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TITLE: **SPECTRAL WEIGHT CHANGES AT THE SUPERCONDUCTING TRANSITION OF $Bi_2Sr_2CaCuO_{8+}$Delta**

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Summary

" Spectral Weight Changes at the Superconducting Transition of $Bi_2Sr_2CaCu_2O_{8+\delta}$"

Daniel S. Dessau, Zixun Shen, Barret O. Wells, William E. Spicer, Aloysius J. Arko

An overview of our gap studies in high-Tc superconductors is presented for the workshop on Fermiology of high-Tc's.The work is centered on the study of single crystal $Bi_2Sr_2CaCu_2O_{8+\delta}$. In a conventional BCS suprconductor, a superconducting gap Δ is formed when the near Frmi edge electrons condense to form Cooper pairs at low temperatures. As the material goes superconducting the density of states is modified such that the spectral intensity in the region from the Fermi energy down to an energy Δ is transferred to a region just below Δ. While this spectral weight transfer has in the past been studied with tunneling spectroscopy, the size of the gap as well as improvements in our instrument resolution allow us now to study it with photoelectron spectroscopy. We have found that as the sample goes superconducting, not only is there spectral weight transfer from the gap region as in BCS theory, but along the Γ-M direction there is also some spectral weight transfer from higher binding energies resulting in a dspectral dip at about -90 meV relative to E_F. The total spectral weight decreases along the Γ-M direction, but actually increases along the Γ-X direction. This temperature dependent spectral transfer is dicussed in terms of 1) a two to three dimensional phase transition from RVB theory; 2) a manifestation of the electron-boson interaction in the form of α^2F oscillations; and 3) conformity with the theory of Van Hove singularities. The latter are particularly attractive in that there are several other observations possibly explained by them: 1) the observation that the magnitude of the gap is anisotropic in the a-b plane; 2) the observation that for overdoped samples the magnitude of D appears to fall off faster than Tc.

Workshop on Fermiology
of High Tc Superconductors
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SPECTRAL WEIGHT CHANGES AT THE SUPERCONDUCTING TRANSITION OF $Bi_2Sr_2CaCu_2O_{8+\delta}$

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Abstract -- We overview our recent angle-resolved photoemission studies of the spectral weight changes that occur at the superconducting transition of $Bi_2Sr_2CaCu_2O_{8+\delta}$. We have found that (1) as the sample goes superconducting, not only is there spectral weight transfer from the gap region to the pile-up as in BCS theory, but along the Γ-$\overline{M}$ direction there is also some spectral weight transfer from higher binding energies in the form of a dip, (2) at the superconducting transition there is a decrease (increase) in the occupied spectral weight for the spectra taken along Γ-$\overline{M}$ (Γ-X), (3) the magnitude of the superconducting energy gap appears to be anisotropic in the $\mathbf{k}_{xy}$ plane, and (4) for the overdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples that we studied the gap Δ appears to fall off much more rapidly with doping than does the T_C. Recent theoretical attempts to understand our data are briefly reviewed.

Keywords: high temperature superconductivity, superconducting energy gaps, doping behavior, angle-resolved photoemission spectroscopy,

INTRODUCTION -- In the BCS theory for traditional superconductors the electron Fermi sea is unstable to attractive interactions mediated by phonons. A superconducting gap is formed when the near Fermi edge electrons condense to form pairs at low temperatures. As illustrated in figure 1, the spectral intensity in the region from the Fermi energy to an energy Δ is lost at the transition to superconductivity. This spectral weight is transferred to a region just below the gap (higher binding energy) and thus there is a pile-up of intensity in this region. Such spectral weight changes have traditionally been studied with tunneling spectroscopy. The application of tunneling spectroscopy to the study of the high temperature superconductors has been quite difficult however, due in a large part to the difficulty of preparing very clean and abrupt interfacial junctions. In this paper we will report on studies of the spectral weight changes in the high temperature superconductors observed by angle resolved photoemission spectroscopy (ARPES), which gives us information similar to that obtained by tunneling (they both are measurements of the spectral weight function) with the very important advantage that by constraining the photoelectron's emission angle relative to the sample surface one constrains the **k** value of the initial state. Thus with ARPES we can study the spectral weight changes that occur at the superconducting transition at different locations in the Brillioun zone.

