of the separation boundary plays an important role under equilibrium conditions. The period d of the intermediate state is much less according to the theory[5] than the layer thickness δ_1. The difference between the conditions used for the calculation and the experimental condition is, first, that an immobile structure was used for the calculation while in the experiment the layer was moving. It is difficult to estimate the extent to which the structure that exists under the experimental conditions agrees with the equilibrium structure at the same field configuration. The only indication, in our opinion, that the structure is close to equilibrium is the experimental fact that the volume of the superconducting phase hardly changes during the lifetime of the layer.

The use of expression (5) of Ref. 5 allows us to connect the measured value of the electric field at a distance on the order of δ_1 from the surface with an intermediate-state structure period

$$E \approx \frac{c}{8\pi\sigma}\frac{3dH_c(T)\Delta}{16\delta_1^3},$$

where Δ is of the order of the coherence length and σ is the static conductivity. Substituting the indium parameters $\Delta \sim 4\times10^{-5}$ cm, $\sigma \sim 2\times10^{22}$ cgs esu, $\delta_1 \sim 2\times10^{-4}$ cm, $H_c(T) \approx 50$ Oe, and $E \sim 2\times10^{-7}$ cgs esu, we get $d \approx 10^{-1}$ cm. This result disagrees with the assumptions made by Andreev and Dzhikaev.[5] It is possible that it precisely the motion of the structure which accounts for this contradiction.

In an inclined magnetic field the structure of the layer is determined by three factors: the electric field in the layer, the normal component of the magnetic field $H_\perp$, and the magnetic field component $H_\parallel$ parallel to the surface. In the region of the plateau a (Fig. 10) the ratio of the areas of the surfaces occupied by the normal and superconducting phases is close to $H_\perp/H_c - H_\perp$, i.e., it is determined by the normal component of the magnetic field. It is not yet clear what causes the sharp change of the surface impedance on going over to the plateau b. We note however, that this change can mean not only a change in the concentration of the normal phase on the surface, but can also be connected with the change of the microstructure of the layer. In films, for example, a transition was observed from a laminar structure typical of the intermediate state of thick plates to penetration of the magnetic field via individual islands containing several magnetic-flux quanta, at film thicknesses (10–100)ξ and $H_\perp \sim 0.4H_c$.[6-8]

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Destruction of superconductivity of hollow cylindrical tin samples by current

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Results are reported of measurements made on two single-crystal tin samples. The samples were thin-wall hollow cylinder with identical dimensions but substantially different values of the residual resistance. The current-voltage characteristics of the samples and the influence of a static longitudinal magnetic field were studied and the rate of penetration of a weak longitudinal magnetic field into the bore of the sample was measured. The reduction of the measurement results leads to the conclusion that the angle between the electric field and the current in a layer of a two-dimensional mixed state is determined by the relative orientation of the electric and magnetic field on the boundary between the layer and the normal metal.

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When the superconductivity of a hollow cylindrical sample is destroyed by current flowing through the sample, a thin layer of two-dimensional mixed state (TDM) of a type-I superconductor is produced on the outer surface of the sample.[1-7] If the current I through the sample is only slightly larger than the critical value $I_c = cr_2H_c/2$ (r_2 is the radius of the outer surface of the sample and H_c is the critical magnetic field) there can

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exist inside the sample, in principle, a region occupied by the intermediate state. We shall not concern ourselves here with the conditions for the existence of an intermediate state in hollow cylinders (see Refs. 8 and 9); it can be stated, however, that in any case when

$$I>I_i=\frac{r_1^2+r_2^2}{2r_1r_2}I_c$$

(r_1 is the radius of the bore) no intermediate state can exist in the body of the sample. We consider henceforth only the relatively simple case when all the deviations of the sample properties from those of a normal metal are due only to the presence of the TDM layer. It must be noted that this restriction is in no way essential in our case, inasmuch as in the samples investigated in the present study $I_i \approx 1.003\, I_c$.

