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THE STRUCTURE OF THE SUPERCONDUCTORS IN THE INTERMEDIATE STATE. II*

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The structure of the intermediate state of the superconducting sphere was investigated by means of very small, movable bismuth probes. The distribution of the superconducting and normal regions of the sphere in the intermediate state is measured. The non-equilibrium character of the distribution obtained in our experiments is established. The dependence of the distribution of the regions upon the two examined types of the transition into the intermediate state is established and are found the peculiar features of the distribution for every type. It is proved that the superconducting and normal regions in the sphere cut along the equatorial plane possess a property to go out onto the equatorial planes at small separations between the hemispheres as well as at the large ones.

As it was shown by one of us (1) earlier, it was possible to observe in course of the transition of the tin sphere from the normal state into the superconducting one a peculiar splitting of the superconducting body into normal and superconducting regions when the intermediate state appears. The presence of such a splitting was predicted by Landau (2,3) and was proved by us by means of measuring the induction in a narrow slit between two tin hemispheres. This slit is perpendicular to the direction of the external magnetic field.

A bismuth band, with a resistance depending non-linearly upon the magnetic field strength, was placed in such a slit. We have succeeded to show that the magnetic field in the slit is not homogeneous. This proves the existence of the regions of normal and superconducting phases in the intermediate state, as it was predicted by Landau's theory (*l. c.*). Increasing the separation between the tin hemispheres, *i. e.* increasing the width of the slit, we have shown that the field in the "wide" slit becomes homogeneous again.

The critical width of the slit (*i. e.* the width for which the bismuth band, placed in the slit, began to show the homogeneity of the field) appears, according to our measurements, to be about 50 μ. Using this value we were able to calculate, according to Landau's theory, the value of the surface tension between the superconducting and the normal phases for tin, and also the total thickness of the normal and superconducting regions. For a sphere 28 mm in diameter this thickness was about 0.5 mm, *i. e.* about ten times larger than the critical width of the slit. It seems that such large dimensions of the regions and also the width of the slit, which can be realized practically (50μ), offer a possibility to perform direct measurement of the topography of the field in the slit. Just in this direction we concentrated our efforts.

Search for the method

Basing upon the dimensions of normal and superconducting regions calculated according to Landau's theory from the observed critical width of the slit, it would be natural to continue the experiment by an attempt of a direct measurement of the magnetic fields,

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which cross the slit between the tin hemispheres, with the help of a movable bismuth probe. While on the average the induction in the slit is $B=3H-2H_c$ (H is the external field, H_c is the critical field), the field strength in a given point in the slit may be equal only to zero or H_c, depending upon whether this point is crossed by superconducting or normal regions. In Fig. 1 a possible diagram of such an alternation of the fields, for external fields equal to $0.75 H_c$ and $0.9 H_c$, is represented (magnified about 40 times). From this diagram it is clear that if a sufficiently small bismuth probe is moved in the slit, then we may expect that it will alternately get as a whole into the superconducting or normal regions and measure respectively $H=0$ or $H=H_c$.

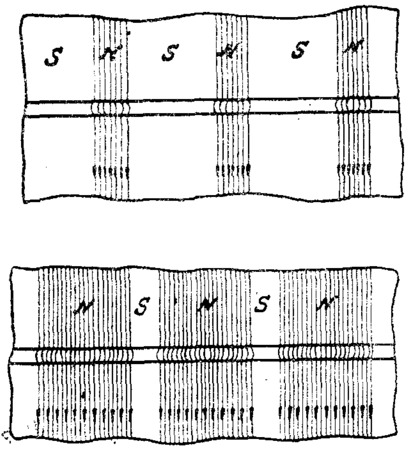

Fig. 1

However, before the exact measurement of the field in the slit was undertaken by this method, we have made at the beginning some attempts to discover the presence of such a structure of the field in the slit in a qualitative way. All these experiments were not successful; however, in our opinion it seems to be necessary to mention them.

a) Method of magnetization of a steel band

The simplest experiment is the recording of the alternating fields, of which one is always equal to zero and the other to H_c, with the help of a thin plate of a magnetic material (possessing a large coercive force) placed in the slit between the tin hemispheres. The sphere is cooled below its critical temperature and with the help of the external homogeneous magnetic field is transferred into the intermediate state. Then the field is switched off. The field distribution which existed at that moment, when the inhomogeneous magnetic field influenced the plate, must be "imprinted" on the magnetic plate which was placed in the slit. Carrying out this experiment at temperatures $2.5-3^\circ$K we could use the magnetizating field about 100—150 Oe. Using then suspensions which are used in the magnetic defectoscopy, we could expect to develop the magnetic image of layers imprinted on a steel plate. The experiments carried out with magnetic models, made of alternating layers of copper and iron, gave hopeful results. However, all our attempts of observing by means of this method the superconducting and normal layers of the sphere in the intermediate state were unsuccessful. This is quite amazing because the introduction of the material with $\mu \neq 0$ into the slit between the superconducting hemispheres could not influence the character of the phenomenon. It is possible that the unsuccessful result of this experiment is due to the fact that in spite of the band being influenced by a transversal magnetic field, its magnetization proceeds in the direction of easy magnetization which coincides for the steel band with the direction of its rolling. This is possible due to the fact that the magnetic field in the slit is not quite transversal and has the shape of "a barrel" in the places of the maximum gradient (Fig. 1), *i. e.* has a component in the plane of the steel band. Certainly, to discover the desirable effect it would be more convenient to make use of a sheet of a magnetic material with the axis of easy magnetization perpendicular to the direction of the rolling. However, we have not continued our work in this way.

b) Method of magnetic powder

Having failed in the experiments with the steel band we proceeded to a simpler possibility, namely to the detection of the layers with the help of the magnetic powder. The experiment was carried out in the following way.

Before the apparatus was mounted, a thin layer of magnetic powder was put into the slit between the hemispheres. We always used a thin cast-iron powder with an average size of the particles of 10—15 μ. In order to get a homogeneous layer of the powder we applied a sieve which we shook with the help of a tuning fork. Different kinds of iron powder, prepared by several methods, appeared to be of little use, because of the cohesion of the particles and their poor mobility. Further operations in our experiment did not differ from those which we performed with the steel band. Usually the temperature was lowered down to 3°K, and then the field equal to $^5/_6 H_c$ was switched on. The apparatus was subjected to mechanical vibrations by means of a slight knocking or with the help of a tuning fork. Then the field was switched off and after heating the apparatus it was dismantled. In some cases the transition of the sphere into the intermediate state was realized by means of lowering the temperature in the constant magnetic field.

