PHYSICAL REVIEW B **69**, 104518 (2004)

Variation of the superconducting transition temperature of hole-doped copper oxides

X. J. Chen
Geophysical Laboratory, Carnegie Institution of Washington, Washington, DC 20015, USA

H. Q. Lin
Department of Physics, The Chinese University of Hong Kong, Hong Kong, China

(Received 7 October 2002; published 23 March 2004)

The experimentally observed difference of the superconducting critical temperature T_c of hole-doped cuprates is studied by using an extended interlayer coupling model for layered d-wave superconductors. We show that the change of the maximum T_c from series to series is determined by the next-nearest-neighboring hopping t', while the difference of the maximum T_c among the compounds in a homogeneous series is controlled by the interlayer pairing strength. Our results also provide helpful guidelines in the search for new high-T_c superconductors.

DOI: 10.1103/PhysRevB.69.104518 PACS number(s): 74.62.−c, 74.72.−h

The nature of high-temperature superconductors is a challenging problem in condensed-matter physics. A common feature of copper-oxide superconductors is the presence of CuO_2 plane. It has been observed that the superconducting critical temperature T_c varies parabolically with the hole concentration n_H in CuO_2 plane with a maximum T_c^{max} at an optimal doping level.[1,2] Furthermore, in the homogeneous series compounds $A_mB_2Ca_{n-1}Cu_nO_{2n+y+\delta}$ ($A=$Bi, Tl, or Hg, $B=$Sr or Ba, $m=2$ or 1, $y=4$, 3, or 2), T_c^{max} initially increases with the number of CuO_2 layers (n) per unit cell, maximizes when $n=3$, and then decreases with further increasing n,[3] as shown in Fig. 1. However, T_c^{max} attainable is different from series to series, e.g., 35 K in $La_{2-x}Sr_xCuO_4$ (Ref. 4) and 97 K in $HgBa_2CuO_{4+\delta}$.[5] An obvious question is what is the crucial parameter that governs the T_c^{max} of each family.

Among various parameters proposed, the Madelung potential at the apical oxygen relative to that at the planar oxygens[6] was found to correlate with T_c^{max} rather well, pointing to the primary importance of the apical oxygens for the electronic structure relevant to superconductivity. Further investigations[7,8] revealed that the effect of the apical oxygens on high-T_c superconductivity in reality translates into a correlation between T_c^{max} and the next-nearest-neighbor hopping parameter t' in the t-t'-J model with t and J being the nearest-neighbor hopping parameter and antiferromagnetic interaction, respectively. In these approaches, t' was considered as a single parameter reflecting the main difference among various cuprates. If we consider the homologous series, the universality of such a correlation would be seriously questioned. For example, the bilayer and trilayer Tl_2-based and Hg-based compounds have almost same t' (Ref. 8), but their T_c^{max}'s are significantly different.

Our goal in this work is to extract and identify which parameters govern the T_c behaviors in hole-doped cuprates. We apply an interlayer coupling model to CuO_2 layer systems and then calculate T_c based on the Bardeen-Cooper-Schrieffer (BCS) gap equation with d-wave symmetry. Our results suggest that the difference of T_c^{max} from family to family is the result of different next-nearest-neighbor hopping t', while the difference of T_c^{max} between the compounds in a homologous family is controlled by the interlayer coupling strength T_J.

The effective layered Hamiltonian we consider is

$$H=\sum_{lk\sigma}(\varepsilon_k-\mu)c_{k\sigma}^{\dagger l}c_{k\sigma}^{l}-\sum_{lkk'}V_{kk'}c_{k\uparrow}^{\dagger l}c_{-k\downarrow}^{\dagger l}c_{-k'\downarrow}^{l}c_{k'\uparrow}^{l}$$
$$+\sum_{\langle ll'\rangle}\sum_{k}T_J(k)c_{k\uparrow}^{\dagger l}c_{-k\downarrow}^{\dagger l}c_{-k\downarrow}^{l'}c_{k\uparrow}^{l'}, \qquad (1)$$

where ε_k is the quasiparticle dispersion, μ is the chemical potential, $c_{k\sigma}^{\dagger l}$ is a quasiparticle creation operator pertaining to the layer (l) with two-dimensional wave vector k and spin σ. The summation over ll' runs over the layer indices of the unit cell. The intralayer interaction $V_{kk'}$ is assumed to be independent of l. The interlayer tunneling is parametrized by $T_J(k)=T_J(\cos k_x-\cos k_y)^4$ (Ref. 9).

