THE RICE INSTITUTE

AN INVESTIGATION OF THE MAGNETIC FIELD, CURRENT, TEMPERATURE PHASE DIAGRAM OF SUPERCONDUCTIVITY

by

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A THESIS
SUBMITTED TO THE FACULTY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ARTS

Houston, Texas
May, 1952
# TABLE OF CONTENTS

**INTRODUCTION** .............................................. 1  
**PHENOMENOLOGICAL BACKGROUND.** .................... 3  
   A. Infinite Conductivity. .......................... 3  
   B. Meissner Effect. ................................. 5  
   C. Thermodynamic Functions. ..................... 6  
   D. The London Equations ............................ 8  
   E. The Anomalous Paramagnetism. .................. 9  
   F. The Experiment of this Thesis .................. 12  
**EXPERIMENTAL ARRANGEMENT** ........................ 14  
**RESULTS.** .................................................. 17  
**CONCLUSIONS.** ............................................. 19  
**ACKNOWLEDGEMENTS** ....................................... 20  
**BIBLIOGRAPHY** ............................................. 21
Although the phenomenon of superconductivity has been known for more than 40 years, it is still one of the fields of physics in which research effort seeks adequately to integrate the experimental facts with fundamental theory. One is often faced with apparently anomalous experimental results which must be checked before the nature of superconductivity can be understood. One such of these reports is the "paramagnetic effect" in superconductors. Professor W. Meissner has reported that a solid, cylindrical superconductor which (a) has a large current flowing through it, (b) is situated in an external magnetic field, and, (c) is at a temperature just greater than the transition temperature, will exhibit an increased magnetic induction component in the longitudinal direction of the cylinder. This result is interpreted as an increase in the magnetic susceptibility of the metal, although, below the transition temperature, the metal shows the apparent perfect diamagnetism characteristic of superconductors.

Professor Meissner's experiments, indicating that the magnetic permeability increases before the metal becomes superconductive, would appear to contradict the present concepts of superconductivity. However, these induction measurements were made by changing one of the external parameters (the magnetic field). Professor K. Mendelssohn has suggested that the observed increase in induction is an apparent increase, because the induction in only one direction is measured. The increase
might correspond to a rearrangement of the flux, caused by super-currents being induced in the specimen during the time of change of the magnetic field.

In light of these circumstances, it seemed desirable to make induction measurements for equilibrium states of the sample, at constant values of the temperature, current, and magnetic field. Thus, one could determine whether this "paramagnetism" is an intrinsic property of a superconductor in a stable state, or, whether it is caused by the particular measuring technique. This thesis is a report of such an experiment. We shall show that, at least for the magnitudes of the variables used in our experiment, tin shows no steady state corresponding to an increase of the magnetic susceptibility. We conclude that the observed paramagnetism is a transient effect caused by the dynamic nature of the measuring method.
A. Infinite Conductivity

In 1911, H. K. Onnes (1) observed that at a temperature of about 4.25° K. the electrical resistance of mercury virtually vanished. Many other metals and alloys have since been shown to exhibit this phenomenon of "superconductivity." Even with the most sensitive instruments available today, the resistance of superconductors is indistinguishable from zero.

H. K. Onnes also found that the resistance of the sample could be restored by placing the specimen in a suitably large external magnetic field. The magnitude of this critical field, above which the metal does not exist in the superconductive state, increases as the temperature is lowered. The critical field, as a function of temperature, is a characteristic for a given superconductor.

It was also discovered that the superconductivity of the sample could be destroyed by sending a large enough current through the specimen. Silsbee postulated that the critical current is just that current which produces, at the surface of the sample, the critical magnetic field. This principle seems now to be completely confirmed by experiment.