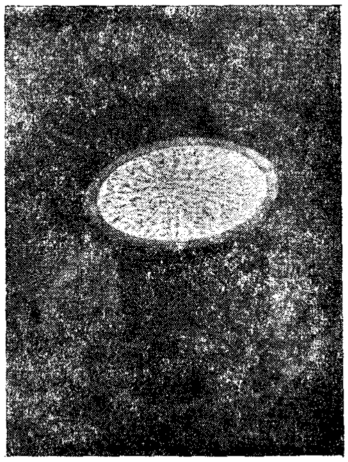

Fig. 2

Nearly in all of these experiments (over twenty in all), performed with different spheres and at different slits, we have observed a completely clear picture of the distribution of the magnetic powder, as it can be seen from Fig. 2. The obtained patterns always had a sharply expressed radial character. Such a distribution of the powder, in spite of its regularity, however, did not probably correspond to the actual distribution of the field. It appeared to be only "the shadow" of the actual distribution. For example, the possibility is not excluded that the observed radial pictures are due to the axial-symmetric location of the layers. In this case the powder particles, having been orientated in the direction of the magnetic gradient, will in their turn orientate each other in such a way as to be directed to the centre of the sphere. Besides the cast-iron powder we tried to perform this experiment with a powder of a superconductor (lead), however, without any essential results.

Method of a movable microprobe

After we had failed in the application of these qualitative methods we decided to try the quantitative method of a moving bismuth probe which, although being more complicated, had to lead us to more definite results.

Our problem was to make bismuth probe of sufficiently small sizes (further on we call them microprobes) and then to work out a construction which should permit us to move the microprobe in the slit not exceeding 50 μ. As in the beginning we had at our disposal only a simple coil for obtaining a homogeneous field, the problem of moving a microprobe in a comparatively narrow Dewar vessel appeared to be difficult enough.

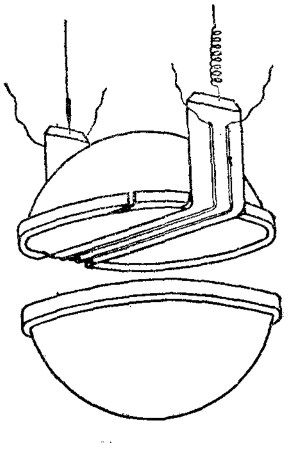

Fig. 3

In its final solution the arrangement we had used is shown in Fig. 3.

The microprobe was a thin bismuth strip of 0.7 mm in length, 0.1 mm in width and 5 μ in thickness, soldered or welded to copper bands, which were stuck with shellac to a thin mica strip (15 μ thick). The ends of the mica strip were pressed between thin copper plates. Each tin hemisphere was stuck with wax to brass rings. The guides which helped to realize the smooth turning of the mica strips through 90° were made along the diameter of the ring of the upper hemisphere. The tension and turning back of the strip was realized with the help of a spring. A thin rod fastened to the other end of the mica strip was led outside the Dewar vessel through its lid. This arrangement, even in its final version, had many drawbacks. The essential drawback was that even at a completely free movement of the strip of mica between the hemispheres, one could never be sure that for the slit of 40 μ the resistance of the microprobe would not change noticeably during its movement. The cause of such a resistance change was not the mechanical gearing, but the fact that the elastic tensions of the strip of mica influence in some way the microprobe. However, with this apparatus we have been able to make a number of experiments which directly confirmed the inhomogeneity of the field in the slit and gave us the first allusion to the structure of the "layers". The encouraging results allowed us to undertake further improvement of the methods.

The greatest simplification of the experiment should be attained if we placed the slit of the sphere in a vertical position and directed the magnetic field horizontally. We realized this by using Helmholtz's coils to produce the horizontal field. The sections of the coils are shown in Fig. 4. The examined sphere is shown in the same scale in the centre of the figure. We verified the homogeneity of the field in such a system with the help of a bismuth probe having the shape of a small spiral (1.5 mm in diameter and 3 mm in length).

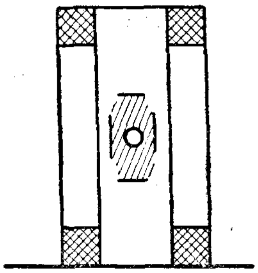

Fig. 4

The resistance of the spiral was calibrated by means of the magnetic field at the temperature of 4.2° K. This spiral could be moved from the centre of the system along all the three coordinate axes. The measurements of the field by such a method have shown that in the region, shaded in the figure, the deviation of the absolute value of the field does not exceed 0.5 per cent.

The planned experiments would be much more simplified if there were the possibility to observe the structure of the intermediate state in a wider slit than that which was used to obtain preliminary results mentioned above, *i. e.* in a slit wider than 50 μ. According to Landau's theory the critical width of the slit is $d_c \sim L^{1/3}$, where L is the length of the force line of the field piercing the specimen before the intersection with the slit [3]. We hoped, therefore, to increase the critical width of the slit by using a sphere of a diameter greater than 28 mm, which was used in the preliminary experiments. Besides that, we wanted to examine a single crystal sphere, rather than a polycrystalline one. Basing on all these considerations we undertook the preparation of a great single-crystal tin sphere.

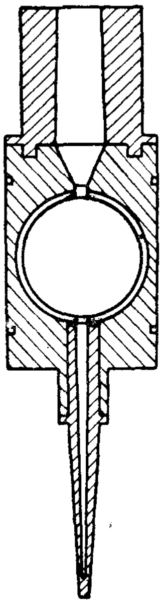

Fig. 5

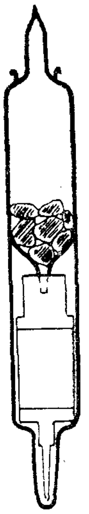

Fig. 6

For this purpose a cylindrical dismantable form of steatite (the section of which is shown in Fig. 5) was made. When the form was mounted a circular glass plate 0.7 mm thick was put between two halves of it. Thus we have obtained two separate hemispheres, which were afterwards filled with molten tin. This filling in as well as the further process of tin crystallization was performed as follows. The form being mounted and fastened with wire rods was soldered into a glass cylinder shown in Fig. 6. Bits of tin "Chempure", from which the sphere had to be casted, were put into the same cylinder. Then the glass cylinder with the form was joined in horizontal position to a diffusion pump. The tin and the form were heated thoroughly at the temperature of 400° C about two hours under the pumping out to remove the occluded gases and moisture. After that the apparatus was unsoldered from the pump and was set into a vertical position. The molten tin flowed through a funnel and filled up the form. In such a state the apparatus was suspended to a watch mechanism and was placed inside a cylindrical electric oven, the temperature of which was kept at about 300° C. With the help of the watch mechanism the apparatus was slowly put down (with the velocity of 15 mm per hour) thus securing a gradual crystallization of tin in the form, starting from its lower appendix, when it reached the region of sufficiently low temperature. When the crystallization was finished, the form was dismantled and the rest of the tin, which remained from the lower appendix of the form and its upper part were sawn off and etched with nitric acid. Thus there remained two single-crystal tin hemispheres which were easily separated from the intermediate glass, since the glass was previously covered by a layer of soot.

