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Doping dependence of electromagnetic response in electron-doped cuprate superconductors

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ABSTRACT

Within the framework of the kinetic energy driven superconducting mechanism, the doping dependence of the electromagnetic response in the electron-doped cuprate superconductors is studied. It is shown that although there is an electron–hole asymmetry in the phase diagram, the electromagnetic response in the electron-doped cuprate superconductors is similar to that observed in the hole-doped cuprate superconductors. The superfluid density depends linearly on temperature, except for the strong deviation from the linear characteristics at the extremely low temperatures.

The parent compounds of cuprate superconductors are Mott insulators with an antiferromagnetic (AF) long-range order (AFLRO) [1], then the AF phase is subsided and superconductivity is realized by doping a moderate amount of holes or electrons into these Mott insulators [2,3]. It has been found that only an approximate symmetry in the phase diagram exists about the zero doping line between the hole-doped and electron-doped cuprate superconductors [4–6], and the significantly different behaviors of the hole-doped and electron-doped cuprate superconductors are observed, reflecting the electron–hole asymmetry. Among the various unusual properties in cuprate superconductors, the electromagnetic response is a key ingredient to understand the still unresolved mechanism of superconductivity [7]. To elucidate it, the knowledge of the magnetic field penetration depth (then the superfluid density) and its evolution with doping and temperature is of crucial importance [7].

Experimentally, by virtue of systematic studies using the muon-spin-rotation measurement technique, some essential features of the electromagnetic response in cuprate superconductors have been established now for all the temperature $T \leqslant T_c$ throughout the SC dome. For the hole-doped cuprate superconductors [7–11], an agreement for the electromagnetic response has emerged that a simple *d*-wave superconducting (SC) gap leads to a crossover of the superfluid density from the linear temperature dependence at low temperatures to a nonlinear one at the extremely low temperatures. However, there are some controversies in the electron-doped side. The early muon-spin-rotation experimental results of the electron-doped cuprate superconductors [12,13] showed that the electrodynamics are consistent with a gaped *s*-wave behavior. Later, the muon-spin-rotation experimental data [14–16] showed that at the low doping levels, the superfluid density at low temperatures is quadratic in temperature, but at the higher dopings, the superfluid density has an activated behavior, suggesting a *d*-wave to *s*-wave pairing transition near the optimal doping. However, the recent muon-spin-rotation experimental results [17–19] showed that the superfluid density exhibits a linear temperature behavior, indicative of a pure *d*-wave state. In particular, these experimental results [17–19] found a behavior of the electromagnetic response of the electron-doped cuprate superconductors similar to that observed in the hole-doped case [7–11]. Theoretically, the most of the interpretations for the unusual electromagnetic response are focused on the hole-doped cuprate superconductors. In order to elucidate the mechanism of superconductivity, it is necessary to look into electron-doped cuprate superconductors too, and then to identify the differences and similarities between the hole-doped and electron-doped cuprate superconductors.

In our recent work [20], the electromagnetic response in the hole-doped cuprate superconductors has been studied based on the kinetic energy driven SC mechanism [21,22], and then the main features of the doping and temperature dependence of the local magnetic field profile, the magnetic field penetration depth, and the superfluid density observed on the hole-doped cuprate superconductors [7–11] are well reproduced. In this paper, we study the doping and temperature dependence of the electromagnetic response in the electron-doped cuprate superconductors along with this line. We show explicitly that although the electron–hole asymmetry is observed in the phase diagram [4–6], the main features of the electromagnetic response in the electron-doped cuprate superconductors are similar to that observed in the hole-doped cuprate superconductors [20]. The superfluid density is the wide range of

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linear temperature dependence at low temperature, extending from close to the SC transition temperature to down to the temperatures $T \sim 8$ K for different doping concentrations, then at the extremely low temperatures $T < 8$ K, the superfluid density crosses over to a nonlinear temperature behavior.

