ANALYSIS OF THE RESULTS OF EXPERIMENTS ON THE INTERMEDIATE STATE OF A SUPERCONDUCTING CYLINDER WITH CURRENT

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An analysis is made of the experimentally discernible departures from the London model in a superconducting cylinder with current which arise due to Joule heat generated in the domains of normal phase, deformations of the superconducting domains caused by surface energy at the boundaries of the normal and superconducting phases, and shortening of the free path of conduction electrons because of scattering at the surface of the superconducting domains.

It was proved that these perturbing factors can be eliminated by performing expeiiments with samples of sufficient purity, sufficiently large diameters and close enough to the critical temperature. On the basis of an analysis of the experimental material it was shown that despite refinements the results of experiments contradict the London theory.

No analysis was made of the experiments performed with samples of small diameters (50 to 100 microns) or performed at temperatures much different than the critical temperatures. For under these conditions the thermal energy density due to the Joule effect is large, the superconducting domains may become deformed, a Londonean structure cannot become fully formed, and the influence of the shortening of the free path of conduction electrons by scattering at the wire surface comes into play.

1. *Introduction*

As is known, apart from the pure superconducting and pure normal states of superconductors of the first kind there also exists an intermediate state, in which the superconductor becomes a mixture of normal and superconducting domains. These domains exist side by side in a single piece of metal. This state can, in principle, be brought about by any of the factors causing a transition from the normal state to the superconducting state or the opposite. In particular, this can be a change in the helium bath temperature of the superconductor

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or a change of the magnetic field in which it is placed. It makes no difference whether this field is generated by a source outside the superconductor or by the current flowing in it. Of the researches on the intermediate state, a large number dealt with the intermediate state of superconducting cylinders in which a current from an external emf source flows. In some of these experiments an additional external transverse or longitudinal magnetic field was superimposed on the field of the current flowing along the cylinder.

In this paper we shall treat only the problem of the intermediate state of a superconducting cylinder with current. A mathematically simple theory of this phenomenon has been given by London [1]. It enables making a comparison between theory and experiment by measuring the electric resistance, magnetic induction distribution and core radius.

2. Theory of the intermediate state of a superconducting cylinder with current

If in a superconducting cylinder of radius a there flows a current i of intensity lower than the critical value i_c, then the superconductor remains in the superconducting state and the current flows over its surface. When the current reaches the critical intensity $i_c = a\,H_c/2$ the superconductor abruptly transits into the intermediate state and the current is conducted throughout the volume and not only over the surface. With a further increase in current intensity to $i > i_c$ there arises around the central core of radius r_0, consisting of a mixture of superconducting and normal domains, a region of normal state surrounding the core od width $a - r_0$.

As is known, there is no magnetic field inside the superconducting phase. According to the theory of London, in the surface layer of the superconductor in an external magnetic field there arise superconducting currents known as screening currents, distributed in such a way that the magnetic field associated with them cancel the magnetic field inside the superconductor and which penetrated it from outside. In this way the London theory explains the Meissner effect. In the core of a superconducting cylinder with current in the intermediate state there are normal and superconducting domains side by side in equilibrium. Hence, the magnetic field in the normal phase must have the critical value H_c, whereas in the superconducting phase the resultant field is equal to zero, for here the external field and the field of the screening currents cancel each other out. Since in the state of equilibrium the screening currents make stationary closed circuits on the surfaces of the superconducting domains, they cannot appear explicitly in the integral form of the Maxwell equation $2i(r)/r = H_c$ for the core. This is why a magnetic field of critical value H_c corresponds to the current $i(r)$ flowing in the core parallel to the cylinder's axis through the cross-section of a circle of radius r, for this is the condition of equilibrium for the two phases in the core. Therefore, the current i is distributed in the core in such a way that the field in it is equal to H_c. Hence, we write

$$\frac{2i(r)}{r} = H_c \quad \text{for} \quad 0 < r \leqslant r_0. \tag{1}$$

Moreover, London assumes that the electric field in the cylinder, which owing to the symmetry of the phenomenon must be perpendicular to the current's magnetic field, is constant in every point of the cylinder's cross-section. If we imagine there is a hollowed out cylinder in the core, the base of which is limited by circles of radii r and $r+dr$, and denote by $x(r)$ the relative content of normal phase at a distance r from the cylinder's axis, then $\varrho \frac{x(r)}{2\pi r dr}$ will be the value of the resistance of the hollowed out cylinder per unit length, and $\varrho \frac{x(r)}{2\pi r} \frac{di(r)}{dr}$ will be the electric potential along this segment. Here, ϱ denotes the specific electric resistance of the normal phase.

