would, through charge exchange, lead to a much shorter lifetime of the high-energy group. It is therefore necessary to postulate containment of the observed plasma either as a target or as a reacting plasma. The evidence favors the latter interpretation. We conclude that the plasma is contained for times which exceed the *e*-folding time for hydromagnetic instabilities by three orders of magnitude. Furthermore, the close agreement of the observed ion energy gain to that predicted from adiabatic theory indicates that the energy transport from ions to electrons does not greatly exceed the rate calculated on the basis of Coulomb collisions.

It is a pleasure to acknowledge the many profitable discussions with R. F. Post, and to express our indebtedness to D. R. Branum, who has had the responsibility for the design, construction, and operation of the extensive electrical systems.

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DIRECT MEASUREMENT OF THE SUPERCONDUCTING ENERGY GAP

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Giaever[1] has reported experiments on the tunneling of electrons through a thin aluminum oxide layer between a film of aluminum in the normal state and a film of lead maintained either in the normal or in the superconducting state. The results were interpreted qualitatively in terms of the change in the density-of-states function at the Fermi level of lead upon passage from the normal to the superconducting state.

In this Letter, the tunneling current vs voltage characteristic of an Al-Al_2O_3-Pb sandwich is presented when both Pb and Al are superconducting. This characteristic exhibits a negative resistance region (see Fig. 1). Analysis of the problem of electron tunneling through an insulating layer between two superconductors shows that the negative resistance region is a direct consequence of the existence of an energy gap in the superconducting density-of-states function. The voltage difference between the points of maximum and minimum current which define the negative resistance region is a direct and unambiguous measure of the full energy gap of the metal with the lower transition temperature. The I - V characteristic is symmetric through the origin. The magnitude of the difference in voltage between the mid-points on the negative resistance regions for positive and for negative voltage is a direct and unambiguous measure of the full energy gap of the metal with the higher transition temperature.

Samples were prepared by evaporating an Al strip onto a glass substrate, oxidizing in air, and evaporating a Pb cross strip. The area of crossing was approximately one square millimeter; the thickness of Al_2O_3 was estimated to be about 20 A. A specially built curve tracer was used to display the I - V characteristic on an oscilloscope. The resistance of each metal was

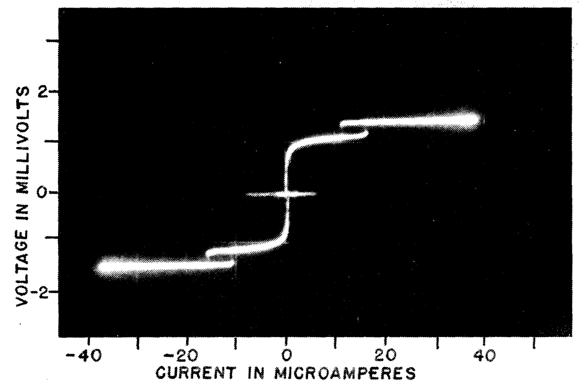

FIG. 1. Voltage vs tunneling current for an Al-Al_2O_3-Pb sandwich at 1°K.

also measured. The sample was in contact with liquid helium at 4.2°K and below. Temperature was determined from the liquid helium vapor pressure or from a carbon resistance thermometer.

The tunneling current vs voltage characteristic was measured at several temperatures for a number of $Al-Al_2O_3-Pb$ sandwiches. The experimental curves for both metals normal or for Pb alone superconducting essentially duplicated those of Giaever. As shown in Fig. 1, new results were obtained when both metals were superconducting. In particular, over a certain region, the current decreased as the voltage increased, i.e., the I-V characteristic exhibited a negative resistance region. This region first appeared at the Al transition temperature and increased in voltage amplitude as the temperature was reduced. When the Al was brought into the normal state by an external magnetic field, the negative resistance disappeared.

To account for these results, consider the expression for the tunneling current. For small voltages the tunneling probability can be taken as constant. Then the one-way tunneling current is proportional to an integral over all energies of the product of the number of electrons in one metal by the number of unoccupied states (holes) in the other metal at the corresponding energy. The net current is given by the difference in the opposed one-way currents. With the energy zero at the Fermi level for metal 1, and with metal 1 at a positive potential,

$$I \propto \int \{\rho_2(E-V) f(E-V) \rho_1(E)[1-f(E)] - \rho_2(E-V)[1-f(E-V)]\rho_1(E) f(E)\} dE. \quad (1)$$

With all energies measured in units of kT, V is the energy equivalent of the applied voltage, ρ_1 is the density-of-states function for metal 1, ρ_2 is that for metal 2, and $f(E)$ is the Fermi function,

$$f(E) = 1/(1+e^E). \quad (2)$$

Equation (1) reduces to

$$I = \text{const} \times \int \rho_2(E-V)\rho_1(E)\{f(E-V)-f(E)\} dE. \quad (3)$$