It is commonly accepted that the essential physics of cuprate superconductors is properly accounted by the two-dimensional t-J model on a square lattice [23]. This t-J model with the nearest neighbor hopping t has a particle-hole symmetry because the sign of t can be absorbed by changing the sign of the orbital on one sublattice. However, the particle-hole asymmetry in the phase diagram of cuprate superconductors can be described by including the next-nearest neighbor hopping t' [24–26], which therefore plays an important role in explaining the difference between electron and hole doping. Furthermore, for discussions of the doping and temperature dependence of the electromagnetic response in the electron-doped cuprate superconductors, the t–t'-J model can be extended by including the exponential Peierls factors as,

$$H = t\sum_{i\hat{\eta}\sigma} e^{-i(e/\hbar)\mathbf{A}(l)\cdot\hat{\eta}} PC^{\dagger}_{i\sigma}C_{i+\hat{\eta}\sigma}P^{\dagger} - t'\sum_{i\hat{\tau}\sigma} e^{-i(e/\hbar)\mathbf{A}(l)\cdot\hat{\tau}} PC^{\dagger}_{i\sigma}C_{i+\hat{\tau}\sigma}P^{\dagger} - \mu\sum_{i\sigma} PC^{\dagger}_{i\sigma}C_{i\sigma}P^{\dagger} + J\sum_{i\hat{\eta}} \mathbf{S}_i\cdot\mathbf{S}_{i+\hat{\eta}}, \quad (1)$$

where $t<0$, $t'<0$, $\hat{\eta} = \pm\hat{x}, \pm\hat{y}$, $\hat{\tau} = \pm\hat{x}\pm\hat{y}$, $C^{\dagger}_{i\sigma}$ $(C_{i\sigma})$ is the electron creation (annihilation) operator, $\mathbf{S}_i = (S^x_i, S^y_i, S^z_i)$ are spin operators, and μ is the chemical potential. In the Hamiltonian (1), the hopping terms together with exponential Peierls factors account for the coupling of the electron charge to an external magnetic field [20] in terms of the vector potential $\mathbf{A}(l)$, while the nontrivial part resides in the projection operator P which restricts the Hilbert space to exclude the zero occupancy in the electron-doped cuprate superconductors, i.e., $\sum_{\sigma} C^{\dagger}_{i\sigma}C_{i\sigma} \geqslant 1$.

For description of the hole-doped cuprate superconductors, the charge-spin separation (CSS) fermion-spin theory [27,22] has been developed for incorporating the electron single occupancy local constraint. However, to apply this CSS fermion-spin theory to the electron-doped counterparts, the Hamiltonian (1) should be rewritten in terms of a particle-hole transformation $C_{i\sigma} \to f^{\dagger}_{i-\sigma}$ as [28],

$$H = -t\sum_{i\hat{\eta}\sigma} e^{-i(e/\hbar)\mathbf{A}(l)\cdot\hat{\eta}} f^{\dagger}_{i\sigma}f_{i+\hat{\eta}\sigma} + t'\sum_{i\hat{\tau}\sigma} e^{-i(e/\hbar)\mathbf{A}(l)\cdot\hat{\tau}} f^{\dagger}_{i\sigma}f_{i+\hat{\tau}\sigma} + \mu\sum_{i\sigma} f^{\dagger}_{i\sigma}f_{i\sigma} + J\sum_{i\hat{\eta}} \mathbf{S}_i\cdot\mathbf{S}_{i+\hat{\eta}}, \quad (2)$$

then the local constraint without the zero occupancy $\sum_{\sigma} C^{\dagger}_{i\sigma}C_{i\sigma} \geqslant 1$ is transferred as the single occupancy local constraint $\sum_{\sigma} f^{\dagger}_{i\sigma}f_{i\sigma} \leqslant 1$, where $f^{\dagger}_{i\sigma}$ $(f_{i\sigma})$ is the hole creation (annihilation) operator. Now we follow the CSS fermion-spin theory [27,22], and decouple the hole operators as $f_{i\uparrow} = a^{\dagger}_{i\uparrow}S^{-}_i$ and $f_{i\downarrow} = a^{\dagger}_{i\downarrow}S^{+}_i$, respectively, where the spinful fermion operator $a_{i\sigma} = e^{-i\Phi_{i\sigma}}a_i$ represents the charge degree of freedom together with some effects of the spin configuration rearrangements due to the presence of the doped electron itself (charge carrier), while the spin operator S_i represents the spin degree of freedom, then the single occupancy local constraint in the electron-doped cuprate superconductors in the hole representation is satisfied in analytical calculations. In this CSS fermion-spin representation, the Hamiltonian (2) can be expressed as,

