Observation of the structure of the intermediate state produced in tin cylinders by a current

Ya. S. Kan and V. A. Frolov

Khar'kov Physico-technical Institute, Ukrainian Academy of Sciences
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By measuring the distribution of the magnetic permeability along a current-carrying cylindrical superconductor in the intermediate state we were able to observe directly details of the intermediate-state structure.

The restoration of the electric resistance of superconducting wires by current was first experimentally observed by Shubnikov and Alekseevskiĭ.[1] In the London theory,[2] which explained qualitatively the observed phenomenon, it was assumed that, at a current larger than critical, a cylinder of radius a breaks up into a normally-conducting outer layer ($r_0 < r < a$) and a core ($r < r_0$) consisting of a number of disklike superconducting domains alternating with normal-phase regions. Further numerous investigations of the restoration of the resistivity by current does not contradict this model. The structure of the current-produced intermediate state was investigated more directly by Makeĭ[3] with the aid of a bismuth probe that moved in a narrow slit cut in the diametral plane of the cylinder, in analogy with the procedure first employed by Meshkovskiĭ and Shal'nikov[4] for a sphere. Makeĭ's experiments, as well as those of Rinderer,[5] proved the existence of a core in intermediate states.

It should be noted that even if the London structure is indeed realized it is difficult to observe it with the aid of the known procedures (powder, magnetooptical), inasmuch as a current barely larger than the critical value causes the intermediate state to go off to the interior of the cylinder. There is only one known attempt at directly observing the layered structure on the surface of a cylinder,[6] and there the authors had to "clamp" the core to the surface[5] by a transverse magnetic field, after which it became observable with the aid of powder. Unfortunately, the transverse field (of value $0.2H_c$) distorted the symmetry of the problem and it is doubtful whether the primary structure of the core was preserved. The authors' great success was the establishment of the static character of the structure, which did not confirm Gorter's dynamic model.[7]

Recently Andreev,[8] examing the problem from the microscopic point of view, concluded that the most convenient is a structure intermediate between those of London and Gorter.

We attempted to observe the structure of the current-induced intermediate state in cylindrical superconductors, using a new procedure consisting of measuring the distribution of the magnetic permeability along the cylinder. To this end, measurements were performed of the self-inductance of a short coil that surrounded the sample and moved along it. In the presence of a periodic structure, i.e., of a periodic variation of the magnetic constant, the self-inductance of the coil also would change periodically as a function of the position of the coil on the sample.[1)]

The required coil length could be tentatively estimated from[6], and also from the theoretical papers,[9,10] according to the first of which a period of 2.88 mm should be expected for a cylinder of 5 mm diameter, and according to the second, 3.56 mm. In our experiments, the coil was 0.5 mm long. The gap between the sample and coil was approximately 0.1 mm. The coil could move along the sample and set at the required position with the aid of a micrometric device. The displacement pitch was 0.1–0.2 mm. To verify the procedure, three models of the superconducting part of the London structure with the critical current were prepared from tin, with outside diameter 5 mm and with periods 3.6, 2.4, and 1.2 mm (Fig. 1b shows the model with the period 1.2 mm). Above T_c of tin, the self-inductance of the coil was independent of its position on the model (Fig. 1a, curve 1). Below T_c, the self-inductance, naturally, decreased and was likewise independent of the coil position on the solid part (Fig. 1a, curve 3). When the coil was placed over the threaded part, the self-inductance of the coil varied with the period of the model (Fig. 1a, curve 2).

The investigated sample was a tin single-crystal cylinder[2)] of 5 mm diameter and 70 mm length. That the single crystal was sufficiently pure and perfect could be judged from the fact that the sample's magnetic-permeability jump at the superconducting transition took place

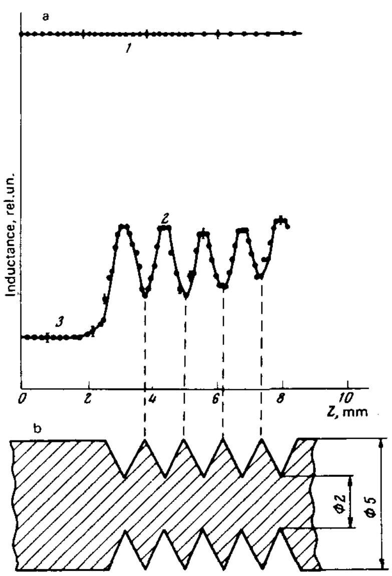

FIG. 1.

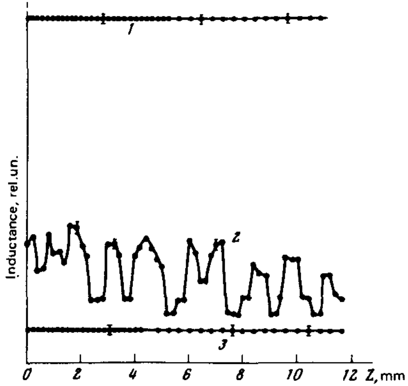

FIG. 2.

in an interval of 1 mK. The sample was mounted on the Dewar vertically. The experiments were performed near T_c ($\Delta T = 13$ mK) at approximate critical currents 2 A. Above T_c and below T_c, at zero current in the sample, the self-inductance of the coil was independent of its position on the sample (Fig. 2, curves 1 and 3). On the other hand, when a current somewhat larger than critical flowed through the sample, then in this case the axial distribution of the magnetic permeability of the sample revealed a rather distinct periodicity (Fig. 2, curve 2) with a period 1.3 ± 0.1 mm, although the structure was not so geometrically regular as in the model. The observed picture was surprisingly well duplicated during the day and even during different days. The character of the curve remained unchanged if the vertical component of the earth's field and the field of the measuring coil were cancelled out. The indicated curves were plotted over different time intervals, from 20 min to 1 h, and the temperature was maintained accurate to 0.5 mK during the experiment, while the current instability in the sample did not exceed 5 mA,

It seems that in the foregoing experiments we were able to observe directly an intermediate-state structure produced by the current in tin cylinders. It turned out to be static and similar to that proposed by London.

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[1)]The procedure of the precision measurements of small inductances will be described later on.
[2)]We are grateful to B. N. Aleksandrov for supplying the single crystal.

[1]L. V. Shubnikov and N. E. Alekseevskiĭ, Zh. Eksp. Teor. Fiz. **6**, 1200 (1936).
[2]F. London, Superfluids, **1**, 120, New York-London, 1950.
[3]B. V. Makeĭ, Zh. Eksp. Teor. Fiz. **34**, 312 (1958) [Sov. Phys.-JETP **7**, 217 (1958)].
[4]A. G. Meshkovskiĭ and A. L. Shal'nikov, Zh. Eksp. Teor. Fiz. **17**, 851 (1947).
[5]L. Rinderer, Helv. Phys. Acta **29**, 339 (1956).
[6]L. Rinderer and F. Haenssler, Helv. Phys. Acta **32**, 320 (1959).
[7]C. J. Gorter, Physica **23**, 45 (1957).
[8]A. F. Andreev, Zh. Eksp. Teor. Fiz. **54**, 1510 (1968) [Sov. Phys.-JETP **27**, 809 (1968)].
[9]C. G. Kuper, Phil. Mag. **43**, 1264 (1952).
[10]D. C. Baird and B. K. Mukherjee, Phys. Rev. Lett. **21**, 996 (1968).