INVESTIGATION OF THE DYNAMIC INTERMEDIATE STATE OF SUPERCONDUCTORS

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The previously discovered[10] motion of domains of the normal and superconducting phases under the action of a direct current (dynamic intermediate state) is studied in single crystal indium samples by observing oscillations of the resistance of thin wires in contact with the sample surface. It is found that moving layer structures possess a spatial period close to that of the static structures. Layers oriented by an external field can move at various angles with respect to the current direction. The measured value of the velocity is in satisfactory agreement with theoretical predictions.[5, 13] Layers parallel to the current are displaced with a velocity that is proportional to the resistance of the normal phase and inversely proportional to H_c. At temperatures far from T_c the velocity of layers perpendicular to the current is proportional to the Hall constant and close to the drift velocity of the charge carriers in the normal phase.

THIS paper is devoted to an investigation of the mechanism of the passage of current through a type-I superconductor when the superconductivity of the conductor is already partly destroyed under the action of an external magnetic field and of the current itself, and the conductor is in the intermediate state. It has already been shown in the early papers[1, 2] that the appearance of the electrical resistance is connected with the penetration of the magnetic field into the sample. After it was established[3] that a sample in the intermediate state is divided into macroscopic superconducting and normal domains (s and n domains), it became obvious that the electrical resistance is due to the passage of the current through the n regions.

It is in this case possible to make two alternative assumptions regarding the structure of the intermediate state.

1. In a sample carrying a direct current there exists a static domain structure.

In this case the sample can have a nonzero resistance only when there are no superconducting "bridges" for the current. The electric field **E** in the n phase in the vicinity of a stationary phase-separating surface should be perpendicular to that surface by virtue of the continuity of its tangential component. In 1937 London[4] proposed for a cylindrical sample with a current satisfying these conditions the model of a structure consisting of a system of stationary s and n layers located across the cylinder.

2. The action of a direct current leads to a continuous motion of the domains ("dynamic intermediate state").

This assumption was made in 1957 by Gorter[5] who drew attention to the fact that the electrical resistance to a direct current can also exist in the presence of superconducting "bridges" or layers extended in the direction of the current if these layers are moving, since in this case the nonzero electric field component in the n phase is tangential to the surface separating the phases:*

$$E_t = c^{-1}[\mathbf{v}\mathbf{H}_c],$$

where **v** is the rate of motion of the layer and $\mathbf{H}_c$ is the magnetic field intensity in the n phase which is equal to the critical field.

It is readily seen that layers extended along the current should indeed start moving because when a current passes through the sample the layers and lines of force of the field in the n phase are bent somewhat. If the layers were stationary, the entire current would have to flow along the s phase, whereas the condition curl **H** = 0 would be satisfied in the n phase; this leads in the presence of bending to values of the field on opposite boundaries of the n layer that differ from one another and from H_c. However, the question of the stability of such a moving system of layers remains open.

The experimental investigations of this problem were started by Shal'nikov[6] who observed the structure of the intermediate state of a cylindrical tin sample with a direct current along its axis, placed in a transverse magnetic field, and observed that the layers are stationary and are located perpendicular to the direction of the current in accordance with assumption 1. Analogous results were subsequently also obtained for samples of other shape.[7, 8] On the other hand, in a series of papers (the earliest is, apparently, that of Misener[9]) fluctuations have been observed in the resistance of wires in the intermediate state, a fact which can be considered to be an indication of the possibility of the spontaneous motion of domains.

In [10] it was observed that in definite instances under stationary external conditions continuous motion of s and n domains of a regular nature takes place in the samples. The aim of our further experiments in this

*$[\mathbf{v}\mathbf{H}_c] = \mathbf{v} \times \mathbf{H}_c$.

direction, described below (see also [11, 12]), was the measurement of the parameters of the moving structures and the elucidation of the principal mechanisms of this phenomenon which, as it turned out, occurs in a broader class of cases than was initially assumed. Theoretically this problem was considered by Andreev[13] on the basis of the macroscopic electrodynamics of the intermediate state set up by him.

Using a method completely different from our method, Solomon[14] observed in type-I superconductors the so-called "flux transfer" which is an indubitable confirmation of the existence of domian motion under the action of a current (see below on p. 1052).

