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ARPES STUDY OF THE SUPERCONDUCTING GAP AND PSEUDOGAP IN $Bi_2Sr_2CaCu_2O_{8+x}$

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Abstract—In this paper, we review some of our ARPES results on the superconducting and pseudo gaps in $Bi_2Sr_2CaCu_2O_{8+x}$. We find that optimally and overdoped samples exhibit a d-wave gap, which closes at the same temperature, T_c, for all **k** points. In underdoped samples, a leading edge gap is found up to a temperature $T^* > T_c$. We find that T^* scales with the maximum low temperature gap, increasing as the doping is reduced. The momentum dependence of the pseudogap is similar to that of the superconducting gap; however, the pseudogap closes at different temperatures for different **k** points. © 1998 Published by Elsevier Science Ltd. All rights reserved

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The nature of the energy gap has been an important issue in the field of high temperature superconductivity. In conventional BCS superconductors, there is an isotropic energy gap (s-wave order parameter) below the critical temperature, T_c, which is a direct consequnce of electron pairing mediated by phonons. However, high T_c superconductors appear to be very different in this respect. First, the superconducting gap is highly anisotropic. In fact, an intense debate on the s- or d-wave symmetry of the order parameter has dominated this field for the past several years [1]. More recently, attention has focused on the pseudogap which is formed above T_c in underdoped samples [2]. The origin of the pseudogap and its relation to the superconducting gap below T_c is still a subject of great controversy. Angle-resolved photoemission spectroscopy (ARPES) has played a major role in understanding the superconducting and pseudo gaps due to its much improved energy resolution and unique momentum-resolving capability. ARPES has been particularly successful in measuring $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi2212)single crystals, because when these materials are cleaved to expose a clean surface, the potential at the surface is not significantly altered due to the van der Waals bonds between the two BiO cleavage planes. Furthermore, the electronic structure of Bi2212 is nearly perfectly two-dimensional, which simplifies the interpretation of the data.

In this paper, we review our ARPES results on the superconducting and pseudo gaps, and evidence for a connection between them. In summary, we have found that in optimally and overdoped samples of Bi2212, a d-wave superconducting gap closes at T_c for all **k** points on the Fermi surface. However, in underdoped samples, the superconducting gap below T_c smoothly evolves into a pseudogap above T_c, which closes at different temperatures for different **k** points on the Fermi surface.

Earlier ARPES results had found the superconducting gap in optimally doped Bi2212 to be highly anisotropic [3, 4]. However, due to either sparse sampling of **k** points or the complications caused by the superlattice in the BiO layers, neither study conclusively established the momentum dependence of the excitation gap. We later carried out more careful measurements in a number of near-optimally doped Bi2212 samples, using a dense sampling of **k** points and avoiding superlattice bands [5]. A clear d-wave picture emerged from those experiments. As an example, in Fig. 1 we plotted fitted gap values of a lightly overdoped sample ($T_c = 87$K) at different **k** points along the CuO Fermi surface. Great care was taken in identifying Fermi surface crossing points. Because of a narrow (resolution-limited) spectral lineshape in the superconducting state, a simple BCS spectral function broadened by (energy and momentum) resolution can be used to fit the spectra. Although ARPES does not measure the order parameter, combining the observation that the excitation gap in Fig. 1 follows a simple d-wave form, $|\cos(k_x) - \cos(k_y)|$, with phase-sensitive experiments [6], one can safely conclude that

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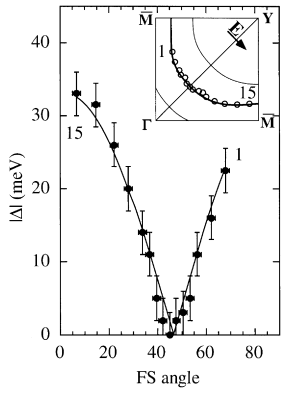

Fig. 1. The superconducting gap of an 87K overdoped Bi2212, extracted from fits, versus angle on the Fermi surface (filled circles) compared to a d-wave gap (solid curve). Locations of measured points and the Fermi surface are shown in the inset.

the order parameter in Bi2212 has a nearly pure $d_{x^2-y^2}$ form.