To proceed further, the integrals must be evaluated numerically. Clearly the shape of the I-V characteristic is intimately connected with the density-of-states function and may be used to obtain that function. Detailed analysis, including machine computation, is reserved for future publication. However, initial results show good agreement, provided the Fermi function is taken into account. In Fig. 2, experimental I-V curves for an $Al-Al_2O_3-Pb$ sandwich at 4.2°K and 2.1°K, hence for Pb alone superconducting, are compared with points calculated using Eq. (3). A constant value was assumed for the density-of-states function of aluminum, and for that of lead the Bardeen, Cooper, and Schrieffer (BCS) expression[2] was used; namely,

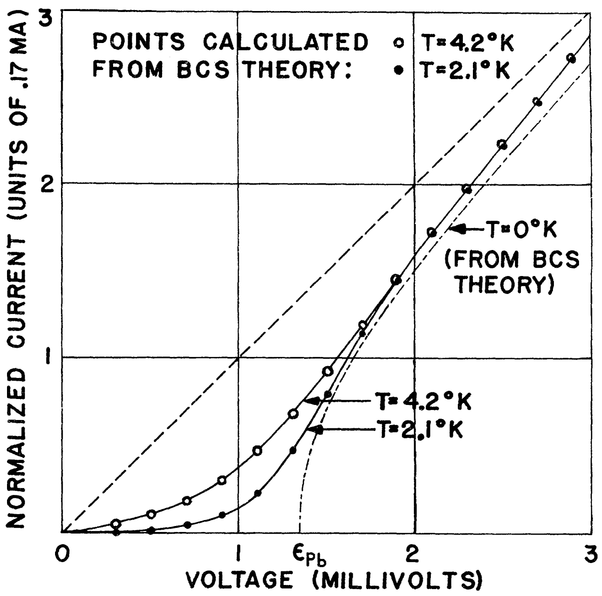

FIG. 2. Experimental curves at 4.2°K and 2.1°K for an $Al-Al_2O_3-Pb$ sandwich compared with points calculated using the BCS density-of-states function for superconducting lead. The value used for the energy gap of lead, $4.35kT_c$, is that measured from experimental curves taken at lower temperatures when both Al and Pb are superconducting. Also shown is the limiting expression at $T = 0°K$ calculated for one metal normal, $I \propto (V^2 - \epsilon_{Pb}^2)^{1/2}$.

$$\rho(E) = N(0)\left|\frac{E}{[E^2-\epsilon(T)^2]^{1/2}}\right|, \quad |E| \geqslant \epsilon(T)$$
$$\rho(E) = 0, \quad |E| < \epsilon(T) \quad (4)$$

where $N(0)$ is the density-of-states at the Fermi level in the normal state and $2\epsilon(T)$ is the temperature-dependent energy gap. The value used for the energy gap of Pb was that measured by the technique to be described below. At 2.1°K the full limiting value was used; at 4.2°K a correction factor of 0.93 was applied as obtained from BCS. The calculated points are sensitive to the value of the gap; use of the value $3.5kT_c$

destroys the good agreement obtained with the measured value. The data are normalized so that the characteristic approaches a 45° slope at higher voltages. Also included in the figure is the limiting form of the characteristic at $T=0°\mathrm{K}$, $I\propto(V^2-\epsilon_{\mathrm{Pb}}^2)^{1/2}$. This curve would be approached were a metal that remained normal used in place of Al in forming the sample.

It remains to account for the negative resistance region and to demonstrate that it is a direct measure of the superconducting energy gap. Fig. 3 sketches the density-of-states function and the filled states in a small energy interval about the Fermi level for a sandwich formed of two superconducting metals separated by a thin insulating layer. The energy gap and peaking of states on both edges of the gap are indicated. The sketch is not to scale but represents a sandwich formed from a high transition temperature metal and a low transition temperature metal. In the absence of an applied voltage, the two Fermi levels are at the same energy. Applying a voltage is equivalent to sliding one density-of-states curve with respect to the other. Clearly the number of unoccupied states in metal 1 into which electrons of metal 2 may tunnel increases with voltage until the left-hand edges of each gap coincide. Similarly, the number of electrons in metal 1 decreases with voltage until the left-hand edges of each gap are within ϵ_1 or so of coinciding. Over this last interval the number of electrons in metal 1 increases because of the peaking of states; however, the product of electrons in metal 1 by holes in metal 2 is still smaller than the product of electrons in metal 2 by holes in metal 1 because of the Fermi function acting on two different gaps. The result is a net positive current from metal 1 to metal 2 which reaches a maximum at a voltage

