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# *DISTRIBUTION OF MAGNETIC INDUCTION IN THE INTERMEDIATE STATE OF A CURRENT-CARRYING SUPERCONDUCTOR*

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The distribution of the magnetic field in a slot cut out in the middle part of a tin cylinder carrying a current was measured by the bismuth probe method. The slot was located in a diametral plane of the cylinder. The results obtained are compared with the London and Landau phenomenological theory of the distribution of current density in the intermediate state of a cylindrical superconductor. The existence of a core of intermediate state in a superconducting wire carrying a current above critical is directly demonstrated by the experiments.

INVESTIGATIONS of the breakdown of superconductivity by current are basically devoted to the study of the change of electrical resistivity of a specimen in dependence on temperature and the electric current flowing through it.[1-4] As it appears to us, measurement of the magnetic induction inside a specimen through which an electric current is flowing can also give valuable information on the intermediate state of a superconductor.

In the present work we report the results of measurements of the magnetic induction inside a current-carrying tin specimen 4 mm in diameter and 56 mm long. A $0.2 \times 3.5$ mm rectangular slot was cut in the central portion of the cylinder and situated in a diametral plane (with the long side of the slot parallel to the axis of the specimen). The magnetic field was measured by means of a bismuth probe (Fig. 1), such as is used in the study of the microstructure of magnetic fields.[5,6] The

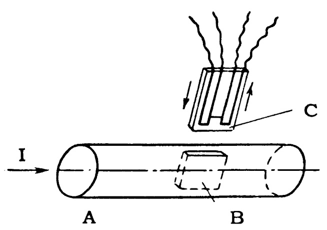


FIG. 1. Diagram of the experiment. A – specimen, B – slot, C – platelet with probe.

probe was a straight segment of bismuth wire 1.5 mm long and 20 $\mu$ in diameter, soldered to thin copper strips which served as potential and current leads. To protect the probe against mechanical disturbances, the copper strips were glued between rectangular mica platelets. The probe was moved along the slot (perpendicular to the axis of the specimen) by means of a mechanism with a micrometer screw. The current was fed to the specimen under test by copper tubes tinned with lead and connected to the specimen by means of special contacts. The electrical resistance of the probe, situated at a known distance from the surface of the specimen, was measured before and after switching on the current in the circuit of the specimen under test. In order to avoid the effect of frozen-in magnetic fields, the specimen was warmed for complete removal of superconductivity before each new measurement. A low resistance type PPTN-1 potentiometer was used to measure the resistance of the probe, the working current of which amounted to 3 ma.

After preliminary compensation of the voltage a FEOU-18 photoelectric amplifier with an automatic recording type EPP-09 potentiometer was connected to the terminals of the probe instead of a galvanometer. The overall voltage sensitivity of the entire apparatus reached $1.3 \times 10^{-9}$ v/mm of the potentiometer scale. The basic measurements were carried out at a temperature of 3.57°K. At this temperature the critical current for our specimen was 23 amp. The resistance of the specimen at 3.8°K was $7.5 \times 10^{-8}$ ohm, and at 293°K it was $3.6 \times 10^{-4}$ ohm.

Before each series of measurements, a calibration of the probe was carried out through the dependence of the magnetic field intensity at the surface of the specimen on the current flowing through the specimen. In order to determine whether or not the method we selected gives correct results, and to measure the edge effect of the slot, measurements of the magnetic induction were carried out along the radius of the specimen at a temperature of 3.80°K, i.e., in the normal state with currents of 23 and 25 amp. The results of the measurements at 23 amp are shown in Fig. 2. For distances of the probe from the surface of the specimen greater than 0.4 mm the experimental points fall on a straight line. Extrapolation of the line to intersection with the axis shows that the presence of the slot decreases the magnetic field intensity at the edge of the slot, on the average, by 11%, while at depths exceeding 0.4 mm the edge effect of the slot is practically unnoticeable. Measurements of the magnetic field intensity outside the specimen showed that it varies, with sufficient accuracy, in inverse proportion to the distance of the probe from the axis of the cylindrical specimen.

