Observation of *a-b* Plane Gap Anisotropy in $Bi_2Sr_2CaCu_2O_8$ with a Low Temperature Scanning Tunneling Microscope

Jeffrey Kane, Qun Chen, and K.-W. Ng
Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055

H.-J. Tao
Institute of Physics, Chinese Academy of Sciences, P.O. Box 603, Beijing, China
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Significant gap anisotropy within the *a-b* plane of $Bi_2Sr_2CaCu_2O_8$ has been observed with a low temperature scanning tunneling microscope. The energy gap is largest along the *a*-axis direction, with $\Delta_{p\text{-}p}=36.6$ meV and decreases gradually to a value of 23 meV along the direction 45° from the *a* axis. The tunneling data have been fit well using a simple model which assumes a *d*-wave-pairing energy gap, and allows tunneling in all directions close to the normal of the surface.

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Energy gap anisotropy in the high T_c cuprate superconductors, particularly in the *a-b* plane, can have serious implications about the quasiparticle pairing mechanisms [1,2]. For instance, *d*-wave pairing requires the existence of nodal lines at which directions the superconductivity is gapless. Although nodal lines are more reliably detected by phase sensitive techniques, angular resolved measurements of the energy gap should provide their signature if they exist. Furthermore, knowledge of the exact gap symmetry with respect to the crystal structure is crucial to the understanding of the origin of the pairing mechanism. To date, the study of gap anisotropy within the *a-b* plane has been limited to angular resolved photoemission experiments. One of these experiments has provided evidence of *d*-wave pairing in $Bi_2Sr_2CaCu_2O_8$ (Bi2212), with the gapless direction along the axis of the unit cell [3]. So far, no tunneling experiments which investigate in-plane gap anisotropy have been reported. Tunneling should provide more reliable results because of its higher energy resolution, and more importantly, its direct measurement of the quasiparticle density of states (DOS). Our earlier experiments [4] and research work from other groups [5–8] have demonstrated that tunneling techniques can be effectively used to study the gap anisotropy in the *c* axis and *a-b*-plane directions. In this Letter, we report results from a sequence of tunneling experiments in which we have examined the angular dependence of the DOS within the *a-b* plane in Bi2212 using a low temperature scanning tunneling microscope (STM).

The sample of single crystal Bi2212 used in our experiments was prepared by methods reported by Mitzi *et al.* [9]. The critical temperature for the samples we used was measured to be 85 K. The cell constants were determined by x-ray diffraction to be 5.3995, 5.4572, and 30.7236 Å, in good agreement with Sunshine *et al.* [10]. Samples of size $\simeq 2$ mm $\times$ 1 mm $\times$ 0.1 mm were carefully selected from a batch of single crystals for smooth and uniform surfaces. Crystal orientation was determined by x-ray diffraction. First the *c* axis was determined using an optical goniometer. Then reflections and their intensities were matched to predicted values to determine the directions of the *a* and *b* axis so that angle-resolved tunneling spectroscopy could be performed. The tunneling direction is measured as angle Θ from the *a* axis, as shown in the inset of Fig. 1.

The STM functioned in a vacuum chamber immersed in liquid helium. In its regular operation mode, the tip at the top of the piezoelectric tube is pointing upward. Since the samples were very thin, it was difficult for the tip to locate the sample edge. Therefore, we replaced the vertical tip of the STM with a horizontal length of Pt-Ir wire. Samples were transferred from room temperature to the STM at liquid helium temperature, and the sample edge is always perpendicular to the wire once it is locked in the STM.

The Bi2212 sample was mechanically cut in air with surgical quality blades to expose edges at different angles for tunneling. The sample was mounted on a rotary sta-

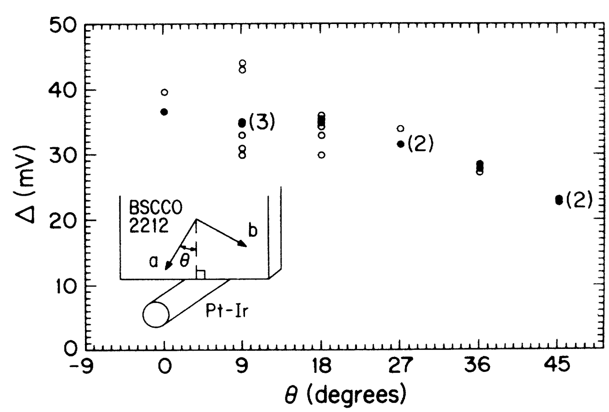

FIG. 1. Plot of all experimental $\Delta_{p\text{-}p}$ values versus tunneling direction. The number shown is the number of different junctions with the same $\Delta_{p\text{-}p}$. Solid points are the data used for further analysis, and their conductance curves are shown in Fig. 2. The inset shows the configuration of the junction.

