Observation of fine structure in the paramagnetic effect in superconductors of the first kind

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It has been found that in the case where the paramagnetic effect is due to a combination of magnetic field and electric current such that H_z/H_c is small (~ 0.01), the apparent magnetic permeability μ^* of a specimen in a longitudinal magnetic field oscillates as a function of the current.

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If a cylinder with current I in a longitudinal magnetic field H_z proceeds from a superconducting state into a normal state (or vice versa), the so-called paramagnetic effect (PME) occurs,[1] which is characterized by the apparent magnetic permeability of a specimen in the transition region for a longitudinal field being greater than unity, $\mu^* = \Phi/\pi a^2 H_z$ (Φ is the magnetic flux in a specimen, a is the cylinder radius).

Heretofore, the PME has not been investigated for the case where the determining parameter $\phi = H_z/H_c$ is small (~ 0.01), i.e., when PME occurs in an intermediate state that is basically due to current. We believe that apart from its own value, investigation of PME in this case is also interesting from the standpoint of studying the structure of the intermediate state produced by the current.

To study this kind of PME we chose out of all existing possibilities a superconducting transition achieved due to the effect of variation of current I at $H_z = \text{const}$ and $T = \text{const}$ (T is temperature). In the case of ϕ investigated earlier, the behavior of $\mu^*(I)$ in such transitions is shown schematically in the inset in Fig. 1 (see, e.g., Ref. 2).

A single-crystal tin cylinder (5-mm in diameter, 80-mm long, $\rho_{3.7}/R_{300} = 1.4\times 10^{-3}$) was fed direct current from VS-25 rectifier; moreover, one of the supply lines was a copper tube (30-mm diameter, 120-mm length) along whose axis the specimen was placed (vertically). The longitudinal field $H_z = 0.078$ Oe was set up by a solenoid (80-mm in diameter, 400-mm long) placed on a helium dewar. A double permalloy screen was used to attenuate the magnetic field to not less than 0.01 Oe. The temperature of the helium bath was maintained by means of an automatic pressure regulator with a manual correction to $\pm 3\times 10^{-4}$ K. The experiment was conducted at a temperature lower by 3.6×10^{-2} K than T_c (the specimen resistance jump in the case of a superconducting transition in the absence of current and field in the interval 1.3×10^{-3} K). The critical current I_c at this temperature was 6.5 A, such that $\phi = 0.015$.

The resistance R/R_n of the middle 20-mm section of the specimen (R_n is the normal resistance of a section) and the magnetic flux Φ in the specimen were measured.[3] The Φ pickup was a single-layer lead 1-mm long coil (9 turns) that was wound on a specimen through a thin insulating layer between the potential leads. The

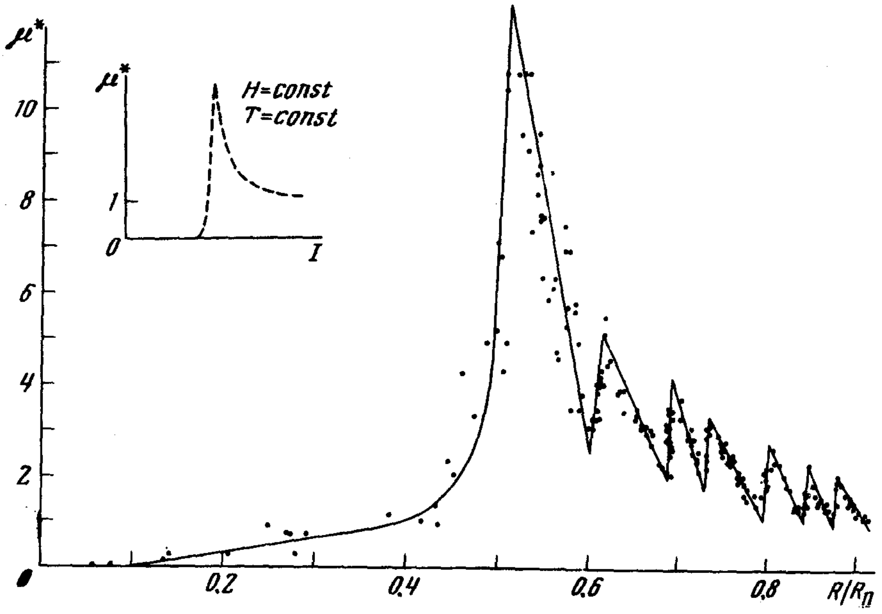

FIG. 1.

measure of flux was the induced curent in the coil as the specimen state changed. This current was measured by using a compensation method (in order to avoid affecting the specimen).1)

Measurements were carried out in the following sequence. Current I was switched in at $H_z = 0$, imparting to the specimen a certain resistance R/R_n that was measured twice in the course of 5–10 sec; the magnetic field was applied between the measurements and Φ was measured.

