Quasiparticle excitations in cuprate superconductors and their relations to superconductivity

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In superconductors, quasiparticles are created when a Cooper pair of electrons breaks apart. Hence a better understanding of quasiparticle dynamics may help to uncover the mechanism for Cooper pairing in cuprate superconductor. Due to d-wave symmetry of the gap function, the quasiparticle spectra in cuprate are strongly momentum-dependent. The minimum excitation energy is zero for momenta in the "nodal" direction (oriented at 45° relative to the Cu-O bond), and is largest for momenta in "anti-nodal" direction (nearly parallel to the bond). It is found that both these two kind of excitations are closely related to the superconductivity. In our study, we review the experimental studies on the spectra properties and dynamics of these two quasiparticle excitations and examine their underlying relations to superconductivity phenomena.

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I. INTRODUCTION

The discovery of High temperature superconductors (HiTc) in copper oxide compounds has attracted wide interest both in the theoretical understanding of the superconductivity mechanisms beyond the conventional BCS theory and in possible technology applications [1, 2]. These superconductors all share a layered structure made up of one or more copper-oxygen planes. The phase diagram of a typical cuprate is given in Fig. 1. There are four phases: antiferromagnetic phase, pseudogap phase, superconducting phase and normal metal. Superconductivity emerges under the hole or electron doping of a Mott insulator to a critical amount [3] at sufficiently low temperature. The symmetry of the order parameter is d-wave $\Delta(k) \sim \Delta_0[cos(k_x a)cos(k_y a)]$ ($d_{x^2-y^2}$), where k is the wave vector [4]. The gap is maximal for momenta parallel to the Cu-O-Cu bond (anti-nodal direction) and zero for momenta at angles of 45° to this bond (nodal direction). This strongly momentum-anisotropy is reflected in the distinct behaviors of the quasiparticle (QP) excitations in different regions of the Brillouin zone [5]. This phenomenon is called the nodal and anti-nodal dichotomy.

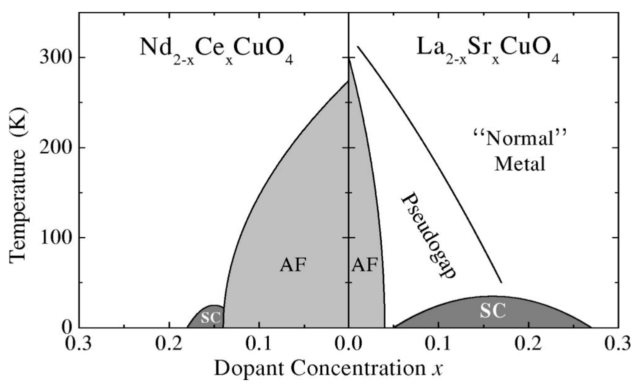

FIG. 1. Phase diagram of a typical cuprate superconductor. Figure quoted from Ref.[3]

People generally believes that the superconductivity in cuprates are due to the strong correlated nature of materials [6, 7]. Due to the complexity of the strong correlated systems, after decades of study, the underlying mechanism of the superconductivity still remains unknown. Although various theoretical models have been proposed to explain the underlying mechanism of the superconductivity in cuprate [6, 7], non of them can fully explain all the experimental results. Based on current understanding, people generally believe that the cuprate superconductivity is basically BCS like, despite that the binding mechanism the cooper pairs is not electron-phonon interactions. The complexity of directly addressing the cooper pairing drives us to indirect ways of understanding the superconductivity. QP is the fundamental concept underlying the modern understanding of the physics of metals. The idea is that the crucial low-energy eigenstates of interacting electron systems are "dressed"/renormalized ones similar to conventional electrons that they may be used in standard ways to calculate transport and other quantities. In conventional BCS superconductors, QPs are created when a Cooper pair of electrons breaks apart. Hence, we expect that if the QP picture works in cuprate, studying the properties and dynamics of QP in cuprate may shine some light on the mechanism of Cooper pairing.