We assume that the superconducting gap is characterized by the nonvanishing order parameter $b_k^l=\langle c_{k\uparrow}^l c_{-k\downarrow}^l\rangle$. Based on the BCS theory, the gap function Δ_k^l satisfies the following equation:

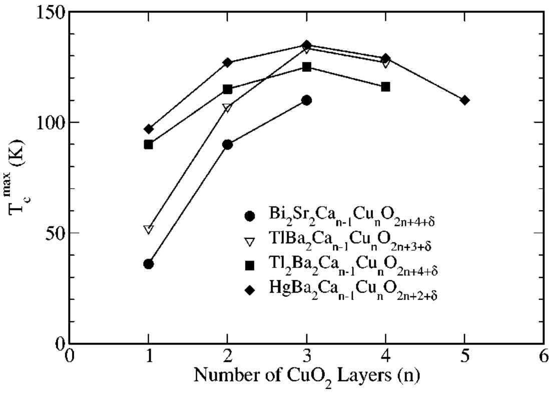

FIG. 1. Dependence of the critical temperature T_c^{max} at optimal doping as a function of the number of CuO_2 layers (n) of various homogeneous series.

$$\Delta_k^l = \sum_{k'} V_{kk'} b_{k'}^l + T_J(k)(b_k^{l+1} + b_k^{l-1}), \tag{2}$$

where $b_k^l = \Delta_k^l \chi_k^l$ and the generalized pair susceptibility is $\chi_k^l = (2E_k^l)^{-1} \tanh(\beta E_k^l/2)$ with the quasiparticle spectrum $E_k^l = \sqrt{(\varepsilon_k - \mu)^2 + |\Delta_k^l|^2}$.

The spatial dependence of the gap takes the form[10] $\Delta_k^l = \Delta_k^{\pm} e^{\pm i\alpha l}$. Then the general solution of the homogeneous part is

$$\Delta_k^l = \Delta_k^+ e^{i\alpha l} + \Delta_k^- e^{-i\alpha l}. \tag{3}$$

Considering the fact that the gap vanishes on the layer ends $l=0$ and $n+1$, the natural boundary conditions for the gap are $\Delta_k^0 = \Delta_k^{n+1} \equiv 0$. The wave vector of the oscillating gap is then determined by

$$\begin{pmatrix} 1 & 1 \\ e^{i\alpha l} & e^{-i\alpha l} \end{pmatrix} \begin{pmatrix} \Delta_k^+ \\ \Delta_k^- \end{pmatrix} = 0.$$

The vanishing determinant of the matrix provides a nontrivial solution only when $\alpha = \xi\pi/(n+1)$ with ξ being an integer. Thus we obtain $\Delta_k^+ = -\Delta_k^- \equiv \Delta_k$. The solution of spatial dependence of the gap is then given by

$$\Delta_k^l = 2i\Delta_k \sin\left(\frac{l\pi\xi}{n+1}\right). \tag{4}$$

The solution with the lowest energy is nodeless inside the n CuO$_2$ layers which leads to $\xi=1$ for the superconducting state. Thus, the spatial dependence of the gap has the form

$$\Delta_k^l = 2i\Delta_k \sin\left(\frac{l\pi}{n+1}\right). \tag{5}$$

Around critical temperature T_c, we can take χ_k^l in a simple form: $\chi_k^l \simeq (2E_k)^{-1} \tanh(\beta E_k/2) \equiv \chi_k$ with $E_k = \sqrt{(\varepsilon_k - \mu)^2 + |\Delta_k|^2}$. In this case, Eq. (2) can be rewritten as

$$\Delta_k^l = \sum_{k'} V_{kk'} \chi_{k'} \Delta_{k'}^l + T_J(k)(\chi_k \Delta_k^{l+1} + \chi_k \Delta_k^{l-1}). \tag{6}$$

