Vortex Structure in Superconducting Stripe States

Masanori ICHIKAWA, Mitsuaki TAKIGAWA and Kazushige MACHIDA

Department of Physics, Okayama University, Okayama 700-8530

(Rceived August 14, 2000)

The vortex structure in superconducting stripe states is studied according to the Bogoliubov-de Gennes theory on the two-dimensional Hubbard model with nearest-neighbor sites pairing interaction. The vortex is trapped at the outside region of the stripe line, where the superconductivity is weak. The superconducting coherence length along the stripe direction becomes long. There are no eminent low-energy electronic states even near the vortex core. These characters resemble the Josephson vortex in layered superconductors under a parallel field.

KEYWORDS: vortex structure, stripe state, local density of states, Bogoliubov-de Gennes theory

Recently, much attention has been focused on the stripe state of underdoped high-$T_c$ cuprates. The stripe state was proposed to explain the static magnetic incommensurate structure observed by means of elastic neutron scattering experiments on La$_{2-\delta}$Sr$_\delta$CuO$_4$ (LSCO) and La$_{1.6-\delta}$Nd$_{0.4}$Sr$_{1.6}$CuO$_4$ (LNSCO). It is considered that doped holes are localized in the stripe region, which contributes to the one-dimensional (1D) metallic conduction, and the outside region of the stripe is an antiferromagnetic (AF) insulator. Angle-resolved photoemission (ARPES) experiments were carried and the 1D-like Fermi surface in the stripe state was observed. In YBa$_2$Cu$_3$O$_{7-\delta}$, incommensurate fluctuations that were consistent with the above stripe concept were reported by means of inelastic neutron scattering experiments.

In high-$T_c$ superconductors, it is considered that the low-energy electronic state around the vortex is completely different from that of conventional superconductors. Theoretical studies suggest that the low-energy electronic state around the vortex core extends a significant distance due to the line node of the $d$-wave superconducting gap in high-$T_c$ superconductors. However, in the direct observation of the vortex core by scanning tunneling microscopy (STM), there is no eminent low-energy state around the vortex core. There appears only a small unexplained shoulder or isolated peak at a higher energy within the superconducting gap. This results suggest that we must consider the vortex state, including the exotic character of the electronic state which is unique to high-$T_c$ materials. We study the effect of the stripe state in this paper.

Although there are many theoretical approaches to the stripe state, we base this study on the self-consistent Hartree-Fock (HF) theory of the Hubbard model. It is believed that the stripe concept is valid beyond the HF approximation. We can consider the metallic stripe state by using the self-consistent HF theory if we consider the realistic Fermi surface topology. It can reproduce “the 1D Fermi surface with the gap near (\frac{\pi}{2}, 0)” as suggested by the results of ARPES experiments. It also qualitatively reproduces the relationship between the incommensurability and the hole density $n_h$, including the phase transition between the diagonal stripe in the insulator phase ($n_h < 0.05$) and the vertical stripe in the metallic and superconducting phases ($n_h > 0.05$). Thus, HF theory can successfully describe the stripe structure in high-$T_c$ cuprates as a first approximation. Therefore, we further investigate various phenomena in the superconducting state by extending this theory. Once the density of states (DOS) remains at the Fermi energy (i.e., metallic state), we can produce the superconductivity by introducing the pairing interaction, at least as a phenomenological model. In the superconducting state of this framework, the metallic 1D stripe region becomes dominantly superconducting, and penetrates the outside AF region. In this paper, we investigate the vortex state under a magnetic field in this superconducting state, and study the structure of the order parameter and the electronic state around the vortex.

We begin with the conventional Hubbard model on a two-dimensional square lattice, and introduce the mean field $n_{i,\sigma} = \langle a^\dagger_{i,\sigma} a_{i,\sigma} \rangle$ at the $i$ site, where $\sigma$ is a spin index and $i = (i_x, i_y)$. We assume a pairing interaction $V$ between nearest-neighbor (NN) sites. This type of pairing interaction gives the $d$-wave superconductivity. Thus, the HF Hamiltonian under a magnetic field is given by