$$V_{\max}=\epsilon_2-\epsilon_1. \tag{5}$$

As the voltage is increased further the left-hand edge of the electron distribution for metal 2 passes into a region where there are no states available. Hence there is a decrease in the current as the voltage increases; this is the negative resistance region. Only when the voltage exceeds a value

$$V_{\min}=\epsilon_2+\epsilon_1, \tag{6}$$

at which the left-hand edge of the gap for metal 2 coincides with the right-hand edge of the gap for metal 1, does the current increase again. [Note that at $T=0°\mathrm{K}$ there would be no negative resistance region; the current would remain zero up to a voltage given by Eq. (6).] From Eqs. (5) and (6) it is apparent that the voltage difference between the points of maximum and minimum current that define the negative resistance region is a direct measure of the full energy gap, $2\epsilon_1$, for metal 1. Knowing ϵ_1, ϵ_2 is immediately determined. Uncertainty in the location of the origin may be eliminated by using the symmetry of the characteristic and measuring the full gap, $2\epsilon_2$, for metal 2 as the difference in voltage between the mid-points of the negative resistance regions for positive and negative voltages.

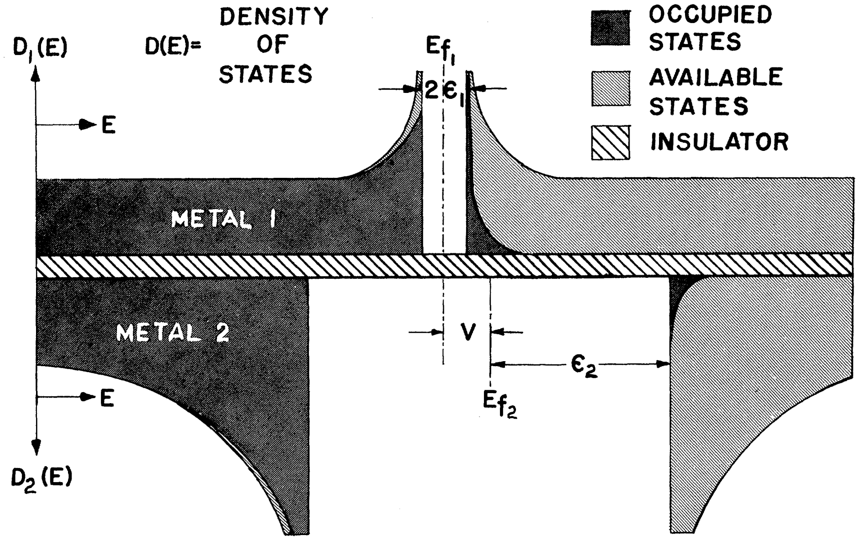

FIG. 3. The density-of-states function and the filled states sketched in a small energy interval about the Fermi level for a sandwich formed of two different superconductors separated by a thin insulating layer. A positive voltage, V, is applied to metal 1.

Using these relations, the value of the gap for Pb was determined to be $2\epsilon_{\text{Pb}} = (4.35 \pm 0.10)kT_c$, independent of temperature in the interval 0.8°K-1.2°K. The measured gap for Al was $2\epsilon_{\text{Al}}(1°\text{K}) = (1.8 \pm 0.3)kT_c$ and $2\epsilon_{\text{Al}}(0.8°\text{K}) = (2.3 \pm 0.3)kT_c$. The values 7.2°K and 1.2°K were used for the transition temperatures of Pb and Al, respectively. Using the temperature dependence of the gap given by BCS, these values imply a limiting gap for Al at absolute zero of $2\epsilon_{\text{Al}} = (2.7 \pm 0.3)kT_c$.

It is to be emphasized that these values were obtained using Al films that exhibited broad superconducting transitions in both temperature and magnetic field. The values of the energy gap, especially for Al, should therefore be regarded as provisional. Experiments are in progress to obtain the detailed temperature and field dependence of the superconducting energy gap for bulk Al and will be reported at a future date.

The authors would like to acknowledge helpful discussions with R. S. Davis and thank M. L. Cohen for the loan of equipment. The cooperation and advice of P. F. Strong with the computations are greatly appreciated.

