Two phase transitions in \((d_{x^2-y^2} + is)\)-wave superconductors

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We study numerically the temperature dependencies of specific heat, susceptibility, penetration depth, and thermal conductivity of a coupled \((d_{x^2-y^2} + is)\)-wave Bardeen-Cooper-Schrieffer superconductor in the presence of a weak \(s\)-wave component (1) on square lattice and (2) on a lattice with orthorhombic distortion. As the temperature is lowered past the critical temperature \(T_c\), a less ordered superconducting phase is created in \(d_{x^2-y^2}\) wave, which changes to a more ordered phase in \((d_{x^2-y^2} + is)\) wave at \(T_{c1}\). This manifests in two second-order phase transitions. The two phase transitions are identified by two jumps in specific heat at \(T_c\) and \(T_{c1}\). The temperature dependences of the superconducting observables exhibit a change from power-law to exponential behavior as temperature is lowered below \(T_{c1}\) and confirm the new phase transition.

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The unconventional high-\(T_c\) superconductors \([1]\) with a high critical temperature \(T_c\) have a complicated lattice structure with extended and/or mixed symmetry for the order parameter \([1,2]\). It is generally accepted that for many of these high-\(T_c\) materials, the order parameter exhibits anisotropic behavior. However, it is difficult to establish the detailed nature of anisotropy, which could be of an extended \(s\)-wave, a pure \(d\)-wave, or a mixed \((s + exp(i\theta)d)\)-wave type. Some of the high-\(T_c\) materials have singlet \(d\)-wave Cooper pairs and the order parameter has \(d_{x^2-y^2}\) symmetry in two dimensions \([2]\). Recent measurements \([4]\) of the penetration depth \(\lambda(T)\) and superconducting specific heat at different temperatures \(T\) and related theoretical analysis \([3,4]\) also support this point of view. In some cases there is the signature of an extended \(s\)- or \(d\)-wave symmetry \([3,4]\).

The possibility of a mixed \((s - d)\)-wave symmetry was suggested sometime ago by Ruckenstein et al. and Kotliar \([4]\). Several different types of measurements which are sensitive to the phase of the order parameter indicate a significant mixing of \(s\)-wave component with a predominant \(d_{x^2-y^2}\) state at lower temperatures below \(T_{c1}\). For temperatures between \(T_{c1}\) and the critical temperature \(T_c\) only the \(d_{x^2-y^2}\) state survives. There are experimental evidences based on Josephson supercurrent for tunneling between a conventional \(s\)-wave superconductor (Pb) and single crystals of \(YBa_2Cu_3O_7\) (YBCO) that YBCO has mixed \(d \pm s\) or \(d \pm is\) symmetry \([5]\) at lower temperatures. A similar conclusion may also be obtained based on the results of angle-resolved photoemission spectroscopy experiment by Ma et al. in which a temperature dependent gap anisotropy in \(Bi_2Sr_2CaCu_2O_{8+x}\) was detected \([6]\). The measured gaps along both high-symmetry directions are non-zero at low temperatures and their ratio was strongly temperature dependent. This observation is also difficult to reconcile employing a pure \(s\)- or \(d\)-wave order parameter and suggests that a mixed \([d_{x^2-y^2} + exp(i\theta)s]\) symmetry is applicable at low temperatures. However, at higher temperatures one could have a pure \(d_{x^2-y^2}\) symmetry of the order parameter. Recently, this idea has been explored to explain the NMR data in the superconductor YBCO and the Josephson critical current observed in YBCO-SNS and YBCO-Pb junctions \([10]\). Recently, a new class of \(c\)-axis Josephson tunneling experiments are reported by Kouznetsov et al. \([11]\) in which a conventional superconductor (Pb) was deposited across a single twin boundary of a YBCO crystal. In that case measurements of critical current as a function of the magnitude and angle of a magnetic field applied in the plane of the junction provides a direct evidence of an order parameter of mixed \([d_{x^2-y^2} + exp(i\theta)s]\) symmetry in YBCO. The microwave complex conductivity measurement in the superconducting state of high quality \(YBa_2Cu_3O_{7-\delta}\) single crystals measured at 10 GHz using a high-Q Nb cavity also strongly suggests a multicomponent superconducting order parameter in YBCO \([12]\).

