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Experimental Test of the Theory of the Proximity Effect in Superconductors* †

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We have measured the transition temperatures of superimposed films of indium and thallium to test the theory of the proximity effect. There is good agreement between the experimental results and the theory. We have also measured the transition temperatures of superimposed films of lead and indium, for which strong electron-phonon coupling might invalidate the theory. The agreement with theory is again good, as found by other investigators.

I. INTRODUCTION

THE superconducting transition temperatures of superimposed indium and thallium films were measured by us. Our purpose has been to test the validity of the theory of the proximity effect.[1–4] Such a test of the theory should fulfill the following conditions:

(1) The two metals in proximity should both be superconductors with transition temperatures that can be measured in the experiment. There are then no parameters appearing in the theory that cannot either be measured or taken from the literature.

(2) Because the theory is developed in the weak-coupling approximation, neither of the two metals should be a strong-coupling superconductor like lead or mercury.

(3) The transition temperature of the superimposed films may depend on the order in which the two films are evaporated onto the substrate.[5–7] If this is the case, the order that yields the lower transition temperature is the one that should be compared with the theory.[7] Both orders must be tried, of course, to determine which is the proper one.

Neither of the previous investigations[8,9] designed to test the theory of the proximity effect satisfy the second and third of these criteria; this motivated us to make the measurements described here. The previous investigations (in which good agreement was found with the theory) have been reviewed elsewhere.[4]

We have used indium and thallium as the two superconductors; in both there is weak electron-phonon coupling. Both orders of condensation have been used. The films were deposited onto glass substrates that were cooled by liquid helium; the purpose of this cooling was twofold: (1) to prevent the two metals from diffusing into each other appreciably, and (2) to produce films with the short electron mean free paths that are assumed in the theory. A special type of extremely smooth glass was used for the substrate. At the same time the superimposed films were produced, separate films of the two metals were also made, so that their resistivities and critical temperatures could be measured. The films were not warmed to room temperature or exposed to the atmosphere until after their transition temperatures and resistances had been measured. The film thicknesses were determined both from optical measurements and from the temperature dependence of the resistances.

The experimental techniques are described in Sec. II, and the results are presented in Sec. III. The data are compared with theory in Sec. IV; good agreement is found. In Sec. V we present a few data on superimposed films of lead and indium. These data were obtained to try to compare our techniques with those used by other investigators. The results are included for completeness, although they do not contribute to our main purpose of testing the theory.

II. EXPERIMENT

The cryostat used in this work was very similar to one described previously,[10] so we do not describe it here.

A. Sample Preparation

Since the films investigated in these experiments were rather thin (on the order of 100 Å), very smooth substrates were required. We therefore used Corning type 7059 glass slides (1.02 mm thick); these slides were

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[1] P. G. de Gennes and E. Guyon, Phys. Letters **3**, 168 (1963).

[2] N. R. Werthamer, Phys. Rev. **132**, 2440 (1963).

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[4] A. E. Jacobs, Phys. Rev. **162**, 375 (1967).

[5] P. Hilsch, Z. Physik **167**, 511 (1962).

[6] J. J. Hauser, H. C. Theuerer, and N. R. Werthamer, Phys. Rev. **136**, A637 (1964).

[7] J. J. Hauser, H. C. Theuerer, and N. R. Werthamer, Phys. Rev. **142**, 118 (1966).

[8] J. J. Hauser and H. C. Theuerer, Phys. Letters **14**, 270 (1965).

[9] G. Bergmann, Z. Physik **187**, 395 (1965).

[10] J. S. Shier and D. M. Ginsberg, Phys. Rev. **147**, 384 (1966).

made directly from the melt and were not mechanically polished. The slides were cleaned by rinsing them with deionized water, acetone, benzene, and isopropyl alcohol, the last three solvents being of reagent grade. They were then placed in an isopropyl alcohol vapor degreaser. Gold electrodes were deposited in a room-temperature vacuum system and the slides were returned to the degreaser, where they were kept until used.