Substitution of Eq. (5) into Eq. (6) yields a simple Δ_k equation

$$\Delta_k - \sum_{k'} V_{kk'} \chi_{k'} \Delta_{k'} = f(n) T_J(k) \chi_k \Delta_k, \tag{7}$$

where $f(n) = 2\cos[\pi/(n+1)]$.

To account for the experimental observed d-wave gap, we assume a d-wave pairing potential

$$V_{kk'} = V g(k) g(k'), \quad g(k) = \cos k_x - \cos k_y. \tag{8}$$

The gap magnitude is thus $\Delta_k = \Delta_0 g(k)$ and the parameter Δ_0 is determined by the following self-consistent equation:

$$1 = \frac{1}{2N} \sum_k \frac{V g^2(k) + f(n) T_J(k)}{E_k} \tanh\left(\frac{\beta E_k}{2}\right). \tag{9}$$

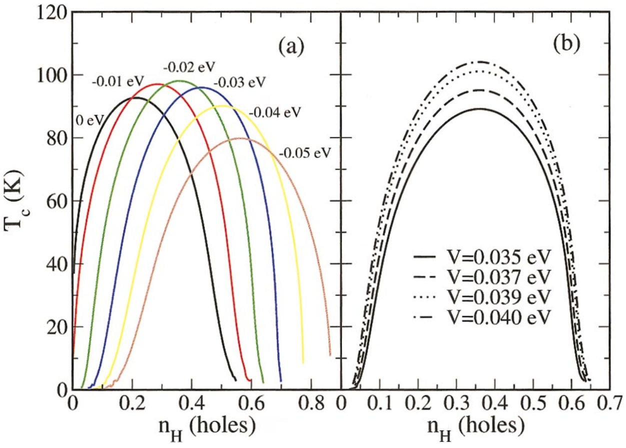

FIG. 2. (Color) The critical temperature T_c vs the hole concentration n_H for various next-nearest-neighbor hopping parameters t' with the interaction strength $V=0.038$ eV (a) and for various V with $t'=-0.02$ eV (b) in monolayer cuprates.

The value of T_c in layered d-wave superconductors is then obtained by solving Eq. (9) at $\Delta_0 = 0$.

In order to self-consistently calculate T_c for a given μ in conjunction with the equation determining n_H, we need an explicit form of ε_k. It has been established[11–15] that the quasiparticle excitation spectrum of cuprates can be well described by the t-t'-J model. Within the framework of the t-t'-J model, the dispersion ε_k is given by[13,15]

$$\varepsilon_k = (J + 2t') \cos k_x \cos k_y + \frac{J}{4}(\cos 2k_x + \cos 2k_y). \tag{10}$$

For monolayer insulator La$_2$CuO$_4$, experiments[16] and theoretical calculations[17] give a $J=0.128$ eV. There are small variations of J among various Cu-O insulators[18] but we expect a value of $J=0.128$ eV is a generally good representation for all Cu-O materials. Then one can determine T_c as a function of n_H based on Eqs. (9) and (10) once having knowledge of t', V, or/and T_J.

First we consider the variation of T_c in monolayer ($n=1$) hole-doped cuprates. Figures 2(a) and 2(b) show the calculated T_c in monolayer superconductors as a function of n_H in some interested parameter range of t' and V. As shown, T_c initially increases with increasing n_H, takes a maximum around an optimal doping level n_H^{opt}, and then decreases with further increasing n_H. This parabolic relation between T_c and n_H agrees with general experimental observations in monolayer cuprates.[1,2] We notice that T_c^{max} systematically changes with t', but it monotonically increases with V, as one expects. The difference between these two parameters is that n_H^{opt} depends significantly on t', while it scarcely changes for different values of V. These results indicate that the parameters controlling T_c^{max} would be either t' or V or both of them.