More recently, Krishana et al. \([13]\) reported a phase transition in the high-\(T_c\) superconductor \(Bi_2Sr_2CaCu_2O_{8}\) induced by a magnetic field from a study of the thermal conductivity as a function of temperature and applied field. Possible interpretation of this measurement could be the induction of a minor \(s\) or \(d_{xy}\) component with a \(d_{x^2-y^2}\) symmetry with the application of a weak field \([14,15]\).

There have also been certain recent theoretical studies using mixed \(s\)- and \(d\)-wave symmetries \([14,15]\) and it was noted that it is more likely to realize a stable mixed \(d + is\) state than a \(d + s\) state considering different couplings and lattice symmetries. As noted by Liu et al. \([16]\), a stable \(d + s\) solution can not be realized on square lattice. However, in the presence of orthorhombic distortion, such a solution can be obtained. The special interest in these investigations was on the temperature dependence of the order parameter of the mixed \(d + is\) state within the Bardeen-Cooper-Schrieffer (BCS) model.
The study by Liu et al. [16] of the order parameter on mixed $d + is$ state also explored the effect of a van Hove singularity in the density of states on the solutions of the BCS equation. Laughlin has provided a theoretical explanation of the observation by Krishna et al. [13] that at low temperatures and for weak magnetic field a time-reversal symmetry breaking state of mixed symmetry is induced in Bi$_2$Sr$_2$CaCu$_2$O$_8$. From a study of vortex in a $d$-wave superconductor using a self-consistent Bogoliubov-de Gennes formalism, Franz and Žežanović [17] also predicted the possibility of the creation of a superconducting state of mixed symmetry. Although, the creation of the mixed state in this case is speculative, they conclude that a dramatic change should be observed in the superconducting observables when a pure superconducting $d_{x^2-y^2}$ state undergoes a phase transition to a mixed-symmetry state. In many cases there are evidences of a $s$-wave mixture with a $d_{x^2-y^2}$ state. In view of this, in this study we present an investigation of this phase transition on specific heat, spin susceptibility, penetration depth, and thermal conductivity.

There is no suitable microscopic theory for high-$T_c$ superconductors. Although it is accepted that Cooper pairs are formed in such materials, there is controversy about a proper description of the normal state and the pairing mechanism for such materials [18]. In the absence of a suitable microscopic theory, a phenomenological tight-binding model in two dimensions which incorporate the proper lattice symmetry within the BCS formalism [19] has been suggested [20]. This model has been very successful in describing many properties of high-$T_c$ materials and is often used in the study of high-$T_c$ compounds. We shall use this model in the present investigation.

In all previous theoretical studies on mixed-symmetry superconductors a general behavior of the temperature dependence of the order parameters emerged, independent of lattice symmetry employed [4,11]. The tight-binding BCS model for a mixed $d + is$ state becomes a coupled set of equations in the two partial waves. The ratio of the strengths of the $s$- and $d$-wave interactions should lie in a narrow region in order to have a coexisting $s$ and $d$ wave phases in the case of $d + is$ symmetry. As the $s$-wave ($d$-wave) interaction becomes stronger, the $d$-wave ($s$-wave) component of the order parameter quickly reduces and disappears and a pure $s$-wave ($d$-wave) state emerges.

In this work we study the temperature dependencies of different observables, such as specific heat, susceptibility, penetration depth, and thermal conductivity, of a $(d_{x^2-y^2} + is)$-wave BCS superconductor with a weak $s$-wave admixture both on square lattice and on a lattice with orthorhombic distortion and find that it exhibits interesting properties. A pure $s$-wave ($d$-wave) superconducting observable exhibits an exponential (power-law) dependence on temperature. In the case of mixed $(d_{x^2-y^2} + is)$-wave symmetry, we find that it is possible to have a crossover from an exponential to power-law dependence on temperature below the superconducting critical temperature and a second second-order phase transition.

For a weaker $s$-wave admixture, in the present study we establish in the two-dimensional tight-binding model (1) on square lattice and (2) on a lattice with orthorhombic distortion another second-order phase transition at $T = T_{c3} < T_c$, where the superconducting phase changes from a pure $d$-wave state for $T > T_{c3}$ to a mixed $(d + is)$-wave state for $T < T_{c3}$. The specific heat exhibits two jumps at the transition points $T = T_{c1}$ and $T = T_{c2}$. The temperature dependencies of the superconducting specific heat, susceptibility, penetration depth and thermal conductivity change drastically at $T = T_{c3}$ from power-law behavior (typical to $d$ state with node(s) in the order parameter on the Fermi surface) for $T > T_{c3}$ to exponential behavior (typical to $s$ state with no nodes) for $T < T_{c3}$. The order parameter for the present $(d + is)$ wave does not have a node on the Fermi surface for $T < T_{c3}$ and it behaves like a modified $s$-wave one. The observables for the normal state are closer to the superconducting $l = 2$ state than to those for the superconducting $l = 0$ state [16]. Consequently, superconductivity in $s$ wave is more pronounced than in $d$ wave. Hence as temperature decreases the system passes from the normal state to a “less” superconducting $d$-wave state at $T = T_{c}$ and then to a “more” superconducting state with dominating $s$-wave behavior at $T = T_{c1}$ signaling a second phase transition.

