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Magnetic nature of superconductivity in doped cuprates

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Abstract

Within the kinetic energy driven superconducting mechanism, the magnetic nature of cuprate superconductors is discussed. It is shown that the superconducting state is controlled by both charge carrier gap function and quasiparticle coherent weight. This quasiparticle coherent weight grows linearly with the hole doping concentration in the underdoped and optimally doped regimes, and then decreases with doping in the overdoped regime, which leads to that the maximal superconducting transition temperature occurs around the optimal doping, and then decreases in both underdoped and overdoped regimes. Within this framework, we calculate the dynamical spin structure factor of cuprate superconductors, and reproduce all main features of inelastic neutron scattering experiments, including the energy dependence of the incommensurate magnetic scattering at both low and high energies and commensurate resonance at intermediate energy.

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1. Introduction

The interplay between the strong electron correlation and superconductivity is one of the most important problems raised by the discovery of cuprate superconductors [1]. After intensive investigations over more than a decade, it has become clear that the strong electron correlation in doped cuprates plays a crucial role not only for the unusual normal-state behavior but also for the superconducting (SC) mechanism [1–3]. The parent compound of cuprates superconductors is a Mott insulator with the antiferromagnetic (AF) long-range order (AFLRO), then changing the carrier concentration by ionic substitution or increasing the oxygen content turns these compounds into the SC-state leaving the AF short-range correlation (AFSRC) still intact [4]. As a function of the hole doping concentration, the SC transition temperature reaches a maximum in the optimal doping, and then decreases in both underdoped and overdoped regimes [5]. Moreover, this SC transition temperature is dependence of both charge carrier gap parameter and quasiparticle coherent weight [6], which strongly suggests that the quasiparticle coherence plays an important role in superconductivity.

By virtue of systematic studies using the nuclear magnetic resonance, and muon spin rotation techniques, particularly the inelastic neutron scattering, the doping and energy dependent magnetic excitations in doped cuprates in the SC-state have been well established: (a) at low energy, the incommensurate (IC) magnetic scattering peaks are shifted from the AF wave vector $[\pi,\pi]$ to four points $[(1\pm\delta)\pi,\pi]$ and $[\pi,(1\pm\delta)\pi]$ (in units of inverse lattice constant) with δ as the incommensurability parameter [7–9]; (b) then with increasing energy these IC magnetic scattering peaks are converged on the commensurate $[\pi,\pi]$ resonance peak at intermediate energy [7,10–12]; and (c) well above this resonance energy, the continuum of magnetic excitations peaked at IC positions in the diagonal direction

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are observed [13–15]. It has been emphasized that the geometry of these IC magnetic excitations is two-dimensional [16,13]. Although some of these magnetic properties have been observed in the normal-state, these IC magnetic scattering and commensurate resonance are the main new feature that appears into the SC-state. Moreover, AFSRC coexists with the SC-state in the whole SC regime [9], and the unusual magnetic excitations at high energy have energies greater than the SC pairing energy, are present at the SC transition temperature, and have spectral weight far exceeding that of the resonance [13,14]. These provide a clear link between the charge carrier pairing mechanism and magnetic excitations in cuprate superconductors.

Recently, we [17] have discussed the kinetic energy driven SC mechanism in doped cuprates based on the charge–spin separation (CSS) fermion–spin theory [18], where the dressed holons interact occurring directly through the kinetic energy by exchanging dressed spin excitations, leading to a net attractive force between dressed holons, then the electron Cooper pairs originating from the dressed holon pairing state are due to the charge–spin recombination, and their condensation reveals the SC ground-state. The SC transition temperature is proportional to the hole doping concentration in the underdoped regime. However, an obvious weakness is that the SC transition temperature is too high, and not suppressed in the overdoped regime [17]. In this paper, we study the magnetic nature of the kinetic energy superconductivity in doped cuprates along with this line. A short version of this work was published earlier [19]. One of our main results is that the SC transition temperature is suppressed to low temperatures by considering the quasiparticle coherence, and therefore the SC transition temperature is controlled by both charge carrier gap function and quasiparticle coherent weight. This quasiparticle coherent weight is closely related to the dressed holon self-energy from the dressed spin pair bubble, and grows linearly with increasing doping in the underdoped and optimally doped regimes, then decreases with increasing doping in the overdoped regime, which leads to that the maximal SC transition temperature occurs around the optimal doping, and then decreases in both underdoped and overdoped regimes. Within this SC mechanism, we give a theoretical explanation of inelastic neutron scattering experiments on cuprate superconductors [7,10–15] in terms of the collective mode in the dressed holon particle–particle channel.

