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TUNNELING SPECTROSCOPY IN $Bi_2Sr_2CaCu_2O_8$: IS THE ENERGY GAP ANISOTROPIC?

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Electron tunneling experiments have been performed on single crystals of the superconductor $Bi_2Sr_2CaCu_2O_8$ using point contact and break junction configurations. For tunnel current injected in the the a-b plane and c-axis directions, the respective current-voltage characteristics suggest zero-temperature energy gap values of Δ_{ab}≈23meV and Δ_c≈12meV, corresponding to $2\Delta_{ab}/k_BT_c$=6.2±0.3 and $2\Delta_c/k_BT_c$=3.3±0.3. The observed gap temperature dependence is in good agreement with BCS (mean field) behavior.

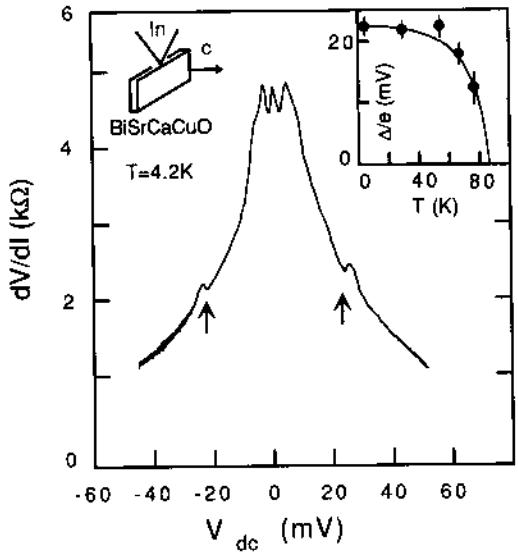
The anomalously high transition temperatures and reduced isotope effects[1] associated with new classes of "high-T_c" oxide superconductors suggests the possibility of novel superconductivity mechanisms. Numerous models have been proposed but they remain largely untested. Indeed, some of the most fundamental characteristics of the new materials have not yet been experimentally determined with good reliability.

One such feature is the superconducting energy gap, Δ. Of the traditional methods used to determine Δ, 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[2-10] tunnel gap values range from $2\Delta_o/k_BT_c$~3 to ~13, while for Bi-Sr-Ca-Cu-O the reported[10,11-14] gap ratios range from 4.5 to ~7). No conclusive evidence for anisotropic gap structure in a single crystal has been reported[2]. Much of the problem in performing and interpreting tunneling measurements is that it is a surface measurement, and often the surface is poorly characterized[8]. 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.

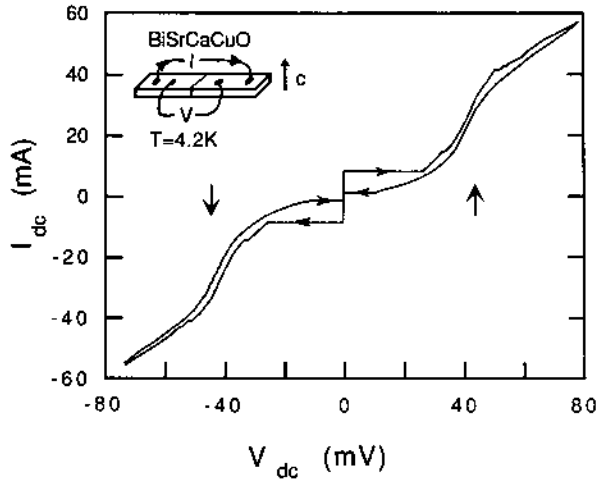
We here report on tunneling measurements of the energy gap in single crystals of $Bi_2Sr_2CaCu_2O_8$, with emphasis on gap anisotropy. To insure reliability of the results, different tunnel configurations have been utilized on well characterized samples with freshly exposed surfaces. Point contact tunneling was performed using superconductor-insulator-superconductor (SIS), superconductor-insulator-normal (SIN), and break-junction (SIS and Josephson) methods. Tunneling electrons were injected the into the a-b plane (Cu-O sheet direction) and c-axis directions. The results suggest a significant gap anisotropy, with $2\Delta_{ab}/k_BT_c$≈6.2 and $2\Delta_c/k_BT_c$≈3.3.

High purity single crystals of $Bi_2Sr_2CaCu_2O_8$ were prepared as described elsewhere[15]. 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 homogeneous superconducting properties. The samples were characterized by dc magnetic susceptibility and electrical resistivity measurements, which indicated a bulk T_c=85K. Our tunneling probe was similar in design to that described by Levinstein and Kunzler[16], 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.

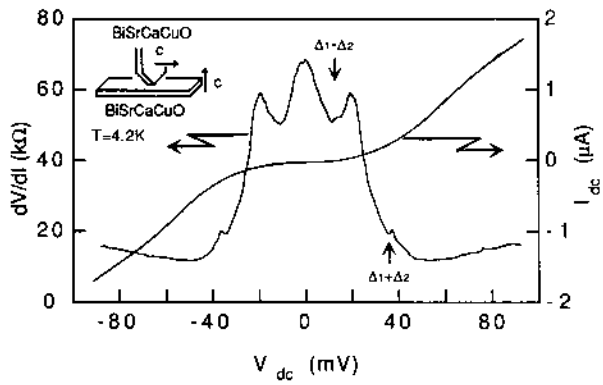
Fig. 1 shows the dV/dI characteristics of an SIN junction at 4.2K, formed between a normal indium tip and a $Bi_2Sr_2CaCu_2O_8$ ab plane "edge" exposed by cleanly breaking a crystal along a plane parallel to the c-axis. The direction of electron tunneling is presumably along the a-b plane. At low bias 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 ±20mV. We associate this feature with the superconducting energy gap. If we take the local conductivity maximum as the value of the gap, then Δ_{ab}=22.5meV 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 $Bi_2Sr_2CaCu_2O_8$. The arrows identify Δ_{ab}. The inset shows the temperature dependence of Δ_{ab}; the solid line is the BCS gap.