The substrate was mounted in the cryostat by pressing it against the copper block attached to the inner helium tank; a thin, uniform layer of Apiezon N grease was used for thermal contact between the substrate and the copper block. While the substrate was in the cryostat, the areas where films would be (or had been) deposited were protected by covering them with the mask except during the film depositions. This procedure decreased the condensation of residual gases onto the cooled substrate, and reduced the measured transition widths.

The indium and thallium (both 99.999% pure) were evaporated from electrically heated molybdenum boats onto the substrate, which was at a temperature of approximately 6°K. The evaporations were begun and ended by opening and closing a shutter. Before the shutter was opened, the filaments were heated to partially evaporate the metals and to drive off any surface contamination. (At the conclusion of a run, the charges in the boats were evaporated to completion; fresh charges were used for each run.) The film thickness was controlled by monitoring the electrical resistance as the film condensed on the substrate. The evaporation rates ranged from 10 to 50 Å/sec. The pressure outside the 77°K heat shield was about 1×10^{-7} Torr during the evaporations.

In each run, three indium and three thallium films were deposited. The superimposed pair was formed by one indium film and one thallium film; the former was narrower than the latter so the superimposed structure would not be short circuited by an indium film. Two of the four separate films were used to determine the resistances as functions of temperature and to measure the transition temperatures of the components of the superimposed pair. The other two separate films were used to determine the optical film thicknesses, as described below; optical film-thickness measurements were also performed on the superimposed films.

B. Data Acquisition

The transition temperature of each film was defined as the temperature at which its electrical resistance was half the normal-state resistance. An ac oscillator, a lock-in amplifier, and a chart recorder were used to monitor the resistance, and the usual 4-terminal technique was used. The frequency was 97.5 Hz, and the peak-to-peak voltage across the film was about 6 μV. (The transition temperature shifted less than 3×10^{-3} °K on using 100 times as much power.) Temperatures below 4.2°K were determined from the T_{58} temperature scale by measuring the vapor pressure above the helium bath that cooled the sample block. Temperatures above 4.2°K were measured with a calibrated germanium thermometer. From the reproducibility of the data and estimates of the thermal resistances involved, we estimate the uncertainty of the temperature data to be less than 1×10^{-2} °K.

After the transition temperatures had been determined, we prepared for the optical film-thickness measurements by depositing a layer of indium (approximately 2000 Å thick) on the superimposed films and on two of the four separate films. By depositing this indium overlayer onto the substrate while it was still at 4°K (rather than at 300°K), we avoided errors that might otherwise result from the loss, during warmup, of any of the gas that might have condensed on the substrate before the films were produced.[11] For a few of the samples, the overlayer had a low reflectivity, and the optical thicknesses could not be determined.

We then prepared to determine the thicknesses of the films from the temperature dependence of their electrical resistances. To do this, the sample block was warmed to 160°K to anneal the films, and recooled to 77°K. [A few of the films became electrically discontinuous during the annealing, and the $R(T)$ thicknesses could not be determined.] The resistances of two of the four separate films were then measured at nine temperatures between 77 and 150°K. A chromel-alumel thermocouple was used to determine temperatures; a standard calibration table[12] for this type of thermocouple was used in conjunction with a linear deviation function fitted at 77 and 273°K. The film thicknesses were then calculated from Eq. (2) of Ref. 11.[13]

After removing the substrate from the cryostat, we measured the film thicknesses optically with multiple beam interferometry,[14,15] using Fizeau fringes. The uncertainty of the measurements was approximately ±10 Å for films 150 Å thick and ±40 Å for films 1000 Å thick. Although the substrates were very smooth, they were not precisely flat; the result was that the inter-

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[11] A. v. Bassewitz and G. v. Minnigerode, Z. Physik **181**, 368 (1964).

[12] R. L. Powell, L. P. Caywood, Jr., and M. D. Bunch, in *Temperature*, edited by C. M. Herzfeld and A. I. Dahl (Reinhold Publishing Corp., New York, 1962), Vol. 3, part 2, p. 65.

