Single Electron Tunneling Spectroscopy in Superconductors

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Abstract

The mechanism responsible for the pairing of electrons into Cooper pairs in superconductors has been an active area of superconductor research, especially in research involving more exotic superconducting materials. Tunneling spectroscopy has proven to be a powerful tool in improving our understanding of the nature of the interactions among superconducting electrons. This paper briefly examines some of the theory behind the formation of electron pairs and how tunneling spectroscopy can be used to investigate this phenomenon. Next, a typical tunneling experiment is discussed. Finally an explanation of how tunneling spectroscopy data are analyzed and interpreted is provided.

1 Introduction

Despite being an elementary phenomenon of quantum mechanics, tunneling was not employed as an experimental tool for studying superconductors until 1960. By this time a variety of techniques, including nuclear relaxation, ultrasonic attenuation, electromagnetic absorption, and measurements of specific heat and thermal conductivity had provided evidence for the existence of the enegy gaps in the excitation spectra of superconductors which had been predicted by Bardeen-Cooper-Schrieffer (BCS) theory[1]. Today tunneling spectroscopy gives the most accurate measurements of the energy gap in superconductors as well as information about the electronic density of states and characteristic excitations in the insulating barrier [2].

2 The Superconducting Energy Gap

The existence of an energy gap between the BCS ground state and states of excited free electrons with energies above the ground state is one of the key features of the BCS theory. Experimental confirmation of this energy gap by tunneling spectroscopy and other techniques is considered a great triumph for this theory.

According to BCS theory, when an electron travels through the lattice of a superconductor it creates a mechanical disturbance in the lattice which takes the form of a spectrum of phonons, or quantized packets of acoustic energy. These phonons interect with other electrons as they propagate through the lattice. Through this interaction it is possible for an electron to experience a mutually attractive interaction with another electron whose momentum is equal and opposite its own momentum $\mathbf{k}$. The attractive nature of this interaction lowers the energy of an electron pair (Cooper pair) relative to the mean energy (Fermi energy) of unpaired electrons, thereby making it energetically favorable for a large number of Cooper pairs to form in the superconductor. It is the collective interaction of many electron pairs that produces the energy gap in a superconductor [3].

A quantity of particular interest which can be calculated by BCS theory is the condensation energy of the superconducting phase (i.e. the energy difference per unit volume between the superconducting ground state and the normal conducting ground state). It can be shown that this condensation energy is given by

$$(W^0_{BCS} - W^0_n)/L^3 = -Z(E^0_F)\Delta^2/2 \tag{1}$$

where W^0_{BCS} and W^0_n are the ground state energies of the superconductor and a normal conductor respectively and $Z(E^0_F)$ is the density of states for one spin type at the Fermi surface.. In effect, this means that $Z(E^0_F)\Delta$ electron pairs per unit volume from the energy region of width Δ below the Fermi level condense into an energy state exactly Δ below E^0_F, resulting in an average energy loss per pair of $\Delta/2$ [2].

In order to raise the superconductor to the first excited state above the BCS ground state energy must be added to the system to break up a single Cooper pair. BCS theory predicts that this energy is

$$\Delta E = 2(\hbar^2 k^2/2m - E^0_F + \Delta^2)^{1/2} \tag{2}$$

The first two terms in the square root describe the kinetic energy relative to the Fermi energy for an electron from a broken Cooper pair and can be arbitrarily small. Consequently,

the minimum energy needed to excite the ground state is 2Δ. Similarly, if an unpaired electron is added to the BCS ground state (e.g. in a tunneling experiment) then it will be unable to find another electron with which to form a pair and will be forced to occupy a state at least Δ above the energy of the BCS ground state.

3 Theory of Tunneling Experiments

There are three different tunneling experiments worth considering: (1) Tunneling of single electrons between two normal conductors, (2) Tunneling of single electrons between a normal conductor and a superconductor, and (3) tunneling between two superconductors. These three experiments are illustrated in Figs.1 and 2.

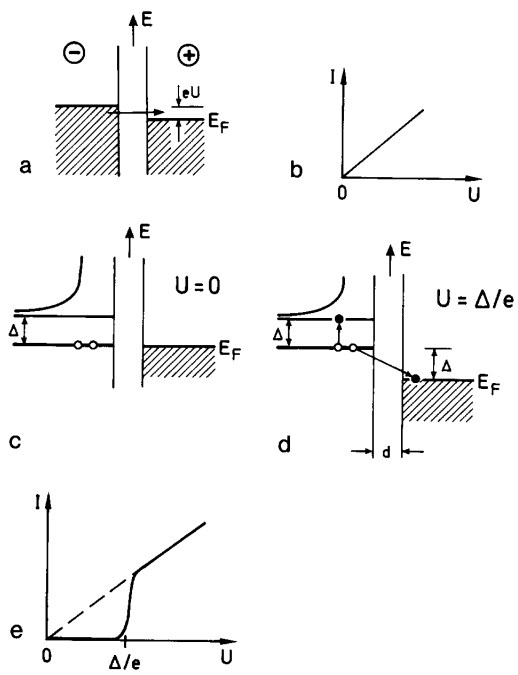

Figure 1: *Schematic representation of single electron tunneling in two normal metals (a-b) and a metal and superconductor(c-e) [2]*