Thus we have obtained a comparatively large single-crystal sphere 39 mm in diameter, consisting of two separate hemispheres. Washer made of paper of needed thickness in the form of two segments were stuck in by shellac between two hemispheres in order to produce a slit in the sphere. The two halves of the spheres were also pasted together by condenser paper to make them more solid.

The details of the fastening of the sphere in the apparatus are shown in Fig. 7. The sphere is pressed between two brass rings *1* with felt linings. The slit in the sphere is placed in a vertical position, its width in the direction of its diametrical plane is limited by the stuck paper segments. A mica band *2* with a bismuth probe moves in the slit. The band is stretched down by means of the load *3* placed in the limiting tube *4* which is fastened to the under ring. The band is stretched up with the help of the wire *5* which passes through the cover of a helium Dewar vessel.

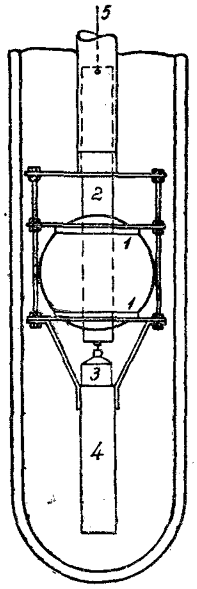

Fig. 7

The construction of the band and the micro-probes placed upon it are shown in Fig. 8. The band consists of two strips of mica 20 μ thick and 10 mm in width, pasted with shellac. The

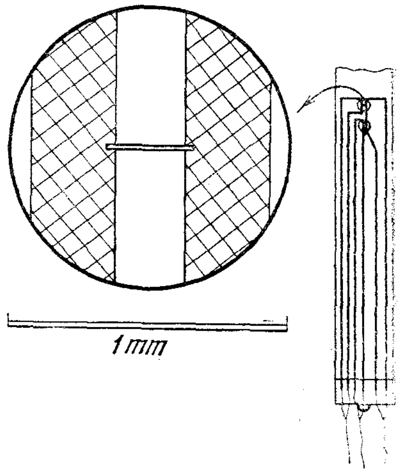

Fig. 8

upper strip has two circular windows 1 mm in diameter for mounting the probes. Current and potential leads in the form of copper bands obtained by pressing of 50 μ wire were stuck between the strips. In the necessary places these bands were covered beforehand with tin, in such a way as to fix the tinned places opposite to the windows of the upper strip. The microprobes are soldered in the windows normally to the leading copper bands, as it is shown in Fig. 8 separately. The maximum thickness of the mounted band of mica is 60 μ.

It is natural that we intended to prepare a bismuth probe as small as possible. A bismuth wire obtained by the usual method (the bismuth to be pressed out through an opening in the steel matrix by means of a hydraulic press) has a minimum diameter of 30 μ. For the purpose of this work it was necessary to have a bismuth wire or a band of a considerably smaller section. At the beginning Taylor's method was used for the preparation of such a wire. A piece of bismuth was put into a glass tube which was heated by means of a gas burner in the place where bismuth was situated. Then the molten tube was quickly stretched in opposite directions. The molten bismuth remained in the thin glass capillary formed in this way. The glass was dissolved in hydrogen fluoride. However, by this method it was possible to obtain bismuth wires not thinner than 15 μ. As the thickness of the upper strip of mica (which preserves the bismuth probe from graze against the plane of the hemisphere at the movement of the band) is 20 μ, it is clear that such a wire appeared to be too thick. Besides it was desirable to get a wire not of a round but of a square section to facilitate the process of its soldering to the cross leading bands.

Therefore, another method of preparation of the microprobe was tested. The initial material was the bismuth wire, diameter of 30 μ, obtained by a usual method. This wire was pressed by means of a hydraulic press between two hardened steel optical mirrors. Bits 2—3 mm in length were cut off from the bismuth band, obtained by the method mentioned above; the width of the band was 0.5 mm, the thickness was 5 μ. Strips of a possibly small width were cut off from these bits by means of a safety blade. Thus we succeeded to cut off the strips of about 10 μ thick. Since the leading copper bands were placed on the strip of mica in such a way that the clearance between them in the place of the soldering of the bismuth probes was 0.25—0.3 mm, the final sizes of this bismuth probe were $5 \times 10 \times 300$ μ.

Experiments with the probes made by such a method showed, however, their unfitness for our aims. It became clear that the probes lose practically their property to change the resistance in the magnetic field (in weak fields). It may be due to the splits which appear in the bismuth strip in the process of its pressing and cutting with the blade. To destroy the splits and make the bismuth again sensitive to the magnetic field we placed the cut bismuth strips into an electrical oven, with the temperature about 300° C, *i. e.* more than the melting temperature of bismuth. The bismuth strips placed in such an oven were melted in it, preserving, however, their shape owing to an oxide layer which covered the melted bismuth. After taking out of the oven, the strips became again solid and thus restored their wholeness, as seen from the experiment, becoming again sensitive to the magnetic field.

The obtained bismuth probes were soldered then to the leads on a strip of mica. Unfortunately, the probe, having secured its wholeness after the soldering, was often broken down at the cooling of the apparatus and the successful experiment appeared to be casual. Therefore, in order to double the probability of an experiment to be successful we have mounted on the strip two probes at once. The resistance of the probe at the liquid helium temperature was usually 0.3—0.4 Ω (about 10 times smaller than at the room temperature).