[13] The required resistivity ratio $\rho(T)/\rho(273°\mathrm{K})$ for the bulk materials were taken from G. K. White and S. B. Woods [Rev. Sci. Instr. **28**, 638 (1957)] and K. Onnes and W. Tuyn [Commun. Kamerlingh Onnes Lab. Univ. Leiden, Suppl. **58** (1926)] for indium and thallium, respectively; the values [*Landolt-Börnstein Tables* (Springer-Verlag, Berlin, 1959), Vol. 6, Sec. 27-11] of $\rho(273°\mathrm{K})$ were taken to be 8.1 and 17.5 $\mu\Omega$ cm.

[14] S. Tolansky, *Multiple-Beam Interferometry of Surfaces and Films* (Oxford University Press, New York, 1948), p. 147.

[15] H. E. Bennett and Jean M. Bennett, Phys. Thin Films **4**, 1 (1967).

ference fringes were not perfectly straight. This was the main limitation on the accuracy of the optically-determined film thicknesses.

III. RESULTS

For brevity and convenience in our later comparison of the data with theory, we refer to the indium film as the "superconductor" (with thickness D_s and transition temperature $T_{cs}\sim 4.3°\mathrm{K}$) and to the thallium film as the "normal" metal (with thickness D_n and transition temperature $T_{cn}\sim 2.9°\mathrm{K}$). The transition temperature of the superimposed pair is denoted by T_c. It will be useful later to plot the results in terms of a reduced critical temperature t, defined by

$$t=(T_c-T_{cn})/(T_{cs}-T_{cn}). \qquad (1)$$

We have kept D_s fixed at approximately 170 Å for all the samples, and we have varied D_n. It has been our experience that values of T_c obtained this way provide a more sensitive comparison between theory and experiment than results obtained by varying D_s.

A. Thicknesses

As we have described in Sec. II, the film thicknesses were obtained by two independent methods, one using optical methods and the other using the temperature dependence of the electrical resistance. For brevity we call the resulting thickness values the optical thickness and the $R(T)$ thickness, respectively. The indium films had an average optical thickness of 175 Å, and an average $R(T)$ thickness of 160 Å. The mean absolute deviations from these mean values were 9 and 4 Å, respectively.

The optical thicknesses and $R(T)$ thicknesses of the thallium films are compared in Fig. 1. [A point with $D_{\mathrm{opt}}=1870$ Å and $D_{R(T)}=1990$ Å is not shown.] The scatter is far larger than observed for the indium films; some points are more than 100 Å from the line $D_{\mathrm{opt}}=D_{R(T)}$. The failure of these two methods to agree has also been observed by other investigators for other metals,[11,16] and possible reasons have been suggested. None of these suggestions explain the random discrepancies we see in the figure. Because the $R(T)$ thickness is obtained by making assumptions which are not strictly true,[17] the optical thickness should perhaps be preferred. Nevertheless, we shall present the results in terms of the film thicknesses obtained by both methods.

As we described in Sec. II, we measured the optical thicknesses of the films comprising the superimposed pair as well as those of two of the separate films on each substrate. Other authors have observed that the optical thickness of a film deposited on the bare substrate may be larger than the optical thickness of a film deposited simultaneously on top of another film on the substrate.[16,18] The difference is assumed to be due to nucleation effects during the initial stages of film formation. We have also observed a small (~10 Å) difference in the apparent thicknesses of the two indium films (regardless of which metal was deposited first), but for our samples the film on the bare substrate had the smaller thickness.

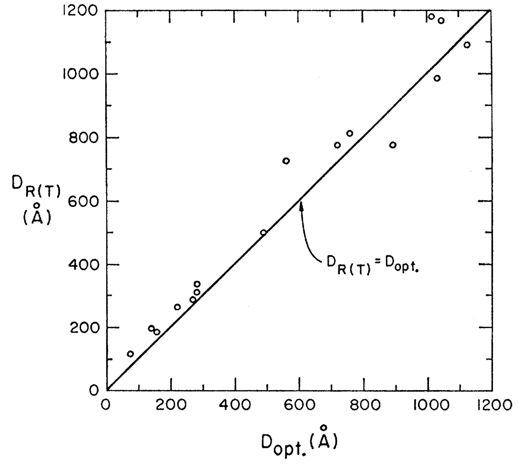

FIG. 1. Comparison of the $R(T)$ thicknesses with the optical thicknesses for the thallium films.