The pronounced change in the nature of the superconducting state at $T = T_{c1}$ becomes very apparent from a study of the entropy. At a particular temperature the entropy for the normal state is larger than that for all superconducting states signalling an increase in order in the superconducting state. In the case of the present $(d_{x^2-y^2} + is)$ state we find that as the temperature is lowered past $T_{c1}$, the entropy of the superconducting $(d_{x^2-y^2} + is)$ state decreases very rapidly (not shown explicitly in this work) indicating the appearance of a more ordered superconducting phase and a second phase transition.

We base the present study on the two-dimensional tight binding model which we describe below. This model is sufficiently general for considering mixed angular momentum states, with or without orthorhombic distortion, employing nearest and second-nearest-neighbour hopping integrals. The effective interaction is taken to possess an on-site repulsion ($v_{r}$) and a nearest-neighbour attraction ($v_{a}$) and can be represented as

$$V_{kq} = v_{r} - v_{a} [\cos(k_{x} - q_{x}) + \beta^{2} \cos(k_{y} - q_{y})], \quad (0.1)$$

where $\beta = 1$ corresponds to a square lattice, and $\beta \neq 1$ represents orthorhombic distortion. On expansion, and keeping only the $s$- and $d_{x^2-y^2}$-wave components of this interaction we have

$$V_{kq} = -V_{0} - V_{2} (\cos k_{x} - \beta \cos k_{y})(\cos q_{x} - \beta \cos q_{y}). \quad (0.2)$$

Here $V_{0} = -v_{r} + (1 + \beta^{2})v_{a}/2$ and $V_{2} = v_{a}/2$ are the couplings of effective $s$- and $d$-wave interactions, respectively.
As we shall consider Cooper pairing and subsequent BCS condensation in both $s$ and $d$ waves the constants $V_0$ and $V_2$ will be taken to be positive corresponding to attractive interactions. In this case the quasiparticle dispersion relation is given by

$$\epsilon_k = -2t[\cos k_x + \beta \cos k_y - \gamma \cos k_x \cos k_y],$$  \hspace{1cm} (0.3)

where $t$ and $\beta$ are the nearest-neighbour hopping integrals along the in-plane $a$ and $b$ axes, respectively, and $\gamma t/2$ is the second-nearest-neighbour hopping integral. The energy $\epsilon_k$ is measured with respect to the surface of the Fermi sea.

We consider the weak-coupling BCS model in two dimensions with $(d_{x^2-y^2} + is)$ symmetry. At a finite $T$, one has the following BCS equation

$$\Delta_k = -\sum_q V_{kn} \frac{\Delta_q}{2E_q} \tanh \frac{E_q}{2T}$$  \hspace{1cm} (0.4)

with $E_q = [\epsilon_q^2 + |\Delta_q|^2]^{1/2}$. We use units $k_B = 1$, where $k_B$ is the Boltzmann constant. The order parameter $\Delta_q$ has the following anisotropic form: $\Delta_q = \Delta_0 + i\Delta_2\cos q_x - \beta \cos q_y$). Using the above form of $\Delta_q$ and potential (0.2), Eq. (1.4) becomes the following coupled set of BCS equations

$$\Delta_0 = V_0 \sum_q \frac{\Delta_q}{2E_q} \tanh \frac{E_q}{2T}$$  \hspace{1cm} (0.5)

$$\Delta_2 = V_2 \sum_q \frac{\Delta_2 \cos k_x - \beta \cos k_y)^2}{2E_q} \tanh \frac{E_q}{2T}$$  \hspace{1cm} (0.6)

where the coupling is introduced through $E_q$. In Eqs. (0.5) and (0.6) both the interactions $V_0$ and $V_2$ are assumed to be energy-independent constants for $|\epsilon_q| < T_D$ and zero for $|\epsilon_q| > T_D$, where $T_D$ is a mathematical cutoff to ensure convergence of the integrals. It should be compared with the usual Debye cutoff for the conventional superconductors.

