because of effects due to annihilation gamma rays. Of course, none of these background counts should cause true coincidences, but they will contribute an accidental coincidence rate.

On the other hand, bremsstrahlung produced by positrons in the anthracene might cause coincidences indistinguishable from annihilation in flight. The probability of this process[5] should be about the same for positive and negative electrons, too small to be detected in our experiment. This was verified by means of electrons from a Sr^{91}-Y^{91} source.

Annihilation-in-flight coincidence measurements were made for the positron kinetic energies 0.765, 1.02, 2.2, and 3.3 Mev and, at each energy, at the gamma-counter angles 0°, 20°, 40°, and 60° with the spectrometer axis. Depending on the coincidence counting rate in the clamped discriminator channel (which ranged from 25 to less than $\frac{1}{2}$ counts per min) data were taken in separate runs lasting from 20 min to 3 hr. The spectrometer current remained quite constant once the unit had reached a stable temperature. The total number of coincidences from all similar runs corrected for background counts was divided by the total number of incident positrons (Table I). These values can be compared directly with the theoretical expressions [Eq. (11)]. This comparison is made in Figs. 4 and 5 and in Table I. The experimental error indicated is the standard deviation of the total number of counts. Table II lists the windows, ΔE, ΔE_s, and $\pi^{\frac{1}{2}}\alpha$ for the four positron energies. The slightly lower accuracies at gamma-counter angle 60° were due to the low counting rates.

The data are, within the experimental error (estimated to be $\pm 5\%$), in good agreement with the theoretical expression, both as to angular distribution and absolute value.

ACKNOWLEDGMENTS

We wish to express our gratitude to Professor J. W. Irvine, Jr., who supplied the Ga^{66} separation procedure carried out by Mrs. Elizabeth Backofen and to Mr. Earle White conducted the cyclotron bombardments.

PHYSICAL REVIEW VOLUME 101, NUMBER 1 JANUARY 1, 1956

Measurements of Contact Resistance between Normal and Superconducting Metals*†

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(Received September 21, 1955)

The contact resistance between crossed wires of Pb and Sn, Pb and Cu, Sn and Cu, Sn and In separated by their natural oxide layers has been measured at constant temperatures as a function of current direction and magnitude. Plots of these measurements in the case of a normal and a superconducting element show the resistance at low currents to be constant and to increase suddenly above a critical current. The low current resistance generally decreased with decreasing temperature. Calculation of the radius of the current-bearing area gives radii of atomic dimensions and shows that in some cases part of the barrier resistance disappears. Furthermore, four contacts showed an immeasurably small resistance at a temperature where only one of the contact members was superconducting. These measurements and earlier ones by others suggest a schematic representation of the resistance as a function of current and temperature. No significant rectification between normal conductors and superconductors was observed.

I. INTRODUCTION

EXPERIMENTS have been performed by Meissner and Holm[1] on the contact resistance between two superconductors separated by the thin oxide films of both elements. They found that the resistance attributable to the barrier itself remained essentially constant with temperature as long as the metals were in the normal conducting state. However, at a temperature below the critical temperature of the metal, in the case of identical contact members, the total resistance disappeared. In the case of lead-tin contacts, this temperature was below the critical temperature of tin. The temperature at which this took place was found to agree with Silsbee's hypothesis, namely that the quenching of superconductivity was due to the magnetic field created by the current. It was felt that the barrier penetration was a quantum mechanical tunnel effect which apparently became resistanceless when both contact members were superconducting.

Further experiments were performed by Dietrich[2] on contacts between tantalum elements separated by barriers up to 120 A thick of CeO_2 and TiO_2. Barriers up to 40 A thick were found to have an immeasurably small resistance at a sufficiently low temperature and current. However, in these experiments Silsbee's

* This report is part of a thesis (F.B.) submitted in partial fulfillment of the requirements for the degree Doctor of Philosophy at the Johns Hopkins University.

† A preliminary report of this work was given at the Baltimore meeting of the American Physical Society in March, 1955 [Phys. Rev. 98, 1539(A) (1955)].

‡ National Science Foundation Predoctoral Fellow.

[1] W. Meissner and R. Holm, Z. Physik 74, 715 (1932).

[2] F. Dietrich, Z. Physik 133, 499 (1952).

