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Electrons in cuprates: A consistent ARPES view

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ABSTRACT

Angle resolved photoemission spectroscopy (ARPES) has been playing a crucial role in understanding of physics behind high-temperature superconductivity. Our ARPES investigation of superconducting cuprates, performed over a decade and accomplished by very recent results, suggests a consistent view of electronic interactions in cuprates which provides natural explanation of both the origin of the pseudogap state and the mechanism for high-temperature superconductivity. Within this scenario, the spin-fluctuations play a decisive role in formation of the fermionic excitation spectrum in the normal state and are sufficient to explain the high transition temperatures to the superconducting state while the pseudogap phenomenon is a consequence of a Peierls-type intrinsic instability of electronic system to formation of an incommensurate density wave. In view of these results and their projection to numerous other materials, two general questions are arising: is the normal state in 2D metals ever stable and how does this intrinsic instability interplay with superconductivity?

For many years now, the search for the mechanism of high-temperature superconductivity has been mostly reduced to a simple dilemma: phonons vs. spin-fluctuations [1]. Our commitment to the "spin-fluctuations camp" had started with the observation of strong doping dependence of the renormalization of the fermionic spectrum of Bi-2212 in the antinodal region of the Brillouin zone, known as a peak-dip-hump lineshape [2]. Such a dependence, the vanishing with overdoping and strong increase with underdoping, had suggested its magnetic origin due to "proximity to antiferromagnet" but had been difficult to reconcile with phonons. Later, the careful self-energy analysis of the nodal direction [3,4] had revealed the same strong trend with doping. This, together with the other peculiarities of the fermionic spectrum [5–7], forced us to conclude that the spin-fluctuations provide the main contribution to the scattering of the electrons and are, therefore, the main candidate for the superconducting pairing.

However, despite similar results of other groups, the spin-fluctuations scenario had not became generally accepted. On one hand, there were some open questions left. Among the most important was the 'kink puzzle', namely, why the nodal and antinodal renormalizations exhibit essentially different temperature dependence: the latter disappears just above T_c while the former, the 'kink', persists at much higher temperatures? On the other hand, the newly developed models for the electron–phonon coupling in HTSC [8] had a potential to adopt any particular property of the fermionic spectrum observed in experiment. This had called forth the necessity of a detailed comparison of the entire fermionic and bosonic excitation spectra measured for the same sample and search for distinctive fingerprints of one in another.

Since we have managed to disentangle the surface and bulk fermionic spectra in YBCO [9], a suitable material for inelastic neutron scattering (INS) experiments, we have been able to analyse the charge- and spin-excitation spectra determined by ARPES and INS, respectively, on the same crystals of $YBa_2Cu_3O_{6.6}$ [10]. In simple, these spectra are related by the Dyson equation: $G^{-1} = G_0^{-1} + U^2\chi \times G$, where $G_0(\mathbf{k}, \omega)$ and $G(\mathbf{k}, \omega)$ are the bare and renormalized fermionic Green's functions, respectively (the fermionic or charge-excitation spectrum is represented by the spectral function $A = \mathrm{Im}G$), $\chi(\mathbf{Q}, \Omega)$ is the spin susceptibility (the spin-excitation spectrum measured by INS is $\mathrm{Im}\chi$), U is the spin–fermion coupling constant, and the "correlation" $U^2\chi\star$G gives the fermionic self-energy. The detailed description of the "correlation" procedure can be found in Ref. [10]. Fig. 1a shows the Fermi surface, the Fermi level cut of the fermionic spectrum modelled based on ARPES data. Fig. 1b shows the intensity of spin-excitations along $Q = q(2\pi, 2\pi)$ that represents $\mathrm{Im}\chi(\mathbf{Q}, \Omega)$ and is derived from numerical fits to the INS spectra [10]. As we have found, a self-consistent description of both spectra can be obtained by adjusting a single parameter, U.

The comparison between the spectral functions, calculated in this way by T. Dahm and measured experimentally is presented in Fig. 2. The overall similarity demonstrates clearly that the spin-fluctuations can explain all the peculiarities of the elec-