The specific heat per particle is given by

$$C(T) = \frac{2}{NT^2} \sum_q f_q(1 - f_q) \left( E_q^2 - \frac{1}{2} T \frac{d|\Delta_q|^2}{dT} \right)$$  \hspace{1cm} (0.7)

where $f_q = 1/(1 + \exp(E_q/T))$. The spin-susceptibility $\chi$ is defined by

$$\chi(T) = \frac{2\mu_N^2}{T} \sum_q f_q(1 - f_q)$$  \hspace{1cm} (0.8)

where $\mu_N$ is the nuclear magneton. The penetration depth $\lambda$ is defined by

$$\lambda^{-2}(T) = \lambda^{-2}(0) \left[ 1 - \frac{2}{NT} \sum_q f_q(1 - f_q) \right].$$  \hspace{1cm} (0.9)

The superconducting to normal thermal conductivity ratio $K_s(T)/K_n(T)$ is defined by

$$\frac{K_s(T)}{K_n(T)} = \frac{\sum_q (\epsilon_q - 1)f_q(1 - f_q)E_q}{\sum_q (\epsilon_q - 1)^2 f_q(1 - f_q)}.$$  \hspace{1cm} (0.10)

**Figure 1.** The $s$- and $d$-wave parameters $\Delta_0$, $\Delta_2$ in Kelvin at different temperatures for $(d_{x^2-y^2} + is)$-wave models 1(a) (square lattice: full line) and 2(b) (orthorhombic distortion: dashed line) described in the text with different mixtures of $s$ and $d$ waves.

**Figure 2.** Specific heat ratio $C(T)/C_n(T_c)$ versus $T/T_c$ for models 1(a) and 1(b) on square lattice: 1(a) (full line) and 1(b) (dashed line). The dashed-dotted line represents the result for the normal state for comparison.

We solved the coupled set of equations (0.3) and (0.6) numerically and calculated the gaps $\Delta_0$ and $\Delta_2$ at various temperatures for $T < T_c$. We have performed calculations (1) on a perfect square lattice and (2) in the presence of an orthorhombic distortion with Debye cutoff $k_BT_D = 0.02586$ eV ($T_D = 300$ K) in both cases. The parameters for these two cases are the following: (1) Square lattice $- (a)$ $t = 0.2586$ eV, $\beta = 1$, $\gamma = 0,$
\(V_0 = 1.8t\), and \(V_2 = 0.73t\), \(T_c = 71K\), \(T_{c1} = 25K\); (b) \(t = 0.2586\ eV, \beta = 1, \gamma = 0, V_0 = 1.92t\), and \(V_2 = 0.73t\), \(T_c = 71K\), \(T_{c1} = 51K\); (2) Orthorhombic distortion—(a) \(t = 0.2586\ eV, \beta = 0.95, \gamma = 0, V_0 = 2.06t\), and \(V_2 = 0.97t\), \(T_c = 70K\), \(T_{c1} = 25K\); (b) \(t = 0.2586\ eV, \beta = 0.95, \gamma = 0, V_0 = 2.2t\), and \(V_2 = 0.97t\), \(T_c = 70K\), \(T_{c1} = 50K\). For a very weak \(s\)-wave (\(d\)-wave) coupling the only possible solution corresponds to \(\Delta_0 = 0\) (\(\Delta_2 = 0\)). We have studied the solution only when a coupling is allowed between Eqs. (3) and (6).

In Fig. 1 we plot the temperature dependencies of different \(\Delta\)'s for the following two sets of \(s-d\) mixing corresponding to models 1(a) (full line) and 2(b) (dashed line), respectively. In the coupled \((d_{25} + is)\) wave as temperature is lowered past \(T_c\), the parameter \(\Delta_2\) increases up to \(T = T_{c1}\). With further reduction of temperature, with the appearance of the parameter \(\Delta_0\), the \(d\)-wave component begins to decrease and the parameter \(\Delta_0\) is suppressed in the presence of a non-zero \(\Delta_0\).

