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Destruction of the Fermi surface in underdoped cuprates

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Abstract

We review some of our recent angle-resolved photoemission results on $Bi_2Sr_2CaCu_2O_8$ as a function of doping. We find that the Fermi surface is progressively destroyed as the temperature is lowered below the pseudogap temperature T^*. Furthermore, the superconducting gap behaves quite differently at different $\boldsymbol{k}$-points. All of these results point to a non-mean-field behavior of the superconducting transition. © 1999 Published by Elsevier Science B.V. All rights reserved.

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Angle-resolved photoemission (ARPES) of the high-temperature superconductors is quite unusual, in that the lineshape is strongly temperature and doping dependent. We begin by discussing the overdoped samples of $Bi_2Sr_2CaCu_2O_8$, which have a simpler electronic structure [1]. In Fig. 1 we show the temperature dependence of the spectra near the (•, 0) point, indicated in the inset of Fig. 1 [2].

We have shown [2] that the ARPES photoemission intensity is given by a product of the Fermi function $f(\omega)$ and the spectral function $A(\boldsymbol{k}, \omega)$, scaled by the matrix element for ARPES, $I(\boldsymbol{k})$, which depends on the photon energy and its polarization, as well as the final states as $I(\boldsymbol{k}, \omega) = I_0(\boldsymbol{k}) f(\omega) A(\boldsymbol{k}, \omega)$.

Since $I(\boldsymbol{k})$ only determines the overall amplitude of the spectrum, we will ignore it in the present discussion. The other terms are of interest to us, since they determine the lineshape. $A(\boldsymbol{k}, \omega)$ is the probability of adding or removing a particle from a many-body interacting system, and in turn is given by the imaginary part of the self-energy.

The data in Fig. 1 can then be most easily understood if we remove the Fermi function, as shown in Fig. 2 [3].

With this technique we obtain the spectra shown in Fig. 3 [4].

The top curve, at $T = 170$ K, above T_c, shows a broad spectrum centered at $\omega = 0$. This broad spectrum has a full-width at half-maximum of 200 meV, and shows no evidence for a quasiparticle peak, exhibiting the unusual nature of the states in this material. As the temperature is lowered, two changes occur in the spectrum: (1) the peak splits in two, moving to higher binding energy as the superconducting gap opens, and (2) the peak gets much sharper as the lifetime of the state increases [4]. We have shown in Ref. [5] that the spectrum moving to higher binding energy is in fact due to the superconducting energy gap, as one can in addition observe the clear signature of particle–hole mixing in the energy dispersion. The sharpening of the peak is a consequence of the reduced scattering rate in the superconducting state, which is strongly temperature-dependent because it is dominated by electron–electron scattering.

We now return to the superconducting gap. It is observed that the leading edge of the spectrum in Fig. 1 is always resolution-limited. Note that only the leading edge is resolution-limited, as quasiparticle damping begins to occur below the superconducting gap energy Δ, which is given by the peak position, i.e. the maximum in the spectral function. At other points on the Fermi

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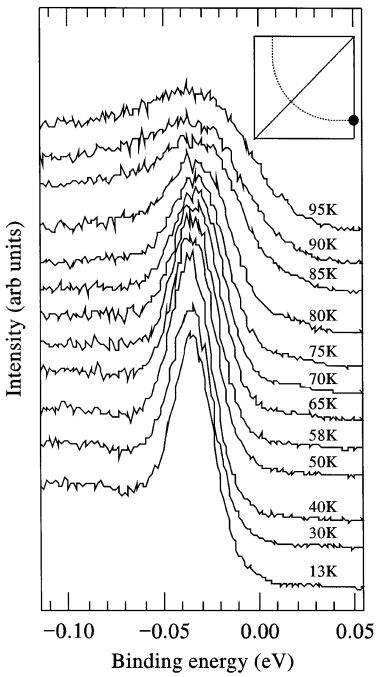

Fig. 1. Temperature dependence of the ARPES lineshape. The Fermi surface crossing is indicated in the inset.

