Anisotropic order parameters with *s*- and *d*-wave-like symmetry and the transition temperature in high-T_c layered superconductors

A. K. Rajagopal
Naval Research Laboratory, Washington D.C. 20375-5320

Sudhanshu S. Jha
Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Bombay 400 005, India and Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore 560 064, India

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The wave-vector dependence of superconducting order parameters and the corresponding transition temperature in three-dimensional layered metals are investigated. It includes planar anisotropic *s*-wave-like as well as *d*-wave-like pairing contributions, but for simplicity only intralayer pairing of electrons has been considered for tetragonal and orthorhombic crystal structures, relevant to high-T_c materials. It is shown that for the orthorhombic case order parameters are likely to have mixed symmetry, whereas in tetragonal structures it is possible to have only planar *d*-wave-like symmetry with a possible correction term with an additional wave-vector dependence in the direction perpendicular to the reciprocal layer plane. [S0163-1829(96)02530-1]

Recent Josephson-coupling experiments[1–3] probing the symmetry of the order parameter in high-T_c superconductors have provided strong evidence for a planar *d*-wave-like ($d_{k_x^2-k_y^2}$-type) pairing in contrast to an almost isotropic *s*-wave-like pairing found in most conventional superconductors. There are still other experiments which support anisotropic *s*-wave-like pairing.[3,4] Based on the Hubbard model and spin-fluctuation exchange mechanism for pairing, Pines[5] was one of the first to argue for the *d*-wave-like superconductivity in high-T_c materials. For a review of more recent work on *d*-wave-like superconductivity, see Scalapino.[6] Most of these investigations, however, do not consider explicitly the three-dimensional layer structure present in these systems. On the other hand, we[7] have already developed a general microscopic framework for describing spin-singlet pairing theory of superconductivity in layered systems which included both intralayer and interlayer pairing interactions. But while deriving expressions for T_c and the corresponding order parameters, in our earlier work we focused only on the completely isotropic *s*-wave-like order parameters in the layer planes (independent of k_x and k_y), depending only on k_z. Here $\vec{k}$ is a wave vector of the electron and the layer plane in the reciprocal space is the (k_x,k_y) plane. Explicit dependence of T_c on the number of interacting conducting layers per unit cell was obtained to show its saturation property.[8,9]

In this paper, we will consider the dependence of the order parameters also on (k_x,k_y), which includes planar *s*- and *d*-wave-like pairing contributions, restricting ourselves for simplicity to only intralayer pairing of the electrons. We will examine scenarios in which pure isotropic *s*-wave-like, anisotropic *s*-wave-like, and pure *d*-wave-like pairings in the layer plane may occur individually, or in combinations, for tetragonal and orthorhombic crystal structures. We also give expressions for T_c and the nature of the order parameters ($\vec{k}$ dependence) in each case. For simplicity of presentation, explicit expressions are given here for systems with one conducting layer per unit cell or, whenever possible, for N equivalent layers per unit cell.

Following our previous work,[7,10] for *intralayer* spin-singlet paring T_c is determined by the simplified equation

$$\Delta_J(\vec{k})=-\sum_{J',\vec{k}'} V_{JJ'}(\vec{k},\vec{k}')\Delta_{J'}(\vec{k}')\,\frac{\tanh[\xi_{J'}(\vec{k}')/2k_BT_c]}{2\xi_{J'}(\vec{k}')}, \tag{1}$$

