TUNNELING SPECTROSCOPY IN Bi2Sr2CaCu2O8: IS THE ENERGY GAP ANISOTROPIC?

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Electron tunneling experiments have been performed on single crystals of the superconductor Bi2Sr2CaCu2O8 using point contact and break junction configurations. For tunnel current injected in the a-b plane and c-axis directions, the respective current-voltage characteristics suggest zero-temperature energy gap values of $\Delta_{ab}=23$ meV and $\Delta_c=12$ meV, corresponding to $2\Delta_{ab}/k_B T_c=6.250.3$ and $2\Delta_c/k_B T_c=3.30.3$. The observed gap temperature dependence is in good agreement with BCS (mean field) behavior.

The anomalously high transition temperatures and reduced isotope effects associated with new classes of "high-$T_c$" oxide superconductors suggest the possibility of novel superconductivity mechanisms. Numerous models have been proposed but they remain largely untested. Indeed, some of the most fundamental characteristics of the new materials have not yet been experimentally determined with good reliability.

One such feature in the superconducting energy gap, $\Delta$, of the traditional methods used to determine $\Delta$, one of the most direct is electron tunneling spectroscopy, which can in principle also determine gap anisotropy in single crystal specimens. Although many tunneling studies have been performed on high-$T_c$ oxides, the magnitudes of the reported gaps have been inconsistent. In Y-Ba-Cu-O, for example, reported tunnel gap values range from $2\Delta_0/k_B T_c=0.1$ to $3$, while for Bi-Sr-Ca-Cu-O the reported gap ratios range from 4.5 to 7.5. No conclusive evidence for anisotropic gap structure in a single crystal has been reported. Much of the problem in interpreting tunneling measurements is that it is a surface measurement, and often the surface is poorly characterized. The high oxygen mobility together with a relatively short coherence length in high-$T_c$ oxides makes these materials prone to poor tunnel junction formation.

We here report on tunneling measurements of the energy gap in single crystals of Bi2Sr2CaCu2O8, with emphasis on gap anisotropy. To ensure reliability of the results, different tunnel configurations have been utilized on well characterized samples with freshly exposed surfaces. Point contact tunneling was performed using superconductor-insulator-superconductor (SIS), superconductor-insulator-normal (SIN), and break junction (SIS and Josephson) methods. Tunneling electrons were injected into the a-b plane (Cu-O sheet direction) and c-axis directions. The results suggest a significant gap anisotropy, with $2\Delta_{ab}/k_B T_c=6.2$ and $2\Delta_c/k_B T_c=3.3$.

High purity single crystals of Bi2Sr2CaCu2O8 were prepared as described elsewhere. The stoichiometry of the crystals was confirmed by SEM x-ray elemental analysis. After the initial synthesis, the crystals were carefully annealed in oxygen to insure homogenous superconducting properties. The samples were characterized by dc magnetic susceptibility and electrical resistivity measurements, which indicated a bulk $T_c=85K$. The tunneling probe was similar in design to that described by Levinstein and Kuntzler, with the additional capability of forming in-situ break junctions in the crystals. All $T=4.2K$ measurements were performed with the sample immersed in liquid helium; higher temperature measurements were performed in a helium gas flow cryostat. $I$-$V$ characteristics were obtained using a ramped constant-current source. Differential $dV/dI$ measurements were obtained using conventional lock-in techniques.

Fig. 1 shows the $dV/dI$ characteristics of an SIN junction at 4.2K, formed between a normal indium tip and a Bi2Sr2CaCu2O8 ab plane "edge" exposed by cleanly breaking a crystal along a plane parallel to the c-axis. The direction of electron tunneling is presumably along the a-b plane. At low bias voltages, unusual structure is observed in $dV/dI$; this structure was not always reproducible and its origin is unknown. However, a reproducible feature is observed close to $\pm 20mV$. We associate this feature with the superconducting energy gap. If we take the local conductivity maximum as the value of the gap, then $\Delta_{ab}=22.5$ meV at 4.2K. The SIN tunneling experiment described in Fig. 1 was repeated at selected temperatures, and the gap feature was found to vary smoothly with temperature. The inset to Fig. 1 shows the position of the local differential conductivity maximum as a function of temperature. The solid
1. NIS tunneling into the a-b plane of Bi$_2$Sr$_2$CaCu$_2$O$_8$. The arrows identify $\Delta_{ab}$. The inset shows the temperature dependence of $\Delta_{ab}$; the solid line is the BCS gap.

