photoemission current might have been below the sensitivity available for the reasons previously described.

Low-temperature measurements on the Ag-thallium halides showed a photoresponse in the spectral region 0.3–2.5μ. This response was independent of polarity of the silver film but was dependent on length of intrinsic irradiation at low temperature. The enhanced photocurrent could be bleached either by long-wavelength irradiation at low temperature or by thermal activation at room temperature. It is clear, therefore, that the observed response is photoconductive rather than photoemissive in nature.

The negative result of the search for photoemission from a metal into an insulator casts some doubt on the theoretical treatment of the metal-insulator contact as suggested by Mott and Gurney. The experimental evidence in support of this picture is less convincing in the light of the findings reported in this paper. Future experiments should be done with better samples prepared under ultra-high vacuum to avoid adsorbed gases between metal and insulator. An ac method of measurement might be more successful than the dc method used in this investigation. Finally, the interpretation of the photoemissive threshold must involve a knowledge of the Fermi level in the insulator.

ACKNOWLEDGMENTS

The author wishes to thank Dr. R. G. Breckenridge, former chief of the Solid State Physics Section, for suggesting the problem and for his advice and discussions on the work; Professor Karl F. Herzfeld and Professor Richard L. Petritz for their thesis guidance; Dr. M. A. Gilleo of Bell Telephone Laboratories and the Solid State Physics Section of the National Bureau of Standards for their suggestions and cooperation; William J. McKean, Joseph M. Smith, and John J. Madine for their assistance in construction of apparatus.

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Paramagnetic Effect in Superconductors. III. Measurements on Hollow Cylinders of Mercury and Tin*

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The circular flux which is set up by a longitudinal current passing through a hollow cylinder has been measured in the intermediate state by ballistic and fluxmetric methods. The flux has a maximum in the transition region and drops to zero in the pure superconducting state, which is in qualitative agreement with theoretical predictions. The dependance of the maximum of the flux increase on the current and on the ratio of the inner to the outer diameter of the sample was found to be different from the the theory. It was found, in particular that the ratio $\tilde{K}_{m\varphi}$ of the maximum flux, $\Phi_{\max}$, to the flux in the normal conducting state Φ_n is not independent of the current. It is not possible to correct the theory from these measurements alone. However, it seems very likely that the correction which has to be applied here is intimately connected with the correction term $1-I_g/I$ which has to be applied to the theory of the paramagnetic effect.

It was further found that the value of the maximum of the circular flux does not change if a longitudinal magnetic field is superimposed. This is in line with theoretical predictions. The longitudinal field intensity in the hole and the resistance of the sample were also measured and the results compared with the present theory. The technique of introducing currents up to 15 amp into the cryostat and an all-metal Dewar vessel are described.

I. INTRODUCTION

It was pointed out recently[1] that the circular flux which is set up by a longitudinal current in a hollow cylinder should show an increase in the transition region before it goes to zero in the pure superconducting state. Previous experiments by Steiner *et al.*[2] were quite contradictory and did not give the absolute value of the flux increase. They observed the deflection of a ballistic galvanometer, connected to a toroidal search coil which was wound around the sample, when the temperature was changed, so that the sample passed through the transition point while the current was held constant. Their contradictory results were due to the following facts: (1) time effects, insofar as the ballistic deflection of a galvanometer allows the measurement of a change in flux, only if this change occurs in a time short compared to the period of the galvanometer, which was not the case under the conditions which they used. (2) Frozen-in fluxes, insofar as they may totally obscure what would be going on if no flux would freeze in. (3) Differences in the surface conditions, insofar as a higher transition temperature for the inner surface would concentrate the current on the inner

* Supported by a grant of the National Science Foundation.
[1] H. Meissner, Phys. Rev. 97, 1627 (1955).
[2] K. Steiner, Physik Z. 38, 880 (1937); Stark, Steiner, and Shoeneck, Physik Z. 38, 887 (1937); K. Steiner and H. Schoeneck, Physik Z. 40, 43 (1939).

surface and give rise to a flux increase which would not be observed in a pure sample.

The measurements which are reported here were conducted in the following way: A galvanometer was connected to the search coil, and the deflection observed while the current was reversed. The temperature was changed extremely slowly (about 0.001°K per minute) over the transition region. The fluxmeter was used if the time constant of the change of the flux was not short compared to the period of the ballistic galvanometer. No frozen-in flux appears in the measurements, since the current is frequently reversed, as shown earlier by fluxmeter recordings.[3]

Furthermore, the samples were prepared such that there could be hardly any difference between the inner and outer surface. The mercury samples were prepared by filling forms of formica with mercury. Although there is probably some stress set up due to the cooling down, this should not affect the surface conditions. The tin samples were cast in vacuum as single crystals on a graphite core in a precision ground glass tube. They were easily removed from the glass tube and the bulk of the graphite drilled out in the lathe. The last few mils of graphite were loosened by etching and either fell out or were easily cracked away. The specimen was then electrolytically polished and varnished. Such a procedure should also insure uniform surface conditions.