B. Resistivities

In comparing the data with theoretical predictions, we will need to know the resistivities of the films. These can be calculated from the dc resistance (measured with the usual 4-terminal technique) and the sample dimensions. (All the films were 0.80 mm wide except the thallium films of the superimposed pairs, which were 1.68 mm wide.[19] The distance between the voltage electrodes was 13.0 mm for all the films.) The resistivities so determined included a contribution from the scattering of electrons at the films' surfaces; the desired resistivity is, however, the bulk value. The contribution from surface scattering was therefore subtracted by using Eq. (10) of Ref. 11. This correction has been applied to yield the data that we present here; it was less than 20% for all but our thinnest films.

The average resistivity of the indium films was 14.4 μΩ cm for the $R(T)$ thicknesses and 16.5 μΩ cm for the optical film thicknesses, with mean absolute deviations from the mean of 0.42 and 1.06 μΩ cm, respectively. The resistivities of the thallium films

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[16] A. v. Bassewitz, Z. Physik **201**, 350 (1967).

[17] It is assumed, for example, that Matthiessen's rule is valid. See Ref. 11.

[18] G. v. Minnigerode, Z. Physik **192**, 379 (1966).

[19] The transition temperatures have been corrected for the shunting effect of the portion of the thallium film lying outside the indium film. The correction to the reduced transition temperature t was at most 0.01 and was usually much less.

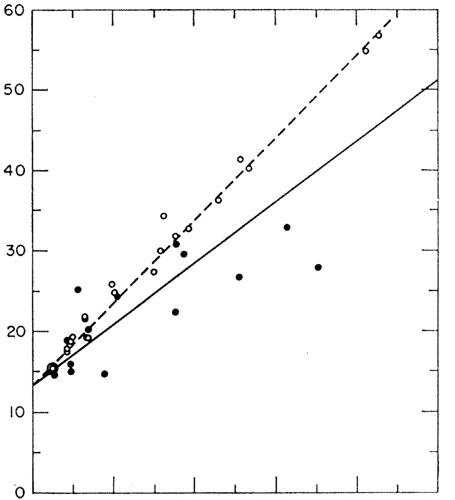

FIG. 2. Resistivity versus the reciprocal of the film thickness for the thallium films. The straight lines are visual fits to the data points. The open circles and dashed line indicate resistivities calculated from the $R(T)$ thicknesses. The filled circles and full line indicate resistivities calculated from the optical thicknesses.

are plotted in Fig. 2; two points for the thinnest thallium films have not been plotted. The straight lines are visual fits to the data; these lines were used in the theoretical calculations of Sec. IV to estimate the resistivity of the thallium film component of each superimposed film pair. The scatter is much less for the $R(T)$ thicknesses than for the optical thicknesses, probably because both the film resistance and the $R(T)$ thickness were determined from electrical-resistance measurements.

If the structure of the films were independent of the film thickness, the resistivity as plotted in Fig. 2 would be independent of the film thickness, since the effects of surface scattering have been subtracted. However, one sees from the figure that the resistivity increased as the film thickness decreased. This behavior has been observed by other investigators[5,11,16,18] and is believed to indicate that the films were inhomogeneous. The first few layers to be deposited were probably more disordered (and more resistive) than later layers.

Another possible nucleation effect is indicated by comparing the resistance of a superimposed film pair with the resistances of the separate films. The measured resistance of the superimposed film pair was less than that which one calculated from the parallel resistance of the separate indium and thallium films; the ratio of the former to the latter was about 0.9 for thallium films 2000 Å thick and about 0.5 for thallium films 100 Å thick, independent of the order in which the two metals are evaporated. We believe these results to indicate that the resistivity of the first few atomic layers of the second film of a superimposed pair is considerably less than the resistivity of the first few atomic layers of the same material deposited on the bare substrate. In other words, the first film of a superimposed pair promotes nucleation of the second film.[20] There is, however, no known way of calculating the resistivity of the second film from such data. Fortunately, for the films investigated in these experiments, the theoretical prediction of the transition temperature of the superimposed film pair is insensitive to the resistivity; if the resistivities of the indium and thallium films are decreased by a factor of 2, t is decreased by less than 0.015 for $D_n \leq 2000$ Å.