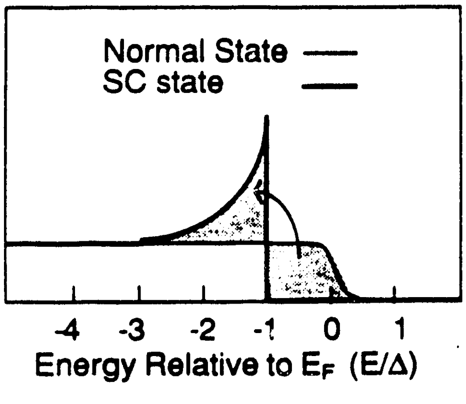

Fig 1. Schematic of effect of a BCS gap Δ on the density of states

In our ARPES studies of single crystalline samples of $Bi_2Sr_2CaCu_2O_{8+\delta}$ we have found spectral weight changes which do not appear consistent with those predicted by the BCS theory, and we find that these changes are anisotropic in the $\mathbf{k}_{xy}$ plane of the Brillioun zone. In particular we have found that not only is weight transferred from the "gap" region to the pileup as is illustrated in figure 1, but also spectral weight appears to be transferred from higher binding energies in the form of a "dip" which forms at the superconducting transition temperature. The presence of this dip is anisotropic in **k**-space; it is quite strong for the spectra taken along the Γ-$\overline{M}$ zone diagonal but is weak or not present for the spectra taken along the zone edge Γ-X. In addition we note that there may be unusual occupied spectral weight changes (the weight in the pileup does not equal the weight lost from other regions) and that the magnitude of the gap appears to be anisotropic in the $\mathbf{k}_{xy}$ plane of the Brillioun zone. These effects are reproducible and strongly dependent upon the doping level of the $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples.

EXPERIMENTAL DETAILS -- Very high quality single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ were grown by the directional solidification technique. The crystals studied in this report were annealed in either a 0.1% H_2 in Ar gas mixture at 450°C to raise T_c to 91K as determined by low field magnetic susceptibility measurements, or in 12 atm of O_2 at 540°C to lower the T_c to 79K. Details of the sample preparation process and characterization are available elsewhere[1]. Single crystals of the material of about 1.5 mm x 1.5 mm x 0.1mm were epoxyed to sample holders that were screwed into our cryostat. Top posts were epoxyed to the sample surface. The crystals were cleaved in a vacuum of 1×10^{-10} torr at approximately 10K by knocking off the top post. Photoemission spectra were recorded by a hemispherical electron energy analyzer mounted on a goniometer inside the vacuum chamber. The analyzer acceptance angle was either ± 1° or ± 4°. Photons of energy 18-22 eV were provided by the Ames/Montana Erg/Seya at the Wisconsin Synchrotron Radiation Center and by a He discharge lamp. The total system energy resolution varied between approximately 30 to 40 meV as determined by the 10-90% transition of a Au Fermi edge measured at 10 K. The Fermi energy was frequently monitored by measuring a Au film deposited on the cryostat beside the sample.

It is very important to realize that in the analysis and presentation of our data we have been forced to employ certain normalization procedures so as to compare spectra taken at different temperatures, angles and times. This is unavoidable due to drifts in the signal intensity which arise from a number of sources, primarily including instabilities in the photon beam and movement of the sample relative to the photon beam due to thermal expansions and contractions as the sample temperature is varied. The normalization procedure that we have found to work most consistently and which we have employed in the work presented here follows: For a comparison of normal state spectra taken at different angles (for instance to measure the dispersion of a feature) we have normalized the intensities so that each curve has the same intensity for energies above the Fermi energy E_F. [see footnote 2] After such a procedure is carried out on the normal state spectra, the spectra in the superconducting state are normalized so that the normal and superconducting state spectra line up for energies < -.2 eV. This represents a correction to the above normalization procedure of no more than 10%. The fact that the normal and superconducting state spectra are typically very parallel for energies < -.2 eV gives us confidence that this is a reasonable normalization procedure.

RESULTS -- Earlier angle resolved photoemission experiments on $Bi_2Sr_2CaCu_2O_{8+\delta}$ have clearly observed dispersive features which cross the Fermi level at approximately the angles predicted by band theory. [3-6] It is near these angles, where there is spectral strength at the Fermi level, that the effects of the superconducting gap can be seen. Therefore that is the general region where we have concentrated our studies. Figure 2 shows temperature dependent [7] near Fermi edge photoemission spectra on a H_2 reduced $Bi_2Sr_2CaCu_2O_{8+\delta}$ sample at 21° (± 4°) along Γ-$\overline{M}$ (near the $\overline{M}$ point) and at 15° (± 4°) along Γ-X. For orientation, we show as the inset to the figure the Fermi surface as calculated by Freeman et al using the LDA approach. [8] The spectra have been normalized by the method discussed in the above section. As the sample temperature is lowered through its superconducting transition temperature (91K) very dramatic spectral lineshape changes are observed. As expected by conventional pairing theories, spectral weight is transferred (for both k-space locations) from the gap region (approximately 0 to -20 meV) to a pile-up peak at about -45 meV. However, at 21° along Γ-$\overline{M}$ spectral weight is also depleted from a region centered at approximately 90 meV below the Fermi level. We note that the dip-like feature at -90 meV appears only below T_c and then increases in strength as the sample temperature is further low-