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tion for precision cutting, with an accuracy of about 1°. We have previously studied similar edges with scanning electron microscopy and observed that straight and smooth edges can easily be obtained by this method without destroying the layered structure. The reactivity of these freshly cut edges when exposed to air is not well characterized yet. However, these edges have been studied by other researchers with STM in air, and atomic resolution images have been obtained with alternating Cu-O and Bi-O layers [11]. Furthermore, the Cu-O layers were shown to be metallic even when the measurement was performed in ambient atmosphere. Together with the consistency in the energy gap values measured in the various directions, we believe these edges should be considered as stable as the cleaved *a*-*b*-plane surfaces with brief exposure to air. The sample in the present experiment was cut six times, the first to expose the surface perpendicular to the *a* axis. Five successive cuts allowed us to measure the tunneling current at $\Theta = 0°$, 9°, 18°, 27°, 36°, and 45° with respect to the *a* axis. The process of cutting and the quality of each new edge were carefully monitored under a microscope, and the sample was then immediately transferred to the STM at low temperatures. We cautiously approached the sample towards the Pt-Ir wire to avoid crash and subsequent surface damage, and the junction resistance remained sensitive to the longitudinal motion of the piezoelectric tube throughout the experiment.

$\Delta_{p\text{-}p}$ was determined by the peak to peak separation in the conductance curve divided by 2. For the same tunneling angle, we measured several different junctions by withdrawal then reapproach, or by repositioning the junction using the piezoelectric tube. Figure 1 summarizes values of $\Delta_{p\text{-}p}$ we obtained from all these measurements. Gap values observed are consistent with the values of 30 to 40 meV widely reported by other tunneling measurements [12,13]. $\Delta_{p\text{-}p}$ measurements from the same Θ varied slightly due to differences in tunneling conditions, such as the depairing term Γ and the angular sampling range. Despite such an uncertainty in $\Delta_{p\text{-}p}$, it can be seen that the smallest peak to peak gap values occur at 45°, and gradually increase towards a maximum at 0°. Although no particular direction shows definite evidence of a nodal line, the gap anisotropy within the *a*-*b* plane is clearly evident. It is not clear why there is a 45° difference in the direction of maximum energy gap between our data and that of the recent photoemission experiment [3]. However, this photoemission experiment is in contradiction to another earlier photoemission report in which a significant energy gap is observed along the *a* axis [14]. Moreover, the results we present here are consistent with data we obtained from earlier experiments [15] in which only two to three different angles close to each other could be measured on the same piece of sample. The use of a superconductor as counterelectrode in those experiments also caused difficulty in analyzing the data. Nevertheless, it was quite clear that the largest $\Delta_{p\text{-}p}$ occurred along the *a* and *b* axes.

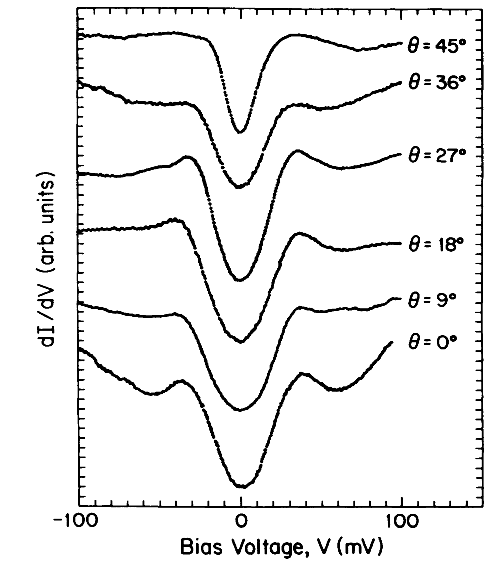

FIG. 2. Actual conductance curves at six different angles. A widening of the energy gap can be seen as the tunneling direction approaches the *a* axis. The curves are more severely smeared at angles close to 45°.