line is the BCS gap, fit to the T=4.2K and T=76K data points. The fit suggests $\Delta_{ab}(T=0)=22.3$meV and $T_c=85.4K$, where the relation $\Delta(T)/\Delta(0)=1.74[1-(T/T_c)]^{1/2}$ was used near $T_c$. The tunneling determined "local" transition temperature $T_c=85.4K$ is in excellent agreement with the bulk $T_c=85K$ for this particular crystal, consistent with high sample homogeneity. With $T_c=85K$, we find $2\Delta_{ab}(T=0)/k_BT_c=6.203$.

To confirm the above value of $\Delta_{ab}$ and to further test the reliability of NIS tunnel junctions formed using Bi$_2$Sr$_2$CaCu$_2$O$_8$ crystal "edges", we formed a break junction across the a-b plane of a single crystal. The junction was formed and measured at 4.2K to ensure pristine crystal surfaces. The inset to Fig. 2 shows the junction configuration. The separation distance between superconductors in the break region could be adjusted from outside the cryostat, and the I-V characteristics could be reversibly changed from "Josephson like" (small separation) to non-supercurrent NIS like. Fig. 2 shows a typical I-V curve in the Josephson regime. The junction is highly hysteretic at low voltages, but the maximum slope occurs reproducibly near 45mV. If this value is taken as $2\Delta_{ab}$, we find $\Delta_{ab}=22.3$meV, in accord with the SIN results.

To explore the energy gap structure along the c-axis, we employed a "differential" tunneling configuration, as shown in the inset of Fig. 3. Well characterized Bi$_2$Sr$_2$CaCu$_2$O$_8$ crystals were mounted and cleaved such that tunneling would take place from the ab-plane direction of one crystal into the c-axis direction of another crystal. The junction is of the $S_1-T-S_2$ type, where the subscripts refer to potentially different values of the energy gap. Fig. 3 shows the I-V and dV/dI characteristics of the differential tunnel junction. dV/dI shows two distinct features, which we identify as corresponding to the sum and differences of the energy gaps in the ab-plane and c-axis directions. Again taking the local maximum in the differential conductance as the relevant energy, we find $\Delta_{ab}+\Delta_c=35$meV and $\Delta_{ab}-\Delta_c=11$meV. Solving for $\Delta_{ab}$ and $\Delta_c$ gives $\Delta_{ab}=23$meV and $\Delta_c=12$meV. The value for $\Delta_{ab}$ is in good agreement with that determined above, 22.3meV. Again with $T_c=85K$, we find $2\Delta_{ab}/k_BT_c=6.203$. These measurements suggest an energy gap anisotropy in Bi$_2$Sr$_2$CaCu$_2$O$_8$ at low temperatures of about a factor of two.

The features described above are characteristic of the majority of our tunneling measurements for numerous Bi crystals, employing different break junction configurations and different normal-metal and superconducting tunnel electrodes. In some cases, however,
sharp multiple-peak ‘charging’ structures, similar to those reported by van Bentum et al., were observed which obscured the smaller magnitude gap structure. On occasion we also observed evidence for two independent gap structures in a given I-V trace for a particular tunneling direction. For example, in one break tunnel junction we observed at 4.2 K local conductivity maxima at 25 mV and 6.2 mV. Interpreting these features in terms of 818 tunneling implies gap values of 12.5 mV and 27 mV. The lower value corresponds well to the previously identified $\Delta_L$, while the larger value is close to $\Delta_H$.