The influence of a superimposed longitudinal magnetic field on the circular flux was studied, using the mercury samples. An analysis, which was presented in Part II,[4] showed that this should have no influence on the maximum value of the circular flux.

It was further studied whether under these conditions the maximum of the magnetic field in the hole,[3] the maximum of the circular flux and the breakoff of the resistance coincide. Theoretically all three should occur at the temperature at which $H_c=(H_{\varphi 0}^2+H_{z0}^2)^{\frac{1}{2}}$, where H_c, $H_{\varphi 0}$, and H_{z0} are defined as in Part I[1] of this series. Earlier experiments had shown, that in a solid cylinder the maximum of the paramagnetic effect and the breakoff of the resistance nearly coincide[5] and that in a hollow cylinder the maximum of the field in the hole coincides with the maximum of the longitudinal flux through the whole cross section.[3]

II. EXPERIMENTAL ARRANGEMENT

(a) Cryostat

The high current connections which are necessary for this experiment require a liquid nitrogen temperature level. This is easily obtained by enclosing the helium Dewar in a brass can and submerging the whole can in liquid nitrogen as previously described.[6] No

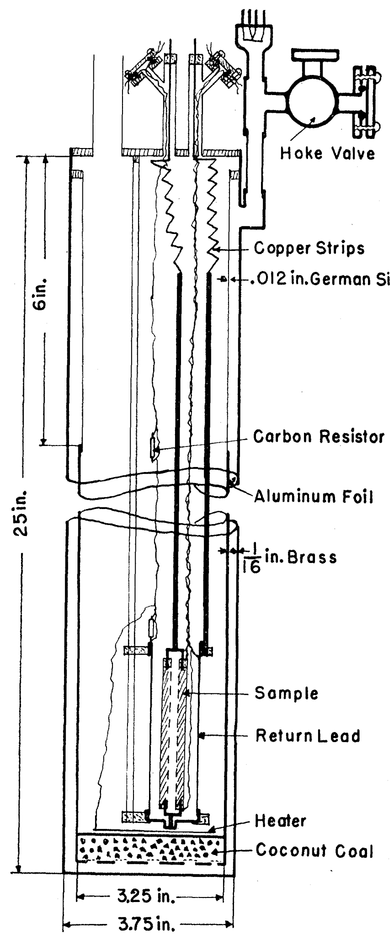

FIG. 1. All metal helium Dewar for circular flux measurements.

difficulty was encountered in these earlier experiments where soft glass Dewars were used. The diffusion rate of the helium gas through Pyrex Dewars, however, was, under these conditions, relatively high, so that finally an all-metal Dewar as shown in Fig. 1 was constructed. The details can be easily seen in the figure. If properly precooled to 77°K, the glass Dewar, as well as the metal Dewar, required 3–4 liters of liquid helium in order to cool the vessel further and collect 2–2½ liters in it. This amount of helium allowed experiments with currents up to 15 amp for about 3–4 hours in the glass Dewar, and for about 2–3 hours in the metal Dewar, the lower figure being valid for the runs with tin, the higher figure being valid for the runs with mercury. The temperature was coarsely regulated with a needle valve, while fine regulation was done with a heater at the bottom of the Dewar.

(b) High Current Connections

The high current was taken from an automotive lead storage battery, which was recharged at the same time. The current was brought to the feed-through's shown

[3] Meissner, Schmeissner, and Meissner, Z. Physik **132**, 529 (1952) (see especially page 532).
[4] H. Meissner, Phys. Rev. **101**, 31 (1956).
[5] Meissner, Schmeissner, and Meissner, Z. Physik **130**, 524 (1951).
[6] Meissner, Schmeissner, and Meissner, Z. Physik **130**, 521 (1951).

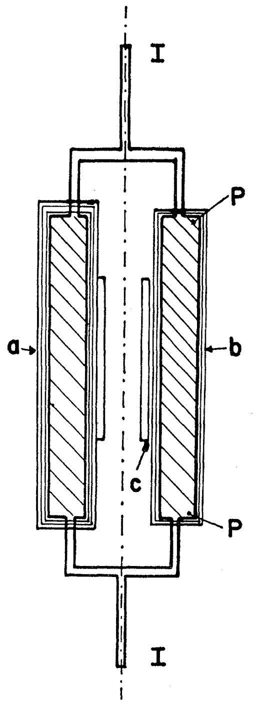

FIG. 2. Sample (schematic) with current connections I, potential leads P, toroidal search coils a and b and solenoidal search coil c in the hole.

in Fig. 1 with No. 6 wire, and from there with No. 16 wire to copper plates which were in thermal contact with the top plate of the Dewar, though electrically insulated from it. From there the current was fed through two copper strips 0.001 in. thick, $\frac{5}{16}$ in. wide and about 4 in. long to No. 6 copper wires, which went all the way down into the Dewar. These copper strips were calculated for a current of 10 amp according to the formula given by W. Meissner.[7]

$$(V_2-V_1)^2=\tfrac{1}{2}\int_{T_1}^{T_2}\lambda/\kappa dT, \tag{1}$$

where V_1-V_2 is the potential difference between the endpoints of the strip, which are at the temperatures T_1 and T_2, λ the thermal and κ the electrical conductivity of the copper.