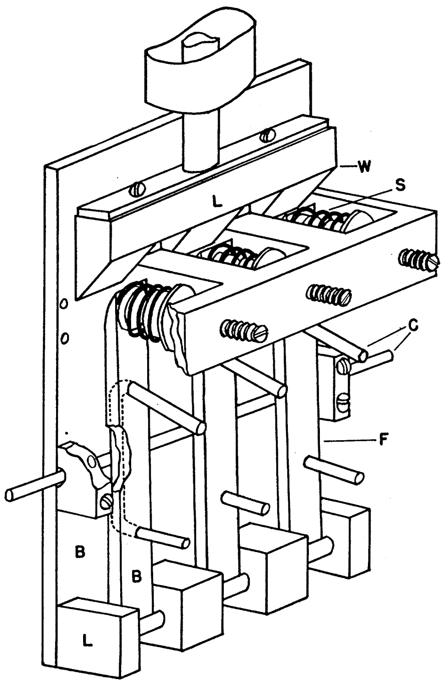

FIG. 1. Mount for crossed-wire contacts. The Lucite wedge (W) is inserted under the flaps (F), holding the contact wires (C) against the force of the springs (S). The wedge is withdrawn when contact is desired. Brass parts are designated by (B), Lucite by (L).

hypothesis yielded a current-bearing radius of contact of only atomic dimensions.

The experiments to be described here were a preliminary investigation of the contact resistance between different superconductors and between a normal conducting metal and a superconductor at a constant temperature as a function of both the current magnitude and direction. The latter measurement was made in order to find whether the electrons move more easily from the superconductor to the normal conductor than in the opposite direction, i.e., whether the contact would show a rectifying character.

II. EXPERIMENTAL ARRANGEMENT

The superconducting metals selected for contact members were lead (purity 99.99%), tin (purity 99.998%) and indium (purity 99.97%), the normal conducting metal was commercial copper wire. Copper wire of 1.5-mm diameter was used with cast wires of Pb, In, and Sn of 1.7-mm diameter for one group of experiments, while copper wire of 1.25-mm diameter was used with 1-mm diameter extruded wires of Pb and Sn for another group.

The contact was formed by crossed wires which were mounted as shown in Fig. 1. The contact load of 40 or 110 g was provided by a calibrated spring. The test panel was in a standard cryostat. Temperatures below 4.21°K were obtained by pumping off the helium vapor and maintained by throttling the pump. The temperature was determined by measuring the vapor pressure of the He to better than ± 0.2 mm Hg at all pressures.

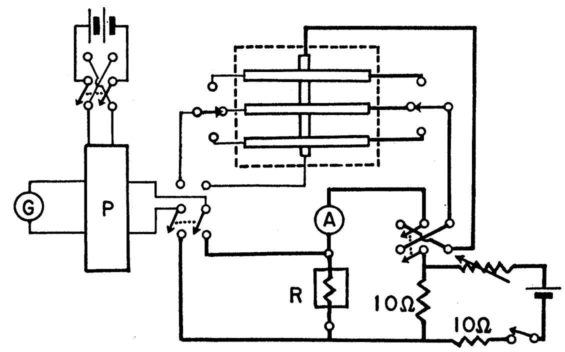

FIG. 2. Electrical circuit for measuring contact resistance. G: Leeds & Northrup Galvanometer, model HS 2284-b. P: L & N Potentiometer model K-2. R: Wolff 1-international-ohm standard resistor. A: Simpson model 373 milliammeter. The parts enclosed by dashed lines are at liquid helium temperature.

The electrical circuitry is shown in Fig. 2 where the specifications of the instruments used are also given.

III. EXPERIMENTAL PROCEDURE

The wires, which had been exposed to air at room temperature for a minimum of 24 hours, were mounted on the test panel, taking care that they did not make contact. After the entire assembly had been cooled to liquid nitrogen temperature by an inserted well the contacts were closed and the inner Dewar filled with liquid helium.

The potential drop across a contact maintained at constant temperature was measured as a function of the current magnitude and direction, and compared with the potential drop across a standard resistor. For small potentials, the galvanometer, which had a sensitivity of 1.67×10^{-8} v/mm, was used as a voltmeter. The zero point was determined by switching off the current. The measurements were made at successively increased currents for each temperature. The temperatures chosen, both above and below the critical temperatures of the elements, were attained in successively decreasing order, care being taken that the selected temperature was not "overshot" by more than an amount corresponding to 1 mm Hg of vapor pressure.

