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Superconducting coherent quasiparticle weight in high-T_c superconductor from angle-resolved photoemission

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Abstract

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.

High-T_c superconductors (HTSCs) have many properties that differ from conventional BCS superconductors. One of the important differences is related to the quasiparticle (QP). In a Fermi liquid, a QP is a dressed particle which has a one-to-one relation with an electron in the system. It has a zero-temperature lifetime approaching infinity at the Fermi energy that scales as $1/\omega^2$ in the vicinity of the Fermi surface. In a broader sense, an excitation whose spectral line-width (inversely proportional to the lifetime) is longer than its energy (peak position) is usually called a QP. In BCS superconductors, the QP, which is already formed in the normal state, is modified into the Bogoliubov QPs in the superconducting (SC) state. However, in the HTSCs, there is no QP in the normal state, as observed in angle-resolved photoelectron spectroscopy (ARPES) [1]. A sharp QP peak emerges only in the superconducting state. The appearance of the QP peak is not related with the opening of an energy gap either. Instead, it is associated with the establishment of superconducting phase coherence, as observed in the underdoped HTSCs [2,3]. Another important difference between the two types of superconductors is in the ratio of $2\Delta/k_B T_c \equiv R$. 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 the 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 $z_A(T)$ with increasing temperature resembles that of the c-axis superfluid density.

We have recently shown [4] that, although the ARPES spectral function is broad in the normal state, indicating that there are no QPs, in the superconducting state it separates into coherent and incoherent components everywhere along the Fermi surface. We call the coherent component the QP piece and its spectral weight (normalized energy integral), z_A. In this paper, we focus on the coherent spectral weight in the vicinity of the $(\pi, 0)$ point of the Brillouin zone. The vicinity of $(\pi,0)$ contributes most of the angle-integrated spectral weight. This assertion derives from a comparison of

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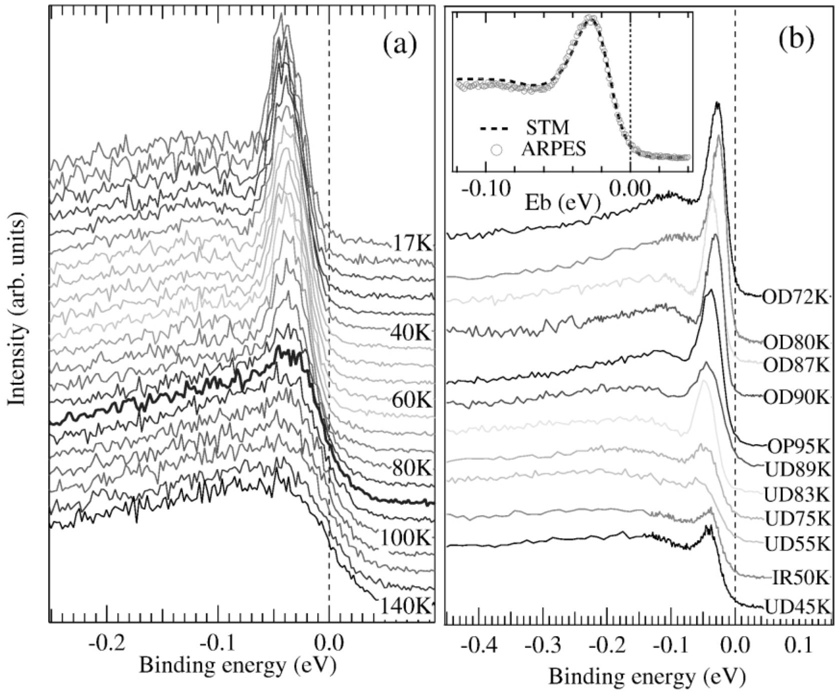

Fig. 1. (a) ARPES spectra at (π,0) of slightly overdoped doped Bi2212 (T_c = 90 K) for different temperatures (T = 17, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 110, 120, 130, 140 K), (b) spectra at (π,0) at low temperature (14 K) of differently doped Bi2212 samples (OD—overdoped,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

the density of states as measured by STM [5] and the ARPES spectral function at (π,0) on identical samples, shown in the inset of Fig. 1(b). There is a remarkable similarity between the two spectra, giving us a good reason to believe that the spectral function in the vicinity of (π,0) dominates the total density of states. In addition, the d-wave gap, and therefore the pairing energy scale, is maximized at (π,0).