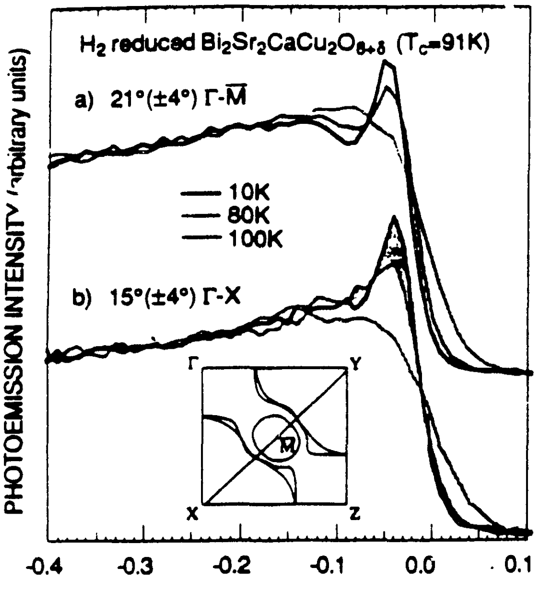

Fig 2. Angle resolved photoemission spectra taken at three different temperatures near the Fermi surface (a) along Γ-$\overline{M}$ and (b) along Γ-X. The spectra have been normalized to equal intensities for energies less than -.2 eV. The inset shows a calculated Fermi surface from ref 8.

ered. It is not present at temperatures only slightly above T_C, and so we conclude that it is most likely directly related to the sample going superconducting. This dip-like feature is very weak or not present in the spectra taken at 15° along Γ-X. These results have been reproduced on a large number of $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples, all of which gave qualitatively similar results.

There is quite a bit more information present in figure 2. However, before we discuss any of that we instead choose to focus on the high binding energy dip that appears in the spectra along Γ-$\bar{M}$ at the superconducting transition. The simplest explanation for the appearance of this dip is that there are two bands in close proximity to each other along Γ-$\bar{M}$, and by coincidence they superimpose to form one feature in the normal state. As the temperature is lowered, one or both of these bands sharpen up (due perhaps to reduced lifetime broadening as a result of decreased electron-electron scattering in the superconducting state) and the dip appears between them. It is difficult to definitively rule out such a scenario, particularly with data at only a few points in **k**-space. With data available at many points in **k**-space we can make a much better informed judgement as to the origin of such a feature. The data which we will present next does not appear to support the simple two-band explanation of the dip, and implies that the dip is more likely an intrinsic spectral feature of the superconducting state.

Figure 3 shows normal state dispersion data taken along the Γ-$\bar{M}$ high symmetry direction with higher angular resolution (± 1) than the data of figure 2. We observe a feature starting some 200 meV below the Fermi level and then dispersing upwards towards the Fermi level as the electron emission-angle (and hence the **k** value) is changed from near the Γ point out to the $\bar{M}$ point. As Olson et. al. observed along the Γ-X and Γ-Y directions, the feature grows and sharpens up dramatically as it approaches the Fermi level. [3,4] This behavior has been interpreted as simply due to lifetime effects [4,9] and as evidence for very new physics [9,10]. At approximately 80% of the way out to $\bar{M}$, the intensity of the feature falls off rapidly, as if the feature is crossing through the Fermi level. [see footnote 11] It is important that for all of these curves *we always observe only one feature*. If two bands existed in this region it must be a great coincidence that they always superimpose to form one feature, for this feature is dispersing rapidly and being strongly modulated in intensity as we change the **k** value.

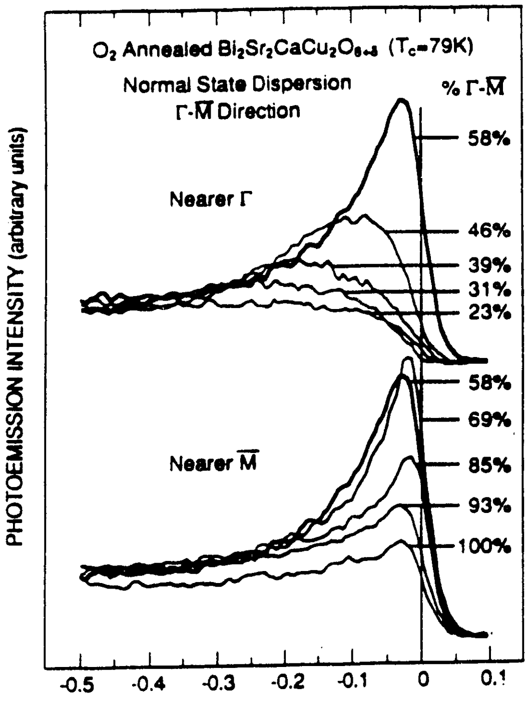

Fig 3. Normal state dispersion curves taken along Γ-$\bar{M}$. The photon energy was 19 eV and the angular resolution ±1° (±4% Γ-$\bar{M}$)