The magnitudes of the critical fields and currents vary greatly with the particular shapes of samples. This dependence on geometry is, for large bodies at least, just due to the demagnetizing factor. If a cylindrical sample with longitudinal fields and currents is studied, then the demagnetizing factor

1. H. K. Onnes, Leiden Comm., 124 b, 124 c (1911).
is unity.

One may construct a sort of phase space for superconductivity (figure 1), using the current density, J, the surface magnetic induction, $B_s$, and the temperature, T, as dependent variables. The volume inside the surface of figure 1 represents values of the parameters for which the cylindrical sample is in the superconductive state, and the outside corresponds to the metal in the normal state.

The curve representing the intersection of the phase boundary surface with the $J = 0$ plane is just the curve of critical $B_s$ versus T for zero (external) current. This curve is essentially parabolic for most superconductors, and may be approximated by

$$B_s^* = B^* \left[ 1 - \left( \frac{T}{T_0} \right)^2 \right]$$

where $B_s$ is the critical surface induction, $B^*$ is the (extrapolated) critical induction at $0^\circ$ K., and $T_0$ is the transition temperature for zero induction.

From the fact that there is no measurable potential difference between different points of a superconductor, one may infer that, inside a superconductive body

$$\mathbf{E} = - \nabla \mathbf{\nu} = 0$$

Since electromagnetic field theory makes no essential assumptions as to the nature of physical matter, it would certainly be expected that Maxwell's equations would yield a complete description of the field distributions in the neighborhood of superconductors. Thus, from equation (2)
Figure 1. The boundary surface between the normal and the superconductive phases.
\[- \frac{\partial \vec{B}}{\partial t} = \nabla \times \vec{E} = 0 \]
\[\vec{B} = \text{const.} \tag{3}\]
for any point within a superconductor.

From figure 1, it is clear that we may approach the phase boundary with an arbitrary value of \(\vec{B}\) in the specimen. After crossing into the superconductive state, the external parameters may be changed so that the sample is at any point of the phase space. But, from equation (3), \(\vec{B}\) depends only on the conditions existing when the superconductivity was established. This implies that, for any given values of the external parameters, we have possibly an infinite number of stable states of the system.

This situation is clearly unpleasant from a thermodynamic point of view. Since \(\vec{B}\) in the sample is not a single valued function of the temperature and external field, it is difficult to see how one could formulate an equation of state for the system. Also, since it seemed obvious that currents holding \(\vec{B}\) constant would produce Joule heating when the resistivity of the sample was restored, the transitions in external field are irreversible.

B. Meissner Effect

For many years, the assumption of infinite conductivity for superconductors seemed to yield a satisfactory interpretation of most of the experimental data, despite the theoretical difficulties of such a hypothesis. In 1933, Meissner and Ochsenfeld\(^{(1)}\) observed that if a single crystal of tin is made super-

\(^{(1)}\) W. Meissner and R. Ochsenfeld, Naturwissenschaften, V. 21, 787 (1933).
conductive, in the presence of an external magnetic field, then nearly all of the flux is forced out of the metal. That is, the magnetic induction inside of a superconductor is zero, regardless of what induction exists in the body at the time of the transition from normal to superconductivity.

The discovery that \( B \) is zero in a superconductor had the immediate consequence of putting the thermodynamic treatment on a firm foundation. Since the internal \( B \) is a single valued function of the external field (the inverse is not true), an equation of state can, in principle, be formulated. Also, since \( B \) is zero regardless of the path of transition between the states, the transition in the presence of external fields is reversible.

C. Thermodynamic Functions

The important thermodynamic functions for superconductors may be obtained by considering the Helmholtz potential, \( \Phi \). For isothermal magnetizations, the free energy is a function of the temperature, \( \Phi(T) \), plus the magnetic field energy

\[
\Phi = \Phi(T) + \int B \cdot dH
\]

In order to change the independent variables from \( T \) and \( B \) to \( T \) and \( H \), we may add \( -\frac{2\Phi}{dT}B \), and obtain a "magnetic Gibbs potential"

\[
\Phi(T, H) = \Phi(T) - \int_0^H \vec{B} \cdot d\vec{H}
\]