We now discuss the temperature dependence of the gap. It is generally difficult to extract the temperature dependence of Δ because the spectral peaks acquire significant widths at higher temperatures, and the assumption of negligible linewidths for fitting the spectra is no longer valid. As an example, in Fig. 2 we show the full width at half-maximum (FWHM) of the spectral peak near the $(\pi,0)$ point as a function of temperature. We note that this width does not provide the inverse lifetime of the state, because at low temperatures the width is given by the experimental resolution, while at higher temperatures (above T_c) the Fermi function controls the leading edge width. Nevertheless, the plot provides an indication of the very steep decrease in lifetime on approaching T_c. We can obtain a crude estimate of the temperature dependence of the gap by plotting the midpoint of the leading edge of the spectra as a function of temperature, as shown in Fig. 3. Again, the sample is a lightly overdoped 87K one. It is clear from Fig. 3 that gaps at different **k**-points vanish at the same temperature, close to the bulk T_c. This result is

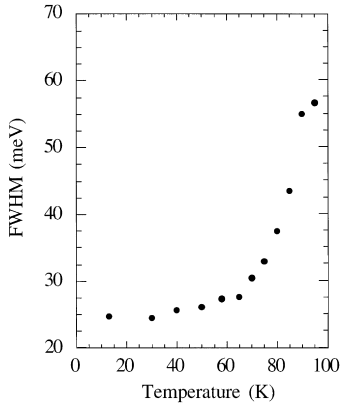

Fig. 2. FWHM of the spectral peak as a function of temperature in a slightly overdoped 87K Bi2212 sample.

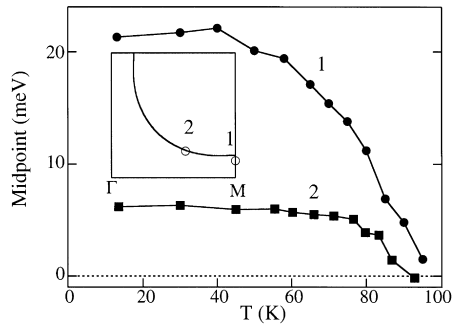

Fig. 3. The superconducting gap of an 87K overdoped Bi2212 (estimated by midpoints of the leading edge of the spectra) at two different **k** points (indicated in the inset) as a function of temperature. Note both gaps close near T_c.

significant, because it indicates that in lightly overdoped samples, there is only one gap at the Fermi surface, the superconducting gap, consistent with the fact that the momentum dependence of this gap follows a simple d-wave function.

The picture changes dramatically in underdoped samples. ARPES experiments have shown that there is a leading edge gap above T_c [7, 8]. This can be clearly seen from Fig. 4, where we plot spectra at the $(\pi,0)$–(π,π) Fermi surface point of an underdoped ($T_c = 83$K) sample at six different temperatures. Note that above T_c, i.e. at 90K, there is a sizeable (16 meV) shift between the leading edge of the sample (solid line) and that of polycrystalline

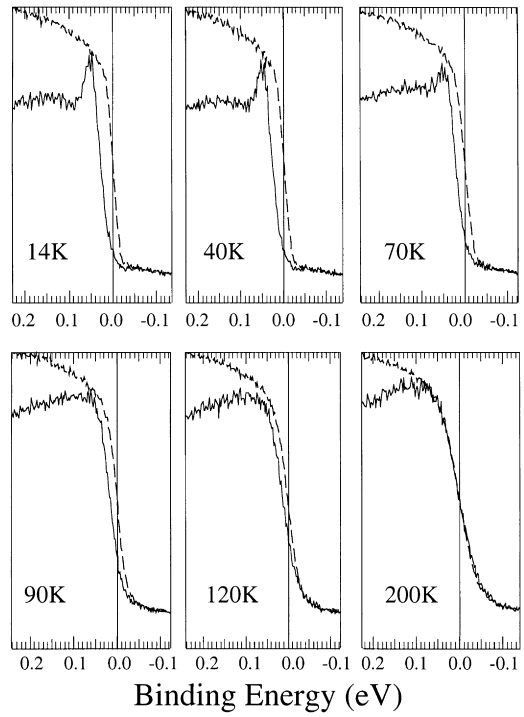

Fig. 4. ARPES spectra at the Fermi surface along the M–Y direction for an 83K underdoped Bi2212 sample at various temperatures (solid curves). The dotted curves are reference spectra from polycrystalline Pt.

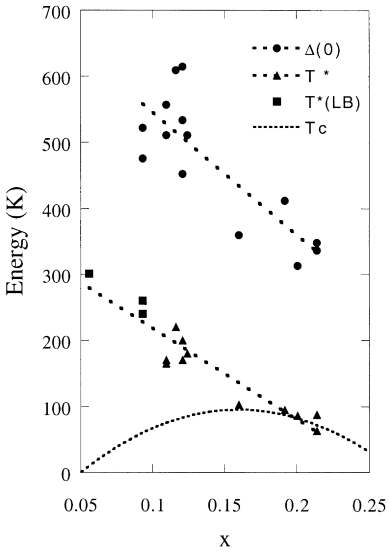

Fig. 5. Low temperature superconducting gap $\Delta(0)$ near $(\pi, 0)$ measured by peak positions (circles), T^* (triangles for determined values, squares for lower bounds) and T_c (dashed line) as a function of carrier concentration, x. Note a similar trend for both $\Delta(0)$ and T^*.

Pt (dotted line) which is used as a chemical potential reference. This pseudogap eventually disappears at a much higher temperature T^* ($\approx$200K in this case).

