ENERGY GAP IN SUPERCONDUCTORS MEASURED BY ELECTRON TUNNELING

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If a potential difference is applied to two metals separated by a thin insulating film, a current will flow because of the ability of electrons to penetrate a potential barrier. The fact that for low fields the tunneling current is proportional to the applied voltage[1] suggested that low-voltage tunneling experiments could reveal something of the electronic structure of superconductors.

Aluminum/aluminum oxide/lead sandwiches were prepared by vapor-depositing aluminum on glass slides in vacuum, oxidizing the aluminum in air for a few minutes at room temperature, and then vapor-depositing lead over the aluminum oxide. The oxide layer separating aluminum and lead is thought to be about 15-20A thick.

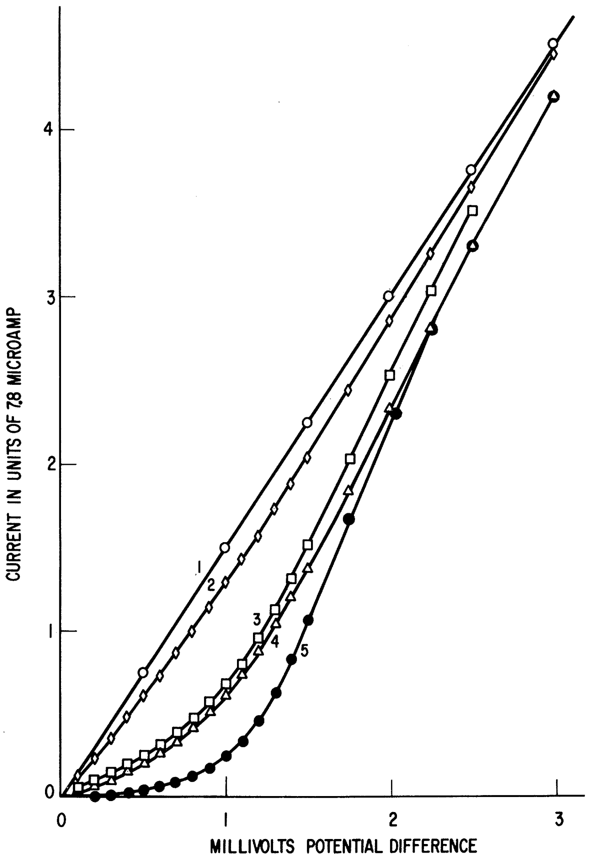

FIG. 1. Tunnel current between Al and Pb through Al_2O_3 film as a function of voltage. (1) $T=4.2°K$ and $1.6°K$, $H=2.7$ koe (Pb normal). (2) $T=4.2°K$, $H=0.8$ koe. (3) $T=1.6°K$, $H=0.8$ koe. (4) $T=4.2°K$, $H=0$ (Pb superconducting). (5) $T=1.6°K$, $H=0$ (Pb superconducting).

At liquid helium temperature, in the presence of a magnetic field applied parallel to the film and sufficiently strong to keep the lead in the normal state, the tunnel current is linear in the voltage. However, when the magnetic field is removed, and lead becomes superconducting, the tunnel current is very much reduced at low voltages as shown in Fig. 1. There is no influence of polarity, identical results being obtained with both directions of current flow.

The slope dI/dV of the curve in Fig. 1 where $H=0$, $T=1.6°K$, divided by dI/dV for normal lead, is plotted in Fig. 2. On the naive picture that tunneling is proportional to density of states,[2] this curve expresses the density of states in superconducting lead relative to the density of states when lead is in its normal state, as a function of energy measured from the Fermi energy. It seems clear that the density of states at the Fermi level is drastically changed when a metal becomes a superconductor, the change being symmetric with respect to the Fermi level. The curve resembles the Bardeen-Cooper-Schrieffer[3] density of states for quasi-particle excitations. There is a broadening of the peak that decreases with decreasing temperature. An approximate measure of half the energy gap