If we define

\[
\Phi_0(T) = \Phi(T) - \frac{\mu}{2} [\mathcal{E}_c(T)]^2
\]

where \( \mathcal{E}_0(T) \) is the critical surface field for the temperature \( T \),
and note that, from Meissner's experiment

\[
\vec{B} = 0 \quad \text{for} \quad |\vec{H}| \leq H_c
\]

\[
\vec{B} = \mu \vec{H} \quad \text{for} \quad |\vec{H}| > H_c
\]

then

\[
\begin{align*}
S_s &= \phi_s(T) - \frac{\mu}{2} H_c^2 \\
S_n &= \phi_s(T) - \frac{\mu}{2} H^2
\end{align*}
\]

where the subscripts s and n refer to the superconductive and normal states, respectively. The difference of entropy between the phases is

\[
S_s - S_n = -\frac{3}{2}\tau (\phi_s - \phi_n)
\]

\[
= \mu H_c \frac{dH_c}{dT}
\]

This means that the phase change is a first order transition, except at the zero field transition temperature and at absolute zero. Also, the entropy difference is independent of the external field.

For some time, it was believed that postulating infinite conductivity and zero magnetic permeability would give an adequate account of the electrodynamic behavior of superconductors. However, it was found to be possible to "freeze" a magnetic field in the hole of a doughnut-shaped superconducting ring. If we consider the line integral of \(\vec{H}\) along a path through the hole, and encircling the ring, then we find that there must be a true current in the superconductor, not a magnetization current as implied by zero permeability.
D. The London Equations

In 1935, F. and H. London\(^1\)(2) proposed that the electrodynamics of superconductors could be described by assuming that the currents may be divided into two parts, (1) a normal current, \(J_n\), and (2) a supercurrent, \(J_s\)

\[
\mathbf{J} = \mathbf{J}_n + \mathbf{J}_s
\]

The normal current is related to the electric field by Ohm's law

\[
\mathbf{J}_n = \sigma \mathbf{E}
\]

The supercurrent, however, is coupled with the electric and magnetic fields by the London equations

\[
\nabla \times (\lambda \mathbf{j}_s) = -\frac{2}{\sigma} \mathbf{E}
\]

\[
\frac{\partial}{\partial t} (\lambda \mathbf{j}_s) = \mathbf{E}
\]

where \(\lambda = \frac{m}{ne^2}\) and \(n\) is the number of "superelectrons" per unit volume.

Many theoretical attempts, none wholly satisfactory, have been made to derive equations (12) and (13). One simple derivation considers the superelectrons as being acted on only by the accelerating force of the electric field. Thus

\[
\mathbf{F} = e \mathbf{E} = m \frac{d}{dt} \left( \lambda \mathbf{j}_s \right) = \frac{m}{e} \frac{d}{dt} \left( \lambda \mathbf{j}_s \right) \]

\[
\frac{\partial}{\partial t} (\lambda \mathbf{j}_s) = \mathbf{E} - \frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E} = \nabla \times \left( \lambda \frac{d}{dt} \mathbf{j}_s \right)
\]

\(\frac{d}{dt} \mathbf{j}_s = \lambda \frac{d}{dt} \mathbf{j}_s\)

\[ \text{curl}(j_s) = -\vec{\beta} \tag{13} \]

if we assume \( j_s = 0 \) when \( \vec{B} = 0 \).

The most generally accepted concept of superconductivity is that \( E = 0 \) does not mean that the "conductivity" of the metal is infinite. As far as the normal electrons are concerned, the interactions producing resistance are not significantly affected at the transition to superconductivity. Rather, \( E \) is zero in the metal means that the superelectrons, which are free from any dissipative effects, effectively short circuit the volume of the metal. Similarly, the Meissner effect is not believed to be caused by a large scale diamagnetism, or a magnetization. It is believed that \( \vec{B} \) is zero in a superconductor because the superelectrons are coupled with the fields by equations (12) and (13). The supercurrents are so distributed that they produce an \( \vec{H}_s \) which just cancels the externally produced \( \vec{H} \) throughout the volume of the body.