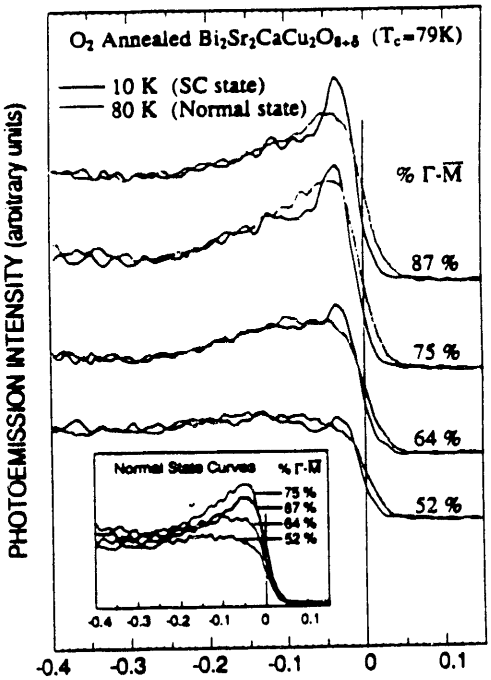

Fig 4. Temperature dependent data taken along Γ-$\bar{M}$ from a different T_c = 79 K sample than that shown in figure 3. The photon energy used was 21.2 eV and the angular resolution ±1° (±4% Γ-$\bar{M}$)

Figure 4 shows both normal and superconducting state spectra taken along Γ-$\overline{M}$ for a different sample than was shown in figure 3 (low temperature data was not available for that sample). The normal state spectra are stacked together in the inset to the figure. We see that the behavior of the normal state spectra is qualitatively similar to that observed in figure 3: the feature disperses towards E_F and grows in intensity as we move from Γ to $\overline{M}$, and then gets weaker as the feature apparently crosses through E_F.[12] We observe that the dip appears in the superconducting state over quite a large portion of the zone diagonal, including positions inside and outside the calculated location of the Bi-O electron "pocket" (the pocket is calculated to begin at approximately 75% of the way from Γ to $\overline{M}$). Thus it appears unlikely that the presence of the dip is directly due to the presence of the Bi-O electron pocket (see footnote 11), or to a superposition of bands from the Bi-O pocket and from the underlying Cu-O states. With the combination of the data shown in figures 3 and 4, the simple explanation of two bands in the normal state which by coincidence superimpose to appear as one seems to be unlikely, though we can not definitively rule it out. We feel instead that the dip is most likely an intrinsic feature of the superconducting state of $Bi_2Sr_2CaCu_2O_{8+\delta}$ and may even be one of the keys to our understanding of the mechanism of the high temperature superconductivity. We feel that it therefore deserves concerted theoretical as well as experimental attention.

As we mentioned in the beginning of this paper, both photoemission and tunneling spectroscopies are measurements of the spectral weight function of a material. Thus if the high binding energy dip that we are seeing in the low temperature photoemission spectrum is truly an intrinsic feature of the superconducting state, then one would also expect to observe it with tunneling spectroscopy. Unfortunately, the wide variability of reported tunneling results has not yet enabled us to reach a consensus on what is the intrinsic tunneling spectrum of the high temperature superconductors. Our best option is therefore to use the tunneling results from conventional superconductors as guidance and look for consistencies between different tunneling measurements on high T_c superconductors. We feel that the recent work of Mandrus et. al. stands out as especially interesting.[13] They formed ab-plane break junctions of single crystalline $Bi_2Sr_2CaCu_2O_{8+\delta}$ in vacuum and found a clear gap region and corresponding strong pile-up in addition to very low zero-bias tunneling current, symmetric behavior around the zero voltage bias, and essentially flat behavior at high bias. These aspects to the data are what one would expect to see in an "ideal" tunnel junction, though the combination of all these features has not to our knowledge been observed before in the tunneling spectra of a hign T_c superconductor. Thus we feel that the tunneling spectra presented by Mandrus et. al. is especially interesting and must be taken very seriously. It is thus significant that Mandrus et. al.'s data shows a high binding energy dip very reminiscent of the high binding energy dip of our Γ-$\overline{M}$ data. Other tunneling studies including the very nice work of Gurvitch et. al. on $YBa_2Cu_3O_{7-\delta}$ films [14] also show a dip at high binding energies, though all of the aspects of the "ideal" tunneling spectra mentioned above are not present in these earlier measurements. Thus it appears that both the photoemission and the tunneling are qualitatively in agreement about the presence of a high binding energy dip in the spectral weight function of the superconducting state, though of course the tunneling can not give us any information about its **k** dependence.

