Measurements on the Temperature, Current, Magnetic Field Phase Diagram of Superconductivity

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Experiments have been carried out to investigate the existence of a paramagnetic effect, reported by other workers, at the transition to superconductivity. While, in the other experiments, the induction in the sample was measured during changes of the magnetic field, the work described in the present paper deals with induction measurements at constant values of magnetic field, current, and temperature. The transition region of tin was investigated by separately varying, stepwise, each of these three parameters. With the current of 10 amperes used in our experiments, no paramagnetic effect was observed anywhere in the transition region.

INTRODUCTION

SINCE the discovery, in 1933, by Meissner and Ochsenfeld, that superconductivity is accompanied by zero magnetic induction ($B=0$), it has generally been assumed that, as the metal becomes superconductive, its susceptibility becomes strongly diamagnetic. Numerous experiments in which the temperature or the magnetic field were changed have, indeed, confirmed this view. However, in 1943, Steiner and Schoeneck[1] reported observations indicating a paramagnetic susceptibility which preceded the change to diamagnetism. This effect occurred only when the destruction of superconductivity was carried out simultaneously by a magnetic field in the longitudinal direction and a current in the same direction. It was pointed out by one of us[2] that the observed increase in induction might possibly have been only an apparent one, because only the flux in the longitudinal direction was measured. Similar experiments have recently been performed by Meissner, Schmeissner, and Meissner,[3] who also observed paramagnetic effects of the same nature. In these experiments, the changes of flux were measured which occur in the specimen when the magnetic field was reversed, while at the same time a steady current was passing through the specimen.

Since in all this work the observation of a paramagnetic effect was coupled with a simultaneous variation of one of the variables of state (the magnetic field), it is clearly desirable to investigate whether there actually exist, in the transition, definite values of magnetic field, current, and temperature, for which the susceptibility of a superconductor is paramagnetic. Assuming the validity of Silsbee's hypothesis, a three-dimensional diagram of state can be constructed (Fig. 1), with the temperature, the magnetic field, and the current as dependent variables. The volume inside the T, H, I, surface represents the superconducting state, and that outside represents the normal state. The transition to superconductivity can be effected in three different ways, as is indicated by the arrows. It was decided, therefore, to carry out measurements of the induction in the longitudinal direction of a long cylinder of tin, at fixed values of magnetic field, current, and temperature, in the transition region. The experiments were carried out in such a way that two variables were held constant throughout, while the third one was changed in small steps in the way indicated by the arrows in Fig. 1.

METHOD

The method consists in moving an induction coil along a cylindrical specimen, which is aligned in the direction of a homogeneous magnetic field. The cylinder is made up of rods of copper, tin, and lead, in series, and the coil can be moved from the center of the tin rod to the center of the lead rod or of the copper rod. Since in the transition region of tin (3.7°K) lead is superconductive and copper is nonsuperconductive, the movement of the coil will compare the flux in the tin rod, at constant field, current, and temperature, with the flux through a superconductive or a normal rod of identical dimensions.

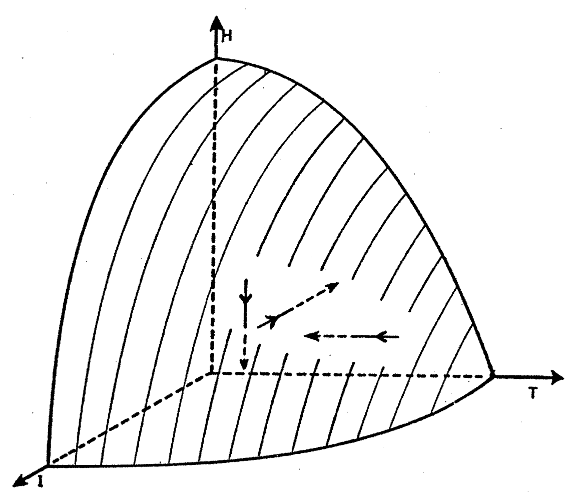

FIG. 1. The T, H, I, surface, separating the normal and the superconducting phases.

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[1] K. Steiner and H. Schoeneck, Physik. Z. 44, 346 (1943).
[2] K. Mendelssohn, Repts. Prog. Phys. 10, 358 (1946) (London: Physical Society).
[3] Meissner, Schmeissner, and Meissner, Z. Physik 130, 521 (1951).