The paper is organized as follows. The interplay between the quasiparticle coherence and superconductivity is discussed in Section 2. In Section 3, we calculate explicitly the dynamical spin structure factor of cuprate superconductors, and reproduce all main features found in experiments in the SC-state [7–15], including the energy dependence of the IC magnetic scattering at both low and high energies and commensurate $[\pi,\pi]$ resonance at intermediate energy. Section 4 is devoted to a summary and discussion.

2. Interplay between the quasiparticle coherence and superconductivity

In doped cuprates, the single common feature is the presence of the two-dimensional CuO_2 plane [4], it is believed that the relatively high SC transition temperature is closely related to doped CuO_2 planes. 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 [1],

$$H = -t\sum_{i\hat{\eta}\sigma} C^{\dagger}_{i\sigma}C_{i+\hat{\eta}\sigma} + \mu\sum_{i\sigma} C^{\dagger}_{i\sigma}C_{i\sigma} + J\sum_{i\hat{\eta}} \mathbf{S}_i\cdot\mathbf{S}_{i+\hat{\eta}}, \tag{1}$$

with $\hat{\eta} = \pm\hat{x}, \pm\hat{y}$, $C^{\dagger}_{i\sigma}$ ($C_{i\sigma}$) 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. The *t–J* model (1) is subject to an important local constraint to avoid the double occupancy, i.e., $\sum_{\sigma} C^{\dagger}_{i\sigma}C_{i\sigma} \leqslant 1$. In the *t–J* model, the strong electron correlation manifests itself by this single occupancy local constraint, and therefore the crucial requirement is to impose this local constraint. This local constraint 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 the spin configuration rearrangements due to the presence of the hole itself (dressed holon), while the spin operator S_i describes the spin degree of freedom (dressed spin), then the electron local constraint for the single occupancy is satisfied in analytical calculations [18]. In this CSS fermion–spin representation, the low-energy behavior of the *t–J* model (1) can be expressed as [17–19],

$$\begin{aligned} H = {} & -t\sum_{i\hat{\eta}}\left(h_{i\uparrow}S^{+}_i h^{\dagger}_{i+\hat{\eta}\uparrow}S^{-}_{i+\hat{\eta}} + h_{i\downarrow}S^{-}_i h^{\dagger}_{i+\hat{\eta}\downarrow}S^{+}_{i+\hat{\eta}}\right) \\ & - \mu\sum_{i\sigma} h^{\dagger}_{i\sigma}h_{i\sigma} + J_{\mathrm{eff}}\sum_{i\hat{\eta}} \mathbf{S}_i\cdot\mathbf{S}_{i+\hat{\eta}}, \end{aligned} \tag{2}$$

with $J_{\mathrm{eff}} = (1-x)^2 J$, and $x = \langle h^{\dagger}_{i\sigma}h_{i\sigma}\rangle = \langle h^{\dagger}_i h_i\rangle$ is the hole doping concentration. As a consequence, the kinetic energy (t) term in the *t–J* model has been expressed as the dressed holon–spin interaction, which reflects that even kinetic energy term in the *t–J* model has strong Coulombic contributions due to the restriction of single occupancy of a given site. This dressed holon–spin interaction is quite strong, and we [17,19] have shown in terms of Eliashberg's strong coupling theory [20,21] that in the case without AFLRO, this interaction can induce the dressed holon pairing state (then the electron Cooper pairing state) by exchanging dressed spin excitations in the higher power of the hole doping concentration x. The angle resolved photoemission spectroscopy (ARPES) measurements [22] have shown that in the real space the gap function and pairing force have a range of one lattice spacing, this indicates that the order parameter for the electron Cooper pair can be expressed as,