ARPES on high-temperature superconductors: Simplicity vs. complexity (Review Article)

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A notable role in understanding of the microscopic electronic properties of high-temperature superconductors (HTSC) belongs to angle-resolved photoemission spectroscopy (ARPES). This technique supplies a direct window into the reciprocal space of solids: the momentum-energy space where quasiparticles (electrons dressed in clouds of interactions) dwell. Any interaction in the electronic system, e.g., superconducting pairing, leads to modification of the quasiparticle spectrum—to redistribution of the spectral weight over the momentum-energy space probed by ARPES. Continued development of the technique had the effect that the picture seen through the ARPES window became clearer and sharper until the complexity of the electronic band structure of the cuprates had been resolved. Now, in the doping range optimal for superconductivity, the cuprates much resemble a normal metal with well-predicted electronic structure, though with rather strong electron-electron interaction. This principal disentanglement of the complex physics from complex structure reduced the mystery of HTSC to the tangible problem of the interaction responsible for quasiparticle formation. Here we present a short overview of recent ARPES results, which, we believe, suggest a way to resolve the HTSC puzzle. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2199429]

I. INTRODUCTION TO HTSC COMPLEXITY

It is the real complexity of the electronic properties of the cuprates that has kept the HTSC problem open over the last 20 years. On a large scale, this complexity manifests itself in a sophisticated phase diagram, which is shown schematically in Fig. 1. In the case of undoped CuO planes, the strong Coulomb repulsion between electrons indeed arranges them into the antiferromagnetic insulating state which, upon hole doping, evolves into a "strange" metal with a sophisticated magnetic spectrum and, upon further doping, into a superconductor. In Fig. 1a we plot such a set of phases which are mostly agreed to now,[1,2] while in Fig. 1b we indicate a variety of "crossover" lines which represent other suggestions.[3–7] Leaving aside the discussion of all these crossovers as beyond the scope of this paper, we note that the complexity of the phase diagram evidently is a result of an intricate evolution of the low-energy electronic excitation spectrum with doping and temperature. The scope of this paper is to review the recent results of the angle-resolved photoemission spectroscopy (ARPES), the most direct and powerful technique that allows one to look in depth on such an evolution. The aim of this review is rather ambitious: to separate the wheat from the chaff in ARPES spectra on the way to resolving the HTSC puzzle. We do it in two steps. First, we disentangle the interaction effects from the structural ones and show that the former can be described by quasiparticle self-energy. Second, we distinguish two main contributions to the self-energy, locating the key interaction which should be responsible for the superconducting pairing.

II. INTRODUCTION TO ARPES ON HTSC

In this Section we give a brief introduction to ARPES experiment. For more details of the technique, the history of its development, as well as the majority of the obtained results, we recommend recent comprehensive reviews.[8,9]

ARPES is an advanced development of the photoelectric effect, the theory of which was suggested by Einstein 100 years ago. Putting a monochromatic light on a sample surface and resolving the kinetic energy of outgoing electrons, one gets a photoemission spectrometer. Resolving the angle of the photoelectrons flying out of a single crystal gives ARPES. In modern ARPES analyzers an angle resolution down to 0.1–0.2° can be achieved without any mechanical movement by using a channel plate as a detector. For 2D solids, such as HTSC, the ARPES snapshot, $I(k,\omega)$, the image recorded by such a channel plate, is just the density distribution of the elementary electronic excitations,[1)] i.e., quasiparticles,[2)] over energy ω and momentum k along a certain direction in the reciprocal space. Figure 2 gives examples of such a distribution. Rotating the sample with respect to the analyzer, one can see any such a cut of 3D momentum-energy space $I(\mathbf{k},\omega)$, $\mathbf{k}=(k_x,k_y)$. The main region of interest is a "low-energy" region of about 0.5 eV in depth from the Fermi level, where interactions form a background for superconducting coupling.