E. The Anomalous Paramagnetism

The important concept of the transition to superconductivity is that of a new energy state in which electrons are free from dissipative interactions. It is difficult to believe that there actually are gross changes taking place in the conductivity and permeability (as we usually think of them). Therefore, the reports of "paramagnetic effects" in superconductors seemed to be quite anomalous.

Steiner and Schoeneck,\(^1\) and more recently, Meissner,

\(^1\) K. Steiner and H. Schoeneck, Phys. Z., V. 44, 346 (1943).
Sohmelasner, and Meissner, reported experiments which indicated an increase in the magnetic susceptibility of a metal under special conditions. This paramagnetic effect occurs just above the transition temperature, but only when the sample carries a large current in the presence of an external magnetic field. The observed increase in susceptibility increases with increasing current.

Meissner and his collaborators worked with cylindrical samples of tin and mercury. The cylinders were mounted so that they were in a longitudinal magnetic field. Also, large currents could be sent through the samples.

An induction coil (connected to a galvanometer) was wrapped around the specimen. Changes of total flux through the coil could be measured by observing the ballistic throw of the galvanometer.

Meissner and co-workers made measurements at fixed values of the temperature and current. Each measurement consisted of reversing the external magnetic field (reversing the current in the solenoid producing the field) and recording the throw of the galvanometer. Their curve of galvanometer deflection plotted against temperature (for several different currents in the tin) is shown in figure 2.

The curves of figure 2 may be interpreted as follows: when no current is flowing in the tin, and the sample is in the normal state, a certain deflection ($\alpha_0$) is obtained when the field is commuted. This deflection remains constant, as the

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Figure 2. The curves of Meissner, Schmeisser, and Meissner.
temperature is lowered, until the transition temperature is reached. When the tin becomes superconductive, the flux is excluded from the volume of the tin. Thus, only small deflections ($\alpha_0$) are obtained when the tin is superconducting. $\alpha_0$ corresponds to a leakage flux between the coil and the sample, and should be a correction independent of temperature and current.

With a current flowing through the sample, and for high enough temperatures, the same deflection as before ($\alpha_0$) is found. It might be expected that one would obtain the same curve, of deflection versus temperature, that was obtained for zero current. An axial current would not affect the magnetic field in that direction and would serve only to lower the transition temperature slightly. Meissner, Schmeissner, and Meissner find, however, that as the transition temperature is approached the deflections become much greater than $\alpha_0$. Below the transition temperature, the deflections fall off to the constant value $\alpha_0$.

The increase in deflections means that the integral changes of longitudinal flux in the sample increase as the transition temperature is neared. When the sample becomes superconductive, however, it still exhibits the apparent perfect diamagnetism characteristic of superconductors.

The increase in the flux changes might be construed as an increase in the magnetic susceptibility of the metal. It is clear, however, that these measurements are made under varying (11)
conditions of the state of the sample. One of the parameters is changed in order to make the measurement. At relatively high temperatures the tin is in the normal state during the entire time of a measurement. Near the transition temperature the metal may spend part of the measurement time in the superconductive phase.

F. The Experiment of this Thesis

K. Mendelssohn(1) has suggested that the apparent increase in susceptibility might be caused by the transient state of the system. The increase in longitudinal flux changes might correspond only to a rearrangement of the currents, as the sample becomes superconductive in an external field. The increased deflections would not necessarily mean an increased total flux in the sample.

To investigate the situation, it was decided to measure the induction for constant values of all three variables of state. One might then determine whether there actually exist equilibrium states, for which, the longitudinal induction in a cylindrical superconductor carrying a current is greater than for one carrying no current. We proposed to do this experiment by using a kind of "flip coil," so that measurements could be made at constant values of the field.

