THE RICE INSTITUTE

RELAXATION TIME FOR THE PARAMAGNETIC EFFECT
AT THE SUPERCONDUCTING TRANSITION

by

JOSEPH A. STAPLES III

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

MASTER OF ARTS

Houston, Texas
April 1956
# TABLE OF CONTENTS

I  INTRODUCTION ............................................. 1

II  BACKGROUND OF THE PARAMAGNETIC EFFECT .... 6

III  EXPERIMENTAL APPARATUS ........................... 15

IV  MEASUREMENTS AND RESULTS ......................... 21

V  CONCLUSIONS ............................................ 33

REFERENCES .................................................. 35

ACKNOWLEDGMENTS .......................................... 36
I INTRODUCTION

In 1911 H. Kammerlingh Onnes\(^1\) found that at a temperature of 4.15\(^\circ\)K the resistance of mercury decreased abruptly to zero. Since this discovery a number of other pure elements, as well as many different compounds and alloys have been found to exhibit the phenomenon of superconductivity at suitably low temperatures. The numerous experimental and theoretical investigations of superconductivity have brought out several characteristic properties of the superconducting state. Among the most important of these are the magnetic properties of superconductors.

Onnes found that at a temperature below the transition temperature, the temperature at which the resistance vanished, the application of a suitably large magnetic field could restore the resistance. It has since been established that the field required must exceed a certain critical value, \(B_c\), in order to restore the superconductor to its normal state at a temperature, \(T\). The critical field as a function of the temperature is approximately parabolic, and the experimental data may be represented approximately by

\[
B_c = B_0 \left(1 - \left(\frac{T}{T_0}\right)^2\right)
\]

where \(B_0\) is the critical field at the absolute zero, and \(T_0\) is the transition temperature in zero magnetic field. For
temperatures greater than $T_0$ the superconducting state does not exist.

The magnetic field required to destroy the superconductivity may be produced by an externally applied field. It was also found that the transition from the superconducting to the normal state could be brought about by passing a current through the sample. Silsbee postulated that the current required was just that current which produced at the surface of the superconductor a magnetic field equal to the critical field at the given temperature. This effect has since been experimentally verified.

In view of these considerations we may consider a space defined by the temperature, magnetic field, and sample current axes, where the superconducting phase lies within a surface described by the critical values of these variables. The normal phase lies outside of this surface. See Figure 1.

Since there is no potential difference across a superconductor, we may imply from Maxwell's equations that

$$\mathbf{E} = -\text{grad} \, V = 0$$

and therefore that

$$\mathbf{B} = \text{curl} \, \mathbf{E} = 0$$

which means that the magnetic induction, $\mathbf{B}$, is constant in the superconducting state. Meissner and Ochsenfeld\(^2\) found that as a sample of tin at the transition temperature
became superconducting in a magnetic field, the magnetic flux was expelled from the sample. This showed that in the superconducting state the magnetic induction was zero within the superconductor irrespective of the initial field. The property $\mathcal{B} = 0$ inside of the specimen is a characteristic property of all superconductors.

Thus the superconducting state is characterized by perfect diamagnetism as well as by infinite conductivity. These two properties are independent in the sense that one does not necessarily imply the other.

The phenomenological approach of F. and H. London\(^{(3)}\) has been found adequate to describe the electrodynamics of superconductors. London assumed that the total current density, $\mathcal{J}$, was divided into two parts. One part is ascribed to the normal current density, $\mathcal{J}_n$, and the other part is due to the "supercurrent" density, $\mathcal{J}_s$, such that

$$\mathcal{J} = \mathcal{J}_n + \mathcal{J}_s \quad \text{(4)}$$

The normal current density is determined by Ohm's law

$$\mathcal{J}_n = \sigma \mathcal{E}$$

and the supercurrent density is related to the magnetic field and the electric field by
\[
\text{curl} \lambda \vec{J}_s = -\vec{B} \\
\partial / \partial t (\lambda \vec{J}_s) = \vec{E}
\]

where \( \lambda \) is a constant for the particular superconductor. Although the various theoretical attempts to derive these equations have been none too successful, the equations are nevertheless considered important for the description of the superconducting state.

In the course of experiments on the transition properties of superconductors located in an external magnetic field and carrying a large current, Steiner and Schoeneck\(^{(4)}\) reported an apparent increase in the magnetic flux content of the sample just as the transition from the normal to the superconducting state took place. This state of increased flux content has been found to be an intrinsic property of superconductors under certain conditions of magnetic field and current. It has been termed the "paramagnetic effect" due to the apparent paramagnetic permeability just prior to the occurrence of the perfect diamagnetism in the superconducting state.

During the studies of this effect carried on at the Low Temperature Laboratory of the Rice Institute, the suggestion was made that the establishment of the extra flux in the superconductor might be studied by driving the sample in and out of the paramagnetic region by means of
an alternating magnetic field. The frequency dependence of this effect might then lead to some knowledge of the time required for this extra flux to be set up.

This thesis is a report of the work which has been done on this problem. The important properties of the paramagnetic effect will be shown, and the results of measurements of the time properties of the paramagnetic state will be discussed.
FIG. 1 BOUNDARY BETWEEN NORMAL AND SUPERCONDUCTING PHASES
II BACKGROUND OF THE PARAMAGNETIC EFFECT

The first indication of the paramagnetic effect in superconductors was reported in the work of Steiner and Schoeneck\(^4\). In their investigations of the effect upon the transition of the simultaneous application of a magnetic field and a current passing through the sample, they noted that the flux content of the sample showed an increase just as the sample became a superconductor. They also found that the current through the sample had to exceed a certain critical or "threshold" value depending upon the temperature and applied magnetic field in order to observe the effect.