We next point out some other very interesting aspects of the data presented in figures 2 and 4. The first of these is that the amount of spectral weight that we gain in the pileup peak does not appear to be equal to the weight that we lose from other regions (the gap plus dip). It is clear from figure 2 that along Γ-X we gain more weight in the pileup, while along Γ-$\overline{M}$ we gain less weight. This is a very interesting result, though experimental complications may play a roll in these effects and so must be considered. The most obvious of these complications is that we have been forced to impose a normalization procedure on our data to compare the normal and superconducting state spectra. The normalization procedures that we have used have already been discussed, though they are by no means unique. Other possible complications are final state or matrix element effects and the possibility that spectral weight has been transferred to the unoccupied states. This last point is especially important since the sum rule that one expects to hold for a k-resolved experiment such as angle resolved photoemission extends over both the occupied and the unoccupied states. Thus any mechanism which transfers weight to or from the unoccupied states will have the effect of altering the weight in the photoemission spectrum.

One mechanism that may have an effect on our data is the act of the Fermi function cutting off a broadened (by for instance lifetime effects) peak. It is clear from the normal state dispersion studies taken from our group and elsewhere [3,4,6] that as the "band" approaches and then crosses the Fermi level, the intensity of the feature weakens as if being cut off by a Fermi function. The amount of weight cut off by the Fermi function could clearly be quite different in the normal and superconducting states. The "coherence factors" that describe the amount of electron-like and hole-like character of the quasiparticle excitations as described by the Bogoliubov transformation of a BCS-like theory may also be important. [15]

Because both the Fermi function cutoff and the coherence factors are dependent on the normal state band position, intuition can be gained by the analysis of a set of high angular resolution temperature dependent data with a fairly wide range of **k** values. Our Γ-$\overline{M}$ data of figure 4 shows a loss of spectral weight in the superconducting state for all **k** values taken. We don't have comparable temperature dependent data along Γ-X, although Olson et. al. have published some data that looks qualitatively similar to our Γ-X data, but with temperature dependence taken for a wide range of **k** values.[3] If we impose the normalization procedures used in this paper on the data of Olson et. al. we find that for all **k** values there is a gain in the spectral weight as the sample goes superconducting (though the magnitude of the gain depends on **k**). Thus the trends in the overall spectral weight transfer that we have observed in figure 2 appear to hold for a wide range of **k** values.

The final aspect of our data that we would like to call attention to is that the superconducting gap values that we infer from our data appear anisotropic in the $\mathbf{k}_{xy}$ plane with larger gaps along the Γ-M direction than along Γ-X. Figure 5 shows the low temperature (10K) data of figure 2 replotted and renormalized for easy comparison. We immediately notice that the edge in the superconducting state is pushed back significantly farther from the Fermi level in the Γ-$\overline{M}$ data than in the Γ-X data. This is our first indication that the superconducting gap may be anisotropic in the $\mathbf{k}_{xy}$ plane with a larger gap along Γ-$\overline{M}$ than along Γ-X. However, as we will discuss below, there are complications to the interpretation of the data that must be considered before this can be taken as conclusive evidence for a truly anisotropic gap in the $\mathbf{k}_{xy}$ plane. These complications have to do with both the angle-resolved nature and the surface sensitivity of the experiments, as well as the crystal structure of the $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples.

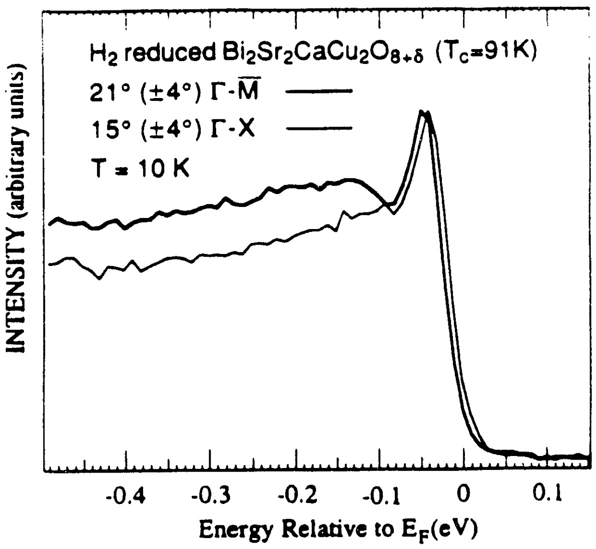

Fig 5. The Superconducting state data from fig 2 renormalized for easy comparison