The resistance of these copper strips is given by[8]

$$R=(l/q)(V_2-V_1)\left[\int_{V_1}^{V_2}\kappa dV\right]^{-1}, \tag{2}$$

where l is the length and q the cross section of the strip.

For copper with a residual resistance of about 2% of the room temperature resistance, one has

$$\lambda/\kappa\approx aT \text{ with } a=1.75\times10^{-8}\ \mathrm{v}^2/(^\circ\mathrm{K})^2. \tag{3}$$

From Eqs. (1), (2), and (3) it follows that one has to make

$$l/q=(a^{\frac{1}{2}}/I)\int_{T_1}^{T_2}\kappa dT, \tag{4}$$

where I is the current in the strip. The value of the integral in Eq. (4) can be easily obtained from the known resistivity curve. For $T_1=4^\circ$K, $T_2=80^\circ$K, one then obtains

$$l/q=19.2\times10^4/I, \tag{5}$$

where l and q are in cm and cm^2, respectively, and I is in amperes.

The heat input from the wires to the helium under these conditions is given by[9]

$$\dot{Q}=I(V_2-V_1). \tag{6}$$

The whole calculation is strictly correct for wires which go through a *vacuum space*. Since the connection actually goes through helium gas, one takes strips instead of wires and makes use of the additional cooling of the escaping gas. The actual heat input is then considerably smaller than given by Eq. (6) and one can safely use the strips for currents which are somewhat larger than the one used in the calculation.

(c) Samples, Search Coils, and Galvanometers

Most of the information on the samples is contained in Table I and Fig. 2. The mercury samples were probably polycrystalline, the structure changing from run to run, since they always were molten between runs. The mercury filling was occasionally renewed between runs.

The tin samples were single crystals, which were prepared as mentioned in the introduction. They had

TABLE I. Data on the mercury and tin samples.

Sample No.	Hg I	Hg II	Sn IV	Sn I
Source of metal	Metal Salts Corporation, Hawthorne, N. J. triple-distilled mercury		Vulcan Detinning Co. high-purity tin	
Purity	>99.99%		99.998%	
Analysis	nonvolatile matter 0.001%; insoluble matter 0.000%; foreign metals 0.00 %		lead 0.0005%; iron 0.0002%; antimony 0.0005%; others 0.0008%	
o.d.	19.0 mm	19.0 mm	19.0 mm	19.0 mm
i.d.	4.0 mm	12.7 mm	6.4 mm	12.7 mm
Length	60 mm	60 mm	60 mm	60 mm
$\rho_*=R_i/R_0$	0.21	0.67	0.33	0.67
$R_{273^\circ\mathrm{K}}$ (ohms)	1.66×10^{-4}	2.95×10^{-4}	2.18×10^{-5}	3.40×10^{-5}
$R_{4.2^\circ\mathrm{K}}$ (ohms)	6×10^{-8}	10×10^{-8}	6×10^{-10}	7×10^{-10}
Toroidal coils				
a	49 turns	77 turns	60 turns	59 turns
b	196 turns	305 turns	200 turns	295 turns
Longitudinal coil c in hole:				
i.d.	1 mm	8.0 mm	no coil installed	no coil installed
o.d.	2.2 mm	8.1 mm		
length	40 mm	8 mm		
No. of turns	3428	172		

[7] W. Meissner, *Handbuch der Experimental Physik* (Verlag Julius Springer, Berlin, 1935), Vol. 11, part 2, p. 185; and Ann. Physik **47**, 1001 (1915).

[8] Reference 7, p. 182.

[9] Reference 7, p. 185.

a few deviations from perfect symmetry at the upper end of the inner surface due to uneven filling of the form during casting, although the casting was done in high vacuum in order to prevent contamination from dissolved gases.

The toroidal search coils, a and b, see Fig. 2 and Table I, were always placed opposite to these shallow holes. All serach coils were wound from No. 40 copper wire. The longitudinal search coils c were wound on a core and placed in the holes of the samples.

Two samples were mounted in separate concentric copper tubes, which served as return lead for the current, which always passed through both samples.

The earth's magnetic field was compensated with Helmholtz coils to a value of less than 0.0035 amp/cm.

The Leeds and Northrup galvanometer type *HS* No. 2284-b was used with a telescope and a scale at 5 m distance for ballistic and potential measurements. It has a ballistic sensitivity of 2.6×10^{-8} v sec/mm and a voltage sensitivity of 0.87×10^{-8} v/mm. Larger potentials were measured with a type K_2 potentiometer, using the galvanometer as null instrument.

A Leeds and Northrup galvanometer type *HS* No. 2285e (special) was used for the flux metric measurements. It is similar to the No. 2285e instrument, but fitted with a thinner suspension. It has an open circuit period of 33 sec and a critical damping resistance of 600 ohms, while its internal resistance is only 18 ohms. It was used with external resistances of a few ohms and had a fluxmetric sensitivity of 45×10^{-8} v sec/mm with the scale at a distance of 5 m. This galvanometer returns, under these conditions, to half of the deflection in about 2 minutes.

