Coherent Quasiparticle Weight and Its Connection to High-T_c Superconductivity from Angle-Resolved Photoemission

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(Received 13 October 2000; published 7 November 2001)

We study the doping and temperature dependence of the single-particle coherent weight, z_A, for high-T_c superconductors $Bi_2Sr_2CaCu_2O_{8+x}$ using angle-resolved photoemission. We find that at low temperatures the coherent weight z_A at $(\pi, 0)$ is proportional to the carrier concentration x and that the temperature dependence of z_A is similar to that of the c-axis superfluid density. We show that, for a wide range of carrier concentration, the superconducting transition temperature scales with the product of the low-temperature coherent weight and the maximum superconducting gap.

DOI: 10.1103/PhysRevLett.87.227001 PACS numbers: 71.18.+y, 74.25.Jb, 74.72.Hs, 79.60.Bm

In conventional superconductors, the pairing energy gap (Δ) and superconducting phase coherence go hand-in-hand; both appear at the transition temperature T_c. In contrast, in underdoped high-T_c superconductors (HTSCs), a pseudogap appears below a much higher temperature T^*, smoothly evolving into the superconducting gap at T_c [1,2]. Phase coherence on the other hand is established only at T_c, signaled by the appearance of a sharp quasiparticle (QP) peak [3] in the excitation spectrum. Another important difference between the two types of superconductors is in the ratio of $2\Delta/T_c \equiv R$. In BCS theory, $R \sim 3.5$ is constant. In the HTSCs this ratio varies widely, continuing to increase in the underdoped region, where the gap increases while T_c decreases. Here we report that in HTSCs it is the ratio $z_A \Delta_m / T_c$ which is approximately constant, where Δ_m is the maximum value of the d-wave gap, and z_A is the weight of the coherent excitations in the spectral function. This is highly unusual, since, in nearly all phase transitions, T_c is determined by an energy scale alone. We further show that, in the low-temperature limit, z_A increases monotonically with increasing doping x. The growth is linear, i.e., $z_A(x) \propto x$, in the underdoped to optimally doped regimes, and slows down in overdoped samples. The reduction of z_A with increasing temperature resembles that of the c-axis superfluid density.

This brings us to the important question of the meaning of z_A and its determination by angle-resolved photoemission spectroscopy (ARPES). We have recently shown [4] that, although the ARPES spectral function is very broad in the normal state, indicating that there are no quasiparticles, in the superconducting (SC) state it separates into coherent and incoherent components everywhere along the Fermi surface. We call the coherent component the quasiparticle piece and its spectral weight (normalized energy integral) z_A. For a Fermi liquid, this is the quasiparticle residue z. The validity of a Fermi liquid picture in the superconducting state of HTSCs has not been established, but the restoration of electronic coherence below T_c is demonstrated by a developing z_A in ARPES spectra. In the highly anisotropic HTSCs one expects z_A to be dependent on the in-plane momentum. We focus on the coherent spectral weight in the vicinity of the $(\pi, 0)$ point of the Brillouin zone, which contributes most of the angle-integrated spectral weight. This assertion derives from a comparison of the density of states as measured by scanning tunneling microscopy (STM) [5] and the ARPES spectral function at $(\pi, 0)$ on identical samples, shown in the inset of Fig. 1(b). Once the tunneling spectrum is modified by a Fermi function and convoluted with the ARPES energy resolution, we find a remarkable similarity between the two, indicating that the spectral function in the vicinity of $(\pi, 0)$ dominates the total density of states, though it is argued that the tunneling matrix element in STM may enhance the contribution from $(\pi, 0)$ [6]. In addition, the d-wave gap, and therefore the pairing energy scale, is maximized at $(\pi, 0)$.

The experiments used procedures and samples described previously [1]. The doping level was controlled by varying oxygen stoichiometry, with samples labeled by their onset T_c. Spectra were obtained with a photon energy of 22 eV and a photon polarization along the CuO bond direction. Spectra had energy resolutions (FWHM) of 15–25 meV with a momentum window of radius $0.045\pi/a$.