In Fig. 3 we plotted the t' dependence of both T_c^{max} and n_H^{opt} for monolayer cuprates. As t' increases, T_c^{max} increases and then decreases through a maximum for all V studied. Note that the enhancement of T_c^{max} from 25 to 100 K occurs

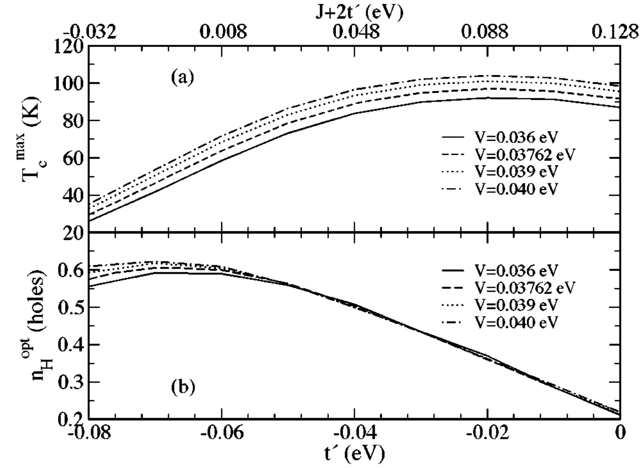

FIG. 3. The calculated maximum critical temperature T_c^{max} (a) and the optimal hole concentration n_H^{opt} (b) as a function of the next-nearest-neighbor hopping parameter t' (or $J+2t'$) for various interaction strengths V in monolayer cuprates.

over a rather wide parameter space. Such a huge enhancement completely covers the variation of T_c^{max} among the monolayer high-T_c superconductors. The occurrence of the maximum implies that the enhancement of T_c^{max} due to the increase in t' is limited. Since $J+2t'$ is the coefficient of the $\cos k_x \cos k_y$ term in Eq. (10), the effect of $J+2t'$ on T_c^{max} is obviously the same as that of t'. That means that T_c^{max} increases with increasing the coefficient of the $\cos k_x \cos k_y$ term in quasiparticle dispersion, saturates, and then decreases with the further increase of this coefficient. This nonmonotonic T_c^{max} dependence is consistent with those reported previously within the framework of the tight-binding approximation.[19,20] We also notice that n_H^{opt} behaves in a similar manner with t' as T_c^{max}. For $J+2t'>0$, n_H^{opt} decreases with increasing t'. Although T_c^{max} depends on V, n_H^{opt} is nearly independent of V over a wide range of t'.

To trace the clue to the change of T_c^{max} among monolayer cuprates, we list in Table I the experimental results of T_c^{max} (Refs. 2, 4, 5, 21, and 22) the distance $d_{\text{Cu-O}(a)}$ between the copper and apical oxygen atoms, and the distance $d_{\text{Cu-O}(p)}$ between the copper and in-plane oxygen atoms taken from the works in Refs. 5 and 6, the calculated values of bond valence sums (BVS) of copper V_{Cu} and the difference in the Madelung site potential for a hole between the copper and the in-plane oxygen ΔV_M. To get effective BVS of copper, we follow the method proposed by Brown.[23] The results of ΔV_M based on the structural data are taken from the works in Refs. 6 and 24. Here we observe one important experimental fact: T_c^{max} increases systematically with enlarging $d_{\text{Cu-O}(a)}$. Band-structure calculations[8] revealed that t' increases with $d_{\text{Cu-O}(a)}$ for the monolayer cuprates reported so far. Thus the increase of T_c^{max} with increasing t' should capture the basic physics of the monolayer cuprates.