The movement of the band in first experiments was realized by hands by means of a cremaliere placed over the Dewar vessel equipped with a vernier for indicating the band positions. In order to increase the speed of the measurements the calibration of the bismuth probe with respect to the magnetic field was made without compensation by means of potentiometer, *i. e.* according to the direct deflection of the galvanometer. The first experiments with the movable probe just showed the sharp inhomogeneity of the magnetic field in the slit of the sphere which is in an intermediate state. Therefore, it appeared that the method of the movement of the probe by hands and the visual reading of the galvanometer deflection was too laborious to examine the field in the slit in details. For example, a thorough examination of the field over the whole diameter of the sphere required a measurement of the field in 650 points, which took about seven hours of continuous experiment. To accelerate the measurement process another method was, therefore, adopted. In this method the light beam reflected from a short period galvanometer fell upon a photographic film fixed on a revolving drum. A pulley, winding the wire, which pulled the band of mica in the slit of the sphere through the lid of the Dewar vessel, was placed on the drum axis. Such a simultaneous replacement of the band and the rotation of the drum with the photographic film made it possible to obtain the whole picture of the field distribution in the sphere slit in five minutes. This method permitted to obtain a great number of results with the same bismuth probe with different external fields and different types of transitions into the intermediate state.

Results

a) Determination of the critical width of the slit

As has been shown by **Shalnikov** (¹), the magnetic field in the sphere slit is inhomogeneous, if the separation between the hemispheres is less than some critical value (the critical width of the slit). If the separation is larger than the critical one, the magnetic field is homogeneous. This fact was experimentally detected while measuring the field by means of a large bismuth probe ("macroprobe") and was explained as an effect of the disappearance of the regions of the superconducting and normal phases upon the hemisphere planes, due to the branching when the separation between the hemispheres becomes larger than the critical one. In order to choose a width of the slit that would give the possibility to observe clearly the structure of the intermediate state we had obviously to determine the critical width for the given sphere.

For this purpose we performed some experiments similar to those described in (¹). At first, we took a slit 0.3 mm in width. We mounted in the slit a field probe in the form of an immovable bismuth band, situated upon the sphere diameter. Then the curve of magnetic induction *vs.* external field was measured. The results show that the slit 0.3 mm in width is larger than the critical one as the field in such a slit appears to correspond exactly to the average induction of the sphere in the intermediate state $B=3H-2H_c$, *i. e.* that the superconducting and normal layers evidently disappear at the surface of the slit. Then we took a slit 0.15 mm in width. The curve, obtained in the region of the intermediate state, manifests the inhomogeneity of the field in the slit, *i. e.* the slit 0.15 mm in width is less than the critical one.

Thus it is shown that for our sphere 0.15 mm$<d_c<$0.30 mm. Therefore, for the first experiments with a movable probe we took a slit of 0.12 mm in width.

b) General considerations

It is convenient to represent the normal, the superconducting, and the intermediate states of the sphere in the form of a phase diagram shown in Fig. 9. In this figure the values of absolute temperature are taken as abscissae and the values of magnetic field as ordinates. The upper curve represents the critical field as a function of the temperature $H_c(T)$, the lower curve, $^2/_3H_c(T)$. Obviously, all the points of the plane situated to the right of the curve $H_c(T)$ correspond to the normal phase of the metal, all the points to the left of the curve $^2/_3H_c(T)$ correspond to the superconducting phase (in the case of the sphere). The region between the two curves is the region of the intermediate state of the sphere.

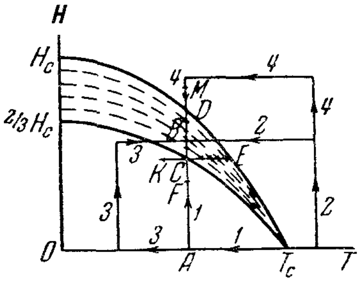

Fig. 9

If a sphere in the intermediate state is split along the equator by a diametrical plane then, as it is known, the portion of the section occupied by the normal phase is determined, according to the theorem of the conservation of the flow of the magnetic induction, by the expression

$$x_n=B/H_c$$

with $B = 3H - 2H_c$ (H — the external field). It is easy to show that in the represented diagram the part of the normal phase for the given point B of the intermediate state is expressed by means of the ratio BC/CD. Further, the points of the intermediate state which correspond to the given value of x_n lie on the isolines:

$$H = \frac{2 + x_n}{3} H_c(T).$$

In the diagram several such isolines are drawn. For each of them the part of the area occupied by the normal state increases by 20%.

One may obviously come to the given point B of the intermediate state of the sphere in different ways. For example, one can at first lower the temperature down to $T_A < T_0$ and then increase the external field up to $H_B > {}^2/_3 H_c$ (the way *1* in Fig. 9). *Vice versa*, one can first increase the field and then lower the temperature (the way *2*). There may be also many other ways (*e. g. 3* and *4*). *A priori* we have no reasons to suppose to get in the point B the identical configuration of the regions of the normal and superconducting phases for all the four ways given in the figure. Therefore, the examination of the dependence of the regions distribution in the given point B upon the ways of the transition is an obvious experimental task for the investigation of the intermediate state. Further, there are no reasons to suppose that even at the same way of the transition, for example, at the way *1* we have to get the identical distribution of the regions for all points of the intermediate state, which are on the same curve, *i. e.* for all the points with identical x_n. As a result of the above considerations it is obvious that the problem of observing the successive change of the configuration and the increase of normal and superconducting phase regions with the variation of the value of x_n ranging from 0 to 1 may become dependent upon the way along which the variation runs. The field distribution in the slit for a certain set of points, lying on the CD segment (the way *1*), may appear to be different than for the set of points lying on the segment CE (the way *2*) even in the case when the points of both sets lie on the same curve of equal values of x_n.

All these considerations were taken as a base for our first experiments upon the examination of the structure of the intermediate state in the sphere.

c) Phenomena at 0.12 mm slit

The axis of abscissae of all the further curves represents the diameter of the sphere and the ordinates are the galvanometer deflections. The calibrating curve of the field probe, allowing to determine the field values, was measured before each experiment.

All the results were obtained by means of the same bismuth probe, which moved along the diameter of the sphere.