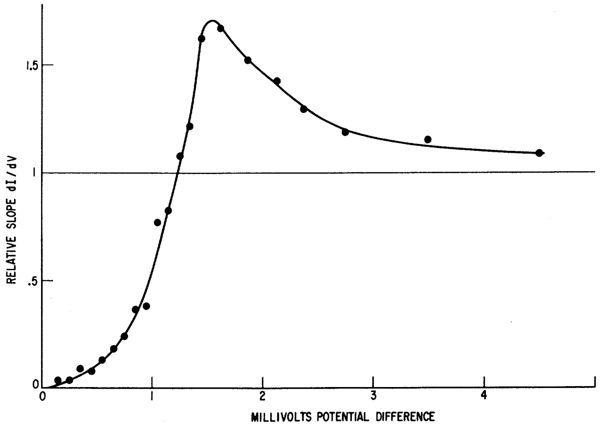

FIG. 2. From Fig. 1, slope dI/dV of curve 5 relative to slope of curve 1.

is given by the point at which the relative slope $dI/dV = 1$. On this basis the gap width for lead is $(4.2 \pm 0.1)kT_c$.

The experiment has been repeated with tin and indium giving entirely similar results; the gap in each case is approximately $4kT_c$. These results are of a preliminary nature, and experiments at lower temperatures will make them more precise.

I wish to thank C. P. Bean and J. C. Fisher for their interest and encouragement, and P. E. Lawrence for his help in performing the experiments.

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[1] J. C. Fisher and I. Giaever (to be published).

[2] W. A. Harrison (private communication) has pointed out that the tunnel current is not proportional to the density of states except in the limiting case of a low density of states.

[3] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 108, 1175 (1957).

CRITICAL FIELD FOR SUPERCONDUCTIVITY IN NIOBIUM-TIN

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It is well known[1] that Nb_3Sn is a superconductor with a high critical temperature, 18°K. The measurements here reported show that it has also an exceptionally high critical field, about 70 000 oersteds at 4.2°K, necessary for the suppression of all superconductivity.

The material was prepared by melting together niobium and tin in the argon arc, and the button so obtained was formed by grinding into a rod about 2 cm long and 4 mm in diameter, with rounded ends. The magnetic moment per gram, σ_g, was measured by pulling the specimen from one search coil to another in a constant field, the two search coils being connected in series opposition to a ballistic galvanometer. Calibration was with nickel of high purity.

Measurements were made in increasing fields, after cooling in zero field to liquid helium temperature. Results are shown in Fig. 1. The initial points (circles) follow accurately the line for $B = 0$ ($H = -4\pi\sigma_g d$, where d is the density, 8.9), and then begin to deviate at about 4000 to 5000 oersteds. The variations in the readings in fields from 5000 to 20 000 oersteds reflect the well-known irregular changes in magnetization resulting from changes in domain structure in the intermediate state, as observed by Schawlow et al.[2] and others. The general shape of the magnetization curve is that observed in a hard superconductor. Polishing, or annealing the specimen at 1100°C for several hours, made no essential change in the character of the curve.

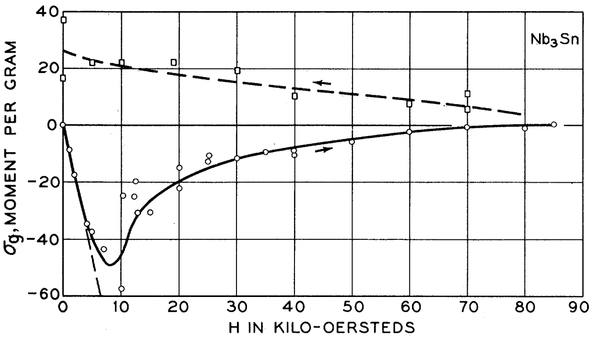

FIG. 1. Magnetization of Nb_3Sn as dependent on field strength, showing superconduction in entire specimen to about 5000 oersteds and superconduction in some parts of specimen to about 70 000 oersteds.

When the field was decreased from its maximum value (points marked with squares) some of the flux was frozen in, and irregularities were again observed.

The authors are indebted to E. Corenzwit for preparation of the material, to W. E. Henry of the Naval Research Laboratory for details of the method of measurement, and to H. W. Dail for assistance with the experiment. The field was produced in a Bitter coil excited with a motor generator with a nominal power rating of one megawatt.

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[1] B. T. Matthias and T. H. Geballe, Phys. Rev. 95, 1435 (1954).

[2] A. L. Schawlow, G. E. Devlin, and J. K. Hulm, Phys. Rev. 116, 626 (1959).