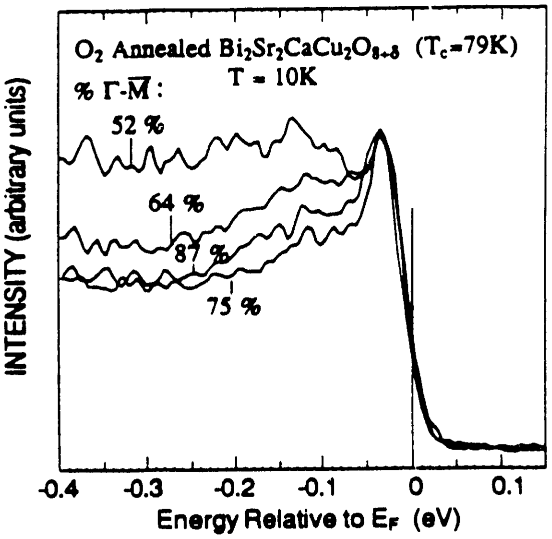

Fig 6. Data from fig 4 rescaled to highlight emission onset

In a BCS type of pairing theory, the quasiparticle excitations of the superconducting state have an energy $E_k = \sqrt{\varepsilon_k^2+\Delta^2}$ where ε_k is the normal state band energy relative to the Fermi level E_F. Thus the quasiparticle excitation energy is at a minimum equal to the "gap" Δ when $\varepsilon_k = 0$ or the normal state band is at the Fermi level. For ε_k small but nonzero, $E_k > \Delta$ and the edge of the spectra taken in the superconducting state will be pushed farther away from E_F than it would be if $\varepsilon_k = 0$. Thus the edge of the spectra of the superconducting state in an angle resolved experiment should be determined by E_k which may be considerably larger than Δ. This is one possible explanation why the edge has been pushed farther away from E_F for the spectra along Γ-$\overline{M}$ than along Γ-X. To see if this is the case we replot in figure 6 the superconducting state data from figure 4, with a new normalization chosen to highlight the position of the low energy edge. Figure 6 shows us the very surprising result that the edge of the spectra in the superconducting state is at the same energy regardless of the position ε_k of the normal state band. This is not what we would expect based on the above arguments, and may signal that the energy of the quasiparticle excitations can not be described so straightforwardly. This also tells us that most likely we are not overestimating the value of the gap Δ due to the position ε_k of the normal state band.

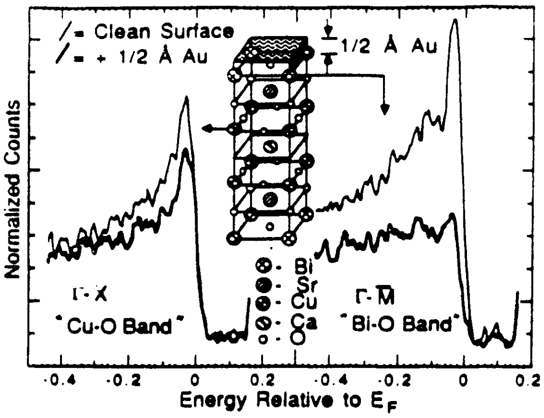

Fig 7. Photoemission spectra of the states at the Fermi level along both the Γ-X and Γ-$\overline{M}$ directions before and after deposition of 0.5 Å of Au. Spectra were taken at 20K with 19-eV photons and were normalized to incident photon flux.

We must also keep in mind the fact that photoemission is a very surface sensitive spectroscopy with probing depths significantly shorter than the size of the unit cell of $Bi_2Sr_2CaCu_2O_{8+\delta}$ perpendicular to the surface. This surface sensitivity can be both an advantage and a disadvantage to an experiment. Combined with the knowledge that the $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals cleave between the Bi-O planes, we have used the surface sensitivity to determine that the states along Γ-$\overline{M}$ have some Bi-O or surface-like character mixed in, as opposed to the states along Γ-X which appear to be solely Cu-O derived. This experiment was carried out by depositing a submonolayer thickness of gold on top of the cleaved $Bi_2Sr_2CaCu_2O_{8+\delta}$ surface. As shown in figure 7, the states along Γ-X were essentially unaffected by this deposition, whereas the states along Γ-$\overline{M}$ were severely altered. Thus we made the determination that the states along Γ-$\overline{M}$ had much more surface-like or Bi-O character than the states along Γ-X. [16] This finding is qualitatively consistent with the results of the band structure calculations [8], though of course it is does not tell us whether the Bi-O " electron pocket" actually exists. This experiment also should alert us to the possibility that the apparent gap size may be affected by surface effects or by differences in the character of the states along the different directions.

We have put some effort into quantifying the values of the superconducting gap Δ. This is a very difficult problem for a number of reasons. In addition to the lack of a generally accepted theoretical gap function for the high T_c superconductors upon which to base the fitting, the most obvious reasons are the complications discussed above dealing with the energy position ε_k of the normal state band, and the fact that the best presently attainable energy resolution for these experiments is roughly comparable to the gap size. The obvious solution is to use some type of fitting procedure, so that the experimental broadening can be accurately taken into account. The first step in such a procedure must be to accurately fit the normal state "bands", though the description of these bands is at the time still highly controversial. After a proper fit of these bands, taking into account the energy and angular broadening correctly, one can then embark upon fitting the superconducting state.