where $\xi_{J'}(\vec{k}')$ is the single-particle electron energy in the layer J' as measured from the Fermi energy. The interaction parameter $V_{JJ'}(\vec{k},\vec{k}')$ stands for the matrix element $V_{JJ,J'J'}(\vec{k},\vec{k}')$ describing the scattering of two electrons in the states $(J',\vec{k}'\uparrow)$, $(J',-\vec{k}'\downarrow)$ to $(J,\vec{k}\uparrow)$, $(J,-\vec{k}\downarrow)$, and $\Delta_J(\vec{k})$ stands for the intralayer order parameter $\Delta_{JJ}(\vec{k})$ for the layer J. In our earlier calculations[7–9] for an isotropic *s*-wave-like pairing in the plane, we assumed $V_{JJ'}(\vec{k},\vec{k}')$ to depend only on k_z and k_z'. Several authors[5,6,10,11] have already constructed a planar *d*-wave-like intralayer pairing interaction V_{JJ} to discuss superconductivity in high-T_c materials with a single layer per unit cell. More generally, we include here both intralayer and interlayer interactions $V_{JJ'}$ which depend on $\vec{k}$ and $\vec{k}'$. We obtain the general form of the interaction by following the procedure[7] of expanding it in lattice Fourier series in k_x,k_x', k_y,k_y', and k_z,k_z'. There is no need to expand the resulting truncated series (keeping the first few terms) for $\vec{k}$ and $\vec{k}'$ to lie near the Fermi surface. However, in what follows we make this additional approximation only for the sake of illustration. By going over to the energy representation with variables (ξ_J,ϕ,k_z) where ϕ, k_z are the usual cylindrical coordinates, and performing the $\xi_{J'}$ integration near the Fermi surface open in the k_z' direction, we obtain the following equation to determine T_c and the symmetry of the order parameters:

$$I_J(T_c)\widetilde{\Delta}_J(\phi k_z) = -\sum_{J'}\int_0^{2\pi}\frac{d\phi'}{2\pi}\int_0^{2\pi/d}\frac{dk_z'}{(2\pi/d)} \times \lambda_{JJ'}(\phi k_z;\phi' k_z')\widetilde{\Delta}_{J'}(\phi' k_z'), \qquad (2)$$

where

$$\widetilde{\Delta}_J(\phi k_z) = [N_J(0)]^{1/2} I_J^{-1}(T_c)\Delta_J(\phi k_z), \qquad (3)$$

$$I_J^{-1}(T_c) = \int_{-\hbar\Omega_J}^{\hbar\Omega_J} d\xi' \, \frac{\tanh(\xi'/2k_BT_c)}{2\xi'} \equiv \ln(1.13\hbar\Omega_J/k_BT_c) \qquad (4)$$

and

$$\lambda_{JJ'}(\phi k_z;\phi' k_z') = [N_J(0)]^{1/2} V_{JJ'}(\phi k_z;\phi' k_z')[N_{J'}(0)]^{1/2}. \qquad (5)$$

Here d is the lattice constant in the z direction (c axis), $\hbar\Omega_J$ is the effective energy cutoff associated with the pairing interaction, and $N_J(0)$ is the density of states in the Jth layer at the Fermi surface. To leading orders near the Fermi surface, we find

$$\lambda_{JJ'}(\phi k_z;\phi' k_z') \simeq \lambda_{JJ'}^{(0)}(\phi;\phi') + \lambda_{JJ'}^{(1)}(\phi;\phi')\cos k_z d \, \cos k_z' d + \lambda_{JJ'}^{(2)}(\phi;\phi')(\cos k_z d + \cos k_z' d), \qquad (6)$$

where, for $\alpha = 0,1,2,$

$$\lambda_{JJ'}^{(\alpha)}(\phi;\phi') = \lambda_{JJ'}^{(\alpha)0s} + \lambda_{JJ'}^{(\alpha)1s}\cos 4\phi \cos 4\phi' + \lambda_{JJ'}^{(\alpha)2s}(\cos 4\phi + \cos 4\phi') + \lambda_{JJ'}^{(\alpha)1d}\cos 2\phi \, \cos 2\phi' + \lambda_{JJ'}^{(\alpha)2d}(\cos 2\phi + \cos 2\phi') \qquad (7)$$

