Using these relations, the value of the gap for Pb was determined to be $2\epsilon_{\rm Pb} = (4.35 \pm 0.10)kT_c$, independent of temperature in the interval 0.8°K-1.2°K. The measured gap for Al was $2\epsilon_{\rm Al}(1°{\rm K}) = (1.8 \pm 0.3)kT_c$ and $2\epsilon_{\rm Al}(0.8°{\rm K}) = (2.3 \pm 0.3)kT_c$. 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 $2\epsilon_{\rm Al} = (2.7 \pm 0.3)kT_c$.

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.

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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-

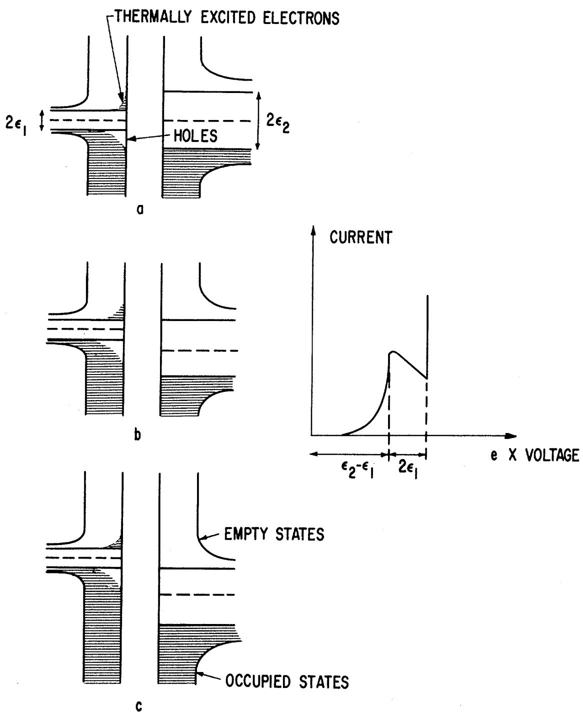

FIG. 1. Analysis of the current-voltage characteristic of two superconductors separated by a thin film. (a) The two superconductors with no voltage applied. Thermally excited electrons and holes are shown for the smaller gap, while for the larger gap there will be relatively few thermally excited electrons. (b) When a voltage is applied, a current will flow and will increase with voltage, because more and more of the thermally excited electrons in the left-hand superconductor are raised above the forbidden gap in the right-hand superconductor, and can tunnel. When the applied voltage corresponds to half the difference of the two energy gaps, $\epsilon_2-\epsilon_1$, it has become energetically possible for all the thermally excited electrons to tunnel through the film. (c) When the voltage is increased further, only the same number of electrons can tunnel, and since they now face a less favorable (lower) density of states, the current will decrease. Finally, when a voltage greater than half the sum of the two energy gaps, $\epsilon_2+\epsilon_1$, is applied, the current will increase rapidly because electrons below the gap can begin to flow.

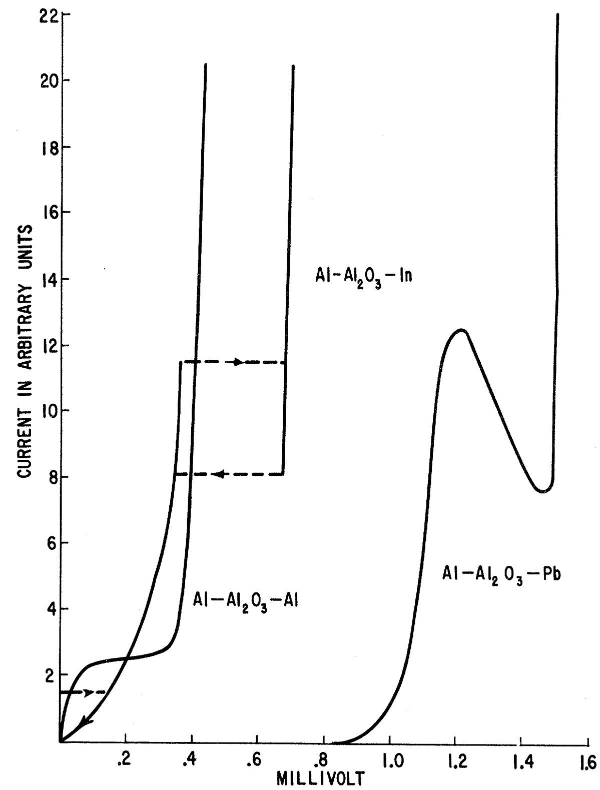

FIG. 2. Characteristic curves for tunneling between two superconductors, showing agreement with the analysis of Fig. 1. The curves Al-Al_2O_3-In and Al-Al_2O_3-Al are taken at $T\sim 1.1°K$, while the curve Al-Al_2O_3-Pb is at $T\sim 1.0°K$.

