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Interplay between superconductivity and pseudogap state in bilayer cuprate superconductors

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ABSTRACT

The interplay between the superconducting gap and normal-state pseudogap in the bilayer cuprate superconductors is studied based on the kinetic energy driven superconducting mechanism. It is shown that the charge carrier interaction directly from the *interlayer* coherent hopping in the kinetic energy by exchanging spin excitations does not provide the contribution to the normal-state pseudogap in the particle–hole channel and superconducting gap in the particle–particle channel, while only the charge carrier interaction directly from the *intralayer* hopping in the kinetic energy by exchanging spin excitations induces the normal-state pseudogap in the particle–hole channel and superconducting gap in the particle–particle channel, and then the two-gap behavior is a universal feature for the single layer and bilayer cuprate superconductors.

The conventional superconductors are characterized by the energy gap, which exists in the excitation spectrum below the superconducting (SC) transition temperature T_c, and therefore is corresponding to the energy for breaking a Cooper pair of the charge carriers and creating two quasiparticles [1]. However, in the cuprate superconductors, an energy gap called the normal-state pseudogap exists [2,3] above T_c but below the pseudogap crossover temperature T^*, which is associated with some anomalous properties. Although the charge carrier pair gap in the cuprate superconductors has a domelike shape of the doping dependence [4,5], the magnitude of the normal-state pseudogap is much larger than that of the charge carrier pair gap in the underdoped regime [2,3], then it smoothly decreases upon increasing doping, and seems to merge with the charge carrier pair gap in the overdoped regime, eventually disappearing together with superconductivity at the end of the SC dome [2]. In this case, the charge carrier pair gap and normal-state pseudogap are thus two fundamental parameters of the cuprate superconductors whose variation as a function of doping and temperature provides important information crucial to understanding the details of superconductivity [2,3].

Experimentally, a large body of experimental data obtained by using different measurement techniques have provided rather detailed information on the low-energy excitations of the single layer and bilayer cuprate superconductors [2–5], where the Bogoliubov-quasiparticle nature of the low-energy excitations is unambiguously established [6]. However, there are numerous anomalies for the bilayer cuprate superconductors [4,5], which complicate the physical properties of the low-energy excitations in the bilayer cuprate superconductors. This follows a fact that the bilayer splitting (BS) has been observed in the bilayer cuprate superconductors in a wide doping range [7], which derives the low-energy excitation spectrum into the bonding and antibonding components due to the presence of the bilayer blocks in the unit cell. In particular, it has been argued that this BS may play an important role in the form of the well-pronounced peak-dip-hump structure in the low-energy excitation spectrum of the bilayer cuprate superconductors [8–10]. In this case, an important issue is whether the behavior of the normal-state pseudogap observed in the low-energy excitation spectrum as a suppression of the spectral weight is universal or not. Within the framework of the kinetic energy driven SC mechanism [11], the interplay between the SC gap and normal-state pseudogap in the single layer cuprate superconductors has been studied recently [12], where the interaction between charge carriers and spins directly from the kinetic energy by exchanging spin excitations induces the normal-state pseudogap state in the particle–hole channel and SC-state in the particle–particle channel, then there is a coexistence of the SC gap and normal-state pseudogap in the whole SC dome. In particular, this normal-state pseudogap is closely related to the quasiparticle coherent weight, and both the normal-state pseudogap and SC gap are dominated by one energy scale. In this Letter, we study the interplay between

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the SC gap and normal-state pseudogap in the bilayer cuprate superconductors along with this line. We show explicitly that the weak charge carrier interaction directly from the *interlayer* coherent hopping in the kinetic energy by exchanging spin excitations does not provide the contribution to the normal-state pseudogap in the particle–hole channel and SC gap in the particle–particle channel, while only the strong charge carrier interaction directly from the *intralayer* hopping in the kinetic energy by exchanging spin excitations induces the normal-state pseudogap in the particle–hole channel and SC gap in the particle–particle channel, and then the two-gap behavior is a universal feature for the single layer and bilayer cuprate superconductors.

The single common feature in the layered crystal structure of the cuprate superconductors is the presence of the two-dimensional CuO_2 plane [4], and then it is believed that the unconventional physics properties of the cuprate superconductors is closely related to the doped CuO_2 planes [13]. In this case, it is commonly accepted that the essential physics of the doped CuO_2 plane [13] is captured by the t–J model on a square lattice. However, for discussions of the interplay between the SC gap and normal-state pseudogap in the bilayer cuprate superconductors, the t–J model can be extended by including the bilayer interaction as [8],