C. Transition Temperatures

The temperature width of each transition was defined as the size of the temperature interval in which the film's resistance increased from 10 to 90% of the normal-state value. The mean widths were 1.9×10^{-2} and 2.1×10^{-2} °K for the indium and thallium films, respectively. These small widths indicate that the films are of relatively high quality. Moreover, the small average transition width of the superimposed films, 2.5×10^{-2} °K, indicates that the films were uniformly thick over an area with dimensions of the order of the coherence length (~100 Å).

The data are presented in terms of a convenient reduced transition temperature t, which is defined in Eq. (1). The dependence of t on D_n is shown in Figs. 3 and 4. (The theoretical curves in these figures will be discussed in Sec. IV.) The experimental values of t have not been adjusted to take into account the small variations in the indium film thicknesses. The data for those runs in which the thallium (indium) was deposited

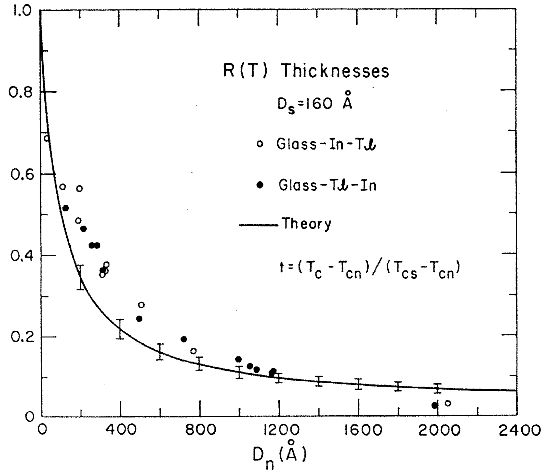

FIG. 3. Indium and thallium superimposed films: theoretical and experimental values of the reduced transition temperature t plotted against the $R(T)$ thicknesses.

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[20] A portion of the discrepancy between the measured and calculated resistances of the superimposed films is undoubtedly due to a reduction in surface scattering; this effect is, however, too small to account for the observed difference.

first are given by the filled (open) circles. There is no systematic difference between these two sets of data. This fact, together with the relatively small scatter of the data, indicates that the interface between the two metals did not have any strange and unexpected influence on the results.

To obtain more direct information about the quality of the interface, we made the following check. The evaporation of the second film usually began about 2 min after the end of the first film's evaporation. Although the first film was protected by the mask during this time, its surface could conceivably have become contaminated by adsorbed gas. We looked for evidence of such contamination in one run by letting 30 min elapse between the two evaporations; the first film was not protected by the mask during this time. The measured value of t was just the value expected from our data on other films of approximately the same thickness (1060 Å) which were produced in the normal manner. Therefore no evidence of interface contamination was found. This is negative evidence, of course, but it is still suggestive.

The theory of the proximity effect, which we will apply in Sec. IV, is derived by assuming that the electron mean path l is very short compared to the film thickness D and the coherence length ξ. The mean free path can be estimated from the measured resistivity ρ and the value of the constant ρl for the particular material ($\rho l=1110$ $\mu\Omega$ cm Å for indium[21] and $\rho l=$ 2200 $\mu\Omega$ cm Å for thallium[22]). We find that $l/\xi=0.3$ to 0.4 and $l/D=0.3$ to 0.6 for the indium films; for the thallium films the corresponding ratios are 0.5 to 0.7 and 0.1 to 1.0. Since these ratios are not small compared with unity, we wished to see whether the data were sensitive to the size of the mean free path. We could decrease l significantly only by adding a considerable number of impurity atoms ($\sim$5 to 10%). This would have introduced serious uncertainties in the material constants (such as the density of electron states at the Fermi level) that are needed in the theoretical calculation. We therefore took the opposite approach of increasing the mean free path.