An experiment which compares the flux in a sample of tin with the flux in a superconducting sample (lead, of the same dimensions and under the same external conditions as the tin) has been carried out. Each measurement is made for an equili-

brium state which is represented as a point in the phase space of figure 1. From these measurements, we conclude that the observed increases in susceptibility are not an equilibrium property of superconductors. The apparent increase in induction must be caused by transient effects introduced by the particular measuring method.
EXPERIMENTAL ARRANGEMENT

The experimental apparatus consists of copper, tin, and lead cylinders, placed end to end in series. A small induction coil is placed around the cylinders, such that the coil may be rapidly moved from one cylinder to another. The coil is connected to a ballistic galvanometer so that the changes of total flux through the coil may be measured.

The arrangement is such that an external magnetic field may be applied in the longitudinal direction of the cylinders. At the same time, a large current may be sent through the cylinders. The temperature of the samples is controlled by placing the specimen in a bath of liquid helium. A measurement consists of moving the coil from the tin to the lead cylinder, at a constant value of the temperature, current, and magnetic field.

A schematic cross section of the apparatus (not to scale) is shown in figure 3. The specimen, S, consists of copper, tin, and lead cylinders (each approximately 8 cm. long and 2.8 mm. in diameter) soldered together in series, and packed into a thin German Silver tube. This rod is mounted vertically, with the upper end (copper) held in a textolite block, B.

The sample holder, B, is suspended from the main plate, P, by steel and textolite tubes, P₁ and P₂, respectively, in series. The sample holder has a slot cut in it so that one of the current leads, K, may be attached to the upper end of the copper cylinder.

The induction coil, C, is hung from a micarta rod, R, by
FIGURE 3. SCHEMATIC CROSS SECTION OF EXPERIMENTAL APPARATUS
means of two German Silver capillary tubes, T. The drive rod, R, passes up through the tubes $P_1$ and $P_2$, and extends on through the plate and brass tube, D. Above the brass tube the rod is fastened to a cylindrical block of iron, I. A glass vacuum cover, G, is waxed around the brass tube. The coil may be raised and lowered by moving the iron with a small solenoid which slides outside the vacuum jar.

Since it was necessary to pass large currents through the sample, most of the current leads were of #12 copper wire. To reduce heat leaks caused by this large wire, a can for liquid nitrogen, N, was suspended from the upper plate by two monel tubes, M. Two #12 wires extend downward from the plate and these wires are thermally connected with the nitrogen can. From the can to just above the sample holder, the current leads are of #26 wire wound in a helix (to increase the length). Below the sample holder, #12 wire is again used for the current leads. The sample was shielded from the magnetic field caused by the return current by placing a superconductive lead tube, L, around the return current lead. This technique of wiring seemed quite effective, as we had little difficulty making the liquid helium last for rather long periods of time.

The apparatus shown in figure 3 is surrounded by a flask for liquid helium, H. Around H, and not shown, is placed an outer dewar flask for liquid nitrogen. The solenoid for producing the external magnetic field is mounted outside the nitrogen flask. The field of the solenoid was known to be homogenous, to within one percent, over the volume of the tin. The tempera-
ture was controlled and measured by the vapor pressure of the helium bath, and the bath could be stirred by moving the coil up and down.

The leads from the induction coil (of #40 copper wire) were brought out through a wax seal in the upper plate. The coil leads were connected to a galvanometer (figure 4a) so that ballistic deflections could be observed. The currents for the sample and the field solenoid were supplied by a D.C. generator (figure 4b) in parallel with a set of batteries. A separate set of batteries provided the current for the small solenoid used to move the coil.

The experimental procedure was as follows: the parameters were adjusted so that the sample was at any desired point of the phase space of figure 1. The coil would then be dropped from the middle of the tin cylinder to the middle of the lead. The lead was superconductive, so that $B$ was zero inside the lead cylinder. Thus, the change in flux through the coil is a measure of the longitudinal flux in the tin. One of the parameters was then changed (the point representing the system was shifted parallel to one of the axes in figure 1) and the system allowed to come to equilibrium. The flux change for this new state was then measured. This process was continued for a series of points in the neighborhood of the phase boundary surface.
**Figure 4A.** Galvanometer Circuit.

