Scattering of electrons by impurities within the framework of two band model of order parameter anisotropy.

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The impurity concentration dependence of superconducting transition temperature $T_c$ is studied within the framework of two band model of order parameter anisotropy. Both intraband and interband electron scattering by nonmagnetic and magnetic impurities are taken into account. It is demonstrated that at various values of model parameters both types of impurity concentration dependence of $T_c$ are possible: weak dependence typical of the model with $s$-wave order parameter and strong suppression of $T_c$ by impurities with critical impurity concentration at which $T_c = 0$. It is found that in some cases there is a possibility of a rise of critical temperature with increasing impurity concentration. The obtained results are consistent with existing experimental data for the high-temperature superconductors.

The most important and still unresolved problem in the theory of high-temperature superconductivity (HTSC) is the mechanism of formation of electron-electron attraction responsible for unusual properties of these compounds. In this connection an investigation of order parameter symmetry is of great importance. On the one hand, a variety of experimental data suggests strong anisotropy of order parameter [1,2]. On the other hand, a number of experiments displays the behavior typical of models with $s$-wave order parameter [3,4]. It was shown earlier that order parameter anisotropy can be explained by symmetry properties of superconductor crystal lattice within the framework of the universal multi-band model [5]. The approach offers a non-contradictory explanation of a number of experimental data for high-temperature superconductors irrespective of the nature of superconducting pairing.

Order parameter symmetry proves to be essential if the effect of impurities on critical temperature is investigated. Single-band models (BCS-like) with $d$-wave order parameter
display strong reduction of $T_c$ with increasing nonmagnetic impurity concentration [6,7,8]. Analogous effect on $T_c$ is produced by electron scattering by magnetic impurities in model with $s$-wave order parameter [9,10]. In either case critical temperature vanish at certain impurity concentration. However, the suppression of superconductivity induced by scattering from nonmagnetic impurities is inconsistent with existing experimental data [11], including the earlier ones, when samples were not pure enough. There are several different ways of possible explanation of weak reduction of critical temperature with increasing nonmagnetic impurity concentration in models with strongly anisotropic order parameter. The inclusion of anisotropy of scattering matrix element in the models with anisotropic order parameter [12,13,14] can lead to weak impurity concentration dependence of $T_c$. Relative arrangement of nodes of order parameter and those of impurity potential plays an important role here. It was demonstrated in [15], that non-trivial topology of Fermi surface can strongly affect superconducting properties, and in particular inhibit reduction of $T_c$ with increasing impurity concentration. There is a separate class of models describing formation of order parameter anisotropy, namely, multi-band models. Although scattering by impurities was repeatedly investigated within the framework of these models [12,15,16,17,18,19,20], a number of questions concerning consideration of real crystal structure and symmetry properties of electron spectrum remains unsolved.

The present article is concerned with effect of electron scattering by impurities on critical temperature within the framework of previously proposed two-band model of an order parameter anisotropy [3]. The width of one band is assumed to be much greater than that of another band. Hamiltonian of the model has the form

$$H_0 = \sum_{i,j,\alpha} (\varepsilon_a \delta_{ij} + t_{ij}^a) a_{i,\alpha}^+ a_{j,\alpha} + \sum_{i,j,\alpha} (\varepsilon_c \delta_{ij} + t_{ij}^c) c_{i,\alpha}^+ c_{j,\alpha} + \sum_{i,j,\alpha} (W_{ij} a_{i,\alpha}^+ c_{j,\alpha} + h.c.) + U_a \sum_i a_{i\downarrow}^+ a_{i\uparrow}^+ a_{i\uparrow} a_{i\downarrow}$$
\[ + U_c \sum_i c_{i+}^+, c_\alpha^+, c_{i+}^+, c_\alpha, \] (1)

where the operators \( a_{i,\alpha}^+ \) and \( c_{i,\alpha}^+ \) create electrons on the \( i \)-th site with spin \( \alpha \) in the wide and the narrow bands respectively; \( \varepsilon_{a0} \) and \( \varepsilon_{c0} \) are the energies of levels forming the wide and the narrow bands; \( t_{ij}^a \) and \( t_{ij}^c \) are the matrix elements of single-particle transitions between sites in the wide and the narrow bands; \( W_{ij} \) is the matrix element of single-particle interband transitions. It is significant that since \( W_{ij} \) depend on the indices of different sites, in the \( k \)- representation the parameter \( W \) must be a function of \( k \). It is assumed that superconductivity is caused by isotropic attraction in the narrow band \( U_c < 0 \) and there is isotropic effective interaction (either repulsive or attractive) between electrons in the wide band \( U_a \).

