Paramagnetic effect in type-I superconductors

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It is suggested that destruction of superconductivity by a current in the presence of a longitudinal magnetic field can be described by assuming a structure consisting of coaxial layers of a two-dimensional mixed state[4,5] moving toward the sample axis. Results of an experimental study are presented which are in good agreement with the model proposed.

The paramagnetic effect in superconductors was observed by Steiner and Schoeneck in 1943[1]. It turned out that as the superconductivity of a cylindrical sample is destroyed by current in the presence of the longitudinal magnetic field, then the average magnetic permeability of the sample exceeds unity for a longitudinal field.

Attempts to attribute the paramagnetic effect to the onset of special structures consisting of superconducting (s) and Normal (n) domains were made in 1955 by Meissner[2] and in 1957 by Gorter[3]. We consider it quite likely, however, that an important role in the mechanism of the onset of the paramagnetic effect is played by layers of a two-dimensional mixed (TM) state (TM layers) similar to the layers that are produced when superconductivity of hollow cylindrical samples is destroyed by current[4, 5].

The model proposed by us is a development of an idea by Gorter[3], who suggested that when superconductivity is destroyed by current there can be produced a structure consisting of regions of s and n phases in the form of coaxial cylinders. An essential feature of the "Gorter" structure is continuous motion of the interphase boundaries towards the sample axis. Gorter has noted that if such a structure is produced in the presence of a longitudinal magnetic field, then the contraction of the cylindrical s-regions should lead to a concentration of a longitudinal magnetic field inside the sample. It is obvious, however, that it is impossible to construct a non-contradictory model of the paramagnetic effect by this method. Indeed, the continuous motion of the s-layers should lead to an infinite growth of the field inside the sample; on the other hand, the motion of the layers cannot stop, since the existence of immobile s-layers in the sample would lead to a vanishing of the sample resistance.

A consistent model of the paramagnetic effect can apparently be constructed by assuming that the s-layer produced near the surface of the sample is transformed as it moves to the axis into a TM layer before a new s-layer is around it. Since the resistance of the TM state differs from zero[4,5], such a model does not lead to contradictions. In the time interval τ_s when the s-layer exists "pumping" of the magnetic flux into the sample takes place. In the time interval τ_l between the transformation of the s layer into a TM layer and the nucleation of the new s layer, a decrease of the magnetic flux takes place in the region subtended by the TM layer, and in the sample as a whole. Thus, the magnetic flux in the sample should oscillate in the proposed model, with a period $\tau_s + \tau_l$. Obviously, the sample resistance should oscillate simultaneously. In spite of the "leakage" of the magnetic flux from the region surrounded by the TM layer, the field on its inner surface should remain equal to H_c. This is possible if the radius of the TM layer is continuously decreased. In this case a region in which the magnetic field is smaller than H_c appears in the normal metal outside the layer. The new s-layer is produced at the minimum of the magnetic field at a certain $r = r'$.

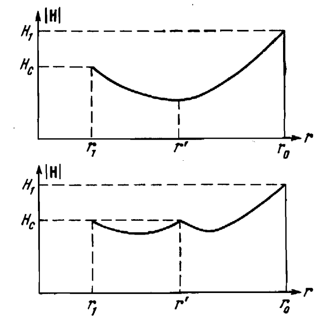

FIG. 1. Distribution of the magnetic field in the normal metal outside the TM-state layer before the nucleation of the s layer (above) and after the nucleation (below).

Figure 1 shows schematically the distribution of the absolute value of the magnetic field in a sample of radius r_0 directly before and after nucleation of the s layer. At the point $r = r_1$ there is in this case a TM layer, through which the current flows with a surface density determined by the difference between the intensity vectors of the magnetic field on its inner and outer surfaces. Thus, a system consisting of a certain number of TM layers moving toward the sample axis and vanishing near it should be produced in the sample in the case of the paramagnetic effect.