**Figure 4B.** Current supply for solenoid and specimen.
RESULTS

The experimental data are given in tables 1, 2, and 3, with the results given graphically in figures 5, 6, and 7. Each of these sets of data is a series of measurements with two of the variables held constant throughout. The third parameter was changed in small steps. In figures 4, 5, and 6, the abscissa is the variable which was changed, while the ordinate is the ballistic throw of the galvanometer when the coil was dropped from the tin to the lead cylinder.

The superconductivity of the tin could be destroyed by (1) high temperatures, (2) large currents, or (3) large external fields. When the sample was in the normal state a large deflection was obtained, since the field penetrated the tin but was excluded from the superconductive lead. By decreasing one of the parameters, the superconductive state could be entered (along a line parallel to one of the three axes of figure 1). When the tin became superconductive, the deflections were reduced to zero, since B was then zero in both the tin and the lead. An increased longitudinal induction at any point would correspond to an increased throw of the galvanometer for that point.

There is a rather large scatter of the points in figures 5, 6, and 7. This scatter may be attributed to two main sources: (1) the galvanometer deflections were so rapid that it was not possible to make readings accurate to less than one or two millimeters uncertainty; (2) current fluctuations in the solenoid.
TABLE I

\[ H = 27.5 \text{ gauss} \quad T = 3.513 \degree \text{K.} \]

<table>
<thead>
<tr>
<th>I (Amps.)</th>
<th>( H )</th>
<th>Final Reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Reading</td>
<td>( T )</td>
<td>Deflection (cm.)</td>
</tr>
<tr>
<td>I.</td>
<td>10.0</td>
<td>29.7</td>
</tr>
<tr>
<td>2.</td>
<td>10.0</td>
<td>29.8</td>
</tr>
<tr>
<td>3.</td>
<td>9.0</td>
<td>29.8</td>
</tr>
<tr>
<td>4.</td>
<td>9.0</td>
<td>29.7</td>
</tr>
<tr>
<td>5.</td>
<td>8.0</td>
<td>29.5</td>
</tr>
<tr>
<td>6.</td>
<td>7.0</td>
<td>29.5</td>
</tr>
<tr>
<td>7.</td>
<td>6.0</td>
<td>29.5</td>
</tr>
<tr>
<td>8.</td>
<td>7.0</td>
<td>29.3</td>
</tr>
<tr>
<td>9.</td>
<td>6.8</td>
<td>30.2</td>
</tr>
<tr>
<td>10.</td>
<td>6.7</td>
<td>29.8</td>
</tr>
<tr>
<td>11.</td>
<td>6.5</td>
<td>29.9</td>
</tr>
<tr>
<td>12.</td>
<td>6.5</td>
<td>29.6</td>
</tr>
<tr>
<td>13.</td>
<td>6.3</td>
<td>29.5</td>
</tr>
<tr>
<td>14.</td>
<td>6.3</td>
<td>29.6</td>
</tr>
<tr>
<td>15.</td>
<td>6.2</td>
<td>29.5</td>
</tr>
<tr>
<td>16.</td>
<td>6.2</td>
<td>29.5</td>
</tr>
</tbody>
</table>
FIGURE 5. PENETRATION OF THE PHASE SURFACE AT CONSTANT TEMPERATURE AND FIELD.
<table>
<thead>
<tr>
<th>T (°K.)</th>
<th>Initial Reading</th>
<th>Final Reading</th>
<th>Deflection (cm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>3.827</td>
<td>28.9</td>
<td>10.5</td>
</tr>
<tr>
<td>2.</td>
<td>3.859</td>
<td>28.9</td>
<td>11.7</td>
</tr>
<tr>
<td>3.</td>
<td>3.810</td>
<td>28.5</td>
<td>11.3</td>
</tr>
<tr>
<td>4.</td>
<td>3.797</td>
<td>28.6</td>
<td>10.8</td>
</tr>
<tr>
<td>5.</td>
<td>3.790</td>
<td>29.2</td>
<td>11.8</td>
</tr>
<tr>
<td>6.</td>
<td>3.771</td>
<td>29.1</td>
<td>11.8</td>
</tr>
<tr>
<td>7.</td>
<td>3.726</td>
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<td>11.6</td>
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<td>10.4</td>
</tr>
<tr>
<td>11.</td>
<td>3.598</td>
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<td>11.6</td>
</tr>
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<td>12.</td>
<td>3.589</td>
<td>29.6</td>
<td>11.5</td>
</tr>
<tr>
<td>13.</td>
<td>3.536</td>
<td>28.7</td>
<td>29.2</td>
</tr>
<tr>
<td>14.</td>
<td>3.531</td>
<td>29.2</td>
<td>20.8</td>
</tr>
</tbody>
</table>
FIGURE 6. PENETRATION OF THE PHASE SURFACE AT CONSTANT CURRENT AND FIELD.
TABLE 3