The experiments were carried out using procedures and samples described previously [2]. 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 directed along the CuO bond direction. Spectra had energy resolutions (FWHM) of 15–25 meV with a momentum window of radius $0.045\pi/a$. Energies are measured with respect to the chemical potential, determined using a polycrystalline Pt (or Au) reference in electrical contact with the sample.

In Fig. 1(a) we show ARPES spectra at (π,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 [6]. 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 [7,8]. The dip separates 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].

We analyze the ARPES data in Fig. 1 by fitting a sharp Gaussian function 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 lineshape, we find that a Gaussian best fits the actual lineshape 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 lineshape is an averaging over a random distribution of a large number of sharper peaks arising from inhomogeneities observed in the tunneling data by STM on Bi2212 [12] which shows a Gaussian-like gap distribution with a width of ~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 describing the hump.

Fig. 2 shows how our fits separate the sharp QP from the incoherent spectrum of a slightly overdoped sample. From the fit, we obtain the QP weight z_A, the

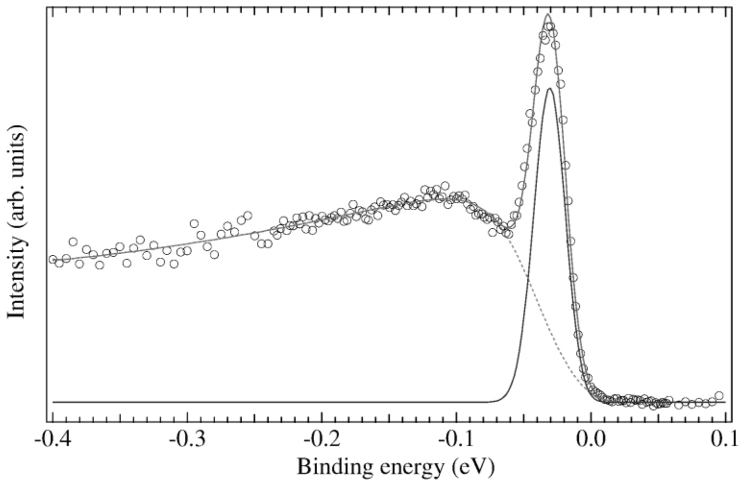

Fig. 2. A fit example of a low-temperature (14 K) spectrum (black open circles) of slightly overdoped Bi2212 ($T_c = 90$ K) at (π,0). The blue solid line is a sharp Gaussian representing the coherent peak. The green dashed line is a broad Lorentzian cut by an asymmetric cutoff function for the incoherent part. The sum of the coherent and the incoherent part gives the fit result (red solid line).

QP line-width Γ,[1] and the QP peak position which gives the maximum gap Δ_m.[2] 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 (below the hump), in the vicinity of -0.5 eV.[3] 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].

We first present our results at a fixed low temperature (14 K). Fig. 3 shows z_A and Δ_m vs. x. From Fig. 3(a) we see that the QP weight grows *linearly* with x in underdoped and optimally doped samples, and tapers off on the overdoped side, similar with a previous work [13]. Together with the observation that the area enclosed by the normal state Fermi surface scales as $1 - x$ [14], 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 (π,0) is plotted in Fig. 3(b) as the QP peak position [15]. 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 temperature-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 [6,11,16]. The overall temperature-dependence of $z_A(T)$ remarkably resembles that of the c-axis superfluid density ρ_s^c [17–19]. This is highly unusual, since unlike z_A which measures the single-particle coherence, the superfluid density ρ_s reflects the two-particle coherence.

