Relation between d-density wave of electron and staggered flux of spinon

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Abstract

A $d_{x^2-y^2}$-density wave (ddw) order of electron in 2-dimensional t-J model is analyzed in saddle point level using the U(1) slave boson formalism. We considered not only the staggered flux (s-flux) order of spinon but also the s-flux order of holon. This analysis provides the relation between the s-flux order of spinon and the ddw order of electron. We discovered a new phase in the phase diagram. In this phase, there is a s-flux order of spinon, but no ddw order of electron.

Our results are that 1) a region of electron ddw exists, 2) there is no coexistence of ddw and $d_{x^2-y^2}$-wave pairing (singlet-RVB) in all region of phase diagram, and that 3) the ground state is a purely $d_{x^2-y^2}$ wave superconducting state.

Key words: Superconductivity; Cuprate; Pseudo gap; d-density wave; t-J model

Recently, Chakravarty et al. [1] proposed that the electron $d_{x^2-y^2}$-density wave (ddw) order exists in the pseudo gap region of high-T_c superconductor. The electron ddw state [2] is the staggered flux (s-flux) state [3,4] of electron coordinate. In this state, $d_{x^2-y^2}$ wave (d-wave) gap exists, time-reversal-symmetry is broken and the 'real' staggered current of the electron exists. The order parameter of the ddw is $y_{\rm e} = -i\sum_{\mathbf{k}\sigma}(\cos k_x - \cos_y)\langle c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}+\mathbf{Q}\sigma}\rangle$, $\mathbf{Q} = (\pi, \pi)$. However they didn't disscuss this scenario microscopically. There remains a question, 'can the electron ddw phase exist in highly correlated system?'.

The 2-dimensional t-J model is a promising model which includes highly correlated effects. Many phases are proposed in this model [3–9]. Zhang [8] analyzed the competition between s-flux order and $d_{x^2-y^2}$-wave pairing order at zero temparature by Gutzwillar approximation. The s-flux state is unstable against infinitesimal d-wave pairing at finite doping. Ubbens and Lee [9] analyzed this model at finite temperature. The s-flux phase of the spinon exsists on the region where doping and temparature are both finite. The SU(2) s-flux state, in which the Fermi-surface of spinon are always points, is also analyzed in SU(2) slave boson model [10,11]. However, there remains a question, 'how do electrons behave in finite temperature s-flux phase?'. The current of the spinon and the electron are not equivalent in finite tempereture s-flux phase bacause there is no Bose condensation of holon. The region of finite temperature s-flux phase exists above the temperature of holon condensation.

In this paper, we revealed the relation between the ddw of electron and the s-flux of spinon. We analyzed it in the 2-dimensional t-J model based on the U(1) slave boson formalism. We introduce order parameters $\bar{\chi}_{ij} = \langle\sum_{\sigma} f^{\dagger}_{i\sigma} f_{j\sigma}\rangle$, $\bar{\eta}_{ij} = \langle f_{i\uparrow} f_{j\downarrow} - f_{i\downarrow} f_{j\uparrow}\rangle$, $\bar{B}_{ij} = \langle b^{\dagger}_i b_j\rangle$ to decouple the Hamiltonian.

We considered not only the staggered flux order of the spinon but also the staggerd flux order of the holon, $\bar{\chi}_{i+\hat{x},i} = x_{\rm s} + {\rm i}(-1)^i y_{\rm s}$, $\bar{\chi}_{i+\hat{y},i} = x_{\rm s} - {\rm i}(-1)^i y_{\rm s}$, $\bar{B}_{i+\hat{x},i} = x_{\rm h} + {\rm i}(-1)^i y_{\rm h}$, $\bar{B}_{i+\hat{y},i} = x_{\rm h} - {\rm i}(-1)^i y_{\rm h}$. Here, $\hat{x}$ and $\hat{y}$ are unit vectors in the x and y direction, $x_{\rm s} = \chi\cos(\phi_{\rm s}/4)$, $y_{\rm s} = \chi\sin(\phi_{\rm s}/4)$, $x_{\rm h} = B\cos(\phi_{\rm h}/4)$, $y_{\rm h} = B\sin(\phi_{\rm h}/4)$. The order parameters $y_{\rm s}$ and $y_{\rm h}$ correspond to the ddw

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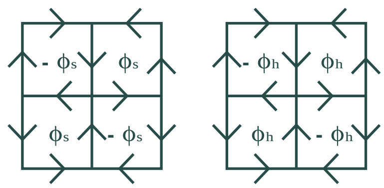

Fig. 1. Staggered flux of spinon $\phi_{\rm s}$ and holon $\phi_{\rm h}$.

order parameter of spinon and holon, respectively. For the pairing symmetry, we considered $d_{x^2-y^2}$, namely $\bar{\eta}_{i+\hat{x},i} = -\ \bar{\eta}_{i+\hat{y},i} = \eta$.