In an extension of his earlier work Steiner\(^5\) determined the values for the threshold current for samples of tin, thallium, and indium. He observed a linear increase of the flux content of the sample as the current at which the effect occurred was increased. In the experiments of Steiner the temperature was increased and decreased at constant values of the sample current and applied magnetic field. The flux change was recorded by the deflection of a ballistic galvanometer which was connected to an induction coil located about the sample.

Meissner, Schmeissner, and Meissner\(^6\) published quantitative results on the paramagnetic effect. They
employed cylindrical samples of mercury and tin placed in a longitudinal magnetic field and carrying a large direct current. The change of flux within the sample was given by the throw of a ballistic galvanometer connected to a coil wrapped around the sample. The measurements were taken at constant values of the temperature and sample current. The measurements were made by either cutting the external magnetic field to zero or commuting the field. This procedure was repeated at a number of different values of the temperature as the transition to the normal state was made. The resulting curves showed a marked increase in the flux content just as the sample went into the normal state.

Meissner, Schmeissner, and Meissner expressed their results in terms of an apparent permeability which they defined as

$$\tilde{\mu} = \frac{(a - a_{oo})}{(a_o - a_{oo})}$$  \hspace{1cm} (7)

where \(a\) is the galvanometer deflection for a given set of the variables \(B, I,\) and \(T, a_0\) is the deflection obtained in the normal state, and \(a_{oo}\) is the deflection in the superconducting state due only to the finite amount of leakage flux through the induction coil (since \(\bar{B} = 0\) within the sample). Thus the curves of the apparent permeability as a function of the temperature showed that \(\tilde{\mu}\) increased from
the normal state value \( \mu = 1 \) to a maximum and then dropped off sharply to the value \( \mu' = 0 \) in the superconducting state.

Transitions were also made at constant temperature and current by increasing the applied field. The paramagnetic peaks which were observed were found to be broader than those obtained for the temperature induced transitions.

From an analysis of their data Meissner, Schmeissner, and Meissner found that the minimum current \( I_0 \) which was required for the observation of the flux increase in an applied field \( B \), could be represented by the expression

\[
I_0 = I_g + \gamma B d
\]

where \( I_g \) is the threshold current in zero magnetic field and is a constant for the particular superconductor, and \( d \) is the diameter of the sample. The factor \( \gamma \) is a constant characteristic of the superconducting material.

The value of \( I_g \) for tin and mercury were obtained by plotting the threshold current as a function of the applied magnetic field for different diameters. The value of \( I_g \) was then taken from the intercept of this curve at \( B = 0 \).

The measurements were then repeated on cylindrical samples which had a longitudinal slit through the length of the sample. There was no indication of the flux increase as the transition from the superconducting to the normal state was made.
From these results they concluded that the flux increase was due to the interaction of the applied magnetic field with the magnetic field due to the sample current in such a manner that the sample current acquired a circular component. The resultant motion of the current would then be in a spiral about the longitudinal axis of the sample. This motion would then produce an extra magnetic field within the sample. The addition of this magnetic field to the applied magnetic field would then give rise to the apparent paramagnetic permeability under the given set of the variables B, I, and T.

It was suggested by Mendelssohn\(^{(7)}\) that due to the fact that in both the measurements of Steiner and Meissner one of the variables B, I, and T was changed in order to determine the flux content of the sample, the flux increase might be a transient state resulting from the nonequilibrium conditions existing in the system.

With this question in mind measurements were made by Mendelssohn, Squire, and Teasdale\(^{(8)}\) using a static method in which all of the variables B, I, and T were held constant during the flux determination. The flux increase was not observed since the conditions were outside of the region necessary for the observation of the effect.

Subsequently, Teasdale and Rorschach\(^{(9)}\) reported that the effect had been found using this method although errors
in the measurement of the temperature prevented a more detailed study of the properties of the extra flux.

Thompson and Squire\(^{10}\) published the results of a quantitative study of the paramagnetic effect using the static method. The technique which was used to overcome the objections raised by Mendelssohn was as follows. The sample in the form of a cylindrical single crystal was established at a constant temperature in a constant longitudinal magnetic field. A fixed current was then passed through the sample. Under these equilibrium conditions the flux content of the sample was measured by moving an induction coil from a position around the sample to a position around a copper rod of the same diameter. The copper rod provided a reference flux since it always remained in the normal state. The deflection of a ballistic galvanometer connected to the induction coil as the coil was raised and lowered indicated the difference in the flux content of the copper and the sample. The current was then increased to a slightly larger value and the measurement repeated. In this manner the transition from the superconducting state to the normal state was made. The resulting deflections when plotted as a function of the sample current for a given temperature and magnetic field showed a sharp increase in the flux content just before the sample reached the normal state.
They found that the magnitude of the paramagnetic peak and its position were independent of the direction of the external magnetic field with respect to the direction of the sample current. The position of the peak was found to occur slightly below the current value at which the total magnetic field was the critical field. This difference in current value corresponded to less than 0.01°K and could be explained by the heating in the current leads. Their results confirm the earlier reports that the magnitude of the peak increases with increasing current at a given temperature. For increasing values of the applied magnetic field the effect became a smaller fraction of the total field. Other than the effect of frozen flux there was no hysteresis exhibited in the transition and the transitions were perfectly reversible. Transitions made by increasing the applied field with sample current and temperature held constant gave wider peaks than those made by increasing the sample current. The amount of extra flux within the sample was found to be several times that due to the external field alone. They also found that the diminishing of the peak with increased magnetic field was not given by a simple power law. Values for the threshold current checked with those given by Meissner, et al.

In a later paper Thompson extended the original measurements on tin to include indium and thallium. He
found that the slope of the threshold current versus applied magnetic field had the same value for each of the superconductors considered. The maximum flux content of the sample was observed to occur when the total magnetic field was just the critical magnetic field. The results of these studies leads to the conclusion that the paramagnetic effect is an intermediate state effect of the superconductor.