If one disregards the effect of the energy and momentum resolutions as well as the matrix elements effect[13] and the extrinsic background,[14,15] the photocurrent intensity is proportional to a one-particle spectral function multiplied by the

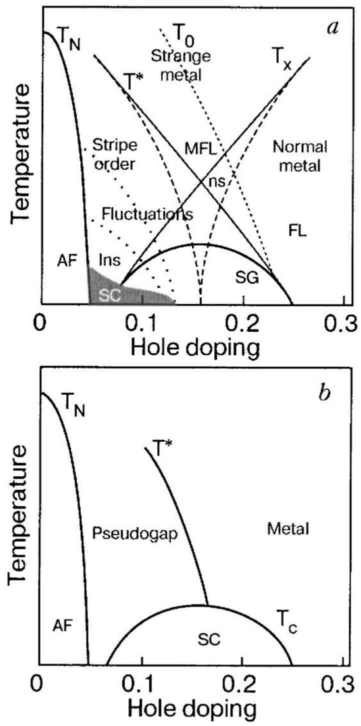

FIG. 1. Schematic phase diagrams of the cuprates: generally accepted version (*a*) and a "discussable" one (*b*). The antiferromagnetic phase (AF), superconducting phase (SC), spin glass (SG) as well as a crossover, T^*, to a pseudogap region are well established,[1,2] while a number of other regions are a matter of scientific discussion.[3] Here, together with the T^* lines that confine a region of fluctuations either of superconducting[4] or "competing order"[5] (e.g., AF, charge density waves, or spin-charge ordering), we plot a T_x crossover either between marginal Fermi-liquid (MFL) and usual FL or between incoherent and coherent states of a "slave" boson (see Ref. 6 and references therein). Different regions at lower doping are proposed for different stripe phases[7] which can result in the insulating (Ins) and spin-glass regions.[3,7]

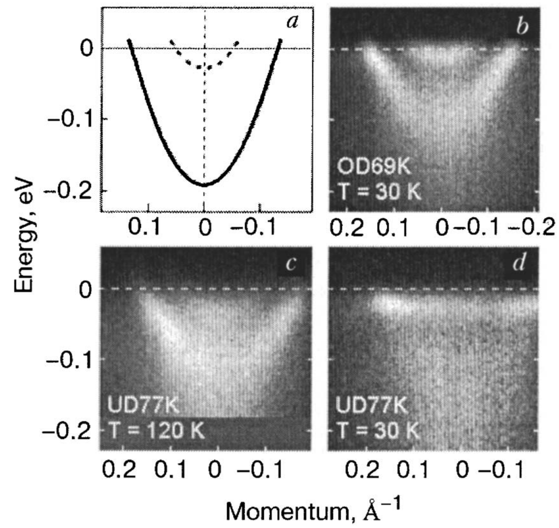

FIG. 2. Electronic structure in the antinodal region (along XMY cut). Bare band structure (*a*) and ARPES snapshots taken at 30 K (below T_c) for an overdoped sample (OD, T_c=69 K, x=0.22) (*b*) and underdoped sample (UD, 77 K) (*d*), and for UD77 at 120 K (*c*). On panels (*b*) and (*c*) two split bands are well visible, while on panel (*d*) a strong depletion of the spectrum can be seen at some "mode" energy.[12]

Fermi function: $I(\mathbf{k},\omega)=A(\mathbf{k},\omega)f(\omega)$, where both also depend on temperature. For a non-interacting case, $A(\mathbf{k},\omega) = \delta[\omega-\varepsilon(\mathbf{k})]$, so the electronic spectrum is completely determined by the bare band dispersion $\varepsilon(\mathbf{k})$. Electronic interactions, which can be described in terms of the quasiparticle self-energy, $\Sigma=\Sigma'+i\Sigma''$, turn the spectral function into a renormalized form:

$$A(k,\omega) = -\frac{1}{\pi}\frac{\Sigma''(\omega)}{(\omega-\varepsilon(k)-\Sigma'(\omega))^2+\Sigma''(\omega)^2}. \tag{1}$$

This is the central formula for one-particle excitation spectra analysis and it has been shown to be perfectly applicable to HTSC.[16]