In Fig. 1(a) we show ARPES spectra at $(\pi, 0)$ for an optimally doped $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi2212) sample as a function of temperature. One can clearly see the evolution from a broad, incoherent spectral function at high temperatures to the sharp peak at low temperatures [7]. Note that a spectral loss (dip) also develops on the high binding energy side of the QP in the SC state, as compared to the normal state spectrum [8]. The dip separates

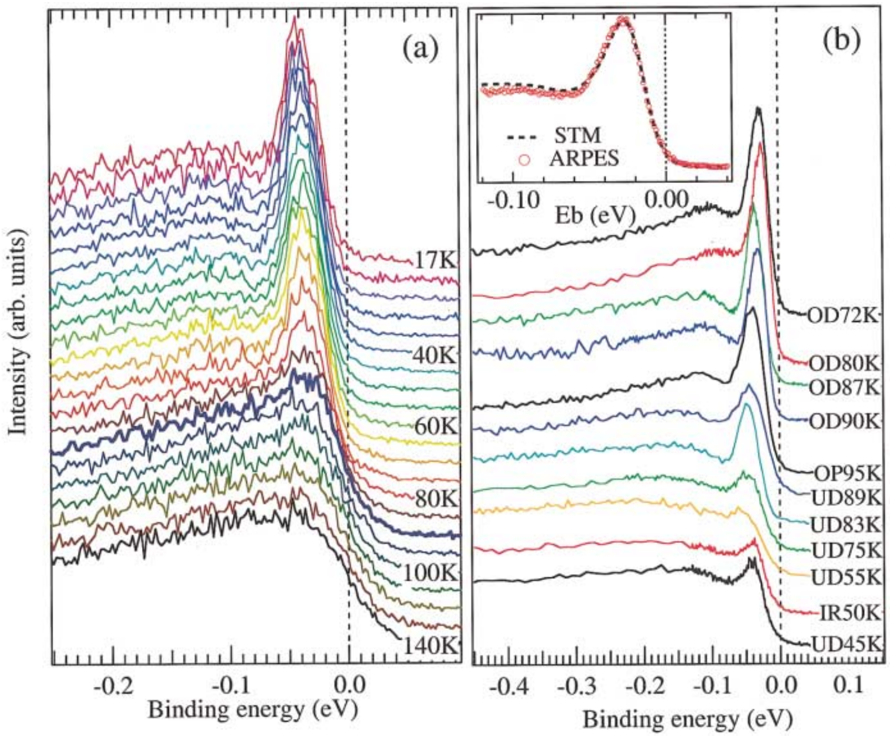

FIG. 1 (color). (a) ARPES spectra at $(\pi, 0)$ of slightly overdoped Bi2212 ($T_c = 90$ K) for different temperatures ($T = 17$, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 110, 120, 130, and 140 K). (b) Spectra at $(\pi, 0)$ at low T (14 K) of differently doped Bi2212 samples (OD—overdoped; OP—optimally doped; UD—underdoped; IR—300 MeV electron irradiated, followed by the value of T_c). Intensity of the spectra is normalized at a high binding energy where the spectral intensity shows a minimum (~ -0.5 eV). Inset: Comparison between low-T ARPES at $(\pi, 0)$ and STM for the same OD72K sample.

the coherent QP from the incoherent part (hump). Most of the intensity associated with the incoherent hump is believed to be an intrinsic part of the single-particle spectral function, based on the observations that it has the same photoemission matrix element as the coherent QP [9] and its position scales with that of the QP [10]. Note that the QP peak is not a direct consequence of the formation of a gap, but is instead related to the onset of phase coherence [1], in sharp contrast to a BCS superconductor.

We analyze the ARPES data in Fig. 1 by fitting a sharp Gaussian to the coherent peak and a broad Lorentzian with an asymmetric cutoff to the hump. Both are multiplied by a Fermi function. Although one would expect the QP peak to have a Lorentzian line shape, we find that a Gaussian best fits the actual line shape at low temperatures. This remains the case even for our higher resolution data, suggesting that the QP peak is not resolution limited [11]. A possible origin of such a line shape is an averaging over a random distribution of many sharper peaks arising from inhomogeneities observed by STM on Bi2212 [12] which shows a Gaussian-like gap distribution with a width of $\sim$20 meV. It is reassuring that at higher temperatures the fit is consistent with a Lorentzian. The fit is insensitive to the form of the broad function for the hump.