III. MEASUREMENTS OF THE CIRCULAR FLUX

One of the search coils, a or b, was connected to the galvanometer circuit and the ballistic or fluxmetric deflection was observed when the current was reversed. The change of flux in the mercury samples always occurred in a time short compared to the period of the ballistic galvanometer, and ballistic and fluxmetric measurements gave the same results. In the tin samples, however, the change of flux at certain temperatures was very slow, and ballistic measurements were not possible. This difference in the time constant is apparently due to the lower resistivity of the tin, which in turn is due to the higher Debye temperature.

The deflection α_0, which is observed at a temperature above the normal transition point, corresponds to the flux in the normal conducting metal and some leakage flux through the outer part of the coil, while the deflection α_{00} which is observed at a very low temperature corresponds to the leakage flux only, since in the pure superconducting state of the metal the current flows at the outer surface.

The ratio of the flux ϕ in the intermediate state to the flux ϕ_n in the normal conducting state is therefore

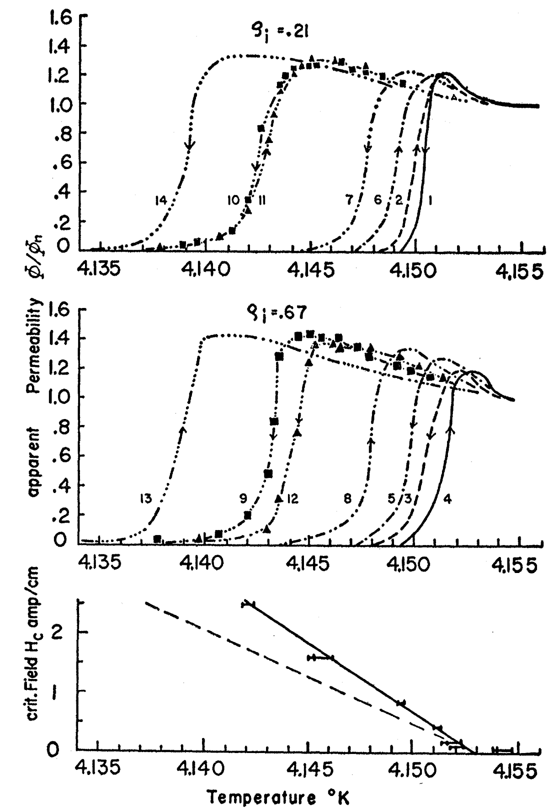

FIG. 3. Measurements of the circular flux on 2 mercury specimens. Upper part: specimen Hg I with $\rho_i = R_i/R_0 = 0.21$. Center part: specimen Hg II with $\rho_i = R_i/R_0 = 0.67$. Bottom part: critical field as given by the peak of the circular flux. —— $I=0.5$ amp ballistic measurement; — — $I=2.5$ amp ballistic measurement; —·— $I=5$ amp ballistic measurement; —··— $I=7.5$ amp ballistic measurement; —···— $I=10$ amp (■ ballistic measurement, ▲ fluxmetric measurement); —····— $I=15$ amp fluxmetric measurement. For clarity, measured points are shown only on the 10-amp curve. The small numbers at the curves indicate the sequence in which they are measured. The helium level was about 30 cm above the specimen for curve 1 and a few cm above the specimen for curve 14. Note the arrows which indicate whether a curve is measured with rising or falling temperature. Dashed curve in bottom part: slope of the H_c-T curve as given by Misener.

given by

$$\phi/\phi_n = (\alpha-\alpha_{00})/(\alpha_0-\alpha_{00}). \tag{7}$$

The two upper parts of Figs. 3 and 4 show plots of ϕ/ϕ_n as a function of the temperature for two mercury and two tin samples for various currents between 0.5 and 15 amperes. ϕ/ϕ_n rises with decreasing temperature and then falls rather abruptly to zero. The peak should theoretically be at a temperature where $H_c = H_{\varphi 0}$. The lower parts of Figs. 3 and 4 show the plots of H_c *versus* T as determined from the peaks. $H_{\varphi 0}$ is easily obtained from the current and the outer radius of the sample. The temperature was obtained from the vapor pressure above the liquid, using the 1948 smoothed temperature scale.[10] No attempt was made to correct

[10] Clement, Logan, and Gaffney, Naval Research Laboratory Report No. 4542 (unpublished).