for the orthorhombic unit cell symmetry. Here, for the sake of illustration we have kept only $\cos 2\phi$ and $\cos 2\phi'$ terms corresponding to only one type ($d_{k_x^2-k_y^2}$) of planar d-wave-like symmetry and have omitted $\sin 2\phi$ and $\sin 2\phi'$ types of terms corresponding to $d_{k_xk_y}$-type symmetry. Similar results follow for the $d_{k_xk_y}$ symmetry. For tetragonal systems, for which we have the invariance required by the symmetry, ($\phi \to \phi + \pi/2$) and ($\phi' \to \phi' + \pi/2$), we have $\lambda_{JJ'}^{(\alpha)2d}$ equal to zero. In this equation, as far as the k_x, k_y dependence in the reciprocal layer plane is concerned, the first term $\lambda_{JJ'}^{(\alpha)0s}$ represents an isotropic s-wave-like pairing interaction, the second and third terms with coefficients $\lambda_{JJ'}^{(\alpha)1s}$ and $\lambda_{JJ'}^{(\alpha)2s}$ represent a purely anisotropic s-wave-like pairing interaction, and the last two terms with coefficients $\lambda_{JJ'}^{(\alpha)1d}$ and $\lambda_{JJ'}^{(\alpha)2d}$ give the purely d-wave-like pairing interactions. With Eqs. (6) and (7) in Eq. (2), we find the order parameter $\widetilde{\Delta}_J(\phi k_z)$ to be of the general form

$$\widetilde{\Delta}_J(\phi k_z) = \Delta_J^{(0)0s} + \Delta_J^{(0)1s}\cos 4\phi + \Delta_J^{(1)0s}\cos k_z d + \Delta_J^{(1)1s}\cos 4\phi \, \cos k_z d + \Delta_J^{(0)d}\cos 2\phi + \Delta_J^{(1)d}\cos 2\phi \, \cos k_z d. \qquad (8)$$

For N layers per unit cell ($J = 1,2,\ldots,N$), the coefficients in the above form of the general order parameter are then determined by a set of $6N$ simultaneous homogeneous linear equations and T_c is determined by the vanishing of the corresponding $6N \times 6N$ determinant. In a compact matrix notion the set of linear equations can be written as

$$\sum_{J'}\begin{bmatrix}
(I_J\delta_{JJ'} + \lambda_{JJ'}^{(0)0s}) & \frac{1}{2}\lambda_{JJ'}^{(0)2s} & \frac{1}{2}\lambda_{JJ'}^{(2)0s} & \lambda_{JJ'}^{(2)2s} & \frac{1}{2}\lambda_{JJ'}^{(1)2d} & \lambda_{JJ'}^{(2)2d} \\
\lambda_{JJ'}^{(0)2s} & (I_J\delta_{JJ'} + \frac{1}{2}\lambda_{JJ'}^{(0)1s}) & \frac{1}{2}\lambda_{JJ'}^{(2)2s} & \frac{1}{4}\lambda_{JJ'}^{(2)1s} & 0 & 0 \\
\lambda_{JJ'}^{(2)0s} & \frac{1}{2}\lambda_{JJ'}^{(2)2s} & (I_J\delta_{JJ'} + \frac{1}{2}\lambda_{JJ'}^{(1)0s}) & \frac{1}{4}\lambda_{JJ'}^{(1)2s} & \frac{1}{2}\lambda_{JJ'}^{(2)2d} & \frac{1}{4}\lambda_{JJ'}^{(1)2d} \\
\lambda_{JJ'}^{(2)2s} & \frac{1}{2}\lambda_{JJ'}^{(2)1s} & \frac{1}{2}\lambda_{JJ'}^{(1)2s} & (I_J\delta_{JJ'} + \frac{1}{4}\lambda_{JJ'}^{(1)1s}) & 0 & 0 \\
\lambda_{JJ'}^{(0)2d} & 0 & \frac{1}{2}\lambda_{JJ'}^{(2)2d} & 0 & (I_J\delta_{JJ'} + \frac{1}{2}\lambda_{JJ'}^{(0)1d}) & \frac{1}{4}\lambda_{JJ'}^{(2)1d} \\
\lambda_{JJ'}^{(2)2d} & 0 & \frac{1}{2}\lambda_{JJ'}^{(1)2d} & 0 & \frac{1}{2}\lambda_{JJ'}^{(2)1d} & (I_J\delta_{JJ'} + \frac{1}{4}\lambda_{JJ'}^{(1)1d})
\end{bmatrix}
\times \begin{bmatrix}
\Delta_{J'}^{(0)0s} \\ \Delta_{J'}^{(0)1s} \\ \Delta_{J'}^{(1)0s} \\ \Delta_{J'}^{(1)1s} \\ \Delta_{J'}^{(0)d} \\ \Delta_{J'}^{(1)d}
\end{bmatrix} = 0. \qquad (9)$$