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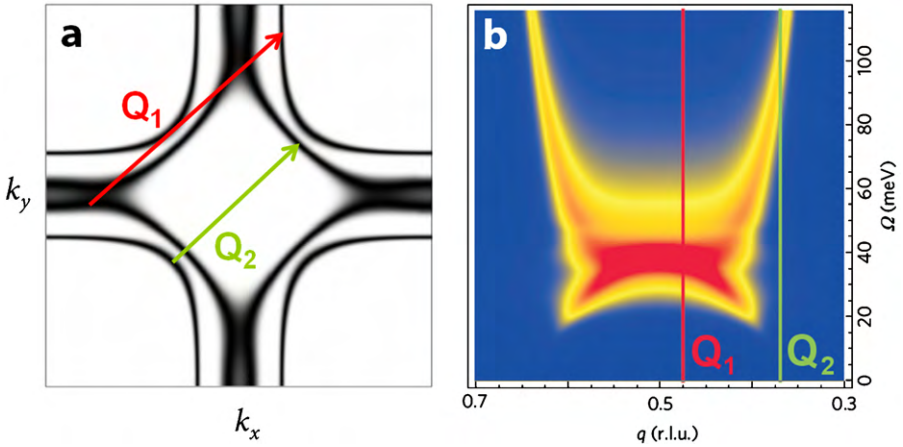

Fig. 1. The Fermi surface of YBCO in the 1st BZ derived from ARPES data [9] represents the fermionic Green's function (a). The intensity of spin-excitations along $Q = q(2\pi, 2\pi)$ resulting from numerical fits to the INS spectra measured by V. Hinkov and B. Keimer (MPI, Stuttgart) [10] (b).

tronic scattering in cuprates. In particular, they provide natural explanation of different temperature dependence of the nodal and antinodal renormalizations. As illustrated in Fig. 1, the nodal 'kink' in fermionic dispersion is a result of the interband scattering on the spin-fluctuations from the upper, universal, weakly temperature-dependent branch of the spectrum (Q_2 vector), while the scattering between the antinodal regions (Q_1 vector) is determined by the middle of the spin-fluctuation spectrum where a large peak, known as a 'resonance mode' [11], appears just below T_c.

The determined value of the spin–fermion coupling constant, $U = 1.59$ eV, gives an estimate of T_c which exceeds 150 K [10]. This demonstrates that spin-fluctuations have sufficient strength to mediate high-temperature superconductivity.

The actual T_c can be reduced by a variety of effects. Two of them, the phase fluctuations of the order parameter and competition with other types of order make a link to the pseudogap phenomenon, not considered in this analysis. In Ref. [12] we have shown that the electronic density ordering is the most probable origin of the pseudogap in cuprates.

Performing careful temperature- and momentum-resolved photoemission experiments [12], we have found that the depletion of the spectral weight in slightly underdoped Bi(Tb)-2212 superconductor, usually called the "pseudogap," exhibits an unexpected non-monotonic temperature dependence: decreases linearly approaching T^* at which it reveals a sharp transition but does not vanish and starts to increase gradually again at higher temperature.

Fig. 3 illustrates the temperature evolution of the pseudogap presenting a temperature map (panel a) and momentum integrated energy distribution curves (EDCs) measured at different temperatures and compared to each other (panels b and e) as well as to the similar EDCs but measured for each temperature along the nodal direction (panels c, d, f, g). The gap is seen as a shift of the leading edge midpoint (LEM) of a gapped EDC. Since the leading edge