The transmission coefficient of a quantum particle through a potential barrier depends exponentially on both the thickness of the barrier and the square root of the height of the barrier [1]. For case (1) when a small voltage U is applied across an insulating barrier there is a difference in the Fermi energies of the two metals equal to eU (a). As long as the applied voltage is small the density of states between E_F and E_F+eU is approximately uniform and the current will be proportional to the voltage since the number of electrons which can flow is proportional to the voltage (b).

The situation is drastically different when one of the metals is superconducting (c). At absolute zero there is no tunneling current until the applied potential U is equal to Δ/e. This can be explained by the fact that it takes energy 2Δ to break the bond of a Cooper pair. As shown in (d), when a voltage Δ/e is applied across the insulator it is possible for one electron from a Cooper pair to loose an energy Δ as it moves from the Fermi surface of the superconductor to the Fermi surface of the metal. The energy gained from this

transition can then be used to boost the other electron in the pair across the energy gap of the superconductor. For higher voltages (e), assuming the current is proportional to the density of states, the current increases rapidly and asymptotically approaches the I-U characteristic of two normal metals as in (b). When the temperature is nonzero there is a nonvanishing current regardless of the magnitude of the applied voltage. Furthermore, since the metals on either side of the insulating barrier are so different, the tunneling current depends strongly on the temperature [1].

For case (3) when both metals are in a superconducting state (Fig.2) there is again no significant current flow for $0 < T < T_c$ until a minimum threshold voltage is applied. If the half-gap energies if the two superconductors are Δ_1 and Δ_2 with $\Delta_1 > \Delta_2$ then it will be possible for electrons already in the excited states above the BCS ground state to tunnel through the insulating barrier when $U/e = (\Delta_1 - \Delta 2)/2$. When the applied voltage reaches $1/2(\Delta_1 + \Delta_2)$ is becomes possible to break Cooper pairs so that one electron from the pair can penetrate the barrier while the other can jump the energy gap (c). As with case (2) the current increases rapidly once the applied potential is great enough to break up Cooper pairs and the I-U characteristic (d) asymptotically approaches that of case (1).

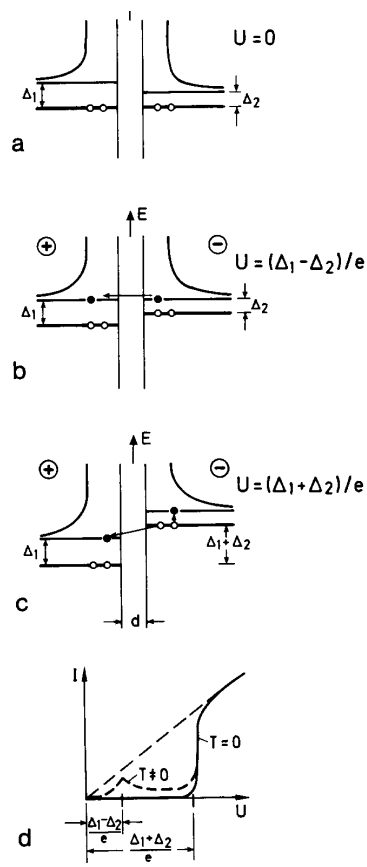

Figure 2: *Schematic Representation of Single Electron Tunneling in Two Superconductors [2]*

An interesting effect can be observed in a tunnleing experiment like the one considered in case (3) for intermediate voltages $1/2(\Delta_1 - \Delta_2) < U < 1/2(\Delta_1 + \Delta_2)$. As the applied voltage is increased in this region the number of electrons with sufficiently high energies to tunnel through the insulating barrier does not change. Meanwhile, they face a lower

density of states so the current actually decreases in this region and the resistance of the junction is negative [1].

4 Experimental Methods

The most widely used method for producing tunneling spectra consists of the deposition of the superconducting electrode, the formation of the insulating barrier, and the final deposition of a metallic or superconducting electrode at right angles to the original film. The cross stripe structure shown in Fig.3 does not requre any sophisticated lithography and can made using contact masks [4]. More sophisticated techinques have been devised recently in which the junctions are made in a trilayer process in which the electrodes and the tunneling barrier are deposited sequentially and the junction is defined afterwards using photlithographic techniques. The advantage of this technique is that it enables the experimenter to make very small and uniform tunnel structures. The first electrode consists of a metal film which is evaporated at low pressure through a mask. By admitting oxygen to the evaporation chamber at significantly higher pressure an oxidized layer is created on the electrode which will act as the insulating tunnel barrier. Finally, the second metal film is evaporated over the layer of oxidation, perpendicular to the first electrode. The tunnel barrier in this arrangement is quite small, with an area of only a fraction of a square millimeter and a resistance between 100-1000 ohms [2]. Since superconductivity experiments must be conducted at low temperatures, the tunnel junction and its electrical contacts are then mounted in a cryostat.