It should be noted that the TM layers, whose existence we propose, differ in this case somewhat from the TM layers observed previously in hollow cylindrical samples. In the latter case it was possible to observe immobile TM layer in the volume of the sample[5], and the discontinuity of the magnetic field at the layer amounted to $2H_c$, i.e., on opposite surfaces of the layer there were oppositely directed magnetic fields of absolute value H_c. Here we assume the possible existence of TM layers on the surfaces of which the field is equal to H_c as before, but the angle β between the magnetic-field vectors on opposite surfaces of the layer lies in the interval $0 < \beta < \pi/2$. As will be shown below, a comparison of the data on the magnetic permeability and on the electric resistance of the sample in the paramagnetic state, and also on the existence of oscillations of the magnetic moment and of the resistance of the sample, provide certain arguments in favor of the proposed model.

EXPERIMENTAL PROCEDURE

The samples on which the measurements were made were cast from indium with 0.01% tin. The resistance ratio was $R(300°K)/R(4.2°K) = 1800$. The relatively high residual resistance of our samples made it much easier to observe the oscillations of the resistance and of the magnetic moment of the sample in the paramagnetic effect. We investigated two approximately identical single crystals of 0.5 mm diameter and 120 mm length. The tetragonal axis of the crystal was parallel tu the sample axis. The tin added to the indium to increase the residual resistance was distributed over the sample with sufficient uniformity. This was demonstrated, in particular, by the small width of the superconducting transition when the superconductivity was destroyed by a current amounting to 0.1% of the critical current.

A block diagram of the measurement setup is shown in Fig. 2. To measure the magnetic flux, a coil C consisting of 2×10^4 turns of copper wire of 0.02 mm diameter was placed on the sample S. The length of the coil along the sample axis was 15 mm. When measuring the magnetic flux, the voltage on the coil was integrated with an F18 microweber meter and was applied to the Y coordinate of a PDS-021 x-y recorder. The voltage applied to the X coordinate of this recorder was proportional to the current in the sample. When the oscillations of the magnetic flux were investigated, the alternating voltage on the coil was amplified with a low-frequency amplifier A (bandwidth 0.1–20 Hz, gain 1.7×10^4). We could measure the oscillation frequency with a ChZ-24 frequency meter, and also carry out visual observations and photography on the screen of a two-beam S1-51 long-memory oscilloscope. To observe the resistance oscillations we used a step-up transformer Tr. The primary winding of the transformer consisted of one turn of lead wire, the ends of which were welded by capacitor discharge to the sample, at points 25 mm apart. The resistor $R = 10^{-5}$ connected in series with the primary winding prevented shunting of the sample by the superconducting circuit. The current diverted to the primary winding did not exceed 0.1% of the total current through the sample. The secondary winding of the transformer consisted of 2×10^4 turns of copper wire of 0.02 mm diameter. The voltage on the secondary winding was amplified by amplifier A and was fed to the second beam of the S1-51 oscilloscope. We were thus able to register simultaneously the oscillations of the magnetic flux and of the sample resistance. The mean value of the sample resistance was measured with a standard potentiometer circuit not shown in the figure.

The current through the sample came from a bank of storage batteries; it was regulated with the aid of an emitter follower made up of ten P210 transistors. The maximum current of the circuit was 120 A. The current leads were made of copper foil and were actually symmetrical near the sample. The earth's magnetic field was cancelled with the aid of two pairs of Helmholtz coils with accuracy ~0.05 Oe. The external magnetic field was set parallel to the sample with accuracy not worse than 0.5°.

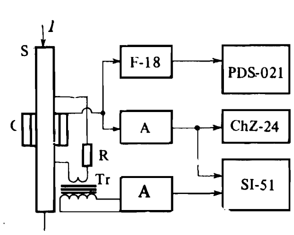

FIG. 2. Diagram of experiment.

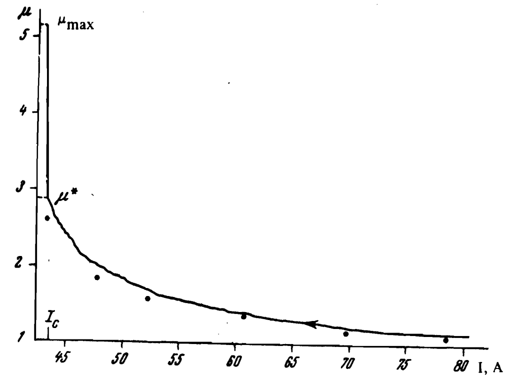

FIG. 3. Experimental dependence of the magnetic permeability on the current through the sample. Sample 1: $T = 3.24°K$, $H_e = 0.1\ H_c = 2.5$ Oe. The points show the values of μ calculated on the basis of the observed values of the sample resistance.