If the result of the second measurement of resistance coincided with the first, it was assumed that the temperature remained unchanged between the readouts of R/R_n and the measurement was considered to be consistent. Because of temperature fluctuations, approximately one third of all measuring attempts were successful. Temperature instability within the limits of accuracy shown above was also responsible for the fact that the stochastic $\mu^*(R/R_n)$ rather than the causative $\mu^*(I)$ function was measured in the experiment since it was more convenient to compensate temperature drift by small variation in the current amplitude than to expect random restoration of the temperature. To exclude the possible effect of the previous history of the specimen all the data points of the function $\mu^*(R/R_n)$ (Fig. 1) were taken in the same way; for this reason current from the specimen was switched off for several seconds before each measurement (it was dumped into a superconducting shunt). The curve $\mu^*(R/R_n)$ (Fig. 1) was obtained during several days of experimentation with daily thermocycling from 2.4 K to room temperature. It is appropriate to observe that the curve $\mu^*(R/R_n)$ in every respect follows a similar curve obtained six months ago from the same specimen under conditions differing from those described above only by direction of the current.

Using the function (R/R_n) (Fig. 1, solid curve in Fig. 2) we converted all the data

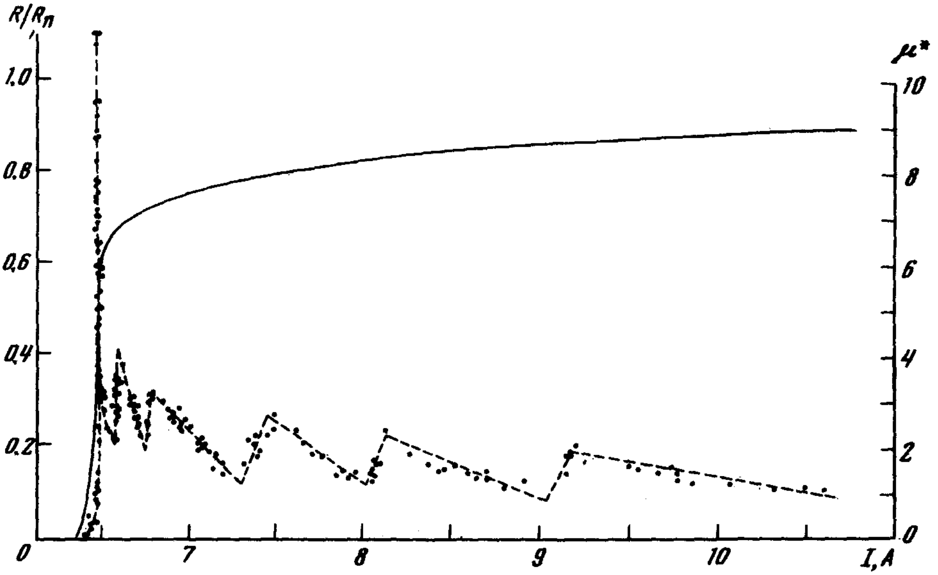

FIG. 2.

points of the experimental function $\mu^*(R/R_n)$ into data points of function $\mu^*(I)$ (Fig. 2, dashed line) that could have been obtained in an experiment with an ideal accuracy of temperature maintenance (not less than $\sim 10^{-4}$ K). We observed, for the first time, that this function is characterized by oscillations. Naturally, there should be as many peaks in the $\mu^*(I)$ curve as there are in the $\mu^*(R/R_n)$ curve, although in the figure there is one less. The point is that the state of a specimen near the critical current varies strongly for small current changes and, in the scale selected, the first two peaks simply cannot be resolved.

Preliminary experiments show that the form of curve $\mu^*(R/R_n)$ and, consequently, $\mu^*(I)$ depends as a rule on the value of ϕ (it changed twice due to H_z).

However, increasing ϕ in the specimen to ~ 0.1 for $I = \text{const}$ caused the occurrence of well-defined time-dependent oscillations in the flux which were independent of temperature oscillations that are probably of the same nature as flux oscillations observed in Ref. 4.

With respect to reasons for which the fine structure of PME has not heretofore been observed, several may be pointed out. First, the stability of the specimen state was possibly given insufficient significance. Second, earlier flux pickups were relatively long coils that would average out Φ in the case where the specimen conditions were for some reason inhomogeneous with respect to length. Lastly, it should be be remembered that the PME with small ϕ has not been studied and, possibly, as ϕ increases there occurs a change in the type of transition from the static, where the intermediate state is almost exclusively due to current, to the dynamic,[4] where the component of external field becomes significant for the formation of the intermediate state. In this case, the observed oscillations in the apparent magnetic permeability μ^* as a function of current *I* are associated with changes in the structure of a pure-current intermediate state with current growth.

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(1) The method of measuring the flux will be described in greater detail elsewhere.

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