The purpose of this paper is focused on the QPs in cuprate superconductor and their relations with superconductivity. We first argue the validity of the QP picture in HiTc cuprate. After this, we will introduce two experimental techniques which have been widely used to detect the spectra and dynamics of QPs in cuprate superconductors. In Sec II, we review some experimental studies of QPs dynamics and the distinct behaviors of nodal and anti-nodal QPs. Finally, we give a brief discussion of the experimental results and propose some theoretical models which may possibly help to explain the experimental results.

II. DETECTION OF THE QP EXCITATIONS

A. Validity of QP picture in HiTc cuprate

In conventional BCS theory, QPs play an essential role in characterizing the superconducting state via quantities such as the superconducting gap and its symmetry. However, theoretically, due to strong correlation and non-Fermi-liquid nature, the validity of the QP concept in HiTc cuprate is controversy on the theoretical aspects [8].

Detailed measurements of the singe electron spectral function in HiTc cuprate via Angle-resolved photoemission spetroscopy (ARPES, we will describe this technique in details in the following subsection) have demonstrated the existence [3, 9–11], near the Fermi surface of optimally doped materials, of reasonably well defined peaks. To give a clear sense of the QP spectrum, we quote the results of Ref.[9] and Ref.[11] in Fig. 2 which presents the coherent spectral weights of $Bi_2Sr_2CaCu_2O_x$ (Bi2212) in the vicinity of the $(\pi, 0)$ point and (π, π) of the Brillouin zone. We see that it is very natural to interpret the peak position in terms of a QP dispersion and the peak width in terms of a QP scattering rate. These QPs are proved to be Bogliubov-BCS like [10], indicating that the mechanism is basically BCS like although the underlying mechanism is still unknown.

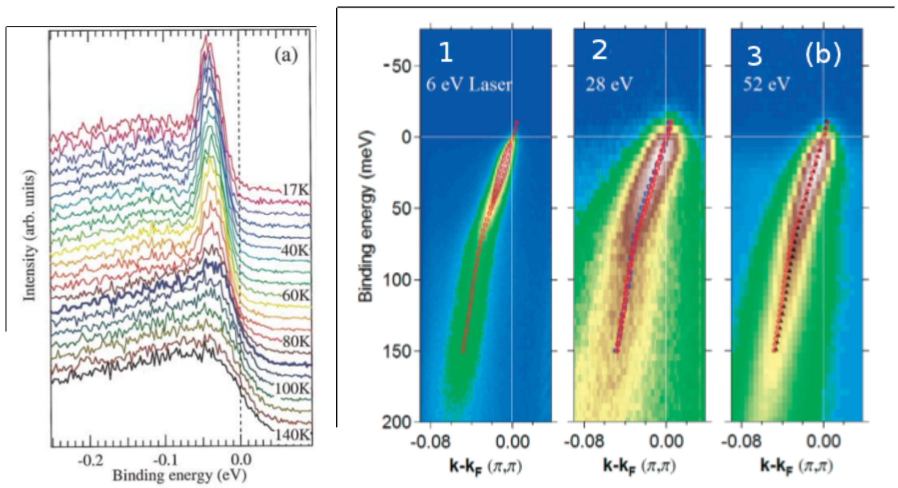

FIG. 2. ARPES spectra of QPs: (a)ARPES spectra at $(p, 0)$ of slightly overdoped Bi2212 ($T_c = 90K$) for different temperatures; (b)ARPES spectra along the node (π, π) in near- optimally doped Bi2212 using: 6 eV photons at T=25 K, 28 eV photons at T=26 K, and 52 eV photons at T=16 K. Figure (a) is quoted from Ref.[9] and Figure (b) is from Ref.[11].

B. Experimental techniques to observe the single particle spectral weight

1. *Pump-probe Spectroscopies*

The most straight forward experimental technique for exploring the QP dynamics is the so called pump-probe spectroscopy [12–14]. This method first excites a material above the ground state of the system with laser pulses which creates a nonequilibium density of QPs and henceforth affects the optical properties of the material, resulting in a measurable change of refraction index. The change as a function of time after injection of QPs are then measured via a time-delayed probe pulse. The dynamics of the QPs are studied by measuring the amplitude of the transmitted or reflected probe as a function of arrival time after the pump. Generically, one can obtain the lifetime of the photogenerated excitation from the rate of decay of the absorption or reflection.