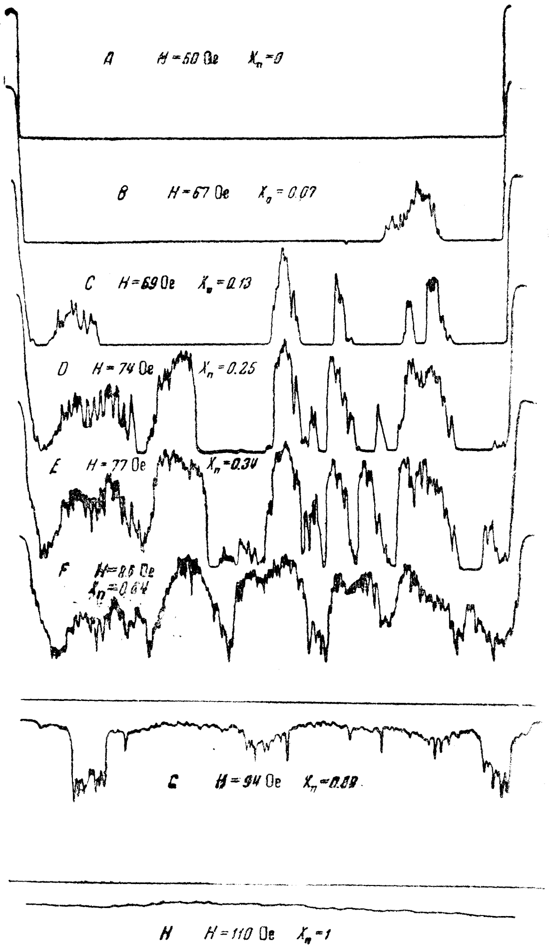

Fig. 10. Slit 0.12 mm, $T = 3°$K.
Field distribution at different external fields

In Fig. 10 a number of curves of the field distribution in the slit (slit width 0.12 mm) for the case of the transition of the type *1*, *i. e.* beginning from the point F in Fig. 9 (superconducting phase) and ending in the point M (normal phase) are plotted. The curves were measured at the temperature 3° K. The curve A corresponds to the superconducting sphere. The absence of noticeable oscillations of the curve at the movement of the probe inside the sphere, where $H=0$, indicates the accuracy of the experiment. The same is confirmed by the good coincidence of the field value at the sphere edges, *i. e.* on its equator, with the value calculated according to the formula $H_{\text{eq}}={}^3/_2 H_{\text{ext}}$.

Curve B is measured in the point where the part of the normal phase $x_n=0.07$. We see that in this case the sphere consists almost only of the superconducting phase, in which separate "islands" of the normal phase are included. One of these islands was met by a probe moved along the sphere diameter and is represented, therefore, on the curve in the form of a region with $H \neq 0$. On the edges of the sphere, as expected, the value of the field equal to H_c was measured. At the further increase of x_n (curves C, D, etc.) we see a gradual growth and appearance of new regions with $H \neq 0$ and also the corresponding decrease of the superconducting regions until the probe stops "to resolve" them at all (curve F).

Quite different pictures of the intermediate state than shown in Fig. 10 we got in the case of the transition of type *2*, *i. e.* along the curve EC of Fig. 9. A set of curves for this transition measured at the field 72 Oe is shown in Fig. 11. Here we see that the curves have not such a strange shape as for the transition of type *1*. Numerous sharp peaks have almost disappeared. The distribution of the regions for all the curves reminds very much "the layers" predicted by the theory. In the first curves A and B we see wide layers of normal phase, separated by very narrow superconducting layers. In the further curves the superconducting layers increase both in number and size. The last curve of this set corresponds to the point K in Fig. 9, *i. e.* to the superconducting sphere. We see, however, that the movable probe, in this case too, has met a region with a non-vanishing field (the peak to the left). It corresponds to some residual magnetic moment of the sphere.

In the course of examination of all the given curves of both sets there arises an impression of an insufficient "resolving power" of our probe, in spite of its smallness. For example, the gradual narrowing of the superconducting layers, which is observed on the curves of the first set, reduces at last to the fact that on the place of a superconducting layer there remains on the curve only a narrow gulf of the field which does not reach the abscissae axis. It looks as if the layer became narrower than the probe (*i. e.* narrower than 10 μ), so the probe now is not entirely in the region of zero field. On the other hand, if we suppose that, besides the layers, we have separate superconducting threads too, which pierce through the sphere [according to Landau (³)], then the phenomenon of the unresolution appears to point out that such a thread became thinner han the length of the probe (*i. e.* 0.3 mm).

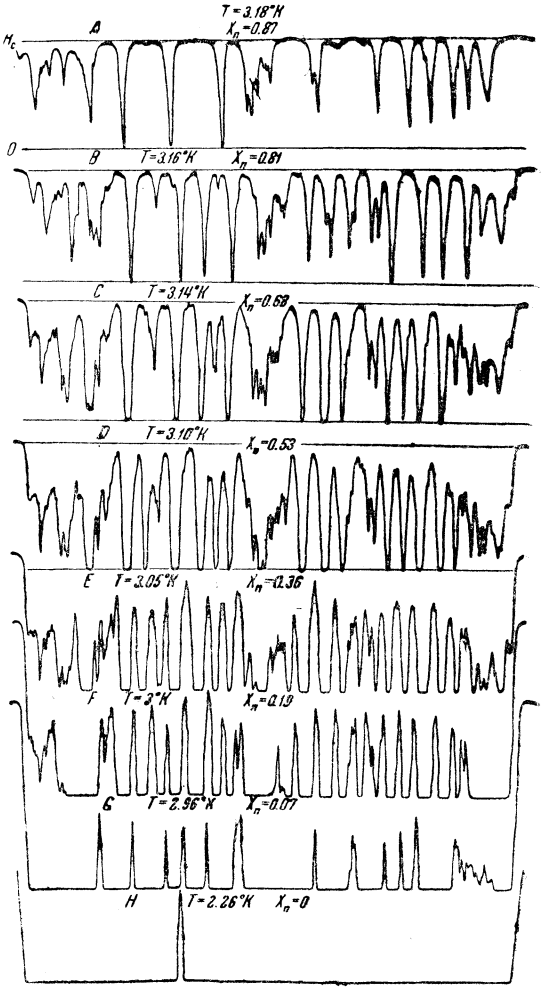

Fig. 11. Slit 0.12 mm, $H=72$ Oe.
Field distribution in slit at different temperatures

These conclusions, however, need an essential correction. There is no doubt that the magnetic force lines in the normal regions entering the space between the two hemispheres do not remain normal to the diametrical plane, but curve themselves, forming a "barrel". Thus the movable probe, measuring the field, does not show the real width of the layers (or the diameter of the threads) but some "effective" width. In particular, it stops to resolve the superconducting layer much earlier than it narrows up to 10 μ. Probably the same "barrel" effect explains why we have not observed within the sphere (except the states close to the normal phase—the beginning of the second set) the fields equal to H_c as it has to be in the regions of the normal phase. Instead of that the field less than H_c is almost always measured in the normal regions, which corresponds to the decrease of the field caused by the spreading of the force lines that had gone out of the hemisphere plane.

As to the numerous peaks peculiar to the curves of the first set, it is supposed that the normal regions in transitions of type *1* are pierced through by very thin superconducting inclusions in the form of thin threads.