In order to introduce some of ARPES vocabulary, we consider a structure of such a 3D momentum-energy space. The energy distribution curve (EDC), a unit of information of ARPES in former days, is the photocurrent intensity at certain momentum $\mathbf{k}_0$: $\mathrm{EDC}(\omega)=I(\mathbf{k}_0,\omega)$. The momentum distribution curve, $\mathrm{MDC}(k)=I(k,\omega_0)$,[17] has the advantages that (i) it has a simple Lorentzian line shape as long as the self-energy in Eq. (1) can be considered as momentum independent, (ii) the Fermi function and extrinsic background do not affect its line shape (disregarding again the energy resolution effect), and (iii) a set of MDC maxima $k_m(\omega)$, by virtue of the definition $\omega-\varepsilon(k_m)-\Sigma'(\omega)=0$, trace the renormalized dispersion. In two dimensions, $I(\mathbf{k},\omega_0)$ gives the momentum distribution map (MDM),[15] with a special case of $I(\mathbf{k},0)$, which is an image of the Fermi surface (FS).[18] Examples of such FSs are shown in Fig. 3.[19] Figure 4a[20] can help to navigate in the momentum space: the YM triangle represents three important directions in the 1st Brillouin zone (BZ), the bare electronic structure along which is shown in Fig. 4b. One can also specify two key cuts, called ΓY and XMY, the ARPES snapshots along which are shown in Figs. 5a and 2, respectively. These two snapshots represent the "nodal" and "antinodal" regions[3)] and contain the essentials of the whole low-energy electronic structure of the cuprates. Historically speaking, these essentials can be further reduced to a couple of heavily discussed plots shown in Fig. 6: (a) a renormalized dispersion with ~70 meV "kink," and (b) a $(\pi,0)$ EDC with so called "peak-dip-hump" (PDH) structure.

Before going further we want to highlight three cornerstones of our experiment (for details see Refs. 12, 13, and 19). They are: (1) the precise cryomanipulator, which allows rotation of the sample around three perpendicular axes with 0.1° precision in ultrahigh vacuum (UHV); (2) the light sources (mainly synchrotrons), of a wide excitation energy range and different polarizations; and (3) high quality samples—superstructure-free[21] single crystals. To be per-

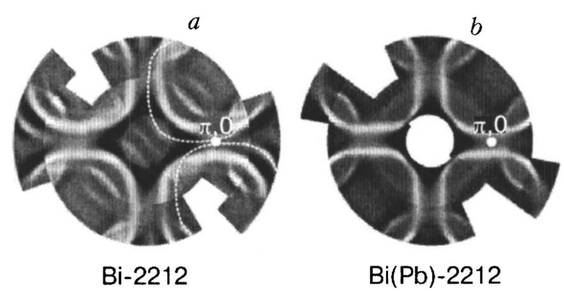

FIG. 3. Fermi surfaces measured on pristine Bi-2212 (*a*) and on superstructure-free lead-doped Bi(Pb)-2212 (*b*).[34]

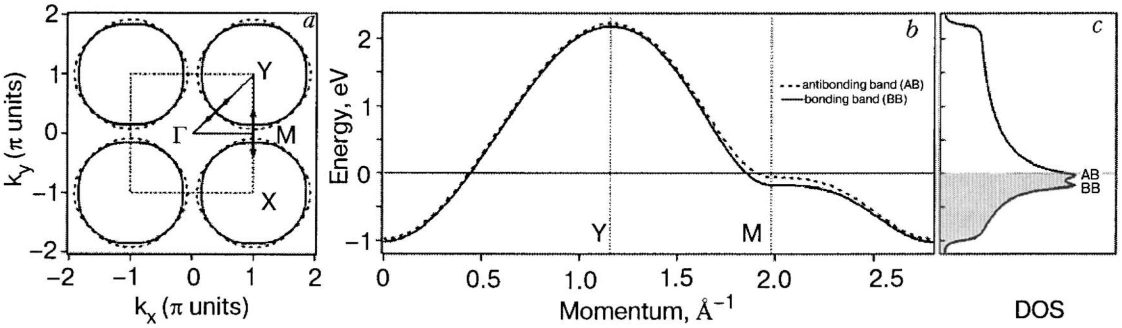

FIG. 4. The bare band dispersion, as extracted from experiment:[20] (*a*) Fermi surfaces, the dotted square denotes the boundary of the 1st BZ, the ΓYM triangle shows the path along which the dispersion is shown on panel (*b*); (*c*) the corresponding density of states (DOS) with two van Hove singularities close to E_F.

fectly "arpesable"[22] a sample should be: (i) highly anisotropic (to be as 2D as possible, in order to eliminate the influence of the k_z dispersion); (ii) easily cleavable in UHV, to reveal a perfectly flat surface; and have a surface representative of the bulk.[23] The only HTSC which fits all of these is the Bi-based cuprate, especially Bi(Pb)-2212, the compound with two CuO layers per unit cell, and doped with lead, in order to get rid of a superstructure in the topmost BiO layer.[21,24] Therefore, here we mainly discuss the data for Bi(Pb)-2212 samples, although it should be noted that they are in agreement with the spectra measured for La- and Y-based samples of yet lower quality.