Likewise, $\varrho \frac{1}{(a^2-r_o^2)\pi}$ is the resistance of the normal region surrounding the core per unit length, and $\varrho \frac{i-i(r_o)}{(a^2-r_o^2)\pi}$ the electric potential along this segment, as $i(r_o)$ is the current flowing through the core's entire cross-section, and $i-i(r_o)$ is the current flowing through the normal region surrounding the core. Hence, the equation

$$\varrho \frac{x(r)}{2\pi r} \frac{di(r)}{dr} = \varrho \frac{i-i(r_o)}{(a^2-r_o^2)\pi} \quad \text{for} \quad 0 < r \leqslant r_o. \tag{2}$$

expresses the constancy of the electric field in the entire cross-section of the cylinder.

At the boundary between the core and normal region surrounding the core only the normal phase remains and, therefore, $x(r_o) = 1$, Thus, Eqs (1) and (2) give

$$\frac{2i(r_o)}{r_o} = H_c \tag{3}$$

$$\frac{1}{2r_o} \left(\frac{di(r)}{dr}\right)_{r=r_o} = \frac{i-i(r_o)}{a^2-r_o^2}. \tag{4}$$

From Eq. (1) we have $di(r)/dr = H_c/2$; hence, Eq. (2) takes the form

$$\frac{x(r)}{2r} \cdot \frac{H_c}{2} = \frac{i-i(r_0)}{a^2-r_o^2} \tag{2'}$$

and Eq. (4)

$$\frac{1}{2r_o} \cdot \frac{H_c}{2} = \frac{i-i(r_o)}{a^2-r_o^2}. \tag{4'}$$

From Eqs (2') and (4') we get

$$x(r) = \frac{r}{r_o}. \tag{5}$$

Moreover, putting $r_oH_c/2$ for $i(r_o)$ in Eq. (4') from Eq. (3) we have the equation

$$H_c r_o^2 - 4ir_o + H_c a^2 = 0$$

the solution of which is

$$r_o = \frac{2i \pm \sqrt{4i^2 - a^2H_c^2}}{H_c}.$$

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Since for critical currents i_c the core radius $r_o = a$, hence, only

$$r_o = \frac{2i - \sqrt{4i^2 - a^2H_c^2}}{H_c} \tag{6}$$

is the solution corresponding to our conditions. In this manner, by means of $i(r)$, r_o and $x(r)$ we have obtained a complete description of the intermediate state of a superconducting cylinder with current.

We shall now calculate the resistance of a superconducting cylinder with current in the intermediate state, the distribution of magnetic induction as a function of distance from the cylinder axis, and the Joule heat generated in the cylinder.

If a hollowed cylinder of length h and base limited by circles of radii r and $r+dr$ is considered in the core, the resistance of such a cylinder is equal to $\varrho\frac{x(r)h}{2\pi r dr}$. The resistance of the normal region surrounding the core is $\varrho\frac{h}{(a^2-r_o^2)\pi}$. Thus, from the known dependence for the total resistance R of parallelly connected conductors we get for the whole cylinder

$$\frac{1}{R} = \frac{1}{\varrho}\frac{(a^2-r_o^2)\pi}{h} + \frac{2\pi}{\varrho h}\int_0^{r_o}\frac{rdr}{x(r)}. \tag{7}$$

As $x(r) = r/r_o$, we get after simple calculations

$$\frac{1}{R} = \frac{(a^2-r_o^2)\pi}{\varrho h} \tag{7'}$$

and

$$\frac{R}{R_n} = \frac{1}{1+\left(\frac{r_o}{a}\right)^2} \tag{8}$$

where $R_n = \varrho\frac{h}{a^2\pi}$ is the resistance of the cylinder in the normal state. For critical currents $r_o = a$; hence,

$$\frac{R}{R_n} = \frac{1}{2}. \tag{8'}$$

The resistance jump at a transition of a superconducting cylinder with current from the superconducting state to the intermediate state is equal to half the value of the cylinder's resistance in the normal state, if the relative content of normal phase $x(r)$ increases linearly with distance from the core axis.