We have obtained some very preliminary results by assuming a BCS gap and using roughly the same fitting procedure described by Olson et. al. (3,4,17). These results are important in that they allow a direct comparison with what is currently in the literature, although the warnings of the preceding paragraph must be remembered. More realistic and detailed fitting procedures are underway in our lab. As described in ref 3, the fit we have used to produce an individual gap value involves using two spectra from one location in k-space from one sample, the first taken above the transition temperature and the second taken at the lowest achieved temperature. First we fit the normal state spectrum. We assumed a peak with a lorentzian shape, on a linear background, cut off by a Fermi function. This whole function was then convolved with a broadening function to account for experimental resolution. This function was a Gaussian for the He lamp data and a similar but asymmetric function for the data taken on the Montana/Ames Seya synchrotron beam line to account for the different broadening functions for the two photon sources. Once the normal state fit is deemed satisfactory, the only changes used to fit the superconducting state are that the Fermi function changes due to the decreased temperature and that the BCS superconducting density of states $\frac{E}{\sqrt{E^2-\Delta^2}}$ is multiplied by the normal state density of states before the energy broadening is convoluted in. The only fitting parameter for the superconducting state is thus the gap size. The fits that we obtain using this method are far from perfect, which is not at all surprising considering the fact that the spectra don't even qualitatively appear to follow BCS theory. Thus we chose the condition for best fit to be when the leading edge (emission onset) of the calculated and measured superconducting spectra most closely matched. Given the method outlined above we can fit most of the data with a precision of ± 2 meV.

Figure 8 shows one of our better fits, along the Γ-X direction. The fit is very good except that the pile up peak in the superconducting state is not large enough, typical of our Γ-X data. For the Γ-$\overline{M}$ data we can come close to fitting the pile up peak but cannot reproduce the dip feature. Preliminary gap values that we have obtained from our fitting efforts are summarized in table 1. Due to the above mentioned fitting problems, the exact numbers that we have obtained should not at this time be considered reliable. What we wish to call attention to however, are the trends that appear in the data. We notice that the magnitude of the gap appears to be anisotropic in **k** space, and that the ratio $2\Delta/k_BT_c$ is not only a function of **k** but of doping.

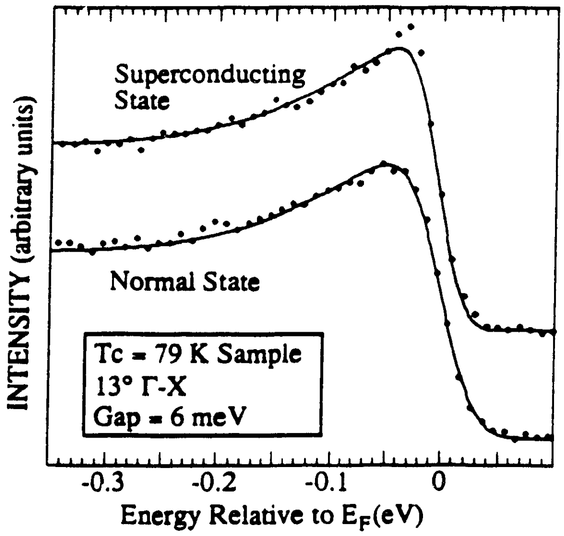

Figure 8. One of our better fits

meV / 2Δ / k_BT_c

k-Space Direction	Sample Type : T_c = 91K	T_c = 79K
Γ-M	27 / 6.9	14 / 4.1
Γ-X	15 / 3.8	6 / 1.8

Table 1. A summary of our fitting results

As we have mentioned previously, the result of the gap anisotropy contradicts the earlier reported result of Olson et. al.. [17] As far as we can tell the actual data is different for the two experiments. More work needs to be done to resolve these apparent discrepancies.

THEORETICAL IMPLICATIONS The data presented above has garnered a large amount of interest in the theoretical condensed matter physics community. We will very briefly review some of the theoretical ideas, beginning first with the question of the high binding energy dip.

Arnold, Mueller and Swihart feel that the dip may be related to the high energy (relative to the pileup peak) oscillations observed in the tunneling spectra of the strong coupling superconductors such as Pb and Nb. In these materials, the phonon spectrum $\alpha^2F(\omega)$ can be obtained from an inversion of the data using the Eliashburg equations. [18,19] Arnold et al have assumed that a similar inversion process on our photoemission data can give an effective $\alpha^2F(\omega)$ for the high temperature superconductors, whether or not phonons are responsible for the superconductivity. They claim good fits to our data along both Γ-$\overline{M}$ and Γ-X, T_c's that closely match the measured values and gap values in qualitative agreement to those we determined using the simpler weak coupling BCS model.[20]

