Measuring the Energy Gap of a Superconductor using Electron Tunneling

Michael Abbott*
Brown University, Providence, RI
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We repeat the 1960 experiment by Giaever[1] which gave the first direct measurement of the energy gap of a superconductor. We measure the gap for lead to be $2\epsilon = 2.2 \pm 0.1 \times 10^{-3}$eV at 2K.

One of the main predictions of the BCS theory of superconductivity [2] is the existance of a gap in the spectrum of allowed electron energies. While this gap had been measured by various indirect means (via thermodynamic and electromagnetic properties of a sample), the first direct measurement was the experiment by Giaever [1].

He measured the current tunneling from an ordinary metal to a superconductor through a thin insulating layer. This is related to the density of states in the superconductor at the metal's Fermi energy, so by adjusting the applied voltage (and so the Fermi energy) he could probe the superconductor's spectrum. By adjusting the magnetic field at the sample, he could adjust the critical temperature of the superconductor, and so study the transtion between normal and superconducting states at fixed temperature.

We repeat this experiment, but omit the use of a magnetic field. As in the original experiment, lead and aluminium are used, with a barrier of aluminium oxide.

APPARATUS

The sample is immersed in a bath of liquid helium, whose temperature can be changed by evacuating the vessel containing it.[3] To minimise the loss of liquid helium, the dewar containing it is surrounded by another, filled with liquid nitrogen. We are able to obtain temperatures in the range $2.0\text{K} \leq T \leq 4.2\text{K}$. This means that we cannot approach the critical temperature of lead (7.2K) nor reach that of aluminium (≈1.5K).

Current is passed trough the junction along one pair of wires. The current is supplied by a function generator, producing a sawtooth wave at 500Hz, and is measured by connecting an oscilloscope across a resistor (76.8Ω) inserted into the circuit.

The voltage drop across the junction is measured using a second pair of wires. Since it is very small, a differential amlifier (set to a gain of 1×10^3) is employed. This is also set to filter out some high-frequency noise, above 30kHz. The result is measured with the oscilloscope.

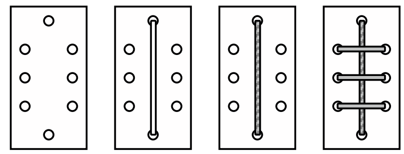

Figure 1: Steps in preparing a sample: chromium dots, aluminium strip, oxidisation in air, lead strips.

SAMPLE PREPARATION

The samples are prepared by vapor-deposition of three metals onto a glass microscope slide. The steps are shown in Fig. 1.

First, chromium is deposited in small dots where the contacts will touch, of thickness about 1500Å. This is to guard against the contacts scratching through the other, softer, metals to rest on the glass.[7]

Second, a strip of aumininium is deposited, also around 1500Å thick. This is allowed to oxidise in air to produce the insulating Al_2O_3 layer, of order 10Å.

Finally, strips of lead are deposited crossing the aluminium perpendicularly, of thickness about 1000Å. This creates three junctions, wired independently but cooled down together, increasing the chances of success.

MODEL

It is a well-known property of quantum systems that particles are able to tunnel through potential barriers. The probability of this happenning (and hence, macroscopically, the rate at which it happens) is related to the height and thickness of the barrier, which we will take to be fixed.

Fig. 2(a) shows an insulating barrier between two metals at finite temperature. Tunneling will only occur from a filled state to an empty state, so at zero applied voltage (when the Fermi energies line up) will occur equally in both directions. As a voltage is applied, the distribution on one side moves up relative to the other, and so number of allowed transitions in one direction grows. At zero temperature it is clear that the resulting current will increase linearly with voltage; this is also true at finite temperature.

If the barrier is between a metal and a superconductor, then things are very different, because the superconduc-

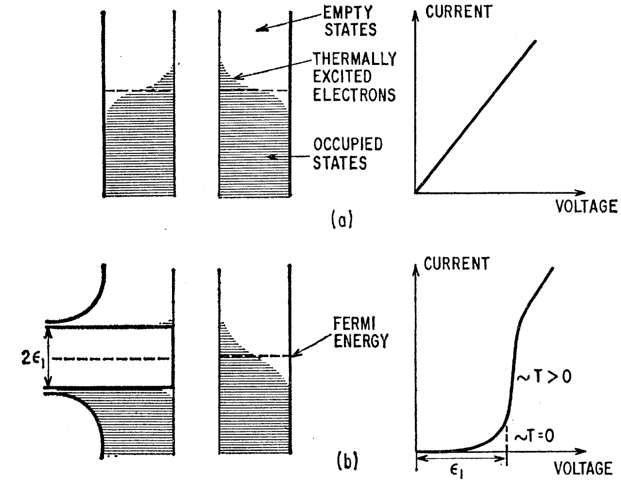

Figure 2: Energy levels on either side of an insulating barrier (a) between two metals, and (b) between a metal and a superconductor. Stolen from [4].

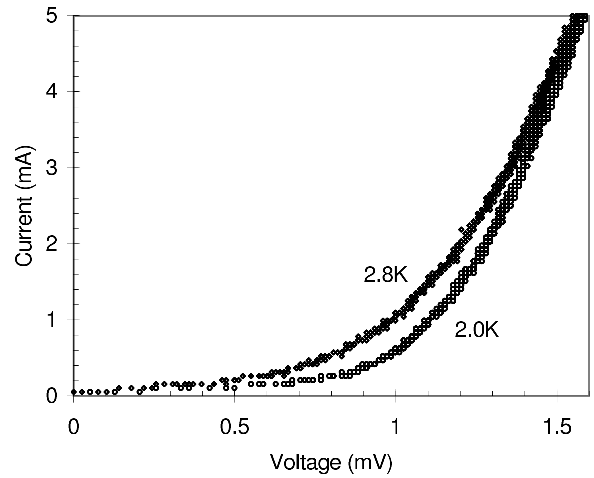

Figure 3: Current-voltage graph at two temperatures.