\begin{equation}
\mathcal{H} = -\sum_{i,j,\sigma} \tilde{t}_{ij} a^\dagger_{i,\sigma} a_{j,\sigma} + U \sum_{i,\sigma} n_{i,\sigma} a^\dagger_{i,\sigma} a_{i,\sigma} + \frac{1}{2} V \sum_{\tilde{\epsilon},i,\sigma} (\Delta_{\tilde{\epsilon},i,\sigma}^\dagger a_{i,\sigma}^\dagger a_{i+\tilde{\epsilon},\sigma} + \Delta_{\tilde{\epsilon},i,\sigma} a_{i+\tilde{\epsilon},\sigma}^\dagger a_{i,\sigma}),
\end{equation}

where $a^\dagger_{i,\sigma}$ ($a_{i,\sigma}$) is a creation (annihilation) operator, and $i + \tilde{\epsilon}$ represents the NN site ($\tilde{\epsilon} = \pm \hat{x}, \pm \hat{y}$). The
transfer integral is expressed as
\[ \tilde{t}_{i,j} = t_{i,j} \exp \left[ \frac{\pi}{\phi_0} \int_{r_i}^{r_j} A(r) \cdot dr \right], \]
with the vector potential \( A(r) = \frac{1}{2} \mathbf{H} \times r \) in the symmetric gauge, and the flux quantum \( \phi_0 \). For the NN pairs \((i,j)\), \( t_{i,j} = t \). For the next-NN pairs situated on a diagonal position on the square lattice, \( t_{i,j} = t' \). To reproduce the Fermi surface topology of LSCO, we set \( t' = -0.12t \) and \( t'' = 0.08t \). The essential results of this paper do not significantly depend on the choice of these parameter values.

In terms of the eigen-energy \( E_\alpha \) and the wave functions \( u_\alpha(r_i), v_\alpha(r_j) \) at the \( i \)-site, the Bogoliubov-de Gennes equation is given by
\[ \sum_j \left( \begin{array}{cc} K_{\uparrow,i,j} & D_{\downarrow,j} \\ -D_{\downarrow,j} & K_{\downarrow,i,j} \end{array} \right) \left( \begin{array}{c} u_\alpha(r_j) \\ v_\alpha(r_j) \end{array} \right) = E_\alpha \left( \begin{array}{c} u_\alpha(r_i) \\ v_\alpha(r_i) \end{array} \right), \]
where \( K_{\sigma,i,j} = -\tilde{t}_{i,j} + \delta_{ij}(U_{\sigma} - \mu) \), \( D_{\sigma,j} = V \sum_k \Delta_{\sigma,j}^k \delta_{j,k+i} \) and \( \sigma \) is an index of the eigenstate.\( \Box \)

The self-consistent condition for the pair potential and the number density is given by
\[ \Delta_{\uparrow,i,j} = \langle a_{j,\uparrow}\hat{a}_{i,\uparrow}\rangle = \sum_\alpha \langle u_\alpha(r_i) \rangle v_\alpha^*(r_j) f(E_\alpha), \]
\[ n_{i,\uparrow} = \langle a_{i,\uparrow}^\dagger a_{i,\uparrow}\rangle = \sum_\alpha |u_\alpha(r_i)|^2 f(E_\alpha), \]
\[ n_{i,\downarrow} = \langle a_{i,\downarrow}^\dagger a_{i,\downarrow}\rangle = \sum_\alpha |v_\alpha(r_i)|^2 (1 - f(E_\alpha)). \]
The charge density \( n_i = n_{i,\uparrow} + n_{i,\downarrow} \) and the spin density \( S_{z,i} = \frac{1}{2}(n_{i,\uparrow} - n_{i,\downarrow}) \). The superconducting order parameter is decomposed into \( d \)- and \( s \)-wave components at each site \( i \) as
\[ \Delta_{d,\sigma,i} = (\Delta_{\uparrow,i,\sigma} + \Delta_{\downarrow,i,\sigma} - \Delta_{\uparrow,i,\sigma} - \Delta_{\downarrow,i,\sigma})/4, \]
\[ \Delta_{s,\sigma,i} = (\Delta_{\uparrow,i,\sigma} + \Delta_{\downarrow,i,\sigma} + \Delta_{\uparrow,i,\sigma} - \Delta_{\downarrow,i,\sigma})/4, \]
with
\[ \Delta_{d,\sigma,i} = \Delta_{d,\sigma,i} \exp \left[ \frac{\pi}{\phi_0} \int_{r_i}^{r_{i+\sigma}} A(r) \cdot dr \right], \]
where \( \Delta_{i+\sigma,\uparrow} = \langle a_{i+\sigma,\downarrow} a_{i,\uparrow} \rangle \) and \( \Delta_{i+\sigma,\downarrow} = -\langle a_{i+\sigma,\uparrow} a_{i,\downarrow} \rangle \).