In addition to the contact measurements, the ratio of the low temperature resistivity to room temperature resistivity of the cast Sn and In wires and of the Cu specimens used was measured. Using the known values of the room temperature resistivities, the following residual resistivities were obtained:

$$\text{Cu: } \rho = 1.2\times10^{-8} \text{ ohm cm;}$$

$$\text{Sn: } \rho = 1.5\times10^{-9} \text{ ohm cm;}$$

$$\text{In: } \rho = 5.2\times10^{-9} \text{ ohm cm.}$$

IV. ANALYSIS OF DATA

The contact resistance between the two members can be broken up into the resistance due to the inter-

TABLE I. Calculated contact radii. a_{ch} is the contact radius obtained from the equation for channel resistance, $R_{ch}=\rho/5a_{ch}$;[a] a_H is the radius obtained from Silsbee's rule, $0.2i=a_H H_c$; the corrected radius for a_H is obtained from Eq. (1); a_L is the average radius of the load-bearing area calculated from $F=P\pi a^2$, where P is the pressure for plastic flow and F the load; σ is the barrier resistivity.

Contact	Load g	T °K	a_{ch} In A	a_{ch} Sn A	a_{ch} Cu A	a_H Sn A	Corrected a_H Sn A	a_H Pb A	Corrected a_H Pb A	a_L μ	σ ohm cm²
1(Cu–Pb)	110	4.21	...	...	0.40	...	...	8.7	130	0.66	...
3(Cu–Pb)	110	3.82	...	...	1.6	...	...	13	160	0.66	...
		3.21	...	...	1.6	...	...	12	160	0.66	...
4(Cu–Pb)	40	3.21	...	...	4.4	4.6	96	...	...	0.19	6×10^{-15}
5(Cu–Sn)	40	3.21	...	...	12	0.33	26	...	...	0.19	$\leq5\times10^{-14}$
		2.3	...	...	24	0.44	30	...	...	0.19	$\leq2\times10^{-13}$
6(Pb–Sn)	110	3.21	...	...	3	2.3	67	...	...	0.31	1.2×10^{-15}
7(Pb–Sn)	110	4.21	...	0.18(110)*	...	...	...	11	150	0.66	...
		3.81	...	0.22(140)*	...	...	...	10	140	0.66	...
		3.51	...	b	...	200	...	b	b	0.66	...
8(Pb–Sn)	110	4.21	...	2.6(1600)*	...	...	...	2.3	66	0.66	...
		3.81	...	4.3(2600)*	...	...	...	2.2	66	0.66	...
9(Pb–Sn)	40	3.81	...	>2500	...	...	...	1.3	52	0.4	...
11(Pb–Sn)	40	3.82	...	>75	...	...	...	0.045	9.4	0.4	...
12(In–Sn)	40	3.54	>6900	...	...	5.3	100	...	...	≥0.19	...
14(In–Sn)	40	3.50	>3500	...	...	27	230	...	...	≥0.19	...

[a] The value of ρ used for the calculation of a_{ch} is that of cast wire with the exception of contacts 7 and 8 where, since the wires were extruded, a value of 10% of the room temperature resistivity has been used to calculate also the upper limit of a_{ch}. These latter values are indicated by an asterisk.
[b] These values are not calculated since the measurements show no unique R_{ch} or i_c.

posed barrier, R_B, and that due to the constriction of the current, the channel resistance R_{ch}. The latter, for each element of a clean contact, is equal to $\rho/4a$ where ρ is the resistivity and a the radius of the current-bearing region.[3] The presence of an alien film on the contact reduces the channel resistance[4] to as little as $\rho/2\pi a$ if $R_B>R_{ch}$. We will assume an average, approximately $\rho/5a$.

The barrier resistance may be written as $R_B=\sigma/\pi a^2$ where σ is the resistivity per unit area.

For contact 1(Pb–Cu) [see Fig. 3(a)] which is at a temperature below the critical temperature of Pb, 7.2°K, one notices two features. First, the resistance is independent of current at low currents; second, there is an abrupt rise in resistance above a critical current.