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ELECTRON TUNNELING BETWEEN TWO SUPERCONDUCTORS

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When two metals are separated by a thin insulating film, electrons can flow between the two conductors due to the quantum mechanical tunnel effect. If a small potential difference is applied between the two metals, the current through the film will vary linearly with the applied voltage, as long as the density of states in the two metals is constant over the applied voltage range,[1] as it is for most metals. In a superconductor, however, the density of states changes rapidly in a narrow energy range centered at the Fermi level, so that the voltage-current characteristic becomes nonlinear.[2] It is relatively easy to correlate the change from linearity with the variation in the density of states. Under the assumption that the tunnel current is proportional to the density of states, the current between normal and superconducting metals is in good agreement with the density of states calculated for a superconductor by the Bardeen-Cooper-Schrieffer[3] theory.[4]

A more direct measure of the energy gap is possible when electrons tunnel between two superconductors, as may be understood from a one-particle model of a superconductor as shown in Fig. 1. All the observed phenomena of tunneling into superconductors can be understood both qualitatively and quantitatively if we are willing to accept this model, which actually guided the experiments.

The samples were prepared by vapor-depositing aluminum on ordinary glass slides and allowing the surface of the aluminum film to oxidize. After a suitable oxide layer had formed, lead, indium, or aluminum was vapor-deposited over it to form a metal-oxide-metal sandwich. The oxide layer is thought to be 15-20 A thick.

In Fig. 2 are shown some typical voltage-current characteristics for the three different metal-oxide-metal sandwiches tested. The voltage scale is in millivolts while the current scale is in arbitrary units. An X-Y recorder was used in taking the data. The sandwich involving the lead behaves exactly as predicted from the model in Fig. 1. Actually to obtain the curve it was necessary to shunt the sample with an RC network to damp out self-induced oscillations. The sandwich involving the indium shows basically the same characteristics, although for indium the unstable region was not traced out. Also, as is apparent from the low-current behavior of this sample, the oxide film is pierced by a superconductive bridge. When the current is increased the bridge goes normal, and its conductivity is too low to affect the general characteristics of the tunneling. When the current is decreased, the bridge remains normal at a lower current due to Joule heating. Finally the sandwich involving the aluminum is a little different, as here the energy gaps on either side of the oxide are equal, and at this temperature the Fermi tail is of the same order of magnitude as half the gap width.

The energy gaps obtained from these experi-

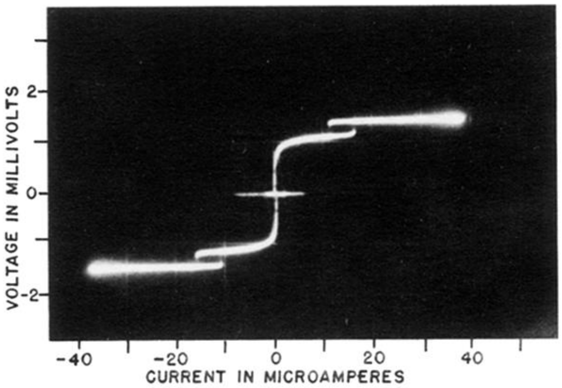

FIG. 1. Voltage vs tunneling current for an Al-Al_2O_3-Pb sandwich at 1°K.

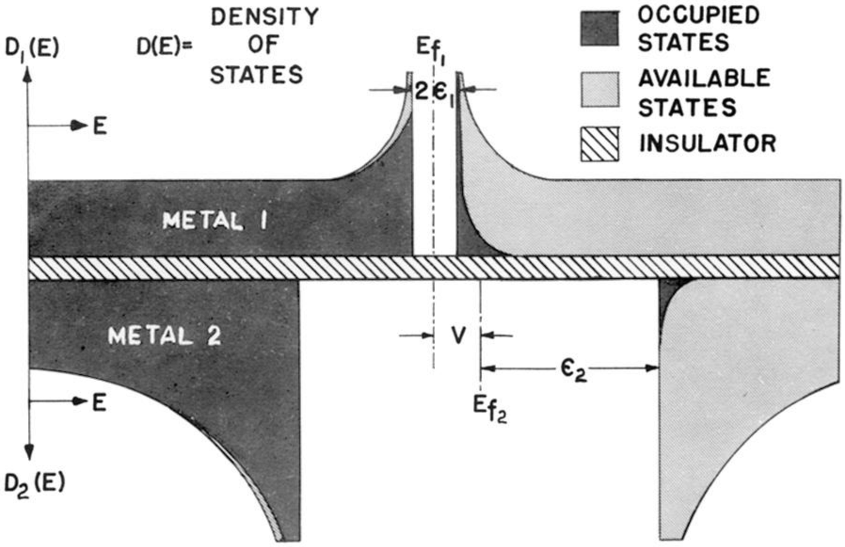

FIG. 3. The density-of-states function and the filled states sketched in a small energy interval about the Fermi level for a sandwich formed of two different superconductors separated by a thin insulating layer. A positive voltage, V, is applied to metal 1.