A closer look at the temperature-dependence of the QP position and line-width plotted in Fig. 4(b) shows that there are qualitative differences between the underdoped and overdoped regimes near T_c. In all cases, the QP line-width saturates at low temperatures due to inhomogeneities described earlier. Thus, the low-temperature line-width should not be regarded as the intrinsic QP scattering rate which might be much smaller. However, for the underdoped sample, the line-width increases rapidly with increasing temperature 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 temperature 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 [20], but the closing of the 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 original resonating valence bond picture

[1] The extracted line-width includes the effect of instrumental resolution. While the effect of resolution conserves integrated spectral weight, it may introduce a degree of uncertainty in separating the sharp coherent peak from the broad incoherent background.

[2] (π,0) is not on the Fermi surface, however, there is virtually no dispersion of the sharp coherent peak near (π,0) in the superconducting state [25]. Therefore, the binding energy of the coherent peak is a good approximation to the energy gap.

[3] Although near E_F particle–hole mixing splits the spectrum into two equal pieces, and we only measure the occupied piece, dividing z_A by $n_{k_F} = 1/2$ restores the whole weight.

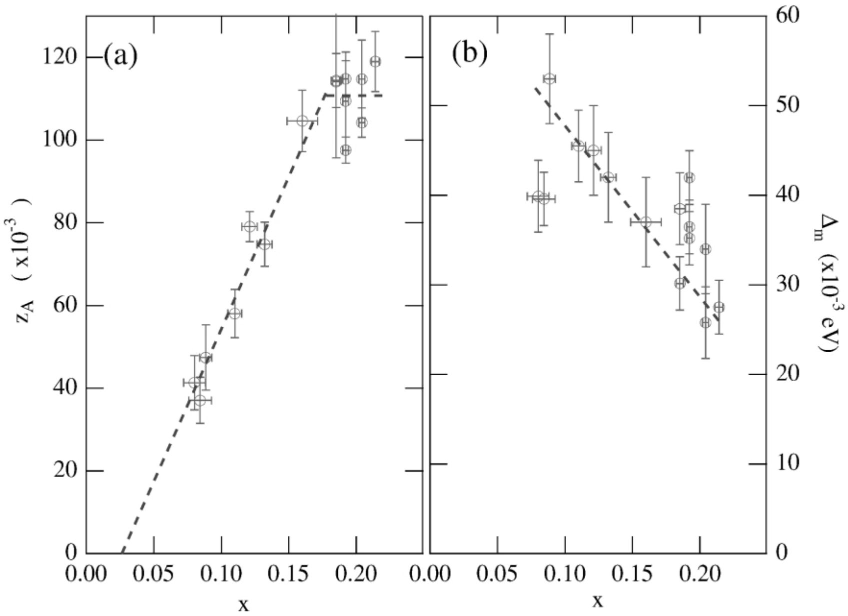

Fig. 3. (a) Doping dependence of the low-temperature (14 K) coherent spectral weight z_A. The dash line is a guide line showing that z_A increases linearly on underdoped side, and tapers off on the overdoped side. (b) Doping dependence of the maximum gap Δ_m at 14 K obtained from the position of the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