ments are

$$2\epsilon_{Pb} = (2.68\pm 0.06)\times 10^{-3} \text{ electron volt},$$

$$2\epsilon_{In} = (1.05\pm 0.03)\times 10^{-3} \text{ electron volt},$$

$$2\epsilon_{Al} = (0.32\pm 0.03)\times 10^{-3} \text{ electron volt},$$

For indium and lead, these gaps should not be significantly different at absolute zero, and we obtain

$$2\epsilon_{Pb} = (4.33\pm 0.10)kT_c,$$

$$2\epsilon_{In} = (3.63\pm 0.10)kT_c,$$

where T_c is the bulk transition temperature. This direct measurement of the energy gap for lead is a little smaller than what was obtained by fitting the experimental results with the BCS theory, where the best fit was obtained with an energy gap of $4.5kT_c$.[4] It should be noted that quite a large spread in the transition temperature of the aluminum films has been found; a transition temperature as high as 1.8°K has been observed. Whether this is true for the lead and indium films as well is not known.

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the experiments.

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IONIC HALL EFFECT IN SODIUM CHLORIDE*

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High-temperature ionic Hall effect measurements in large single crystals of pure sodium chloride were undertaken in order (a) to demonstrate the existence of the Hall effect due to the motion of ionic charge carriers, and (b) to provide an independent measurement of the temperature dependence of the mobility of the ionic charge carriers in sodium chloride.

The ionic Hall effect has previously never been observed in a solid, although an upper limit for the effect in NaCl has been set.[1]

Two ionic drift-mobility measurements in NaCl exist, but neither measurement was carried out near the melting point.[2,3] Both measurements used the impurity-doping method of Koch and Wagner[4] and are subject to the uncertainties implicit in this method.[5] The two experiments, which measured the drift mobility of the sodium ions, gave results which are in only rough agreement with each other.

Hall effect measurements provide a more straightforward means of measuring the mobilities of the ionic charge carriers in NaCl and other ionic conductors and are limited only by the smallness of the effect.

The ionic Hall effect arises from the action of the magnetic field on the asymmetry in the motion of the ionic charge carriers set up by the applied electric field. It can be shown[6] that a nonzero net transverse jump probability exists, and that the temperature dependence of the Hall mobility has the same form as that of the drift mobility. The relationship between the measured rms Hall voltage V_H and the Hall mobility μ_H, in the case where ac applied fields and a square sample are used, is

$$\mu_H = 2.10\, V_H/VB \text{ (meter}^2\text{/volt-sec)},$$

where the correction for the end effect[7] has been included. Here, V is the rms voltage of the applied electric field and B is the rms flux density of the magnetic field.

We used the ac cross-modulation method[8] to make Hall measurements in Harshaw NaCl. The electric and magnetic fields were applied at 85 and 60 cps, respectively, and the 25-cps Hall voltage difference frequency was measured. Square samples and the usual four-electrode configuration were used. The Hall voltage measurement system was able to measure signals as low as 0.05 μv. The linearity of this system was assured by the use of ultralinear cathode follower[9] input stages. Elaborate precautions were taken to insure that no spurious 25-cps signals were produced in the equipment. Also, the environment of the sample was maintained so that no electronic conduction was induced in the sample.

In spite of the presence of a large amount of current noise in the crystal, Hall measurements were made at seven temperatures in the range 610-780°C. The observed Hall voltage was proportional to the magnitude of the applied fields and was not sensitive to the pressure applied on the electric field or Hall electrodes. The apparent Hall mobility (which is the difference between the Hall mobilities of the sodium and chlorine ions) calculated from these measurements is shown in Fig. 1.

The experimental points are fitted by the curve shown in Fig. 1. The shape of this curve is derived from the diffusion data of Laurent and Benard.[10]

In Fig. 2 we have compared our apparent Hall mobility data with extrapolations of the sodium ion drift mobility measurements of Etzel and Maurer[2] and of Bean.[3] The results of Etzel and Maurer as corrected by Lidiard[11] are also given in Fig. 2. The proportionality of the observed Hall voltage to the applied fields is exhibited by the low-field Hall data plotted in Fig. 2.

The Hall data are not accurate enough to permit resolution of the mobilities of the sodium and chlorine ions. However, by extrapolating from the low-temperature portion of the curve, it is