2. Angle-resolved photoemission spetroscopy

Angle-resolved photoemission spectroscopy (ARPES) is a very powerful and sensitive experimental technique to study surface physics. It is based on the photoelectric effect. As we know, high Tc superconductors are layered copper-oxygen planes, which makes ARPES the most idea technique in studying the HiTc cuprate [3]. ARPES is directly observe the distribution of the electrons (more precisely, the density of single-particle electronic excitations) in the reciprocal space of solids and provides the energy-momentum spectrum of the systems. Fig. 3 shows a schematic configuration of of an APRES experiment.

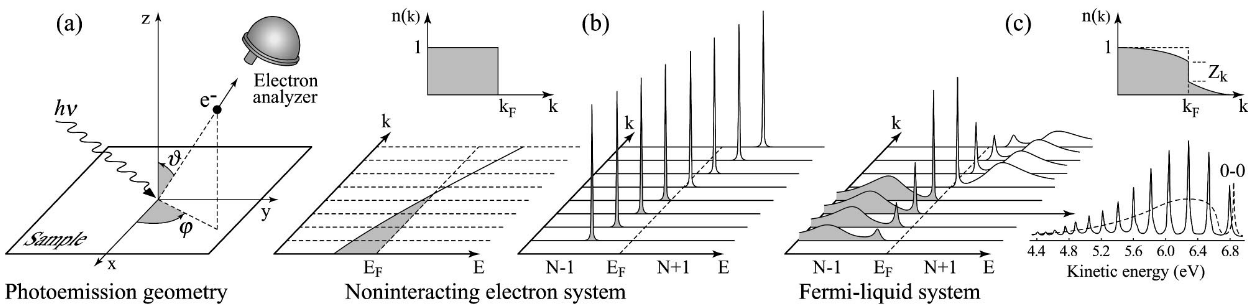

FIG. 3. Angle-resolved photoemission spetroscopy study of electronic system: (a) schematic configuration of an ARPES experiment; (b) momentum-resolved one-electron removal and addition spectra for a noninteracting electron system with a single energy band dispersing across E_F; (c) the same spectra for an interacting Fermi-liquid system. For both noninteracting and interacting systems the corresponding ground state ($T = 0K$) momentum distribution function $n(k)$ is also shown. Quoted from Ref. [3]

III. QUASIPARTICLE DYNAMICS AND RELATIONS TO SUPERCONDUCTIVITY

As we already known, in superconductivity, QPs are generated by breaking the cooper pairs. Hence we expect that by studying the QP excitations may shine some light on the underlying properties and mechanism of the cooper pairs.

A. Pump-probe spectroscopies study of the QP dynamics

Pump-probe techniques are used to study the transient optical response of cuprates [13]. It deals with the dynamics of cooper pair breaking and recombinations. By studying the optical interaction in these materials, one can understand the nonequilibrium superconducting properties which may reflect pairing mechanisms.

The first experimental study of the QP dynamics by using the pump-probe techniques is performed by Han et al in $YBa_2Cu_3O_7$ [13]. The major results are quoted in Fig. 4. They used the pumping probe technique and studied the photoinduced changes in reflectivity after pumping electrons using laser. By such they observed: (1)electron-Cooper-pair inelastic-scattering processes. (2)recombination of the photogenerated QP to form Cooper pairs via nonlinear kinetics. As we see from Fig. 4, comparing to the normal state case, in the superconducting state, there is an abrupt negative jump of the reflectivity at the time of pumping which is due to excitation of QPs via cooper paires. And suprisingly, the maximum of the peak value at different temperature closely follows the variation of the superfluid density as temperature changes, which clearly demonstrated the relations between the QP excitations and superfluid density. The life time of an order of psec of thoes transient QPs are also obtained from studying the reaxiation process — recombination of QPs dominated by releasing phonons.