This was done in the following way: In two of the runs, the critical temperatures of the films were measured in the manner we have described; the films were then annealed at 77°K and the transition temperatures were remeasured. Although the mean free paths increased by a factor of 2 as a result of the annealing, the reduced transition temperature t decreased by only 0.03 in each case. [These runs were made on the samples that had thallium films with $R(T)$ thicknesses of [illegible]35 and 1000 Å.] These results show that t was insensitive to the size of the mean free path, and hence one may sensibly apply the theory to our data.

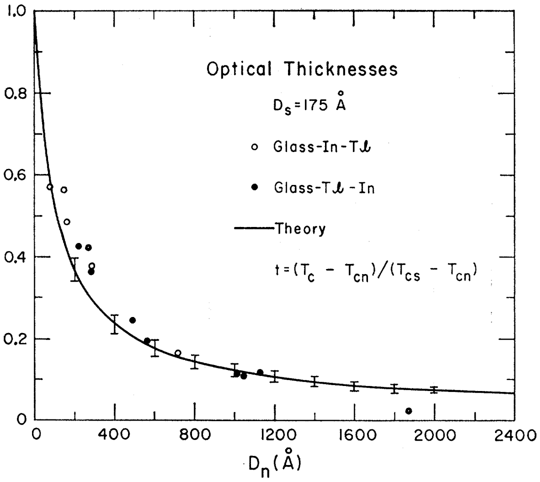

FIG. 4. Indium and thallium superimposed films: theoretical and experimental values of the reduced transition temperature t plotted against the optical thicknesses.

As a check on these results, and to look for evidence of interdiffusion, we performed another run in which the films were deposited on the substrate while it was at 77°K rather than at 6°K. The thallium film thickness for this run was 1000 Å, the same as the thickness of one of the thallium films described in the previous paragraph; the measured values of t differed by only 0.001. This result indicates that there was no appreciable interdiffusion of the two metals in these experiments. Further evidence for this belief was found in the first run of our annealing experiments; we observed that the electrical resistance of the superimposed film pair decreased monotonically as the films were warmed slowly from 4 to 77°K.

IV. COMPARISON OF DATA WITH THEORY

In order to calculate the theoretical curves shown in Figs. 3 and 4, the Debye temperatures $\Theta_s=109$°K and $\Theta_n=88$°K and the Sommerfeld electronic specific-heat constants $\gamma_s=1.08\times10^3$ erg/cm^3 °K^2 and $\gamma_n=$ 1.64×10^3 erg/cm^3 °K^2 were taken from the literature.[23] (The subscripts s and n denote indium and thallium, respectively, as explained at the beginning of Sec. III.) For the theoretical calculation of t, defined in Eq. (1), we took the average values $T_{cs}=4.30$°K and $T_{cn}=2.91$°K. (The mean absolute observed deviations from the mean values were 0.012 and 0.016°K, respectively.) To calculate t, we also needed to know the coherence lengths, which are given by

$$\xi=(\hbar v_F l/6\pi k_B T_c)^{1/2}, \tag{2}$$

where

$$v_F l=(\pi k_B/e)^2/\rho\gamma. \tag{3}$$

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[21] K. R. Lyall and J. F. Cochran, Phys. Rev. **159**, 517 (1967).

[22] P. Hilsch and D. G. Naugle, Z. Physik **201**, 1 (1967).

[23] K. A. Gschneidner, Jr., in *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press Inc., New York, 1964), Vol. 16, p. 275.

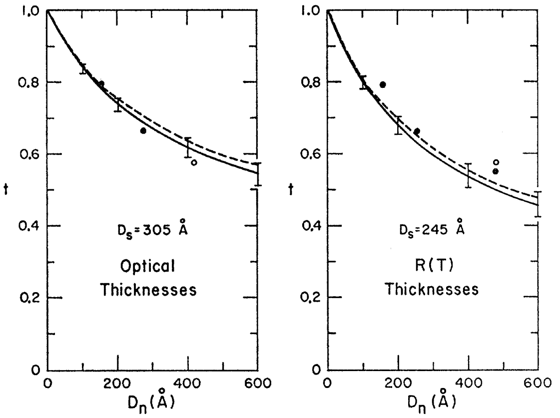

FIG. 5. Lead and indium superimposed films: theoretical and experimental values of the reduced transition temperature t plotted against the thicknesses. The filled (open) circles indicate that the indium (lead) was condensed on the substrate first. The dashed (full) lines show the theoretical values, calculated with the artificial (usual) cutoff.