An attempt to give a theoretical explanation for the paramagnetic effect has been presented by H. Meissner\(^{(12)}\). His theory is based on a model of the structure of the intermediate state as given by London\(^{(13)}\) and Pippard\(^{(14)}\). This model considers the superconducting regions scattered throughout a media of essentially normal conducting material. With the application of an external magnetic field these superconducting regions tend to align themselves in the direction of the resultant field. If the sample current has a circular component, the resultant field will be in the form of a spiral about the longitudinal axis of the sample. Since the path is superconducting, the current tends to follow this spiral direction thus producing a longitudinal magnetic field in excess of the externally applied field.

Meissner's theory predicts the occurrence of the paramagnetic peak. It does not predict the necessity of a threshold current and it gives the same results for all superconducting materials. While the theory gives some
understanding of the nature of the effect it is still not satisfactory in view of the existing experimental data.

Thompson\textsuperscript{(11)} reported measurements in which the sample at a fixed temperature and carrying a given current was subjected to stepwise increase in the magnitude of the applied magnetic field. This procedure was repeated for the same values of initial and final magnetic field as the current was increased through the transition. The resulting deflections of the ballistic galvanometer indicated the difference in the flux content of the sample in the two equilibrium states. It was found that upon increasing the applied magnetic field a decrease of the flux content could occur. An examination of two transition curves taken at the same temperature but different values of external magnetic field shows that this would be expected at certain values of the sample current.

From these measurements Thompson draws the conclusion that the time required for the circular component of the current to adjust itself to the new conditions of magnetic field is short compared with the period of the galvanometer, since there was no observable time delay in its response to the change of magnetic field.

A consideration of this type of measurement suggests that if the external magnetic field were changed periodically and the resultant flux changes within the sample observed with a device of extremely short period, the time required
for the current to adjust to the new conditions could be measured. The flux changes will induce a periodic voltage in an induction coil which can be observed on a cathode ray oscilloscope. The use of the oscilloscope overcomes the limitation of the galvanometer in that the beam is essentially an inertialess indicator and thus has a negligible period.

A series of experiments using this approach have been carried out. An alternating magnetic field was superimposed upon a steady external magnetic field in such a way as to periodically move a superconducting specimen of tin into and out of the paramagnetic region. The induced signal in an induction coil around the sample has been studied as a function of the frequency of the alternating magnetic field and of the sample current and steady applied field.

Experiments have also been performed in which the transient response of the sample to a stepwise increase in current was studied.

It was necessary in these experiments to first establish the conditions for the occurrence of the paramagnetic effect. This was done by a method similar to that of Meissner, et al.
A sample of tin was prepared in the form of a cylindrical rod from Baker Chemical Company 99.99 percent pure laboratory stock. The tin was placed in a 0.25 inch bore pyrex glass tube. The tube had been carefully cleaned and drawn to a closed capillary at one end. The tube containing the tin was then placed along the axis of a cylindrical electric furnace and the temperature set at 300° C. The tube containing the molten tin was then outgassed over a period of several hours by pumping continuously with a high vacuum pump. The furnace was then slowly raised from around the tin at a rate of 6 cm. per hour. After the crystal had been formed, it was carefully removed from the glass tube and polished in hydrofluoric acid. The tin crystal was then examined and found to exhibit several long crystal faces indicating a structure of several large single crystals. The sample was then cut to a length of 7.94 cm. and had a diameter of 0.627 cm.

The tin cylinder was mounted between two copper rods of the same diameter as the sample. The copper rods served as the current contacts for the sample current.

A detection coil consisting of 5,000 turns of No. 48 heavy formvar coated copper wire was wound over a one-inch length of a textolite form. The coil was then slipped
closely about the tin cylinder and positioned at the center of the specimen.

The sample was placed along the axis of a cylindrical lucite sample holder. Openings were provided at either end of the sample container to permit the circulation of the liquid helium bath. A coil of 20,000 turns of No. 28 heavy formvar copper wire was then wound directly on the outside of the cylindrical sample holder.

A thin sheet of copper was fitted about the outside of the sample holder to serve as a return lead for the sample current. This was done to reduce the effect of the magnetic field of the return current on the sample and detection coil. The copper cylinder was left with a longitudinal 5/8 inch gap along its entire length to prevent closed circuit eddy currents from being set up. The entire sample assembly is shown in Figure 2.

A cylindrical nitrogen can was suspended from the brass dewar plate. Monel tubes leading to and from the nitrogen can permitted the passage of liquid nitrogen continuously through the can. The sample assembly was then suspended from the nitrogen can by a 0.5-inch textolite tube.

The sample current leads were brought through the dewar plate by two kovar glass seals using No. 12 insulated copper wire. These leads were connected to leads of No. 22 formvar copper wire which were wrapped several times about the
nitrogen can for good thermal contact. The nitrogen can was then covered with aluminum foil to prevent heat radiation from the current leads down into the dewar. The current leads were then brought to the sample assembly in a parallel spiral to cancel out the effect of their magnetic fields.

The leads from the detection coil and the coil about the sample holder were brought up through a kovar glass seal in the dewar plate using No. 38 formvar copper wire.

The entire assembly was placed in an experimental helium dewar. A second dewar for the nitrogen was placed around the helium dewar and both were then placed along the axis of a large external solenoid. The solenoid was positioned so that the sample was located along the axis of the solenoid and at the center of the solenoid windings. This arrangement is shown in Figure 3.

The solenoid which was used to produce the external longitudinal magnetic fields was capable of producing a magnetic field which was uniform along the axis over a length of 12 cm. to within 0.04 percent. This uniformity of axial field is obtained by placing additional current loops at each end in series with the solenoid windings. The calibration of the solenoid was 17.55 ± 0.1 gauss per ampere.