We typically consider the case of a unit cell with 24×24 sites, where two vortices are accommodated. Regarding the stripe structure, we assume a vertical stripe of the commensurability \( \delta = \frac{1}{3} \), i.e., an eight-site periodic spin structure. It is characterized by the ordering vector \( Q = 2\pi (\frac{1}{3}, \frac{1}{3} - \delta) \), where the lattice constant is unity. The spatially averaged hole density is set to \( n_h = 1 - \frac{n_1}{n} \sim \frac{1}{8} \) by tuning the chemical potential \( \mu \). By introducing the quasimomentum of the magnetic Bloch state, we obtain the wave function under the periodic boundary condition whose region covers many unit cells. We consider the low-temperature case \( T = 0.01t \), where the vortex structure is almost independent of \( T \).

First, we discuss the spatial structure of the order parameter for the \( d \)-wave (s-wave) superconductivity \( \Delta_{d,i} = \Delta_{d,i,\uparrow} + \Delta_{d,i,\downarrow} \) (\( \Delta_{s,i} = \Delta_{s,i,\uparrow} + \Delta_{s,i,\downarrow} \)) and the charge density \( n_i \) by comparing the usual no-stripe case and the stripe case. Figure 1 presents the vortex structure in the no-stripe case \( U = 0 \) and \( V = -2t \). The amplitude \( |\Delta_{d,i}| \) in Fig. 1(a) is suppressed near vortices. The vortex centers are located in the middle and at the four corners of the figure. Around the vortex core, the \( s \)-wave component \( \Delta_{s,i} \) is induced, as shown in Fig. 1(b), because the fourfold symmetry of the system is locally broken where the dominant \( d \)-wave order parameter varies spatially. Figure 1(c) shows that the charge density \( n_i \) is slightly suppressed in the vortex core region. This is a charging effect of the vortex core which has been discussed in the \( s \)-wave pairing case.\( \Box \)

We show that this occurs even in the \( d \)-wave pairing case by means of the microscopic calculation. It is suggested that the charging effect is related to the Hall anomaly in high-\( T_c \) superconductors.\( \Box \) However, to explain the experimental results, we need the opposite sign of the charging to those theoretically obtained thus far. We obtain the opposite sign in the stripe state, as mentioned later.

The stripe structure without a vortex was reported in refs. \( 25, 26 \) and \( 30 \). For finite dopings from half-filling, the AF structure is modulated. For \( \delta = \frac{1}{3} \), the envelope of the AF moment \( (-1)^{s+1} S_{z,i} \) shows the wave of the eight-site period along the \( y \)- (or \( x \)-) direction. Near the stripe line where \( (-1)^{s+1} S_{z,i} \) changes its sign and the \( \pi \)-shift occurs, the magnetic moment is suppressed. Along the stripe line, the doped carriers (holes) accumulate, and the \( d \)-wave superconductivity \( |\Delta_{d,i}| \) is large. Outside of the stripe, \( |\Delta_{d,i}| \) is suppressed.

Figure 2 shows the vortex structure in the stripe state for \( U = 4t \) and \( V = -2t \). Figure 2(a) is for \( |\Delta_{d,i}| \). Here, we show the bond-centered stripe case, where the center of the stripe line is on a bond. The site with large \( |\Delta_{d,i}| \) is in the stripe region, and that with small \( |\Delta_{d,i}| \) is outside of the stripe. While \( |\Delta_{d,i}| \sim 0.24 \) in the no-stripe case in Fig. 1(a), \( |\Delta_{d,i}| \) is suppressed to \( |\Delta_{d,i}| \sim 0.15 \) at its maximum. This is because part of the DOS at the Fermi energy is already used for the stripe formation, and the superconductivity occurs by using the remaining DOS. The vortex center tends to be attracted to the outside of the stripe, where \( |\Delta_{d,i}| \) is weak. We consider various cases for the vortex center position as an initial state of the iterating calculation. However, the vortex center is shifted to the outside of the stripe in the final self-consistent results. This suggests that the stripe functions as a line pinning center for a vortex. This is reasonable because the condensation energy loss required to create a vortex is minimal. Figure 2(a) shows that \( |\Delta_{d,i}| \) is suppressed near the vortex core recovers quickly in the direction perpendicular to the stripe. The effect of the vortex is limited to within about three sites from the vortex center. However, along the parallel direction, \( |\Delta_{d,i}| \) around the vortex core slowly recovers by using the maximal length of the intervortex distance. That is, the superconducting coherence length is short (long) in the perpendicular (parallel) direction. This suggests that the stable vortex lattice configuration is modified from...
the conventional 60° triangular lattice. However, the vortex core structure, which we are studying, will not be significantly affected by the vortex lattice configuration.