The resistivity ρ was measured as described in Sec. III B; v_F is the Fermi velocity, l the electron mean free path, and T_c the transition temperature of the superimposed film pair.

The theoretical calculation of T_c has been described in a previous publication by one of us.[4] The theoretical value of t was insensitive to the cutoff method used, as expected. The de Gennes–Guyon–Werthamer theory[1–3] and the coupled integral equations theory[4] yielded very nearly the same results. This is in agreement with our previous observations, since T_{cn} was not much less than 1°K. As we showed in Sec. III C, the experimental data were insensitive to the size of the electron mean free path, so it is reasonable to use the dirty-limit forms of the theories, and we have done so. The bars on the theoretical curves in Figs. 3 and 4 show how much t is changed when D_s is increased or decreased by 20 Å.

Figures 3 and 4 show that the agreement between experiment and theory is good, in view of the fact that there are no adjustable parameters. There is a small systematic deviation of the data points from the theoretical curves; the data lie above the curves for thin thallium films and below the curves for thick thallium films. Further theoretical work is in progress in an effort to understand these deviations. It is not unlikely, however, that the small systematic deviation of the data from the theory is a result of the imperfect nature of the samples, or of factors (such as crystal anisotropy) that could be included only if the complexity of the theory were vastly increased.

V. EXPERIMENTS ON LEAD-INDIUM FILM PAIRS

We have made similar but far less extensive measurements with lead and indium as the superconductor with the higher- and lower-transition temperatures, respectively. (Following our convention, we denote lead by s and indium by n in this section.) We had hoped to check our techniques by comparing our results with those of Bergmann[9] for the same two metals. Although the resistivities of our indium films agreed well with those of Bergmann, our lead films had resistivities that were approximately twice those of his lead films. Therefore, no direct comparison with his results is possible. We include the results here for completeness. Although the theory is developed by assuming weak electron-phonon coupling, it is interesting to see how critical this assumption is by comparing the theoretical results with data obtained for a system where one of the superimposed films is a strong-coupling superconductor like lead. Since only a few samples were run, we do not discuss the results in detail.

In these measurements, all of the lead films had a thickness D_s of approximately 300 Å. The substrate temperature was approximately 15°K during the film condensations. The data were analyzed in the same way as those obtained for the indium-thallium film pairs.

The average resistivities of the lead films, corrected for surface scattering, were 24.3 $\mu\Omega$ cm for the $R(T)$ thicknesses and 31.1 $\mu\Omega$ cm for the optical thicknesses, with mean absolute deviations from the mean of 0.4 and 0.5 $\mu\Omega$ cm, respectively. The corrected resistivities for the indium films were taken from the straight-line fits

$$\rho=2.92+1680/D_n \tag{4}$$

for the $R(T)$ thicknesses and

$$\rho=0.65+1850/D_n \tag{5}$$

for the optical thicknesses. In Eqs. (4) and (5), ρ is in units of $\mu\Omega$ cm and D_n is in units of Å. The measured values of t, defined in Eq. (1), are shown in Fig. 5. The mean transition widths for the lead, indium, and superimposed films were 0.023, 0.019, and 0.031°K, respectively.

The curves in these figures give the theoretical values of t. In calculating these, we used the literature[23] values $\Theta_s=102$°K, $\Theta_n=109$°K, $\gamma_s=1.72\times10^3$ erg/cm^3 °K^2, $\gamma_n=1.08\times10^3$ erg/cm^3 °K^2, and our average measured values $T_{cs}=7.14$°K and $T_{cn}=4.28$°K. (The mean absolute deviations from the mean transition temperatures were 0.002 and 0.006°K, respectively.) The bars on the curves show how much t is changed when D_s is changed by ±25 Å. As shown in the figures, the theoretical results are sensitive to the cutoff. This is expected because of the relatively small value of Θ/T_c for lead. The results of the coupled integral equations theory are nearly the same as those of the de Gennes–Guyon–Werthamer theory, as expected.