It has been proposed[25,26] that V_{Cu} and ΔV_M are two essential factors governing T_c and represent an essentially equivalent physical content. Materials with larger T_c^{max} tend to have a smaller V_{Cu} (Ref. 25) or ΔV_M (Ref. 26). Since the variation of V_{Cu} or ΔV_M reflects the corresponding change of n_H (Refs. 26–28) the increase of the calculated T_c^{max} with decreasing n_H^{opt} for a wide t' range is obviously consistent with the experimental data shown in Table I. This n_H^{opt} dependence of T_c^{max} is also consistent with the muon spin resonance measurements.[29] On the other hand, the fact that the change of T_c^{max} with V is almost independent of n_H^{opt} [Fig. 3(b)] rules out the possibility of V being a dominant factor in governing the change in T_c^{max}. The present results lead us to conclude that the increase of T_c^{max} with $d_{\text{Cu-O}(a)}$ among the monolayer cuprates is a result of the increase in t'. One prediction is that T_c^{max} decreases with further increasing t' after a saturation. Thus, materials with a relatively long $d_{\text{Cu-O}(a)}$ bond length would not always expect to have a high T_c^{max}.

The values of t' were determined in a self-consistent way as follows. From Fig. 3(a) we learned that there exists a maximum for a given V. Among the monolayer cuprates discovered so far, $HgBa_2CuO_{4+\delta}$ possesses the highest T_c^{max} of 97 K. Assuming this is the highest value in all monolayer cuprates, we derived a value of $V=0.037\,62$ eV from curves of T_c^{max} versus t'. Equation (9) yields $t'=-0.0183$ eV for the optimally doped $HgBa_2CuO_{4+\delta}$. For other optimally doped monolayer compounds with $T_c^{max}<97$ K, t' should be smaller than -0.0183 eV because of their shorter $d_{\text{Cu-O}(a)}$. The relative t' is then obtained by using the experimentally observed T_c^{max}.

TABLE I. Summary of the experimental results of the critical temperature T_c^{max} at optimal doping, the distance $d_{\text{Cu-O}(a)}$ between the copper and apical oxygen atoms, the distance $d_{\text{Cu-O}(p)}$ between the copper and in-plane oxygen atoms, and the calculated values of the bond valence sums of copper V_{Cu} and the difference in the Madelung site potentials ΔV_M for a hole between the in-plane oxygen and copper atoms in some typical monolayer cuprates.

Cuprates	T_c^{max} (K)	$d_{\text{Cu-O}(a)}$ (Å)	$d_{\text{Cu-O}(p)}$ (Å)	V_{Cu}	ΔV_M (eV)
$La_{1.85}Sr_{0.15}CuO_4$	35	2.4124	1.8896	2.539	49.620
$Bi_2Sr_{1.61}La_{0.39}CuO_{6+\delta}$	36	2.461	1.901	2.437	48.437
$TlBa_{1.2}La_{1.8}CuO_5$	52	2.500	1.9240	2.280	48.409
$Tl_2Ba_2CuO_6$	90	2.714	1.9330	2.135	47.081
$HgBa_2CuO_{4+\delta}$	97	2.780	1.9375	2.091	46.81

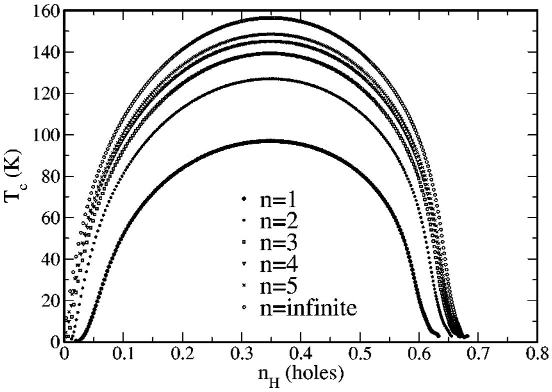

FIG. 4. The calculated critical temperature T_c vs the hole concentration n_H in $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$ as a function of the number of CuO_2 layers.