Figure 2 shows how our fits separate the sharp QP from the incoherent spectrum. From the Gaussian fit, we obtain the QP weight z_A, the QP linewidth Γ [13], and the QP peak position which gives the maximum gap Δ_m [14]. We obtain z_A from the ratio of the area under the fitted QP peak to the area of the total energy distribution curve (EDC) integrated over the range $[E_{\min}, +\infty]$, where $E_{\min}$ is the minimum of the EDC in the vicinity of -0.5 eV [15]. The choice of integrating range is based on the assumption that $E_{\min}$ is where the conduction Cu-O band separates from other bands [9]. The overall amplitude of z_A may be underestimated by this method because some of the extrinsic background (although small) is included in the denominator. It may even introduce small systematic errors as a function of doping since the extrinsic background may be doping dependent, but will not change our conclusions.

We first present our results at a fixed low temperature (14 K). Figure 3 shows z_A and Δ_m vs x. From Fig. 3(a) we see that the QP weight grows *linearly* [16] with x

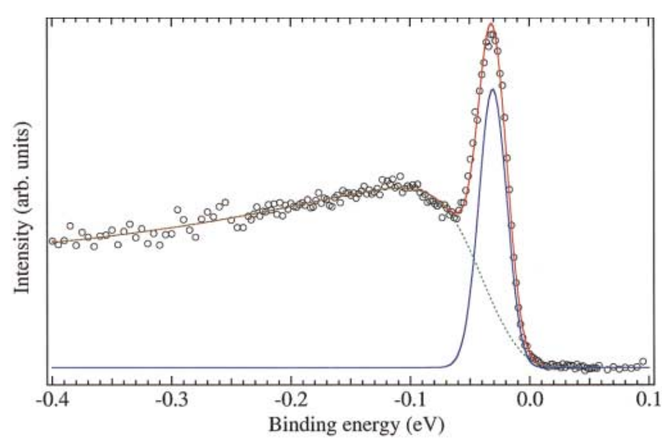

FIG. 2 (color). A fit of a low-T (14 K) spectrum (open circles) of slightly overdoped Bi2212 ($T_c = 90$ K) at $(\pi, 0)$. The blue solid line is a sharp Gaussian for the coherent peak. The green dashed line is a broad Lorentzian with an asymmetric cutoff for the incoherent part. The sum of the coherent and the incoherent part gives the fit result (red solid line).

in underdoped and optimally doped samples, and tapers off on the overdoped side. Together with the observation that the area enclosed by the normal state Fermi surface scales as $1 - x$ [17], the finding of $z_A \propto x$ suggests that only x number of coherent carriers are recovered in the SC state, consistent with the picture of doping a Mott insulator with x holes. The maximum superconducting gap Δ_m at $(\pi, 0)$ is plotted in Fig. 3(b) as the QP peak position [18]. This plot shows a trend that Δ_m increases linearly with decreasing doping in contrast to the behavior of T_c.

We next look at the reduction of QP coherence upon heating. In Fig. 4, we plot $z_A(T)$, $\Delta_m(T)$, and $\Gamma(T)$ for three typical samples in the underdoped, optimally doped, and overdoped regions. At optimal doping [Fig. 4(a)], $z_A(T)$ is only weakly T dependent at low temperatures, but falls off dramatically as T is increased towards T_c, which is consistent with the qualitative trend reported in previous ARPES studies [7,11,21]. The overall T dependence of $z_A(T)$ remarkably resembles that of the c-axis superfluid density ρ_s^c [19,20,22]. A possible explanation is that the interlayer tunneling matrix element is enhanced near $(\pi, 0)$ [6] such that the low-temperature QP weight near $(\pi, 0)$ contributes substantially to ρ_s^c. A recent theoretical work [23] within the stripe picture predicts a direct relation between the QP weight and the ab-plane superfluid density ρ_s^{ab}. The connection we find here is between the QP weight at $(\pi, 0)$ and ρ_s^c which has a much weaker T dependence than ρ_s^{ab} at low temperatures. In Fig. 4(b) we compare the T dependence of $z_A(T)/z_A(0)$ between an underdoped and an overdoped sample. The coherent weight drops faster in the overdoped sample at low temperatures, once again reminiscent of ρ_s^c in overdoped $La_{2-x}Sr_xCuO_4$ and the trend that ρ_s^c is depleted faster upon heating as doping is increased [22].

