Available online at www.sciencedirect.com
ScienceDirect
Physics Letters A 361 (2007) 382–390
PHYSICS LETTERS A
www.elsevier.com/locate/pla

Electronic structure of kinetic energy driven superconductors

Huaiming Guo, Shiping Feng *

Department of Physics, Beijing Normal University, Beijing 100875, China

Received 16 May 2006; accepted 1 September 2006

Available online 29 September 2006

Communicated by J. Flouquet

Abstract

Within the framework of the kinetic energy driven superconductivity, we study the electronic structure of cuprate superconductors. It is shown that the spectral weight of the electron spectrum in the antinodal point of the Brillouin zone decreases as the temperature is increased. With increasing the doping concentration, this spectral weigh increases, while the position of the sharp superconducting quasiparticle peak moves to the Fermi energy. In analogy to the normal-state case, the superconducting quasiparticles around the antinodal point disperse very weakly with momentum. Our results also show that the striking behavior of the superconducting coherence of the quasiparticle peaks is intriguingly related to the strong coupling between the superconducting quasiparticles and collective magnetic excitations.

PACS: 74.20.Mn; 74.20.-z; 74.25.Jb

The parent compounds of cuprate superconductors are the Mott insulators with an antiferromagnetic (AF) long-range order (AFLRO), then changing the carrier concentration by ionic substitution or increasing the oxygen content turns these compounds into the superconducting (SC)-state leaving the AF short-range correlation still intact [1,2]. The single common feature of cuprate superconductors is the presence of the two-dimensional CuO_2 plane [1,2], and it seems evident that the unusual behaviors of cuprate superconductors are dominated by this CuO_2 plane [3]. This layered crystal structure leads to that cuprates superconductors are highly anisotropic materials, then the electron spectral function $A(\mathbf{k},\omega)$ is dependent on the in-plane momentum [4–6]. Experimentally, an agreement has emerged that at least in the SC-state, the electronic quasiparticle excitations are well defined and are the entities participating in the SC pairing [4–9]. According to a comparison of the density of states as measured by scanning tunneling microscopy [10] and angle-resolved photoemission spectroscopy (ARPES) spectral function [4,11] at the antinodal point, i.e., the $[\pi,0]$ point of the Brillouin zone, on identical samples, it has been shown that there is the presence of a shallow extended saddle point in the $[\pi,0]$ point [4–6], where the d-wave SC gap function is maximal, then the most contributions of the electron spectral function come from the $[\pi,0]$ point [4–6,11]. Moreover, recent improvements in the resolution of ARPES experiments allowed for an experimental verification of the particle–hole coherence in the SC-state and Bogoliubov-quasiparticle nature of the sharp SC quasiparticle peak near the $[\pi,0]$ point [7,12]. It is striking that in spite of the high temperature SC mechanism and observed exotic magnetic scattering [13–15] in cuprate superconductors, these ARPES experimental results [7,12] show that the SC coherence of the quasiparticle peak is described by the simple Bardeen–Cooper–Schrieffer (BCS) formalism [16]. It is thus established that the electron spectral function around the $[\pi,0]$ point dramatically changes with the doping concentration, and has a close relation to superconductivity.

Recently, we have developed a kinetic energy driven SC mechanism [17] based on the charge–spin separation (CSS) fermion–spin theory [18], where the dressed holon–spin interaction from the kinetic energy term induces the dressed holon pairing state by exchanging spin excitations, then the electron Cooper pairs originating from the dressed holon pairing state are due to the

* Corresponding author.
E-mail address: spfeng@bnu.edu.cn (S. Feng).

0375-9601/$ – see front matter
doi:10.1016/j.physleta.2006.09.048

charge–spin recombination, and their condensation reveals the SC ground-state. In particular, this SC-state is controlled by both SC gap function and quasiparticle coherence, then the maximal SC transition temperature occurs around the optimal doping, and decreases in both underdoped and overdoped regimes [19]. Within this framework of the kinetic energy driven superconductivity, we [19] have calculated the dynamical spin structure factor, and qualitatively reproduced all main features of inelastic neutron scattering experiments on cuprate superconductors, including the energy dependence of the incommensurate magnetic scattering at both low and high energies and commensurate resonance at intermediate energy [13–15]. It is believed that both experiments from ARPES and inelastic neutron scattering measurements produce interesting data that introduce important constraints on the microscopic models and SC theories for cuprate superconductors [4–6,13–15]. In this Letter, we study the electronic structure of cuprate superconductors under the kinetic energy driven SC mechanism. Within the t–t'–J model, we have performed a systematic calculation for the electron spectral function in the SC-state, and results show that the spectral weight in the $[\pi, 0]$ point increases with increasing doping, and decreases with increasing temperatures. Moreover, the position of the sharp SC quasiparticle peak in the $[\pi, 0]$ point moves to the Fermi energy as doping is increased. In analogy to the normal-state case [20,21], the SC quasiparticles around the $[\pi, 0]$ point disperse very weakly with momentum. Our results also show that the striking behavior of the SC coherence of the quasiparticle peaks is intriguingly related to the strong coupling between the SC quasiparticles and collective magnetic excitations.