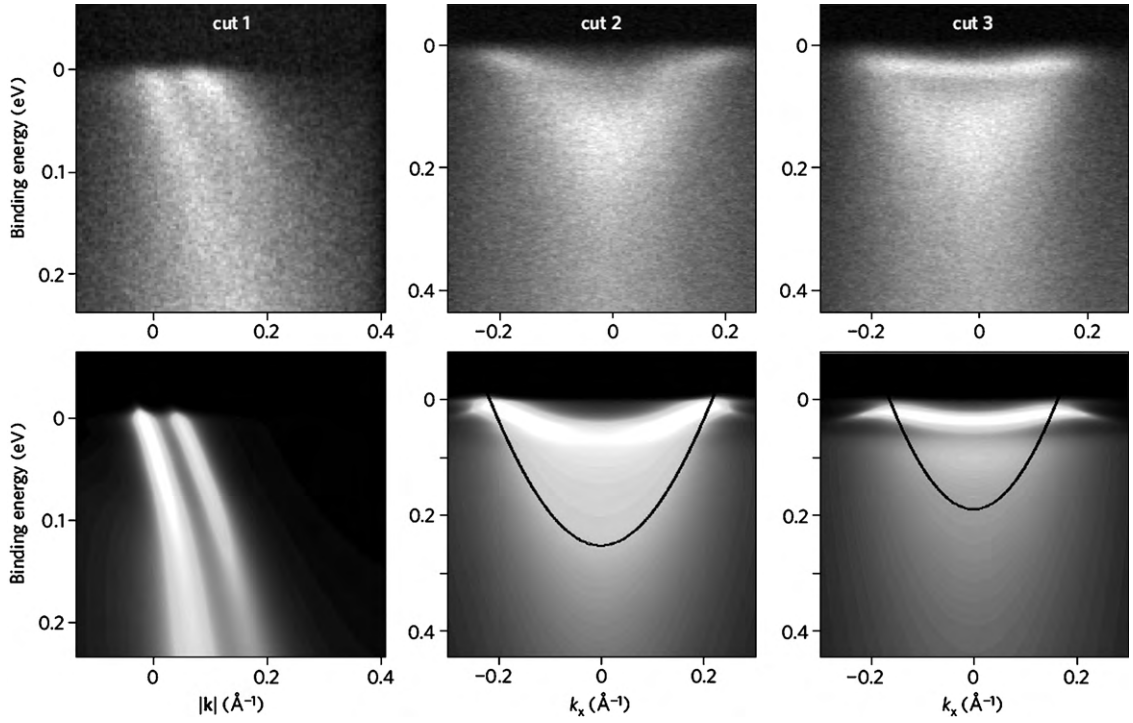

Fig. 2. Comparison of experimental (upper row) and theoretical (lower row) fermionic spectra (see Ref. [10] for details), by T. Dahm (University of Tübingen).

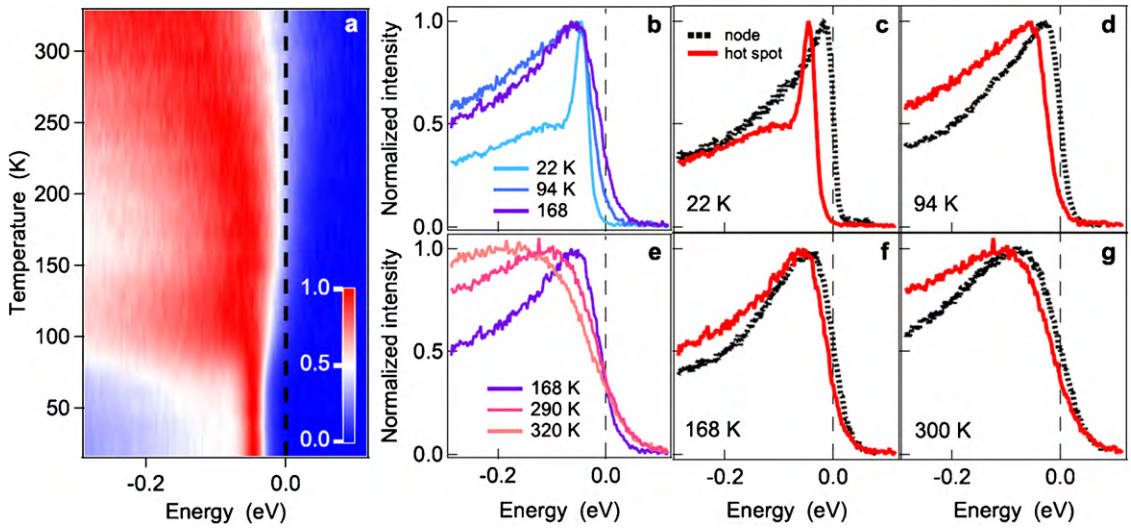

Fig. 3. The temperature map. (a) The temperature map which consists of a number of momentum integrated energy distribution curves (EDCs) measured at different temperatures at a 'hot spot'. Separate EDCs are shown in panels (b–g): as compared to each other (panels b and e) and to the similar EDCs measured each for the same temperature but along the nodal direction (panels c, d, f, g). The gap is seen as a shift of the leading edge midpoint (LEM). In terms of the colorscale of panel (a), the LEM corresponds to white color close to the Fermi level [12].

of the momentum integrated EDC of the non-gapped spectrum is expected to stay at zero binding energy for any temperature, as it is observed for the nodal EDCs (Fig. 2c, d, f, g), the finite shift of the LEM is a good empirical measure for a gap of unknown origin. From the temperature map presented in Fig. 2a one can easily see an unusual temperature evolution of the gap (in terms of the colorscale, the LEM corresponds to the white color): first it decreases with increasing temperature up to about 170 K, then it starts to increase again.

The temperature dependence of the LEM is summarized in Fig. 4 (left panel) where it is compared to the similar quantity measured for $TaSe_2$ (right panel), for which it is known that the pseudogap results from the incommensurate charge density wave [13–15]. The observed one-to-one correspondence between the temperature dependences of the pseudogap for Bi-2212 and $TaSe_2$, which is discussed in details in Ref. [12], suggests that density wave ordering also appears in cuprates and, reducing the electron density of states at the Fermi level, competes with superconductivity. While the evidence for such a competition is also reported by other groups [16,17], the exact nature of the ordering remains unclear. One may assume that the spin-fluctuations, being a dominant mediator for electronic interactions in cuprate, play also the role of the main driving force for the electronic instability resulting in the spin density wave formation. This assumption, however, requires future experimental verification.