Next we consider n, the number of CuO_2 layers, dependence of T_c^{max} in the layered homogeneous series. In general, T_c^{max} initially increases with n, maximizes at $n=3$, and then decreases with further increasing n.[3] To calculate T_c for multilayers, we use the same dispersion ε_k and V as obtained from the monolayer. The interlayer tunneling strength T_J is determined by using the experimental values of T_c^{max} for monolayer and bilayer compounds in the same homogeneous series. As an example, in Fig. 4, we show curves of calculated T_c versus n_H as a function of layer number n in the Hg-based series. The theoretical curves exhibit the generic parabolic behavior. Previously, the relation between T_c and n_H has been well established for the monolayer, bilayer, and trilayer Hg-based superconductors.[30] Compared to the available experimental data, the agreement is excellent.

The calculated T_c^{max} in four typical homogeneous series are summarized in Table II. The experimental results are also listed for comparison. As can be seen, T_c^{max} initially increases with increasing n and then saturates as $n\rightarrow\infty$. This behavior is in good agreement with those obtained from both the interlayer mechanism[10,31] and Ginzburg-Landau theory.[32,33] The upper limit of T_c^{max} for infinite layer compound is in the range of 139.4–164.6 K. The highest T_c^{max} of 164.6 K is found in the Tl-based series. Our results for $n=3$ agree with experiments very well. The predictions made here for T_c^{max} of the trilayer compound are the best ones compared to previous theories.[10,31–33]

The present study shows that interlayer coupling is the driving force for the enhancement of T_c^{max} for multilayer systems. This does not conflict with the experimental fact that T_c^{max} decreases as $n\geqslant 3$. In fact, there exist fivefold (outer) and fourfold CuO_2 (inner) planes surrounded by pyramidal and square oxygens in the multilayer system. Investigations carried out by different experimental techniques and model calculations[28,34–36] showed that the distribution of charge carriers is nonhomogeneous among the CuO_2 sheets and the hole concentration in the outer CuO_2 plane is larger than that in the inner CuO_2 plane. BVS analyses[28] and NMR studies[36] on the Hg-based series revealed that the highest T_c^{max} corresponds to the smallest difference in n_H between two types of CuO_2 planes. When the number of CuO_2 layer is larger than three, the reduction of T_c^{max} comes from the large difference in n_H between the outer and inner CuO_2 planes. For compounds with more than three CuO_2 planes, the enhancement of T_c^{max} seems possible at ambient pressure if one can adequately dope the inner planes.

Finally, we would like to comment on the possibility of applying Eq. (10) to the high-T_c superconducting oxides. Angle-resolved photoemission (ARPES) experiments[37] reveal that there exists a flat region near $(\pi,0)$ in many high-T_c compounds. Such an extended region of flat CuO_2-derived bands seems a universal property of the hole-doped cuprates. The hole dispersion relation of Eq. (10) derived from the t-t'-J model reproduces well the flat bands similar to those observed in ARPES experiments.[37] Dagotto and his co-workers[12] have shown that the effect of strong correlations can quantitatively account for such flat bands. It has been found[12,38] that the sign, doping, and temperature dependence of the Hall coefficient, thermopower, specific heat, magnetic susceptibility is in excellent quantitative agreement with experiments when the dispersion obtained from the t-t'-J model is used. Furthermore, the momentum-dependent spectrum as a function of hole concentration has been calculated based on the t-t'-t''-J model by using both the exact diagonalization and Monte Carlo method.[14,15] The calculated results explain the experimental data of ARPES for hole doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ from underdoped to overdoped regime. The results indicate that once the flat region around $(\pi,0)$ has already formed, it remains almost unchanged upon additional doping. This means that the electronic structure is essentially the same in a high-T_c material with different doping level. Therefore, the dispersion relation of Eq. (10) is essential in describing the low-energy physics of high-temperature superconductors.

