Quasi-One-Dimensional Band in the t-J Model

H. Yamase,[a*] H. Kohno[b] and H. Fukuyama[a]

[a]Institute for Solid State Physics, University of Tokyo, Minato-ku, Tokyo 116-8666, Japan

[b]Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka 560-8531, Japan

We study the two-dimensional (2d) t-J model in a mean filed approximation. Assuming uniform charge distribution, we find that the 2d t-J model has an instability toward forming a quasi-one-dimensional (q-1d) Fermi surface. This q-1d state competes with a d-wave pairing state, which overcomes the q-1d state for a realistic parameter region. However, we can show that the q-1d state coexists with the d-wave pairing state when we introduce a small (about 3%) spatial anisotropy in t and J in the original t-J model.

Elastic neutron scattering on $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (LNSCO)[1–3] has revealed that a static incommensurate antiferromagnetic order coexists with a static charge density modulation even in a superconducting state. Tranquada *et al.* have modeled this state on the so-called 'spin-charge stripe order'. Although this 'spin-charge stripe order' has been a controversial issue both experimentally and theoretically, the model has given a great impact in that it assumes one-dimensional structure in a two-dimensional (2d) CuO_2 plane. In this paper, we show that the 2d t-J model has an instability toward forming a quasi-one-dimensional (q-1d) Fermi surface (FS).

The 2d t-J model defined on a square lattice is given by

$$H = -\sum_{i,\,j,\,\sigma} t^{(l)} f^\dagger_{i\,\sigma} b_i b^\dagger_j f_{j\,\sigma} + J \sum_{<i,j>} \boldsymbol{S}_i \cdot \boldsymbol{S}_j, \qquad (1)$$

$$\sum_\sigma f^\dagger_{i\,\sigma} f_{i\,\sigma} + b^\dagger_i b_i = 1 \quad \text{at each site}, \qquad (2)$$

where $f_{i\,\sigma}$ (b_i) is a fermion operator with spin σ (a boson operator with charge e); $t^{(l)}$ is a hopping integral between the l-th nearest neighbor (n.n.) sites ($l \le 3$); $\langle i, j\rangle$ is taken for the n.n. sites; and $\boldsymbol{S}_i = \frac{1}{2}\sum_{\alpha,\beta} f^\dagger_{i\,\alpha} \boldsymbol{\sigma}_{\alpha\,\beta} f_{i\,\beta}$. Following the previous treatment[4], we introduce mean fields: $\langle \chi_{i\,j}\rangle^{(l)}_\tau \equiv \left\langle \sum_\sigma f^\dagger_{i\,\sigma} f_{j\,\sigma}\right\rangle^{(l)}_\tau$, $\left\langle b^\dagger_i b_j\right\rangle^{(l)}_\tau$ and $\langle \Delta_{i\,j}\rangle^{(1)}_\tau \equiv \langle f_{i\,\uparrow} f_{j\,\downarrow} - f_{i\,\downarrow} f_{j\,\uparrow}\rangle^{(1)}_\tau$, where τ indicates the direction, namely $\boldsymbol{\tau} = \boldsymbol{r}_i - \boldsymbol{r}_j$. Loosening the local constraint eq. (2) to a global one, $\sum_i \left(\sum_\sigma f^\dagger_{i\,\sigma} f_{i\,\sigma} + b^\dagger_i b_i\right) = N$ with N being the number of the total lattice sites, we determine mean fields self-consistently so as to minimize the free energy. Here we approximate bosons to be Bose condensed. We set the parameters, $t^{(1)}/J = 4$, $t^{(2)}/t^{(1)} = -1/6$ and $t^{(3)}/t^{(1)} = 0$, which reproduce the observed FS at $\delta = 0.30$ in $La_{2-x}Sr_xCuO_4$ (LSCO)[5].

We first show the results obtained under the constraint, $\langle \Delta_{i\,j}\rangle^{(1)}_\tau = 0$. Figure 1 shows the value of $\langle \chi_{i\,j}\rangle^{(1)}_\tau$ as a function of temperature, T. The four-fold symmetry is broken spontaneously at $T_{\rm q1d}$, that is $\langle \chi_{i\,j}\rangle^{(1)}_x \neq \langle \chi_{i\,j}\rangle^{(1)}_y$, and the 2d FS (gray line) changes into the q-1d FS (solid line) below $T_{\rm q1d}$. (The alternative solution $\langle \chi_{i\,j}\rangle^{(1)}_x < \langle \chi_{i\,j}\rangle^{(1)}_y$ is also possible.) The δ-dependence of $T_{\rm q1d}$ is shown in Fig. 2 where the q-1d state is realized below a critical doping rate $\delta_c \approx 0.13$.

