth surface, minimum; ⊕) sample with a rough surface, maximum; ⊖) sample with a rough surface, minimum.

dent that H_2 does not alter greatly at a minimum of the rosette, while at a maximum the value of $\Delta\Phi(H)/\Delta\Phi(0)$ first strongly increases and then tends to saturation. The measured maximum value of H_2 is in good agreement with that calculated for the case of concentration of the current lines in the sector denoted by T in Fig. 4. A random distribution of semicircular grooves (radii 0.5—1 mm), produced by means of a chemical "knife," almost completely destroyed the effect (Fig. 5), indicating the importance of the role of surface quality in the observed phenomenon.

The author expresses his deep gratitude to B. G. Lazarev and V. I. Khotkevich for valuable discussions and M. Ya. Azbel' for his interest in this work.

[1)]The technique of growing single crystals with an inner channel from easily melted metals, and the technique of chemical treatment for reduction to the required dimensions will be reported in a separate communication.

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MEASUREMENT OF THE CROSS SECTION OF THE REACTION $C^{12}(p, pn)C^{11}$ *AT* 9 BeV

B. I. BEKKER, V. S. PANTUEV, V. A. SVIRIDOV, and M. N. KHACHATURYAN

Joint Institute for Nuclear Research

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A determination of the proton flux inside an accelerator is necessary for the performance of many experiments [1]. The reaction $C^{12}(p, pn)C^{11}$ can be used for this purpose. The presently available data on this reaction pertain for the most part to the energy range up to 6 BeV [2-4].

We have measured the cross section of this reaction for 9.0-BeV protons, using $3 \times 3 \times 3$ cm plastic-scintillator plates. The emulsion was placed to the rear of the scintillator. The plastic was exposed together with the emulsion to a spatially-dispersed proton beam inside the accelerator vacuum chamber. The total proton flux was $\sim 2 \times 10^6$ protons/cm^2 and was determined by counting tracks in an emulsion $200\,\mu$ thick. The contribution of the secondary particles in the emulsion was determined by measuring the angular distribution of the beam. Tracks with inclination up to $\pm 45°$ were classified as primary. The estimated contribution of the secondary particles is 1.5%. The corresponding correction, accounting for the protons knocked out of the beam by interactions in the scintillator, is 5.5%.

To estimate the contribution of the secondary particles participating in the production of the C^{11} nuclei, a separate experiment was set up, in which three plastic scintillators in tandem, each measuring $3 \times 3 \times 1$ cm, were exposed to the proton beam. It was found that 16% of the C^{11} nuclei were produced by the secondary particles. The number of C^{11} nuclei produced was determined with the aid of scintillation counters by measuring the β^+ activity of the C^{11} nuclei ($C^{11} \rightarrow \beta^+ + B^{11} + \nu$). The proton-activated sample was placed between two photomultipliers connected for double coincidence with a resolution 10^{-8} sec. The third counter with NaI(Tl) recorded the gamma quanta resulting from the annihilation of the positrons in the scintillator material [5]. The system described made it possible at the same time to measure the β-particle counting efficiency, which was found to be (95 ± 0.5)% in the experiment.

Three exposures yielded cross section values 25.2, 26.1, and 27.2 mb with a statistical error $\Delta\sigma = 1.0$ mb. The systematic measurement error is ~ 4%. Taking all errors into account, the final value is $\sigma = 26.2 \pm 1.5$ mb.

The table lists the cross sections of the $C^{12}(p, pn)C^{11}$ reaction in the BeV energy region.

It is seen from the table that our cross section agrees well with the values obtained by others, and confirms that the cross section of the $C^{12}(p, pn)C^{11}$ reaction is constant in the energy interval from 2 to 28 BeV.

In conclusion, the authors consider it their pleasant duty to thank the scientists M. G. Shafranova and L. Strunov of the High-energy Laboratory for help with the measurement and for useful discussions.

E, BeV	σ, mb	E, BeV	σ, mb
2.0	26.2±0,9[2]	6.0	29.5±1.6[3]
3.0	26,8±1.0[2]	9.0	26.2±1.5 present work
3.0	29.5±1.6[3]		
4.5; 27	27.4±1.4[3]	28.0	25.9±1.2[4]