If we assume that the low current resistance is due only to the channel resistance of the Cu, i.e., that the Pb is superconducting and that the barrier resistance, if such existed, also disappeared, we can calculate, knowing the ρ for Cu, the current-bearing radius. Furthermore, if the current at which the break in resistance appears is, according to Silsbee's rule, assumed to be the current necessary to set up the critical magnetic field for Pb at this temperature,[5] we can obtain another value for the current-bearing radius. In addition, with a knowledge of the Brinell hardness number[6] and the contact load we are able to calculate, under the assumption of a plastic deformation of the contacts, the load-bearing area and an average load-bearing radius. These three values for the radius are shown in Table I.

[3] R. Holm, *Electric Contacts* (Hugo Gebers Förlag, Stockholm, 1946), p. 16.
[4] Reference 3, p. 18.
[5] D. Shoenberg, *Superconductivity* (University Press, Cambridge, 1952), p. 224.
[6] R. Holm and W. Meissner, Z. Physik 74, 736 (1932).

Since the radius obtained from Silsbee's rule indicates that $\beta a\ll1$, where β is the reciprocal of the superconducting penetration depth, a corrected radius is calculated for such a case from the equation[7]

$$\frac{0.1i_c}{4\pi a^2}=\frac{H_{c(\mathrm{bulk})}}{c\Lambda^{\frac{1}{2}}}\left[1-\frac{(\beta a)^2}{8}\right], \tag{1}$$

where i_c is the maximum superconducting current in amperes, c is the velocity of light in cm/sec, Λ is the superconducting constant, H_c is the critical magnetic field strength in gauss, and $\beta=[4\pi/\Lambda c^2]^{\frac{1}{2}}$. This corrected a_H is also listed in Table I.

The measurements on contact 1(Pb–Cu) were reproducible for all currents until 50 ma was passed through the contact, after which the contact changed to become contact 2. Contact 2 remained stable until the current was again raised, whereupon it became contact 3, which remained stable.

In view of its history, contact 3 was probably derived from contact 2 by a metal bridge being formed through the oxide barrier. Again calculating the radius under the assumption of a completely absent barrier at small currents and also from the current at which the resistance increases we see that they are smaller than the average load-bearing radius.

The same calculations are repeated for contact 4[Cu–Sn, see Fig. 3(a)], with the additional assumption that the difference between the high current resistance at 3.21°K, which is taken to be the same as the resistance of the contact at 4.21°K, and the low-current resistance is attributable to the presence of a barrier. [R_{ch} of the Sn is neglected since $\rho(\mathrm{Sn})=0.1\rho(\mathrm{Cu})$.] This, together with the radius, provides us with a value

[7] M. Von Laue, *Theory of Superconductivity* (Academic Press, Inc., New York, 1952), p. 115.