EXPERIMENTAL METHOD

The shape of the samples and the direction of the magnetic field in our experiments were chosen such that we would be dealing with the simplest possible structures of the intermediate state, investigated previously in the static case. Plane samples (see the table), equipped with elongated projections for the supply of current, were placed in a field inclined to the sample surface at a small angle $\beta = 10°$ (Fig. 1). The presence of a magnetic field component parallel to the surface leads to the formation of simple layer structures oriented along the direction of this component[15] which corresponds to a minimum of the free energy of the system.[16] In order to decrease fringe effects, it turned out to be essential to equip the plane samples with additional lateral strips of the same material, 3–4 mm wide and separated from the sample by a 10-μ thick layer of electrical insulation.

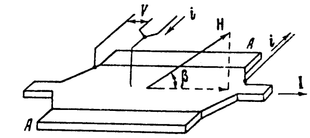
We have also investigated cylindrical samples (see the table) in which the layers were oriented perpendicular to the cylinder axis, i.e., parallel to the projection of the field upon the surface of the sample, a situation which also corresponds to a free energy minimum. The first experiments[10, 11] were also carried out on tin samples, after which we went over to indium which has simpler galvanomagnetic properties and an appreciable Hall coefficient, a fact which was also essential for our experiments. All the samples were prepared from a high-purity metal by casting (except for the sample In1 prepared for comparison by rolling).

As measuring devices, allowing one to observe the motion of layers in the sample and measure their velocity and dimensions, we used thin wires welded to the sample in such a way that the cross sectional dimension of the contact was on the order of 10^{-4} cm (concerning the preparation of such microcontacts and the determination of their dimensions see [17]). In most of

Sample	Dimensions, mm	Crystalline state	$\frac{\rho\ (300°\ K)}{\rho\ (10°\ K)}$
In1	20×10×0.55	Fine crystals	~1·10¹
In2	20×10×0.52	Single crystal,* [001] ‖ I	~1·10¹
In3	20×10×0.52	[001] ⊥ to the surface	5·10⁴
In4	20×10×0.52	[100] ‖ I	7·10⁴
In5	dia. 2.7, length 30	[001] ‖ I	(4–5)·10⁴
In6	dia. 3.2, length 30		
In7	dia. 3.0, length 30		

*Samples In2–In7 are single crystals.

FIG. 1. Schematic diagram of the sample mounting.



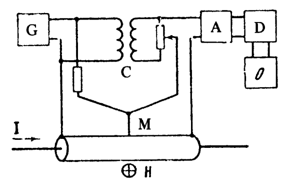


FIG. 2

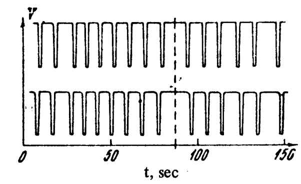


FIG. 3

FIG. 2. One of the two channels of the fast circuit for recording the motion of domains: M—microcontact, G—G3-33 generator, C—compensator, A—U2-6 amplifier, D—detector, O—MP02 loop oscillograph.

FIG. 3. Simultaneous recording of voltage oscillations on two microcontacts located at a distance of 0.1 mm along the direction of motion of the layer. A plane tin single-crystal sample, T = 2.93°K, H = 105 Oe, I = 2A.

the experiments we used small copper wires 25 μ in diameter, although we also used wires of the material of the sample itself, of platinum, gold, niobium, and other materials. A measuring current i of the order of 10^{-3} A was passed through the small wire and the potential difference was measured between the potential leads soldered to the sample and to the small wire (Fig. 1). When the superconductivity of the sample was destroyed, the resistance $R = V/i$ increased abruptly by an appreciable amount $\Delta R \sim 10^{-2}$ ohm.

An F-116/1 galvanometer photoamplifier and a ÉPP-09 chart recorder were used to record changes of the voltage V. Several microcontacts were set up on the sample and two parallel measuring circuits could record the oscillations from any pair of contacts simultaneously. A small modification of the pen of one of the recorders made it possible to record both records on the chart of the second recorder connected in series. The time shift of the signals from the two contacts could be determined with an error of less than 0.05 sec. In these experiments, when the frequency of the oscillations of V exceeded 1 Hz, use was made of a two-channel measurement circuit operating on an alternating measurement current of two different frequencies in the 5–20 MHz band suitable for the recording of oscillations with frequencies up to 1 kHz with an amplitude of 10^{-7} volts (see Fig. 2).