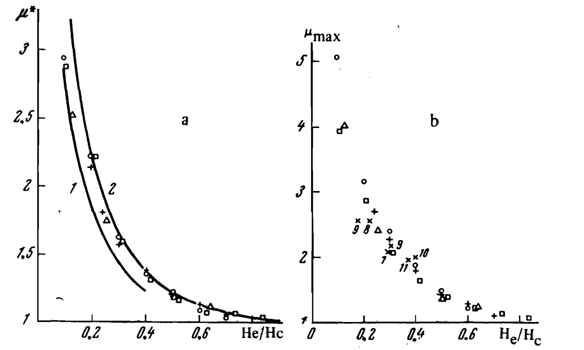

FIG. 4. Plots of $\mu^*(H_e/H_c)$ (a) and of $\mu_{max}(H_e/H_c)$ (b). Sample 1: □) $T = 3.335°K$, △) $T = 3.27°K$, ○) $T = 3.24°K$. Sample 2: +) $T = 3.24°K$, X) results obtained by others, the numbers next to the points denote the corresponding references. The solid curves are the results of the calculation on the basis of the observed values of the sample resistance: 1) $\tau_s \gg \tau_l$, 2) $\tau_s \ll \tau_l$.

RESULTS OF EXPERIMENTS

Figure 3 shows the experimental dependence of the magnetic permeability $\mu = \Phi/\pi r_0^2 H_e$ (Φ is the magnetic flux in the sample, H_e is the external longitudinal magnetic field) on the current through the sample. The course of this curve is interesting: when the current through the sample decreases, the magnetic permeability increases smoothly to a value $\mu = \mu^*$, and at $I = I_c(H_e)$ it increases abruptly to a value $\mu = \mu_{max}$, after which, at practically the same value of the current, it decreases slowly in a time on the order of 10 min. The sample resistance decreases almost to zero with increasing magnetic permeability. Thus, one value of the current $I = I_c$ can correspond to two essentially different values of the magnetic permeability, μ^* and μ_{max}.

The values of μ^* and μ_{max} are plotted in Figs. 4a and 4b as functions of the external longitudinal magnetic field. Simultaneously with the measurement of μ, we measured also the sample resistance. In Fig. 5 the value of the resistance produced at $I = I_c$ is plotted as a function of the external magnetic field.

In addition to measuring the mean values of the magnetic permeability and of the resistance of the sample, we investigated the oscillations of these quantities as

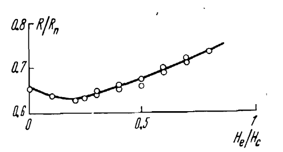

FIG. 5. Jump of sample resistance at $I = I_c$ as a function of the external magnetic field. Sample 2, T = 3.24°K.

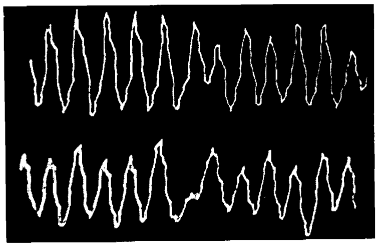

FIG. 6. Oscillations of the magnetic flux in the sample (upper curve) and oscillations of the resistance (lower curve). Sample 2, T = 3.24°K, $H_e = 0.18\ H_c = 4.5$ Oe, I = 1.05 A and I_c = 44 A. The oscillation frequency is 10 Hz. The amplitude of the magnetic-flux oscillations is ~4% of the average value of the magnetic flux in the sample. The amplitude of the oscillations of the resistance is ~2% of the average value.