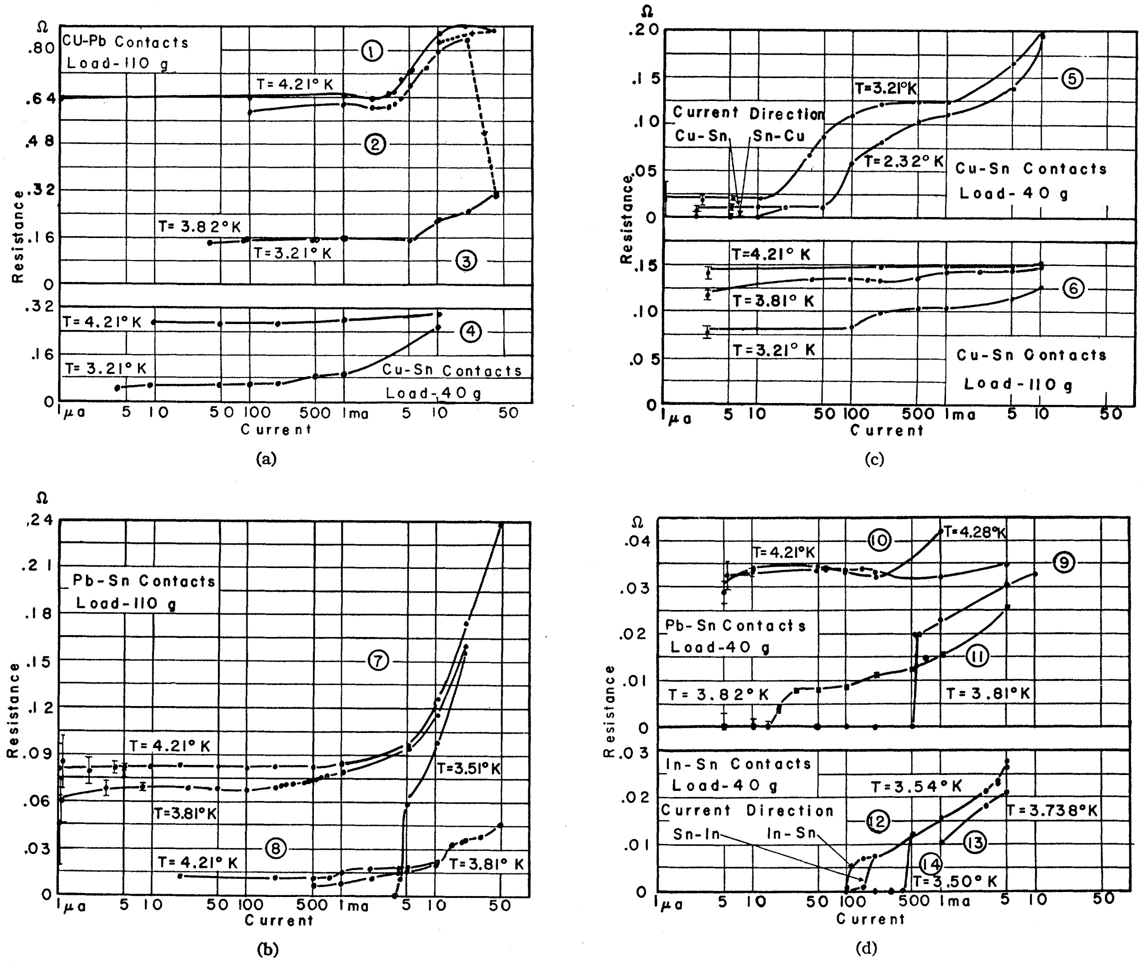

FIG. 3. Plots of observed resistance *vs* current for contacts between crossed wires of normal conducting metals and superconducting metals.

for σ. The radius is taken to be the corrected radius obtained from the critical current.

Contacts 5 through 8 were treated in the same fashion to obtain the radii listed in Table I. Contact 5(Cu–Sn) showed the anomaly that at currents below 10 μa an asymmetry in resistance with respect to current direction was observed.

Since contacts 7 and 8 (both Pb–Sn) were made with extruded tin wires, while measurements of resistivity had been made only for cast tin wires, a higher value for ρ undoubtedly must be used, conceivably as high as 10% of the room temperature resistivity. This assumption has been used to calculate the values of a listed with an asterisk.

In the case of contact 7 at 3.51°K, the reappearance of measurable resistance is attributed to the Sn becoming normal-conducting.

With this relatively simple picture one obtains values for the radius from Silsbee's rule which are of atomic and subatomic dimensions. The corrected radius is of a credible order of magnitude. Secondly one notices the small dimensions of the radius obtained from the channel resistance and, with the exception of contact 5, the poor agreement of the values for the radius of contact obtained by the different methods. Furthermore, as might be expected, the load-bearing average radius is orders of magnitude larger than the other radii.

The graphs for contacts 5, 7, and 8 show that the low current resistance decreases with decreasing temperature. Since only one member is normal conducting and the resistivity of that member at these temperatures is not a function of temperature, it appears that either the barrier resistance is partly present, or that the channel resistance is being reduced. Contact 3, the only other contact for which there exist measurements at more than one temperature, shows no such temperature dependence. In view of the history of contact 3 and the consequent likelihood of its being formed by a metallic bridge, it appears more probable that the temperature dependence of contacts 5, 7, and 8 is due to the presence, at the higher temperature at least, of

