The Electron-Hole Asymmetry in the Cuprate Superconductors

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Abstract

We investigate the electron-hole asymmetry in the superconduting state based on the ingap state and the superexchange interaction $J_{\rm s}$ in the d–p model, where we take the antiferromagnetic fluctuations in the fluctuation-exchange (FLEX) approximation and take the superconducting fluctuations in the self-consistent t-matrix approximation. We show that the superconducting gap in the hole-doped region is several times larger than that in the electron-dopd region. This difference is due to the intrinsic nature of the ingap states which are intimately related with the Zhang-Rice singlets in the hole-doped systems and are correlated d-electrons in the electron-doped systems, respectively.

Key words: cuprate; pseudogap; superconductivity; strong correlation

1. Introduction

Some kinds of electron-hole asymmetry has been observed in the high-$T_{\rm c}$ cuprate superconductors, *e.g.* the doping ranges, where the antiferromagnetic (AF) state and the superconducting (SC) state emerge in the electron-doped cuprates (EDC), are defferent from those in the hole-doped cuprates (HDC), and the SC gap in the EDC is much smaller than that in the HDC[1–3].

In our previous studies[4,5], we obtained the $T-\delta$ phase diagram by taking the AF fluctuations in the fluctuation-exchange approximation and taking the SC fluctuations in the self-consistent t-matrix approximation, which is based on the ingap state and the superexchange interaction $J_{\rm s}$ in the d–p model[6–8], where δ is hole doping rate. The obtained phase diagram is consistent with those observed in cuprates[1,2].

In the present study we investigate the SC gap by using the same approximation as that used in our previous studies[4,5]. We show that the SC gap in the HDC is several times larger than that in the EDC. This electron-hole asymmetry is due to the intrinsic nature of the ingap states.

We take the d–p model for describing the electronic system in the CuO_2 plane:

$$H=\varepsilon_p\sum_{\mathbf{k}\sigma}c^+_{\mathbf{k}\sigma}c_{\mathbf{k}\sigma}+\varepsilon_d\sum_{i\sigma}d^+_{i\sigma}d_{i\sigma}$$
$$+N_{\rm L}^{-\frac{1}{2}}\sum_{i\mathbf{k}\sigma}\{t_{i\mathbf{k}}c^+_{\mathbf{k}\sigma}d_{i\sigma}b^+_i+h.c.\},\qquad(1)$$

which is treated within the physical subspace where local constraints $\hat{Q}_i=\sum_\sigma d^+_{i\sigma}d_{i\sigma}+b^+_i b_i=1$ strictly hold in order to exclude double occupancy of d-holes. In the above, $c_{\mathbf{k}\sigma}$, $d_{i\sigma}$ and b_i are annihilation operators for a p-hole, a pseudo fermion representing a single occupation of d-hole and a slave boson representing a vacancy of the d-hole, respectively.

The quasi-particle Green's functions of the leading order in the $1/N$-expansion are given by [6,7]

$$G_0(\mathbf{k},\omega)=\sum_{\gamma=\pm}A_\gamma(\mathbf{k})/(\omega-E_\gamma(\mathbf{k})+{\rm i}0^+),\qquad(2)$$

with $E_\gamma(\mathbf{k})=\frac{1}{2}[\varepsilon_p+\omega_0+\gamma((\varepsilon_p-\omega_0)^2+4bt^2_{\mathbf{k}})^{1/2}]$, $A_\gamma(\mathbf{k})=\gamma(E_\gamma(\mathbf{k})-\omega_0)/(E_+(\mathbf{k})-E_-(\mathbf{k}))$, where $\gamma=-$ and $+$ denote the ingap state and the p-band, and

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N represents the degeneracy of d-hole. The binding energy ω_0 and the residue b of the slave boson are self-consistently determined together with μ, and then μ is located in the ingap state.

The system is the charge transfer (CT) type of the Mott insulator at $\delta = 0$, where the hole number $n = 1 + \delta$. In the HDC ($\delta > 0$), doped p-holes form the quasi-particle band called as the ingap state inside the CT gap near the p-band. In the EDC ($\delta < 0$), on the other hand, the ingap state is the d-like band inside the CT gap near the localized d-state.