In the case when the sample was in the intermediate state and the magnitude of the current I that passed through the sample exceeded a certain threshold value I_0, we observed periodic variations of the voltage V (Fig. 3) which were caused by the transition of the sample material near the contact from the n to the s state and vice versa as a result of the motion of layers; the presence of the contacts did not, as we convinced ourselves, introduce any appreciable distortions into this motion. In order to provide grounds for these assertions, one can cite the following arguments:

1. The oscillations of V had a rectangular shape corresponding to a transition between two phase states. In order to fulfill this condition, it is essential that the

domains be large compared with the dimensions of the contact, which was always true when working with single-crystal samples. In the case of the rolled sample the oscillations were often irregular in shape.

2. A decrease of the measuring current i by a factor of hundreds (from 10 to 0.1 mA or lower, down to the sensitivity limit of the apparatus) did not change the shape and period of the oscillations of V. It was noted in preliminary experiments that strong currents $i \sim 100$ mA can cause domain motion near the contact for $I = 0$; however, during all the measurements the current i was chosen to be sufficiently small.

3. The frequency of the oscillations of V was determined by the strength of the current I and the relationship between the width of the peaks and minima changed with changing external magnetic field H in accordance with the change in the content of the normal phase C_n in the sample calculated from the magnitude of H/H_c. The difference between the calculated value of C_n and the value obtained from measuring and averaging over 10–15 periods of the V(t) curve did not exceed ±0.1 in the investigated range of C_n values.

4. Placing a number of microcontacts close to one another on the surface of the sample, one can follow the motion of the layer from one contact to the next. In Fig. 3 the resistance oscillations of one contact repeat with a definite delay all the irregularities of the oscillations of another contact. At the instant marked by a dashed line the direction of the current in the sample was reversed, after which the time shift between the oscillations of the two contacts changed sign, i.e., the layers began to move in the opposite direction. Knowing the distance between the microcontacts, which was measured under the microscope, one could determine from such curves the rate of motion of the layers and the averaged spatial period of the structure. No systematic differences were noted in the results obtained with the aid of pairs of contacts of various dimensions and $\Delta R = 10^{-3}-10^{-1}$ ohm.

An unsuccessful attempt to use our method to observe the motion of domains has also been made by Chandrasekhar, Farrel, and Huang[18] who obtained for a contact between a bronze wire and a tin sample irreproducible oscillations of V of complex shape appearing for a sufficiently strong current through the contact and in the absence of an external magnetic field. These observations led the authors of [18] to express doubts about the possibility of establishing a unique connection between the oscillations of V and the motion of domains, in view of which we have dwelt here on this problem in detail.

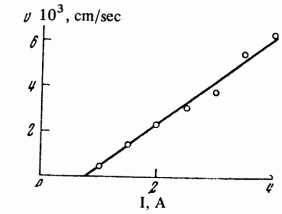


FIG. 4. The v(I) dependence for the sample In3, T = 1.2°K, C_n = 0.5.

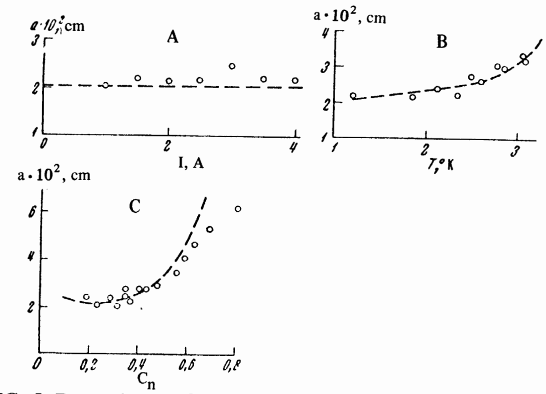


FIG. 5. Dependence of the period of the structure in sample In3: A—on the current, T = 1.2°K, C_n = 0.5; B—on the temperature, C_n = 0.5; C—on the concentration of the n phase, T = 3.06°K. Dashed curves—calculated for I = 0.

MEASUREMENT RESULTS

A. Plane Samples, Projection of an Inclined Field on the Surface Parallel to the Current

The qualitative picture of the motion of layers in tin (Fig. 3, also see [10–12]) and in indium samples was the same. The magnitude of the longitudinal resistivity ρ used for obtaining the values of $\rho(300°)/\rho(0°K)$ cited in the table was measured with the aid of potential leads attached to the central portion of the samples. The measurements were carried out at various temperatures and fields $H > H_c$; the value of ρ for 0°K was obtained by extrapolation to $H = 0$ and $T = 0$.

The results presented in Figs. 4–8 refer to sample In3 provided with additional strips. The rate of motion of the layers v and the period of the structure a were measured as functions of I and T, and the concentration of the n phase C_n directly determined from the ratio of the peak widths of the n state on the records to the length of the period of the curve.