We describe here experiments performed on thin-wall tin samples. Besides the static measurements of the current voltage characteristics and of the magnitude of the paramagnetic effect of the TDM state in a longitudinal magnetic field (see Ref. 6), measurements were made also of the rate of penetration of a weak longitudinal field into the inner bore of the sample.

SAMPLES AND MEASUREMENT PROCEDURE

The measurements were made on two tin single-crystal samples Sn1 and Sn2 having the same dimensions: outside diameter 8 mm, cavity diameter 7.4 mm, length 55 mm. The angle between the fourfold symmetry axis and the sample axis was 15° for Sn1 and did not exceed 2° for Sn2. The resistance ratio was $R_{300\,K}/R_{3.7\,K}=2\times10^4$ for sample Sn1; sample Sn2 was accidentally contaminated in the course of its preparation and had $R_{300\,K}/R_{3.7\,K}=1.5\times10^2$. The samples were grown from the melt in a glass mold with dural inserts using a previously described procedure.[6] To prevent damage to the thin-wall samples during the assembly, the samples were left after preparation of the inserts; the coefficients of thermal expansion of duraluminum and single-crystal tin are in such a ratio that when the samples with our orientation were cooled on the insert they were not deformed.

The experimental setup is shown in Fig. 1. A current up to 200 A was made to flow through the samples from a dc motor-generator set. The regulation and stabilization of the current was with an emitter follower made up of sixteen P210 transistors. The lead current conductors 5 were soldered to the sample with Wood's alloy and were axially symmetrical near the sample. The longitudinal magnetic field was produced on the sample by a single-layer superconducting solenoid 3 of 11 mm diameter and 45 mm length.

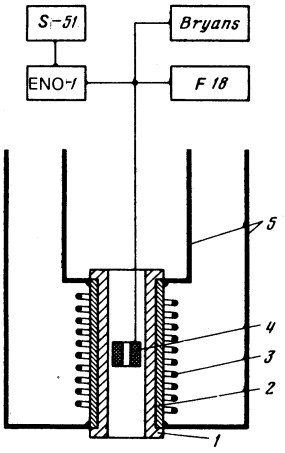

FIG. 1. Experimental step: 1—insert, 2—sample, 3—solenoid, 4—fluxmeter coil, 5—current leads.

The longitudinal magnetic field in the bore of the sample was measured with an F18 microwebermeter; the magnetic-field pickup was coil 4 consisting of several thousand turns of copper wire of 20 μm diameter; the coil was 5 mm long. The coil was placed in a 5-mm opening that passed along the axis of the insert. In measurements of the rate of penetration of the longitudinal magnetic field, the voltage induced in the pickup coil when the current was switched in the solenoid was recorded as a function of the time either with the British "Bryans" automatic plotter (at time constants $\tau > 0.2$ sec), or with an S1-51 memory oscilloscope (at shorter time constants); in the latter case the coil voltage was preamplified with the amplifier on the ENO-1 oscilloscope.

The sample voltage was measured with an F-118 nanovoltmeter (not shown in the figure) and recorded as a function of the current through the sample with an LKD-003 x-y recorder. The distance between the potential contacts was 25 mm for sample Sn1 and 5.5 mm for sample Sn2.

The earth's magnetic field was cancelled with two pairs of Helmholtz coils with accuracy not worse than 10^{-2} Oe.

MEASUREMENT OF THE CURRENT-VOLTAGE CHARACTERISTICS OF THE SAMPLES

In the case when a TDM layer exists on the inner surface of the sample (with a thickness negligibly small compared with the sample wall thickness), while the remainder is in the normal state, the sample voltage can be expressed in the form[1)]

$$V=R_n(I-I^*). \tag{1}$$

Here R_n is the sample resistance in the normal state, I is the total current in the sample, and I^* is the current flowing through the TDM state layer.

