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Interplay between charge order and superconductivity in cuprate superconductors

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ABSTRACT

One of the central issues in the recent study of cuprate superconductors is the interplay of charge order with superconductivity. Here the interplay of charge order with superconductivity in cuprate superconductors is studied based on the kinetic-energy-driven superconducting (SC) mechanism by taking into account the intertwining between the pseudogap and SC gap. It is shown that the appearance of the Fermi pockets is closely associated with the emergence of the pseudogap. However, the distribution of the spectral weight of the SC-state quasiparticle spectrum on the Fermi arc, or equivalently the front side of the Fermi pocket, and back side of Fermi pocket is extremely anisotropic, where the most part of the spectral weight is located around the tips of the Fermi arcs, which in this case coincide with the hot spots on the electron Fermi surface (EFS). In particular, as charge order in the normal-state, this EFS instability drives charge order in the SC-state, with the charge-order wave vector that is well consistent with the wave vector connecting the hot spots on the straight Fermi arcs. Furthermore, this charge-order state is doping dependent, with the charge-order wave vector that decreases in magnitude with the increase of doping. Although there is a coexistence of charge order and superconductivity, this charge order antagonizes superconductivity. The results from the SC-state dynamical charge structure factor indicate the existence of a quantitative connection between the low-energy electronic structure and collective response of the electron density. The theory also shows that the pseudogap and charge order have a root in common, they and superconductivity are a natural consequence of the strong electron correlation.

1. Introduction

The understanding of the mechanism of superconductivity in cuprate superconductors remains one of the most intriguing problems in condensed matter physics. The parent compound of cuprate superconductors is a half-filled Mott insulator [1,2], which occurs to be due to the strong electron correlation [3,4]. Superconductivity is derived from doping this parent Mott insulator [1,2], indicating that superconductivity and the related exotic physics in the doped regime are also dominated by the same strong electron correlation. In conventional superconductors [5,6], 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 electrons and creating two excited states. However, in cuprate superconductors above T_c but below a characteristic temperature T^*, an energy gap called the pseudogap exists [7,8]. In particular, this pseudogap is most notorious in the underdoped regime, where the charge carrier concentration is too low for the optimal superconductivity [7,8].

However, the strong electron correlation also induces the system to find new way to lower its total energy, often by spontaneous breaking of the native symmetries of the lattice [9]. This tendency leads to that the pseudogap regime harbors diverse manifestations of the ordered electronic phases, and then a characteristic feature in the complicated phase diagram of cuprate superconductors is the interplay between different ordered electronic states and superconductivity [7–9]. In particular, by virtue of systematic studies using the scanning tunneling microscopy (STM), resonant X-ray scattering (RXS), angle-resolved photoemission spectroscopy (ARPES), and many other measurement technique [9–22], it has been found recently that charge order is a universal phenomenon in cuprate superconductors, which exists within the pseudogap phase, appearing below a temperature T_{CO} well above T_c in the underdoped regime, and coexists with superconductivity below T_c. T_{CO} is the temperature where charge order develops, and is of the order of the pseudogap crossover temperature T^*. This near coincidence of T^* and T_{CO}, as well as the coexistence of charge order and superconductivity below T_c, suggests that a crucial role in the pseudogap phase is played by charge order [9]. These experimental observations also identified that charge order in the pseudogap phase of cuprate

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superconductors emergences consistently in surface and bulk, and in momentum and real space. Furthermore, the combination of the RXS data and electron Fermi surface (EFS) measured results using ARPES revealed a quantitative link between the charge-order wave vector $Q_{\rm CO}$ and the momentum vector connecting the tips of the straight Fermi arcs [9,10,14], which in this case coincide with the hot spots on EFS, indicating that the hot spots play an important role in the charge-order formation. This correspondence also shows the existence of a quantitative connection between the collective response of the electron density and the low-energy electronic structure. As a natural consequence of a doped Mott insulator, the charge-order state is also doping dependent, with the magnitude of the charge-order wave vector $Q_{\rm CO}$ that decreases upon the increase of doping, in the analogy of the unusual behavior of the doping dependence of the pseudogap [9–22]. These experimental results observed on cuprate superconductors [9–22] therefore show that charge order more intrinsically intertwines with superconductivity. In this case, some crucial questions are raised: (i) does the strong electron correlation play a role in the charge-order state and its interplay with superconductivity? (ii) is charge order also the result of the emergence of the pseudogap? (iii) do charge order and the SC order compete?