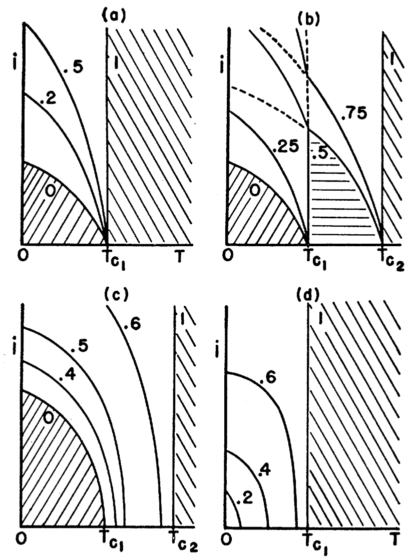

FIG. 4. Schematic curves of constant R/R_n plotted against current and temperature, where R is the contact resistance measured at a current i and a temperature T, R_n is the contact resistance if both metals are fully normal conducting. Shaded regions are regions of constant R/R_n. (a) Contact between 2 identical superconductors as observed by Dietrich.[2] T_{c_1} is the critical temperature at zero field for the material. (b) Contact between two different superconductors as expected; (c) Contact between two different superconductors as observed. (d) Contact between a normal conductor and a superconductor as observed.

part of the barrier resistance. This is in agreement with the findings of Dietrich.[2]

The data of Dietrich appear to roughly agree with the schematic plot shown in Fig. 4(a). It must be pointed out that a similar plot is obtained for the resistance of a thick wire,[8] although probably for entirely different reasons.

The measurements on contact 7(Sn–Pb) seem, roughly, to yield the curves of Fig. 4(c). Whereas, if one schematicizes what might reasonably be expected for the contact resistance between two clean dissimilar superconductors, one would get a set of curves such as in Fig. 4(b).

The observed general trend of the resistance of a contact between a normal conducting metal and a superconducting one is indicated in Fig. 4(d).

Figure 3(d) shows four contacts of particularly anomalous behavior. In all four cases, the contacts had an immeasurably small resistance at low currents and a temperature where one of the members should have been normal conducting. The minimum possible radius such that the channel resistance would not be observed is found to be much larger than that obtained from Eq. (1). In these cases one seems to be left with the alternatives, either that not only the barrier resistance disappeared but moreover the channel resistance in the normal conducting metal has been reduced also, or that the geometry was such that the channel resistance in the normal conducting metal was immeasurably small.

[8] F. London, *Superfluids* (John Wiley and Sons, Inc., New York, 1950), p. 120.

Similar conclusions can be drawn from measurements of Holm and Meissner (see reference 1). In the case of a lead-tin contact which had a metal bridge due to coherer action[9] at a temperature of 4.2°K, they found the following values:

$$i=1.05 \text{ amp}, \quad R=4.1\times10^{-5} \text{ ohm}; \quad i=0.577 \text{ amp},$$
$$R=3.1\times10^{-5} \text{ ohm}; \quad i=0.107 \text{ amp}, \quad R=4\times10^{-7} \text{ ohm};$$

which at the smallest current gives also a resistance lower than one would expect at this temperature.

Contact 12 shows, as does contact 5, an asymmetry in resistance with respect to current direction, such that the resistance is lower if the electron flow is from normal conductor to superconductor.

IV. CONCLUSIONS

The following conclusions seem to follow from this investigation:

(1) Contacts were observed wherein there existed a barrier between the component members.

(2) The barrier resistance was the lower the lower the temperature if one member of the contact was superconducting.

(3) The barrier resistance became immeasurably small when both contact members were superconducting.

(4) There existed no significant rectification at the contact between a normal conductor and a superconductor.

(5) If the contacts are separated by very thin barriers and the temperature is well below the transition temperature of one of the contact materials but slightly above the transition temperature of the other, the total resistance at low currents can be immeasurably small, smaller than what one would reasonably expect for the channel resistance of the normal-conducting member.

(6) As for the two contacts which showed rectification at very low currents, it is suggested that diode rectification may be responsible for this effect.

Summarizing, we can say that the presence of a superconductor on one side of a contact lowers the resistance of an interposed barrier and may even lower the channel resistance of the normal-conducting element if this is a superconducting metal slightly above its transition temperature. Furthermore, the resistance was found to be the same for electron flow from the superconductor to the normal conductor as for the reverse direction.

ACKNOWLEDGMENTS

One of the authors (F.D.B.) wishes to thank the National Science Foundation for a fellowship held during the course of this work.

[9] Reference 3, p. 131 ff.