We will now discuss the various scenarios.

Case (A). For the orthorhombic unit cell symmetry, the form of the coupling constants given by Eqs. (6) and (7) leads to order parameters with completely mixed symmetry as determined by the one out of six solutions of the form (8) which gives maximum T_c. However, for tetragonal unit cell, with $\lambda_{JJ'}^{(\alpha)2d}=0$, $\alpha=0,1,2$, we find that the d-wave-like order parameters split off from the rest, except for an additional term depending on k_z. In this case, the solutions are of the form

$$\tilde{\Delta}_J=\Delta_J^{(0)0s}+\Delta_J^{(0)1s}\cos4\phi+\Delta_J^{(1)0s}\cos k_z d+\Delta_J^{(1)1s}\cos4\phi\ \cos k_z d \tag{10}$$

or

$$\tilde{\Delta}_J=\Delta_J^{(0)d}\cos2\phi+\Delta_J^{(1)d}\cos2\phi\ \cos k_z d. \tag{11}$$

In the latter case, T_c is determined by the relevant solution of the set of homogeneous equations

$$\sum_{J'}\{[I_J(T_c)\delta_{JJ'}+\tfrac{1}{2}\lambda_{JJ'}^{(0)1d}]\Delta_{J'}^{(0)d}+\tfrac{1}{4}\lambda_{JJ'}^{(2)1d}\Delta_{J'}^{(1)d}\}=0,$$
$$\sum_{J'}\{\tfrac{1}{2}\lambda_{JJ'}^{(2)1d}\Delta_{J'}^{(0)d}+[I_J(T_c)\delta_{JJ'}+\tfrac{1}{4}\lambda_{JJ'}^{(1)1d}]\Delta_{J'}^{(1)d}\}=0, \tag{12}$$

which gives maximum T_c.

Case (B). If we can neglect all the terms with $\lambda_{JJ'}^{2}(\phi,\phi')$ and $\lambda_{JJ'}^{(\alpha)2s},\lambda_{JJ'}^{(\alpha)2d}$ ($\alpha=0,1$), i.e., when we can drop all terms containing linear forms like $\cos 2\phi+\cos 2\phi'$, $\cos 4\phi+\cos \phi'$, and $\cos k_z d+\cos k_z' d$, then we note that there is no mixing of the terms with different symmetries in Eq. (8) for the order parameter. In such a case, T_c is determined by

$$\mathrm{Det}[I_J(T_c)\delta_{JJ'}+\lambda_{JJ'}^{(0)0s}]=0 \tag{13}$$

for the purely isotropic s-wave-like order parameter $\Delta_J^{(0)0s}$,

$$\mathrm{Det}[I_J(T_c)\delta_{JJ'}+\lambda_{JJ'}^{(0)1s}]=0 \tag{14}$$

for the purely anisotropic s-wave-like order parameter $\Delta_J^{(0)1s}\cos 4\phi$,