It is significant to note that there are always two features in the spectra: one that is related to the quasi-particle peak in the superconducting state, and gives rise to the sharp leading edge in the pseudogap state; and another at higher binding energy, described in the literature as the ''hump'' [9]. The pseudogap that we describe here is associated with the feature at low binding energy, the leading edge gap [10].

It has been found that T^* increases with deceasing doping in the underdoped region, and merges with T_c in the overdoped region [8], as shown in Fig. 5. In Fig. 5, we also plot the position of the sharp coherent peak near $(\pi,0)$ [see the first panel of Fig. 4] as a function of doping, or carrier concentration x. Since this sharp peak is essentially resolution limited, one can regard the position of its maximum as the value of the gap, $\Delta(0)$. Despite some considerable sample-to-sample variation, $\Delta(0)$ follows the general trend of increasing with decreasing x. In fact, $\Delta(0)$ seems to scale with T^*, not T_c. This is consistent with theories which predict that T_c is controlled by a phase stiffness temperature [11, 12], and not by the temperature at which a pairing gap opens. On the other hand, one may argue that the gap near $(\pi,0)$ is no longer the superconducting gap, since it has no relationship to T_c.

Let us address this problem by looking at some experimental evidence. Temperature-dependent measurements in underdoped samples, shown in Fig. 6, reveal a gap that smoothly evolves through T_c, suggesting

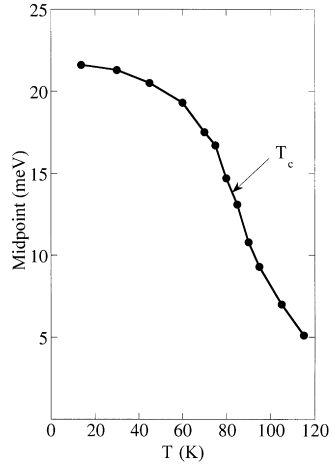

Fig. 6. Midpoints of the leading edge of the spectra for an 83K underdoped Bi2212 near $(\pi,0)$ as a function of temperature. Note the smooth evolution through T_c.

that the gaps below and above T_c have the same origin, i.e the pseudogap is closely related to the superconducting gap. We have also found that the low temperature ($T =$ 14K) gap of an underdoped ($T_c = 83$K) sample has a very similar momentum dependence as the gap of the overdoped 87K sample, which has the d-wave gap shown in Fig. 1 [8]. This is a strong indication that in underdoped samples the gap below T_c near $(\pi,0)$ is still the superconducting gap. It is interesting to note that, although having little effect on the the gap size near $(\pi,0)$, T_c has a strong effect on the lineshape.

As mentioned above, in optimally and overdoped samples the superconducting gap closes at T_c for all **k** points. What will be the case in underdoped samples? To answer this question, we have recently performed ARPES measurements on several underdoped Bi2212 samples. To our surprise, we found that pseudogaps at different **k** points close at different temperatures, in marked contrast with the result obtained in optimally doped samples [13]. Fig. 7 shows one example where we

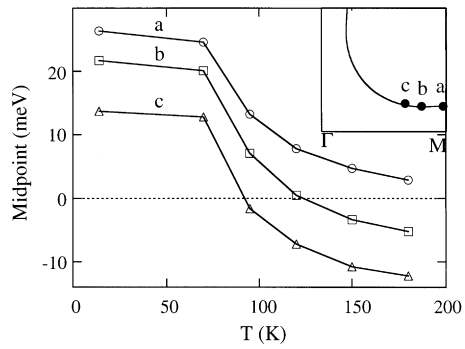

Fig. 7. Midpoints of the leading edge of the spectra for an 85K underdoped Bi2212 at three **k** points (indicated in the Brillouin zone) as a function of temperature. Note the closing of the spectral gap at different temperatures for different **k**.

plot midpoint shifts for an 85K underdoped sample at three **k** points. Point (a) is near the $(\pi,0)$ to (π,π) crossing, with points (b) and (c) progressively closer to the node direction (Γ–Y), as shown in the inset. From this plot, we find that the pseudogap closes at point (a) at a temperature above 180K, at point (b) at 120K, and at point (c) just below 95K. If we view these data as a function of decreasing temperature, we see that the pseudogap first opens near $(\pi,0)$ and progressively gaps out larger and larger portions of the Fermi surface, leading to gapless arcs shrinking with decreasing temperature, eventually collapsing to the point nodes of the $d_{x^2-y^2}$ superconducting ground state below T_c.

In conclusion, we have found that in optimally and overdoped samples, a d-wave superconducting gap closes at the same temperature, T_c, for all **k** points. However, in underdoped samples, the superconducting gap below T_c smoothly evolves into a pseudogap above T_c, which closes at different temperatures for different **k** points. This suggests an intimate, but non-trivial, relation between the superconducting gap and pseudogap.

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