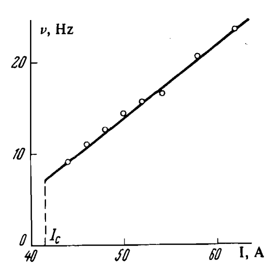

FIG. 7

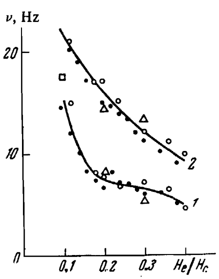

FIG. 8

FIG. 7. Plot of ν(I). Sample 2, T = 3.24°K, $H_0 = 0.24\ H_c$ = 6 Oe.
FIG. 8. Plot of $\nu(H_e/H_c)$. 1) $I = I_c$, 2) $I = 1.21_c$. Sample 1: △) T = 3.15°K, ○) T = 3.24°K; Sample 2: ○) T = 3.24°K. □) frequency calculated from the sample resistance.

functions of the time. Figure 6 shows a typical plot of these oscillations. Figure 7 shows the dependence of the oscillation frequency on the current through the sample, while Fig. 8 shows the dependence on the external magnetic field. The periodicity of the oscillation was quite good in the external-field interval $0.15 \leq H_e/H_c \leq 0.35$. Outside this interval, the periodicity became worse and it was practically impossible to observe the oscillations at $H_e/H_c < 0.1$ and $H_e/H_c > 0.4$. The amplitude of the variation of the magnetic flux reached ~10% of the total magnetic flux in the sample at currents close to critical, and decreased rapidly with increasing current.

The critical magnetic field H_c used to plot the curves was measured in the same experiments. The change in the direction of the current or of the external magnetic field did not lead to any changes in the observed effects.

DISCUSSION OF RESULTS

The calculations in the model with a large number of TM layers is exceedingly complicated. We have therefore attempted to perform some calculations on the basis of a simplified model. We have assumed that only one TM-state layer exists in the sample at any one time. As will be seen from the following, allowance for the real number of layers can lead only to the appearance of small corrections to our calculations.

To calculate values of the magnetic permeability, we must note the average radius of the region with high values of the magnetic field and the value of the magnetic field in this region. It is quite difficult to calculate these quantities by making initial assumptions, since a significant role should be played in such a dynamic model by effects connected with supercooling of the n-phase. We have therefore attempted to connect the observed values of the sample resistance and permeabilities[1)].

Assume that at a certain instant of time there exists in our sample a TM layer of radius r, surrounding a region with a high value of the longitudinal magnetic field. The value of the additional magnetic field in this region will be denoted by $H_{\|}$. Since the TM state has a nonzero resistance, the longitudinal magnetic field included inside the TM layer will decrease in the course of time, and this, as already noted, should lead to a motion of the layer towards the sample axis with a certain velocity v_l. When the TM-layer radius decreased to a value $r = r_1$, a new s layer is produced at the minimum of the magnetic field at $r = r'$ (Fig. 1). The velocity of the outer boundary of this layer will be designated by v_s. This s-layer moves towards the sample axis and pinches the force lines of longitudinal magnetic field; when the intensity of the longitudinal magnetic field inside the s layer reaches a value $H_{\|}$, the s-layer should turn into a TM layer. We denote by r'' the radius at which this transformation takes place. The "lifetime" of the s-layer in the sample is

$$\tau_s = (r' - r'') / v_s. \tag{1}$$

We can analogously express the "lifetime" of the layer of the TM state prior to the nucleation of the new s-layer:

$$\tau_l = (r'' - r_1) / v_l. \tag{2}$$

The period of the oscillations is

$$T = \tau_s + \tau_l. \tag{3}$$

We determined first the connection between the values of r_1, r'', and r'. The value $r = r'$ corresponds to the position of the minimum of the magnetic field in the normal metal outside the TM layer. The magnetic field of the current in this region can be written in the form $H_I = Ar^{-1} + Br$. For the sake of brevity, we introduce the following notation:

$$\alpha = r/r_0, \quad i = I/I_c,$$
$$I_c = {}^1/_2 c r_0 (H_c^2 - H_e^2)^{1/2}.$$

The constants A and B are determined from the boundary conditions and are equal to

$$A = (H_c^2 - H_e^2)^{1/2} \frac{\alpha(1 - i\alpha)}{1 - \alpha^2} r_0, \quad B = (H_c^2 - H_e^2)^{1/2} \frac{i - \alpha}{1 - \alpha^2} \frac{1}{r_0}.$$