$$H = -t\sum_{i\hat{\eta}a\sigma} C^{\dagger}_{ia\sigma}C_{i+\hat{\eta}a\sigma} + t'\sum_{i\hat{\tau}a\sigma} C^{\dagger}_{ia\sigma}C_{i+\hat{\tau}a\sigma} - \sum_{i\sigma} t_{\perp}(i)\big(C^{\dagger}_{i1\sigma}C_{i2\sigma} + H.c.\big) + \mu\sum_{ia\sigma} C^{\dagger}_{ia\sigma}C_{ia\sigma} + J\sum_{i\hat{\eta}a} \mathbf{S}_{ia}\cdot\mathbf{S}_{i+\hat{\eta}a} + J_{\perp}\sum_{i} \mathbf{S}_{i1}\cdot\mathbf{S}_{i2}, \quad (1)$$

supplemented by the local constraint $\sum_{\sigma} C^{\dagger}_{ia\sigma}C_{ia\sigma} \leqslant 1$ to remove double occupancy, where $a = 1, 2$ is plane index, the summation within the plane is over all sites i, and for each i, over its nearest-neighbors $\hat{\eta}$ or the next nearest-neighbors $\hat{\tau}$, $C^{\dagger}_{ia\sigma}$ and $C_{ia\sigma}$ are electron operators that respectively create and annihilate electrons with spin σ, $\mathbf{S}_i = (S^x_i, S^y_i, S^z_i)$ are spin operators, μ is the chemical potential, while the interlayer hopping has the form in the momentum space,

$$t_{\perp}(\mathbf{k}) = \frac{t_{\perp}}{4}(\cos k_x - \cos k_y)^2, \quad (2)$$

which describes coherent hopping between the CuO_2 planes. This functional form of the interlayer hopping (2) is predicted on the basis of the local density approximation calculations [14], and later the experimental observed BS agrees well with it [7]. In this bilayer t–J model (1), the crucial requirement is to impose the electron single occupancy local constraint, which can be treated properly in analytical calculations within the charge–spin separation (CSS) fermion-spin theory [15,16], where the constrained electron operators are decoupled as $C_{ia\uparrow} = h^{\dagger}_{ia\uparrow}S^{-}_{ia}$ and $C_{ia\downarrow} = h^{\dagger}_{ia\downarrow}S^{+}_{ia}$, with the spinful fermion operator $h_{ia\sigma} = e^{-i\Phi_{ia\sigma}}h_{ia}$ that represents the charge degree of freedom together with some effects of the spin configuration rearrangements due to the presence of the doped hole itself (charge carrier), while the spin operator S_{ia} describes the spin degree of freedom, then the electron single occupancy local constraint is satisfied in analytical calculations. In this CSS fermion-spin representation, the bilayer t–J model (1) can be expressed as,

$$H = t\sum_{i\hat{\eta}a}\big(h^{\dagger}_{i+\hat{\eta}a\uparrow}h_{ia\uparrow}S^{+}_{ia}S^{-}_{i+\hat{\eta}a} + h^{\dagger}_{i+\hat{\eta}a\downarrow}h_{ia\downarrow}S^{-}_{ia}S^{+}_{i+\hat{\eta}a}\big) - t'\sum_{i\hat{\tau}a}\big(h^{\dagger}_{i+\hat{\tau}a\uparrow}h_{ia\uparrow}S^{+}_{ia}S^{-}_{i+\hat{\tau}a} + h^{\dagger}_{i+\hat{\tau}a\downarrow}h_{ia\downarrow}S^{-}_{ia}S^{+}_{i+\hat{\tau}a}\big) + \sum_{i} t_{\perp}(i)\big(h^{\dagger}_{i2\uparrow}h_{i1\uparrow}S^{+}_{i1}S^{-}_{i2} + h^{\dagger}_{i1\uparrow}h_{i2\uparrow}S^{+}_{i2}S^{-}_{i1} + h^{\dagger}_{i2\downarrow}h_{i1\downarrow}S^{-}_{i1}S^{+}_{i2} + h^{\dagger}_{i1\downarrow}h_{i2\downarrow}S^{-}_{i2}S^{+}_{i1}\big) - \mu\sum_{ia\sigma} h^{\dagger}_{ia\sigma}h_{ia\sigma} + J_{\mathrm{eff}}\sum_{i\hat{\eta}a} \mathbf{S}_{ia}\cdot\mathbf{S}_{i+\hat{\eta}a} + J_{\mathrm{eff}\perp}\sum_{i} \mathbf{S}_{i1}\cdot\mathbf{S}_{i2}, \quad (3)$$

where $J_{\mathrm{eff}} = J(1-\delta)^2$, $J_{\mathrm{eff}\perp} = J_{\perp}(1-\delta)^2$, and $\delta = \langle h^{\dagger}_{ia\sigma}h_{ia\sigma}\rangle = \langle h^{\dagger}_{ia}h_{ia}\rangle$ is the doping concentration.