The rate of motion of the layers in all samples was for small currents a linear function of the current: $v \approx I - I_0$ for $I_0 < I < 0.02 I_c$ (see Fig. 4) where for plane samples it was assumed that $I_c = 5\pi^{-1}H_c b[a]$ and b is the width of the sample.

Within the same limits (for $I < 0.02 I_c$) the period of the moving structures practically did not depend on I and was in good agreement with the static value calculated in accordance with Landau's theory[19, 20, 15] starting from the data for the magnitude of the surface tension at the boundary between the s and n phases obtained in [21] (see Fig. 5). Assuming that the presence of a threshold current I_0 is caused by secondary reasons, in comparing with the theory we made use of the velocity increment Δv in the linear portion of the curve for a change of the average current density j in the sample by Δj.

The temperature dependence of the rate of motion of the layers is shown in Fig. 6 where $\Delta j/\Delta v$ is plotted on the ordinate axis. Values of $\Delta v/\Delta j$ as a function of C_n are presented in Fig. 7. The results of two measurements carried out on the same sample after the removal of the lateral strips are also shown there. The decrease of the velocity for small C_n occurred in this case apparently because in a sample without the strips the edges had an increased content of the s phase and acted as shunts which lowered the current density in

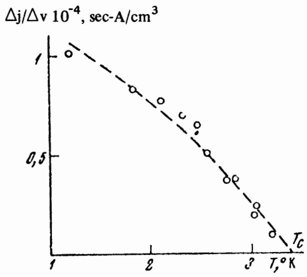


FIG. 6. Temperature dependence of $\Delta j/\Delta v$. Sample In3, $C_n = 0.5$. Dashed curve—dependence proportional to $H_c(T)$.

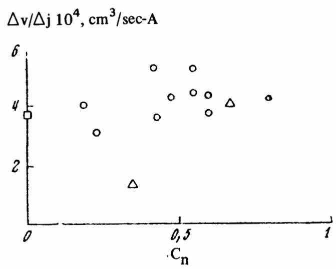


FIG. 7. The dependence of $\Delta v/\Delta j$ on C_n. Sample In3, T = 3.06°K; Δ—measurements without lateral strips, □—calculation for $C_n \to 0$.

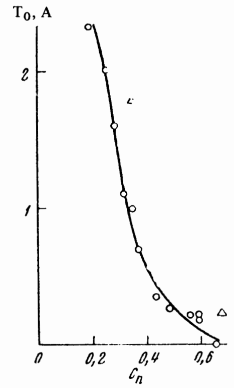


FIG. 8. The $I_0(C_n)$ dependence. Sample In3, T = 3.06°K; Δ—measurements without lateral strips.

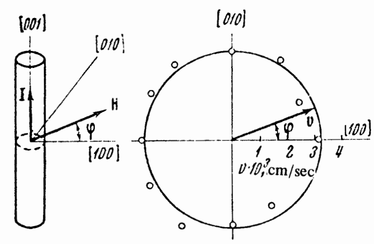


FIG. 9

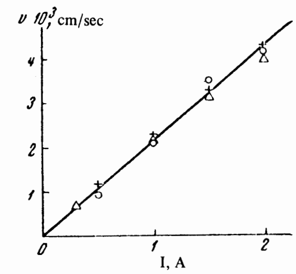


FIG. 10

FIG. 9. $v(\varphi)$ dependence. Sample In5, T = 1.9°K, I = 1.5 A, C_n = 0.5.

FIG. 10. The v(I) dependence for sample In5, T = 1.9°K, O—C_n = 0.37; +—C_n = 0.49; Δ—C_n = 0.7.

the central portion of the sample. For the sample In2 not equipped with lateral strips the relative change of $\Delta v/\Delta j$ as a function of C_n (see [12]) was approximately the same as for sample In3 without strips.

It is seen from Fig. 8 that the shunting of the central part of the sample due to fringe effects also makes an appreciable contribution to the magnitude of the threshold current I_0. The appearance of the threshold current is, in addition, also connected with the presence of inhomogeneities in the samples, in view of which the magnitude of I_0 varied considerably from sample to sample. For the polycrystalline sample In1 the magnitude of I_0 for $C_n = 0.5$ was higher by a factor of two or three compared with single crystals.

B. Cylindrical Samples in a Perpendicular Field

In the experiments described above we observed the motion of layers in a direction perpendicular to the current; this corresponds to Gorter's model. We also undertook a search for the motion of layers along the current, using for this purpose cylindrically shaped samples. Initially the motion was observed[11] for currents I which exceeded the critical value $I_c = 5H_c r$[a] where r is the radius of the cylinder. Subsequently it was found that a steady motion of layers occurs in indium cylinders even for weak currents $I \ll I_c$, and in this region the motion was investigated in more detail.

