Paramagnetism Observed at the Superconducting Transition

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Measurements have been performed on the paramagnetic effect in superconducting tin. The current minimum, I_0, for the appearance of the paramagnetic effect is represented in the $(I-H-T)$ space by the simultaneous equations $I_0=\xi\gamma d(T_c-T)$ and $H_0=\xi(T_c-T)-I_g/\gamma d$. Here I_g, γ, T_c, and ξ are the characteristic constants of the superconductor and have the values 1.2 amp, 0.23 amp/mm oersted, 3.73°K and 1.1×10^2 oersteds/deg respectively for the case of tin. H_0 and d are the magnetic field in oersteds and the specimen diameter in mm respectively. It has been shown that the formula $I_0=I_g+\gamma dH$ hitherto accepted for the minimum current requirement is the one for the orthogonal projection of the critical line in the $(I-H-T)$ space on the $(I-H)$ plane. It seems that there is a lower limit of specimen diameter for the appearance of the paramagnetic effect, which is 1.3×10^{-2} mm for the case of tin.

MEISSNER *et al.*[1,2] and Teasdale and Rorschach[3] have confirmed the paramagnetic effect first discovered by Steiner and Schoeneck.[4,5] We also investigated the paramagnetic effect, and in particular the question of the existence of hysteresis phenomena in the effect.

Two cylindrical specimens were prepared from Johnson-Matthey spectroscopically pure tin; one specimen is a single crystal of diameter 2.4 mm and length 70 mm, and the other specimen is a polycrystalline specimen of diameter 1.5 mm and length 86 mm.

We employed first the static method, similar to that used by Mendelssohn *et al.*,[6] of dropping an induction coil in a uniform magnetic field from a position 7 cm above the specimen to the center portion. We measured the deflection of a ballistic galvanometer connected to the coil. The deflection is proportional to the change of total flux through the coil. For the study of the intrinsic nature of the paramagnetism, measurements were carried out in such a way that two variables, the longitudinal magnetic field H and the temperature T, were held constant throughout, while the third variable, the current I through the specimen, was changed in small steps. The coil was dropped at each step. The hysteresis measurement consisted in holding I and T constant throughout and reducing H in small steps from the value above H_c to zero, followed by a similar increase in H. At the present stage of the investigation, we can conclude that there is no hysteresis and the effect is quite reversible.

The formula for the minimum current requirement proposed by Steiner[4] and extended by Meissner *et al.*[1] is

$$I_0=I_g+\gamma dH. \tag{1}$$

Here I_g and γ, which are characteristic constants of the superconductor, are 1.2 amp and 0.17 amp/mm oersted respectively for tin, when the specimen diameter d and the magnetic field H are measured in mm and in oersted respectively. According to this formula it seems always possible, irrespective of temperature, to observe the paramagnetism with a current larger than I_0 for a fixed value of H. Actually, however, there is a one-to-one correspondence between H in Eq. (1) and the temperature T. Therefore, the current minimum required for the paramagnetism should be determined as a curve in three-dimensional $(I-H-T)$ space, instead of by Eq. (1). The determination of the current minimum referred to above was carried out by holding T constant throughout, taking I as a parameter, and reversing H; the latter was changed in small steps. In this determination the induction coil was fixed around the center of the specimen, and a compensating coil connected in opposition to the induction coil was placed above the specimen in the region of uniform field. Figure 1 is a typical example of the results; a/b shown in the inset gives the apparent permeability μ, which is a function of H provided I and T are constant. μ^*, which designates the maximum of μ for the fixed values of I and T, has a meaning similar to that of $\tilde{\mu}$ defined by Meissner *et al.*[1] μ^* was plotted against I, and the extrapolation to the abscissa for which $\mu^*=1$ defines the current minimum I_0 at that temperature. In this way the I_0-T relation was obtained. This gives the orthogonal projection of the critical line characterizing the current minimum on the $(I-T)$ plane. In a similar way, we plot μ^* against H to obtain H_0, the magnetic field over which we cannot observe the paramagnetism at a given temperature, by the extrapolation to the abscissa. In this way we obtain the H_0-T relation, which is the projection of the critical line on the $(H-T)$ plane. The critical line was determined as a straight line in the $(I-H-T)$ space from two projections obtained. Figure 2 shows schematically the relations between I_0, H_0, and T for two specimens. The critical lines terminate at the points (I_g, T_g) on the $(I-T)$ plane. Though T_g depends on the specimen diameter, I_g is constant, irrespective