$$H = t\sum_{i\hat{\eta}} e^{-i(e/\hbar)\mathbf{A}(l)\cdot\hat{\eta}} \left(a^{\dagger}_{i+\hat{\eta}\uparrow}a_{i\uparrow}S^{+}_iS^{-}_{i+\hat{\eta}} + a^{\dagger}_{i+\hat{\eta}\downarrow}a_{i\downarrow}S^{-}_iS^{+}_{i+\hat{\eta}}\right) - t'\sum_{i\hat{\tau}} e^{-i(e/\hbar)\mathbf{A}(l)\cdot\hat{\tau}} \left(a^{\dagger}_{i+\hat{\tau}\uparrow}a_{i\uparrow}S^{+}_iS^{-}_{i+\hat{\tau}} + a^{\dagger}_{i+\hat{\tau}\downarrow}a_{i\downarrow}S^{-}_iS^{+}_{i+\hat{\tau}}\right) - \mu\sum_{i\sigma} a^{\dagger}_{i\sigma}a_{i\sigma} + J_{\rm eff}\sum_{i\hat{\eta}} \mathbf{S}_i\cdot\mathbf{S}_{i+\hat{\eta}}, \quad (3)$$

where $J_{\rm eff} = (1-\delta)^2 J$, and $\delta = \langle a^{\dagger}_{i\sigma}a_{i\sigma}\rangle = \langle a^{\dagger}_i a_i\rangle$ is the electron doping concentration.

As in the discussions of the hole-doped case [21], the SC order parameter for the electron Cooper pair in the electron-doped cuprate superconductors also can be defined as,

$$\Delta = \left\langle C^{\dagger}_{i\uparrow}C^{\dagger}_{j\downarrow} - C^{\dagger}_{i\downarrow}C^{\dagger}_{j\uparrow}\right\rangle = \left\langle a_{i\uparrow}a_{j\downarrow}S^{\dagger}_iS^{-}_j - a_{i\downarrow}a_{j\uparrow}S^{-}_iS^{+}_j\right\rangle = -\left\langle S^{+}_iS^{-}_j\right\rangle \Delta_a, \quad (4)$$

with the charge carrier pairing gap parameter $\Delta_a = \langle a_{j\downarrow}a_{i\uparrow} - a_{j\uparrow}a_{i\downarrow}\rangle$. For the hole-doped cuprate superconductors, a large body of experimental data [4,29] indicate that the hot spots are located close to the antinodal points of the Brillouin zone, resulting in a monotonic (simple) d-wave gap. However, in contrast, a number of experiments, including angular resolved photoemission [30,31], scanning SC quantum interference device measurements [32], Raman scattering [33], and phase sensitive study [34] show that the hot spots are located much closer to the zone diagonal in the electron-doped side, leading to a nonmonotonic d-wave gap,

$$\Delta(\mathbf{k}) = \Delta\left[\gamma^{(d)}_{\mathbf{k}} - B\gamma^{(2d)}_{\mathbf{k}}\right], \quad (5)$$

where $\gamma^{(d)}_{\mathbf{k}} = [\cos k_x - \cos k_y]/2$ and $\gamma^{(2d)}_{\mathbf{k}} = [\cos(2k_x) - \cos(2k_y)]/2$, then the maximum gap is observed not at the nodal points as expected from the monotonic d-wave gap, but at the hot spot between nodal and antinodal points, where the AF spin fluctuation most strongly couples to electrons, supporting a spin-mediated pairing mechanism.