It is interesting to note that the depression in the DOS next to the gap opening commonly observed by tunneling [16] and photoemission [17] experiments does not appear in the data of the present experiment. Although the origin of this depression is not well understood, it is in general believed that the feature is intrinsic to cuprate high T_c materials [18]. This is consistent with the argument that the dip can only be observed as a pronounced feature in high T_c to high T_c tunneling, and is obscured in high T_c superconductor to normal metal tunneling [16]. It is also important to point out that none of our data exhibit the linear background observed by many other tunneling experiments [19]. It is likely that such a background is a characteristic of tunneling in the *c*-axis direction [20].

As shown by our data $\Delta_{p\text{-}p}$ is not a perfect indicator of gap anisotropy because different physical parameters can change its value, even when the tunneling angle is the same. The proper way to analyze the results is to compare the data with theoretical curves generated by assuming a certain angular dependence of the energy gap. It has been proposed that the difference between tunneling and far infrared measurements could be qualitatively explained by assuming a different energy gap in the *c* axis and *a*-*b*-plane directions [21]. Our data suggest that gap anisotropy within the *a*-*b* plane must also be considered in any thorough analysis of Bi2212.

Although our analysis covers the full set of data, we select one curve from each angle for our discussion here. These curves were chosen because their $\Delta_{p\text{-}p}$ values vary smoothly with Θ (Fig. 1). This will ease our understanding of the fitting parameters. The conductance curves are shown in Fig. 2. With V as the bias voltage on the tip

TABLE I. The physical parameters used to generate theoretical curves in Fig. 3. The first two columns are the nominal angle and the measured $\Delta_{p\text{-}p}$.

Θ (deg)	$\Delta_{p\text{-}p}$ (meV)	$\Theta_{\rm fit}$ (deg)	Δ_0 (meV)	k_f (π/a)	β	Γ (meV)
0	36.6	2.0	89.0	0.65	20.1	7.1
9	35.0	9.1	90.0	0.55	20.0	7.5
18	35.5	19.0	90.0	0.66	20.2	6.8
27	31.6	27.0	89.7	0.66	20.0	6.7
36	28.5	35.9	90.0	0.65	20.0	6.8
45	23.0	40.1	91.0	0.68	18.0	5.7

with respect to the sample, many of these curves are not symmetric about the zero bias. This is more pronounced in the present experiment because the junction does not have a symmetrical configuration. As a result, we can only fit half of the curve at a time. With k_x and k_y along the a and b axes, we assume the angular dependence of energy gap to be of the form

$$\Delta(\theta) = \Delta_0(\cos k_x a - \cos k_y a) .$$

Such a functional form was chosen because of its d-wave symmetry which allows us to investigate how an assumed nodal line would appear in a tunneling experiment with limited angular resolution.

Electrons predominantly tunnel in the direction perpendicular to a surface. Since the tunneling probability depends on the component of the kinetic energy perpendicular to the barrier, the tunneling current decays exponentially as $\exp(-\beta\sin^2\phi)$, where ϕ is the angle between the tunneling electron and the normal to the barrier [22]. β depends on the work function of the material, and also on the distance between the sample and the Pt-Ir wire. It appears to be small in the Bi2212 material we used in this experiment, which reduces the angular resolution of the measurement. With a value of $\beta=20$, the tunneling probability will decrease by a factor of e^{-1} at $\phi=13°$. The tunneling conductance curve can then be generated by summing the density of states from different directions multiplied by the appropriate exponential weighting factor. To account for the smearing of data, the theoretical curve $(dI/dV)_{i,\Gamma=0}$ is broadened by a Gaussian distribution with all the depairing effects included in the deviation (Γ) of the function:

$$\left(\frac{dI}{dV}\right)_{j,\Gamma} = \sum_{i=1}^{N} \left(\frac{dI}{dV}\right)_{i,\Gamma=0} \frac{1}{\sqrt{2\pi}\Gamma} e^{-(V_j-V_i)^2/2\Gamma^2} \Delta V .$$

The model is relatively insensitive to the type of singularity in the DOS because of this broadening effect. The theoretical curve is then multiplied by a parabolic background term and shifted vertically for the best match with experimental data.