The renormalized Green function is given by the coupled equations of the AF fluctuations and the SC fluctuations derived in our previous stuides[4,5].

$$G(\mathbf{k},\omega) = [G_0(\mathbf{k},\omega)^{-1} - \Sigma_{\rm SC}(\mathbf{k},\omega) \\ -\Sigma_{\rm SCf}(\mathbf{k},\omega) - \Sigma_{\rm AFf}(\mathbf{k},\omega)]^{-1}, \qquad (3)$$

where $\Sigma_{\rm SC}(\mathbf{k},\omega) = -G_{\rm n}(\mathbf{k},-\omega)^*|\widetilde{\Delta}_{\rm SC}(\mathbf{k})|^2$, with $G_{\rm n}(\mathbf{k},\omega) = [G_0(\mathbf{k},\omega)^{-1} - \Sigma_{\rm SCf}(\mathbf{k},\omega) - \Sigma_{\rm AFf}(\mathbf{k},\omega)]^{-1}$ and $\widetilde{\Delta}_{\rm SC}(\mathbf{k})$ is determined by the gap equation. $\Sigma_{\rm SCf}(\mathbf{k},\omega)$ and $\Sigma_{\rm AFf}(\mathbf{k},\omega)$ are the self-energy corrections due to the SC and AF fluctuations given by the the fluctuation exchange approximation and the self-consistent t-matrix approximation, respectively.

The energy of quasi-particles in the SC state is given by $Y_{\gamma'}(\mathbf{k}) \cong \gamma' \sqrt{E_-(\mathbf{k})^2 + A_-(\mathbf{k})^2\widetilde{\Delta}_{\rm SC}(\mathbf{k})^2}$ ($\gamma' = \pm$), then the observable superconducting gap is given by $\Delta_{\rm SC}(\mathbf{k}) = A_-(\mathbf{k})\widetilde{\Delta}_{\rm SC}(\mathbf{k})$.

Figure 1 shows the phase diagram obtained in our previous studies[4,5]. The AF state in the EDC persists to higher doping rate than that in the HDC. The SC state and the spin gap region appears in narrower doping range than that in the HDC. Those features account for the phase diagrams observed in cuprates.

Figure 2 shows that the SC gap has $d_{x^2-y^2}$-like symmetry. The inset shows that the SC gap in the HDC is several times larger that that in the EDC, because $\Delta_{\rm SC}(\mathbf{k})$ is renormaliazed by the residue $A_-(\mathbf{k})$, where $A_-([\pi,0]) = 0.052$, 0.189 and 0.162 at $\delta = -0.18$, 0.18 and 0.15.

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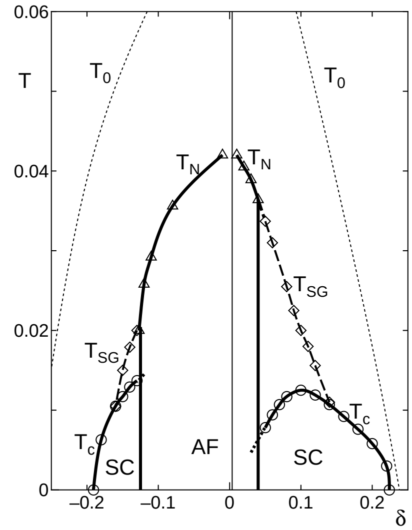

Fig. 1. The T-δ phase diagram where the system is in the superconducting state with $d_{x^2-y^2}$ symmetry in the region of $T \leq T_{\rm c}$, and is in the antiferromagnetic state in the region of $T \leq T_{\rm N}$. The spin gap temperature $T_{\rm SG}$ is defined as the temperature at which $1/T_1T$ has a maximum. The metallic region in $T \lesssim T_0$ is the anomalous metallic phase.

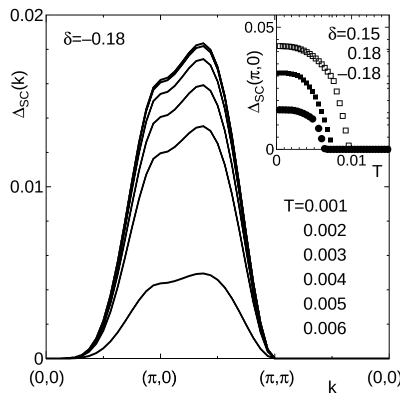

Fig. 2. $\mathbf{k}$- and T-dependence of $\Delta_{\rm SC}(\mathbf{k})$ at $\delta = -0.18$, 0.18 and 0.15.

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