A typical experimental current-voltage characteristic is shown in Fig. 2. As seen from Eq. (1), knowing R_n

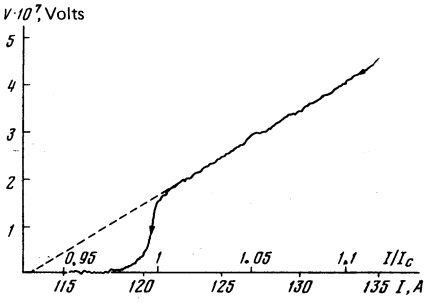

FIG. 2. Current-voltage characteristic of Sn1 sample; T = 3.296 K.

we can determine I^* from the experimental current-voltage characteristics. For the pure Sn1 sample these calculations are made difficult, however, by the noticeable dependence of R_n on the temperature and on the magnetic field of the current flowing through the sample. For a more accurate determination of R_n the sample was converted at the measurement temperature into the normal state (experiments have shown that R_n is practically independent of a longitudinal magnetic field of this magnitude). Even in this case, however, it is necessary to take into account the change produced in R_n by the redistribution of the current, and hence of the magnetic field in the normal metal when the TDM state layer is destroyed.

It is easy to show that if the dependence of the resistance of the sample in the normal state on the current is described by the expression

$$R_n(I)=R_n(0)\,(1+aI^\nu),$$

where $R_n(0)$ is the sample resistance as $I\to 0$, then in the case when a TDM state layer is present on the inner surface of the sample and carries a current I^* we have

$$R_n(I)=R_n(0)\,\{1+a[(\sqrt{\nu+1}-1)I^*+I]^\nu\}. \qquad (2)$$

This expression is valid at a $I^\nu \ll 1$ and $r_2-r_1 \ll r_1$. In the derivation of this formula we have neglected also the possible presence of anisotropy of the magnetoresistance of the normal metal. For the sample Sn1 we have $\nu=2$ and $a=5\times10^{-5}\,\mathrm{A}^{-2}$; thus, for this sample

$$R_n(I)=R_n(0)\,[1+5\cdot10^{-5}(0.71I^*+I)^2]$$

(the current in this formula is in amperes). For the dirtier sample Sn2 the value of R_n, naturally, is independent of either the temperature or the current through the sample.

Figure 3 shows plots of $H^*/H_c=r_2I^*/r_1I_c$ (H^* is the magnetic field on the surface of the TDM layer facing the normal metal) against the current through the sample. The accuracy with which H^*/H_c was determined for sample Sn1 at $T=3.24$ K is about 2%, and becomes worse at higher temperature in view of the difficulty of measuring low voltages on the sample. Another factor that leads to a sustantial uncertainty in the values of H^*/H_c is a possible Joule overheating of the sample to above the temperature of the helium bath. For sample Sn1, and small currents through the sample, the heat released and hence the sample temperature rise are negligible; at higher currents through sample Sn1, however, and at all currents through sample Sn2, the overheating of the sample can lead to an underestimate of H^*/H_c. Thus, the decrease of H^*/H_c when the current through the sample is increased can also be attributed to overheating of the samples under the influence of the current flowing through them.

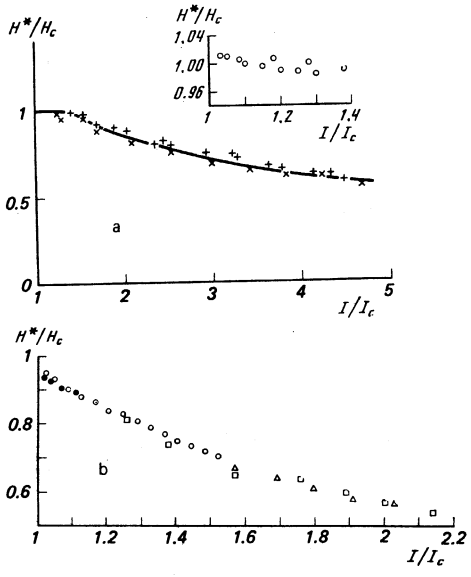

FIG. 3. Dependence of I^*r_2/I_cr_1 on I/I_c. a) Sample Sn1: ○—$T=3.24$, +—3.627, ×—3.69 K. b) Sample Sn2: ●—$T=3.18$, ○—3.364, △—3.42, □—3.53 K.