$$\mathrm{Det}[I_J(T_c)\delta_{JJ'}+\lambda_{JJ'}^{(1)0s}]=0 \tag{15}$$

for the order parameter $\Delta_J^{(1)0s}\cos k_z d$,

$$\mathrm{Det}[I_J(T_c)\delta_{JJ'}+\lambda_{JJ'}^{(1)1s}]=0 \tag{16}$$

for the order parameter $\Delta_J^{(1)1s}\cos 4\phi\cos k_z d$,

$$\mathrm{Det}[I_J(T_c)\delta_{JJ'}+\lambda_{JJ'}^{(0)1d}]=0 \tag{17}$$

for the purely d-wave-like order parameter $\Delta_J^{(0)d}\cos 2\phi$, and finally

$$\mathrm{Det}[I_J(T_c)\delta_{JJ'}+\lambda_{JJ'}^{(1)d}]=0 \tag{18}$$

for the order parameter $\Delta_J^{(1)d}\cos2\phi\cos k_z d$.

The actual T_c and the corresponding order parameters will be governed by the solution of the above equations which yields the largest value for T_c. In the nearest-layer interaction approximation for the case of N equivalent layers per unit cell, if in each of the above cases we assume that the corresponding intralayer coupling constants $\lambda_{JJ}^{(\alpha)}=\lambda_{\rm intra}^{(\alpha)}$ and interlayer coupling constants $\lambda_{J,J\pm1}^{(\alpha)}=\lambda_{\rm inter}^{(\alpha)}$, T_c as a function of N is then determined by the relation

$$T_c=1.13\Theta^{(\alpha)}\exp[-1/g_N^{(\alpha)}],$$
$$g_N^{(\alpha)}=-\lambda_{\rm intra}^{(\alpha)}+2|\lambda_{\rm inter}^{(\alpha)}|\cos[\pi/(N+1)], \tag{19}$$

obtained earlier.[8–10] Here $\Theta^{(\alpha)}=\hbar\Omega^{(\alpha)}/k_B\gg T_c$ is the cutoff temperature for the corresponding pairing interaction. If $\lambda_{\rm intra}^{(\alpha)}$ is negative (attractive), there is superconducting transition even in the absence of the interlayer coupling, but interlayer coupling always enhances T_c. The saturation value of T_c is governed by $g_{N\to\infty}^{(\alpha)}=-\lambda_{\rm intra}^{(\alpha)}+2|\lambda_{\rm inter}^{(\alpha)}|$. This implies that our earlier calculations of T_c as a function of N are still correct even if the symmetry of the order parameters is the planar d-wave like or the anisotropic s-wave like.

Case (C). The neglect of all the terms containing linear forms, $\cos k_z d+\cos k_z' d$, etc., as discussed in case (B), may not be good for a realistic system with tetragonal or orthorhombic symmetry. A better approximation is to neglect all cross terms involving the coefficients $\lambda_{JJ'}^{(\alpha)1s}$, $\lambda_{JJ'}^{(\alpha)2s}$, $\lambda_{JJ'}^{(\alpha)1d}$, and $\lambda_{JJ'}^{(\alpha)2d}$ for $\alpha=1,2$. In other words, one may assume

$$\begin{aligned}\lambda_{JJ'}=&\lambda_{JJ'}^{(0)0s}+\lambda_{JJ'}^{(0)1s}\cos4\phi\ \cos4\phi'\\&+\lambda_{JJ'}^{(0)2s}(\cos4\phi+\cos4\phi')\\&+\lambda_{JJ'}^{(0)1d}\cos2\phi\ \cos2\phi'+\lambda_{JJ'}^{(0)2d}(\cos2\phi+\cos2\phi')\\&+\lambda_{JJ'}^{(1)0s}\cos k_z d\cos k_z' d+\lambda_{JJ'}^{(2)0s}(\cos k_z d+\cos k_z' d).\end{aligned} \tag{20}$$