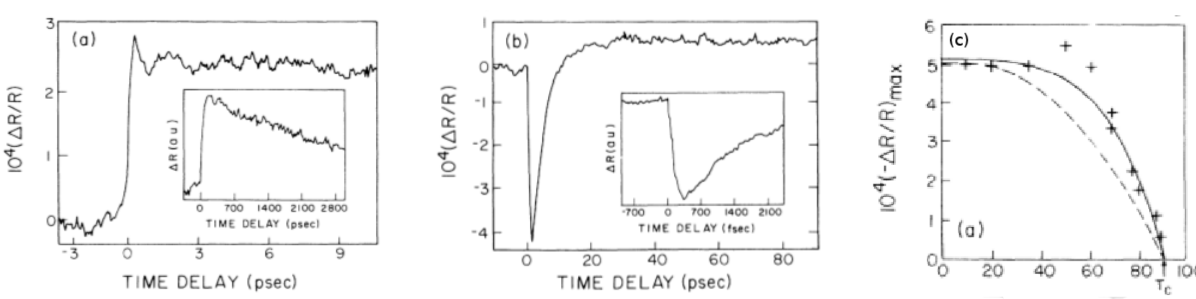

FIG. 4. Transient photoinduced reflectivity of superconducting 3000-Å $YBa_2Cu_3O_7$ (a) relative change of reflectivity in normal state $T = 300K$; relative change of reflectivity in superconducting state $T = 40K$; (c) comparison of the maximum reflectivity change with superfluid density in different temperature. Figures are quoted from Ref.[13] and reorganized.

B. ARPES studies of the quasiparticle spectra

Due to d-wave symmetry of the gap function, the quasi-particle spectrum in cuprate are strongly momentum-dependent. The minimal excitation energy is zero for momenta in the "nodal" direction (oriented at 45° relative to the Cu-O bond), and is largest for momenta in "anti-nodal" nodal direction (nearly parallel to the bond). We can expect that the single particle spectra are distinct in different regions of the Brillouin zone. Using ARPES, we are able to capture the momentum-anisotropy of the cuprate in details. In the following, we focus on the QPs excitations along nodal and anti-nodal directions of the Brillouin zone and investigate their relations with superfluid density.

1. Anti-nodal quasiparticle spectra

A naive thinking is that the superconductivity is closely related to the energy gap between the condensate ground state and the lowest excited quasiparticle state. Since this gap is maximum along the anti-nodal direction of the Brillouin zone. We should expect that the superconductivity is most possibly related to anti-nodal direction. In fact, this is the essential reason why the anti-nodal quasiparticles have been extensively investigated [9, 15].

Experimental studies confirm that the anti-nodal QPs are very sensitive to temperature [15]. As we can see from Fig. 5 (A) and (B) which present the spectra of Bi2212, coherent QP peaks are sharply formed only when $T < T_c$. Above T_c the peaks are very broad and hence the QPs are not well defined. We can conclude that anti-nodal QPs exist only below T_c. This is probably due to the fact that the life time of the anti-nodal QP is closely related to the energy gap $\sim \Delta$. This is reasonable based on the pump-probe studies in the last section. In fact, this is confirmed by the fact that the width of the resonance peaks (related to the life time of the particles) are closely tracking the superfluid density as temperature varies (results not showed here, for details please see Ref.[15]).

Furthermore, the spectral weight Z_A have also been directly linked to superfluid density [9] [See Fig. 5 (C) and (D)]. As we can see, the relative single particle spectral weight $Z_A(T)/Z_A(0)$ closely tracks the curve of the relative superfluid density $\rho(T)/\rho(0)$ (the superfluid density was computed from the penetration depth measurement). This again indicates that the anti-nodal excitations are related to the superconductivity.