The "barrel" effect makes such superconducting threads or layers to be thinner for the field probe and the resolving power of the probe becomes insufficient. The probe, having got into the region of such a structure, is not entirely in the homogeneous field and, therefore, ceases to measure the real field. The galvanometer deflections in this case do not correspond to the calibration curve and we can make only qualitative conclusions from this picture.

It is clear that all the above assumptions need a special examination to prove them.

The comparison of the two given sets of the curves proves that the configuration of the regions of the normal and superconducting phases in the given point of the intermediate state essentially depends on the method of transition to this point. We many times realized in our experiments the transitions of both types (*1* and *2*) and each time got the distribution of the regions, peculiar to the transition of the given type.

It became clear, however, that the configuration of the regions in the given point of the intermediate state and for the given method of transition is not repeated exactly from one experiment to another, *i. e.* it does not depend only upon the method of the transition but upon other causes too. For example, when the set of curves shown in Fig. 10 (the transition of type *1*) was measured, the magnetic field in the coil was changed by means of a rheostat with a sliding contact connected in the coil circuit. In another experiment for the transition of the same type the resistance of the rheostat (and, therefore, the magnetic field) has not been changed gradually, but by jumps which was performed with the aid of a special switch. It appeared that the patterns of the distribution of the field in the sphere, having, however, the same character as the patterns in Fig. 10, still differ very much in details. In other words, it was shown that the configuration of the regions does not depend only on the type of the transition but on the method (or time) of switching on of the magnetic field too. Without presenting the whole set of the obtained curves, it is quite sufficient to illustrate the mentioned above only by one curve *A* shown in Fig. 12 which has to be compared with the curve *E* Fig. 10 measured in the same point ($T = 3°$K, $H = 76$ Oe).

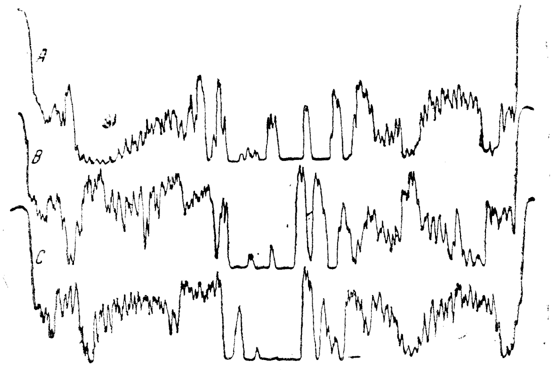

Fig. 12. Slit 0.12 mm, $T = 3°$K, $H = 76$ Oe. **Field distribution in slit measured in different experiments**

Finally, in order to get the more or less same distribution, we made special experiments in which we have intended to maintain, at least in the first approximation, the identical conditions for the transition to this point by measuring the curves in the same points of the intermediate state. In all cases we have obtained different patterns, although similar in character and peculiar to the transition of the definite type. This is seen from Fig. 12, where are given three curves, measured under the same conditions, but on different days.

If the distribution of the regions in the sphere is once established it remains quite stable, provided that the field and temperature are kept constant. In order to check this we sometimes measured the same distribution twice. We always got curves which completely coincided with each other. The smallest details of the curves, sometimes very strange, as is seen from the given curves, were reproduced completely. This proved the stationarity of the phenomenon within the time limit of the experiment (in one of the experiments the second curve was measured in an hour after the first one) and at the same time it was a good control for the whole experiment, as it indicates its sufficient accuracy.

d) Phenomena in wide slits

After having obtained the results for a slit 0.12 mm $< d_c$ in width we undertook a measurement of the field by means of a movable microprobe in a slit, which was wider than the critical one. From many experiments with the macroprobes, situated in the slit with the width $d > d_c$, it followed that the field in such a slit had to be homogeneous and equal to the induction in the sphere being in the intermediate state. Therefore, it may be thought that the experiment with the microprobe in such a slit would be necessary only to control all the work and could not offer any additional interest. The experiment showed, however, that this was not the case.

In the previous experiments with the magnetic powder we performed some measurements with a polycrystalline sphere 28 mm in diameter and the slit width 0.2 mm. It appeared, in spite of our expectations, that the grains of powder formed in this wide slit the same radial picture as in the slit narrower than the critical one. However, a control experiment with the probe, situated along the sphere diameter, showed the usual curve of the induction in the intermediate state $B = 3H - 2H_c$.

To make the contradiction clear we have mounted in the slit, except a long macroprobe, two immovable little probes (1.5 mm in length) situated close to the sphere edge and in its centre. The curves $B(H)$, measured by means of the three probes and given in Fig. 13, still more emphasize the contradiction of the results of the macro- and micromethods of the field examination in a wide slit.

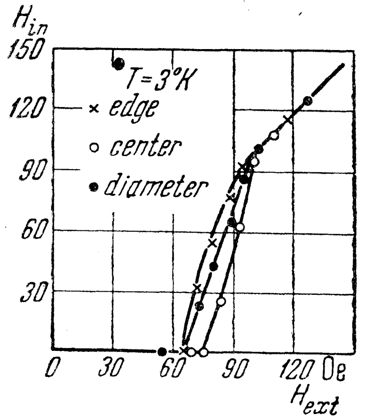

Fig. 13

The cause of the contradiction did not become clearer when we made rough preliminary examinations of the field in a wide slit by means of a small movable probe (with a vertical position of the slit). These experiments showed the inhomogeneity of the field in a wide slit (for brevity the obtained curves are not reproduced here), while the large probe, situated along the sphere diameter, showed as before a homogeneous field.

The results of all these experiments with the wide slits which were performed with two spheres — a polycrystalline, 28 mm in diameter (P 28) and a single-crystal one, 20 mm in diameter (M 20) — are summarized in Table 1, where the data concerning the homogeneity of the field in a wide slit, obtained by different methods of the examination are given. It follows unambiguously from this table that the macromethod of the field examination always showed the field homogeneity in a wide slit, while all the micromethods (2, 3 and 4) always showed the contrary.

In connection with these contradictory results it becomes clear why the thorough examination of the field in a wide slit of a single-crystal sphere 39 mm in diameter offers a more considerable interest than a simple control experiment.