Despite the absence of control over the sample temperature, it can be stated on the basis of our measurements that as $I\to I_c$ the ratio H^*/H_c is equal to unity, within several per cent, for both investigated samples; this is in full agreement with the measurements made on indium.[9] This result differs substantially from the theoretical calculations based on the model of the TDM state layer proposed by Gor'kov and Dorokhov.[10] Calculation by their model yields at $I=I_c$ a value $H^*/H_c=0.75$. This appreciable discrepancy indicates that the real structure of the TDM state differs substantially from this model. The values of H^*/H_c obtained in our experiments agree in principle with the TDM model recently proposed by Andreev and Dzhikaev.[11] It must be noted, however, that both cited models have serious fundamental shortcomings, due to neglect of the surface tension on the phase interface in the region where the concentration of the superconducting phase vanishes. As shown in Ref. 9, a correct allowance for the surface tension in the case of the intermediate-state structure produced when the superconductivity of a bulky cylindrical sample is destroyed by current, leads to quite substantial effects. On the other hand in the case of the TDM structure the analogous effects should be much larger because of the smaller scale of the structure.

Knowing the value of I^* we can determine also the electric conductivity of the TDM layer. Since only the order of magnitude of the layer is known at present, we deal here with the surface conductivity σ^* of the TDM state, which can be defined in the usual manner as the coefficient of proportionality of the surface current density in the layer i^* and the electric field.[2)] If the z axis is parallel to the sample axis, then $\sigma^*=I^*/2\pi r_1E_z$ (E_z is the electric field intensity in the sample). Recognizing that $E_z=V/L$, where V is defined by (1) and L is the distance between the potential contacts, we can express σ^* in the form

$$\sigma^*=\frac{I^*L}{2\pi r_1(I-I^*)R_n}. \qquad (3)$$

Since the sample wall thickness is small compared with the bore radius, we can, introducing $\Delta r=r_2-r_1$, set $r_1=r_2=r$. The sample resistance in the normal state is $R_n=L/2\pi r\Delta r\sigma_n$, where σ_n is the electric conductivity of the sample material in the normal state. Substituting

this expression for R_n in (3), we get

$$\alpha = \frac{\sigma^*}{\sigma_n \Delta r} = \frac{I^*}{I - I^*}. \quad (4)$$

For convience in comparison of the results obtained with different samples, we have introduced here the dimensionless parameter α, which is the ratio of the surface conductivity of the TDM layer to the surface conductivity of the sample in the normal state. The value of α can be determined from the data of Fig. 3.

MEASUREMENTS IN A LONGITUDINAL MAGNETIC FIELD

In earlier experiments with thick-wall indium samples[6] it was observed that at $I > I_i$ the longitudinal magnetic field H_i in the sample bore (with the sample placed in an external longitudinal field H_e) greatly exceeds the external field (the paramagnetic effect). We present below the results of analogous measurements on tin samples. Figure 4 shows a plot of H_i/H_c against H_e/H_c, while Fig. 5 shows the dependence of the paramagnetic effect $\mu = H_i/H_e$ on the current. It is interesting that whereas practically no temperature dependence of the paramagnetic effect is observed for sample Sn1 (in the temperature interval 3.3–3.68 K), in the dirtier sample Sn2 the $\mu(I)$ dependence has a different character and changes noticeably with temperature near I_c. At low values of the external field the field inside the sample bore is proportional to the external one down to the lowest values that can be measured (see Fig. 4). Thus, the paramagnetic effect of the TDM state has no threshold for the longitudinal magnetic field, or at any rate no threshold longitudinal field lower than $6 \times 10^{-4} H_c$.

