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Pseudogap and its connection to particle–hole asymmetry electronic state and Fermi arcs in cuprate superconductors

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ABSTRACT

The particle–hole asymmetry electronic state of cuprate superconductors and the related doping and temperature dependence of the Fermi arc length are studied based on the kinetic energy driven superconducting mechanism. By taking into account the interplay between the superconducting gap and normal-state pseudogap, the essential feature of the evolution of the Fermi arc length with doping and temperature is qualitatively reproduced. It is shown that the particle–hole asymmetry electronic state is a natural consequence due to the presence the normal-state pseudogap in the particle–hole channel. The Fermi arc length increases with increasing temperatures below the normal-state pseudogap crossover temperature T^*, and it covers the full length of the Fermi surface for $T > T^*$. In particular, in analogy to the temperature dependence of the Fermi arc length, the low-temperature Fermi arc length in the underdoped regime increases with increasing doping, and then it evolves into a continuous contour in momentum space near the end of the superconducting dome. The theory also predicts an almost linear doping dependence of the Fermi arc length.

1. Introduction

In the conventional superconductors [1], an energy gap exists in the electronic energy spectrum only below the superconducing (SC) transition temperature T_c, which is corresponding to the energy for breaking a Cooper pair of the charge carriers and creating two excited states. However, in cuprate superconductors above T_c but below a temperature T^*, an energy gap called the normal-state pseudogap exists [2–5]. Although the SC gap has a domelike shape of the doping dependence [6], the magnitude of the normal-state pseudogap is much larger than that of the SC gap in the underdoped regime [2–5], then it smoothly decreases upon increasing doping, and seems to merge with the SC gap in the overdoped regime, eventually disappearing together with superconductivity at the end of the SC dome [4]. Since many of the unusual physical properties of cuprate superconductors have often been attributed to particular characteristics of the low-energy excitations determined by the electronic structure [4–6], the normal-state pseudogap observed in the excitation spectrum as a suppression of the spectral weight is thought to be key to understanding the mechanism of superconductivity.

During the last two decades, the angle-resolved photoemission spectroscopy (ARPES) has been emerged as a powerful tool for studying the electronic structure of cuprate superconductors, since it is a direct method for probing the momentum dependence of the SC gap and the locus in the momentum space where the quasiparticle excitations are gapless [6]. In spite of the nonconventional SC mechanism, the ARPES experimental results have unambiguously established the Bogoliubov-quasiparticle nature of the sharp SC quasiparticle peak in cuprate superconductors in the overdoped regime [7], then the SC coherence of the low energy quasiparticle excitation is well fitted by a simple Bardeen–Cooper–Schrieffer (BCS) formalism [1] with a d-wave SC gap. However, the pseudogap state is particularly obvious in the underdoped regime [2–5], this leads to that the physical properties of cuprate superconductors in the underdoped regime exhibit a number of the anomalous properties [2,4–6,8–12]. In particular, the ARPES experimental data show that in the underdoped regime, although the normal-state of cuprate superconductors is metallic, the part of the Fermi surface is gapped out by the normal-state pseudogap, then the low-energy electron excitations occupy disconnected segments called as the Fermi arcs located at the nodal region in the Brillouin zone [8,9]. Moreover, in corresponding to the doping and temperature dependence of the normal-state pseudogap, the essential feature of the evolution of the Fermi arc length with doping and temperature has been established now [8–12]: (1) the Fermi arc in the underdoped regime increases in length with temperatures, till at about the normal-state pseudogap crossover temperature T^*, then it covers the full length of the Fermi surface (a continuous contour in momentum space) for the temperature $T > T^*$ [8–10]; (2) the Fermi arc increases its length as a function of doping [12], and then it

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evolves into a continuous contour in momentum space near the end of the SC dome. In particular, the experimental data indicate both the particle–hole symmetry breaking and the pronounced spectral broadending due to the presence of the normal-state pseudogap, which reflect the spatial symmetry breaking without long-range order at the opening of the normal-state pseudogap [13–15]. It is thus established that the low-energy quasiparticle excitations at the Fermi energy dramatically change with doping and temperature, and have a close relation to the normal-state pseudogap.