In this case, valid for orthorhombic symmetry, the general solutions for the order parameters have the form

$$\tilde{\Delta}_J=\Delta_J^{(0)0s}+\Delta_J^{(0)1s}\cos4\phi+\Delta_J^{(1)0s}\cos k_z d+\Delta_J^{(0)d}\cos2\phi, \tag{21}$$

involving mixing of different symmetries. For the tetragonal system in which $\lambda^{(0)2d}=0$, one finds that one can have pure planar d-wave-like symmetry which is not mixed with other symmetries. In this case, one has

$$\tilde{\Delta}_J=\Delta_J^{(0)d}\cos2\phi,\quad \mathrm{Det}|I_J(T_c)\delta_{JJ'}+\tfrac{1}{2}\lambda_{JJ'}^{(0)1d}|=0. \tag{22}$$

In the nearest-layer interaction approximation, T_c as a function of N is again given by the same form as in Eq. (13),

$$T_c=1.13\Theta^{(0)1d}\ \exp\left[-\frac{1}{g_N}\right],$$
$$g_N=-\lambda_{\rm intra}^{(0)1d}+2|\lambda_{\rm inter}^{(0)1d}|\cos[\pi/(N+1)]. \tag{23}$$

The other possible solutions involve mixing of pure isotropic s-wave-like and anisotropic s-wave-like symmetries with

TABLE I. Pairing interaction functions $\lambda_{JJ,J'J'}(\phi k_z,\phi' k'_z)\equiv\lambda_{JJ'}(\phi k_z,\phi' k'_z)$ and corresponding possible solutions for intralayer order parameters $\tilde{\Delta}_{JJ}(\phi k_z)\equiv\tilde{\Delta}_J(\phi k_z)$, for orthohombic and tetragonal unit cell structures with N layers per unit cell ($J=1,2,\ldots,N$).