The value $r = r'$ at which the magnetic field has a minimum is

$$r' = \alpha' r_0 = \left(\frac{A}{B}\right)^{1/2} = r_0 \left[\frac{\alpha_1(1 - i\alpha_1)}{i - \alpha_1}\right]^{1/2}. \tag{4}$$

The value $r = r''$ can be determined from the condition of conservation of the magnetic flux inside the s-layer, which in this case takes the form

$$(r_0^2 - r_1^2) H_e = (r''^2 - r_1^2) H_{\|},$$

whence

$$r'' = \alpha'' r_0 = r_0 [(\alpha'^2 - \alpha_1^2) H_e / H_{\|} + \alpha_1]^{1/2}. \tag{5}$$

Since one measures in experiment the mean values of the magnetic permeability and resistance of the sample, we must find relations between just the mean values of these quantities. To this end we calculate first the probability and resistance of the sample as functions of the radius of the layer, and then average over the period of the oscillations of the layer.

The sample resistance is uniquely connected with the radius of the intermediate-state region, on the boundary of which $H = H_c$. Indeed, let current $I > I_c$ flow in a sample of radius r_0, and let an intermediate region[2)] of radius $r < r_0$ exist in the sample; then the current flowing through the region of the intermediate state is

$$I(r) = {}^1/_2 cr(H_c^2 - H_e^2)^{1/2},$$

and the rest of the current flows in the normal metal outside this region. Knowing the current density in the normal metal and the resistance of the normal metal, we can determine the electric field in the sample

$$E = \frac{I - I(r)}{\pi(r_0^2 - r^2)}\rho = \frac{\rho}{\pi r_0^2} I_c \frac{i - \alpha}{1 - \alpha}, \tag{6}$$

The sample resistance per unit length

$$R = \frac{I - I(r)}{I} \frac{\rho}{\pi(r_0^2 - r^2)}$$

and the quantity

$$\gamma = \frac{R}{R_n} = \frac{I - I(r)}{I} \frac{r_0^2}{r_0^2 - r^2} = \frac{i - \alpha}{i(1 - \alpha^2)}, \tag{7}$$

where R_n is the resistance of the sample in the normal state.

We proceed now to a determination of the magnetic permeability. The value of the magnetic flux in the sample at the instant when only the TM layer exists in the sample is

$$\Phi = \pi r^2 H_\parallel + \pi(r_0^2 - r^2) H_e.$$

Here r is the radius of the TM-state layer and $H_\parallel$ is the value of the longitudinal magnetic field inside the layer. The magnetic permeability is

$$\mu = \Phi / \pi r_0^2 H_e = \alpha^2(H_\parallel / H_e - 1) + 1. \tag{8}$$

To determine the value of $H_\parallel$ we use the fact that the summary magnetic field on the internal surface of the TM layer should be equal to the critical value, i.e.,

$$H_\parallel^2 + H_I^2 = H_c^2, \quad H_I = 2I_n(r) / cr;$$

i_n is the current flowing through the normal metal inside the TM layer. To determine $I_n(r)$, we should know the value of E_1 on the longitudinal electric field in the normal metal inside the TM layer.

The longitudinal electric field in this region can in general be written in the form

$$E_1 = E - v_l c^{-1} \Delta H_\varphi, \tag{9}$$

where E is the longitudinal electric field in the normal metal outside the TM layer; ΔH_φ is the discontinuity of the circular component of the magnetic field on the TM layer. The velocity v_l of the TM layer is determined by the internal properties of the layer and is not known to us. It turns out, however, that the longitudinal magnetic field inside the TM layer is in any case close enough to H_c. Indeed, the difference between $H_\parallel$ and H_c is due to the magnetic field of the current flowing through the normal metal inside the TM-state layer. Thus, this difference is maximal in the case when the electric field E_1 is maximal in the normal metal inside the TM layer. However, as seen from (9), E_1 cannot exceed E. In the case when $E_1 = E$ we have

$$I_n(r) = I_c(i - \alpha)\alpha^2 / (1 - \alpha^2),$$

$$\frac{H_c - H_\parallel}{H_c} = 1 - \left[1 - \left(1 - \frac{H_e^2}{H_c^2}\right)\frac{(i-\alpha)^2\alpha^4}{(1-\alpha^2)^2}\right]^{1/2} \approx \frac{1}{2}\left(1 - \frac{H_e^2}{H_c^2}\right)\frac{(i-\alpha)^2\alpha^4}{(1-\alpha^2)^2}$$

Since it turns out in real cases that α is always somewhat smaller than unity, it follows that $H_\parallel$ is close to H_c.