The measurements of the rate of penetration of the longitudinal magnetic field through the TDM state were made in the following manner. At constant sample temperature and current, the solenoid produced a longitudinal magnetic field $H_e = 0.05\ H_c$. At the instant of time $t = t_0$ the direction of the current in the solenoid was reversed[3)] and the signal from the magnetic-pickup coil was recorded as a function of the time. A typical plot, as well as that of the logarithm of the coil voltage against the time, are shown in Fig. 6. As seen from this figure, the coil voltage, which is proportional to

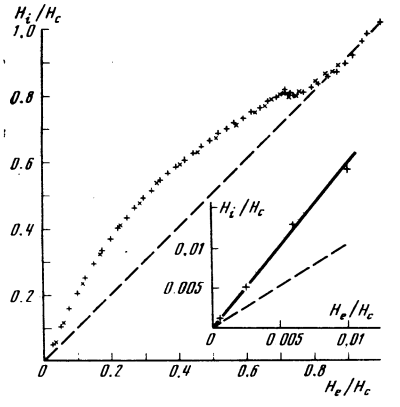

FIG. 4. Dependence of H_i/H_c on H_e/H_c for sample Sn1: +—T = 3.3 K, $I = 1.13 I_c = 134$ A; ×—$T = 3.361$ K, $I = 1.14 I_c = 119$ A.

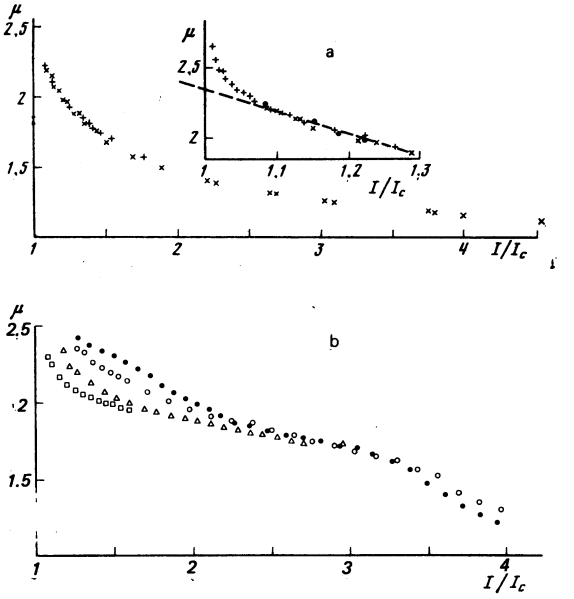

FIG. 5. Dependence of $\mu = H_i/H_e$ on I/I_c. a) Sample Sn1: +—$T = 3.346$, ×—3.574, ●—3.678 K. b) Sample Sn2: □—$T = 3.337$, △—3.504, ○—3.583, ●—3.62 K.

the rate of change of the field in the sample bore, is well described by the exponential dependence that is natural for this case.

From this dependence it is easy to determine the time constant τ of the processes. Measurements of this type were made for both samples at various currents and temperatures. Measurements at a temperature higher than critical give the time constant of the sample in the normal state ($\tau_n = 170$ msec for sample Sn1 and $\tau_n = 1.25$ msec for sample Sn2). These values are in good agreement with the time constant that can be calculated on the basis of data on the resistance of samples in the normal state, if account is taken of the presence of crystal anisotropy of the electric conductivity of the tim and the dependence of this anisotropy at low temperatures on the purity of the sample.[12] The measured τ are shown in Fig. 7 as plots of $(\tau - \mu\tau_n)/\mu\tau_n$ against the previously introduced quantity α [see Eq. (4)]. In this plot the values of α and μ were taken from the results of static measurements at the same temperatures and currents as for the corresponding values of τ. Since the results obtained at different tempera-

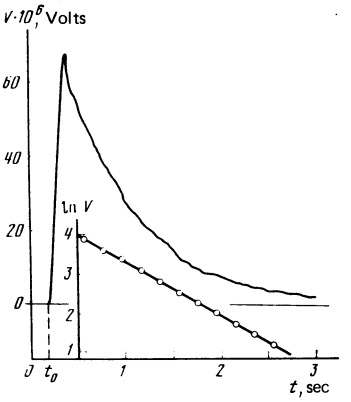

FIG. 6. Dependence of flux-meter coil voltage on the time. Sample Sn1, T = 3.475 K, $I = 1.4 I_c = 104$ A.