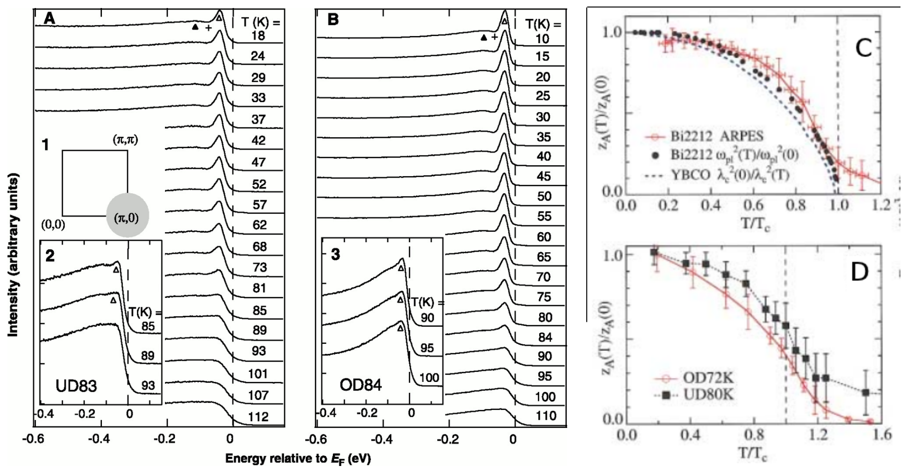

FIG. 5. Anti-nodal single particle spectra and its relations to superfluid density: (A)Temperature dependence of the superconducting state spectra of Bi2212 for (A) an underdoped $T_c = 83K$ sample and (B) an overdoped $T_c = 84K$ sample (E_F, Fermi energy). Insets 2 and 3 are enlargements of spectra taken above T_c; the open triangle markers show that the superconducting peak exists at temperatures slightly above T_c.(C) Normalized $Z_A(T)/Z_A(0)$ vs T/T_c for overdoped Bi2212 ($T_c = 90K$) compared with normalized c-axis superfluid density obtained from Josephson plasma resonance of overdoped Bi2212 ($T_c = 82K$) and microwave penetration depth of optimally doped $YBa_2Cu_3O_7$ ($T_c = 93.5K$). (D) Normalized QP weight, $Z_A(T)/Z_A(0)$ vs T/T_c , comparing overdoped(72K) and underdoped(80K) samples. Figures A and B are quoted from Ref.[15]. Figures C and D are quoted from Ref.[9].

2. *Nodal quasiparticle spectra*

In contrast to anti-nodal direction, the energy gap along the nodal direction vanishes completely. Nodal QPs, have received less attention and are usually regarded as largely immune to the superconducting transition because they seem insensitive to perturbations such as disorder, doping, isotope exchange, charge ordering, and temperature (Nodal QPs exists in both below and above T_c) [3]. Until a couple months ago, a paper published in Nature Physics revealed the relationship between the nodal QP spectra and superconductivity [16]. In this section, we will briefly summarize the main results in this paper.

Basically, Graf et al used a combination of the Pump-probe technique and high time resolution ARPES to study the QP spectra in transient states of optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$

[16]. First, a laser pulse was used to pump the electrons to excited states, generating a large non-equilibrium population of QPs and a depletion of the superconducting condensate; And then the subsequent recombination of these non-equilibrium QPs is detected via photoemission with a probe laser pulse as a function of a variable time delay between the pump and probe. They found that in the superconducting phase, the spectral weight of the nodal QPs are strongly suppressed in transient state compared to equilibrium state (see Fig.6(C) and (D)). No suppression was observed in normal states (see Fig.6(E) and (F)). What is more, the temperature dependent of the nodal spectral weight suppression closely tracks the changes of the superfluid density (see Fig.6(I)). Furthermore, they also found that the relaxation of the nodal QPs closely tracks the relaxation of the superfluid density (results not showed here). All of this discoveries undoubtedly indicate the relations of the nodal QPs with the superconductivity.