Attributing the pseudogap phenomenon to a Peierls-type incommensurate density wave in both cuprates [12] and dichalcogenides [13–15], together with indication of similar electronic instability in other 2D metals such as pnictides [18,19], arise two old and forgotten general questions [20]: is the normal state in 2D metals ever stable and how does this intrinsic instability interplay with superconductivity?

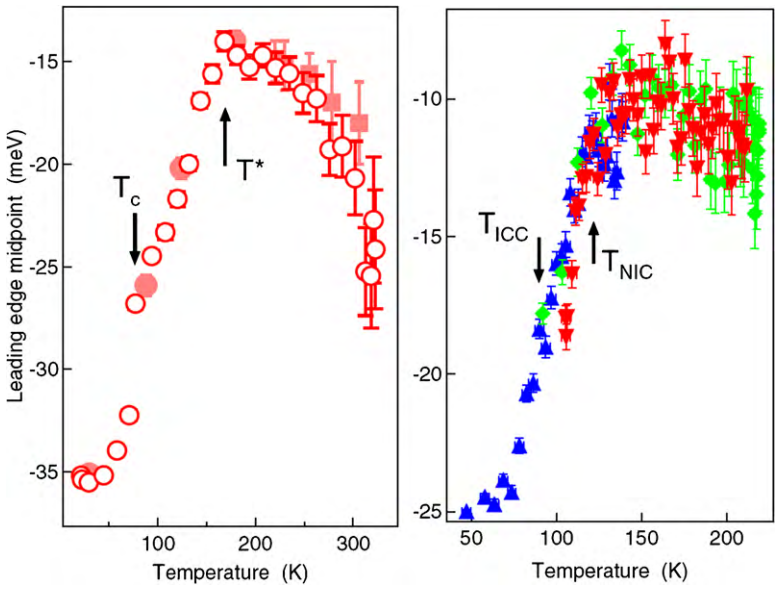

Fig. 4. Non-monotonic gap function. The position of the leading edge midpoint (LEM) of the integrated k_F EDCs (averaged for two Fermi-crossings), as function of temperature for an underdoped Tb-BSCCO (left) [12] with $T_c = 77$ K and $T^* = 170$ K is remarkably similar to the pseudogap in a transition-metal dichalcogenide $TaSe_2$ (right) [13] with the transitions to the commensurate and incommensurate CDW phases at $T_{ICC} = 90$ K and $T_{NIC} = 122$ K, respectively.

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References

[1] E. Schachinger, J.J. Tu, J.P. Carbotte, Phys. Rev. B 67 (2003) 214508.
[2] S.V. Borisenko, et al., Phys. Rev. Lett. 90 (2003) 207001.
[3] A.A. Kordyuk, et al., Phys. Rev. Lett. 92 (2004) 257006.
[4] A.A. Kordyuk, et al., Phys. Rev. Lett. 97 (2006) 017002.
[5] S.V. Borisenko, et al., Phys. Rev. Lett. 96 (2006) 067001.
[6] S.V. Borisenko, et al., Phys. Rev. Lett. 96 (2006) 117004.
[7] V.B. Zabolotnyy, et al., Phys. Rev. Lett. 96 (2006) 037003.
[8] S. Johnston, et al., Adv. Cond. Mat. Phys. 2010 (2010) 968304.
[9] V.B. Zabolotnyy, et al., Phys. Rev. B 76 (2007) 064519; Phys. Rev. B 76 (2007) 024502.
[10] T. Dahm, et al., Nat. Phys. 5 (2009) 217.
[11] M. Eschrig, Adv. Phys. 55 (2006) 47.
[12] A.A. Kordyuk, et al., Phys. Rev. B 79 (2009) 020504 (R).
[13] S.V. Borisenko, et al., Phys. Rev. Lett. 100 (2008) 196402.
[14] D.V. Evtushinsky, et al., Phys. Rev. Lett. 100 (2008) 236402.
[15] S.V. Borisenko, et al., Phys. Rev. Lett. 102 (2009) 166402.
[16] K. Tanaka, et al., Science 314 (2006) 1910.
[17] T. Kondo, et al., Nature 457 (2009) 296.
[18] V.B. Zabolotnyy, et al., Nature 457 (2009) 569.
[19] D.V. Evtushinsky, et al., Phys. Rev. B 79 (2009) 054517.
[20] A.M. Gabovich, A.I. Voitenko, M. Ausloos, Phys. Rep. 367 (2002) 583.