$\lambda_{JJ'}(\phi k_z,\phi' k'_z)$	Solutions $\tilde{\Delta}_J(\phi,k_z)$
General case (A):	
(i) Orthorhombic	(i)
$\lambda^{(0)}_{JJ'}(\phi,\phi')+\lambda^{(1)}_{JJ'}(\phi,\phi')\cos k_z d\,\cos k'_z d$	A1–A6:
$+\lambda^{(2)}_{JJ'}(\phi,\phi')(\cos k_z d+\cos k'_z d)$, with	$\Delta_J^{(0)0s}+\Delta_J^{(0)1s}\cos4\phi$
$\lambda^{(\alpha)}_{JJ'}(\phi,\phi')=\lambda^{(\alpha)0s}_{JJ'}+\lambda^{(\alpha)1s}_{JJ'}\cos4\phi\,\cos4\phi'$	$+\Delta_J^{(1)0s}\cos k_z d+\Delta_J^{(1)1s}\cos4\phi\,\cos k_z d$
$+\lambda^{(\alpha)2s}_{JJ'}(\cos4\phi+\cos4\phi')$	$+\Delta_J^{(0)d}\cos2\phi+\Delta_J^{(1)d}\cos2\phi\,\cos k_z d$
$+\lambda^{(\alpha)1d}_{JJ'}\cos2\phi\,\cos2\phi'$	
$+\lambda^{(\alpha)2d}_{JJ'}(\cos2\phi+\cos2\phi')$	
$\alpha=0,1,2$	
(ii) Tetragonal	(ii)
Same as in (i) above, but with $\lambda^{(\alpha)2d}_{JJ'}=0$	AT1–AT4:
	$\Delta_J^{(0)0s}+\Delta_J^{(0)1s}\cos4\phi$
	$+\Delta_J^{(1)0s}\cos k_z d+\Delta_J^{(1)}\cos4\phi\,\cos k_z d$
	AT5 and AT6
	$\Delta_J^{(0)d}\cos2\phi+\Delta_J^{(1)d}\cos2\phi\,\cos k_z d$
Case (B):	
Orthorhombic or tetragonal	
$\lambda_{JJ}^{(0)(\phi,\phi')+\lambda^{(1)}_{JJ'}(\phi,\phi')\cos k_z d\cos k'_z d}$, with	B1: $\Delta_J^{(0)0s}$
	B2: $\Delta_J^{(0)1s}\cos4\phi$
$\Lambda^{(\alpha)}_{JJ'}\simeq\Lambda^{(\alpha)0s}_{JJ'}+\lambda^{(\alpha)1s}_{JJ'}\cos4\phi\,\cos4\phi'$	B3: $\Delta_J^{(1)0s}\cos k_z d$
$+\lambda^{(\alpha)1d}_{JJ'}\cos2\phi\,\cos2\phi'$, $\alpha=0,1$	B4: $\Delta_J^{(1)1s}\cos4\phi\,\cos k_z d$
	B5: $\Delta_J^{(0)d}\cos2\phi$
	B6: $\Delta_J^{(1)d}\cos2\phi\,\cos k_z d$
Case (C):	
(i) Orthorhombic	(i)
$\lambda^{(0)0s}_{JJ'}+\lambda^{(0)1s}_{JJ'}\cos4\phi\,\cos4\phi'$	C1–C4:
$+\lambda^{(0)2s}_{JJ'}(\cos4\phi+\cos4\phi')+\lambda^{(0)1d}_{JJ'}\cos2\phi\,\cos2\phi'$	$\Delta_J^{(0)0s}+\Delta_J^{(0)1s}\cos4\phi$
$+\lambda^{(0)2d}_{JJ'}(\cos2\phi+\cos2\phi')+\lambda^{(1)0s}_{JJ'}\cos k_z d\,\cos k'_z d$	$+\Delta_J^{(1)0s}\cos k_z d+\Delta_J^{(0)d}\cos2\phi$
$+\lambda^{(2)0s}_{JJ'}(\cos k_z d+\cos k'_z d)$	
(ii) Tetragonal	(ii)
Same as in (i), but with $\lambda^{(0)2d}_{JJ'}=0$.	CT1–CT3:
	$\Delta_J^{(0)0s}+\Delta_J^{(0)1s}\cos4\phi+\Delta_J^{(1)0s}\cos k_z d$
	CT4: $\Delta_J^{(0)d}\cos2\phi$
Case (D):	
(i) Orthorhombic	(i)
$\Lambda^{(0)0s}_{JJ'}+\lambda^{(0)1s}_{JJ'}\cos4\phi\,\cos4\phi'$	D1: $\Delta_J^{(1)0s}\cos k_z d$
$+\lambda^{(0)2s}_{JJ'}(\cos4\phi+\cos4\phi')+\lambda^{(0)1d}_{JJ'}\cos2\phi\,\cos2\phi'$	D2–D4:
$+\lambda^{(0)2d}_{JJ'}(\cos2\phi+\cos2\phi')+\lambda^{(1)0s}_{JJ'}\cos k_z d\,\cos k'_z d$	$\Delta_J^{(0)0s}+\Delta_J^{(01s}\cos4\phi+\Delta_J^{(0)d}\cos2\phi$
(ii) Tetragonal	(ii)
Same as in (i) above, but with $\lambda^{(0)2d}_{JJ'}=0$.	DT1: $\Delta_J^{(1)0s}\cos k_z d$
	DT2: $\Delta_J^{(0)0s}+\Delta_J^{(0)1s}\cos4\phi$
	DT4: $\Delta_J^{(0)d}\cos2\phi$

$$\tilde{\Delta}_J=\Delta_J^{(0)0s}+\Delta_J^{(0)1s}\cos4\phi+\Delta_J^{(1)0s}\cos\,k_z d. \qquad (24)$$

For one layer per unit cell, the corresponding T_c is determined by that solution of the equation

$$[I(T_c)+\tfrac{1}{2}\lambda^{(1)0s}][I(T_c)+\lambda^{(0)0s}][I(T_c)+\tfrac{1}{2}\lambda^{(0)1s}]$$
$$-\tfrac{1}{2}(\lambda^{(0)2s})^2[I(T_c)+\tfrac{1}{2}\lambda^{(1)0s}]$$
$$-\tfrac{1}{2}(\lambda^{(2)0s})^2[I(T_c)+\tfrac{1}{2}\lambda^{(0)1s}]=0, \qquad (25)$$

which gives maximum T_c. This can also be generalized to the case of N equivalent layers per unit cell.