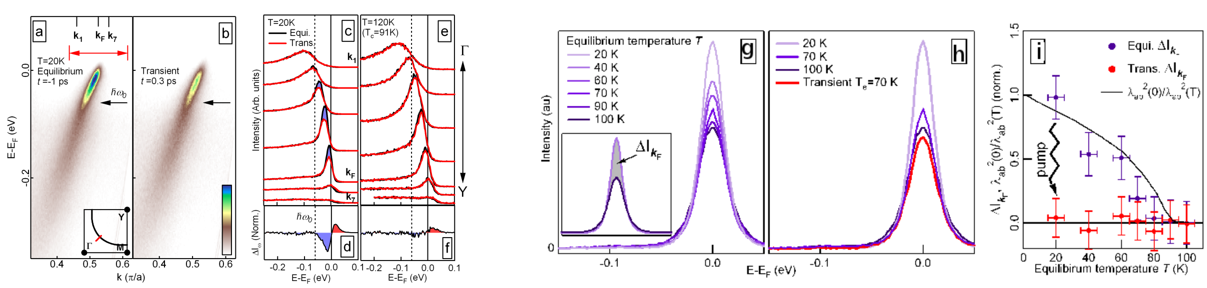

FIG. 6. (a) Energy distribution curves (EDCs) from k_1 to k_7 for the equilibrium (a, in black) and transient state (b, in red). Spectral weight loss (gain) is highlighted by the blue (red) areas. (d) ΔI_ω, the total difference between the transient and equilibrium EDCs, integrated over different momenta. (e-f) Same comparison as in panel (c-d) but with the equilibrium sample temperature at 120 K ($T_c = 91$ K). (f) Plot is shown on the same scale as (d). (g)Symmetrized equilibrium EDCs at k_F at different equilibrium temperatures. (h)Selected equilibrium EDCs from a compared with a transient EDC with an equilibrium temperature of 20 K and a transient electronic temperature of 70 K. (i)Equilibrium and transient ΔI_{E_F} as a function of equilibrium temperature, compared with the changes of superfluid density. The equilibrium and transient values of I_{E_F} are normalized by the equilibrium value of I_{E_F} at 20 K. Figures are quoted from Ref.[16] and reorganized.

IV. CONCLUSIONS AND PERSPECTIVES

In this paper, we investigated the spectral propertie and dynamics of QPs in cuprate. QPs can be generated by breaking cooper pairs via laser pumping and recombine to pairs via scattering and emitting phonons which determine the relaxation time of the excess QPs. Both the QPs along nodal and anti-nodal are related to superconductivity. The spectral weight of anti-nodal ones are directly related to superfluid density. And the spectra suppression of nodal ones in transient states compared to equilibrium states are also related to superfluid density.

Here we see that the relation of the QPs and the superfluid density are revealed by the spectral weight change of renormalized single particle degree of freedom. This is a special property of strong correlated system. In noninteracting or Fermi-liquid theory, the spectral weight is temperature independent. Hence, completely understanding of the HiTc superconductivity relies on a clear capture of the essence of the strong correlation in doped Mott insulator. In the nodal direction quasiparticles case, we see that below E_F, the spectra intensity is suppressed while above E_F the spectra intensity is enhanced (see Fig. 6(d) and (f)). This seems to be a spectra transfer from high energy regimes to low energy regimes as temperature increases. Phillips's charge-2e boson theory may help to capture this spectral weight transfer in strong correlated system, which maybe a possible way for us to understand the underlying theory of the results [7]. Unfortunately, the present theory is a zero temperature one, we need to generalize it to finite temperature cases.

More detailed experimental studies are also needed before completely understand the temperature dependent of the spectra change. The nature of transient states need further study. In Ref.[16], the author used Fermi-Dirac distribution to extract an effective temperature of the system in the transient state which is slightly higher than its original equilibrium state but still lower than T_c. While, the spectra weight decreased to a level even smaller than that at $T > T_c$. Based on this effect, they argued that this spectra suppression/transfer is not a temperature effect. However, the validity of the Fermi-Dirac distribution in a quasi-equilibrium transient state is problematic. One need further examine the statistical physics in transient states both theoretically and experimentally. Another point is that although the spectra transfer has been discovered in nodal direction, but do this effects occur also in anti-nodal direction? We know that the spectra transfer phenomena are common in strong correlated system. Furthermore is there any relation between nodal QPs and anti-nodal ones. In noninteracting system, we know different states of QPs are orthogonal to each other and are independent of filling. However, if the cuprate superconductivity is really governed by strong correlated nature, one should expect the spectra transfer between spectra in different regions of the Brillouin zone.

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