Now, we shall calculate the magnetic induction distribution $B(r)$. Since in the core the magnetic field is restricted to the normal phase and has a value H_c there, we have

$$B(r) = x(r)\cdot H_c = \frac{r}{r_o}\cdot H_c \quad \text{for} \quad 0 < r \leqslant r_o. \tag{9}$$

In the normal state region surrounding the core

$$B(r) = H(r) = \frac{2}{r}\left[i(r_o) + \frac{i-i(r_o)}{a^2-r_o^2}(r^2-r_o^2)\right]$$

and hence after some elementary computations we get

$$B(r) = \frac{H_c}{2}\left[\frac{r}{r_o} + \frac{r_o}{r}\right]. \tag{10}$$

Finally, we shall calculate the Joule heat generated in the cylinder within a time Δt:

$$Q = \Delta t \int_0^{r_o} \varrho \frac{x(r)h}{2\pi r} \cdot \frac{di(r)}{dr} di(r) + \Delta t \cdot \varrho \frac{(i - i(r_o))^2 h}{(a^2 - r_o^2)\pi}$$

and, taking advantage of Eq. (2),

$$Q = \Delta t \int_0^{r_o} \varrho \frac{i - i(r_o)}{(a^2 - r_o^2)\pi} h \cdot di(r) + \Delta t \cdot \varrho \frac{(i - i(r_o))^2 h}{(a^2 - r_o^2)\pi}$$

As $i(O) = O$ and from Eqs (3) and (4) it follows that

$$\frac{i - i(r_o)}{a^2 - r_o^2} = \frac{H_c}{4r_o},$$

we get

$$Q = \Delta t \cdot h \cdot \varrho \frac{H_c}{4\pi r_o} i. \tag{11}$$

We are particularly interested in the instant of the transition from the superconducting state to the intermediate state.
Then $i = i_c$ and $r_o = a$, that is, $2i_c/a = H_c$. Thus

$$Q = \Delta t \cdot h\varrho \frac{H_c^2}{8\pi}. \tag{11'}$$

Hence, for critical currents there is less Joule heat generated when ϱ is smaller, that is, when the sample is purer and when the value of the critical field H_c is lower or, in others words, when work is done closer to the critical temperature T_c. Finally, with critical currents the generated Joule heat is independent of the sample radius. Therefore, by using samples of sufficiently large diameters, of sufficient purity and working at temperatures sufficiently close to T_c we are able to lower the density of the generated thermal flux so that the effect of the Joule heat becomes negligible.

3. *The effect of Joule heat, surface energy and shortening of mean electron free path*

As revealed by experience, a vast majority of the results known in the literature display a systematic departure from the theory of London. The resistance jump at transitions from the superconducting state to the intermediate state has proved to be greater than $R_n/2$

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(see *e.g.* [1] to [6],)the radius of the core has been found to be larger than anticipated by London's theory (*cf.* [2], [7] and [8]), and the values of magnetic induction have mostly been found to be lower than the theoretical values [8].

The reasons for these discrepancies between practice and theory usually cited are *a*) pertubrations caused by the Joule heat generated in the normal phase in the distribution of superconducting and normal domains [9], *b*) the effect of surface energy on the shape and size of superconducting domains, and *c*) shortening of the mean free path of conduction electrons owing to scattering at the superconducting domain surfaces.