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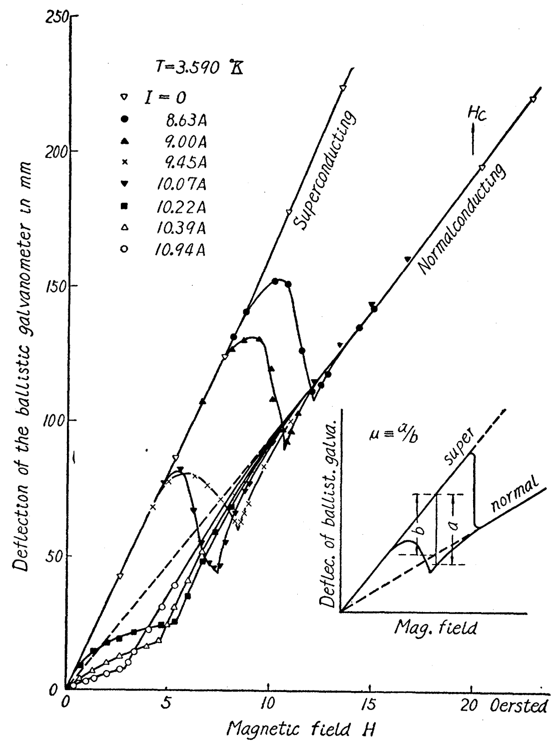

FIG. 1. The deflections of a ballistic galvanometer when the external magnetic field was reversed. a/b shown in the inset gives the apparent permeability μ.

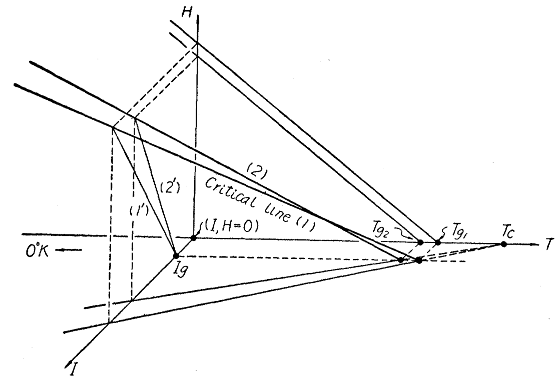

FIG. 2. The minimum of current necessary for the appearance of the paramagnetic effect for two specimens in the three dimensional space. The critical lines (1) and (2) belong to the specimens of diameter 2.4 mm and 1.5 mm respectively. The $(I-H)$ projections (1′) and (2′) of the critical lines are represented well by Eq. (1) in the text.

of the diameter. All the $(I-T)$ projections of the critical lines point to the transition temperature T_c. The $(H-T)$ projections are parallel to each other and T_c-T_g is inversely proportional to d. The critical line is represented in the three-dimensional space by the following simultaneous equations:

$$I_0=\xi\gamma d(T_c-T),\quad H_0=\xi(T_c-T)-I_g/\gamma d. \qquad (2)$$

I_g, γ, T_c, and ξ are the characteristic constants of the superconductor and have the values 1.2 amp, 0.23 amp/mm oersted, 3.73°K, and 1.1×10^2 oersteds/deg respectively for the case of tin. The relation found by Meissner *et al.* corresponds to the one concerning the $(I-H)$ projection of the critical line. Indeed, the projection is represented by Eq. (1) which can be drived from Eq. (2). Though we obtained $\gamma=0.23$ amp/mm oersted instead of 0.17 amp/mm oersted, we verified in the $(I-H-T)$ space that I_g, the minimum current for zero field, was 1.2 amp.

We observed, moreover, the approximately periodic dependence of μ on the magnetic field, apparently similar to the de Haas-van Alphen effect, when measurements were performed in such a way that the magnetic field was changed in smaller steps than usual; for instance, at $I=4.50$ amp and $T=3.697$°K for the case of the specimen of 2.4 mm diameter.

We plotted contour lines for which $\mu=$const in the $(I-H)$ planes at the temperatures studied in order to determine the paramagnetic region in the $(I-H-T)$ space and we obtained closed contour lines at temperatures near T_g. The lines converge with increasing values of μ to the point of finite maximum at finite values of I and H. Finally, although the extension of the I_0-T relation to the absolute zero of temperature would not be permissible, it seems from this extension that there is a lower limit of specimen diameter, d_0, for the appearance of a paramagnetic effect. The limit can be deduced from the equation $I_g=\xi\gamma d_0T_c$. For the case of tin d_0 is 1.3×10^{-2} mm.

Experiments on other superconductors such as mercury and indium are in progress. A detailed report on the experiment described here will appear in a forthcoming issue of Science Report, Research Institute Tohoku University. We would like to express our thanks to Professor T. Fukuroi who gave us facilities for experiments and helpful suggestions.