We also studied the effect of orthorhombicity in this problem. For fixed \(V_0\) and \(V_2\), if a small orthorhombicity is introduced in the model, \(T_c (T_{c1})\) decreases (increases). For example, if, in the model 1(a) above, we vary the parameter \(\beta\) from 1 to 0.95, there is no coupled solution involving \(s\) and \(d\) waves for \(\beta < 0.96\), whereas only the pure \(s\)-wave solution survives. The coupled solution is observed for \(\beta \geq 0.97\) in this case. For \(\beta = 0.97\) (0.99), with the parameters of model 1(a), \(T_c = 58K\) (69K), and \(T_{c1} = 42K\) (28K). So the effect of introducing the orthorhombicity in a model is to increase \(T_{c1}\) and decrease \(T_c\). As a consequence the ratio \(T_{c1}/T_c\) increases.

In order to substantiate the claim of the second phase transition at \(T = T_{c1}\), we study the temperature dependence of specific heat in some detail. The different superconducting and normal specific heats are plotted in Figs. 2 and 3 for square lattice [models 1(a) and 1(b)] and orthorhombic distortion [models 2(a) and 2(b)], respectively. The superconducting specific heat exhibits an unexpected peculiar behavior. In both cases the specific heat exhibits two jumps—one at \(T_c\) and another at \(T_{c1}\). From Eq. (0.7) and Fig. 1 we see that the temperature derivative of \(|\Delta_n|^2\) has discontinuities at \(T_c\) and \(T_{c1}\) due to the vanishing of \(\Delta_2\) and \(\Delta_0\), respectively, responsible for the two jumps in specific heat. For pure \(d\) wave we find that the specific heat exhibits a power-law dependence on temperature. However, the exponent of this dependence varies with temperature. For small \(T\) the exponent is approximately 2.5, and for large \(T (T \rightarrow T_c)\) it is nearly 2. In the \((d + is)\)-wave models, for \(T_c > T > T_{c1}\) the specific heat exhibits \(d\)-wave power-law behavior. For \(d\)-wave models \(C_n(T_c)/C_n(T_c)\) is a function of \(T_c\) and \(\beta\). In Figs. 2 and 3 this ratio for the \(d\)-wave case, for \(T_c = 70K\), is approximately \(3 (2.5)\) for \(\beta = 1 (0.95)\). In a continuous calculation this ratio was 2 in the absence of a van Hove singularity [6]. For \(T < T_{c1}\), we find an exponential behavior in both cases.

In Fig. 4 we study the jump \(\Delta C\) in the specific heat at \(T_c\) for pure \(s\)- and \(d\)-wave superconductors as a function of \(T_{c1}\), where we plot the ratio \(\Delta C / C_n(T_c)\) versus \(T_c\). For a BCS superconductor in the continuum \(\Delta C / C_n(T_c) = 1.43 (1.0)\) for \(s\)-wave (\(d\)-wave) superconductor independent of \(T_c\) [6]. Because of the presence of the van Hove singularity in the present model this ratio increases with \(T_c\) as can be seen in Fig. 4. For a fixed \(T_c\), the ratio \(\Delta C / C_n(T_c)\) is greater for square lattice (\(\beta = 1\)) than that for a lattice with orthorhombic distortion (\(\beta = 0.95\)) for both \(s\) and \(d\) waves. At \(T_c = 100K\), in the \(d\)-wave (\(d\)-wave) square lattice case this ratio could be as high

\[\text{Figure 3}\]

\[\text{Figure 4}\]

The temperature dependencies of different \(\Delta\)'s have been studied in details previously [16]. Here, for completeness, we present the solution only when a coupling is allowed between Eqs. (3) and (6).
as 3.63 (2.92). Many high-$T_c$ materials have produced a large value for this ratio.

Next we study the temperature dependencies of spin susceptibility, penetration depth, and thermal conductivity which we exhibit in Figs. 5–7 where we also plot the results for pure s and d waves for comparison. In Figs. 5–7, we show the results for pure d-wave cases on square lattice and with orthorhombic distortion, (d + is) models 1(a) and 2(b) mentioned above, and pure s-wave case on square lattice. In all cases reported in these figures $T_c \approx 70$ K. For pure d-wave case we obtained power-law dependencies on temperature. The exponent for this power-law scaling was independent of critical temperature $T_c$ but varied from a square lattice to that with an orthorhombic distortion. In case of thermal conductivity, the exponent for square lattice (orthorhombic distortion, $\beta = 0.95$) is 2.2 (1.4). For spin susceptibility, the exponent for square lattice (orthorhombic distortion, $\beta = 0.95$) is 2.6 (2.4). For the mixed (d + is)-wave case, d-wave-type power-law behavior is obtained for $T_c > T > T_{c1}$ with the same exponent as in the pure d-wave case. For $T < T_{c1}$, there is no node in the present order parameter on the Fermi surface and one has a typical s-wave behavior. A passage from d- to s-type state at $T_{c1}$ represents an increase in order and hence an increase in superconductivity. As temperature decreases, the system passes from the normal state to a d-wave state at $T = T_c$ and then to a s-wave-type state at $T = T_{c1}$ signaling a second phase transition.