Table 1

Nos.	Date of experiment	Sphere	Method of the field examination			
			Macroprobe	Magnetic powder	Immovable microprobe	Movable microprobe
1	10.III.45	P 28	—	Inhomogeneous	—	—
2	23.III.45	P 28	—	»	—	—
3	30.III.45	P 28	—	»	—	—
4	6.IV.45	P 28	—	»	—	—
5	13.IV.45	P 28	—	»	—	—
6	24.IV.45	P 28	Homogeneous	»	Inhomogeneous	—
7	27.IV.45	P 28	»	—	»	—
8	29.IV.45	P 28	—	—	»	—
9	11. V.45	M 20	Homogeneous	—	»	—
10	28. V.45	M 20	—	Inhomogeneous	—	—
11	8.VI.45	M 20	—	»	—	—
12	21.VI.45	P 28	—	—	—	Inhomogeneous
13	23.VI.45	P 28	—	—	—	»
14	3.VII.45	M 20	—	—	—	»
15	6.VII.45	M 20	—	—	—	»
16	13.VII.45	M 20	—	—	—	»
17	20.VII.45	M 20	Homogeneous	—	—	—

We have begun with a 0.3 mm slit in which, as it was mentioned above, the homogeneity of the field has already been detected by means of the macroprobe, situated along the sphere diameter. The movable probe was the same as in the experiments with the slit 0.12 mm. With the help of this microprobe we have obtained a set of curves for the transitions of types *1* and *2*. The second of these sets is plotted in Fig. 14.

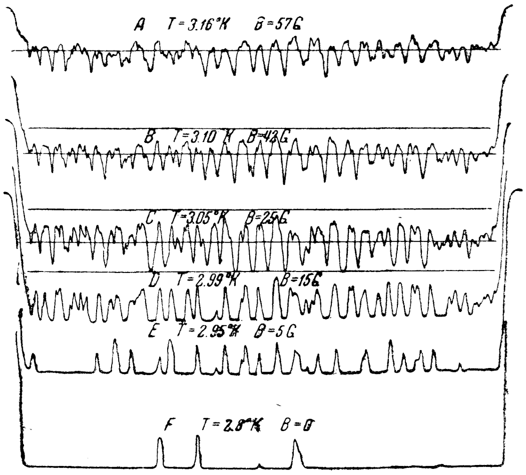

Fig. 14. Slit 0.3 mm, $H = 71$ Oe.
Field distribution in slit at different temperatures

We see that the movable microprobe really does not detect the homogeneous field in the slit, wider than the critical one. This proves that the superconducting and normal regions are not closed near the surface of the wide slit as it was supposed earlier and proved experimentally by means of a macroprobe.

The set, represented in Fig. 14, is very much alike, according to its character, to the similar set, measured at the slit 0.12 mm (Fig. 11). The difference between the two sets is mostly in the amplitude value which has become considerably smaller in the curves of a wide slit. Therefore, there appears an impression that in the slit 0.3 mm we examine the same picture as in the slit 0.12 mm, but with a probe of a lower resolving power. It is particularly clear from the curve near to the normal state, shown in Fig. 15 (measured separately at an-

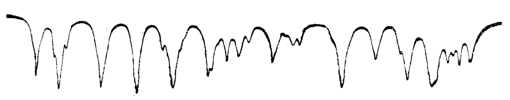

Fig. 15. Slit 0.3 mm, $T = 3.05$°K, $H = 89$ Oe, $B = 84$ gauss.
Transition of type 2

other field), on which the normal layers are observed, but the superconducting ones are not resolved, or from the last curves Fig. 14, where all the superconducting layers are clearly seen but the normal ones are not resolved.

The curves for the transition of type *1* at the slit 0.3 mm also appeared to be very much alike the similar curves for the slit 0.12 mm. We shall not reproduce the whole set but only one of the obtained curves shown in Fig. 16. It is very much like the curve *C* Fig. 10, differing from this one only by a smaller amplitude.

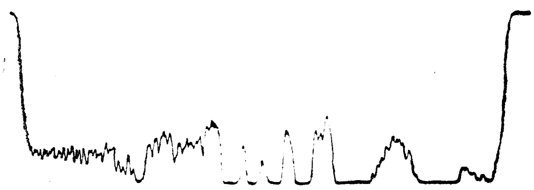

Fig. 16. Slit 0.3 mm, $T = 3°\mathrm{K}$, $H = 72$ Oe. Transition of type *1*

It seems to us that the lowering of the "resolving power" of the probe may be explained by the effect of "the barrel", mentioned above. The bending of the force lines has obviously to be increased with the increase of the separation between the hemispheres, if the layers come out to the surface. All the picture has to be smeared and become less pronounced. Just this is observed in the curves of Fig. 14.

At the further increase of the separation between the hemispheres the increase of the effect, *i. e.* the decrease of the amplitude, may be expected. Actually, the further experiments performed with the slit 1 mm confirmed this assumption. This slit was made in such a way that the band with the probe moved in it along the plane of one of the hemispheres with a clearance of 0.2 mm. In such way the field on the distance $\leqslant 0.1$ mm from the plane of the hemisphere was measured. The obtained results are reproduced in Fig. 17. We see that even at the slit 1 mm the layers come out to the surface and may be easily observed. The amplitude, as was expected, decreased owing to a still larger spreading of the force lines.

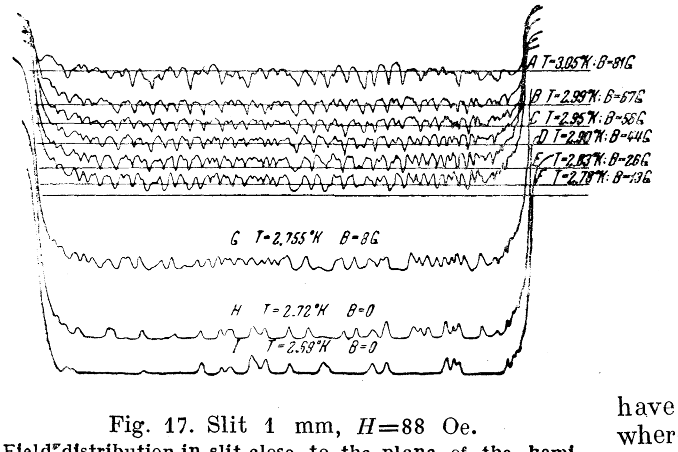

Fig. 17. Slit 1 mm, $H=88$ Oe. Field distribution in slit close to the plane of the hemisphere at different temperatures

It seems to us that the effect of the "barrel" may explain the above mentioned contradiction in the behaviour of the macro- and microprobes. Along with the curves *A*, *B*, *C* in Fig. 14 (slit 0.3 mm) the values of the induction are plotted which have to be in the sphere according to the formula $B = 3H - 2H_c$ (and which were observed in the experiments with the macroprobes). We see that the plotted straight lines coincide approximately with the middle lines of the obtained curves. This coincidence becomes much more striking for the curves, relating to the 1 mm slit, as it is seen from Fig. 17. It means that because of the spreading of the force lines, running out of the body, the microprobe also measures on the average the homogeneous field *B*, but not the alternation of the fields, equal 0 and H_c respectively, as it ought to be directly on the plane of the hemisphere itself, and as it has been observed sometimes in the slit 0.12 mm. Therefore, it becomes obvious that some deviation from the average, detected by the microprobe, are unnoticeable for the large bismuth band, placed along the whole diameter of the sphere and measuring, therefore, the field $B = 3H - 2H_c$. These deviations influence the macroprobe only when the amplitude of the field curve becomes more considerable, *i. e.* at a more narrow slit where the effect of "the barrel" is less. In this case the inhomogeneity of the field is already noted by the macroprobe which, therefore, measures some curve rather than the straight line $B = 3H - 2H_c$.