The current for the solenoid was supplied by Edison cells and was controlled by means of rheostats. The current
in the solenoid was measured with a Leeds and Northrup type K-2 potentiometer and a 1 ohm standard resistance.

The sample current was furnished by an 8 kw. direct current generator in conjunction with an electronic current regulator. The output current from the generator is controlled by varying the current in the exciter field windings electronically in response to changes which may occur in the output current. The output current remained constant over periods of 30 minutes to 2 parts in $10^4$.

The current flowing through the sample was measured with the K-2 potentiometer and a 0.1 ohm standard resistance.

A second bank of Edison cells was available to supply a direct current to the coil about the sample holder. This coil had a calibration of 1.28 gauss per milliampere and the current could be measured with the potentiometer circuit.

The ballistic galvanometer used in conjunction with the detection coil was a Leeds and Northrup type HS with a period of 7.5 sec. and a sensitivity of 0.1µV./mm.

The temperature was established by pumping on the liquid helium bath with a high vacuum pump. The vapor pressure was measured by means of a copper tube leading from the helium dewar to a mercury manometer. The mercury manometer had a 1 cm. bore, and was read with a cathometer equipped with a vernier scale capable of reading to $\pm 0.025$ mm. The temperature was computed from the vapor pressure readings by
means of the 1948 tables of vapor pressure-temperature data.

The temperature was controlled by an electronic regulator circuit designed by Dr. H. E. Rorschach of the Rice Institute. The regulator consists of a glass bulb in which the desired pressure is admitted and then sealed off. A mercury filled u-tube connects this bulb with a second bulb which is open to the helium bath. Contacts located at the surface of the mercury respond to variations in pressure between the two bulbs and operate an electronically controlled valve in the pumping line. The regulation obtained is sufficient to hold the temperature to within 0.001°K under normal conditions.

The source of current for the alternating magnetic field was a Hewlett-Packard Model 200CD audio oscillator which was capable of providing 10 volts to rated load of +600 ohms. The frequency calibration accuracy was -2 percent and line voltage variations caused only a negligible shift in the output frequency. For extremely low frequencies a Hewlett-Packard Low Frequency Function Generator was employed.

A General Radio vacuum tube voltmeter was used to measure the potential drop across a standard noninductive resistance in order to determine the alternating current in the oscillator output circuit.
The induced signal in the alternating magnetic field measurements was fed to a three-stage amplifier with a cathode follower output. The amplifier had a gain of 250 and good frequency response from 1 c.p.s. to above 1,000 c.p.s. The amplifier was provided with a separate voltage regulated power supply.

A Dumont type 304A cathode ray oscilloscope having a persistant screen was used to display the signal induced in the detection coil. The extremely low frequency sweeps were obtained with the aid of external capacitors in the oscilloscope sweep circuit. For the transient measurements an externally triggered driven sweep was employed. For extremely short duration transients the performance of the Dumont 304A scope was checked with the response of a Tektronic pulse scope and found to be quite adequate.

A block diagram of the circuits which were used in the measurements is given in Figure 4. The experimental setup is pictured in Figure 5.
FIG. 2 SAMPLE ASSEMBLY
FIG. 3 EXPERIMENTAL DEWAR ARRANGEMENT
FIG. 4 CIRCUIT DIAGRAM
FIG. 5 Arrangement of the Experimental Equipment
IV MEASUREMENTS AND RESULTS

A series of preliminary experiments were carried out in order to establish the paramagnetic region for the particular sample which was to be used. This was necessary since the application of the alternating magnetic field studies required a detailed knowledge of the magnitude and location of the paramagnetic effect for given values of B, I, and T. Transitions which showed the paramagnetic effect were made prior to all studies with alternating magnetic fields. These measurements were made in the following manner.

The temperature was established and held constant at some value below the zero magnetic field transition temperature \(T_0 = 3.735^\circ K\). A steady direct current was then passed through the sample. A small steady longitudinal magnetic field provided by the external solenoid was then turned on. The corresponding flux change in the sample was indicated by the throw of the ballistic galvanometer connected to the detection coil about the sample. The sample current was then increased to a slightly larger value and the measurement repeated. In this way the flux content of the sample was determined as a function of the sample current as the tin was taken through the transition from the superconducting to the normal state. The temperature and measuring field were kept constant during the entire transition.
The flux content of the sample may be considered in terms of the apparent permeability defined by Meissner (Eq. 7). A typical curve of the apparent permeability $\tilde{\mu}$ as a function of the current at constant temperature and magnetic field is shown in Figure 6. In the superconducting state $\tilde{\rho} = 0$. The small constant deflection obtained is due to the finite amount of leakage flux the detection coil, since $\tilde{B} = 0$ within the sample. As the sample current is increased, flux penetrates sample and the interaction of the applied magnetic field with the magnetic field of the sample current gives rise to a circular component of the current. The flux content then rises sharply to a maximum and then decreases more slowly until the normal state value $\tilde{\rho} = 1$ is reached.

Transitions which show the paramagnetic effect have been made at a number of different temperatures and values of measuring field. The decrease in the value of $\tilde{\rho}$ at the peak with increased measuring field at a constant temperature can be seen in Figures 6 and 7. The increase of $\tilde{\rho}$ with increased current can be seen from Figures 7 and 8. These results are in agreement with all the previous measurements of the properties of the paramagnetic effect.