On the other hand, when we remove the constraint, $\langle \Delta_{i\,j}\rangle^{(1)}_\tau = 0$, the q-1d state is overcome by the d-wave pairing state and does not appear. However, when we introduce a small (about 3%) spatial anisotropy in $t^{(1)}$ and J in the original t-J model, this anisotropy is largely enhanced at low temperature ($T \ll J$), leading the coexistence of the q-1d band and the d-wave pairing[6].

As for the dependence on $t^{(1)}$, $t^{(2)}$ and $t^{(3)}$,

*E-mail: yamase@kodama.issp.u-tokyo.ac.jp

we found[6] that the present choice appropriate to LSCO favors the q-1d state much more than that appropriate to $YBa_2Cu_3O_{6+y}$. Since a small spatial anisotropy in $t^{(1)}$ and J is expected due to the low temperature tetragonal structure in LNSCO[7] or the the Z-point soft phonon mode in LSCO[8], the q-1d state can be realized in La-based cuprates. It is to be noted that charge distribution is uniform in the present q-1d state, and any relation to the 'spin-charge stripe order' has not been obtained.

In summary, we have shown that the 2d t-J model has an intrinsic instability toward forming the q-1d FS, which is manifested by introducing a small spatial anisotropy in $t^{(1)}$ and J. We have argued that this q-1d state can be realized in La-based cuprates.

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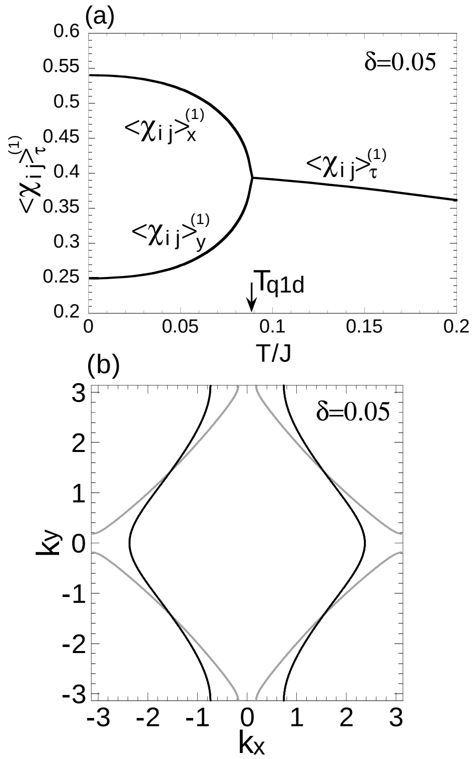

Figure 1. (a) The T-dependence of $\langle\chi_{i\,j}\rangle_\tau^{(1)}$ under the constraint, $\langle\Delta_{i\,j}\rangle_\tau^{(1)} = 0$. Below $T_{\rm q1d}$, the four-fold symmetry is broken, namely $\langle\chi_{i\,j}\rangle_x^{(1)} \neq \langle\chi_{i\,j}\rangle_y^{(1)}$. (b) The Fermi surface for $T > T_{\rm q1d}$ (gray line) and that for $T < T_{\rm q1d}$ (solid line).

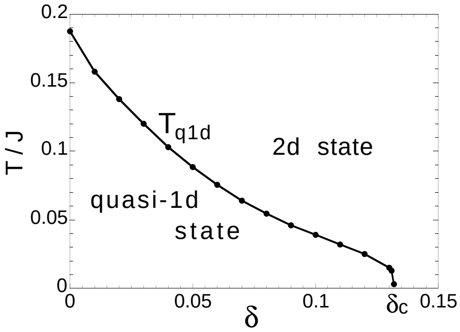

Figure 2. The δ-dependence of $T_{\rm q1d}$. A quasi-1d state is realized below the critical doping rate $\delta_c \approx 0.13$ at low T. Note the constraint, $\langle \Delta_{i\,j} \rangle_\tau^{(1)} = 0$.