III. WHAT IS SIMPLE IN HTSC?

The idea of this Section is to show that the cuprates, in terms of their electronic structure, appear to be not so unusual as had been believed. This evolution from complexity to simplicity has been mainly a consequence of both the development of the ARPES technique (improving energy and momentum resolutions, statistics, increasing the excitation energy range) and accumulating experimental experience—increasing the signal-to-noise ratio of our understanding on a large scale. We believe that the important progress made in the last years consists in the conclusion that the cuprates in the doping range where superconductivity occurs are rather simple, in the sense that we can decompose the quasiparticle spectrum over the whole *Brillouin zone into well-predictable band structure* of the noninteracting electrons and the interaction effect in terms of *quasiparticle self-energy*.

A. HTSC band structure

Earlier ARPES experiments had made a great deal of progress in our understanding of the underlying electronic properties of HTSC cuprates but also, inevitably, were sometimes misleading, giving rise to mistaken ideas. Such was the belief that the observed electronic structure of the cuprates cannot be appropriately described by the local-density approximation (LDA) band structure calculations.[24] Among the features that could not be accounted for by the LDA were: extended flat bands "indistinguishable" from E_F[23] that gave rise to ideas about "pinning" of the van Hove singularity to the Fermi level[25] and to a number of "narrow band" descriptions;[26] strong propensity for (π,π) FS nesting;[23] or experimental "evidence" for the absence of bilayer splitting (BS)[27] which was taken as evidence for electronic confinement within the planes of the CuO bilayer due to strong correlations and deconfinement-driven superconductivity,[28] and also had many other consequences.

Now it is well established that the hole-doped cuprates exhibit a well defined "large" FS,[21] such as shown in Fig. 3. "Large" means that the FS area (in holes) is equal to $(1+x)/2$, where x is the hole density (or doping concentration).

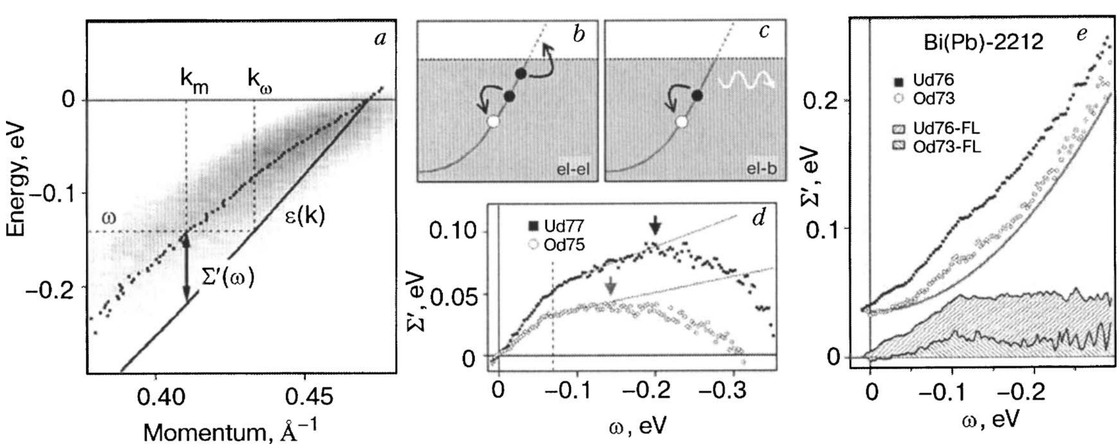

FIG. 5. Nodal spectra analysis.[16] (*a*) Bare band dispersion (solid line) and renormalized dispersion (points) on top of the spectral weight of interacting electrons (in gray scale). Though intended to be general, this sketch represents the nodal direction of an underdoped Bi-2212. The illustrations for the Auger-like scattering (*b*) and scattering by bosons (*c*). The real (*d*) and imaginary (*e*) parts of the self-energy for different doping levels. The solid line in (*e*) represents a Fermi liquid parabola—the Auger-like scattering.

