Local magnetic moments in vortex cores and around nonmagnetic impurities in two-dimensional t-J model

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Abstract

Local antiferromagnetic moments in the vortex cores of high-T_c superconductors are studied using the two-dimensional t-J model. It is found that the doping dependence is important and the local moments can appear only near half-filling. However the absence of the large resonance peak in the local density of states reported in the scanning tunneling spectroscopy is due to the smallness of the core size in high-T_c superconductors. The similar phenomena around nonmagnetic impurities are compared with the vortex case.

Key words: high-T_c superconductors ; vortex ; impurity ; antiferromagnetism

Recent STM/S experiment on $Bi_2Sr_2CaCu_2O_{8+\delta}$ observed a double peak structure at energies ± 7 meV in the STS spectrum at the vortex core center [1]. This result is qualitatively consistent with the previous experimental STS data for vortex cores in $YBa_2Cu_3O_{7-x}$[2]. However, these observations are inconsistent with the theoretical results based on the pure d-wave superconductivity, which predicts the zero-bias-conductance-peak (ZBCP) in the STS spectrum [3].

The discrepancy between the experiments and the theories stimulated further theoretical studies on the vortex core states. Local antiferromagnetic (AF) order induced inside the vortex core [4–6] is considered to be a promising clue to resolve this discrepancy, because it has been shown to exist by several experimental studies such as neutron scattering experiments in LSCO compounds [7–9], and μSR [10] and NMR [11,12] experiments in YBCO compounds. Although there are less experimental grounds, another possible mechanism for the absence of the ZBCP have been proposed, that is, $d_{x^2-y^2} + is$-wave pairing states inside the vortex core [13] and the smallness of the vortex core [14]. At this stage, these theories may not exclude other possibilities and need further experimental and theoretical justification.

In this paper, we consider the above possibilities within the same framework, that is, the Bogoliubov-de Gennes (BdG) equations derived from the t-J model using the extended Gutzwiller approximation, which gives reasonable estimation of AF correlation [15,16].

The Hamiltonian of the t-J model is written as

$$\mathcal{H} = -\sum_{\langle i,j\rangle,\sigma} P_G(t_{ij}c^\dagger_{i\sigma}c_{j\sigma} + \text{h.c.})P_G + J\sum_{\langle i,j\rangle} \boldsymbol{S}_i \cdot \boldsymbol{S}_j - \mu\sum_{i,\sigma} c^\dagger_{i\sigma}c_{i\sigma} \quad (1)$$

in the standard notation where $\langle i,j\rangle$ means the summation over nearest-neighbor pairs. The Gutzwiller's projection operator P_G is defined as $P_G = \Pi_i(1 - n_{i\uparrow}n_{i\downarrow})$. The uniform magnetic field is introduced in terms of Peierls phase of the hopping term as $t_{ij} = t\exp\left(\frac{ie}{\hbar c}\int_i^j \boldsymbol{A}\cdot d\boldsymbol{r}\right)$ [3,13].

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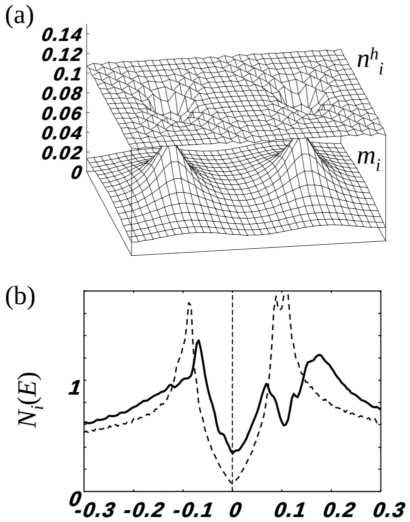

Fig. 1. (a) Local antiferromagnetic moment m_i and the hole density n_i^h inside the vortex core in the t-J model for $\delta = 0.11$. (b) The local density of states inside the vortex core. The dashed line represents the LDOS obtained without the magnetic field.

To make the Peierls phase compatible with vortex lattice symmetry, we need a magnetic unit cell with $2N \times N$ sites including two vortices. In this case, by the appropriate choice of gauge[13], the order parameter Δ_{ij} has a translational symmetry with respect to the magnetic unit cell. Here we take $N = 18$.

We solve numerically the BdG equation and carry out an iteration until the self-consistent equations for Δ_{ij} and ξ_{ij} are satisfied. Using $(u_i^\alpha(\boldsymbol{k}),\, v_i^\alpha(\boldsymbol{k}))$ and $E^\alpha(\boldsymbol{k})$, which are the eigenvectors and eigenvalues of the Fourier transformed BdG equations, we calculate the LDOS defined by

$$N_i(E) = \frac{1}{N_c} \sum_{k,\alpha} \Big[\, |u_i^\alpha(\boldsymbol{k})|^2\, \delta(E^\alpha(\boldsymbol{k}) - E) + |v_i^\alpha(\boldsymbol{k})|^2\, \delta(E^\alpha(\boldsymbol{k}) + E) \,\Big], \qquad (2)$$

where i represents a site, α is the index of the eigenstates, $\boldsymbol{k}$ is the Bloch wave number to the magnetic unit cells. Throughout this paper, we take $J/t = 0.3$.

Figure 1 (a) shows the local AF moment m_i and the hole density n_i^h when the system is near the optimum doping, $\delta = 0.11$, in the present formulation [15]. It is found that AF correlation develops and the hole density decreases inside the vortex core. These results contrast sharply with the ones in the nonmagnetic impurity case where a hole-rich region is locally formed and then AF correlation is collapsed around the impurity [16]. We note here that, when $\delta > 0.12$, the AF vortex core is not realized and the hole density increases inside the vortex core.

The local density of states (LDOS) obtained at the center of the vortex core is shown in Figure 1 (b). The dashed line in Figure 1 (b) represents the LDOS obtained without the magnetic field. We can see that the LDOS at the core center does not have the zero-energy peak (ZEP), but has more spectral weight inside the superconducting gap compared with that of the LDOS obtained without the magnetic field.

We find that an s-wave component is slightly induced inside the vortex core with the magnitude of less than 5% relative to the one of the bulk d-wave component. Here it is tempting to attribute the absence of ZBCP to the local AF moment induced inside the vortex core. However we have confirmed that, when $\delta = 0.11$, the LDOS without the ZEP can be obtained even if we neglect the AF order parameter in the BdG equation. We also confirmed that the size of the vortex core is fairly small, that is, the cores having a radius of about 3 lattice spacings are realized. Thus we conclude that neither the $d{+}is$ state nor the local AF moment but the smallness of the size of the vortex core will account for the absence of ZBCP in the STS spectrum. As the hole doping δ increases, the size of the vortex core increases and the ZEP can be seen in the LDOS when $\delta > 0.12$. More detailed studies are to be published elsewhere.

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