The interaction of electrons with impurities is described by the following Hamiltonian

\[ \hat{H}_{\text{imp}} = \sum_{k, k', \alpha, \beta} U_{aa}(k, \alpha; k', \beta) a_{k, \alpha}^+ a_{k', \beta}^+ \\
+ \sum_{k, k', \alpha, \beta} U_{cc}(k, \alpha; k', \beta) c_{k, \alpha}^+ c_{k', \beta}^+ \\
+ \sum_{k, k', \alpha, \beta} (U_{ac}(k, \alpha; k', \beta) a_{k, \alpha}^+ c_{k', \beta}^+ \\
+ h.c.), \] (2)

where

\[ U_{ij}(k, \alpha; k', \beta) = \sum_l u_{ij}(k, \alpha; k', \beta) e^{-i(k-k')R_l} \]

is the matrix element for electron scattering by impurities from the state \((k', \beta)\) in \( j \) band to the state \((k, \alpha)\) in \( i \) band \((i, j = a, c)\), \( R_l \) is the position of \( l \)-th impurity. In general,

\[ u_{ij}(k, \alpha; k', \beta) = (u_{ij}^m(k, k') + u_{ij}^m(k, k')) \delta_{\alpha \beta} \\
+ \frac{1}{2} J_{ij}(k, k') S_l \sigma_{\alpha \beta} \]

Here \( S_l \) is the spin of magnetic impurity located at \( R_l \), \( \sigma_{\alpha \beta} \) are the matrix elements of Pauli matrices,

\[ u_{ij}^{m(n)}(k, k') = \int \psi_{k}^{(i)*}(r) u^{m(n)}(r) \psi_{k'}^{(j)}(r) d^3 r, \]
where \( u^{n(m)}(\mathbf{r}) \) is the potential of nonmagnetic (magnetic) impurity, \( J(\mathbf{r}) \) is the exchange interaction of electron with magnetic impurity, \( \psi^{(i)}_{\mathbf{k}}(\mathbf{r}) \) is Bloch function of electron in \( i \) band.

The impurity atoms will be assumed to be randomly distributed over the crystal lattice and the mean distance between them is much greater in comparison with interatomic distances. Let us consider short-range impurity potentials, so that the matrix elements \( u^{n(m)}_{ij}(\mathbf{k},\mathbf{k}') \) and \( J_{ij}(\mathbf{k},\mathbf{k}') \) do not depend on quasimomentum and are equal to \( u^{n(m)}_{ij} \) and \( J_{ij} \) respectively. Thus, both intraband and interband electron scattering by impurities are isotropic. All calculations will be performed within Born approximation.

Let us introduce the following Matsubara Green’s functions:

\[
G_{a_{i,j}}(\tau,\tau') = -i \left\langle T a_{i,\alpha}(\tau)a_{j,\alpha}^{+}(\tau') \right\rangle,
\]
\[
G_{c_{i,j}}(\tau,\tau') = -i \left\langle T c_{i,\alpha}(\tau)c_{j,\alpha}^{+}(\tau') \right\rangle,
\]
\[
D_{i,j}(\tau,\tau') = -i \left\langle T a_{i,\alpha}(\tau)c_{j,\alpha}^{+}(\tau') \right\rangle,
\]
\[
i\sigma_{\alpha\beta}^{y} F_{i,j}^{a_{+}}(\tau,\tau') = -i \left\langle T a_{i,\alpha}(\tau)a_{j,\beta}^{+}(\tau') \right\rangle,
\]
\[
i\sigma_{\alpha\beta}^{y} F_{i,j}^{c_{+}}(\tau,\tau') = -i \left\langle T c_{i,\alpha}(\tau)c_{j,\beta}^{+}(\tau') \right\rangle,
\]
\[
i\sigma_{\alpha\beta}^{y} B_{i,j}^{+}(\tau,\tau') = -i \left\langle T c_{i,\alpha}(\tau)c_{j,\beta}^{+}(\tau') \right\rangle.
\]