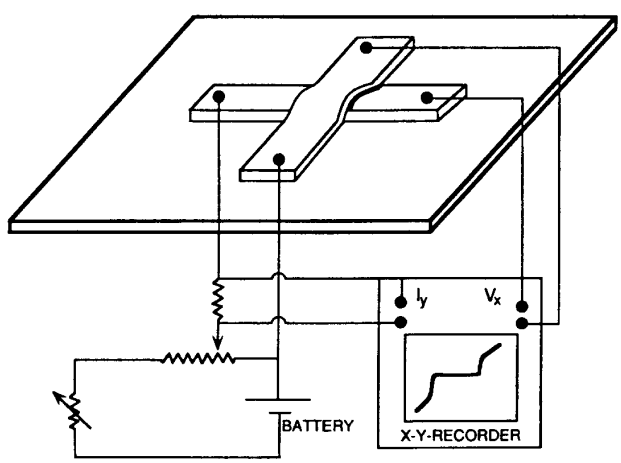

Figure 3: *The Structure of a Simple Tunnel Junction and the Circuitry needed to measure an I-U Characteristic [4]*

Another device which has been employed to investigate oxide superconductors (it is difficult to prepare thin insulateing barriers with these superconductors using the deposition methods decribed above) is the point contact. With this device, a very sharp needle with a small voltage applied to it is moved near the surface of a superconductor until a tunneling current begins to flow [4].

There are three important quantities that need to be calculated in tunneling experiments: the current-voltage charcteristic and its first two derivatives. These quantities

are essential because they allow for a determination of the tunneling density of states and hence a way to make a direct comparison with theoretical models [4]. The second derivative measurements are also used for studying ineleastic processes which affect the tunnel current. These must be measured in both the normal and superconducting states of the sample, with a small magnetic field applied to the sample in the latter case to quench the tunneling of Cooper pairs (the Josephson effect). The measurements are usually made using ac lock-in techniques where a dc voltage (20-50 μvolts) with a small ac component (in the KHz region) is applied across the junction. The component of the tunnel curent at a particular frquency is then measured by a lock-in amplifier.

5 Additional Data Analysis

While the emphasis of this paper to this point has been to show how tunneling spectroscopy can be used to determine the size of the energy gap in a superconductor, it is possible to carry the tunneling spectroscopy data much further. A set of equations known as the Eliashberg gap equations describe the the effect of the phonon density of states in a superconductor on the energy gap. At the same time, the energy gap, which can be determined quite accurately in tunneling experiments, modifies the phonon density of states. By numerically invering the gap equations [5], it is possible to calculate the phonon density of states $\alpha^2 F(\Omega)$ and extract all important information about not only the phonon density of ststes but also the phonon-electron coupling parameter in a superconductor. Once the coupling parameter has been calculated, it is also possible [6] to obtain an expression for the critical temperature of the superconductor.These are what make tunneling spectroscopy so important as a means of verifyng BCS theory. A plot of the phonon denity of ststes in superconducting lead is shown in Fig.4.

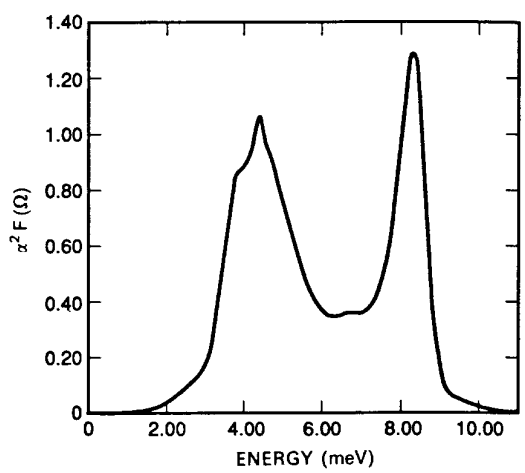

Figure 4: *The function $\alpha^2 F(\Omega)$ for lead [4].*

6 Conclusions

Single electron tunneling spectroscopy has proven to be an invaluable experimental technique in the study of superconductors. In addition to allowing experimentalists to

measure the energy gaps in a wide variety of superconductors, tunneling experiments have enabled scientists to measure other important quatities like the phonon density of states and strength of electron-phonon coupling. The results obtained from these experiments have lent a great deal of credence to theoretical models like BCS theory.

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