Although we have only a few data points from which to judge, the agreement between experiment and theory in Fig. 5, again with no adjustable parameters, is satisfactory. This shows that strong coupling effects are not large, in agreement with the conclusions of previous investigators.[8,9]

In the proximity effect, the gap function is made inhomogeneous by the superposition of two different metals. There is an analogy between the spatial variation of the gap function in this case and the spatial variation of the same quantity in the mixed state of type-II superconductors. Recent theoretical treatments[24–26] of the temperature dependence of H_{c2} and H_{c3} have shown that the strong-coupling corrections are small, provided that the experimentally measured values of the resistivity and the electronic specific-heat coefficient are used in the theoretical calculations. It is therefore plausible that the strong-coupling corrections to the theory of the proximity effect are also small; it would be interesting to see if a theoretical treatment of such corrections would support this conjecture.

ACKNOWLEDGMENT

One of us (AEJ) wishes to thank the Xerox Corporation for two years of fellowship support during this work.

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[24] G. Eilenberger and V. Ambegaokar, Phys. Rev. **158**, 332 (1967).

[25] N. R. Werthamer and W. L. McMillan, Phys. Rev. **158**, 415 (1967).

[26] E. D. Yorke and A. Bardasis, Phys. Rev. **159**, 344 (1967).

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Magnetic Flux Penetration in Type-II Superconductors. I*

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Five magnetoresistance probes were used for mapping the magnetic field between matched pairs of superconducting plates oriented normal to an external magnetic field. All plates were 25×25 mm and their thicknesses varied from 0.23 to 0.79 mm. The separation between plates was 4.7 mm. In Nb–Zr and Lipowitz-alloy plates the field penetrated smoothly into the material; the mappings obtained at different external-field values consisted in symmetric contours conforming with the geometry of the plates. In Nb_3Sn and Nb–Ti only flux jumps were observed; the magnetic contours were very irregular and randomly distributed after each flux jump. Using the five-probe arrangement, a study was made of the frequency and extension of the magnetic-field change during a flux jump. In this case, the external magnetic field varied at the constant rate $dH/dt=5.6$ G/sec within $H=0$ to 2500 G. Only Nb_3Sn plates were studied. A statistical analysis of the results demonstrated that at 4.2°K only extensive jumps occurred in virgin samples for positive values of dH/dt. A distribution with a "tail," consisting of local jumps, was obtained after dH/dt changed sign and in all successive nonvirgin runs. At 1.5°K all distributions had the tail regardless of magnetic history and the sign of dH/dt. It is concluded that, as far as flux jumps are concerned, the reversal in the sign of dH/dt produced (in the superconductor at 4.2°K) a state which made it more susceptible to flux jumps. A state with similar susceptibility is obtained at 1.5°K—in this case, it is presumably originated by thermal effects.

INTRODUCTION

IN our previous report on the low-field magnetic behavior of type-II superconductors,[1] a distinction was made between a group consisting of Nb–Zr and Lipowitz alloy and a second group represented by Nb_3Sn and Nb–Ti. The distinction resulted from the observation that in the first group the magnetic flux penetrated "smoothly" into the material, whereas in the second group only flux jumps were observed. In this paper, we report the results of two new experiments oriented for better understanding of the physical reasons reponsible for this behavior.

MAGNETIC FIELD MAPPING

The first experiment consisted in mapping the magnetic field between two parallel superconducting plates oriented normal to an external magnetic field. The field measurements were made by means of five magnetoresistance microprobes. These were single crystals of bismuth, 25 to 50 μ diam and about 2 mm long. The separation between probes was 4.7 mm, and all five were mounted on a common brass support. The longitudinal axis of the probes was also normal to the magnetic field. The brass support could travel through a 4.4-mm gap between the plates when operated from

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[1] G. del Castillo and R. W. Fast, J. Appl. Phys. **37**, 4597 (1966).