The system of equations for these functions can be obtained by using equations of motion for the operators \( a_{i,\alpha} \) and \( c_{i,\alpha} \). Then make transform to \( (\mathbf{k},\omega) \)-representation and perform Abrikosov-Gorkov procedure of averaging over impurity positions and, if impurities are magnetic, over their spin orientations \( \mathbb{S} \). As a result the system of equations for the narrow band Green’s functions takes the following form:

\[
(i\omega - \varepsilon_{c}(\mathbf{k})) G_{c}(\mathbf{k},\omega) - \tilde{W}_{ca}(\mathbf{k}) D(\mathbf{k},\omega)
\]
\[
+\Delta_{c} F_{c}^{+}(\mathbf{k},\omega) + \Delta_{ca} B^{+}(-\mathbf{k},-\omega) = 1,
\]

(3)
\[ (i\omega_a - \varepsilon_a(k)) D(k, \omega) - \tilde{W}_{ac}^*(k)G_c(k, \omega) + \Delta_a B^+(-k, -\omega) + \Delta_{ac} F_{c}^+(k, \omega) = 0, \tag{4} \]

\[ (i\omega_c^* + \varepsilon_c(k)) F_{c}^+(k, \omega) + \tilde{W}_{ca}(k)B^+(-k, -\omega) + \Delta_c^+ G_c(k, \omega) + \Delta_{ca}^+ D(k, \omega) = 0, \tag{5} \]

\[ (i\omega_a^* + \varepsilon_a(k)) B^+(-k, -\omega) + \tilde{W}_{ac}(k)F_{c}^+(k, \omega) + \Delta_a^+ D(k, \omega) + \Delta_{ac}^+ G_c(k, \omega) = 0. \tag{6} \]

The system of equations for the wide band Green’s functions can be obtained from (3-6) by interchanging of band indices \( a \) and \( c \).

Here new parameters are introduced, among which are renormalized frequencies \( \omega_a, \omega_c \) and anomalous means \( \Delta_a, \Delta_c \) appearing also in single-band models:

\[ i\omega_c = \omega - \frac{n^{(n)}|u_{cc}^n|^2 + n^{(m)}|u_{ac}^m|^2 + |v_{cc}|^2}{(2\pi)^3} \times \int d^3k \, G_c(k, \omega) \]

\[ - \frac{n^{(n)}|u_{ac}^n|^2 + n^{(m)}|u_{ac}^m|^2 + |v_{ac}|^2}{(2\pi)^3} \times \int d^3k \, G_a(k, \omega), \tag{7} \]

\[ \Delta_c = \Delta_{c0} + \frac{n^{(n)}|u_{cc}^n|^2 + n^{(m)}|u_{ac}^m|^2 - |v_{cc}|^2}{(2\pi)^3} \times \int d^3k \, F_c(k, \omega) \]

\[ + \frac{n^{(n)}|u_{ac}^n|^2 + n^{(m)}|u_{ac}^m|^2 - |v_{ac}|^2}{(2\pi)^3} \times \int d^3k \, F_a(k, \omega), \tag{8} \]

where \( \Delta_{c0} = -U_c \langle c_i^* c_i \rangle \), \( n^{(n)} \) and \( n^{(m)} \) are concentrations of nonmagnetic and magnetic impurities respectively, \( |v_{ij}|^2 = \frac{1}{4} J_{ij}^2 S(S + 1) \) \((i, j = a, c)\), \( \omega = (2n + 1)\pi T \).

In addition, electron scattering by impurities leads to renormalization of matrix element of hybridization \( W \), as well as to appearance of interband anomalous self-energy \( \Delta_{ca} \):

\[ \tilde{W}_{ca}^* = W^* + \frac{n^{(n)}u_{cc}^nu_{ca}^n + n^{(m)}(u_{cc}^mu_{ca}^m + v_{cc}v_{ca})}{(2\pi)^3} \]
\[ \Delta_{ca} = \frac{n^{(n)} u_{ca}^n u_{ca}^{* n} + n^{(m)} (u_{ca}^m u_{ca}^{* m} - v_{ca} v_{ca}^{*})}{(2\pi)^3} \]
\[ \times \int d^3k G_c(k,\omega) \]
\[ + \frac{n^{(n)} u_{ca}^n u_{aa}^{* n} + n^{(m)} (u_{ca}^m u_{aa}^{* m} - v_{ca} v_{aa}^{*})}{(2\pi)^3} \]
\[ \times \int d^3k G_a(k,\omega), \]

\[ \Delta_{ca} = -U_a T \sum_n \int \frac{d^3k}{(2\pi)^3} F_a(k,\omega), \quad (11) \]
\[ \Delta_{c0} = |U_c| T \sum_n \int \frac{d^3k}{(2\pi)^3} F_c(k,\omega). \quad (12) \]

The expressions for \( \omega_a, \Delta_a, \overline{W}_{ac} \) and \( \Delta_{ac} \) can be obtained from (7-10) by interchanging of band indices \( a \) and \( c \).