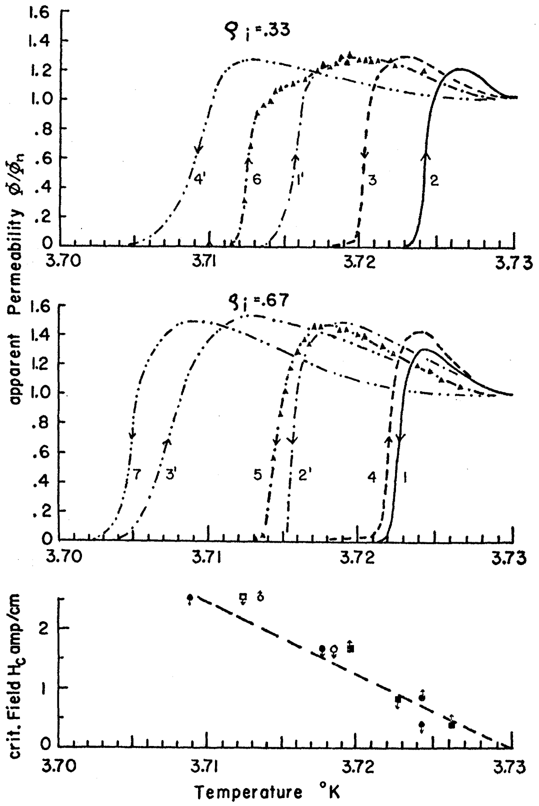

FIG. 4. Measurements of the circular flux on 2 tin specimens. Upper part: specimen Sn IV with $\rho_i=0.33$; center part: specimen Sn I with $\rho_i=0.67$; bottom part: critical field as given by the peak of the flux. —— $I=2.5$ amp; — — $I=5$ amp; —·— $I=10$ amp; —··— $I=15$ amp. For clarity measured points are only shown on one each of the 10-amp curves. The small numbers of the curves indicate the sequence at which they are measured. The curves 1–7 were measured on one day, while the curves 1′–4′ were measured on another day. The helium level was about 30 cm above the specimen for curve 1, for curve 1′ about 20 cm above the specimen, and for curves 7 and 4′ a few cm above the specimen. Note the arrows which indicate whether a curve is measured with rising or falling temperature. The dashed curve at the bottom part is the H_c-T curve as found by Lock, Pippard, and Shoenberg. The round points refer to peaks of the curves for $\rho_i=0.67$; the square points refer to peaks of the curves for $\rho_i=0.33$. The solid points (square or round) refer to the curves 1–7, the open points (square or round) refer to the curves 1′–4′. The arrows indicate rising or falling temperature.

for the hydrostatic pressure of the liquid helium. The curves on all plates were numbered according to the sequence in which they were measured. The height of the helium varied between 30 cm at the first curves to a few cm at the last curves. The effective pressure and the temperature were therefore somewhat higher for the first curves. This correction would probably shift the points on the H_c-T curve just about enough in order to give it, in the case of mercury, Fig. 3, the same slope as found by Misener[11] and, in the case of tin, Fig. 4, bring the points onto the curve found by Lock, Pippard, and Shoenberg.[12] There remains one discrepancy at the mercury measurements, which would not be removed by this correction: The first rise of the ϕ/ϕ_n curves seems to be at a higher temperature than the normal critical temperature obtained from the peaks. This may be due to stresses or impurities in the mercury.

The difference between the measurements at rising and at descending temperature can be seen on the runs on tin (Fig. 4). The temperature of the sample lagged about 0.001°K behind the bath temperature. The heat input by the heater at the bottom of the vessel had also some influence on the correspondence between temperature of the sample and the vapor pressure reading: The difference between curve 6 and curve 1′ on Fig. 4 is probably due to an abrupt change in the heat input while curve 6 was being measured. On the whole it seems to be true that the peak of ϕ/ϕ_n occurs actually at the temperature where $H_{\varphi 0}=H_c$.

From the fluxmetric measurements it follows that the flux is constant with time at all temperatures, if current and temperature are kept constant.

Figures 5 and 6 show plots of the maximum value $\tilde{K}_{m\varphi}$ of ϕ/ϕ_n as a function of the current. The points shown for mercury (Fig. 5) are all taken on the same day, partially by ballistic, partially by fluxmetric measurements. There was some scattering from one day to the next, which is probably because the mercury is not "ideally pure" and the crystal orientation, stresses etc. vary from run to run.

The points shown for tin (Fig. 6) were taken on two different days and reproduce fairly well. It was necessary to limit the measurements to currents above 2.5 amperes because ballistic measurements were not possible.

It appears that $\tilde{K}_{m\varphi}$ is independent of ρ_i at low currents, increases with current, and approaches limiting values which depend on ρ_i. The latter fact follows especially from the tin runs, which are probably more reliable than the mercury runs, since the tin samples were quite good single crystals.

The values of $\tilde{K}_{m\varphi}$ which were found for tin are different from the ones which were found for mercury.

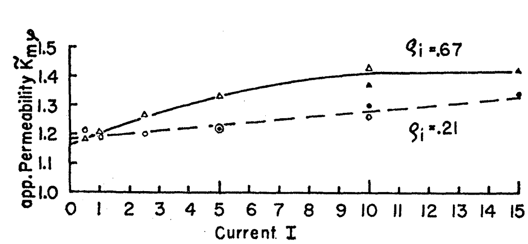

FIG. 5. Maximum of the circular flux as a function of the current for mercury specimens Hg I ($\rho_i=0.21$) and Hg II ($\rho_i=0.67$). Open points: ballistic measurements. Solid points: fluxmetric measurements.