Figure 2(b) shows the small s-wave component $|\Delta_{s,i}|$ induced by the spatial variation of the dominant $|\Delta_{d,i}|$. There, the effect of the stripe is large compared with the vortex effect. In the stripe region, $|\Delta_{s,i}|$ is large, and $|\Delta_{d,i}|$ is slightly suppressed near the vortex. As shown in Fig. 2(c), $n_i$ is large outside of the stripe. There, $n_i$ is enhanced at the vortex core. It is important to note that the sign of the charging is opposite to that of the no-stripe case. This sign change is related to the AF moment of the stripe state. Also, when the AF moment is induced around the vortex, this type of sign change is reported. The structure of $S_{\pm,i}$ is not strongly affected by the vortex in our results.

Next, we investigate the electronic structure around the vortex by calculating the LDOS $N(E, r_i) = N_{\uparrow}(E, r_i) + N_{\downarrow}(E, r_i)$ at the i-site, where $N_{\uparrow}(E, r_i) = \sum_{\alpha} |\psi_{\alpha}(r)|^2 \delta(E - E_{\alpha})$ for up-spin and $N_{\downarrow}(E, r_i) = \sum_{\alpha} |\psi_{\alpha}(r)|^2 \delta(E + E_{\alpha})$ for down-spin contributions. At the site where $S_{\pm,i} > 0$, $N_{\uparrow}(E, r_i) > N_{\downarrow}(E, r_i)$ for $E < E_F$. In our numerical calculation, we use the derivative $f'(E)$ of the Fermi function instead of $\delta(E)$. In this case, $N(E, r)$ corresponds to the differential tunnel conductance of STM experiments.

The no-stripe case of Fig. 1 is shown in Fig. 3(a). Far from the vortex, $N(E, r_i)$ shows the typical $d$-wave superconductor’s DOS at zero field. The superconducting gap $\Delta_0 = 2|V\Delta_{d,i}| \sim 0.96t$. At the vortex core, the superconducting gap is smeared, and a low-energy peak appears at $E \sim 0$. As for the stripe case of Fig. 2, Fig. 3(b) shows $N(E, r_i)$ for the site within the stripe region, and Fig. 3(c) for the site outside of the stripe. The metallic stripe region has more low-energy states than the outside region. Far from the vortex, the LDOS is reduced to that of the zero-field case. It is noted that there appears a small gap $\Delta_1 (\sim 0.2t)$ within the $d$-wave superconducting gap $\Delta_0 (= 2|V\Delta_{d,i}| \sim 0.6t)$, because the s-wave component is induced in the $d$-wave superconductivity. This is also understandable from the ARPES results which report that the Fermi energy state near $(\pi, \pi)$ vanishes as a result of the stripe formation. Then, the low-energy state at the gap-node direction $(\pi, \pi)$ of $d$-wave superconductivity is absent in the superconducting stripe state, and a small gap opens in the $d$-wave superconducting gap. The structure of the

---

**Fig. 1.** Vortex structure in the no-stripe case for $U = 0$ and $V = -2t$. (a) $|\Delta_{d,i}|$, (b) $|\Delta_{s,i}|$, (c) $n_i$. The area of 24 × 24 sites is plotted, where vortices are located in the middle and at the four corners of the figure.

**Fig. 2.** Vortex structure in the stripe state for $U = 4t$ and $V = -2t$. (a) $|\Delta_{d,i}|$, (b) $|\Delta_{s,i}|$, (c) $n_i$. The area of 24 × 24 sites is plotted, where vortices are located in the middle and at the four corners of the figure. Bond-centered stripe lines run along the $x$ direction, which are at the bond $i_y = 2-3, 6-7, 10-11, 14-15, 18-19, 22-23$. 