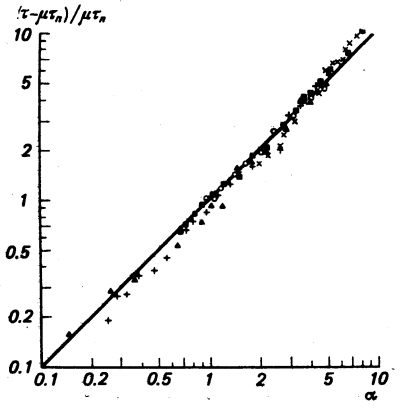

FIG. 7. Dependence of $(\tau-\mu\tau_n)/\mu\tau_n$ on α. Sample Sn1: ×—$T=3.26$, +—3.57 K; sample Sn2: ○—$T=3.3$, ■—3.377, ▲—3.568 K.

tures fit one and the same plot of $(\tau-\mu\tau_n)/\mu\tau_n$ against α, any current-induced overheating that might distort the dependences of α, μ, and τ on the current through the sample can in no way affect the results presented in this form.

The existence of a paramagnetic effect of the TDM state means that in the presence of a longitudinal magnetic field there is produced in the layer a circular component of the current, in other words, the current in the TDM layer is in this case no longer parallel to the electric field. It can be proposed that the decisive factor in this case is the relative orientation of the electric and magnetic fields on the boundary between the layer of the TDM states and the normal metal. Inasmuch as at $H_e \ll H_c$ the magnetic field in the bore is proportional to the external field, this means that the circular component of the current in the field is proportional to the deviation of the angle between the electric and magnetic fields from a right angle.

When the external longitudinal magnetic field is abruptly turned off, a circular component of the electric field is likewise produced in the sample. Neglecting the wall thickness compared with the bore radius, we can write $E_\varphi = rH_i/2c$, where $\dot{H}_i$ is the rate of change of the longitudinal magnetic field in the bore of the sample. The longitudinal magnetic field on the outer surface of the TDM state, H_1 is in this case equal to

$$H_1 = \frac{2\pi r\Delta r}{c^2}\sigma_n\dot{H}_i.$$

If it is assumed that the current component in the TDM layer, which is parallel to the electric field, is determined by the same value of the surface conductivity as in the static measurements, and that the current component perpendicular to the electric field is connected as before with the angle between the electric and magnetic field, the circular component of the current in the TDM layer can be expressed in the form

$$i_\varphi^* = \frac{r\Delta r\sigma_n\dot{H}_i}{2c(I-I^*)}\left[1+\frac{I}{I^*}(\mu-1)\right].$$

The first term in this expression is connected with the circular component of the electric field, and the second is determined by the deviation of the current direction from the direction of the electric field. The magnetic field in the sample bore is

$$H_i = H_1 + \frac{4\pi}{c}i_\varphi^* = \frac{2\pi r\Delta r}{c^2}\sigma_n\dot{H}_i\mu\left(\frac{I^*}{I-I^*}+1\right).$$

Solving this equation, we readily obtain the time constant of the process

$$\tau = \mu\tau_n\left(\frac{I^*}{I-I^*}+1\right), \quad \tau_n = \frac{2\pi r\Delta r}{c^2}\sigma_n.$$

We find thus that under our assumptions

$$\frac{\tau-\mu\tau_n}{\mu\tau_n} = \frac{I^*}{I-I^*} = \alpha. \tag{5}$$

As seen from Fig. 7, relation (5) is satisfied within the limits of the measurement accuracy for both samples at all the investigated values of the current and temperature, although the dependences of μ, α, and τ on the current are themselves greatly different for different samples. The good agreement of the experimental results with (5) attests to the validity of the assumptions made. Let us formulate these assumptions once more. First, the time constant of the restructuring of the state of the TDM layer is much shorter than τ_n. Second, the deviation of the direction of the current in the TDM layer from the direction of the electric field is determined by the relative orientations of the electric and magnetic fields on the TDM surface facing the normal metal.