We shall now analyse each of these factors, and for comparing theory with experiment we shall choose only those experiments which had these perturbations eliminated.

a) In study [11] the temperature distribution along the radius in the intermediate state of a superconducting cylinder with current was calculated. It was found that for samples which are not too thin differences in the temperatures at the axis and surface of the sample are so small that the effect of sample heating on the distribution of superconducting and normal domains is negligible. This is illustrated by several examples. For a tin cylinder [5] of diameter 3 mm and $R_{4.2}/R_{300} = 6.4\times10^{-5}$ and indium cylinders [6] of diameter 3 mm and $R_{4.2}/R_{300} = 1.15\times10^{-4}$, 5×10^{-4} and 8×10^{-4} it was calculated that the temperature differences between the sample axis and the surface of the cylinder are of the order of 10^{-4} to 10^{-5} °K. Temperature differences such as these cannot, naturally, explain the experimentally observed differences in the values of resistance jump as compared with the values predicted by London's theory. The cited temperature differences refer to temperatures not lower than 0.2 °K below the critical temperature of tin or indium for, apart from the closeness to T_c, where the values of H_c and, hence, the values of Joule heat generated, are small; this is a range in which, according to the Ginzburg–Landau theory, the London theory is still valid. Values of the temperature differences of the same order were calculated for a tin cylinder [8] of diameter 4 mm and $R_{4.2}/R_{300} = 1.56\times10^{-4}$ with which measurements of the magnetic induction distribution were made in the 5.577 to 3.70 °K temperature range. In the work [2] the resistance jump was measured for several tin samples of different purities and a diameter of 0.75 mm. For the least pure sample, with $R_{4.2}/R_{300} = 6.0\times10^{-3}$, the author estimates that at 3.27°K the difference in temperatures at the axis and surface of the sample for the critical current amounted to 4×10^{-6} °K. Hence, it could not bear any effect on the found departure of the electric resistance from that predicted by London's theory.

b) We shall now deal with the effect of surface energy at the boundary of the normal and superconducting phases on the departure of experimental results from those predicted by London's theory. As is known, London pointed out the possibility that in the intermediate state of a superconducting cylinder with current the superconductingp hase exists in the form of a number of discs positioned along the axis of the cylinder. Although this is only one of the possibilities which agree whith the assumptions of London's model, many researchers believe that such discs actually do exist, even though there is no experimental proof of this. These researchers explain the departures of experimental results from theoretical predictions by supposing that under the effect of surface energy the shape of the London discs become deformed which, among other things, changes the cylinder's electric resistance. It seems,

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however, that the following reasoning contradicts this existence of discs. If discs really exist, then each one of them constitutes an individual superconducting domain. For the critical current i_c the diameter of a disc, hence, the diamter of one superconducting domain, is equal to that of the cylinder. Thus, at a certain temperature of the helium bath we would be able to obtain superconducting domains of any dimensions, depending only on the diameter of the examined cylinder. This is inconsistent with experimental facts which indicate that the mean domain size is established uniquelly by the temperature of the helium bath and the magnetic field strength. For tin these dimensions are assessed to be from 0.05 to 0.2 mm. Because of this we assume that the core of the superconducting cylinder with current consists of superconducting domains, the mean dimensions of which depend on the temperature of the helium bath, surrounded by a normal phase, wherein the relative content of normal phase at a distance r from the core axis is determined by the function $x(r)$.

A necessary condition for the realization of the Londonean structure is, therefore, the smallness of the superconducting domain dimensions relative to the cylinder diameter so that at least several domains may be arranged along the cylinder diameter. On the other hand, if the sample diameter is of the order of the diameter of one superconducting domain or less, the Londonean structure cannot be realized, the domain reaches the surface of the samples, and the resistance in this case must depend on the surface energy at the boundary between the normal and superconducting phases.

c) The biggest difficulties are encountered in assessing the quantitative effect of the shortening of the mean free path of conduction electrons owing to scattering at the superconducting domain surfaces on the departures of the experimental results from those predicted by London's theory. We can only assume qualitatively that the effect of free path shortening is larger where the concentration of superconducting domains is larger, that is, nearer to the core axis; we are unable to asses this effect quantitavely, however.

Moreover, we know that in the non-steady state a distinct rise in electric resistance of the sample is observed, owing to the creation of nuclei of superconducting phase or the diminution and disintegration of superconducting domains. Thus, the perturbations associated with shortening of the mean free path of conduction electrons will be the smallest in a measurement when the intermediate state is established with certainty. Finally, we only know the mean dimensions of the superconducting domains for tin, *viz.* 0.05 to 0.2 mm; we do not have such values for indium, with which we are deailng with in this work. From Refs [12] and [13] we know the mean free paths of conduction electrons for tin and indium. For the tin samples investigated in this work we assess $l \sim 0.1$ to 0.3×10^{-2} cm, and for indium $l \sim 10^{-2}$ cm.