From the polar diagram in Fig. 9 it is seen that for the indicated disposition of the crystallographic axes the velocity did not depend on the field orientation in the plane perpendicular to the axis of the sample. The direction of motion of the layers coincided in sign with the direction of motion of the positive charges. The velocity practically did not depend on the magnitude of the field, i.e., on C_n, and increased linearly with the current (Fig. 10). Appreciable deviations from linearity towards decreasing dv/dI were observed at the temperature of the experiment starting from 4 A, i.e., approximately from 0.03 I_c.

As in the case of plane samples, the period of the structure a did not depend on the magnitude of I (Fig. 11A) and was in good agreement with the static value calculated for a system of plane layers perpendicular to the axis (see Fig. 11B). (It can be readily shown that the calculation can be carried out by means of Landau's formula for a platelet in a perpendicular field[19, 20] with the thickness of the platelet replaced by the diameter of the cylinder.)

Data on the dependence of the magnitude of $\Delta v/\Delta j$ on T for $I \ll I_c$ are given in Fig. 12. v was also determined for strong currents. To this end a critical current was passed through the sample, for which the inner part of the sample went over to the intermediate state and the surface of the sample became completely normal. As small a transverse field as possible H = 0.14 H_c, was then switched on; this allowed one to observe the moving structure from the side of the sample on which the directions of the external field and of the field of the current were opposed. The surface of the cylinder was in the n state for $H < 0.12\ H_c$ and $I \geq I_c$. The temperature dependence of the velocity, referred to I_c, is shown in Fig. 13. The direction of motion was the same as in the case of weak currents. For $T \ll T_c$ the period of the structure was ~0.4 mm.

C. Dependence of the Rate of Motion of the Layers on Their Orientation

In order to clarify how v depends on the orientation of the layers with respect to the current, experiments were carried out with plane samples in which the angle φ (see Fig. 14) between the projection of the magnetic field upon the surface of the sample and the direction of

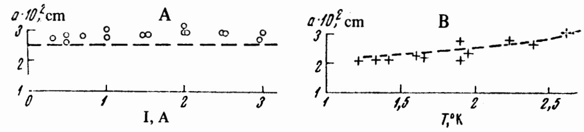


FIG. 11. Dependence of the period of the structure for sample In5: A—on the current, T = 1.9°K, C_n = 0.5; B—on the temperature, C_n = 0.5; dashed curves—calculated for I = 0.

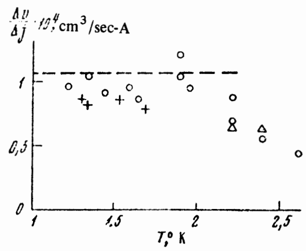


FIG. 12. Temperature dependence of $\Delta v/\Delta j$, C_n = 0.5. Samples: O—In5, Δ—In6, +—In7. Dashed line—theoretical value.

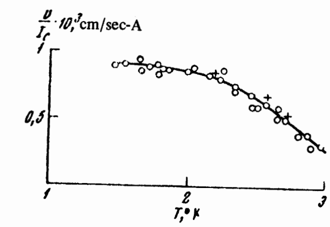


FIG. 13. The dependence of v/I_c on T for I ≈ I_c and H = 0.14H_c. Samples: O—In6, +—In7.

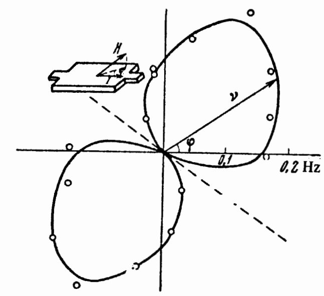


FIG. 14. $\nu(\varphi)$ dependence. Sample In4, T = 1.4°K, I = 3.5 A, C_n = 0.5.

the current was varied with the value of the angle $\beta = 10°$ remaining constant. The frequency of the oscillations of the resistance of the microcontact ν was measured and the results are presented in the form of a polar diagram. It is assumed that v is proportional to ν, since it was shown that a is practically independent of v.