[11] A. D. Misener, Proc. Roy. Soc. (London) **A174**, 262 (1940).

[12] Lock, Pippard, and Shoenberg, Proc. Cambridge Phil. Soc. **47**, 811 (1951).

IV. DISCUSSION OF THE MEASUREMENTS OF THE CIRCULAR FLUX

The theory, which was presented in Part I (see reference 1), predicted that the peak of ϕ/ϕ_n should occur at a temperature where $H_{\varphi 0}=H_c$, in good agreement with the experimental results.

The theory predicted further, that the maximum value $\tilde{K}_{m\varphi}$ should be independent of the current, but should depend on ρ_i as

$$\tilde{K}_{m\varphi}=\frac{(1-\rho_i^2)^2}{(1-\rho_i^2)+\rho_i^2\ln\rho_i^2}. \tag{8}$$

The remarkable feature of the experiment is, contrary to the theoretical prediction, that $\tilde{K}_{m\varphi}$ depends on the value of the current. This means that the distribution of the mean induction B_φ (see reference 1) depends on the value of the current. This is different from either the normal conducting or the pure superconducting state.

One may ask, whether at least the high current values of $\tilde{K}_{m\varphi}$ agree with the theoretical prediction. Table II shows a comparison between the theoretical and experimental values, which indicates that the experimental values are larger than the theoretical ones at low values of ρ_i, while they are smaller than the theoretical ones at large values of ρ_i.

On the whole, the theory gives only qualitatively but not quantitatively the right result. Unfortunately, it is not possible to correct the theory from these measurements alone. This would mean that one has, as a first step, to determine the function $B_\varphi(R_i,R_0,I,r)$ from the integral equation

$$\tilde{K}_{m\varphi}=\frac{1}{\phi_n}\int_{R_i}^{R_0}B_\varphi dr. \tag{9}$$

This cannot be done, since no kernel is known.

One can, however, make a strong argument, that the correction which one has to make in this case is closely connected with the correction term $1-I_g/I$ (see reference 1) which has to be applied to the theory of the paramagnetic effect:

(1) The shift from the low current value to the high current value of $\tilde{K}_{m\varphi}$ takes place at current values which are of the same order of magnitude as the values of I_g.

(2) The values of $\tilde{K}_{m\varphi}$ for tin are different from those for mercury as are the values of I_g.

TABLE II. Comparison of the experimental values of $\tilde{K}_{m\varphi}$ found at high currents with the theoretical value for the mercury and tin specimens.

ρ_i	$\tilde{K}_{m\varphi}$ (theor)	$\tilde{K}_{m\varphi}$ at high currents for sample Hg I	Hg II	Sn IV	Sn I
0.21	1.12	~1.34	...	...	...
0.33	1.22	...	...	1.30	...
0.67	1.60	...	1.42	...	1.50

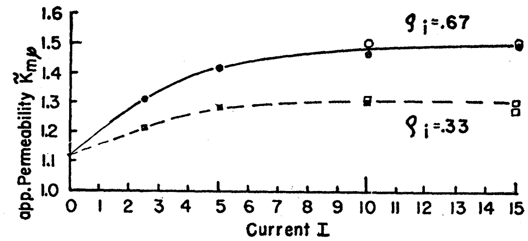

FIG. 6. Maximum of the circular flux as a function of the current for tin specimens Sn IV ($\rho_i=0.33$) and Sn I ($\rho_i=0.67$). Open points: from curves 1′–4′ of Fig. 4. Solid points: from curves 1–7 of Fig. 4.

It is very probable that an extensive investigation would reveal the connection between the circular flux and a quantity, not necessarily I_g, which changes from one metal to another in the same fashion as I_g does. This, however, would yield only another empirical formula, but would not give very much information as to how the basic assumptions which enter into the theory, have to be changed. The measurements of the circular flux were therefore not carried further, especially since other types of experiments, which do not involve an integrated quantity such as the flux seem to be more promising.

V. MEASUREMENTS WITH SUPERIMPOSED LONGITUDINAL FIELD

A longitudinal magnetic field was superimposed by passing a current through a field coil which was wound directly on the return tube. The return tube was in this case slotted and made considerably longer than the sample.

The specimen shows, under these conditions, the paramagnetic effect as previously described (see references 1 and 3). Representative measurements on mercury of the circular flux, the intensity of the longitudinal field in the hole, and the resistance as a function of the temperature are shown in Figs. 7 and 8.

The circular flux was measured with a ballistic galvanometer by reversing the current through the sample as described in Sec. III. Again ϕ/ϕ_n as given by Eq. (7) is plotted.