Measurements were made of the effect of a stepwise increase in the value of the applied magnetic field at a constant temperature and current. The sample was established
at a fixed temperature in a given magnetic field and carrying a known current. The applied magnetic field was then increased by turning on a second field provided by the coil around the sample container. The deflection resulting from the addition of this field was taken as an indication of the flux change due to the rearrangement of the sample current to meet the new conditions. This procedure was repeated at different values of the sample current as the transition to the normal state was made. The results of these measurements are typified by Figure 9 where the normalized deflections are plotted as a function of the sample current. It will be noted that the initial and final values of the magnetic field represent the equilibrium conditions shown in Figures 6 and 7. The curve Figure 9 shows the same form as is expected from Figures 6 and 7.

From the fact that the response of the galvanometer to the increase in magnetic field did not indicate a measurable time delay, we may say that the time which is required for the sample current to respond to the change in magnetic field is certainly less than the period of the galvanometer. Thus we may tentatively set an upper limit of 0.5 sec. on the time necessary for the currents responsible for the paramagnetic flux to be set up.

The effect of an alternating magnetic field on the tin superconductor in the transition region was investigated in
the following manner. The output of the audio oscillator was fed to the coil wound on the outside of the sample holder. The signal voltage induced in the detection coil about the sample was amplified and displayed on the cathode-ray oscilloscope. The circuit arrangements are shown in Figure 4.

When the sample was at a temperature below the transition temperature and the sample current and applied steady magnetic field were zero, a signal voltage was induced in the detection coil due only to the leakage flux of the alternating magnetic field. The magnitude of the alternating magnetic field was increased so that the critical field at the given temperature was exceeded once during each half cycle. During the time interval that the alternating magnetic field was greater than the critical magnetic field, the signal voltage showed an observable increase. As the magnitude of the alternating magnetic field was further increased, the sample remained in the superconducting state for shorted intervals of time during each half cycle.

In Figure 10 is shown a detailed view of the transition region for one half cycle of the induced voltage. The entire induced signal voltage wave form is shown in Figure 11a. These pictures of the signal voltage are typical of the scope patterns which were obtained. In Figures 10 and 11a the temperature was 3.682°C, the sample current and applied steady magnetic field were zero, and the alternating magnetic
field was approximately $10 \times 10^{-4}$ W/M$^2$ at a frequency of 50 cycles/second.

The sinusoidal increase of the signal voltage corresponds to a decreasing magnetic field. As the magnetic field decreases below the critical field value, the sample becomes superconducting and the signal voltage drops abruptly. When the magnetic field exceeds the critical value again (but in the opposite direction) the sample goes into the normal state and the signal voltage rises sharply. This process occurs twice during each cycle since the alternating magnetic field can exceed the critical value in either direction.

The Meissner Effect in which the condition that $\vec{B} = 0$ occurs upon the transition to the superconducting state and is destroyed as the sample goes into the normal state is seen as a sharp inflection in the signal voltage just as the signal voltage drops from its normal state value and again as it increases from its superconducting state value.

It will be noted that the induced voltage obtained when the sample is in the superconducting state and that obtained when the sample is in the normal state differ only by a few percent. This is due to the fact that when the sample is in the superconducting state ($\vec{B} = 0$ within the sample), the magnetic field just outside of the surface of the superconductor is considerably greater than when the sample is in the normal state. This results from the bunching of the
lines of magnetic flux near the surface of the tin due to the Meissner Effect. Consequently the induced voltage due to the leakage flux does not differ greatly from the normal state signal voltage.

The effect of the application of a steady longitudinal magnetic field is shown in Figure 11b where a steady magnetic field of $5 \times 10^{-4} \text{ W/m}^2$ acts along the axis of the sample. The other variables have the same values as specified above for Figure 11a. The occurrence of the transition is shifted in time due to the bias effect of the steady magnetic field. Thus the sample remains in the normal state for a longer time interval when the two fields are in the same direction. This is due to the fact that the alternating component of the magnetic field required to give a total magnetic field greater than the critical field value is less when the two fields are in the same direction. The opposite holds true when the two fields are opposing each other, and the sample then remains in the normal state for a shorter time interval.

If the steady component of the magnetic field is zero and a current is passed through the sample, the time that the sample remains in the superconducting state decreases with increased values of the current. This is shown in Figure 12a for a current of 6.0 amperes, the steady magnetic field is zero, and the other conditions are the same as previously specified. When the sample current exceeds the critical
value set by the Silsbee Effect, the alternating magnetic field will not cause the transition to occur. This is shown in Figure 12b where the current has been increased to 8.0 amperes.

This may be understood by the following considerations. Since the magnetic field due to the sample current is azimuthal about the sample axis, it will not act as a bias to the alternating magnetic field. The presence of the azimuthal magnetic field effectively lowers the value of the critical field. Thus the alternating component of the field required to drive the superconductor into the normal state becomes smaller as the sample current increases. When the sample current exceeds its critical value, the alternating magnetic field will have no effect on the transition. There is no shift of the transition in time due to the action of the sample current since these considerations hold regardless of the direction of the alternating field.

The effect of the alternating component of the magnetic field upon the sample in the paramagnetic region was studied as follows. The sample was established at a constant temperature. A current corresponding to the maximum of the paramagnetic peak was sent through the sample. The applied magnetic field was composed of a steady component and an alternating component such that the sample was swept through the paramagnetic region at the frequency of the alternating
field. This procedure was repeated at a number of different values of temperature, sample current, steady magnetic field and alternating magnetic field. In each case the entire range of frequencies from 0.5 c.p.s. to 1000 c.p.s. was investigated. In no instance was any signal observed which could be attributed to the effect of an extra flux buildup in the sample corresponding to the paramagnetic effect. In each case extreme care was taken that the values of the temperature, magnetic field, and sample current corresponded to the paramagnetic region. This was done with the aid of the ballistic galvanometer method previously discussed. It was decided that this approach to the study of the time involved in the paramagnetic flux buildup was not suitable due to the large leakage signal present.