DISCUSSION OF THE RESULTS

On the basis of simple electrodynamic considerations Gorter[5] obtained the expression

$$v = cj\rho / H_c \tag{1}$$

for the rate of motion of layers extended along the current, in a metal with an isotropic resistivity ρ of the n phase in n layers for a field $\mathbf{H}_c \perp \mathbf{j}$ where $\mathbf{j}$ is the current density averaged over the s and n layers. Our experiments show that a similar motion in fact exists in a comparatively regular reproducible form in pure single-crystal samples to which, however, Gorter's expression can no longer be directly applied. The problem here is not only that in this case the relationship between the current and the electric field is expressed by a tensor which depends appreciably on the magnitude and direction of the magnetic field and which is, in addition, in our experiments with plane samples not perpendicular to the current. A more essential difficulty appears because the electron mean free path in our samples $l \sim 1$ mm and exceeds the thickness of the n layers a_n. In this case the galvanomagnetic properties of the n layers should, generally speaking, differ from the properties of the bulk metal in the n state.

This problem has been considered by Andreev[22] who showed that at temperatures not too close to T_c this difference is small and disappears for $T \to 0$ because of the specific nature of the reflection of electrons at a sn boundary. However, obviously this important simplification can only be used under the condition that a_n is much smaller than the dimensions of the sample. The conditions of our experiments with plane and cylindrical samples differed in this sense considerably.

A. The use of an inclined field essential for obtaining in plane samples a system of layers stably oriented along the direction of the current leads[15] to an increase of the period of the structure compared with the case of a perpendicular field. In our case, for a sample thickness $d = 5 \times 10^{-2}$ cm the value of a_n changes at 3.06° K (Fig. 6) from 4×10^{-3} cm for $C_n = 0.2$ to 5×10^{-2} cm for $C_n = 0.5$ and the approximation $a_n \ll d$ may no longer be used even for $C_n \sim 0.5$. The system of currents flowing through the n layers has a complex configuration since in addition to the longitudinal current during the motion of layers currents are induced which circulate in the transverse plane. The quantitative solution of the problem of the motion of the layers, difficult even for $l \ll a_n \sim d$, turns out to be practically impossible for $l \sim a_n \sim d$.

The experiments, however, show (Fig. 7) that the factors influencing the $v(C_n)$ dependence compensate one another approximately (in accordance with approximate estimates on which we shall not dwell here). The data of Fig. 7 obtained at T = 3.06° and the series of measurements at T = 2.77° also showed that v depends little on C_n. By virtue of this one can compare the obtained values of v with the limiting value of v for $C_n \to 0$ which can be estimated. In this case $a_n \ll d$ and, in addition, the field in the n phase is perpendicular to the surface of the sample. The value of ρ for substitution in formula (1) was calculated from the resistivity of the sample in the n state for T = 3.06° as 2.6×10^{-10} ohm-cm (the resistivity was measured in a longitudinal field on whose magnitude it depends little and was extrapolated to H = 0). In calculating ρ a correction was introduced for the diffuse scattering of the electrons at the surface of the sample,[23] determined from the value of $\rho l = 1.35 \times 10^{11}$ ohm-cm^2.[24] Then, starting from the data on the resistivity of our samples in a transverse field the increase of the resistivity in a transverse field H_c = 51 Oe was determined from Kohler's rule. From the final value obtained $\rho = 1.9 \times 10^{-10}$ ohm-cm we determined in accordance with (1) the value of v/j for $C_n \to 0$ marked on the ordinate axis in Fig. 7. The absolute value of v is thus in satisfactory agreement with the estimate obtained with the aid of the Gorter–Andreev theory.

The temperature dependence of v is also in agreement with relation (1). The change in the resistivity of our samples on decreasing the temperature and on simultaneously increasing the field $H_c(T)$ is not large and by virtue of this the value of $\Delta j/\Delta v$ varies within the measurement accuracy in proportion to H_c (Fig. 6). The dashed line in Fig. 6 is the curve proportional to $H_c(T)$.

B. The case of the longitudinal motion of layers in cylindrical samples for $I \ll I_c$ is more convenient for calculation than the case of transverse motion discussed above. Here there are no convective currents, the current in the n phase is always parallel to the axis of the sample, the sample diameter exceeds the thickness of the n layers considerably, and for the calculation one can make use of the resistivity tensor of the bulk metal. The tangential component of the electric field E_t on the boundaries of the layers perpendicular to the current appears in the presence of nondiagonal terms in the resistivity tensor. If, as was the case in our experiment, the direction of the current coincides with the principal axis of the tensor, then $E_t = RH_c j$ and $v = cRj$, where R is the Hall constant and j is the average current density in the sample. If one assumes that $R = 1/nce$, where n is the density of the number of charge carriers in the metal (holes in the case of indium), then $v = j/ne = v_d$, where v_d is the drift velocity of the carriers. The velocity thus turns out to be independent of H_c and since R depends little on the temperature v should also not depend on the temperature. These conclusions are confirmed experimentally (see Fig. 12) at temperatures below 2° K where the velocity of the layers is close to the value calculated from the value of the Hall constant $R = 1.1 \times 10^{-12}$ ohm-cm-Oe^{-1} determined directly for sample In7 at T = 3.6° K and H = 200–300 Oe. The calculated value of the velocity amounts to about $0.7\ v_d$. However, above 2° K the velocity of the layers decreases, the motion becomes unstable, and for $T > 2.6°$ it practically ceases.