The intensity of the longitudinal field in the hole was measured with a fluxmeter connected to the search coil c (see Fig. 2 and Table I), by reversing the current through the field coil. The fluxmeter was used instead of the ballistic galvanometer because the time constant of the reversal of the field in the hole (not the external field) was relatively large. One observes in the normal conducting state a deflection α_0, which is proportional to the external magnetic field H_{z0}. The field intensity in the hole shows a maximum in the intermediate state, if the current which passes through the sample is large enough. It is again equal to H_{z0} in the pure superconducting state, as earlier flux meter recordings have shown (see reference 3). However, the change of the field intensity with the reversal of the external field goes to zero in the pure superconducting state because the field in the hole is shielded by the sample. The shielding is only complete when the temperature is a few hundredths of a degree lower than the transition temperature at this particular field and current, as was also shown earlier (reference 3). There is no leakage flux involved, and the field intensity is therefore given in dimensionless form by

$$\chi = H_z/H_{z0} = \alpha/\alpha_0. \tag{10}$$

The resistance was measured by observing the deflection of a galvanometer connected to the potential leads, when the sample current was reversed.

For the determination of temperature and compensation for the earth's magnetic field (see Sec. III).

VI. DISCUSSION OF THE MEASUREMENTS WITH SUPERIMPOSED LONGITUDINAL MAGNETIC FIELD

(a) The maxima of the circular flux and the longitudinal field strength in the hole coincide within a few thousandths of a degree with the breakoff of the resistance, in agreement with the theory.

(b) The maximum value of the circular flux does not change if a longitudinal magnetic field is superimposed, in agreement with a prediction made in Part II (see reference 4). The slight drop of the maximum in Fig. 8 as one changes the external field from a value of 0 to 4 amp/cm may be due to the fact that the peak is sharper at larger external fields and that it is more difficult to maintain the sample at a sufficiently uniform temperature. At very large values of $H_{z0}/H_{\varphi0}$

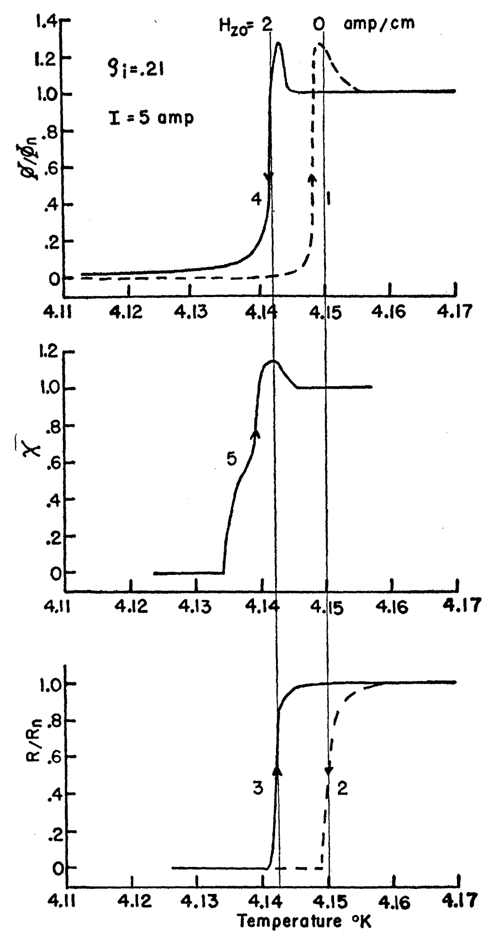

FIG. 7. Measurements of the circular flux (upper part), the field intensity in the hole (center part) and the resistance (bottom part) as a function of the temperature on mercury sample Hg I ($\rho_i=0.21$) with a current of $I=5$ amp and longitudinal fields of $H_{z0}=2$ and 0 amp/cm. Note the numbers giving sequence of curves and arrows indicating rising or falling temperature. The helium level was about 30 cm above the specimen for curve 1, and about 15 cm above the specimen for curve 5.

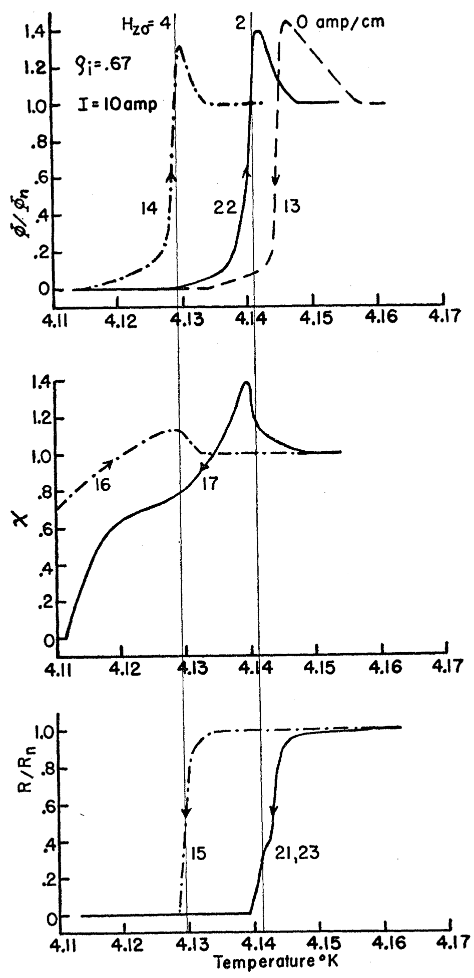

FIG. 8. Measurements of the circular flux (upper part), the field intensity in the hole (center part), and the resistance (bottom part) as a function of temperature on mercury sample Hg II ($\rho_i=0.67$) with a current of $I=10$ amp and longitudinal fields of $H_{z0}=4$, 2, and 0 amp/cm. Note the numbers giving the sequence of curves and arrows indicating rising or falling temperature. The helium level was about 25 cm above the sample at curve 13 and a few cm above the sample at curve 23.