The second approach to this problem has been the study of the response of the sample to a stepwise increase of the sample current. If a change of the magnetic flux within the sample occurred due to the stepwise current change, a transient voltage would be induced in the detection coil about the sample. An analysis of this transient signal would then lead to a knowledge of the time required for the flux to build up in the sample.

The arrangement for stepping the current was as follows. A resistance and a switch were put in parallel with the sample current circuit as indicated in Figure 4. Since the
current supply functioned as a constant current source, the output current could be maintained constant to a change of the load. Thus if the circuit in parallel with the sample were opened, the current through the sample would increase in a stepwise manner. The current supplied to the two parallel branches was adjusted so that the current in the sample corresponded to the superconducting state under the given conditions of temperature and magnetic field. The current through the second branch was of such a value that when added to the current in the sample, it gave a total current through the sample corresponding to either the normal state or to the paramagnetic region. A measurement of the transient voltage across the resistance in the parallel branch indicated that the current change was completed in 0.15 milliseconds.

The occurrence of a flux change within the sample due to the stepwise increase in the sample current was established in the following way. At a constant temperature and in a constant applied magnetic field a stepwise increase in the current was made such that the sample remained in the superconducting state. There was no resulting deflection on a ballistic galvanometer connected to the detection coil. When the stepwise increase in sample current corresponded to a shift from the superconducting state to the normal state, a deflection corresponding to the appearance of the
applied magnetic field through the sample was obtained. Finally, if the current increase corresponded to a shift from the superconducting state to the maximum of the paramagnetic region, an even larger deflection resulted, indicating an extra flux buildup within the sample. Since there was no delay in the response of the galvanometer to the change of current, these measurements indicate that the time required for the occurrence of both the Meissner Effect and the Paramagnetic Effect are quite small compared to the period of the galvanometer.

The detection coil was then connected to an amplifier and oscilloscope. The oscilloscope was set to operate with a driven sweep. The triggering pulse was obtained from across the resistance in the circuit in parallel with the sample. Thus when the parallel circuit was opened, the transient voltage across the resistance triggered the scope sweep, and any subsequent transient signal induced in the detection coil could be seen on the scope.

The operation of this circuit was checked; and it was found that a transient signal resulting from a stepwise increase of the current through a coil of a few turns could be induced in a detection coil and displayed on the scope. This transient signal was in the form of short voltage pulse which could be easily detected.
The procedure for these studies was as follows. The temperature, applied magnetic field, and sample current were set such that the sample was in the superconducting state. The throw of the ballistic galvanometer was used to verify the fact that the sample was actually in the superconducting state. The sample current was then given a step-wise increase and the scope sweep examined for the appearance of a resulting transient voltage. The final state was then checked with the galvanometer. This procedure was repeated for a number of different values of the temperature, applied magnetic field, and sample current. Shifts from the superconducting to the normal state as well as to the paramagnetic region were made. Sweep times from 1 second to 100 microseconds were employed.

It was found that the only transient voltage induced in the detection coil was due to the current change in the sample leads. This transient is shown in Figure 13. It is not dependent upon the applied magnetic field or the temperature and as such represents only a leakage signal. There were no indications of a transient voltage arising either from the penetration of the applied magnetic field when the sample was shifted into the normal state, or from the occurrence of the paramagnetic effect when the sample was shifted into this region.
Since the galvanometer measurements indicated that the expected flux changes were actually occurring upon the current shift, these results seem to indicate that the present arrangement is not of sufficient sensitivity to detect the small, long duration transient voltages induced by these flux changes.
<table>
<thead>
<tr>
<th>Sample Current (amp.)</th>
<th>Deflection (cm.)</th>
<th>Permeability $u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.00</td>
<td>5.68</td>
<td>0.00</td>
</tr>
<tr>
<td>7.00</td>
<td>5.68</td>
<td>0.004</td>
</tr>
<tr>
<td>7.60</td>
<td>5.69</td>
<td>0.049</td>
</tr>
<tr>
<td>7.80</td>
<td>5.70</td>
<td>0.096</td>
</tr>
<tr>
<td>8.00</td>
<td>5.96</td>
<td>0.263</td>
</tr>
<tr>
<td>8.10</td>
<td>6.23</td>
<td>0.510</td>
</tr>
<tr>
<td>8.20</td>
<td>7.18</td>
<td>0.849</td>
</tr>
<tr>
<td>8.30</td>
<td>8.59</td>
<td>1.45</td>
</tr>
<tr>
<td>8.40</td>
<td>10.52</td>
<td>1.71</td>
</tr>
<tr>
<td>8.50</td>
<td>13.94</td>
<td>1.81</td>
</tr>
<tr>
<td>8.60</td>
<td>15.43</td>
<td>1.73</td>
</tr>
<tr>
<td>8.70</td>
<td>16.02</td>
<td>1.51</td>
</tr>
<tr>
<td>8.80</td>
<td>15.54</td>
<td>1.36</td>
</tr>
<tr>
<td>9.00</td>
<td>14.31</td>
<td>1.25</td>
</tr>
<tr>
<td>9.20</td>
<td>13.41</td>
<td>1.16</td>
</tr>
<tr>
<td>9.40</td>
<td>12.82</td>
<td>1.13</td>
</tr>
<tr>
<td>9.60</td>
<td>12.28</td>
<td>1.11</td>
</tr>
<tr>
<td>9.80</td>
<td>12.12</td>
<td>1.05</td>
</tr>
<tr>
<td>10.00</td>
<td>12.00</td>
<td>1.00</td>
</tr>
<tr>
<td>11.00</td>
<td>11.67</td>
<td></td>
</tr>
<tr>
<td>12.00</td>
<td>11.38</td>
<td></td>
</tr>
</tbody>
</table>
$T = 3.682 \, ^\circ K$