Fig. 4 shows similar “double gap” features in a point contact $S/N$ measurement made by tunneling from a normal Pt/Rh tip into the c-axis direction of a freshly cleaved Bi$_2$Sr$_2$CaCu$_2$O$_{8+}$ crystal. Here structure is observed at 12 mV and 22 mV. The former value again corresponds to our assumed $\Delta_L$, while the later value is comparable to (but slightly less than) $\Delta_H$. One possible interpretation of such data is that for some junctions the tunnel current is not always confined to a single junction, and different junctions may (because of steps in the cleavage planes) correspond to tunneling into different crystal directions. There also exists the possibility that for certain junction configurations the tunnel current in a highly anisotropic system is non-ballistic, and that for different bias voltages the tunnel current independently probes different crystal directions. Alternatively, the gap parameter in Bi$_2$Sr$_2$CaCu$_2$O$_{8+}$ may be modulated along the c-axis direction and essentially double-valued along this direction (see below).

Our measurements show that in the a-b plane, $2\Delta_L/k_BT_c=6.7$. This a-b plane value is in accord with several previous tunneling measurements, and is also consistent with data determined by recent high resolution photoemission studies\textsuperscript{25} where (for incident photon E-field in the a-b plane) it was found $2\Delta/k_BT_c=8.1$. The observed ratios are far in excess of the expected BCS (weak coupling) result: \begin{equation} 2\Delta_L/k_BT_c=3.5 \end{equation} and are also in excess of the ratios determined for conventional strong-coupled superconductors.

On the other hand, the gap magnitude determined for the c-axis in Bi$_2$Sr$_2$CaCu$_2$O$_{8+}$ is in accord with Eq. (1).

The extreme structural and electrical anisotropy\textsuperscript{9} of Bi$_2$Sr$_2$CaCu$_2$O$_{8+}$, it is not unreasonable to expect some energy gap anisotropy. One (highly oversimplified) picture of Bi$_2$Sr$_2$CaCu$_2$O$_{8+}$ might be one of highly conducting Cu-O layer complexes separated by insulating Bi-O layers. In the superconducting state, the Bi-O layers are superconducting, but the superconductivity is "weaker" there. The situation is somewhat analogous to a reduced order parameter by the proximity effect. Such an argument would suggest an order parameter constant in the a-b plane, but a gap value modulated along the c-axis direction. Since Bi$_2$Sr$_2$CaCu$_2$O$_{8+}$ is known to cleave along the Bi-O layers, a c-axis tunneling measurement would invariably extract the reduced gap value near the surface. High voltage current injection well above the surface gap energy may then probe the secondary gap structure of the underlying Cu-O plane complex, consistent with the double gap structure seen in Fig. 4.

The above description suggests a strong correlation between normal state electrical anisotropy and gap anisotropy. In YBa$_2$Cu$_3$O$_y$, the normal state electrical anisotropy is significantly less than that in Bi$_2$Sr$_2$CaCu$_2$O$_{8+}$. Although reliable single crystal anisotropic tunneling data do not exist for YBa$_2$Cu$_3$O$_y$, Teal et al.\textsuperscript{18} have tunneled into clean edges of preferentially oriented films, and find $2\Delta_L/k_BT_c=6.1$ and $2\Delta_L/k_BT_c=3.5$. Hence the implied gap anisotropy in that material is comparable to that suggested for Bi$_2$Sr$_2$CaCu$_2$O$_{8+}$. An important question is thus whether or not the gap anisotropy is a direct manifestation of the Cu-O plane structure and relatively independent of other structural and electronic details of the material.

In conclusion, tunneling measurements into different crystal directions of Bi$_2$Sr$_2$CaCu$_2$O$_{8+}$ suggest that the energy gap may be anisotropic by about a factor of two, being larger in the a-b plane direction. The temperature dependence of $\alpha$ is good with the BCS curve (or mean field theory in general), but the largest gap value is $2\Delta_L/k_BT_c=6.3$, a ratio significantly greater than the expected from BCS theory.

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