In summary, we have investigated the observed T_c variation in hole-doped cuprates on the basis of an extended in-

TABLE II. The critical temperature T_c^{max} and the ratio of T_J/V in homogeneous copper-oxide series at optimal doping. The brackets are the experimental data taken from the works of Refs. 2–6, 21, 22, 28, and 33.

n	1	2	3	4	5	∞	T_J/V
$Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4+\delta}$	36 (36)	90 (90)	115.5 (110)	127.8	134.7	150.7	0.1945
$TlBa_2Ca_{n-1}Cu_nO_{2n+3+\delta}$	52 (52)	107 (107)	131.3 (133.5)	143.0 (127)	149.5	164.6	0.1930
$Tl_2Ba_2Ca_{n-1}Cu_nO_{2n+4+\delta}$	90 (90)	115 (115)	125.2 (125)	130.1 (116)	132.9	139.4	0.0906
$HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$	97 (97)	127 (127)	139.2 (135)	145.2 (129)	148.6 (110)	156.4	0.1135

terlayer coupling model. We demonstrate that the next-nearest-neighboring hopping t' dominates the variation of the maximum T_c from series to series and the interlayer coupling strength controls the difference of the maximum T_c among the compounds in a layered homogeneous series. These results also provide helpful guidelines in the search for new high-T_c superconductors.

The authors are grateful to O. K. Andersen, H.-U. Habermeier, R. J. Hemley, H. K. Mao, J. S. Schilling, V. V. Struzhkin, and W. G. Yin for many helpful discussions. X.J.C. would like to acknowledge the U.S. Department of Energy awards DEFG02-02ER4595 and DEFC03-03NA00144. This work was supported in part by the Earmarked Grant for Research of Project No. CUHK 4037/02P.