For the bilayer cuprate superconductors, there are two coupled CuO_2 planes in one unit cell. In this case, the SC order parameter for the electron Cooper pair is a matrix [8] $\Delta = \Delta_{\mathrm{L}} + \sigma_x\Delta_{\mathrm{T}}$, with Δ_{L} and Δ_{T} are the corresponding longitudinal and transverse parts, respectively. In the doped regime without an antiferromagnetic long-range order (AFLRO), the charge carriers move in the background of the disordered spin liquid state, and then the longitudinal and transverse SC order parameters can be expressed in the CSS fermion-spin representation as, $\Delta_{\mathrm{L}} = -\chi_1\Delta_{\mathrm{hL}}$ and $\Delta_{\mathrm{T}} = -\chi_{\perp}\Delta_{\mathrm{hT}}$, with

$$\Delta_{\mathrm{hL}} = \langle h_{i+\hat{\eta}a\downarrow}h_{ia\uparrow} - h_{i+\hat{\eta}a\uparrow}h_{ia\downarrow}\rangle, \quad (4a)$$

$$\Delta_{\mathrm{hT}} = \langle h_{i2\downarrow}h_{i1\uparrow} - h_{i2\uparrow}h_{i1\downarrow}\rangle, \quad (4b)$$

are the corresponding longitudinal and transverse parts of the charge carrier pair gap parameter, respectively, and the spin correlation functions $\langle S^{+}_{ia}S^{-}_{i+\hat{\eta}a}\rangle = \langle S^{-}_{ia}S^{+}_{i+\hat{\eta}a}\rangle = \chi_1$ and $\langle S^{+}_{i1}S^{-}_{i2}\rangle = \langle S^{-}_{i1}S^{+}_{i2}\rangle = \chi_{\perp}$. The result in Eq. (4) shows that as in the single layer case [11], the SC gap parameter in the bilayer cuprate superconductors is also closely related to the corresponding charge carrier pair gap parameter, and therefore the essential physics in the SC-state is dominated by the corresponding one in the charge carrier pairing state.

Within the framework of the kinetic energy driven SC mechanism [11], the electronic structure of the bilayer cuprate superconductors has been discussed [8,16], and the result shows that the low-energy excitation spectrum is split into the bonding and antibonding components due to the presence of BS, then the observed peak-dip-hump structure is mainly caused by BS, with the peak being related to the antibonding component, and the hump being formed by the bonding component. Following our previous discussions [8,16], the self-consistent equations that satisfied by the full charge carrier normal and anomalous Green's functions are obtained as,

$$g(\mathbf{k},\omega) = g^{(0)}(\mathbf{k},\omega) + g^{(0)}(\mathbf{k},\omega)\big[\Sigma^{(\mathrm{h})}_1(\mathbf{k},\omega)g(\mathbf{k},\omega) - \Sigma^{(\mathrm{h})}_2(-\mathbf{k},-\omega)\Im^{\dagger}(\mathbf{k},\omega)\big], \quad (5a)$$

$$\Im^{\dagger}(\mathbf{k},\omega) = g^{(0)}(-\mathbf{k},-\omega)\big[\Sigma^{(\mathrm{h})}_1(-\mathbf{k},-\omega)\Im^{\dagger}(-\mathbf{k},-\omega) + \Sigma^{(\mathrm{h})}_2(-\mathbf{k},-\omega)g(\mathbf{k},\omega)\big], \quad (5b)$$

respectively, where the full charge carrier normal Green's function $g(\mathbf{k},\omega) = g_{\mathrm{L}}(\mathbf{k},\omega) + \sigma_x g_{\mathrm{T}}(\mathbf{k},\omega)$, the full charge carrier anomalous Green's function $\Im^{\dagger}(\mathbf{k},\omega) = \Im^{\dagger}_{\mathrm{L}}(\mathbf{k},\omega) + \sigma_x\Im^{\dagger}_{\mathrm{T}}(\mathbf{k},\omega)$, the charge carrier self-energies $\Sigma^{(\mathrm{h})}_1(\mathbf{k},\omega) = \Sigma^{(\mathrm{h})}_{1\mathrm{L}}(\mathbf{k},\omega) + \sigma_x\Sigma^{(\mathrm{h})}_{1\mathrm{T}}(\mathbf{k},\omega)$ and $\Sigma^{(\mathrm{h})}_2(\mathbf{k},\omega) = \Sigma^{(\mathrm{h})}_{2\mathrm{L}}(\mathbf{k},\omega) + \sigma_x\Sigma^{(\mathrm{h})}_{2\mathrm{T}}(\mathbf{k},\omega)$ in the particle–hole and particle–particle channels, respectively, while the mean-field (MF) charge carrier normal Green's function $g^{(0)}(\mathbf{k},\omega) = g^{(0)}_{\mathrm{L}}(\mathbf{k},\omega) + \sigma_x g^{(0)}_{\mathrm{T}}(\mathbf{k},\omega)$, with the corresponding longitudinal and transverse parts have been obtained as [8,16],