In the case of zero magnetic field, it has been shown [21,22] in terms of Eliashberg's strong coupling theory that the charge carrier-spin interaction from the kinetic energy term in the Hamiltonian (3) induces a charge carrier pairing state with the d-wave symmetry by exchanging spin excitations, then the SC transition temperature is identical to the charge carrier pair transition temperature. Moreover, this d-wave SC state is controlled by both SC gap function and quasiparticle coherence, which leads to that the maximal SC transition temperature occurs around the optimal doping, and then decreases in both underdoped and overdoped regimes. In particular, within this kinetic energy driven SC mechanism [35,22], some main features of the doping dependence of the low-energy electronic structure [28], the dynamical spin response [36], and the electronic Raman response [37] in the electron-doped cuprate superconductors have been quantitatively reproduced. Following these previous discussions [28,36,37], the full charge carrier Green function of the electron-doped cuprate superconductors can be obtained in the Nambu representation as,

$$g(\mathbf{k}, i\omega_n) = Z_{\rm aF}\,\frac{i\omega_n\tau_0 + \bar{\xi}_{\mathbf{ak}}\tau_3 - \bar{\Delta}_{\rm aZ}(\mathbf{k})\tau_1}{(i\omega_n)^2 - E^2_{\mathbf{ak}}}, \quad (6)$$

where τ_0 is the unit matrix, τ_1 and τ_3 are Pauli matrices, the renormalized charge carrier excitation spectrum $\bar{\xi}_{\mathbf{ak}} = Z_{\rm aF}\xi_{\mathbf{ak}}$, with the mean-field charge carrier excitation spectrum $\xi_{\mathbf{ak}} = Zt\chi_1\gamma^{(s)}_{\mathbf{k}} - Zt'\chi_2\gamma^{(2s)}_{\mathbf{k}} - \mu$, the spin correlation functions $\chi_1 = \left\langle S^{+}_iS^{-}_{i+\hat{\eta}}\right\rangle$ and $\chi_2 = \langle S^{+}_iS^{-}_{i+\hat{\tau}}\rangle$, $\gamma^{(s)}_{\mathbf{k}} = (1/Z)\sum_{\hat{\eta}} e^{i\mathbf{k}\cdot\hat{\eta}}$, $\gamma^{(2s)}_{\mathbf{k}} = (1/Z)\sum_{\hat{\tau}} e^{i\mathbf{k}\cdot\hat{\tau}}$, Z is the number of the nearest neighbor or next-nearest neighbor sites, the renormalized charge carrier d-wave pair gap $\bar{\Delta}_{\rm aZ}(\mathbf{k}) = Z_{\rm aF}\bar{\Delta}_{\rm a}(\mathbf{k})$, with the effective charge carrier d-wave pair gap $\bar{\Delta}_{\rm a}(\mathbf{k}) = \bar{\Delta}_{\rm a}\left[\gamma^{(d)}_{\mathbf{k}} - B\gamma^{(2d)}_{\mathbf{k}}\right]$, and the charge carrier quasiparticle spectrum $E_{\mathbf{ak}} = \sqrt{\bar{\xi}^2_{\mathbf{ak}} + |\bar{\Delta}_{\rm aZ}(\mathbf{k})|^2}$, while the effective charge carrier pair gap $\bar{\Delta}_{\rm a}(\mathbf{k})$ and the quasiparticle coherent weight $Z_{\rm aF}$ satisfy the following equations [28] $\bar{\Delta}_{\rm a}(\mathbf{k}) = \Sigma^{(a)}_2(\mathbf{k}, \omega = 0)$ and $Z^{-1}_{\rm aF} = 1 - \Sigma^{(a)}_{1o}(\mathbf{k}, \omega = 0)|_{\mathbf{k}=[\pi,0]}$, where $\Sigma^{(a)}_1(\mathbf{k},\omega)$ and $\Sigma^{(a)}_2(\mathbf{k},\omega)$ are the charge carrier self-energies obtained