This formalism is an extension of the study by Ubbens and Lee [9]. The $\sum_\sigma f^\dagger_{j\sigma} f_{i\sigma}$ term couples not only to $(3J/8)\chi_{ij}$ but also to tB_{ij}, i.e. the spinon feels the spinon s-flux($\phi_{\rm s}$) and the holon s-flux($\phi_{\rm h}$). The expectation values of the holon, B and $\phi_{\rm h}$, have finite value for the solution of self-consistency equations. Two advantages exist in our formalism; 1) this is a new saddle point solution whose free enery is lower than the previous one, 2) this solution provides the relation between the ddw of the electron and the s-flux of the spinon. In this formalism, the hopping order parameter of the electron is a product of the hopping order parameters of spinon and holon.

$$\langle \sum_\sigma c^\dagger_{i\sigma} c_{j\sigma} \rangle = \langle \sum_\sigma f^\dagger_{i\sigma} f_{j\sigma} \rangle \langle b^\dagger_j b_i \rangle = \ \bar{\chi}_{ij} \bar{B}^*_{ij} \qquad (1)$$

The electron s-flux order parameter $\phi_{\rm e}$ and the electron ddw order parameter $y_{\rm e}$ are given by $\phi_{\rm e} = \phi_{\rm s} - \phi_{\rm h}$, and $y_{\rm e} = \chi B \sin(\phi_{\rm e}/4)$.

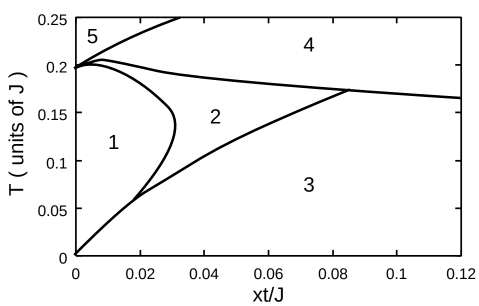

Fig. 2. MF phase diagram for t/J=1. The electron ddw order exists only in region 2. Here, x is hole concentration. The phase diagram for t/J=2 is quantitatively similar to the phase diagram for t/J =1. With the boson order paramer B_{ij}, the π-flux phase and s-flux phase of spinon and holon extends to the higher-doped region compared to the previous work [9], where B_{ij} were not considered.

We solved the self-consistency equations numerically, and obtained the phase diagram(Fig. 2). At half-filling, the holon order parameter $\bar{B}_{ij}$ is zero and the degeneracy of spinon between the s-flux state and the d-wave pairing state exists due to the local SU(2) symmetry; $\chi \neq 0, \bar{B}_{ij} = 0, y_{\rm s}^2 + \eta^2 = {\rm const} \neq 0$. In region 1, spinon s-flux exists but electron ddw doesn't exixt. The spinon and holon state are π-flux order state respectively. In electron picture, the s-flux is canceled completely; $\chi \neq 0, B \neq 0, \phi_{\rm s} = \phi_{\rm h} = \pi, \eta = 0$. The electron ddw order parameter, $y_{\rm e} = \chi B \sin\big((\pi-\pi)/4\big) = 0$. The electron ddw order exists only in region 2. The staggered current of electron can be observed experimentally. The spinon s-flux $\phi_{\rm s}$ and holon s-flux $\phi_{\rm h}$ are not equal to π or 0, and $\phi_{\rm s} \neq \phi_{\rm h}$; $\chi \neq 0, B \neq 0, \phi_{\rm s} \neq 0, \phi_{\rm h} \neq 0, \eta = 0$, and $y_{\rm e} = \chi B \sin\big((\phi_{\rm s}-\phi_{\rm h})/4\big) \neq 0$. In region 3, $d_{x^2-y^2}$-wave pairing exists; $\chi \neq 0$ and $B \neq 0, \phi_{\rm s} = \phi_{\rm h} = 0, \eta \neq 0$. and $y_{\rm e} = 0$. In region 4, there exists only uniform hopping order; $\chi \neq 0, B \neq 0, \phi_{\rm s} = \phi_{\rm h} = \eta = 0$, and $y_{\rm e} = 0$. In region 5, all order parameters are zero. Spinon and holon cannot hop; $\chi = B = \phi_{\rm s} = \phi_{\rm h} = \eta = 0$. and $y_{\rm e} = 0$.

The transition between region 1 and region 2 is a 2nd order transition in our theory. (If one only focuses on spinon degree of freedom, this doesn't look like phase transition [9–11].) There exists an order parameter which charactrizes this transition. It is the electron ddw order parameter.

In conclusion we have found a possibility for the electron ddw phase in the t-J model at finite temperature, which does not coexists with the singlet-RVB state.

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References

[1] S. Chakravarty, R.B. Laughlin, D.K. Morr, C. Nayak, Phys. Rev. B **63** (2001) 94503.

[2] C. Nayak, Phys. Rev. B **62** (2000) 4880.

[3] I. Affleck, J.B. Marston, Phys. Rev. B **37** (1988) 3774.

[4] J.B. Marston, I. Affleck, Phys. Rev. B **39** (1989) 11538.

[5] P.W. Anderson, Science **235** (1987) 1996.

[6] I. Affleck, Z. Zou, T. Hsu, P.W. Anderson, Phys. Rev. B **38** (1988) 745.

[7] G. Kotliar, J. Liu, Phys. Rev. B **38** (1988) 5142.

[8] F.C. Zhang, Phys. Rev. Lett. **64** (1990) 974.

[9] M.U. Ubbens, P.A. Lee, Phys. Rev. B **46** (1992) 8434.

[10] X.-G. Wen, P.A. Lee, Phys. Rev. Lett. **76** (1996) 503.

[11] P.A. Lee, N. Nagaosa, T.K. Ng, X.-G. Wen, Phys. Rev. B **57** (1998) 6003.