The parameters \( \Delta_{a0} \) and \( \Delta_{c0} \) obey the self-consistency equations

\[ \Delta_{a0} = -U_a T \sum_n \int \frac{d^3k}{(2\pi)^3} F_a(k,\omega), \]

\[ \Delta_{c0} = |U_c| T \sum_n \int \frac{d^3k}{(2\pi)^3} F_c(k,\omega). \]

If impurities are absent in a superconductor \( n^{(n)} = n^{(m)} = 0 \), the system (4-7) is reduced to the Gorkov’s system of equations for the functions \( G_c \) and \( F_c^+ \) with effective order parameter

\[ \overline{\Delta}_c(k) = \frac{W^2(k) \Delta_a}{\varepsilon_a^2(k) + \Delta_a^2} + \Delta_c. \quad (13) \]

The essential feature of considered model is the strong anisotropy of the matrix element of single-particle interband hybridization \( W(k) \) which has lines of nodes along the diagonals of Brillouin zone for different types of symmetry of initial orbitals [5]. As a result the effective order parameter (13) depends on quasimomentum in the case of nonzero interaction in the wide band. From Eqs.(11-13) it follows that if the interaction in the wide band is repulsive and its value is less than the critical one, at which superconductivity in the system
is destroyed ($U_{a}^{crit} > U_a > 0$), then $\Delta_a/\Delta_c < 0$ and the order parameter $\tilde{\Delta}_c(k)$ changes its sign. Such a behaviour determines the main features of the model and makes it possible to explain some properties of HTSC compounds non-contradictory, e.g. strong anisotropy of the order parameter and experimentally observed $s$-like behaviour of $dI/dV$-characteristics of SIS junctions [21].

The impurity concentration dependence of $T_c$ can be determined by solving the systems of equations (3-6) and (7-12) in the limit $\Delta_a, \Delta_c \to 0$ at $T \to T_c$.

The chemical potential will be considered to be situated in the middle of the wide band with energy dispersion $\varepsilon_a(k) = t_a(cosk_x + cosk_y)$. The location of the narrow band with energy dispersion $\varepsilon_c(k) = \varepsilon_{c0} + t_c(cosk_x + cosk_y)$ relative to $\mu$ is defined by the parameter $\varepsilon_{c0}$. The matrix element of hybridization, assuming different symmetries of initial orbitals, namely of $s$- and $d$- types, has the form $W(k) = W_0(cosk_x - cosk_y)$. For numerical calculations of impurity concentration dependencies of $T_c$ the following values of parameters were used: $t_a = 30$, $W_0 = 5$, $U_a = 27$, $U_c = -8$ (expressed in terms of $t_c$).

The relative value of intraband and interband scattering matrix elements strongly depends on location of impurity atom in a unit cell. For example, these can be of the same order of magnitude, i.e. $u_{aa} \propto u_{cc} \propto u_{ac}$. However, for substitutional impurities, scattering of electrons of one of the initial bands by impurities can overwhelm, while interband scattering turns out to be much weaker for symmetry reasons. It will be shown below that a behaviour of $T_c$ with increasing impurity concentration is different for various cases.
FIG. 1. The dependencies of the superconducting transition temperature $T_c$ on the parameter $nu^2$ corresponding to electron scattering by nonmagnetic impurities calculated for A) $\varepsilon_{c0} = 0$, B) $\varepsilon_{c0} = -3$ and a) $u = u_c$, $u_{ac} = u_a = 0$; b) $u = u_a$, $u_{ac} = 0.5u_a$, $u_c = 0$; c) $u = u_c$, $u_{ac} = 0.5u_c$, $u_a = 0$; "s" - within the framework of single-band model with $s$-wave order parameter; "d" - within the framework of single-band model with $d$-wave order parameter.

In what follows the effect of electron scattering by nonmagnetic (Fig.1) and magnetic (Fig.2) impurities on the critical temperature depending on the location of the center of the narrow band $\varepsilon_{c0}$ relative to the chemical potential $\mu$ is considered. The obtained $T_c(n)$ dependencies are compared with the results calculated within the framework of single-band models with $s$- and $d$-wave order parameters. Here mean electron density of states of these models corresponds approximately to that of two-band model.