$B = 1 \times 10^{-4} \, \text{W/M}^2$

FIG. 6 TRANSITION AT CONSTANT TEMPERATURE AND FIELD
TABLE II

\( B = 1.5 \times 10^{-4} \text{ w/m}^2 \quad T = 3.682 \, ^\circ K \)

<table>
<thead>
<tr>
<th>Sample Current (amp.)</th>
<th>Deflection (cm.)</th>
<th>Permeability ( u )</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.00</td>
<td>7.78</td>
<td>0</td>
</tr>
<tr>
<td>7.00</td>
<td>7.78</td>
<td>0</td>
</tr>
<tr>
<td>7.80</td>
<td>7.89</td>
<td>0.015</td>
</tr>
<tr>
<td>8.00</td>
<td>8.48</td>
<td>0.093</td>
</tr>
<tr>
<td>8.20</td>
<td>11.39</td>
<td>0.478</td>
</tr>
<tr>
<td>8.40</td>
<td>18.63</td>
<td>1.44</td>
</tr>
<tr>
<td>8.50</td>
<td>20.56</td>
<td>1.69</td>
</tr>
<tr>
<td>8.60</td>
<td>20.74</td>
<td>1.71</td>
</tr>
<tr>
<td>8.70</td>
<td>19.98</td>
<td>1.61</td>
</tr>
<tr>
<td>8.80</td>
<td>19.12</td>
<td>1.50</td>
</tr>
<tr>
<td>9.00</td>
<td>18.01</td>
<td>1.35</td>
</tr>
<tr>
<td>9.20</td>
<td>17.29</td>
<td>1.26</td>
</tr>
<tr>
<td>9.40</td>
<td>16.62</td>
<td>1.17</td>
</tr>
<tr>
<td>9.60</td>
<td>16.21</td>
<td>1.11</td>
</tr>
<tr>
<td>9.80</td>
<td>15.98</td>
<td>1.08</td>
</tr>
<tr>
<td>10.00</td>
<td>15.82</td>
<td>1.06</td>
</tr>
<tr>
<td>12.00</td>
<td>15.34</td>
<td>1.00</td>
</tr>
</tbody>
</table>
$T = 3.682 \, ^{\circ} K$

$B = 1.5 \times 10^{-4} \, \text{W/M}^2$

**FIG. 7 TRANSITION AT CONSTANT TEMPERATURE AND FIELD**
TABLE III

\[ B = 1.5 \times 10^{-4} \text{ W/m}^2 \quad T = 3.671^\circ K \]

<table>
<thead>
<tr>
<th>Sample Current (amp.)</th>
<th>Deflection (cm.)</th>
<th>Permeability ( u )</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.00</td>
<td>7.72</td>
<td>0</td>
</tr>
<tr>
<td>9.00</td>
<td>7.72</td>
<td>0</td>
</tr>
<tr>
<td>10.00</td>
<td>7.76</td>
<td>0.005</td>
</tr>
<tr>
<td>10.10</td>
<td>7.79</td>
<td>0.008</td>
</tr>
<tr>
<td>10.20</td>
<td>7.88</td>
<td>0.018</td>
</tr>
<tr>
<td>10.40</td>
<td>8.33</td>
<td>0.070</td>
</tr>
<tr>
<td>10.50</td>
<td>8.78</td>
<td>0.121</td>
</tr>
<tr>
<td>10.60</td>
<td>11.18</td>
<td>0.396</td>
</tr>
<tr>
<td>10.70</td>
<td>13.19</td>
<td>0.626</td>
</tr>
<tr>
<td>10.80</td>
<td>14.51</td>
<td>0.777</td>
</tr>
<tr>
<td>10.90</td>
<td>23.29</td>
<td>1.78</td>
</tr>
<tr>
<td>11.00</td>
<td>25.09</td>
<td>1.99</td>
</tr>
<tr>
<td>11.10</td>
<td>26.01</td>
<td>2.09</td>
</tr>
<tr>
<td>11.20</td>
<td>23.18</td>
<td>1.77</td>
</tr>
<tr>
<td>11.40</td>
<td>21.76</td>
<td>1.61</td>
</tr>
<tr>
<td>11.60</td>
<td>20.68</td>
<td>1.48</td>
</tr>
<tr>
<td>11.80</td>
<td>19.93</td>
<td>1.40</td>
</tr>
<tr>
<td>12.00</td>
<td>19.57</td>
<td>1.36</td>
</tr>
<tr>
<td>12.40</td>
<td>18.31</td>
<td>1.21</td>
</tr>
<tr>
<td>12.80</td>
<td>17.61</td>
<td>1.13</td>
</tr>
<tr>
<td>13.20</td>
<td>17.22</td>
<td>1.09</td>
</tr>
<tr>
<td>13.60</td>
<td>16.89</td>
<td>1.05</td>
</tr>
<tr>
<td>14.00</td>
<td>16.46</td>
<td>1.00</td>
</tr>
<tr>
<td>15.00</td>
<td>16.46</td>
<td>1.00</td>
</tr>
</tbody>
</table>
FIG. 8 TRANSITION AT CONSTANT TEMPERATURE AND FIELD

$T = 3.671 \text{ K}$

$B = 1.5 \times 10^{-4} \text{ W/M}^2$
TABLE IV

$B_{\text{initial}} = 1.0 \times 10^{-4} \text{ w/m}^2; \quad B_{\text{final}} = 1.5 \times 10^{-4} \text{ w/m}^2;