Although the main features of the particle–hole asymmetry electronic state in cuprate superconductors and the related doping and temperature dependence of the Fermi arc length are well-established by now [8–15], their full understanding is still a challenging issue. In our recent work [16], the interplay between the SC gap and normal-state pseudogap in cuprate superconductors has been studied based on the kinetic energy driven SC mechanism [17], where the charge carriers interact directly through the kinetic energy by exchanging spin excitations, then this microscopic interaction provides a natural explanation of both the origin of the normal-state pseudogap state in the particle–hole channel and the pairing mechanism for superconductivity in the particle–particle channel [16]. In this paper, we study the low-energy electronic structure of cuprate superconductors along with this line [16]. We evaluate explicitly the electron spectral function by taking into account the interplay between the SC gap and normal-state pseudogap, and then qualitatively reproduce the main features of the ARPES measurements on cuprate superconductors [8–14], including the doping and temperature dependence of the Fermi arc length.

The rest of this paper is organized as follows. We present the basic formalism in Section 2, while the quantitative characteristics of the particle–hole asymmetry electronic state are discussed in Section 3, where we show that the particle–hole asymmetry electronic state and the related doping and temperature dependence of the Fermi arc length are intriguingly related to the emergence of the normal-state pseudogap in the particle–hole channel. Finally, we give a summary in Section 4.

2. Theoretical framework

In cuprate superconductors, the single common feature is the presence of the CuO_2 plane [6], and it seems evident that the unusual behavior is dominated by this plane. Very soon after the discovery of superconductivity in cuprate superconductors, it has been argued that the essential physics of the doped CuO_2 plane is contained in the t–J model on a square lattice [18],

$$H = -t\sum_{i\hat{\eta}\sigma} C^{\dagger}_{i\sigma} C_{i+\hat{\eta}\sigma} + t'\sum_{i\hat{\tau}\sigma} C^{\dagger}_{i\sigma} C_{i+\hat{\tau}\sigma} + \mu\sum_{i\sigma} C^{\dagger}_{i\sigma} C_{i\sigma} + J\sum_{i\hat{\eta}} \mathbf{S}_i \cdot \mathbf{S}_{i+\hat{\eta}}, \tag{1}$$

supplemented by an important on-site local constraint $\sum_{\sigma} C^{\dagger}_{l\sigma} C_{l\sigma} \leqslant 1$ to remove the double occupancy, where the summation is over all sites i, and for each i, over its nearest-neighbors $\hat{\eta}$ or the next nearest-neighbors $\hat{\tau}$, $C^{\dagger}_{i\sigma}$ and $C_{i\sigma}$ are electron operators that respectively create and annihilate electrons with spin $\sigma, \mathbf{S}_i = (S^x_i, S^y_i, S^z_i)$ are spin operators, and μ is the chemical potential. For a proper treatment of the electron single occupancy local constraint in the t–J model (1), a charge-spin separation (CSS) fermion-spin theory [19,20] has been proposed, where a spin-up annihilation (spin-down annihilation) operator for the physical electron is given by a composite operator as $C_{i\uparrow} = h^{\dagger}_{i\uparrow} S^{-}_i \left(C_{i\downarrow} = h^{\dagger}_{i\downarrow} S^{+}_i \right)$, with the spinful fermion operator $h_{i\sigma} = e^{-i\Phi_{i\sigma}} h_i$ that keeps track of the charge degree of freedom of the electron together with some effects of spin configuration rearrangements due to the presence of the doped hole itself (charge carrier), while the spin operator S_i describes the spin degree of freedom of the electron, then the electron single occupancy local constraint is satisfied in analytical calculations. In this CSS fermion-spin representation, the t–J model (1) can be rewritten as [19,20],