P.W. Anderson has some very interesting ideas about the origin of the dip. He writes that due to the hopping matrix element connecting the two close Cu-O layers (or the Cu-O planes with the Bi-O planes) in $Bi_2Sr_2CaCu_2O_{8+\delta}$, there is a doubling of the calculated energy bands at general points in the two dimensional zone with a splitting of order .1 eV, though the splitting vanishes along the Γ-X symmetry direction. The fact that this splitting has not been observed in angle resolved photoemission is, he says, strong support for the 2-dimensionally correlated non-Fermi liquid theory of the normal state. In the superconducting state, the quasiparticle fermion-like nature of the electronic excitations is partially restored and the 3-dimensional band structure reappears. He thus ascribes the two features of the data along Γ-$\overline{M}$ (separated by the dip) to quasiparticle poles belonging to odd and even linear combinations of states at the same **k**, with the anisotropy of the results natural due to the details of the 3-dimensional band structure. [21]

Lastly, the phenomenological "marginal Fermi liquid" theory of Littlewood and Varma shows two peaks (one at Δ and one at 3Δ) in the calculated spectral weight function of the superconducting state, and thus the -90 meV dip that we observe may be due to a valley between these two peaks. According to their theory, the dip is not observed along Γ-X because of increased smearing due to the much more rapid dispersion rate of the bands along that direction. [22]

The only theoretical work that we are aware of that directly addresses the overall changes in occupied spectral weight is the work of Anderson. [10,21] In order to satisfy the sum rules within his model, it is necessary that spectral weight be transferred into the pileup from higher binding energies. If we renormalize our data so that the areas of the normal and superconducting state spectra are the same, this will certainly appear to be the case for the spectra taken along Γ-X. If this same normalization procedure was applied to our Γ-$\overline{M}$ data it would seem that we must arrive at the conclusion that the spectral weight transfer for the states along Γ-$\overline{M}$ is in the opposite direction to that along Γ-X, that is, weight must be transferred to the high binding energy states as the sample temperature is lowered. At present, Anderson's theory does not appear to be able to account for this.

Let us next discuss the issue of the $\mathbf{k_{xy}}$ plane anisotropy of the superconducting gap. One set of possible explanations has to do with the inherent symmetry of the physics involved, as for instance if the superconducting order parameter had d-wave instead of s-wave symmetry. Another set of possible explanations has to do with the fact that the states along Γ-$\overline{M}$ have some Bi-O or surface-like character mixed in, as opposed to the states along Γ-X which appear to be solely Cu-O derived. [16] With this set of explanations and the assumption that the Bi-O surface layer is metallic (a controversial issue) it is quite easy to argue that the states along Γ-$\overline{M}$ should have a smaller gap than the states along Γ-X. Arguments include the possibility that the Bi-O states go superconducting via the proximity effect and so have a smaller gap, or that the gap at the surface is smaller due to the fall-off of the order parameter as in Ginzburg-Landau theory. The theoretical work of Valls et al. [23] may however, be able to explain the data. They show that the correct description of the gap near a surface involves Freidel-like oscillations which are not present in the phenomenological Ginzburg-Landau theory valid for materials in which the coherence length (ξo) is larger than the lattice spacing. For small ξo (comparable to the lattice parameter) the oscillations are significant and lead to the possibility of a gap enhancement near the surface depending upon whether the electronic state which becomes superconducting is at a maximum or minimum of the oscillation. The differences between our data and that published by Olson et al. may be related to a small change in the surface of the materials; the period of the oscillations may be small enough that a small change in the position of the electronic state with respect to the physical surface will have a dramatic effect on the gap size.

A number of groups have proposed that a Van Hove singularity in the density of states may be responsible for the high temperature superconductivity (24,25]. If a Van Hove singularity existed in $Bi_2Sr_2CaCu_2O_{8+\delta}$ it would occur along the Γ-$\overline{M}$ direction. This may be related to the larger gap values that we observe along Γ-$\overline{M}$, and the fact that the dip appears along Γ-$\overline{M}$ and not along Γ-X.

In the theory proposed by P.W. Anderson, interlayer coupling is one of the keys to the superconductivity. [21] Thus if the interlayer coupling is strongest along the Γ-$\overline{M}$ direction, the increased coupling could lead to the larger gap size we see experimentally.

It will be quite some time before a consensus is reached on the correct theoretical description of the high T_c superconductors. It is reasonable to expect that the very rich yet direct information obtained from the angle-resolved photoemission experiments will be instrumental in the search for an understanding of these very unique, interesting and important materials.

In summary, we have used high energy resolution angle-resolved photoemission spectroscopy to determine that in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (1) as the sample goes superconducting, not only is there spectral weight transfer from the gap region to the pile-up as in BCS theory, but along the Γ-$\overline{M}$ direction there is also some spectral weight transfer from higher binding energies in the form of a dip, (2) at the superconducting transition there is a decrease (increase) in the occupied spectral weight for the spectra taken along Γ-$\overline{M}$ (Γ-X), (3) the magnitude of the superconducting energy gap appears to be anisotropic in the $\mathbf{k}_{xy}$ plane, and (4) for the overdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples that we studied the gap Δ appears to fall off much more rapidly with doping than does the T_c. Recent theoretical attempts to understand our data were briefly reviewed.

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