T = 3.682^\circ\text{K}

<table>
<thead>
<tr>
<th>Sample Current (amp.)</th>
<th>Deflection (cm.)</th>
<th>Normalized Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.00</td>
<td>2.80</td>
<td>0</td>
</tr>
<tr>
<td>7.00</td>
<td>2.80</td>
<td>0</td>
</tr>
<tr>
<td>7.80</td>
<td>3.18</td>
<td>0.380</td>
</tr>
<tr>
<td>8.00</td>
<td>4.19</td>
<td>2.39</td>
</tr>
<tr>
<td>8.20</td>
<td>6.62</td>
<td>3.82</td>
</tr>
<tr>
<td>8.40</td>
<td>4.78</td>
<td>0.440</td>
</tr>
<tr>
<td>8.60</td>
<td>4.50</td>
<td>-0.800</td>
</tr>
<tr>
<td>8.80</td>
<td>4.78</td>
<td>-0.520</td>
</tr>
<tr>
<td>9.00</td>
<td>4.93</td>
<td>-0.370</td>
</tr>
<tr>
<td>9.20</td>
<td>5.20</td>
<td>-0.100</td>
</tr>
<tr>
<td>9.40</td>
<td>5.21</td>
<td>-0.090</td>
</tr>
<tr>
<td>9.60</td>
<td>5.22</td>
<td>-0.080</td>
</tr>
<tr>
<td>9.80</td>
<td>5.30</td>
<td>0</td>
</tr>
<tr>
<td>10.00</td>
<td>5.30</td>
<td>0</td>
</tr>
<tr>
<td>12.00</td>
<td>5.30</td>
<td>0</td>
</tr>
</tbody>
</table>
$T = 3.682 \, ^\circ K$

$B_{initial} = 1 \times 10^{-4} \, \text{W/m}^2$

$B_{final} = 1.5 \times 10^{-4} \, \text{W/m}^2$

**FIG. 9** EFFECT OF A FIELD CHANGE AT CONSTANT TEMPERATURE FOR A CURRENT TRANSITION
FIG. 10 Induced Voltage for the Transition Region of the Superconductor (T = 3.682° K, B = 0, I = 0, B_a.c. = 10x10^-4 W/m^2, frequency = 50 c.p.s.)
FIG. 11a Induced Voltage (T = 3.682°K, B = 0, I = 0, Ba.c. = 10x10^{-4} W/M^2, frequency = 50 c.p.s.)

FIG. 11b Induced Voltage (T = 3.682°K, B = 5x10^{-4} W/M^2, I = 0, Ba.c. = 10x10^{-4} W/M^2, frequency = 50 c.p.s.)
FIG. 12a Induced Voltage for the Transition Region ($T = 3.682^\circ K, B = 0, I = 6.0$ Amps., B.a.c. = $10 \times 10^{-4}$ W/M$^2$, frequency = 50 c.p.s.)

FIG. 12b Induced Voltage for the Transition Region ($T = 3.682^\circ K, B = 0, I = 8.0$ Amps., B.a.c. = $10 \times 10^{-4}$ W/M$^2$, frequency = 50 c.p.s.)
FIG. 13  Current Transient  \( T = 4.21^\circ K \)
\( B = 0, \text{ Initial} = 3.0 \text{ Amps. } \text{ I}_{\text{final}} = 4.0 \text{ Amps.} \)
Sweep time = 0.2 millisecond.)
V CONCLUSIONS

The results of the measurements made by the shift of the applied magnetic field between two equilibrium states indicate that the time which is required for the extra flux due to the paramagnetic effect to be set up within the sample is less than the period of the galvanometer. Since there was no observed time delay in the response of the galvanometer to the change in the applied magnetic field, we may tentatively adopt the value of 0.5 second as an upper limit on the relaxation time for the paramagnetic effect. This is in accord with the conclusions of Thompson(11).

The occurrence of the Meissner Effect is clearly indicated in the studies with the alternating magnetic fields. This implies that the effect takes place in an extremely short time interval. The fact that the observed signal resulting from the Meissner effect was small may indicate that the field penetrates only a short distance into the superconductor during the time that the magnetic field is greater than the critical field. This would result in a smaller induced voltage since a part of the sample cross section area would remain superconducting. The conclusion that the time required for the occurrence of the Meissner Effect is extremely short is in agreement with the observation of Faber(15) who estimates a time of 0.2 microsecond.
The absence of any signal corresponding to a change of paramagnetic flux within the sample which was found in the studies using alternating magnetic fields may be attributed to the following reasons. A large part of the voltage induced by the alternating magnetic field was a result of the high leakage flux. Any small signal arising from the change of extra flux in the paramagnetic region might well have been obscured. It is also possible that since the resultant magnetic field was such that the sample was being shifted continuously through different equilibrium states, the occurrence of the paramagnetic effect was not sufficiently fast in any given time interval to produce a measurable signal.

Transient voltage signals due to the magnetic flux changes within the sample have not been observed. That the flux changes occur upon a stepwise increase of current has been definitely established by means of the galvanometer measurements. It seems likely that the occurrence of a flux change when the sample is shifted from the superconducting to the normal state produces a voltage pulse of small magnitude and long duration such that it is below the detection limit of our equipment. Thus the results of the transient measurements must be considered as representing only a preliminary study. An entirely new method will have to be devised in order to study in detail the flux changes which occur in the transition region of the superconductor.
REFERENCES


2. W. Meissner and L. Ochsenfeld, Naturwissenschaften 21, 787 (1933).


ACKNOWLEDGMENTS

The author would like to express his appreciation to Dr. C. F. Squire under whose direction and instruction this research was carried on. He is indebted to Dr. H. E. Rorschach for many helpful discussions during the course of this work and to the personnel of the Low Temperature Group of the Rice Institute whose assistance has been invaluable. He would also like to acknowledge the services of Mr. Clarence Belcher and of Mr. Frans Van der Henst of the Physics Shop.

The author gratefully acknowledges the grant of the Magnolia Petroleum Company Research Fellowship for the period 1955 - 1956.