In all three cases, z_A drops significantly as T approaches T_c. However, the extracted value of z_A is nonzero above, but close to T_c. This could be due to superconducting fluctuations and/or the inhomogeneity mentioned above. Nevertheless, we caution that the error bars increase significantly above T_c where the contribution from the QP becomes small and thus difficult to separate from the incoherent spectrum. Taking a nonzero z_A above T_c at face value might suggest that the QP has already formed above T_c for all doping values. However, a closer look at the T dependence of the QP position and linewidth plotted in Fig. 4(c) shows that there are qualitative differences between the underdoped and overdoped regimes near T_c. In all cases the QP linewidth saturates at low temperatures due to inhomogeneities described above. Thus, the low-T linewidth should not be regarded as the intrinsic QP scattering rate which might be much smaller. However, for the underdoped sample, the linewidth increases rapidly with increasing T while the QP position remains roughly unchanged until the width crosses the position near T_c, and the QP loses its identity. The opposite trend is found for the overdoped sample. Here the width remains approximately independent of T across T_c while the position decreases. Thus, it is the loss of coherence near T_c that destroys the QP on the underdoped side [24], but the closing of the

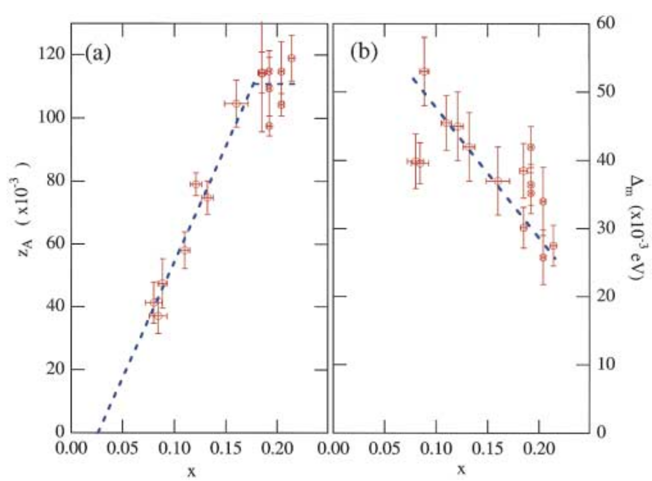

FIG. 3 (color). (a) Doping dependence of the low-T (14 K) coherent weight z_A. The dashed line is a guideline showing that z_A increases linearly on the underdoped side, and tapers off on the overdoped side. (b) Doping dependence of the maximum gap Δ_m at 14 K obtained from the fitted position of the QP peak. Vertical error bars plotted in this and following figures are mostly from fitting uncertainty rather than from measurement. Notice that two heavily underdoped samples (UD45K and IR50K) have smaller gaps. This may be due to the effect of impurities as reflected in their broader transition width.