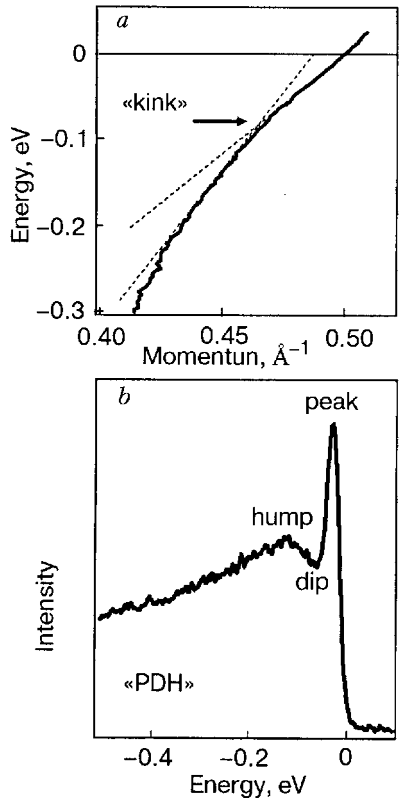

FIG. 6. The best known representatives for the nodal and antinodal regions: (*a*) a "70 meV kink" on the renormalized dispersion[16] and (*b*) a "peak-dip-hump" (PDH) line shape of a $(\pi,0)$ EDC.[12]

We have shown[19] that such a relation holds for a wide doping range: $x=0.1-0.2$. This means that the FS precisely satisfies the Luttinger theorem—the FS does not depend on interactions. This simple result has a far-reaching consequence, allowing one to conclude that *superconductivity in cuprates emerges from a metallic phase* but not from the AF insulating phase, the evolution from which would require a "small" $(\sim x)$ hole-like FS.[4)]

From high resolution FS maps measured for Bi-2212 in a wide doping range, taking into account the applicability of the Luttinger theorem, we have derived, within the tight-binding (TB) model, the bare band dispersion for this compound and found it to be in good agreement with LDA prediction.[20] Figure 4 shows a result of such a procedure—the bare band dispersion for an overdoped Bi(Pb)-2212 ($x=0.22$). Recent observation of small bilayer splitting along the nodal direction of Bi-2212 can be considered as the most precise measure of the agreement between LDA and experiment:[31] 0.012(1) Å^{-1} in momentum or 48(4) meV in energy (ARPES), 0.015 Å^{-1} or 50 meV (LDA).[5)]

The ability to resolve the BS for the cuprates with two adjacent CuO layers per unit cell is a distinguishing feature of new-century ARPES.[8] Now it has been observed not only for overdoped samples[8] but also for optimally doped and underdoped ones.[19,31,32][6)] The existence of the BS not only refutes the existence of the aforementioned electronic confinement[28] but also questions some interpretations of a "complex" line shape in terms of many-body effects in a number of photoemission spectra. Of particular interest has been the famous peak-dip-hump (PDH) structure seen in the $(\pi,0)$ region[33] (see Fig. 6b). This line shape was widely believed to be the result of a single spectral function (see Ref. 34 and references therein), the details of which are expected to reveal, at a fundamental level, the identity of the interactions involved in the generation and perpetuation of the superconducting state in these systems.[35,36] Using a wide range of excitation energies, we have shown[34] that the PDH structure mainly has a structural cause—is caused by the BS. In the overdoped case the structural PDH is entirely dominating, while for the underdoped compounds, the interaction really produces a PDH-like structure on the $(\pi,0)$ spectrum (intrinsic PDH) for only one antibonding band.[12] The magnitude of such a "dip" is much lower than the structural one and depends strongly on doping: it vanishes to the overdoped side.[37] Thus the interactions really effect the electronic density of states in the whole antinodal region[12,37,38] in the way proposed earlier,[35,36] but their influence is much less than had been believed and, more important, is highly doping dependent.

Another interesting "structure-related" issue is the position of the van Hove singularity (vHS), which is crucial for quantitative approbation of any proposed HTSC mechanisms, especially so-called van Hove scenarios.[40] Despite its importance, the evolution of the vHS with doping in Bi-2212 was not addressed in previous experiments.[7)] Now we can firmly say that for the doping range from $x=0.11$ to 0.22[19] the position of the bonding bare band at the saddle point, $\varepsilon_B(M)$, changes from ≈ 260 meV to 190 meV, and for the antibonding band, $\varepsilon_A(M)$—from 90 meV to 30 meV. This shift is consistent with the rigid band model[20] with $d\varepsilon/dx \approx 0.5$ eV, and one can speculate that the onset of superconductivity at $x=0.27$ is structure related—it happens when the antibonding vHS crosses the Fermi level. This intriguing hypothesis, however, seems not to be valid for one-layer compounds.[8)]

To summarize, the resolved electronic band structure of the cuprates keeps no mystery[9)] in the doping range where superconductivity occurs. In the normal state, even in the pseudogap region,[45] it is in good agreement with LDA band structure calculations. In the superconducting state a *d*-wave gap opens,[8] influencing the dispersion in a BCS manner.[45,46] The electronic interactions appear in renormalization effects: shifting and smearing out the distribution of the electronic states in momentum-energy space.