---

![Image](image_url)
peaks above $\Delta_0$ is due to the stripe structure. The vortex core state is completely different from that of the no-stripe case. There is no eminent low-energy state. At the vortex core, small peaks or shoulders appear above the small gap $\Delta_1$. They have similar structures to those of the STM results.

The vortex structure in the stripe case has characteristics in common with the Josephson vortex in layered superconductors under a parallel magnetic field. Since the superconductivity appears dominantly on the metallic 1D stripe lines, the interstripe coupling between the 1D superconducting stripes can be considered as Josephson-like coupling. Also, in the layered superconductors, the interlayer coupling is Josephson-like coupling. Furthermore, the vortex is trapped in the interlayer space, where the superconductivity is weak. There, the coherence length around the vortex is long (short) parallel (perpendicular) to the layer. While there appears a zero energy state (precisely speaking, there is a small gap of the order $\Delta^2/E_F$ in the $s$-wave pairing) in the vortex core state for a perpendicular field, the low-energy core state does not appear for a parallel field. The vortex core state has the energy of the order $\Delta_0^{1/2}$. In contrast to the layered superconductors, the stripe line can move thermally. We sometimes need pinning centers in order to obtain the static stripe state, such as the partial substitution of Nd in LNSCO. The vortex core is a candidate for the pinning center to trap a stripe line.

In summary, we have studied the vortex structure in the superconducting stripe state, based on the Bogoliubov-de Gennes theory. The vortex state has a different structure from that of the usual no-stripe case. The vortex is trapped in the weak superconducting region outside of the stripe. The eminent low-energy quasiparticle states do not appear even at the vortex core, where only small peaks or shoulders appear above a small gap. These characteristics resemble those of the Josephson vortex in the layered superconductors under a parallel magnetic field. Although Figs. 2 and 3 represent the bond-centered stripe case, we observe the same type of behavior even in the site-centered stripe case.

Our calculation assumes the static stripe order. Thus, precisely speaking, our results can be applied only to the static stripe state near $\frac{1}{8}$-filling. Apart from $\frac{1}{8}$-filling, we must consider the fluctuation effect of the stripe line, which will smear the structure of the static stripe case. However, we expect that the main characteristics such as the lack of an eminent low-energy electronic state will remain even in the fluctuating stripe case. Thus, the effect of stripes should be taken into account when we analyze the exotic LDOS structure of the vortex state as observed by means of STM experiments.

Fig. 3. Local density of states $N(E, r_i)$ at the vortex core (solid lines) and far from the vortex (dotted lines). (a) The no-stripe case of Fig. 1. We plot $N(E, r_i)$ at the site $(i_x, i_y) = (1, 1)$ for the vortex core, and at the $(12, 1)$-site far from the vortex. (b) The stripe region in the stripe case of Fig. 2. We plot $N(E, r_i)$ at the $(1, 2)$-site in the vortex core, and at the $(12, 2)$-site far from the vortex. (c) The outside region of the stripe in the stripe case of Fig. 2. We plot $N(E, r_i)$ at the $(1, 1)$-site in the vortex core, and at the $(12, 1)$-site far from the vortex.