Since the discovery of charge order and its evolution with doping and temperature in the pseudogap phase of cuprate superconductors, the intense efforts at the experimental and theoretical levels have been put forth in order to understand the physical origin of charge order and of its interplay with superconductivity [9]. On the one hand, the possible special role played by the tips of the Fermi arcs has been discussed phenomenologically within the context of a magnetically-driven charge-order instability [23–28], where the charge-order wave vectors spanning the hot spots are a manifestation of the pseudogap formation due to charge order, rather than being suggestive of pre-existing Fermi arcs that are unstable to charge order. However, a different proposal attributes the pseudogap phase to the pair-density-wave state [29,30], while charge order only appears in the pseudogap phase as a subsidiary order parameter, and the tips of the Fermi arcs themselves result from an EFS instability around the antinodal region that is distinct from charge order. In particular, the physical origin of charge order has been studied based on the $t-J$ model by taking into account the pseudogap effect [31], where the charge-order state is driven by the pseudogap-induced EFS instability, with the charge-order wave vector corresponding to the straight hot spots on EFS. This study [31] also indicates that charge order is intimately related to pseudogap, and they are a natural consequence of the strong electron correlation in cuprate superconductors. On the other hand, it has been argued that the emergence of charge order in the SC-state is consistent with the picture of the anticorrelation between charge order and superconductivity [9,22,32], i.e., these two order parameters are related, as opposed to simply coexisting and competing. Moreover, a possible common origin of the main instabilities in cuprate superconductors has been suggested, namely, the possibility that the sequence of ordering tendencies ($\mathbf{Q}=0$ order precedes charge order, which in turn precedes the SC order) and the phase diagram as a whole are driven by the strong electron correlation [9,32]. However, up to now, the finial consensus on the physical origin of charge order and of its interplay with superconductivity has not reached. In this paper, we study the physical origin of charge order and of its interplay with superconductivity in cuprate superconductors within the framework of the kinetic-energy-driven SC mechanism, where the SC-state quasiparticle excitation spectrum is obtained explicitly by taking into account the intertwining between the SC gap and pseudogap. Based on this SC-state quasiparticle excitation spectrum, the main features of charge order in the SC-state of cuprate superconductors are qualitatively reproduced [9–22], including the doping dependence of the charge-order wave vector. In particular, we show that as charge order in the normal-state [31], charge order in the SC-state is also driven by the pseudogap-induced EFS instability, with the charge-order wave vector that is well consistent with the wave vector connecting the straight hot spots on EFS. Although there is a coexistence of charge order and superconductivity below $T_{\rm c}$, this charge order antagonizes superconductivity.

This paper is organized as follows. In Section 2, we briefly introduces the general formalism of the SC-state quasiparticle spectral function of the $t-J$ model in the charge-spin separation fermion-spin representation obtained in terms of the full charge-spin recombination scheme. The quantitative characteristics of the interplay of charge order with superconductivity are discussed in Section 3, where we show that the physical origin of charge order can be interpreted in terms of the formation of the pseudogap by which it means a reconstruction of EFS to form the Fermi pockets, while the intimate interplay between charge order and superconductivity is similar to the intrinsical intertwining between the SC gap and pseudogap. In other words, the pseudogap and charge order have a root in common, they and superconductivity are a natural consequence of the strong electron correlation. Finally, we give a summary and discussions in Section 4.

2. Formalism

Superconductivity in cuprate superconductors is a phenomenon in which an assembly of electrons goes into the electron pair-condensed phase as a consequence of the dominance of the interaction between electrons by the exchange of a collective-mode [33]. This exchanged collective-mode acts like a bosonic glue to hold the electron pairs together, and is closely related to the SC-state quasiparticle excitations determined by the low-energy electronic structure [34–36]. On the other hand, the charge-order state is defined as a broken-symmetry state occurring when electrons self-organize into the periodic structures [9]. Therefore charge order and its interplay with superconductivity should be reflected in the low-energy electronic structure. The electronic structure of cuprate superconductors in the SC-state is manifested itself by the energy and momentum dependence of the SC-state quasiparticle excitation spectrum $I(\mathbf{k},\omega)$, which is closely related to the SC-state quasiparticle spectral function as [34–36],

$$I(\mathbf{k},\omega)=|M(\mathbf{k},\omega)|^{2}n_{\rm F}(\omega)A(\mathbf{k},\omega), \tag{1}$$

where $M(\mathbf{k},\omega)$ is a matrix element between the initial and final electronic states, and therefore depends on the electron momentum, on the energy and polarization of the income photon. However, following the common practice, the magnitude of $M(\mathbf{k},\omega)$ has been rescaled to the unit in this paper. $n_{\rm F}(\omega)$ is the fermion distribution, while $A(\mathbf{k},\omega)$ is the SC-state quasiparticle spectral function, and is related directly with the imaginary part of the single-electron diagonal Green's function $G(\mathbf{k},\omega)$ as $A(\mathbf{k},\omega)=-2{\rm Im}G(\mathbf{k},\omega)$. This SC-state quasiparticle excitation spectrum in Eq. (1) is measurable via the ARPES technique and can provide the crucial information on EFS, the quasiparticle dispersions, and even the momentum-resolved magnitude of the SC gap [34–36].

The quasiparticle excitation spectrum $I(\mathbf{k},\omega)$ in Eq. (1) also shows that the microscopic understanding of the physical origin of charge order and of its interplay with superconductivity regains a central role in the context of the essential physics of cuprate superconductors, since the calculation of $I(\mathbf{k},\omega)$ must be performed within the microscopic mechanism of superconductivity. After intensive investigations over more than three decades, now it is widely believed that the $t-J$ model on a square lattice contains the essential ingredients to describe superconductivity and the related exotic physics in cuprate superconductors [3]. Its Hamiltonian is given by,

$$H=-\sum_{\langle l\hat{a}\rangle\sigma}t_{l\hat{a}}C^{\dagger}_{l\sigma}C_{l+\hat{a}\sigma}+\mu\sum_{l\sigma}C^{\dagger}_{l\sigma}C_{l\sigma}+J\sum_{\langle l\hat{\eta}\rangle}\mathbf{S}_{l}\cdot\mathbf{S}_{l+\hat{\eta}}, \tag{2}$$

supplemented by the local constraint $\sum_{\sigma}C^{\dagger}_{l\sigma}C_{l\sigma}\leq 1$ to exclude double occupancy, where $C^{\dagger}_{l\sigma}$ ($C_{l\sigma}$) is creation (annihilation) operator for electrons with spin orientation $\sigma=\uparrow,\downarrow$ on lattice site l, $\mathbf{S}_{l}=(S^{x}_{l},S^{y}_{l},S^{z}_{l})$ is spin operator, μ is the chemical potential, and J is the exchange