$I = 10$ Amps. $T = 3.501 \, ^\circ K.$

<table>
<thead>
<tr>
<th>$H$ (gauss)</th>
<th>Initial Reading</th>
<th>Final Reading</th>
<th>Deflection (cm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 35.0</td>
<td>23.5</td>
<td>4.5</td>
<td>-19.0</td>
</tr>
<tr>
<td>2. 32.5</td>
<td>24.0</td>
<td>6.5</td>
<td>-17.5</td>
</tr>
<tr>
<td>3. 32.5</td>
<td>26.0</td>
<td>7.5</td>
<td>-16.5</td>
</tr>
<tr>
<td>4. 30.0</td>
<td>25.0</td>
<td>7.6</td>
<td>-17.4</td>
</tr>
<tr>
<td>5. 27.5</td>
<td>24.5</td>
<td>21.5</td>
<td>-3.0</td>
</tr>
<tr>
<td>6. 27.5</td>
<td>25.0</td>
<td>21.8</td>
<td>-3.2</td>
</tr>
<tr>
<td>7. 25.0</td>
<td>24.0</td>
<td>23.1</td>
<td>-0.9</td>
</tr>
<tr>
<td>8. 25.0</td>
<td>24.2</td>
<td>22.9</td>
<td>-1.3</td>
</tr>
<tr>
<td>9. 22.5</td>
<td>24.5</td>
<td>23.0</td>
<td>-1.5</td>
</tr>
<tr>
<td>10. 22.5</td>
<td>24.3</td>
<td>22.7</td>
<td>-1.6</td>
</tr>
</tbody>
</table>
FIGURE 7. PENETRATION OF THE PHASE SURFACE AT CONSTANT TEMPERATURE AND CURRENT.
and small uncontrolled movements of the coil, caused zero shifts of the order of several millimeters. It is believed that these uncertainties would certainly not mask an effect of the sizes reported by Meissner, Schmeissner, and Meissner.

It is clear that our results do not indicate an increase in the longitudinal flux in the tin for any point of the region which we investigated.
CONCLUSIONS

The results indicate that, for the range of values used in our experiment at least, there exists no stable state corresponding to paramagnetism of the metal specimen. This result is not necessarily in conflict with the work of Dr. Meissner and co-workers, since they measured a quantity different from the one measured by us. Our measurements were for equilibrium conditions. We must conclude, therefore, that the paramagnetic effects which have been observed are to be attributed to the particular method of measurement. Such effects do not represent an intrinsic property of a superconductor in an equilibrium state.
ACKNOWLEDGEMENTS

The author would like to express his sincere thanks to Dr. Kurt Mendelssohn, of Oxford University, who suggested this problem and under whose direction the research was carried out. The author would also like to thank Professor Charles F. Squire, and the other members of the Low Temperature Department of the Rice Institute, for their assistance throughout the course of this project. Without the aid of J. F. van der Henst, and the other members of the Rice Institute Physics Department Shop, this work could not have been completed.
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