Fig.1A gives the critical temperature $T_c$ as a function of parameter $n^{(n)}u^2$ (where $u =
$u_{aa}, u_{cc}, u_{ac}$), chemical potential being in the narrow band ($\varepsilon_{c0} = 0$). As can be seen in the figure, scattering in the narrow band has a strongest effect on the critical temperature. Including of interband scattering scarcely affects the result. This is supported by the fact that interband scattering together with intraband one in the wide band produces a weak effect on $T_c$. Corresponding curve coincide with the one calculated within the framework of single-band model with $s$-wave order parameter very closely.

If the center of the narrow band is far from the chemical potential ($\varepsilon_{c0} = -3$), the behaviour of $T_c$ with increasing impurity concentration is changed (Fig.1B). In this case interband scattering decreases the critical temperature while intraband scattering in the narrow band raises it in the region of small values of parameter $n^{(n)}u_{cc}^2$. The increase of $T_c$ at small impurity concentration can be explained by the fact that electron density of states increases in energy region near the chemical potential because of broadening of a peak originating from the van Hove singularity of the initial narrow band. The effect in this region of parameters overwhelms destruction of superconductivity caused by scattering by impurities.

It is seen from Fig.1 that though the order parameter of considered model changes its sign, nonmagnetic impurities suppress superconductivity much weaker than in single-band models with $d$-wave order parameter. There is also no critical impurity concentration, at which the superconductivity in the system disappears. Intraband scattering in the wide band and interband scattering scarcely affect the critical temperature.

A series of experiments aimed at investigating magnetic impurity concentration dependence of $T_c$ of HTSC compounds have been performed. As magnetic impurities Zn and Ni atoms substituting for copper sites in CuO$_2$ plane were used. Experimental data indicates that these impurities influence critical temperature as impurity magnetic centers rather than by changing carrier concentration. It should be noted that while Zn substitution results in strong $T_c$ suppression in the copper oxides similar to that induced by magnetic impurities in conventional superconductors, Ni substitution was experimentally observed to affect $T_c$ weakly.
FIG. 2. The dependencies of superconducting transition temperature $T_c$ on parameter $nu^2$ corresponding to electron scattering by nonmagnetic (n) and magnetic (m) impurities calculated for A) $\varepsilon_{c0} = 0$, B) $\varepsilon_{c0} = -3$ and a) $u = u_c^n$, $u_{ac}^n = u_a^n = 0$; b) $u = u_a^n$, $u_{ac}^n = 0.5u_a^n$, $u_c^n = 0$; c) $u = u_n^n$, $u_{ac}^n = 0.5u_c^n$, $u_a^n = 0$; a') $u = u_c^m$, $u_{ac}^m = u_a^m = 0$; b') $u = u_a^m$, $u_{ac}^m = 0.5u_a^m$, $u_c^m = 0$; c') $u = u_c^m$, $u_{ac}^m = 0.5u_c^m$, $u_a^m = 0$.

Fig.2 presents magnetic impurity concentration dependencies of $T_c$. For comparison the $T_c(nu^2)$ curves for the case of nonmagnetic impurities are also shown in the figure. If the chemical potential is in the narrow band (Fig.2A), the quickest reduction of $T_c$ is caused by intraband scattering in it ($a'$, $c'$ curves). As in single-band models [4], the critical temperature vanish at a certain impurity concentration. A comparison of $b'$ and $c'$ curves shows that unusually weak effect on $T_c$ is produced by interband scattering from magnetic impurities. This fact as well as that intraband scattering scarcely affects the critical temperature can be
explained by small value of electron density of states in the energy region near the chemical potential and by the fact that superconductivity is due to attraction between electrons in the narrow band. The possibility of weak dependence of $T_c$ on magnetic impurity concentration by considering interband scattering was discussed earlier [20].

If the center of the narrow band is far from the chemical potential (Fig.2B), then both intraband scattering in the narrow band and interband scattering results in the usual strong reduction of $T_c$ with increasing magnetic impurities concentration.