To confirm the above considerations we have made an experiment with a 1 mm slit, where the field was measured not close to the plane of one of the hemispheres, but at an equal distance between two hemispheres, *i. e.* in the middle of the slit. The effect of "the barrel", if it exists at all, has obviously increased when going away from the planes, *i. e.* the layers distribution must in this case become more smeared. As the curves reproduced in Fig. 18 show, this phenomenon really takes place. One cannot observe the layer at all, but the coincidence of the average lines of the curves with the value of the induction is everywhere extremely good. If we take into account that in all experiments with macroprobes they were mounted approximately in the middle of the slit (owing to the insulating lining and the leads) then it becomes obvious why the homogeneous field was always observed in a wide slit when measuring by means of the macroprobes.

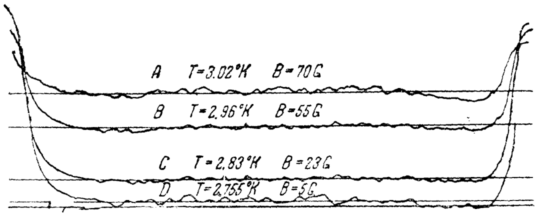

Fig. 18. Slit 1 mm, $H = 87$ Oe.
Field distribution in slit at equal distance from the hemispheres at different temperatures

It was pointed out in (¹) that by means of a macroprobe in some slits there was observed a "transition" phenomenon. Namely the curve $B(H)$ was a curved line, peculiar for narrow slits only for the first half of the interval of the intermediate state, passing on in the second half into a straight line, peculiar for a wide slit. Owing to the considerations concerning the "barrel effect" such a transition phenomenon is quite explicable. The inhomogeneity of the field in the slit is always larger for the section of the intermediate state, which is near to the superconducting phase, than for that section, which is near to the normal phase, because of the larger width of the superconducting regions in the first interval. This is clear from the character of the field distribution in the slit discussed above. Therefore, the effect of "the barrel" in an insufficiently wide slit does not change so much the real field distribution at the beginning of the intermediate state as at its end, and the macroprobe, detecting the field deviation from the homogeneous one, gives in the first section a curved line, which becomes a straight one when the accuracy of the measurements by means of the macroprobe is insufficient to detect the inhomogeneity of the field.

Besides the field examination in the sphere at the slits 0.3 mm and 1 mm, we have still performed experiments with the slit 2.3 mm. The field in such a slit was measured at the distance $\leqslant 0.1$ mm from the plane surface of one of the hemispheres. The distributions similar to the obtained ones for the slit 1 mm (Fig. 17) were observed. In other words, in this case one could also observe the regions of superconducting and normal phases, which go out on the surface. The further decrease of the curve amplitude in comparison with the slit 1 mm was not observed in this experiment.

Thus it is established, that the supposition of the disappearance of the superconducting and normal phases on the planes of the hemispheres at the separation between the hemispheres larger than some critical value is wrong. Once formed regions come out into the planes of the hemispheres in a rather marked way and the problem of their observation may be solved quite positively by a sufficiently accurate experiment.

Conclusions

1. The splitting of the sphere in the intermediate state into superconducting and normal layers as predicted by Landau's theory (²,³) and proved experimentally by Shalnikov (¹) has been confirmed by direct measurements. It became clear that the regions distribution in the given point of the intermediate state is not reproduced exactly from experiment to experiment, as it depends even for the same thermodynamic type of the transition into the intermediate state upon some additional causes (upon the previous states, upon the method and rate of the switching on of the field, on the rate of the temperature variation, etc.). In other words, it became clear that the observed splitting into layers does not possess the properties of the equilibrium state required by Landau's theory. Therefore, the quantitative check of the theory (for example, the calculation of the layer width, the calculation of the surface tension between the superconducting and normal phases, etc.), cannot be made so long as a method will not be found to realize the

equilibrium transition into the intermediate state.

2. It is observed that there exists a peculiar difference in the distributions of regions for two examined cases of the transition into the intermediate state. It became clear that the regions distribution which more closely corresponds to the "layers" predicted by the theory is obtained at the transition realized by the lowering down of the temperature at the constant external field. Much less regular distribution patterns, accompanied by the presence of a fine structure not resolved by the probe, are obtained at the transition realized by the increase of the external field at a constant temperature. All patterns of the regions distribution were examined at the movement of the probe along the sphere diameter, *i. e.* in the one-dimensional case. Therefore, the total conclusion concerning the distribution of regions within the equatorial surface of the sphere cannot be made until the two-dimensional distributions are obtained. We intend to do it in future.

3. It is proved that the superconducting and normal regions, arising into the sphere cut along the equator, come out into the plane surfaces of the hemisphere even at a large separation between the hemispheres, and not only at a separation smaller than the critical one as it was assumed earlier. There are two logical alternatives concerning this phenomenon. At first, it may be a general case, *i. e.* the coming out of the superconducting and normal regions onto the surface without formation of a macroscopically homogeneous "mixed" state is a general property of superconductors of an arbitrary shape. If it is so, the superconducting and normal regions may be observed, for example, upon the sphere surface by means of sufficiently small field microprobes. Secondly, it may be a phenomenon due to the presence of a slit in the sphere, *i. e.* because of some breaking of the sphere integrity. In other words, it may appear that the presence of a comparatively wide slit in the sphere is just the cause of those fanciful unequilibrium distributions that we have observed. If the latter is true, then the assumption concerning the critical width of the slit (which seemed to be disproved by the above mentioned experiments) can preserve its meaning at such narrow slits that their dimensions possibly cannot be realized by experiments. We hope to perform experiments in order to make a choice between these two logically possible alternatives.

In conclusion we express our deep gratitude to Prof. P. Kapitza for his interest in this work, to Prof. L. Landau for valuable discussions and to J. Sharvin for a number of suggestions and advice.

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