---

[1] See, J.B. Torrance, Y. Tokura, A.I. Nazzal, A. Bezinge, T.C. Huang, and S.S.P. Parkin, Phys. Rev. Lett. **61**, 1127 (1988); Z.F. Ren, J.H. Wang, and D.J. Miller, Appl. Phys. Lett. **71**, 1706 (1997); Y. Cao, Q. Xiong, Y.Y. Xue, and C.W. Chu, Phys. Rev. B **50**, 10 346 (1994).
[2] Y. Ando, Y. Hanaki, S. Ono, T. Murayama, K. Segawa, N. Miyamoto, and S. Komiya, Phys. Rev. B **61**, R14 956 (2000).
[3] Recent measurements on $TlBa_2Ca_{n-1}Cu_nO_{2n+3+\delta}$ show $T_c^{max} = 133.5$ K for $n=3$ and 127 K for $n=4$, respectively, see, A. Iyo, Y. Aizawa, Y. Tanaka, M. Tokumoto, K. Tokiwa, T. Watanabe, and H. Ihara, Physica C **357-360**, 324 (2001).
[4] R.J. Cava, A. Santoro, D.W. Johnson, Jr., and W.W. Rhodes, Phys. Rev. B **35**, 6716 (1987).
[5] J.L. Wagner, P.G. Radaelli, D.G. Hinks, J.D. Jorgensen, J.F. Mitchell, B. Dabrowski, G.S. Knapp, and M.A. Beno, Physica C **210**, 447 (1993).
[6] Y. Ohta, T. Tohyama, and S. Maekawa, Phys. Rev. B **43**, 2968 (1991).
[7] R. Raimondi, J.H. Jefferson, and L.F. Feiner, Phys. Rev. B **53**, 8774 (1996).
[8] E. Pavarini, I. Dasgupta, T. Saha-Dasgupta, O. Jepsen, and O.K. Andersen, Phys. Rev. Lett. **87**, 047003 (2001).
[9] S. Chakravarty, A. Sudbø, P.W. Anderson, and S. Strong, Science **261**, 337 (1993).
[10] K. Byczuk and J. Spalek, Phys. Rev. B **53**, R518 (1996).
[11] K.J. von Szczepanski, P. Horsch, W. Stephan, and M. Ziegler, Phys. Rev. B **41**, 2017 (1990).
[12] E. Dagotto, A. Nazarenko, and M. Boninsegni, Phys. Rev. Lett. **73**, 728 (1994); E. Dagotto, A. Nazarenko, and A. Moreo, *ibid.* **74**, 310 (1995).
[13] V.I. Belinicher, A.L. Chernyshev, and V.A. Shubin, Phys. Rev. B **53**, 335 (1996); **54**, 14 914 (1996).
[14] W.G. Yin, C.D. Gong, and P.W. Leung, Phys. Rev. Lett. **81**, 2534 (1998).
[15] S. Maekawa, T. Tohyama, and Y. Shibata, Mater. Sci. Eng., B **63**, 159 (1999).
[16] B. Keimer, N. Belk, R.J. Birgeneau, A. Cassanho, C.Y. Chen, M. Greven, M.A. Kastner, A. Aharony, Y. Endoh, R.W. Erwin, and G. Shirane, Phys. Rev. B **46**, 14 034 (1992).
[17] M.S. Hybertsen, E.B. Stechel, M. Schluter, and D.R. Jennison, Phys. Rev. B **41**, 11 068 (1990).
[18] P.E. Sulewski, P.A. Fleury, K.B. Lyons, S.-W. Cheong, and Z. Fisk, Phys. Rev. B **41**, 225 (1990).
[19] K. Machida and M. Kato, Phys. Rev. B **36**, 854 (1987).
[20] A. Mishima, Physica B & C **148**, 371 (1987).
[21] M.A. Subramanian, G.H. Kwei, J.B. Parise, J.A. Goldstone, and R.B. Von Dreele, Physica C **166**, 19 (1990).
[22] C.C. Torardi, M.A. Subramanian, J.C. Calabrese, J. Gopalakrishnan, E.M. McCarron, K.J. Morrissey, T.R. Askew, R.B. Flippen, U. Chowdhry, and A.W. Sleight, Phys. Rev. B **38**, 225 (1988).
[23] I.D. Brown, J. Solid State Chem. **82**, 122 (1989).
[24] M. Muroi, Physica C **219**, 129 (1994).
[25] D.M. de Leeuw, W.A. Groen, L.F. Feiner, and E.E. Havinga, Physica C **166**, 133 (1990).
[26] S. Tanaka, Jpn. J. Appl. Phys., Part 1 **33**, 1004 (1994).
[27] M.-H. Whangbo and C.C. Torardi, Science **249**, 1143 (1990).
[28] X.J. Chen, Z.A. Xu, J.S. Wang, Z.K. Jiao, and Q.R. Zhang, Chem. Phys. Lett. **258**, 1 (1996).
[29] Y.J. Uemura, Physica C **282-287**, 194 (1997).
[30] A. Fukuoka, A. Tokiwa-Yamamoto, M. Itoh, R. Usami, S. Adachi, and K. Tanabe, Phys. Rev. B **55**, 6612 (1997).
[31] J.M. Wheatley, T.C. Hsu, and P.W. Anderson, Nature (London) **333**, 121 (1988).
[32] J.L. Birman and J.P. Lu, Phys. Rev. B **39**, 2238 (1989).
[33] X.J. Chen and C.D. Gong, Phys. Rev. B **59**, 4513 (1999).
[34] M. Di Stasio, K.A. Müller, and L. Pietronero, Phys. Rev. Lett. **64**, 2827 (1990).
[35] A. Trokiner, L.Le. Noc, J. Schneck, A.M. Pougnet, R. Mellet, J. Primot, H. Savary, Y.M. Gao, and S. Aubry, Phys. Rev. B **44**, 2426 (1991).
[36] H. Kotegawa, Y. Tokunaga, K. Ishida, G.-q. Zheng, Y. Kitaoka, K. Asayama, H. Kito, A. Iyo, H. Ihara, K. Tanaka, K. Tokiwa, and T. Watanabe, J. Phys. Chem. Solids **62**, 171 (2001).
[37] A. Damascelli, Z. Hussain, and Z.-X. Shen, Rev. Mod. Phys. **75**, 473 (2003).
[38] S.A. Trugman, Phys. Rev. Lett. **65**, 500 (1990).