Case (D). The situation discussed in the case (C) simplifies further if the last term in Eq. (14) involving the coefficients $\lambda_{JJ'}^{(2)0s}$ is negligible. In other words, for the orthorhombic case we assume

$$\lambda_{JJ'}=\lambda_{JJ'}^{(0)0s}+\lambda_{JJ'}^{(0)1s}\cos4\phi\ \cos4\phi' +\lambda_{JJ'}^{(0)2s}(\cos4\phi+\cos4\phi')+\lambda_{JJ'}^{(0)1d}\cos2\phi\ \cos2\phi' +\lambda_{JJ'}^{(0)2d}(\cos2\phi+\cos2\phi')+\lambda_{JJ'}^{(1)0s}\cos k_z d\cos k_z' d. \tag{26}$$

Now, one finds that one can either have the pure solution

$$\tilde{\Delta}_J=\Delta_J^{(1)0s}\cos k_z d,\quad \mathrm{Det}|I_J(T_c)\delta_{JJ'}+\tfrac{1}{2}\lambda_{JJ'}^{(1)0s}|=0 \tag{27}$$

or the composite solution of the form

$$\tilde{\Delta}_J=\Delta_J^{(0)0s}+\Delta_J^{(0)1s}\cos4\phi+\Delta_J^{(0)d}\cos2\phi, \tag{28}$$

in which there is a complete mixing of the isotropic planar s-wave-like, the anisotropic s-wave-like, and the d-wave-like symmetries.

For the tetragonal system in which $\lambda_{JJ'}^{(0)2d}=0$, apart from the solution of the form (21), the mixing of d-wave-like symmetry with other symmetries in Eq. (22) is removed. One then finds the possibility of either pure d-wave-like symmetry, with

$$\tilde{\Delta}_J=\Delta_J^{(0)d}\cos2\phi,\quad \mathrm{Det}|I_J(T_c)\delta_{JJ'}+\tfrac{1}{2}\lambda_{JJ'}^{(0)1d}|=0, \tag{29}$$

as in Eqs. (16) and (17), or the mixed isotropic and anisotropic s-wave-like solutions

$$\tilde{\Delta}_J=\Delta_J^{(0)0s}+\Delta_J^{(0)1s}\cos4\phi. \tag{30}$$

For one layer per unit cell, T_c in the latter case is determined by the solution of the equation

$$[I(T_c)+\lambda^{(0)0s}][I(T_c)+\tfrac{1}{2}\ \lambda^{(0)1s}]-\tfrac{1}{2}(\lambda^{(0)2s})^2=0, \tag{31}$$

which gives its maximum value.

All the results discussed above are collected together in Table I, where only significantly different and distinct types of solutions are displayed. It should be emphasized that the layer structure adds extra features to the purely two-dimensional discussions of the s- and d-wave-like solutions for the order parameters. In general, for orthorhombic crystal symmetry one can obtain mixed d-wave-like, isotropic s-wave-type, and anisotropic s-wave-type of solutions. For a tetragonal crystal symmetry, the d-wave-like order parameters do not mix with either the isotropic s-wave-like or the anisotropic s-wave-like order parameters.

In summary, our theoretical analysis shows that in high-T_c materials with orthorhombic unit cell structure, d-wave-like order parameters are likely to have an admixture of s-wave-like symmetries. In the case of tetragonal systems, one can either have d-wave-like symmetry or s-wave-like symmetry, without any mixing. For both symmetries of the unit cell, in general there are correction terms which take into account the additional variation of the order parameters with k_z, the wave vector in the direction perpendicular to the reciprocal layer planes. We hope that these results are taken into account while making any careful analysis[12] of experimental results. We plan to consider later a more general formulation of the problem without making the expansion for $\vec{k}$ and $\vec{k}'$ to lie near the Fermi surface.

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