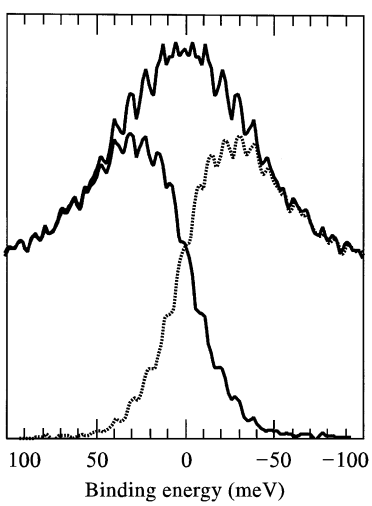

Fig. 2. Given ARPES data described by $I(\omega) = I_0 A(\boldsymbol{k}, \omega) f(\omega)$ (with the sum over a small momentum window about the Fermi momentum $\boldsymbol{k}_F$), we can generate the symmetrized spectrum $I(\omega) + I(-\omega)$. Assuming particle–hole (p–h) symmetry for a small range of ω and ε_k, we have $A(\varepsilon_k, \omega) = A(-\varepsilon_k, -\omega)$ for $|\omega|, |\varepsilon|$ less than few tens of meV. It follows, using the identity $f(-\omega) = 1 - f(\omega)$, that $I(\omega) + I(-\omega) = \Sigma_k I_0 A(\boldsymbol{k}, \omega)$.

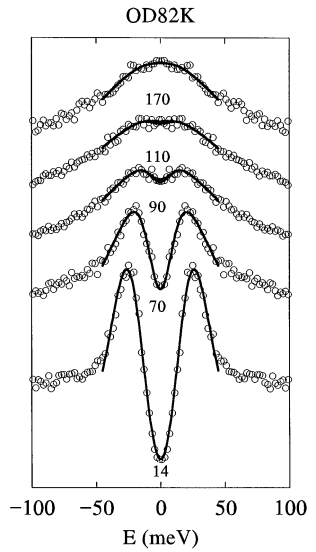

Fig. 3. Symmetrized data for a $T_c = 82$ K overdoped sample at the same $\boldsymbol{k}$-point as in Fig. 1 at five temperatures, compared to the model fits described in Ref. [4].

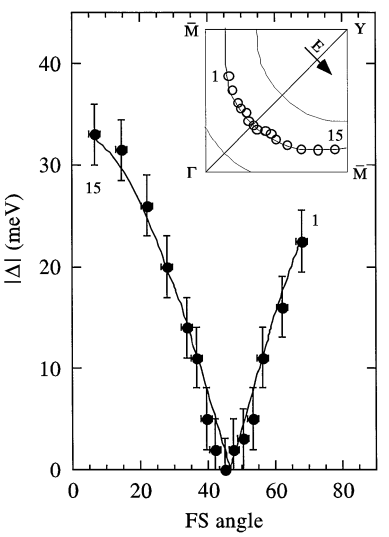

Fig. 4. The superconducting gap, extracted from fits, versus angle on the Fermi surface (filled circles) compare to a d-wave gap (solid curve). Locations of measured points and the Fermi surface are shown in the inset.

surface, we must fit the spectra, as discussed in detail in Refs. [6,15]. The resulting functional dependence of the superconducting gap in $Bi_2Sr_2CaCu_2O_8$ exhibits a d-wave character, as shown in Fig. 4 [7].

We find that in the case of overdoped samples the gap closes at the same temperature at all points along the Fermi surface, i.e. the transition exhibits the classic

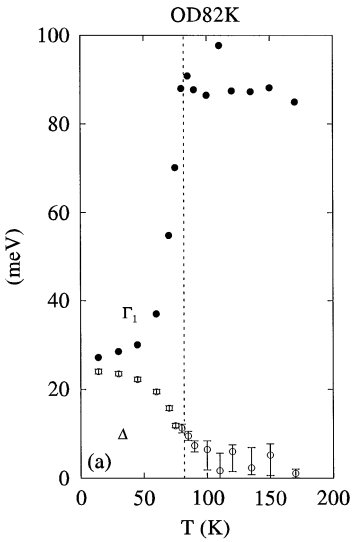

Fig. 5. Δ (open circles), and quasiparticle lifetime (solid circles) versus T for the data in Fig. 3. The error bars for Δ are based on a 10% increase in the RMS error of the fits.