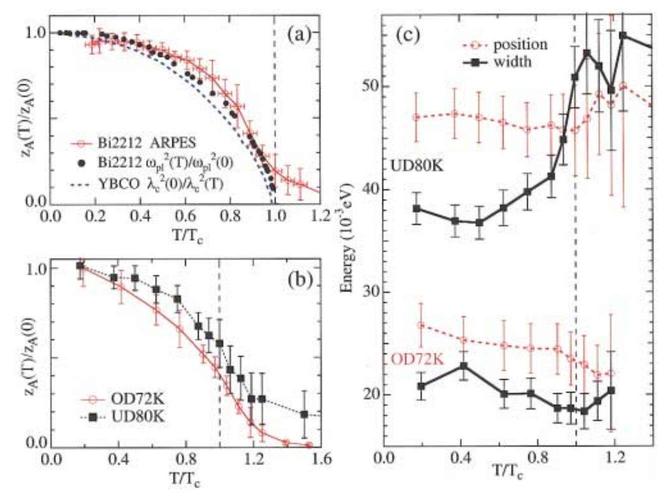

FIG. 4 (color). T-dependence of the extracted QP properties for three samples (OD72K, OD90K, and UD80K) near $(\pi, 0)$. (a) Normalized $z_A(T)/z_A(0)$ vs T/T_c for OD90K Bi2212 compared with normalized c-axis superfluid density obtained from Josephson plasma resonance [19] of overdoped Bi2212 ($T_c = 82$ K) and microwave penetration depth [20] of optimally doped $YBa_2Cu_3O_7$ ($T_c = 93.5$ K). (b) Normalized QP weight, $z_A(T)/z_A(0)$ vs T/T_c, comparing OD72K and UD80K samples. (c) QP position (that defines Δ_m) and QP width vs T/T_c, again comparing OD72K and UD80K samples. The effect of the energy resolution ($\sim$15 meV) is removed from the linewidth through the approximate relation $\Gamma = \sqrt{\Gamma_{\rm measured}^2 - \text{Resolution}^2}$.

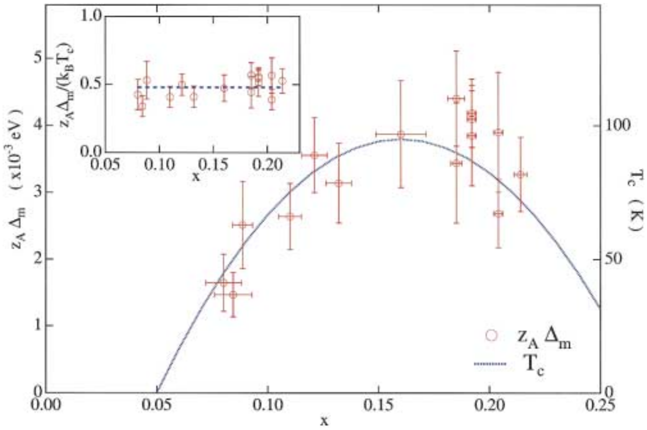

FIG. 5 (color). Doping dependence of $z_A \Delta_m$ (open circles) at $(\pi, 0)$ at 14 K. The dash line is the empirical relation [32] between T_c and x given by $T/T_c^{\max} = 1 - 82.6(x - 0.16)^2$ with $T_c^{\max} = 95$ K. The inset shows that the ratio of $z_A \Delta_m$ and $k_B T_c$ is a constant over the doping range studied.

energy gap near T_c that weakens the QP signature above T_c on the overdoped side.

A natural conclusion is that superconducting order is established through an emerging QP coherence z_A in the underdoped regime (where $\Delta_m \neq 0$ above T_c), while it is controlled by the development of the superconducting gap Δ_m on the overdoped side. This, on the gross level, is consistent with the resonating valence bond picture [25] and its variants [26]. Motivated by our results, we conjecture that a new quantity $z_A(0)\Delta_m$, with the dimension of energy, possibly plays the role of the superconducting order parameter and determines T_c. In Fig. 5, we plot $z_A(0)\Delta_m$ and T_c vs x, which reveals the proportionality between the two quantities [27], suggesting that, for Bi2212,

$$R = \frac{z_A(0)\Delta_m}{k_B T_c} = \text{const},$$

as demonstrated in the inset. This result differs from BCS theory. It is known that the effect of z_A typically does not enter this formula in the Fermi liquid approach. Our experimental findings strongly suggest that, unlike in conventional superconductors, single-particle coherence plays an important role in high-T_c superconductivity. It is interesting to note that the relation $x\Delta_m/k_B T_c \approx 3J/t$ was derived in the *underdoped* regime in a gauge theory formulation of the t-J model [28]. This is consistent with our observations provided that $z_A \propto x$ holds in this theory.

We thank T. Yokoya, T. Takeuchi, A. Kaminski, T. Sato, H. Fretwell, J. Mesot, and Y. DeWilde for experimental help and M. R. Norman for theoretical discussion. We also thank S. H. Pan for providing STM results. This work is supported by U.S. NSF DMR-0072205, DOE DE-FG02-99ER45747, Sloan Foundation, Research Corporation, the CREST of JST, and the Ministry of Education, Science and Culture of Japan. The Synchrotron Radiation Center is supported by the NSF DMR-0084402.

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[14] $(\pi, 0)$ is not on the Fermi surface; however, there is virtually no dispersion of the sharp coherent peak near $(\pi, 0)$ in the superconducting state [29]. Therefore, the binding energy of the coherent peak is a good approximation to the energy gap, although asymmetry of the intrinsic linewidth and inhomogeneity may add small uncertainties.
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