B. Role of interaction

The interactions in cuprates are anisotropic. In the end, this appears as a *d*-wave superconducting gap,[8] but a strong anisotropy is also present in the normal state, appearing as a pseudogap[1] and anisotropic scattering rate (Ref. 47).[10)] In order to illustrate the role of interactions in HTSC, we consider the nodal direction, along which the both superconducting gap and pseudogap vanish.

Figure 5a represents essentials of the nodal spectra analysis. The real distribution of the quasiparticle spectral weight is shown as a blurred region in a gray scale. It differs from the bare dispersion of noninteracting electrons, $\varepsilon(k)$, in two ways: it is shifted and smeared out. These can be described by two quantities: mass renormalization and finite lifetime, which, in terms of Eq. (1), are equal to the real and imaginary parts of the self-energy, respectively. In the case of weak dependence on k, the real part is just the difference between the bare dispersion and renormalized dispersion (derived as a set of positions of MDC maxima), while the imaginary part $\Sigma''(\omega)=v_F W(\omega)$, where $W(\omega)$ is the half width at half maximum of this quasiparticle cloud (MDC HWHM), and v_F, in a simplest case of linear dispersion $\varepsilon(k)=v_F(k-k_F)$, is the bare Fermi velocity. Given that $\varepsilon(k)$ is *a priori* unknown, the self-energy parts cannot be extracted from the photoemission spectra unless an additional correlation between these quantities takes place. If the quasiparticle description is applicable to the cuprates, the function $\Sigma(\omega)$, being derived from the causality-consistent Green's function, should be an analytical function, the real and imaginary parts of which are related by the Kramers-Kronig (KK) transformation.[48] This transformation is, however, nonlocal, meaning that both $\Sigma(\omega)$ and $\varepsilon(k)$ cannot be disentangled from APRES spectra locally (in narrow energy range, in practice). Nevertheless, we have shown recently[16] that, going deeper in energy, such a spectrum can be self-consistently described by Eq. (1) in the sense that the derived self-energy parts stay KK-related. This demonstrates the applicability of the quasiparticle approach to HTSC and opens a way to extract both the bare band structure and interaction functions from ARPES. Figures 5d and 5e show some results of such a procedure: $\Sigma'(\omega)$ (Ref. 16) and $\Sigma''(\omega)$ (Ref. 49). So, the main conclusion of this Section is that the renormalization effect—the quasiparticle self-energy—is the only place where the mystery of HTSC is hidden. To resolve this mystery, one should just understand the nature of the interactions that form the quasiparticles.

IV. NATURE OF INTERACTION

In order to understand the renormalization phenomenon in cuprates one should study its evolution in the phase-diagram arena—as a function of doping and temperature. Here we focus on two key spots in the Brillouin zone: nodal and antinodal regions.

First we go over the nodal direction. Since 1999,[17] an important feature is seen by ARPES in the nodal spectra—a so-called "kink" on the renormalized dispersion ~70 meV below E_F (see Fig. 6a and Refs. 8 and 9). Since one does not expect such a feature on the bare dispersion here, neither of such an energy scale nor so sharp, it has been treated as a renormalization effect,[17] and so it is. Therefore, a kink on the renormalized dispersion is a result of a kink on $\Sigma'(\omega)$ and, as a general consequence of causality, on $\Sigma''(\omega)$.[49] Historically, the kink has been associated first with a coupling to a bosonic mode,[50] and the magnetic resonance observed by inelastic neutron scattering (INS) (see Ref. 36 and references therein) has been suggested as a first candidate. Later,[51] the same group has reported a ubiquity of the kink for a number of families of HTSCs in a wide range of doping and temperature, and concluded in favor of a phononic nature of the mode. It is the most important result of recent studies[16,39,49] that both kinks on the renormalization[16] and scattering[49] have appeared to be *highly doping and temperature dependent*. The reason why in the previous studies such a strong dependence was not highlighted can be explained in part by unresolved bilayer splitting[31] but mainly by the influential contribution of the strong electron-electron interaction (see Fig. 5d).