CONCLUSION

Despite the rather long history of the question, it is still difficult to state at present anything definite concerning the internal structure of the TDM state. Various models[10,11] were proposed for the structures of the TDM, made up in analogy with the intermediate state of purely superconducting and purely normal domains. Although, as already noted, both models suffer from substantial principal shortcomings, one cannot exclude the possibility that this approach can lead to a model that is not inherently contradictory. It must be noted, however, that the large complexity of the calculations will hardly make for much progress in this direction in the nearest future.

Another interesting approach to this problem was developed by Andreev and Bestgen.[4] They considered the case when the superconductivity in the TDM layer is suppressed by the electric field and by the current to such an extent that the superconducting current in the layer is much smaller than the normal one, and the superconducting pairs can be regarded as fluctuations. In this case the Ginzburg-Landau equation greatly simplify and can be solved exactly. The TDM state in this model constitutes a homogeneous layer. Particularly interesting is the fact that, in developing this approach, Bestgen[5,7] considered the influence of the longitudinal magnetic field. His results yield not only the paramagnetic sign of the effect in the case when the TDM layer is an the inner surface of the sample, but many other phenomena observed in experiment.[6] A quantitative comparison of the results of these theoretical papers with experiment, however, is impossible because the

principal assumption of the theory, that the superconducting current be small, was not satisfied in the experiment.

The lack of calculations for the case when the superconducting current is not weak is due mainly to mathematical difficulties and of course does not mean that actually the TDM state cannot be arranged in similar fashion. It must be noted here that in very pure samples, near the critical temperature, a situation is possible wherein

$$eEL \ll \Delta^2/\varepsilon_F. \tag{6}$$

Here e is the electron charge, E is the electric field in the sample, L is the sample length, Δ is the energy gap, and ε_F is the Fermi energy. Expression (6) means that the velocity to which the superconducting electrons must be accelerated by the electric field, is much lower than the critical pairing velocity. In this case the calculation seem to be somewhat simpler. It may turn out, for example, that the TDM layer is in this case a sort of superconductor in which the superconducting pairs behave like an ideal superconducting liquid accelerated by an electric field. Despite the presence of the electric field, the superconducting current remains nondissipative—the field energy drawn from the electric field goes over into the kinetic energy of the condensate.

At large values of the electric field intensity, this approach leads to a periodic structure; in fact, the superconducting pairs accelerated by the electric field should reach critical velocity, at which the pairs break up and the accumulated energy is dissipated; the electrons that have lost excess energy can then form new pairs. Several recent theoretical papers[13-16] treat the supercritical current states in thin superconducting channels. It turns out in this case, when the electric field in the channel is not too strong, this analysis leads to a periodic structure that consists of thin regions of almost-normal state alternating with regions in which both the superconducting order parameter and the electric field differ from zero. It should be noted, however, that the case of superconductivity breaking by current in a macroscopic sample in the form of a hollow cylinder differs substantially from the situation in a microscopically thin channel. In particular, when the TDM layer is considered one must take into account the magnetic field, which should play a rather substantial role in this case.

I am grateful to Yu. V. Sharvin for numerous helpful discussions and for constant interest in the work, to A. F. Andreev for a discussion of questions touched upon in the article, and to W. Bestgen for reporting his results prior to publication.

[1)]Here and below we shall mark with asterisks the quantities that characterize properties of the TDM state.
[2)]We denote by I the total value of the current, and by i the surface current density.
[3)]We have verified that turning on, turning off, and reversal of the longitudinal magnetic field lead to absolutely identical time dependences of the coil voltage, and therefore in most cases, to increase the signal, it was the direction of the magnetic field which was switched.

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