2. I-V characteristics of a-b plane Josephson-like break junction in $Bi_2Sr_2CaCu_2O_8$. The arrows identify the maximum slope at $2\Delta_{ab}$=45meV.



3. "Differential" SIS tunneling between two orthogonal $Bi_2Sr_2CaCu_2O_8$ crystals. The vertical arrows identify the sum and difference gaps, $\Delta_{ab}+\Delta_c$ and $\Delta_{ab}-\Delta_c$.

line is the BCS gap, fit to the T=4.2K and T=76k data points. The fit suggests $\Delta_{ab}(T=0)$=22.5meV 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 $2\Delta_{ab}(T=0)/k_BT_c$=6.2±0.3.

To confirm the above value of Δ_{ab} and to further test the reliability of SIS tunnel junctions formed using $Bi_2Sr_2CaCu_2O_8$ 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 insure 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 SIS 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 Δ_{ab}=22.5meV, 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 $Bi_2Sr_2CaCu_2O_8$ 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 thus of the S_1-I-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 $\Delta_{ab}+\Delta_c$=35meV and $\Delta_{ab}-\Delta_c$=11meV. Solving for Δ_{ab} and Δ_c gives Δ_{ab}=23meV and Δ_c=12meV. The value for Δ_{ab} is in good agreement with that determined above, 22.5meV. Again with T_c=85K, we find $2\Delta_c/k_BT_c$=3.3±0.3. These measurements suggest an energy gap anisotropy in $Bi_2Sr_2CaCu_2O_8$ 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[17], 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 4.2K local conductivity maxima at 25mV and 46.2mV. Interpreting these features in terms of SIS tunneling implies gap values of 12.5meV and 23.1meV. The lower value corresponds well to the previously identified Δ_c, while the larger value is close to Δ_{ab}.

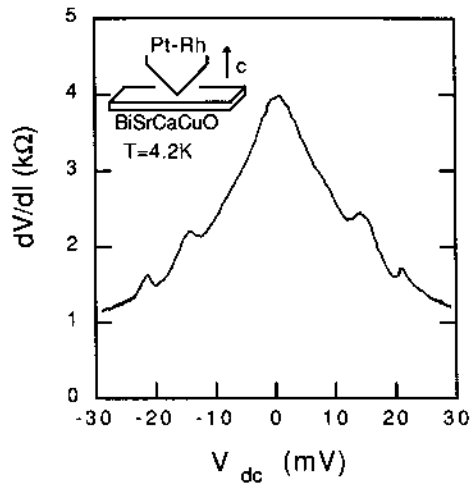
Fig. 4 shows similar "double gap" features in a point contact SIN measurement made by tunneling from a normal Pt/Rh tip into the c-axis direction of a freshly cleaved $Bi_2Sr_2CaCu_2O_8$ crystal. Here structure is observed at 12mV and 20mV. The former value again corresponds to our assumed Δ_c, while the later value is comparable to (but slightly less than) Δ_{ab}. 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 $Bi_2Sr_2CaCu_2O_8$ 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, $2\Delta_{ab}/k_BT_c$~6-7. This a-b plane value is in accord with several previous tunneling measurements, and is also consistent with that determined by recent high resolution photoemission studies[15] where (for incident photon E-field in the a-b plane) it was found $2\Delta/k_BT_c$=8±1.4. The observed ratios are far in excess of the expected BCS (weak coupling) result[18]

$$2\Delta_o/k_BT_c=3.5 \qquad (1)$$

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 $Bi_2Sr_2CaCu_2O_8$ is in accord with Eq. (1).

From the extreme structural and electrical anisotropy[19] of $Bi_2Sr_2CaCu_2O_8$, it is not unreasonable to expect some energy gap anisotropy. One (highly oversimplified) picture of $Bi_2Sr_2CaCu_2O_8$ 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 $Bi_2Sr_2CaCu_2O_8$ is known to cleave along the Bi-O layers, a c-axis



4. NIS tunneling into the c-axis of $Bi_2Sr_2CaCu_2O_8$. Two gap structures are observed.

tunneling measurement would invariable 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 $YBa_2Cu_3O_7$, the normal state electrical anisotropy[20] is significantly less than that[19] in $Bi_2Sr_2CaCu_2O_8$. Although reliable single crystal anisotropic tunneling data do not exist for $YBa_2Cu_3O_7$, Tsai et al[10] have tunneled into clean edges of preferentially oriented films, and find $2\Delta_{ab}/k_BT_c$~6.1 and $2\Delta_c/k_BT_c$~3.6. Hence the implied gap anisotropy in that material is comparable to that suggested for $Bi_2Sr_2CaCu_2O_8$. 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 $Bi_2Sr_2CaCu_2O_8$ 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 Δ agrees well with the BCS curve (or mean field theory in general), but the largest gap value is $2\Delta_{ab}/k_BT_c$~6.3, a ratio significantly greater than that expected from BCS theory.

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