The results of the measurements of a current-carrying superconductor in the intermediate state at T = 3.57°K are shown in Fig. 3. Also shown in the figure are results of measurements with currents of 19 and 22 amp. With a current of 19 amp, the specimen is in a superconducting state and the magnetic field in the slot arises from the "lingering" of the external field. The magnetic field intensity decreases rapidly with increasing depth beneath the surface of the specimen, and at a depth of 0.4 mm it is no longer detectable. Results of the measurements with a current of 22 amp demonstrate that a transition from the superconducting into the intermediate state has begun, and that the current is no longer constrained to the surface. Since our specimen is not a single crystal, some electrical resistance is observed at currents somewhat below critical. The relatively large scatter of the experimental points is probably due to the instability of the state of the specimen in the region of its transition from the superconducting to the intermediate state and to changes of the current distribution in the specimen with time.

For comparison with the results of the phenomenological theory of the distribution of current density in the intermediate state of a superconductor,

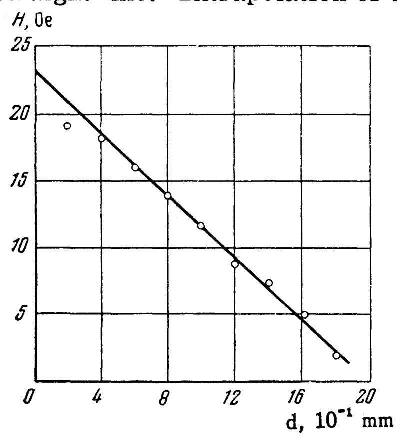


FIG. 2. Dependence of the magnitude of the field inside the slot on distance from the surface of the cylinder; T = 3.80°K.

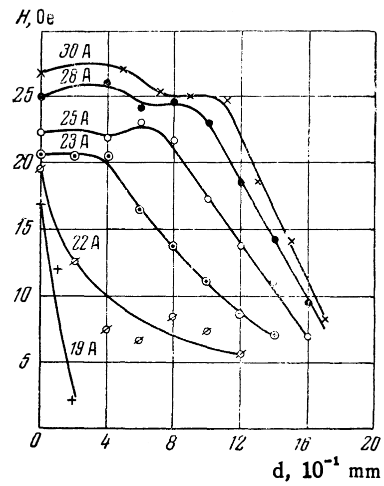


FIG. 3. Dependence of the magnitude of the field inside the slot on distance from the surface of the specimen for different currents in the specimen; T = 3.57°K.

according to London and Landau,[7*] the theoretical curves of the magnetic induction are given in Fig. 4. The slopes of the linear sections of these curves, which determine the quantities $H_c/r_0$ ($H_c$ is the critical magnetic field intensity and $r_0$ is the radius of the core in the intermediate state), agree, within the limits of experimental error, with the results of the experiments. The existence of a core of intermediate state in a superconducting wire carrying current above critical is thus demonstrated by these experiments. Comparing the experimental curves with the theoretical, we must take it into account that, as a result of the edge effect, the magnetic induction measured in the slot close to the surface of the specimen is less than the actual magnetic induction in a specimen. Therefore, although the course of the experimental curves differs from the theoretical ones in the region of the "crust" of normal conductivity, nothing can be concluded about any incompatibility of the measurement results with the theory, since the maximum deviation of the experimental points from the theoretically expected values exceeds only slightly the mean error of the measurements (±4% of the magnitude of the magnetic field measured in this region). A more exact determination of the course of the curves as functions of the current and of the temperature can render more precise our conceptions on the distribution of current over the entire cross section of a conductor in an intermediate state and, besides, can give some indirect information on the shape of the superconducting regions.

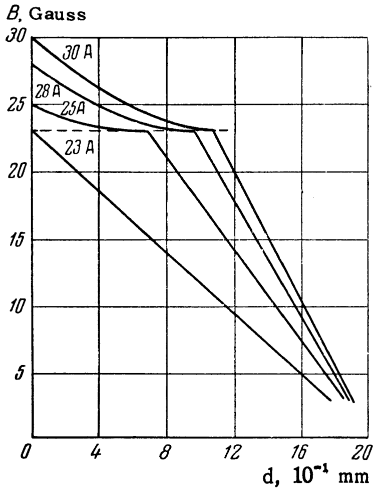


FIG. 4. Dependence of the magnetic induction on distance from the surface of the specimen in the intermediate state, from theoretical data.

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