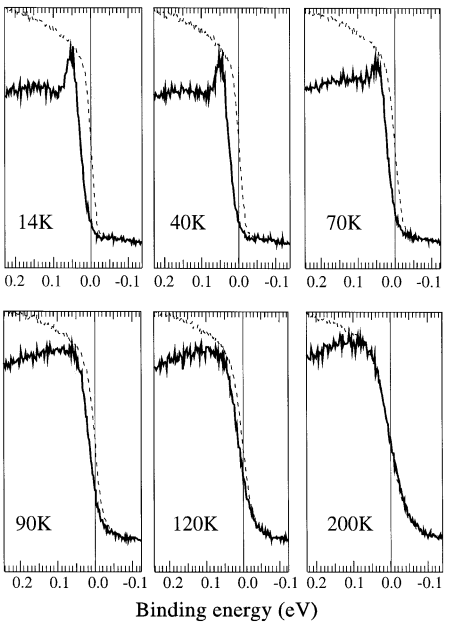

Fig. 6. ARPES spectra at the Fermi surface along the M–Y direction for an 85 K underdoped Bi2212 sample at various temperatures (solid curves). The dotted curves are reference spectra from polycrystalline Pt.

mean-field behavior with the gap closing at T_c [3]. We can obtain an estimate of the temperature dependence of the gap using a phenomenological analysis described in Ref. [4], shown in Fig. 5.

As the doping is reduced, the behavior drastically changes. The most notable difference is, that even at optimal doping, as the temperature is reduced, a pseudogap appears in the excitation spectrum [8,9].

In Fig. 5 we plot spectra at the Fermi surface along the $(\pi, 0)$–(π, π) direction of an underdoped ($T_c = 83$ K) sample at six different temperatures. Note that above T_c, i.e. at 90 K, there is a sizeable (16 meV) shift between the leading edge of the sample (solid line) and that of polycrystalline Pt (dotted line) which is used as a chemical potential reference. This pseudogap eventually disappears at a much higher temperature T^* ($\sim$200 K in this case).

It is significant to note that there are always two features in the spectra, one that is related to the quasiparticle peak in the superconducting state, and gives rise to the sharp leading edge in the pseudogap state, and another feature at higher binding energy, the "hump" [4,11], which remains in the pseudogap state and only disappears at a higher temperature. The pseudogap that we describe here is associated with the feature at low binding energy, the leading edge gap, see Fig. 6 [12].

We find that T^* increases with decreasing doping in the underdoped region, and merges with T_c in the overdoped region, as shown in Fig. 7. In Fig. 7, we also plot the position of the sharp coherent peak near $(\pi, 0)$ (see first panel of Fig. 6) 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, Δ_0. Despite some considerable sample-to-sample variation, Δ_0 follows the general trend of increasing with decreasing x. In fact, Δ_0 seems to scale with T^*, not with T_c. This is consistent with theories which predict that T_c is controlled by a phase stiffness temperature [13,14], and not by the temperature at which a pairing gap opens.

It is easy to understand how in an overdoped sample the system evolves from one with a full Fermi surface to one with the point-nodes of the d-wave state by spontaneous symmetry breaking at T_c. But the question is, how does the underdoped system evolve? At high temperatures, the system exhibits the full Fermi surface, if we define the Fermi surface as the locus of gapless excitations, since we are discussing high temperatures. We find [3] the unusual result that as the temperature is lowered, different regions of the Fermi surface begin to gap at different temperatures.

In Fig. 8 we show the temperature evolution of the spectra at three points along the Fermi surface, marked a,b, and c in panel d. At point a, the Fermi surface crossing point with the largest gap, the pseudogap fills in at $\sim$180 K. The surprise is that at points b and c closer to the d-wave node, the pseudogap fills in at progressively lower temperatures, of 120 and 95 K, respectively. This data implies that, as the temperature is lowered, the Fermi surface is progressively destroyed, as shown in Fig. 9.

This is quite a novel and unusual situation, where the Fermi surface changes topology without a change in

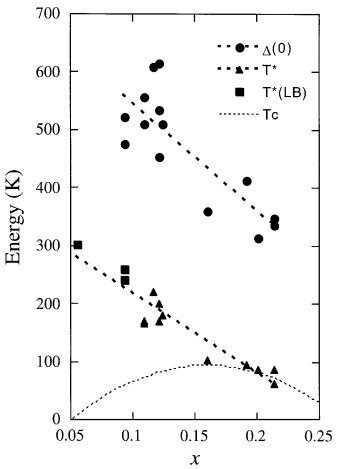

Fig. 7. Dependence of T^* and Δ on doping (in K).