These data, however, are insufficient for making a quantitative estimate of the effect of shortening of the mean free path of conduction electrons on the differences between the London theory and experiment, as stated before.

Nonetheless, there is a possibility of eliminating the effect of the shortening of the mean free path of conduction electrons on electric resistance indirectly by analysis of the distribution of magnetic induction in the examined sample. Namely, if the magnetic induction distribution is known for an examined superconducting sample in a magnetic field, then by this the distribution of normal and superconducting domains in the sample is known,

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and this in turn is equivalent to a possibility of calculating the electric resistance of the sample. We assume for the specific resistance ϱ of the sample the value determined from measurement in the sample's normal state; hence, the effects associated with the shortening of the free path of conduction electrons will be ousted.

In the case of a superconducting cylinder with current in the intermediate state we proceed as follows. Since in the core $B(r) = x(r) \cdot H_c$ and $B(r_0) = H_c$, we can determine $x(r) = B(r)/H_c$ and r_0 from the empirical depenendence of magnetic field on distance r from the core axis. With these values we make the approximate calculation of the integral $\frac{2\pi}{\varrho} \int\limits_0^{r_0} \frac{rdr}{x(r)}$ in Eq. (7) and from this we calculate without difficulty the electric resistance of the sample without any error resulting from shortening of free path of conduction electrons.

Recapitulating, we may say that if samples used are of sufficiently small remanent resistance ϱ and large enough diameters $2a$, and work is done near the critical temperature T_c, then the conditions will be such that the perturbing influence of Joule heat and structure deformation of the domains will be negligible. The effect of shortening of mean free paths of conduction electrons on the results of measurements can be approximately estimated by analysing the results of measurements of the magnetic induction distribution $B(r)$ and core radius r_0, for we need not know anything about the sample resistance in the intermediate state in order to be able to determine these quantities.

To a large extent these conditions are satisfied by the studies in Refs [2] to [7]. Therefore, we shall compare the results of these studies with London's theory. On the other hand, there will be no analysis of studies which do not satisfy these conditions. Hence, for example, those made with wires of small diameters of the order of 50 to 100 microns or at tempertures distant from the critical temperature, for this already leads to high densities of Joule heat for critical currents, causes the formation of deformed superconducting domains and shortens the mean free path of conduction electrons due to scattering from the wire surface. Moreover, they are performed in a temperature range for which, according to the Ginzburg–Landau theory, London's theory does not hold. Because of this, measurements performed under such conditions cannot be understood otherwise than as an attempt to "prove" the London theory assumed *a priori* by throwing the responsibility for the experimentally observable departures from theory onto factors which perturb the course of the phenomena prepared beforehand.

4. *Analysis of experimental data*

Resistance jump

In the work [2] measurements of the resistance jump were made on polycrystalline tin wires with $R_{3.8}/R_{300} = 6.0\times10^{-3}$ to 2.0×10^{-4} and diameter 0.75 mm. As can be seen in Fig. 5 of the cited paper, concerning the purest sample, and also Fig. 4, the resistance jump is greater than $0.5\, R_n$; R_n being the resistance of the sample in the normal state. Also, the author performed an analysis of the sample heating due to Joule heat and showed that the difference of temperatures of the sample with critical current and the liquid helium is for the best sample about 3×10^{-4} °K, which cannot explain the discrepancy between theory and experiment. The appropriately larger temperature differences for the less pure samples, according to the author, are also not large enough to explain the observed discrepancies.

In [3] the resistance jumps of tin cylinders, almost wholly single crystal, were measured. They displayed asymptotic values R_{0K}/R_{273}°K $= 0.70\times10^{-5}$ to 12.3×10^{-5} and had diameters between 0.156 and 3.390 mm. The values of the resistance jump for samples of diameters from 1.02 to 3.39 mm and near the critical temperatures are given in Table I.