Figure 2 shows the apparatus with the induction coil, C, which is connected to a ballistic galvanometer, so that the deflections of the galvanometer are proportional to the changes of total flux through the coil. The coil moves from one position around the specimen to another.

The specimen, S, consists of lengths of 8 cm each of lead, tin, and copper cylinders, soldered together in series in a thin German silver tube. The diameter of the metal samples is 2.8 mm. The rod is mounted vertically, with the upper end (copper) held in a textolite block, B. The sample holder is suspended from the upper plate, P, by steel and textolite pipes, P_1 and P_2, in series.

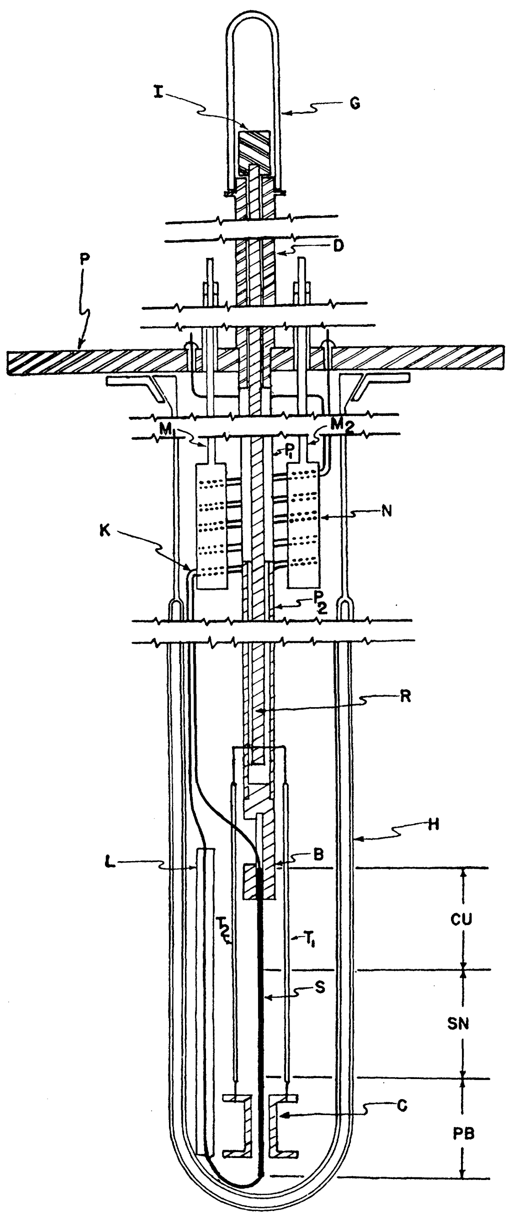

FIG. 2. Schematic cross section of the experimental apparatus (not to scale).

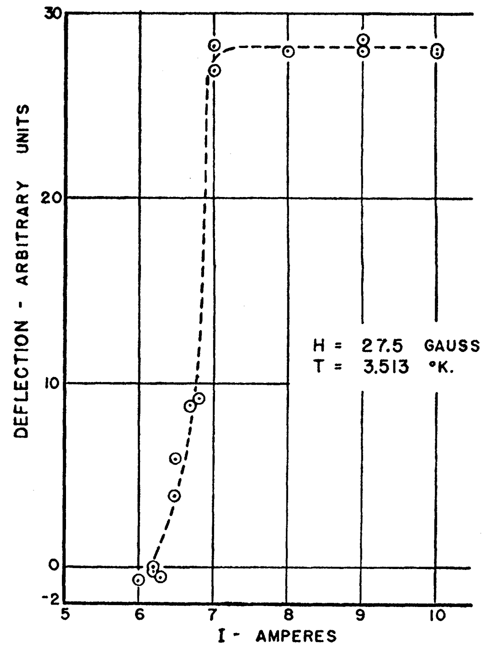

FIG. 3. Penetration of the T, H, I, surface at constant temperature and magnetic field.

The coil is hung by means of two German silver tubes, T_1 and T_2, from a textolite rod, R. The rod R extends up through the pipes P_1 and P_2, and on through the plate and brass tube, D. Above the brass tube, the rod is fastened to an iron cylinder, I. The coil may be raised and lowered by moving the block of iron with a small solenoid placed on the outside of the glass vacuum cover, G.