The diagonalization of Hamiltonian of the considered model leads to the problem on anisotropic electron scattering by impurities in bands with highly anisotropic order parameters which are roughly of $s + d$ symmetry type. The symmetry of effective scattering matrix elements resulting from the diagonalization of the model Hamiltonian as well as that of the order parameter are determined by properties of electron spectrum. The degree of anisotropy of impurity potential depends on the symmetry of initial bands and on relative value of initial intraband and interband scattering matrix elements. The anisotropic component could also be introduced into initial impurity potentials, but this is beyond the scope of this article.

Thus, within the framework of the two-band model of a superconductor with anisotropic order parameter based on symmetry properties of crystal lattice the impurity concentration dependence of the critical temperature was investigated. The performed calculations suggest that the results depend on both the location of the chemical potential relative to the narrow band and relative value of the intraband and interband impurity scattering matrix elements. It was found that the critical temperature is much less sensitive to the increase in concentration of nonmagnetic impurities than in one-band model with $d$-wave order parameter. As in the article [17], the conditions for $T_c$ increasing with impurity concentration were found. In accordance with standard theories strong dependence of the critical temperature on magnetic impurity concentration was found at some values of the model parameters.

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[1] M.R. Norman, M. Randeria, H. Ding, J.C. Campuzano, Phys. Rev. B 52, 615 (1995).

[2] Y. Zhao, Phys. Rev. B 64, 024053, (2001).

[3] Ya.G. Ponomarev, Chong Soon Khi, Kim Ki Uk, M.V. Sudakova et al., Physica C 315, 85 (1999).

[4] M. Suzuki, T. Watanabe, A. Matsuda, Phys. Rev. Lett. 82, 5361 (1999).

[5] P.I. Arseyev, N.K. Fedorov, B.A. Volkov, Sol. St. Commun., 100, 581, (1996).

[6] Gor’kov, L. P., and P. A. Kalugin, Pis’ma Zh. Eksp. Teor. Fiz. 41, 208, (1985) [JETP Lett. 41, 253 (1985)].

[7] M. Sigrist, K. Ueda, Rev. Mod. Phys., 63, 239, (1991).

[8] Y. Sun, K. Maki Phys. Rev. B 51, 6059, (1995).

[9] A. A. Abrikosov and L. P. Gor’kov, Zh. Eksp. Teor. Fiz. 39, 1781 (1960) [Sov. Phys. JETP, 12, 1243 (1961)].

[10] L.A. Openov, Phys. Rev. B 58, 9468 (1998).

[11] R.J. Radtke, K. Levin, H.-B. Schuttler, M.R. Norman, Phys. Rev. B 48, 653, (1993).

[12] M.L. Kulic, O.V. Dolgov, Phys. Rev. B 60, 13062, (1999).

[13] G. Haran, A.D. Nagi, Phys. Rev. B 58, 12441, (1998).

[14] G. Haran, A.D. Nagi, Phys. Rev. B 63, 012503, (2000).

[15] D.F. Agterberg, V. Barzykin, L.P. Gor’kov, Phys. Rev. B 60, 14868, (1999).

[16] V.A. Moskalenko, M. E. Palistrant, Zh. Eksp. Teor. Fiz. 49, 770 (1965) [Sov. Phys. JETP, 22, 536 (1966)].
[17] T. Kusakabe, Progr. Theor. Phys., 43, 907, (1970).

[18] R. Gajic, J. Keller, M.L. Kulic, Solid State Commun. 76, 731, (1990).

[19] R. Combescot, X. Leyronas, Phys. Rev. B 54, 4320, (1996).

[20] A.A. Golubov, I.I. Mazin, Phys. Rev. B 55, 15146, (1997).

[21] S.O. Loiko, N.K. Fedorov, P.I. Arseyev, Zh. Eksp. Teor. Fiz. 121, 453 (2002) [Sov. Phys. JETP, 94, 387 (2002)].

[22] B. Jayaram, S.K. Agarwal, C.V. Narasimbha Rao, A.V. Narlikar, Phys. Rev. B 38, 2903, (1988).

[23] Y. Zhao, H.K. Liu, G. Yang, S.X. Dou, J. Phys.: Condens. Matter 5, 3623, (1993).

[24] S.K. Tolpygo, J.-Y. Lin, M. Gurvitch, S.Y. Hou, J.M. Philips, Phys. Rev. B 53, 12462, (1996).

[25] R. Killian, S. Krivenko, G. Khalliulin, P. Fulde, Phys. Rev. B 59, 14432, (1999).

[26] G.V.M. Williams, J.L. Tallon, R. Meinhold, Phys. Rev. B 52, 7034, (1995).