TABLE I

1	2	3	4
Sample	Diameter, in mm	T°K	Resistance jump R/R_n
SnXVI	2.21	3.636	0.56±0.05
SnXXI	2.19	3.681	0.610±0.04
		3.603	0.578±0.04
SnXVII	1.00	3.679	0.618±0.030
		3.676	0.663±0.010
		3.637	0.649±0.020
		3.636	0.649±0.020
		3.597	0.654±0.020
		3.565	0.629±0.015
		3.538	0.665±0.020
		3.502	0.660±0.010
SnX	1.02	3.681	0.681±0.030
		3.640	0.680±0.030

From all of his measurements the author arrives at the conclusion that for ideally pure tin the resistance jump depends only slightly on the diameters contained within 0.1 and 3.0 mm and amounts from 0.57 to 0.73 R_n. Moreover, the author states that the resistance jump for samples of the largest diameter is distinctly larger than the theoretical value 0.5 R_n and that this increase is undoubtedly not due to heating of the cylinder which would cause its temperature to be higher than that of the helium bath. The author also found an increase of resistance jump with shorter free electron paths, and this increase is more pronounced in samples of small diameters.

In [5] only one tin cylinder of diameter 3 mm and consisting of a small number of big crystals had been examined. The distance between the potential leads was 132 mm. Here, $R_{4.2}/R_{300} = 6.4\times10^{-5}$. In fourteen series of measurements, performed at temperatures between 3.597 and 3.70°K the values of resistance jump ranged between 0.54 and 0.69 R_n; the mean value of resistance jump was 0.62 R_n. Thus, the obtained results are in full agreement with Ref. [3].

In [4] a number of indium samples of diameters from 0.04 to 2 mm and $R_{0°K}/R_{0°C} = 2$ to 7×10^{-4} were investigated. The values of the resistance jump for samples of diameters greater than 1 mm and close to the critical temperature are given in Table II.

TABLE II

1	2	3	4
Sample	Diameter, in mm	T°K	Resistance jump R/R_n
In I	1.11	3.284	0.75 ±0.05
		3.174	0.723±0.05
		3.057	0.726±0.05
In IV	1.140	3.281	0.712±0.02
		3.174	0.694±0.04
In IX	1.936	3.355	0.715±0.02
		3.314	0.714±0.02
		3.281	0.722±0.02
		3.228	0.717±0.02
		3.174	0.707±0.02

On this basis the authors state that the values of resistance jump for indium are distinctly larger than the teoretical value 0.5 R_n, also for samples of the highest purity and largest diameters. Moreover, it was found that the values of resistance jump increase when the electron free path is decreased and when the sample diameter becomes smaller. It is noteworthy that the authors did not account for heating of samples due to Joule heat, for an analysis of this problem for tin [3] led them to the conclusion that this effect is also negligible for indium.

In [6] the resistance jump was examined in three polycrystalline indium samples, of diameter 3 mm and different purity with $R_{4.2}/R_{300} = 1.15$ to 8×10^{-4}. It was found that the resistance jump value decreases with increased sample purity: $R/R_n = 0.77$, 0.75 and 0.695. A graphical extrapolation of these values of resistance jump leads to the conclusion that for an ideally pure sample $R/R_n = 0.67\pm0.02$. A decrease in the values of resistance jump with increased sample purity was also revealed in ref. [4]. As in [4], the authors of ref. [6] also found that the resistance jump in indium is distinctly larger than 0.5 R_n.

Magnetic induction distribution

The distribution of magnetic induction was examined in the work [8] by means of a bismuth probe moving in a narrow slit inside a polycrystalline tin cylinder 4 mm in diameter. The slit was in the axial plane of the cylinder. The cylinder, under the effect of the magnetic field of the current (25.8 amp) flowing through it, was in the intermediate state. $R_{4.2}/R_{300} = 1.56\times10^{-4}$. Experiments were made at five different temperatures between 3.577 and 3.70°K. Figure 1 presents the results of measurements of the magnetic induction distribution as a function of distance from the cylinder axis for $T = 3.620$°K. The continuous curve corresponds to the theoretical formulae (9) and (10). As is seen, almost all experimental values are lower than theoretical determinations. The pronounced departures of magnetic induction values from the theoretical ones near the sample surface beginning at about 0.4 mm under the sample surface are due to the strayed magnetic field which gets out of the slit in which the bismuth probe moves to the space around the cylinder. Similar results were obtained for all temperatures at which experiments were performed. Estimates were