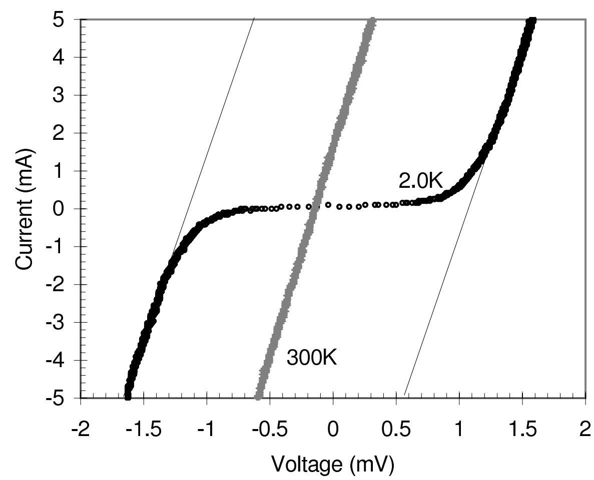

Figure 4: Method of finding the energy gap. Two parallel lines are drawn to fit the straight line portion of the I-V curve, and the horizontal distance between them is measured. This is not sensitive to the zero of either axis. Also shown is the I-V data at room temperature.

tor has a gap in its spectrum, Fig. 2(b). Consider first the case of zero temperature, and apply a small voltage in the direction which raises the metal's Fermi energy. Initially no current flows, because there are no states available for the electrons to tunnel into. Only above a certain voltage ϵ_1, when electrons at the Fermi energy are able to tunnel into states above the gap, does the current start flowing. A similar argument holds for voltage in the reverse direction.

At finite temperature, there are some filled states above the Fermi energy (and some empty ones below) so we expect the onset of current flow to be less distinct.

In addition to having a gap in its spectrum, a superconductor also has a concentration of states on either side of this gap, drawn as peaks in Fig. 2 (b). These should cause the current to increase more rapidly at first. We were unable to observe this secondary effect.

EXPERIMENTAL RESULTS

Fig. 3 shows the data obtained from two runs at different temperatures. Comparison with Fig. 1 of [1] shows that we are seeing the same phenomenon: an energy gap 2ϵ of order 2mV, growing less pronounced as the temperature is raised.

To measure the energy gap, two parallel lines were fitted to the straight portions of the voltage-current graphs (Fig. 4). 2ϵ is then the horizontal distance between them. The results in Fig. 5. We conclude that

$$2\epsilon = 2.2 \pm 0.1 \times 10^{-3}\text{eV} \quad \text{at 2K.}$$

For comparison, [4] quotes $2\epsilon_{\text{Pb}} = 2.68 \pm 0.06 \times 10^{-3}$eV at 1K.

PROBLEMS

The two points at highest temperature in Fig. 5 are probably incorrect. They are the last two measurements we made, after going below $T_\lambda = 2.17$K, the superfluid transition point. Doing so upsets the correlation between temperature and pressure, apparently even after coming to atmospheric pressure (the '4.2K' point.)

To show the secondary effect mentioned above, [1] plots a graph of the $\frac{dI}{dV}$ against V. The peak in this corresponds to the increased density of energy levels on either side of the energy gap. An attempt to reproduce this, by

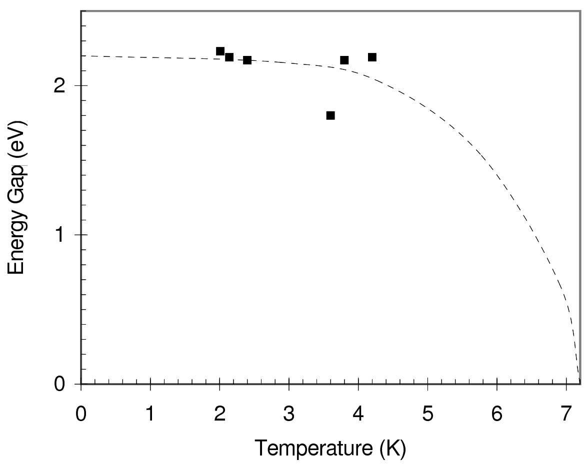

Figure 5: Measured energy gap at various temperatures. Note that the right-most two points are probably incorrect, see text. The dashed line is BCS theory (approximate, traced from [5]'s Fig. 8, because solving the required equations numerically [6, p. 446] was too slow.)

fitting a curve to the 2.0K line in Fig. 4, does not show a peak. Had we taken data at $|V| > 1.6$mV this might be visible.

* Electronic address: `abbott@het.brown.edu`

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[2] Bardeen, Cooper, and Schrieffer, Phys. Rev. **108**, 1175 (1957).

[3] Brickwedde, van Dijk, Durieux, Clement, and Logan, *The 1958 He 4 Scale of Temperatures* (National Bureau of Standards Monograph 10).

[4] I. Giaver and K. Megerle, Phys. Rev. **122**, 1101 (1961).

[5] L. Cooper, Am. J. Phys. **29**, 91 (1960).

[6] A. L. Fetter and J. D. Walecka, *Quantum Theory of Many-Particle Systems* (McGraw-Hill, NY, 1971).

[7] In cases when the contacts touched these dots instead of the strips, this introduced a few ohms of extra resistance. So it seems unlikely that, if we did scratch through the other metal, the slide would work.