TABLE III. Ratio of the longitudinal to the circular component of the magnetic field strength for the curves shown in Figs. 7 and 8 and the angle which the field at the surface makes with the axis of the sample.

Fig.	Curve No.	ρ_i	I, amp	$H_{z0}/H_{\varphi 0}$	φ_0	θ
7	1	0.21	5	<0.00042	>240	90°
7	4	0.21	5	2.40	0.418	23°
8	13	0.67	10	<0.00021	>480	90°
8	22	0.67	10	1.20	0.835	40°
8	14	0.67	10	2.40	0.418	23°

TABLE IV. Comparison of the experimental values of the maximum of the field intensity in the hole with the theoretical value and with the critical field. All are normalized by dividing by H_{z0}.

Fig.	Curve	ρ_i	I amp	H_{z0} amp/cm	χ_{exp}	χ_{theoret}	$(1+\varphi_0^2)^{\frac{1}{2}}$
7	5	0.21	5	2	1.14	1.08	1.08
8	17	0.67	10	2	1.36	1.18	1.30
8	16	0.67	10	4	1.13	1.05	1.08
not shown		0.21	10	2	1.40	1.29	1.30
not shown		0.21	10	4	1.18	1.08	1.08
not shown		0.67	5	2	1.14	1.05	1.08

the peak would, theoretically, be of the same height as at $H_{z0}/H_{\varphi 0}=0$ but confined to a very small temperature range, i.e., would practically be unobservable. Table III shows the values of $H_{z0}/H_{\varphi 0}$ and its inverse $\varphi_0=H_{\varphi 0}/H_{z0}$ and the angle θ, which the magnetic field at the surface makes with the axis of the sample for the various curves shown in Figs. 7 and 8.

(c) Measurements of the maximum of the longitudinal field in the hole were reported earlier (see reference 3) and discussed in Part I (see reference 1). The maximum of the field intensity in the hole, under the assumption of very long and thin superconducting particles ($C\rightarrow\infty$) in the present theory, is given by

$$\chi_{\max}=H_{z\,\max}/H_{z0}=[1+\varphi_0^2(1-\rho_i^2)]^{\frac{1}{2}}. \tag{11}$$

Even if the present theory would not be valid, it follows from quite general considerations that the maximum of the field intensity should not be larger than the critical field, or

$$\chi_{\max}\leqslant(1+\varphi_0^2)^{\frac{1}{2}}. \tag{12}$$

Table IV shows a comparison of the experimental values of $\chi_{\max}$ with the values given by Eqs. (11) and (12). It can be seen that the experimental value of $\chi_{\max}$ is always larger than the theoretical one and is even larger than the value given by the critical field. This was already observed for some of the curves of the earlier experiments (see reference 1). It is very unlikely that an error in the calibration makes χ always too large, since every curve has its own calibration. One seems to be left with the conclusion that the maximum field intensity in the hole is always at least as large as the critical field, and may even be slightly larger.

(d) The resistance at the temperature where the total field at the surface is equal to H_c should theoretically be equal to $R_c=\frac{1}{2}R_n$ (see reference 3), independent of the value of a superimposed longitudinal field. However, this cannot be experimentally verified for samples of such a large diameter, since already at $H_{z0}=0$ the resistance curve is so sharp that R_c is not defined as a break in the curve as it is for instance in Scott's[13] experiments. Superimposing a longitudinal field shifts the transition curve toward lower temperatures and makes it still sharper. It is therefore not possible to say from these experiments whether R_c does or does not change if a longitudinal field is superimposed.

VII. CONCLUSIONS

The experiments which are reported here confirm qualitatively the theoretical predictions presented in Part I and Part II, although not quantitatively.

The theory of the circular flux increase is nothing but an application of London's theory of the current-carrying wire. However, this theory had a strange feature: It did not contain a boundary condition for the inner surface of the hollow cylinder. This seemed immediately to indicate that the theory could only be an approximation, a fact which is confirmed by the present experiments. Unfortunately, it is not possible to correct the theory from these measurements alone, for reasons mentioned above.

The measurements with the superimposed longitudinal field were undertaken in order to see which features of the theory of the paramagnetic effect agree fairly well with experiment and which do not. Part of the theoretical work which was presented in Part II was actually undertaken in order to make this comparison possible. It is found that some details of the theory agree fairly well with the experiment. This knowledge should help very much in finding the final theory.

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[13] R. B. Scott, J. Research Natl. Bur. Standards 41, 581 (1948).