[1] M. Matsuda, M. Fujita, K. Yamada, R. J. Birgeneau, M. A. Kastner, H. Hiraka, Y. Endoh, S. Wakimoto and G. Shirane: Phys. Rev. B 62 (2000) 9148.
[2] S. Wakimoto, G. Shirane, Y. Endoh, K. Hirota, S. Ueki, K. Yamada, R. J. Birgeneau, M. A. Kastner, Y. S. Lee, P. M. Gehring and S. H. Lee: Phys. Rev. B 60 (1999) 769.
[3] T. Suzuki, T. Goto, K. Chiba, T. Shinoda, T. Fukase, H. Kimura, K. Yamada, M. Ohashi and Y. Yamaguchi: Phys. Rev. B 57 (1998) R3229.
[4] J. M. Tranquada, B. J. Sternlieb, J. D. Axe, Y. Nakamura and S. Uchida: Nature 375 (1995) 561.
[5] J. M. Tranquada, J. D. Axon, N. Ichikawa, A. R. Moodenbaugh, Y. Nakamura and S. Uchida: Phys. Rev. Lett. 78 (1997) 338.
[6] T. Noda, H. Eisaki and S. Uchida: Science 286 (1999) 265.
[7] X. J. Zhou, P. Bogdanov, S. A. Kellar, T. Noda, H. Eisaki, S. Uchida, Z. Hussain, Z. -X. Shen: Science 286 (1999) 268.
[8] A. Ino, C. Kim, T. Mizokawa, Z. -X. Shen, A. Fujimori, M. Takabe, K. Tamasaku, H. Eisaki and S. Uchida: J. Phys. Soc. Jpn. 68 (1999) 1496.
[9] A. Ino, C. Kim, M. Nakamura, T. Yoshida, T. Mizokawa, Z. -X. Shen, A. Fujimori, M. Kakeshita, H. Eisaki and S. Uchida: Phys. Rev. B 62 (2000) 4137.
[10] A. Ino, C. Kim, M. Nakamura, T. Yoshida, T. Mizokawa, Z. -X. Shen, A. Fujimori, M. Kakeshita, H. Eisaki and S. Uchida: cond-mat/0005370.
[11] H. A. Mook, P. Dai, S. M. Hayden, G. Aeppli, T. G. Perring and F. Doğan: Nature 395 (1998) 580.
[12] H. A. Mook, P. Dai, F. Doğan and R. D. Hunt: Nature 404 (2000) 729.
[13] M. Arai, T. Nishijima, Y. Endoh, T. Egami, S. Tajima, K. Tomimoto, Y. Shimohara, M. Takahashi, A. Garrett and S. M. Bennington: Phys. Rev. Lett. 83 (1999) 608.
[14] G. E. Volovik: JETP Lett. 58 (1993) 469.
[15] M. Ichioka, A. Hasegawa and K. Machida: Phys. Rev. B 59 (1999) 184.
[16] M. Ichioka, A. Hasegawa and K. Machida: Phys. Rev. B 59 (1999) 8902.
[17] Y. Wang and A. H. MacDonald: Phys. Rev. B 52 (1995) 3876.
[18] M. Franz and Z. Tešanović: Phys. Rev. Lett. 80 (1998) 4763.
[19] E. W. Hudson, S. H. Pan, A. K. Gupta, K. -W. Ng and J. C. Davis: Science 285 (1999) 88.
[20] Ch. Renner, B. Revaz, K. Kadowaki, I. Maggio-Aprie and Ø. Fischer: Phys. Rev. Lett. 80 (1998) 3606.
[21] I. Maggio-Aprie, Ch. Renner, A. Erb, E. Walker and Ø. Fischer: Phys. Rev. Lett. 75 (1995) 2754.
[22] I. Maggio-Aprie, Ch. Renner, A. Erb, E. Walker and Ø. Fischer: J. Low Temp. Phys. 105 (1996) 1129.
[23] A. Himeda, M. Ogata, Y. Tanaka and S. Kashiwaya: J. Phys. Soc. Jpn. 66 (1997) 3367.
[24] M. Ogata: Int. J. of Mod. Phys. B 13 (1999) 3560.
[25] J. H. Han and D. H. Lee: Phys. Rev. Lett. 85 (2000) 1100.
[26] J. Zaanen and A. M. Oleś, Ann. Phys. 5 (1996) 224.
[27] K. Machida and M. Ichioka: J. Phys. Soc. Jpn. 68 (1999) 2168.
[28] M. Ichioka and K. Machida: J. Phys. Soc. Jpn. 68 (1999) 4020.
[29] M. Ichioka and K. Machida: Physica B 281&282 (2000) 804.
[30] I. Martin, G. Ortiz, A. V. Balatsky and A. R. Bishop: cond-mat/0003316.
[31] T. Tohyama, S. Nagai, Y. Shibata and S. Maekawa: Phys. Rev. Lett. 82 (1999) 4910.
[32] M. Takigawa, M. Ichioka and K. Machida: Phys. Rev. Lett. 83 (1999) 3057.
[33] D. I. Khomskii and A. Freimuth: Phys. Rev. Lett. 75 (1995) 1384.
[34] N. Hayashi, M. Ichioka and K. Machida: J. Phys. Soc. Jpn. 67 (1998) 3368.
[35] T. Nagaoka, Y. Matsuda, H. Obara, A. Sawa, T. Terashima, I. Chong, M. Takano and M. Suzuki: Phys. Rev. Lett. 80 (1998) 3594.
[36] M. Ichioka and T. Tsuneto: J. Low Temp. Phys. 96 (1994) 213.