$$\begin{aligned} H = {} & t\sum_{i\hat{\eta}} \left(h^{\dagger}_{i+\hat{\eta}\uparrow} h_{i\uparrow} S^{+}_i S^{-}_{i+\hat{\eta}} + h^{\dagger}_{i+\hat{\eta}\downarrow} h_{i\downarrow} S^{-}_i S^{+}_{i+\hat{\eta}} \right) \\ & - t'\sum_{i\hat{\tau}} \left(h^{\dagger}_{i+\hat{\tau}\uparrow} h_{i\uparrow} S^{+}_i S^{-}_{i+\hat{\tau}} + h^{\dagger}_{i+\hat{\tau}\downarrow} h_{i\downarrow} S^{-}_i S^{+}_{i+\hat{\tau}} \right) - \mu\sum_{i\sigma} h^{\dagger}_{i\sigma} h_{i\sigma} \\ & + J_{\rm eff}\sum_{i\hat{\eta}} \mathbf{S}_i \cdot \mathbf{S}_{i+\hat{\eta}}, \end{aligned} \tag{2}$$

where $J_{\rm eff} = (1-\delta)^2 J$, and the doping concentration $\delta = \left\langle h^{\dagger}_{i\sigma} h_{i\sigma} \right\rangle = \left\langle h^{\dagger}_i h_i \right\rangle$.

As in the conventional superconductors [1], the SC-state in cuprate superconductors is also characterized by the Cooper pairs, forming SC quasiparticles [21]. However, as a natural consequence of the unconventional SC mechanism that is responsible for the high SC transition temperatures [18], the Cooper pair in cuprate superconductors has a dominant d-wave symmetry [6,21]. In this case, one of the main concerns in the field of superconductivity in cuprate superconductors is about the origin of the d-wave Cooper pairs. From the experimental side, it has been well established that the antiferromagnetic short-range correlation coexists with the SC-state in the whole SC regime [22–26], which provides a clear link between the pairing mechanism and magnetic excitation. On the theoretical hand, we have developed a kinetic energy driven SC mechanism [17] based on the t–J model (2), where the charge carrier interaction directly from the kinetic energy by exchanging spin excitations induces a d-wave charge carrier pairing state in the particle–particle channel, then the electron Cooper pairs originating from the charge carrier pairing state are due to the charge-spin recombination, and their condensation reveals the SC ground-state. Moreover, this SC-state is controlled by both the SC gap and quasiparticle coherence, which leads to that the maximal SC transition temperature occurs around the optimal doping, and then decreases in both the underdoped and overdoped regimes. This microscopic SC theory gives a consistent description of the physical properties of cuprate superconductors, including the doping and temperature dependence of the microwave conductivity [27], the extinction of the quasiparticle scattering interference [28], and the doping dependence of the Meissner effect [29]. In particular, it has been shown recently that besides the pairing mechanism in the particle–particle channel provided by the charge carrier interaction directly from the kinetic energy by exchanging spin excitations, this same microscopic interaction also induces the normal-state pseudogap state in the particle–hole channel [16]. Based on this work [16], we [30] have discussed the doping dependence of the specific-heat of cuprate superconductors, and shown that the striking behavior of the specific-heat humplike anomaly near T_c in the underdoped regime can be attributed to the emergence of the normal-state pseudogap. Following our previous discussions [16,17], the full charge carrier diagonal and off-diagonal Green's functions of the t–J model (2) in the SC-state can be obtained as,

$$g(\mathbf{k},\omega) = \frac{1}{\omega - \xi_{\mathbf{k}} - \Sigma^{(\rm h)}_1(\mathbf{k},\omega) - \bar{\Delta}^2_{\rm h}(\mathbf{k}) \Big/ \left[\omega + \xi_{\mathbf{k}} + \Sigma^{(\rm h)}_1(\mathbf{k},-\omega) \right]}, \tag{3a}$$

$$\Gamma^{\dagger}(\mathbf{k},\omega) = -\frac{\bar{\Delta}_{\rm h}(\mathbf{k})}{\left[\omega - \xi_{\mathbf{k}} - \Sigma^{(\rm h)}_1(\mathbf{k},\omega) \right] \left[\omega + \xi_{\mathbf{k}} + \Sigma^{(\rm h)}_1(\mathbf{k},-\omega) \right] - \bar{\Delta}^2_{\rm h}(\mathbf{k})}, \tag{3b}$$