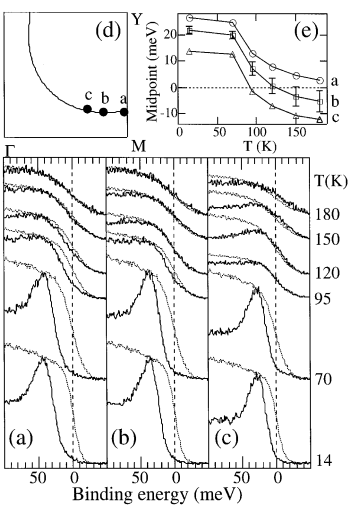

Fig. 8. (a–c) Data obtained at three $\boldsymbol{k}$ points in the Y quadrant (d) of the Brillouin zone for an 85 K underdoped Bi2212 sample at various temperatures (solid curves). The dotted curves are reference spectra from polycrystalline Pt used to determine the chemical potential. Note the closing of the spectral gap at different T for different $\boldsymbol{k}$. This feature is also apparent in the plot (e) of the midpoint of the leading edge of the spectra as a function of T.

symmetry. The pseudogap suppression first opens up near (•, 0) and progressively gaps out larger portions of the Fermi contour, leading to gapless arcs which shrink with decreasing T. It is important to note that the arcs found here are not the hole pockets of a lightly doped antiferromagnet [10]. We find that although the d-wave superconducting gap below T_c smoothly evolves into the pseudogap above T_c, the gaps at different $\boldsymbol{k}$ points are not related to one another above T_c the same way as they are

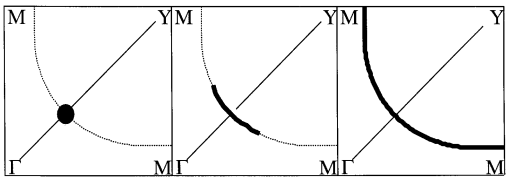

Fig. 9. Schematic illustration of the T-evolution of the Fermi surface in underdoped cuprates. The d-wave node below T_c (left panel) expands with increasing T to form the full Fermi surface at T^* (right panel).

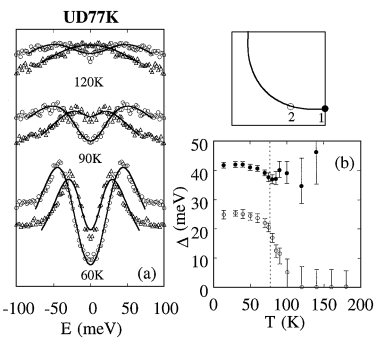

Fig. 10. (a) Symmetrized data for a $T_c = 77$ K underdoped sample for three temperatures at (open circles) $\boldsymbol{k}_F$ point 1 in the inset, and at (open triangles) $\boldsymbol{k}_F$ point 2, compared to the model fits. (b) $\Delta(T)$ for these two points (filled and open circles), with T_c marked by the dashed line.

below, implying an intimate, but non-trivial relation, between the two. This can more easily be seen by the use of symmetrized data, which also allows us to determine that the T dependence of the Fermi arc is not simply due to inelastic scattering above T_c broadening the d-wave node. These points are illustrated in Fig. 10, which shows data at two $\boldsymbol{k}$-points on the Fermi surface. It is apparent that the gap "fills in" for $\boldsymbol{k}$-point 1 (at the maximum gap) as T is raised, whereas it "closes" for $\boldsymbol{k}$-point 2. Fig. 10b shows the gap values extracted at these two points using a phenomenological model [4] with a self-energy of the form

$$\Sigma(\boldsymbol{k}, \omega) = -i\Gamma_1 + \Delta^2/[\omega + \varepsilon(\boldsymbol{k}) + i\Gamma_0].$$

This purely phenomenological self-energy is simply obtained by adding a damping term Γ_0 to the Nambu–Gorkov propagator to remove the singularity at $\omega = 0$ and take into account the filling-in of the pseudogap above T_c. Γ_0 can be thought of as a "pair lifetime". The term Γ_1 describes the quasiparticle lifetime.

We believe that the unusual T-dependence of the pseudogap anisotropy will be a very important input in reconciling the different crossovers seen in the pseudogap regime by different probes.

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