Regarding the velocity of structures for $I \ll I_c$ (Fig. 13) it is difficult to express any kind of theoretical considerations, since the applied perpendicular field $H = 0.14\ H_c$ required for observing the structures was necessarily large, in view of which the conditions of the experiment were complicated considerably compared with the case of axial symmetry (H = 0) considered by Andreev.[25] As is seen from the figure, in the case of strong currents we also observed a slowing down and cessation of the motion with increasing temperature.

The most probable reason for the cessation of longitudinal motion is, apparently, the deviation of the layers from a direction perpendicular to the current. On increasing the temperature the Hall field decreases as H_c and becomes appreciably smaller than the longitudinal field ρj. Therefore even a small rotation of the layers can decrease E_t and v considerably. At 2.6° K, for instance, a rotation of the layers by 10° should lead to a halving of v. Although the magnetic field orients the layers in a direction perpendicular to the axis of the cylinder, any inhomogeneities that stop the motion of layers at individual points of the sample should lead to a rearrangement of the system of layers and to its rotation towards its static position.

C. In the case of layers making an arbitrary angle φ with the current (Fig. 14) one can for weak currents consider the state of the sample as a linear superposition of the states of motion under the action of components of the average current density parallel and perpendicular to the direction of the layers. Here the polar diagram $v(\varphi)$ should have the form of the figure eight consisting of two equal circles which is approximately confirmed experimentally. The direction in which the stationary layers should be located was calculated from the measured value of v for layers directed along the current and from the Hall constant. This direction shown in Fig. 14 by a dashed line is approximately at the center of an interval of about 20° in which the motion was unstable or was altogether not observed.

The simple rule for the $v(\varphi)$ dependence presented above should be also equally valid in the case of a perpendicular field. It follows from it that a structure consisting of layers having various directions at various points of the surface should be displaced as a whole in the case in which the entire sample is homogeneous.[13] However, the presence of inhomogeneities can influence appreciably the shape and the velocity of the structures. The immobility of the layers observed in [6-8] and their location along equipotentials of the electric field[7] are apparently connected with the rotation of layers under the influence of inhomogeneities at the beginning of the experiment.

Convincing data relating to the dynamic intermediate state were obtained by Solomon[14, 26] who observed a voltage generated during the motion of structures in a film of sample material deposited on a plane sample on top of a thin insulating layer. In a perpendicular field **H** smaller than some limit $H_1 \sim 0.5\ H_c$ he observed steady motion of structures consisting of closed n domains whose patterns were obtained in separate experiments with the aid of the powder method. For $H > H_1$ the structures were in the form of layers and were stationary by virtue of the rotational effect. For a field **H** inclined along the direction of the current the motion also appeared in the region of fields larger than H_1 in agreement with our results. It is essential to note that the generation of voltage in the film does not attest to the fact that n regions surrounded on all sides by the s phase (vortices) move through the sample. It can be readily shown that the motion of a system of layers making an angle α with the current **I** will also lead to the generation of a voltage $V_s = V_p \cos^2 \alpha$ in the sample where V_p is the voltage applied to the sample.

Among other confirmations of the existence of the motion of domains obtained recently we shall mention qualitative observation of motion with the aid of magnetic particles deposited on the surface of the sample[27] and investigations of voltage fluctuations appearing in impurity containing samples in the course of the motion of domains.[28]

Indirect confirmations of the real nature of the motion of domains were also obtained by observing thermal effects. In our experiments when samples with good heat conduction were submerged in a helium bath the conditions were practically isothermal and estimates show that the effect of the evolution of heat at the domain boundaries on their velocity is negligibly small (see also [29]). However, in the case of a thermally insulated sample the entropy transfer during the motion of n domains should lead to the appearance of a temperature gradient in the direction of motion.[10] The temperature drop in the direction perpendicular to the current observed by Solomon and Otter[30] exceeds considerably the magnitude of the Ettingshausen effect in the normal metal and no doubt attests to the motion of domains. We note here that the energy transfer for longitudinal motion of layers in samples with sufficiently small resistivity can occur with a small evolution of Joule heat so that in principle longitudinal motion can be utilized for constructing a cold machine.