Until now no high-$T_c$ material has clearly shown two jumps in specific heat as noted in the present study. If this transition to a mixed state occurs at a low temperature this jump is expected to be small and very high precision experimental data will be needed for its confirmation. The same will be needed for confirming this phase transition from a measurement of Knight shift which should show a change from a power-law to exponential dependence on temperature. However, if a transition from a pure d-wave state to a mixed-symmetry state takes place in any compound, they could be identified by a study of the temperature dependencies of the observables considered in this work.

In conclusion, we have studied the (d$_{x^2-y^2}$ + is)-wave superconductivity employing a two-dimensional tight binding BCS model on square lattice and also for or-
thorhombic distortion and confirmed a second second-order phase transition at \( T = T_{c1} \) in the presence of a weaker \( s \) wave. We have kept the \( s \)- and \( d \)-wave couplings in such a domain that a coupled \( (d_{x^2-y^2} + is) \)-wave solution is allowed. As temperature is lowered past the first critical temperature \( T_{c1} \), a weaker (less ordered) superconducting phase is created in \( d_{x^2-y^2} \) wave, which changes to a stronger (more ordered) superconducting phase in \( (d_{x^2-y^2} + is) \) wave at \( T_{c1} \). The \( (d_{x^2-y^2} + is) \)-wave state is similar to an \( s \)-wave-type state with no node in the order parameter. The phase transition at \( T_{c1} \) is also marked by power-law (exponential) temperature dependencies of \( C(T) \), \( \chi(T) \), \( \Delta\lambda(T) \) and \( K(T) \) for \( T > T_{c1} \) \(< T_{c1} \). Furthermore, the effect of orthorhombic distortion is shown to increase the transition temperature between these two superconducting phases, thus stabilizing the mixed state.

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[1] J. G. Bednorz and K. A. Müller, Z. Phys. B 64 (1986) 1898.
[2] H. Ding, Nature 382 (1996) 51;
D. J. Scalapino, Phys. Rep. 250 (1995) 329;
J. P. Carbotte and C. Jiang, Phys. Rev. B 48 (1993) 4231;
B. G. Levi, Phys. Today 49, #5, (1996) 19.
[3] B. E. C. Koltenbah and R. Joynt, Rep. Prog. Phys. 60 (1997) 23.
[4] W. Hardy et al., Phys. Rev. Lett. 70 (1993) 3999;
K. A. Moler et al., Phys. Rev. Lett. 73 (1994) 2744;
K. Gofron et al., Phys. Rev. Lett. 73 (1994) 3302.
[5] M. Prohammer, A. Perez-Gonzalez, and J. P. Carbotte, Phys. Rev. B 47 (1993) 15152;
J. Annett, N. Goldenfeld, and S. R. Renn, Phys. Rev. B 43 (1991) 2778;
N. Momono and M. Ido, Physica C 264 (1996) 311;
M. Houssa and M. Ausloos, Physica C 265 (1996) 258.
[6] S. K. Adhikari and A. Ghosh, Phys. Rev. B 55 (1997) 1110;
J. Phys.: Cond. Mat. 10 (1998) 135;
A. Ghosh and S. K. Adhikari, Euro. Phys. J B 2 (1998) 31.
[7] A. E. Ruckenstein, P. J. Hirschfeld, and J. Apel, Phys. Rev. B 36 (1987) 857;
G. Kotliar, Phys. Rev. B 37 (1988) 3664.
[8] A. G. Sun, D. A. Gajewski, M. B. Maple, and R. C. Dynes, Phys. Rev. Lett. 72 (1994) 2267;
A. G. Sun et al., Phys. Rev. B 52 (1995) R15731.
[9] Jian Ma et al., Science 267 (1997) 83;
P. Chaudhuri and S. Y. Lin, Phys. Rev. Lett. 72 (1994) 1084.
[10] J. H. Xu, J. L. Shen, J. H. Miller, Jr., and C. S. Ting, Phys. Rev. Lett. 73 (1994) 14803.