Table I summarizes the values of physical parameters we used for the best fittings. Since β depends only slightly on the tunneling distance, it remains roughly constant

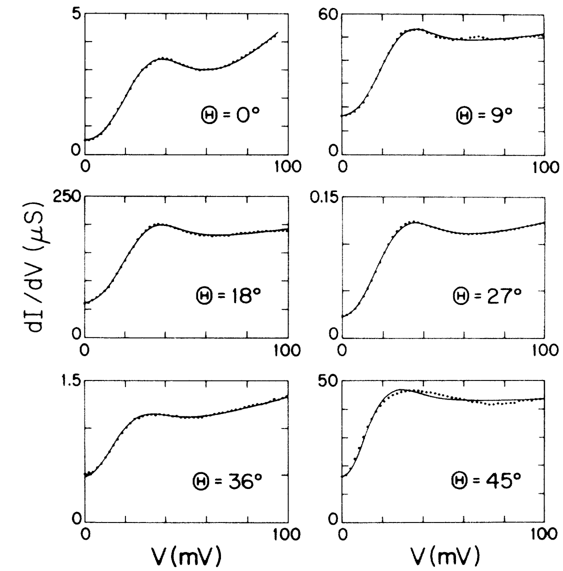

FIG. 3. Fitting of the original data using the procedure discussed in the text. The same procedure can be applied to other data not presented in this Letter. The least satisfactory fitting occurs at $\Theta=45°$. Peak features appear even if a nodal line is assumed in this direction.

at 20 in all of the six curves. This also demonstrates that the tunneling conditions for different junctions are actually quite similar. This value of β is smaller than values from junctions of conventional materials [22]. This may be due to a lowering in the work function on Bi2212 surfaces and may partly explain why parabolic backgrounds are commonly observed in high T_c tunneling spectroscopy [23]. The parabolic background has no systematic variation with other junction properties and bears no physical importance related to this Letter. The depairing term Γ fluctuates between 5.7 and 7.5 meV. These values of Γ are consistent with those from other tunneling measurements [12] on high T_c superconductors, but are significantly larger than values from similar measurements on $NbSe_2$ [24]. This large depairing energy may be intrinsically related to the inelastic scattering of electrons, in agreement with the observation that $2\Delta/kT_c$ for Bi2212 is much larger than the BCS value of 3.5 [25]. Experimentally, we should not ignore the role of surface impurities which can also produce smearing effects because of the short coherence length of high T_c materials. Although the Fermi surface in this material is quite complex [26], it is surprising to find that the k_f used in this simple model varies only slightly between 0.65 and $0.68\pi/a$. The only exception occurred at $\Theta=9°$ ($k_f=0.55\pi/a$). All curves can be fit consistent with Δ_0 nearly constant at about 90 meV. Note that Δ_0 is a fitting parameter and should not be confused with the observed gap value, $\Delta_{p\text{-}p}$. To demonstrate the consistency within the data, we also allow Θ to vary for the best fit. In any case, $\Theta_{\rm fit}$ is close to the nominal value at all angles.

The theoretical curves together with the original data at different angles are shown in Fig. 3. Some data points are removed from the figure for clarity. The general shape of the conductance curves match well, both inside and outside the gap region, with the theoretical curves. The fit depicted in these curves is greatly improved in comparison to curves generated using the BCS DOS with a single gap value. To our knowledge, this is the first comprehensive model which satisfactorily fits tunneling conductance curves of high T_c superconductors, and its applicability to other tunneling data should be examined. The fitting at $\Theta = 45°$ (corresponding to the direction with the smallest gap) has the largest deviation. This may be due to some unknown factors that appear more significantly as the gap value becomes small. Nevertheless, we have demonstrated that gap features should be observed by tunneling spectroscopy, even in the direction of nodal lines, due to sampling in nearby directions.

In conclusion, we have measured significant gap anisotropy in the high T_c superconductor Bi2212. We have observed consistently the decrease of the energy gap from $\Theta = 0°$ to 45° and conclude that the maximum energy gap occurs along the a and b axes. There is no direct evidence of a gapless direction, however, we cannot ignore the possibility of a nodal line because of the intrinsic limitation in angular resolution. As an example, we have demonstrated that an energy gap with a d-wave symmetry can fit the data extraordinarily well. This shows that the extra density of states within the gap region in tunneling spectroscopy can be satisfactorily explained by the effect of gap anisotropy. High T_c to high T_c tunneling may help to improve the angular resolution slightly and the results we present here will provide a basic understanding for this type of more complicated experiment.

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