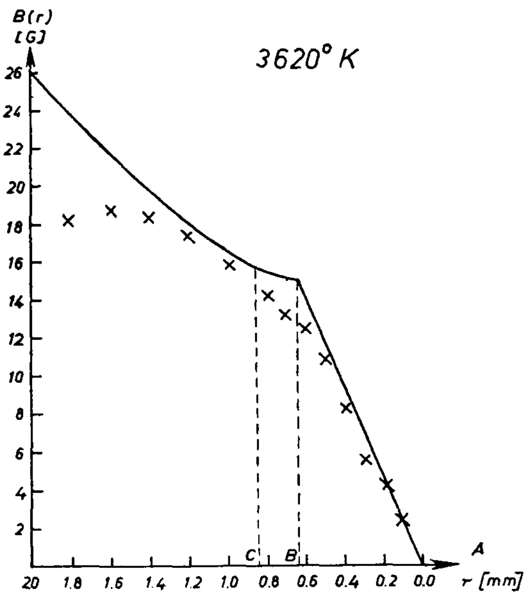

Fig. 1. Magnetic induction distribution $B(r)$ as a function of distance r from cylinder axis for $T = 3.620$°K. The continuous curve corresponds to London's theory, the crosses to the measured points according to ref. [8]. AB corresponds to the theoretical core radius, AC to the experimental value

also made of the effect of Joule heat on the shape of the magnetic induction distribution and it was found that the increments of sample temperature linked with this effect are too small to be able to have any measurable influence.

Core radius

From Eq. (9) we have $B(r_0) = H_c$. Hence, from [8] we can graphically find the core radius. The segment AB in Fig. 1 obviously corresponds to the theoretical value of core radius, and AC to the experimental value. We see thus that the core radius has in reality higher values than the theoretical ones.

In [2] and [7] the core radius was measured by a different method. To the magnetic field of the current flowing through the cylindrical sample in the intermediate state a low magnetic field was applied perpendicularly to the sample axis. This caused an eccentric shift of the core without change of its structure. Hence, the total resistance of the sample remained unchanged up to the instant when the perpendicular field reaches such a value that the core starts to touch the cylinder surface. The instant the perpendicular field exceeds

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this value the core becomes deformed and the sample resistance becomes altered. By this way the core radius had been determined for various critical currents for one of the samples.

The crosses in Fig. 2 represent the results of core measurements (to be more precise, the ratio of the core radius and sample radius) on the basis of the papers [2] and [7], whereas the circles are the values obtained on the basis of ref. [8].

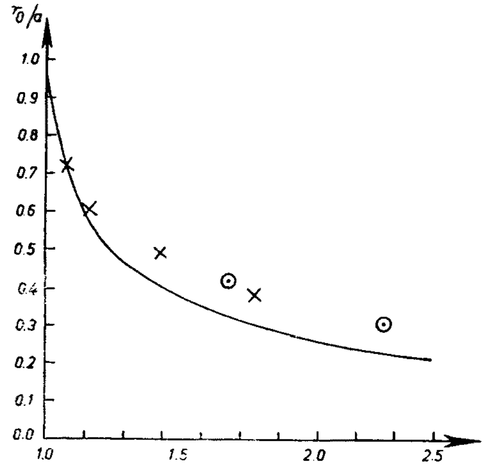

Fig. 2. Reduced core radius r_0/a as a function of reduced current i/i_c. Crosses correspond to experimental values according [7], circles to measurements in [8]

Neither the Joule heat, nor the shortening of the mean free path could perturb the results of measurements in these studies. It may be said, therefore, that the core radius really is larger than that predicted by London's theory.

5. *Conclusions*

Measurements of the resistance jump at the transition of a superconducting cylinder with current into the intermediate state, the magnetic induction distribution inside the cylinder and the core radius, made on samples of sufficiently large diameters, sufficiently low remanent resistance and close enough to the critical temperature, lead to results contradicting the London theory. This is so despite acounting for the effect of Joule heat generated in the normal phase, deformations of the superconducting domains and shortening of the mean free path of conduction electrons.

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