These results show that the use of a model with one TM layer for the calculations is perfectly justified. Indeed, the existence of a system of TM layers does not affect at all the resistance of the sample, which is determined only by the outside diameter of the intermediate-state region; as to the magnitude of the paramagnetism, the existence of a system of TM layers can lead apparently only to a large concentration of the longitudinal magnetic field, i.e., to a decrease in the difference $H_c - H_\parallel$. We see thus that regardless of the real properties of the TM state, we can assume that $H_\parallel = H_c$.

We now attempt to average the obtained expressions for the magnetic permeability and of the resistance of the sample over the period of the oscillations. The magnetic permeability μ has a minimum at the instant of nucleation of the new s-layer; the TM layer has in that case a radius $r = r_1$. After nucleation of the s layer, the value of μ increases during a certain time τ_s, reaches a maximum when the s-layer is transformed at $r = r''$ into the TM layer, and then decreases in a time τ_l to its minimum value. The mean value of μ can be written with sufficient accuracy in the form

$$\mu_{av} = \mu\left(\frac{\alpha_1 + \alpha''}{2}\right) = \left(\frac{\alpha_1 + \alpha''}{2}\right)^2\left(\frac{H_\parallel}{H_e} - 1\right) + 1 \tag{10}$$

(the function $\mu(\alpha)$ can be determined from (8)). The situation is somewhat more complicated when it comes to determining the average value of the sample resistance. The resistance has a minimum after the nucleation of the s layer, then increases during the entire period, and drops abruptly to the minimum value when the new s-layer is produced. The value of γ averaged over the period can be written in the form

$$\gamma_{av} = \frac{1}{T}\left[\gamma\left(\frac{\alpha' + \alpha''}{2}\right)\tau_s + \gamma\left(\frac{\alpha_1 + \alpha''}{2}\right)\tau_l\right] \tag{11}$$

(the form of the function $\gamma(\alpha)$ is determined by formula (7)). The quantities τ_s and τ_l in (11) are determined by Eqs. (1) and (2). The velocity v_s, according to Andreev and Sharvin[6], can be written in the form

$$v_s = \frac{cE}{(H_c^2 - H_e^2)^{1/2}} = \frac{c^2\rho}{2\pi r_0} \frac{i - \alpha}{1 - \alpha^2}, \tag{12}$$

where E is the electric field in the normal metal outside the s-layer (formula (6)).

Knowing the velocity v_s, we can determine also the value of τ_s. On the other hand, we do not know the velocity of the TM layer, and hence the time τ_l; the calculations can therefore be carried out only in two limiting cases:

1) $T \approx \tau_l \gg \tau_c$. This situation is realized when $\alpha'' - \alpha_1 \gg \alpha' - \alpha''$ (strong external field). Then

$$\gamma_{av} = \gamma\left(\frac{\alpha_1 + \alpha''}{2}\right). \tag{13}$$

2) $T \approx \tau_s \gg \tau_l$. This situation is realized when $\alpha' - \alpha'' \gg \alpha'' - \alpha_1$ (weak external field). Then

$$\gamma_{av} = \gamma\left(\frac{\alpha' + \alpha''}{2}\right). \tag{14}$$

In this case we can determine also the oscillation frequency

$$\nu = \frac{1}{T} = \frac{cE}{r_0(H_c^2 - H_e^2)^{1/2}} \frac{1}{\alpha'' - \alpha'} = \frac{c^2\rho}{2\pi r_0^2} \frac{1}{\alpha'' - \alpha'}. \tag{15}$$

For our samples we have $c^2\rho/2\pi r_0 \approx 5.3\ \mathrm{sec}^{-1}$.

Thus, by using the obtained formulas we can construct $\mu = f(\gamma, I, H_e)$, and the function f will be different for the two indicated limiting cases.