In Ref. 49, we have managed to distinguish two scattering channels: the Auger-like decay and interaction with a mode. Panels (*b*) and (*c*) in Fig. 5 illustrate them, respectively. These two mechanisms describe the scattering of the photohole. In both mechanisms the hole is filled by an overlying electron, but in the former the energy excess is used to excite another electron above the Fermi level (Auger-like process), while in the later it is taken off by a boson. For a simplest case of constant density of states (DOS), the first process gives a typical Fermi-liquid behavior—quadratic dependence of the scattering rate on energy (or, for finite temperature, $\Sigma'' \sim \omega^2+\pi^2T^2$). The bosonic scattering yields a convolution of the occupied DOS with the bosonic spectrum and, in case of a single bosonic mode, is a steplike function stepped at the mode energy. Figure 5e shows the experimental scattering rate for an underdoped (UD) and overdoped (OD) Bi-2212 and its subdivision into two such channels. In reality, the Auger channel may deviate from a simple parabola due to peculiarities in the DOS, caused by van Hove singularities, gaps in the spectrum, etc., but these deviations have been found to be marginal.[49] In contrast, the bosonic channel exhibits strong dependence on temperature and doping—it vanishes completely vanishes with overdoping and above T^*.[39] Therefore, we associate the bosonic spectrum in question with the spectrum of magnetic excitations (spin fluctuations), which reveal similar dependences on doping and temperature.[36] In addition, very recently[52] we have found that the scattering between the bonding and antibonding bands exhibits an odd parity, similarly to the parity of the spin-fluctuation spectrum.

Beyond the properties mentioned, the magnetic spectrum exhibits a sophisticated structure over the momentum plane, peaked at (π,π) (see Ref. 36 and references therein). This turns us to the antinodal region, where in fact the renormalization effects have been found to be much stronger. Like the "kink" for the nodal region, the heavily discussed PDH line shape[33] (see Fig. 6d and Section III) is an undoubted hallmark of the antinodal area. It had been observed long before the kink, but the story of its understanding is very similar. First it was associated with the magnetic resonance, but later, being observed in the whole doping range in Bi-2212,[53] it has been reinterpreted in terms of phonons.[54] Later we have shown that, due to the bilayer splitting, one should distinguish a big "structural" PDH[34] and a much weaker "intrinsic" PDH.[12] The former is just a superposition of two bands, as it is seen in Fig. 2b for an OD sample. It makes the main contribution in PDH line shape of the $(\pi,0)$ EDC over the whole doping range. The later is negligible for OD samples but increases with underdoping producing, in total, a clear formation of a "gapped" region at a finite binding energy (manifestation of a sharp bosonic mode), as is shown in Fig. 2d.[12] By varying the excitation energy we have disentangled the effects of splitting and renormalization and evaluated the dependence of the coupling constant on doping. From this, one can conclude that (i) the sharp bosonic mode appears below T_c (Ref. 12) and (ii) the scattering to it starts from about $x=0.24$, increasing with underdoping so that at x

=0.12 it is about 4 times higher than the Auger-like electron-electron scattering (see Fig. 3 in Ref. 37).

To summarize this Section, the interaction which dresses the quasiparticles in cuprates can be subdivided into two channels: a conventional electron-electron scattering due to Coulomb interaction through the Auger-like decay, and an electron-boson scattering. All of the properties of the latter—doping, temperature and momentum dependence, as well as the parity—unambiguously point to its intimate relation with the spectrum of spin fluctuations. Therefore, it is the interaction between electrons, via both Coulomb interaction and spin exchange, that makes an overwhelming contribution to quasiparticle dynamics in cuprates. The coupling to phonons is much weaker and seems to be irrelevant for the HTSC problem.

V. CONCLUSIONS AND OUTLOOK

In this contribution we have reviewed the recent ARPES results which mark the way of evolution in our understanding of electronic structure of superconducting cuprates—a way from complexity to simplicity. We say "simple" and "complex," having in mind "mainly understandable" and "still mysterious."