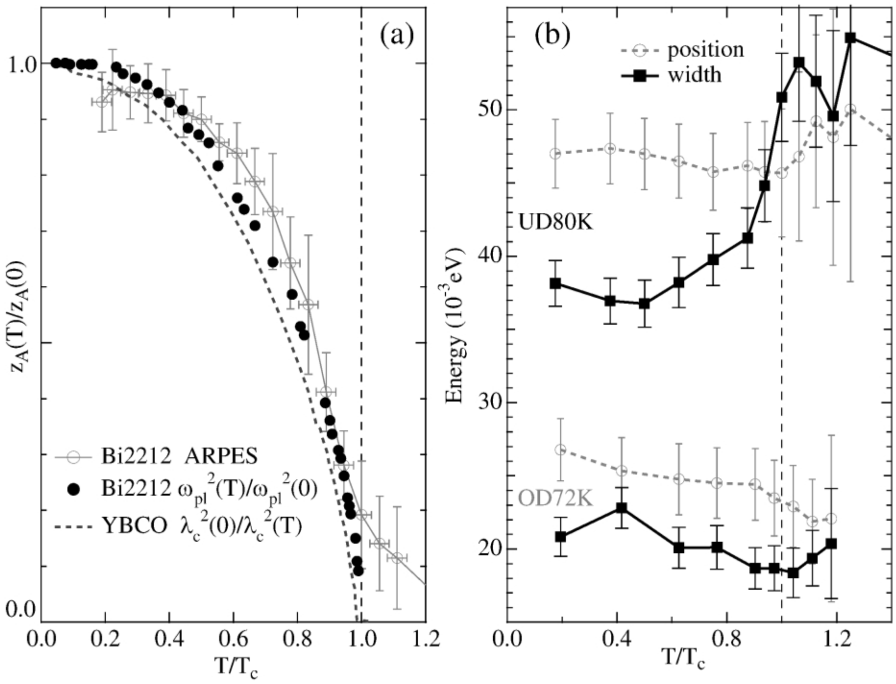

Fig. 4. Temperature-dependence of the extracted QP properties for three samples (OD72K, OD90K, and UD80K) near (π,0). (a) Normalized $z_A(T)/z_A(0)$ vs. T/T_c for OD90K Bi2212 compared with normalized c-axis superfluid density obtained from Josephson plasma resonance [17] of overdoped Bi2212 ($T_c = 82$ K) and microwave penetration depth [18] of optimally doped YBCO ($T_c = 93.5$ K). (b) 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 (∼ 15 meV) is removed from the line-width through the approximate relation $\Gamma = \sqrt{\Gamma_{\text{measured}}{}^2 - \text{Resolution}^2}$.

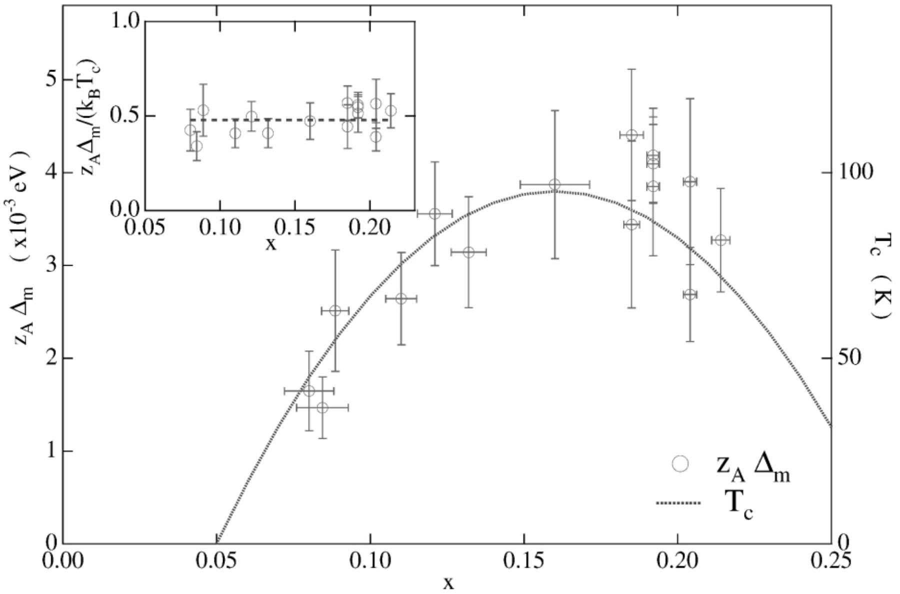

Fig. 5. Doping dependence of the value of $z_A\Delta_m$ (open circles) at (π,0) at low temperature (14 K). The dash line is the empirical relation [26] between T_c and x given by $T/T_c^{\max} = 1 - 82.6(x - 0.16)^2$ with $T_c^{\max} = 95$ K. The inset shows that the ratio of $z_A\Delta_m$ and k_BT_c is a constant over the doping range studied.

[21,22] and its variants [23,24]. 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 a striking proportionality between the two quantities, suggesting that for Bi2212

$$R = \frac{z_A(0)\Delta_m}{k_BT_c} = \text{constant},$$

as demonstrated in the inset. This result differs from the BCS theory. It is known that the effect of z_A typically does not enter this formula in the Fermi liquid approach. The experimental findings reported here strongly suggest that, unlike in conventional superconductors, single-particle coherence plays an important role in high-T_c superconductivity.

Acknowledgments

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