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[1] M. von Laue, Phys. Z. **33**, 793 (1932).
[2] W. J. de Haas, J. Voogd, and J. M. Jonker, Physica 1, 281 (1934).
[3] A. I. Shal'nikov, Zh. Eksp. Teor. Fiz. **16**, 757 (1946).
[4] F. London, Une nouvelle concepcion de la supraconductibilite, Hermann et Cie, 1937, p. 66.
[5] C. J. Gorter, Physica **23**, 45 (1957).
[6] A. I. Shal'nikov, Zh. Eksp. Teor. Fiz. **33**, 1071 (1957) [Sov. Phys.-JETP **6**, 827 (1958)].
[7] F. Haenssler and L. Rinderer, Helv. Phys. Acta **38**, 658 (1965).
[8] B. L. Brandt and R. D. Parks, Phys. Rev. Lett. **19**, 163 (1967); Erratum: Phys. Rev. Lett. **19**, 1216 (1967).
[9] A. D. Misener, Proc. Cambr. Phil. Soc. **34**, 465 (1938).
[10] Yu. V. Sharvin, ZhETF Pis. Red. **2**, 287 (1965) [JETP Lett. **2**, 183 (1965)].
[11] Yu. V. Sharvin, Proc. Tenth International Conference on Low-temperature Physics, 2B, Moscow, VINITI, 1967, p. 323.
[12] Yu. V. Sharvin, Proc. Fifth (Franco-Soviet) Colloquium in Bakuryana on Superfluidity and Superconductivity, 1968, v. 3, Tiflis, 1969, p. 209.
[13] A. F. Andreev and Yu. V. Sharvin, Zh. Eksp. Teor. Fiz. **53**, 1499 (1967) [Sov. Phys.-JETP **26**, 865 (1968)].
[14] P. R. Salomon, Phys. Rev. Lett. **16**, 50 (1966).
[15] Yu. V. Sharvin, Zh. Eksp. Teor. Fiz. **33**, 1341 (1957) [Sov. Phys.-JETP **6**, 1031 (1958)].
[16] I. E. Dzyaloshinskiĭ, Dokl. Akad. Nauk SSSR **105**, 244 (1955).
[17] Yu. V. Sharvin and N. I. Bogatina, Zh. Eksp. Teor. Fiz. **56**, 772 (1969) [Sov. Phys.-JETP **29**, 419 (1969)].
[18] B. S. Chandrasekhar, D. E. Farrel, and S. Huang, Phys. Rev. Lett. **18**, 43 (1967).
[19] L. D. Landau, Zh. Eksp. Teor. Fiz. **7**, 371 (1937).
[20] E. M. Lifshitz and Yu. V. Sharvin, Dokl. Akad. Nauk SSSR **79**, 783 (1951).
[21] Yu. V. Sharvin, Zh. Eksp. Teor. Fiz. **38**, 298 (1960) [Sov. Phys.-JETP **11**, 216 (1960)].
[22] A. F. Andreev, Zh. Eksp. Teor. Fiz. **51**, 1510 (1966) [Sov. Phys.-JETP **24**, 1019 (1967)].
[23] K. Fuchs, Proc. Cambr. Phil. Soc. **34**, 100 (1938).
[24] B. N. Aleksandrov, Zh. Eksp. Teor. Fiz. **43**, 399 (1962) [Sov. Phys.-JETP **16**, 286 (1962)].
[25] A. F. Andreev, Zh. Eksp. Teor. Fiz. **54**, 1510 (1968) [Sov. Phys.-JETP **27**, 809 (1968)].
[26] P. R. Salomon, Flux Motion in Type-I Superconductors, preprint.
[27] H. Träuble and U. Essman, Phys. Stat. Solidi **18**, 813 (1968).
[28] C. J. van Gurp, Phys. Rev. **178**, 650 (1968).
[29] N. I. Shikina and V. B. Shikin, Zh. Eksp. Teor. Fiz. **54**, 1114 (1968) [Sov. Phys.-JETP **27**, 597 (1968)].
[30] P. R. Salomon and F. A. Otter, Jr., Phys. Rev. **164**, 608 (1967).

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