So, what is simple in HTSC? These are (i) the bare electronic structure, and (ii) the way in which the interactions appear. The band structure seen by ARPES is very similar to the one predicted by LDA calculations. Its evolution with doping well follows the rigid band approximation and suggests a structural mechanism of the onset of superconductivity on the overdoped side. The bilayer splitting for the compounds with two adjacent CuO layers per unit cell has essentially complicated the situation earlier but now can be resolved and taken into account. Moreover, the splitting seems to be crucial for high T_c's of these compounds—introducing a strong odd scattering channel. It is surprising that, after 20 years of extensive study, the dominant interactions in cuprates have appeared to be describable by standard quasiparticle approach, in terms of the self-energy. Saying "dominant," we have in mind the pseudogap formation that seems to "fall out" of the quasiparticle approach, although, to make such a conclusion, careful study of the antinodal region is still needed.

Now, what remains complex? This is the mechanism of interaction. Although it is more or less clear that the spectrum of magnetic excitations, namely spin fluctuations, forms the main interaction from which the pairing originates, the exact realization of such a mechanism still waits to be discovered. The progress is anticipated in two directions: First, ARPES measurements with an improved accuracy, and their correlation with INS experiments. The fine structures of the pseudogap[30] and superconducting gap[55] should give information about the exact momentum distribution of the scattering and coupling bosons, and one of the most anticipated results is to locate the real gap maximum—either at the A point or in "hot spots." Second is the location of the interaction in the real space, for which finding a correlation between ARPES and STS becomes of great importance.[56,57] For instance, a hypothesis about phase separation into metallic and isolating regions should be checked, and the role of magnetic excitations in the later should be clarified.

Finally, it seems that the way from complexity to simplicity is one which leads out of the HTSC labyrinth. Although the light at the end is already seen, the unification of different experimental techniques is needed to find a way through.

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[1)] A semi-empirial explanation of why the measured photoelectron carries information about the properties of the remaining excitation (a photohole) is based on the "three step model."[8] In simple words one can say that the photoelectron gets information about the interaction in the first step of photoemission—the breaking of the coupling with other electrons.

[2)] Here we call "quasiparticles" any elementary electronic excitations which can be described in terms of Dyson self-energy[10] by Eq. (1). The excitations with a nonzero coherent component[11] we will call "well-defined quasiparticles."

[3)] This terminology starts from the nodal direction, i.e., $(0,0)-(\pm\pi,\pm\pi)$ or ΓX(Y) directions in the BZ, along which the superconducting *d*-wave gap function has a node—changes sign. The crossing point of the nodal direction with the FS is called the nodal point (N). On the contrary, the point on the FS where the gap is believed to be maximal, or, more precisely, where the FS crosses the BZ boundary, which is called the "antinodal" region, differs from paper to paper; in the most common definition it is thought of as an area around the $(\pi,0)$ point which covers the nearest A points on the FS.

[4)] Here we should mention the idea of FS "arcs" to which the large FS transforms in the pseudogap state and which evolves into four FS points with further underdoping.[29] Our data on pseudogap function[30] do not support this idea, although we admit that measuring the gap in photoemission is not straightforward,[20] and the problem of the pseudogap is still waiting for careful study.

[5)] We note that from TB fit to the FS shape one can extract the shape of the dispersion without the energy scale (reduced TB parameters).[20] In order to determine the scale, one needs to analyze self-consistently the renormalization effects.[16]

[6)] Despite this, there are still ARPES results discussed in favor of the absence of the BS for optimally doped and underdoped Bi-2212.[6]

[7)] The observation of the "extended" saddle point at 19 meV has been reported for Y-124,[40] but this value should be considered with caution because breaking of the chain layer during cleavage should substantially change the doping level of the topmost CuO layer in respect to the bulk. In case of Bi-2212 this point was also complicated by a "complex" PDH lineshape below T_c and very wide spectrum for higher temperatures, so the only position of the $(\pi,0)$ EDC peak ($\sim$50 meV[27]) and not that of the bare band could be determined.

[8)] A hole-to electron-like FS topological transition has been reported for Bi-2201[41] and LSCO,[42] although for Bi-2201 this result is not confirmed.[43]

[9)] Even the "shadow band," which one can see on FS maps of BSCO, and which was suggested to result from AFM correlations,[18] has been shown to have structural origin.[44]

[10)] The existence of the bilayer splitting naturally questions the conclusions of Ref. 47, although it seems that, similarly to the PDH story, some less-pronounced anisotropy really exists.

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