We performed these calculations for $I = I_c$ at different values of the external magnetic field (solid lines in Fig. 4a) and $H\ /H\ = 0.1$ at different values of the current through the sample (points on Fig. 3). The following calculation procedure was used. First we used formula (13) or (14) to determine α from the measured values of $\gamma = R/R_n$ (Fig. 5); in the former case, (13) yields the value $(\alpha_1 + \alpha'')/2$, which was then substituted in (10) to determine μ. In the second case we obtained from (14) the value of $(\alpha' + \alpha'')/2$, and then calculated $(\alpha_1 + \alpha'')/2$ with the aid of formulas (4) and (5) and subsequently the value of μ from formula (10). In addition, in the second case we can calculate the oscillation frequency from formula (15) after first determining $\alpha'' - \alpha'$ from the resistance; for $H_e/H_c = 0.1$ and for $I = I_c$ we obtained for the frequency the value $\nu = 17.5$ Hz.

Generally speaking, knowing the oscillation frequency and the magnetic permeability we can determine the velocity of the TM layer. Indeed, from the experimental measured value of μ we can use formulas (10), (4), and (5) to determine the values of α_1, α', and α''. Since the velocity of the outer boundary of the s layer, v_s, is given by formula (12), and the period T is measured in the experiment, the only unknown remaining in (3) is v_l, which is thus easy to determine. It turned out that $v_l \approx 0.18 v_s = 0.22$ cm/sec in the magnetic-field range $0.15 < H_e/H_c < 0.4$, i.e., the velocity of the TM layer is much lower than the velocity of the s layer. This result agrees well with the fact that the approximation $\tau_l \gg \tau_s$ used to determine the magnetic permeability from the resistance of the sample agrees well with the observed values of μ in almost the entire interval of the external magnetic field (see Fig. 4).

The fact that regular oscillations of the magnetic moment and of the resistance of the sample have been observed, and the rather good agreement between all the calculated values and the observed ones, offers convincing evidence in favor of the proposed model of the paramagnetic effect.

Teasdale and Rorschach[7] observed random oscillations of the magnetic flux in the samples during the course of the paramagnetic effect. The amplitude of these oscillations agrees in order of magnitude with our observations. The irregularity of the oscillations, which was noted in[7], is probably due to the low quality of the sample.

If our data concerning the effective magnetic permeability are compared with results obtained by others on the paramagnetic effect (for example, [7-11]), then it turns out that the values of μ at $I = I_c$, obtained in these references, agree well with the values of μ_{max} obtained by us (Fig. 4a). This seems quite natural to us, since, as already noted in the description of the experimental results, the value $\mu = \mu_{max}$ is preserved for a rather long time. The slow decrease of μ at currents somewhat below critical is due to the fact that when the current decreases below the critical value a superconducting layer is produced on the surface of the sample and the longitudinal magnetic flux turns out to be "frozen-in" in the sample. Apparently the existence of an appreciable longitudinal current in the sample prevents distortion of the actual symmetry of the picture and leads to prolonged existence of the "frozen-in" magnetic flux in the sample.

The causes of the sharp increase of μ at $I = I_c$ are still unclear to us. An appreciable role is apparently played here by nonstationary transient processes that occur when the superconductivity is restored in the sample.

Meissner[2] has proposed an entirely different model of the intermediate states in the paramagnetic effect, namely that the superconducting domains take the form of extremely elongated ellipsoids oriented in the direction of the summary magnetic field. As follows from Meissner's calculations, the resistance of such a structure for a helical current turns out to be less than for a longitudinal current. This model of the paramagnetic effect is static and the observation of oscillations contradicts this model.

I wish to thank P. L. Kapitza for interest in the work and Yu. V. Sharvin and A. F. Andreev for numerous fruitful discussions.

1)The calculations presented below were made in a quasistatic approximation; this approximation, in any case, is valid at currents close to critical, when the period of the oscillations is larger in comparison with the relaxation time of the currents in the normal phase.

2)The relation between R and r does not depend on the concrete arrangement of the intermediate-state region. We shall assume henceforth that this is the TM layer surrounding a region with large value of the longitudinal magnetic field.

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