To reduce heat leaks, a can for liquid nitrogen, N, is hung from the upper plate by two monel pipes, M_1 and M_2. The current carrying wires, K, leading to the sample are thermally connected to the liquid nitrogen can. The top of the copper cylinder is attached to one of the current leads; the return lead is shielded by a superconducting lead tube, so that its magnetic field cannot disturb the field at the specimen.

All of the apparatus shown in Fig. 2 is placed in a flask of liquid helium, H. Outside of this flask, and not shown, is an outer Dewar flask for liquid nitrogen. External to all this is the solenoid for producing vertical magnetic fields. The magnetic field produced by the external solenoid was known to be homogeneous, to within one percent, over the volume of the tin specimen. The temperature was measured and controlled by the vapor pressure of the helium bath, and the bath could be stirred by moving the coil up and down.

RESULTS

The experimental results are shown in Figs. 3, 4, and 5. In each of the figures, two of the three variables,

H, T, and I, were held constant while the third variable was changed in small steps. The abscissa is denoted by the parameter that was varied. The ordinate in the figure is the galvanometer ballistic throw obtained when the coil was taken from the center of the tin rod to the center of the lead rod.

The superconducting state could be destroyed in the tin by a sufficiently large current in the rod, by high enough temperatures, or by a sufficiently large external field. Under these conditions a large galvanometer deflection was obtained. The superconducting state could then be entered as shown by the arrows in the phase diagram of Fig. 1. Under these conditions the galvanometer deflection is reduced to zero, since both the tin and the lead are in the superconducting state. It is clear from the figures that the galvanometer deflection does not at any point increase in the direction of paramagnetism, i.e., showing greater flux in the tin specimen than normal. The scatter of the observed

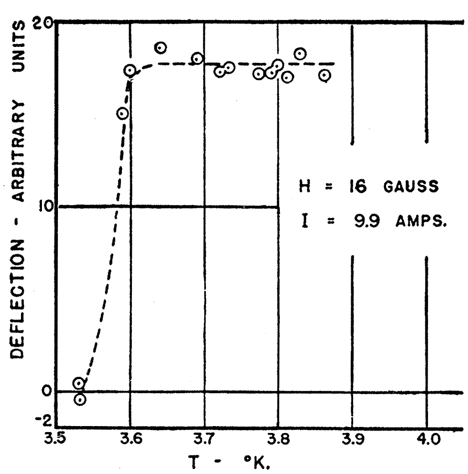

FIG. 4. Penetration of the T, H, I, surface at constant magnetic field and current.

deflections is fully explained by experimental error caused by uneven movement of the induction coil and small shifts in the galvanometer zero.

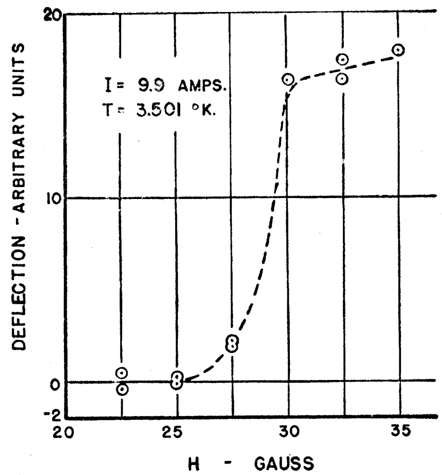

FIG. 5. Penetration of the T, H, I, surface at constant temperature and current.

CONCLUSIONS

Our results leave little doubt that, with the current of 10 amperes used in these experiments, there is no region in the H, T, I, space showing paramagnetic susceptibility. It must be emphasized that our findings are not necessarily in disagreement with the results of Meissner, Schmeissner, and Meissner, because the quantity measured is a different one in the two cases. In their work, the change in the magnetic induction produced by varying the external field is determined, and their observations, therefore, comprise the dynamics of the transition process. Our measurements, on the other hand, were carried out at a series of steady states in the $H-T-I$ space, well after any change in these parameters had taken place. Thus, we must conclude that such paramagnetic effects as have been observed with similar values of the parameters seem to be of a transient nature. They are, as was suggested earlier, possibly due to a re-arrangement of the magnetic flux when, in a cylinder carrying a current, additional currents are inducted in the specimen as it becomes superconducting in an external field.

It is hoped to extend the present work to higher values of the current.