In cuprate superconductors, the characteristic feature is the presence of the CuO_2 plane [1,2] as mentioned above. It has been shown from ARPES experiments that the essential physics of the doped CuO_2 plane is properly accounted by the t–t'–J model on a square lattice [4,22],

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

where $\hat{\eta} = \pm\hat{x}, \pm\hat{y}$, $\hat{\tau} = \pm\hat{x} \pm \hat{y}$, $C^{\dagger}_{i\sigma}$ ($C_{i\sigma}$) is the electron creation (annihilation) operator, $\mathbf{S}_i = C^{\dagger}_i \vec{\sigma} C_i/2$ is spin operator with $\vec{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ as Pauli matrices, and μ is the chemical potential. This t–t'–J model is subject to an important local constraint $\sum_\sigma C^{\dagger}_{i\sigma} C_{i\sigma} \leqslant 1$ to avoid the double occupancy. The strong electron correlation in the t–t'–J model manifests itself by this local constraint [3], which can be treated properly in analytical calculations within the CSS fermion–spin theory [18], where the constrained electron operators are decoupled as $C_{i\uparrow} = h^{\dagger}_{i\uparrow} S^{-}_i$ and $C_{i\downarrow} = h^{\dagger}_{i\downarrow} S^{+}_i$, with the spinful fermion operator $h_{i\sigma} = e^{-i\Phi_{i\sigma}} h_i$ describes the charge degree of freedom together with some effects of spin configuration rearrangements due to the presence of the doped hole itself (dressed holon), while the spin operator S_i describes the spin degree of freedom (spin), then the electron local constraint for the single occupancy, $\sum_\sigma C^{\dagger}_{i\sigma} C_{i\sigma} = S^{+}_i h_{i\uparrow} h^{\dagger}_{i\uparrow} S^{-}_i + S^{-}_i h_{i\downarrow} h^{\dagger}_{i\downarrow} S^{+}_i = h_i h^{\dagger}_i (S^{+}_i S^{-}_i + S^{-}_i S^{+}_i) = 1 - h^{\dagger}_i h_i \leqslant 1$, is satisfied in analytical calculations. Moreover, these dressed holon and spin are gauge invariant [18], and in this sense, they are real and can be interpreted as the physical excitations [23]. Although in common sense $h_{i\sigma}$ is not a real spinful fermion, it behaves like a spinful fermion. In this CSS fermion–spin representation, the low-energy behavior of the t–t'–J model (1) can be expressed as,

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

with $J_{\mathrm{eff}} = (1-\delta)^2 J$, and $\delta = \langle h^{\dagger}_{i\sigma} h_{i\sigma} \rangle = \langle h^{\dagger}_i h_i \rangle$ is the doping concentration. As an important consequence, the kinetic energy terms in the t–t'–J model have been transferred as the dressed holon–spin interactions, this reflects that even the kinetic energy terms in the t–t'–J Hamiltonian have strong Coulombic contributions due to the restriction of no doubly occupancy of a given site. In cuprate superconductors, the SC-state still is characterized by electron Cooper pairs as in the conventional superconductors, forming SC quasiparticles [24]. On the other hand, the range of the SC gap function and pairing force in the real space have been studied experimentally [25,26]. The early ARPES measurements [25] showed that in the real space the gap function and pairing force have a range of one lattice spacing. However, the recent ARPES measurements [26] indicated that in the underdoped regime the presence of the higher harmonic term $\cos(2k_x) - \cos(2k_y)$ in the SC gap function. Since the higher harmonic term $\cos(2k_x) - \cos(2k_y)$ is closely related to the next nearest neighbor interaction, just as the simple $\cos k_x - \cos k_y$ form in the SC gap function is closely related to the nearest neighbor interaction, then the higher harmonics imply an increase in the range of the pairing interaction [26]. In other words, the pairing interaction becomes more long range in the underdoped regime. These higher harmonics are doping dependent, and vanish in the overdoped regime. In particular, the SC gap anisotropy due to the deviations from the simple $\cos k_x - \cos k_y$ form renormalizes the slope of the superfluid density [26]. Although the quantitative description of the SC properties of cuprate superconductors in the underdoped regime needs to consider these higher harmonic effects, the qualitative SC properties are dominated by the gap function with the simple $\cos k_x - \cos k_y$ form [26]. As a qualitative discussions of the electronic structure of cuprate superconductors in this Letter, we do not take into account the higher harmonics in the SC gap function, and only focus on the SC gap function with the simple $\cos k_x - \cos k_y$ form. In this case, we can express the SC order