

## Role of zinc and nickel impurities in high-temperature superconductors

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The local changes produced in the electronic structure and their effect on the physical properties of the superconducting and normal phases when zinc and nickel are substituted for copper are examined on the basis of a multiband  $p$ - $d$  model. It is shown that strong electronic correlations suppress the  $S=1$  configuration of  $\text{Ni}^{2+}$  and cause the superposition of the  $S=1/2$  and  $S=0$  states of nickel. The change in the density of states in  $p$ - and  $n$ -type systems is studied, and the peculiarity of Zn impurity for  $p$ -type systems and Ni impurity for  $n$ -type systems is shown. The universal dependence of the  $T_c$  on the residual resistance in lightly doped superconductors and deviations from it in optimally doped systems are discussed.

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It is well known that transition-metal impurities in high-temperature superconductors (copper oxide HTSCs) lead to behavior that is unusual from the standpoint of the BCS theory. Both magnetic and nonmagnetic impurities strongly suppress  $T_c$ , and the degree of suppression for  $p$ -type HTSCs is greatest for the nonmagnetic impurity Zn and least for the magnetic impurity Ni.<sup>1–3</sup> This effect of Zn is often considered in the literature to be a manifestation of potential scattering in a  $d$ -type superconductor.<sup>4–6</sup> The basis for this hypothesis is the appearance of a large residual density of states ( $N_{res}(\epsilon_f) \neq 0$ ) as a result of nonmagnetic impurities for anisotropic superconductors with an order parameter that possesses zeros on the Fermi surface.<sup>7</sup> The potential and magnetic scattering effects are analyzed in the normal-metal-state model. For HTSCs this approach is hardly applicable for lightly and optimally doped compositions with anomalous metal-phase behavior characterized by strong short-range antiferromagnetic correlations.

A different picture is observed for  $n$ -type HTSCs. The magnetic impurities Ni and Co suppress  $T_c$  much more strongly than the nonmagnetic impurity Zn in polycrystalline samples  $\text{L}_{2-x}\text{Ce}_x\text{CuO}_{4+\delta}$  ( $\text{L}=\text{Pr}, \text{Nd}, \text{Sm}, \text{Eu}$ ). This is interpreted to be a manifestation of a gap with  $S$ -type symmetry.<sup>8,9</sup> Investigations of  $\text{Pr}_{2-x}\text{Ce}_x\text{CuO}_{4+\delta}$  single crystals have shown that Zn does not dissolve in them and substitution of Ni and Co for Cu gives a record (for cuprates) suppression of  $T_c$  with  $dT_c/dx = -20$  K/at.%, an increase of the residual resistance  $450 \mu\Omega \cdot \text{cm/at.}\%$ , and a change in the sign of the Hall constant.<sup>10</sup>

The residual resistance  $\rho_{res}$  in various  $p$ -type HTSCs (La-214, Y-123, Bi-2212) correlates with  $T_c$ : The increase in  $\rho_{res}$  is proportional to the decrease  $\Delta T_c$ , which suggests that the same mechanism produces both effects. Moreover, the dependence  $T_c(\rho_{res})$  in different HTSCs with different Zn impurity concentrations is universal for lightly doped compositions. The universality breaks down for optimally doped compositions.<sup>11</sup>

The effects of the substitution of magnetic and nonmag-

netic impurities for copper are being studied in a multielectron multiband  $p$ - $d$  model.<sup>12,13</sup> It has been shown that strong electronic correlations suppress the magnetic state  $d^8(\text{Ni}^{2+})$  with spin  $S=1$  and realize quantum-mechanical superposition of the paramagnetic  $d^9L(S=1/2)$  and diamagnetic  $d^{10}L^2(S=0)$  states.<sup>14</sup>

As a result, the impurity of the formally magnetic  $\text{Ni}^{2+}$  actually acts as a diamagnetic impurity Zn. This effect is due to the factor  $u_0^2$ , expressing the probability of the  $d^{10}L^2$  configuration. For this reason, the suppression of the Néel point in lightly doped antiferromagnets satisfies

$$\frac{dT_N(\text{Ni})}{dx} \bigg/ \frac{dT_N(\text{Zn})}{dx} = u_0^2. \quad (1)$$

In what follows, we shall examine and compare the changes produced in the electronic structure by substitution of Zn and Ni for Cu. For  $p$ -type systems Zn impurities act like electronic doping, leading to the formation of additional within-gap states with  $a_1$  symmetry of the deep-impurity-level type, while Ni impurities act like additional hole doping, changing only the intensity of already existing peaks in the density of states of the impurity band with  $b_1$  symmetry. We see in this a microscopic reason why the effects of Zn and Ni are different, because the appearance of Zn impurity levels can result in a strong resonance scattering of the carriers,<sup>15</sup> which does not happen in the case of Ni impurities. Conversely, for  $n$ -type superconductors, the substitution of Ni for Cu results in coexistence of electronic and hole states, which is well-known from experiments.

### 1. FORMATION SCHEME OF THE QUASIPARTICLE BAND STRUCTURE

In the multiband, multielectron  $p$ - $d$  model, the Hamiltonian of the  $\text{CuO}_2$  layer can be written in the hole representation

$$\begin{aligned}
 H = & \sum_{i\lambda\sigma} \varepsilon_i^\lambda a_{i\lambda\sigma}^+ a_{i\lambda\sigma} \\
 & + \sum_{i,j} \sum_{\lambda_1\lambda_2\sigma_1\sigma_2\sigma_3\sigma_4} V_{ij}^{\lambda_1\lambda_2} a_{i\lambda_1\sigma_1}^+ a_{i\lambda_1\sigma_3} a_{i\lambda_2\sigma_2}^+ a_{i\lambda_2\sigma_4} \\
 & + \sum_{\langle i,j \rangle} \sum_{\lambda_1\lambda_2\sigma} t_{ij}^{\lambda_1\lambda_2} a_{i\lambda_1\sigma}^+ a_{j\lambda_2\sigma}. \quad (2)
 \end{aligned}$$

Here  $a_{i\lambda\sigma}$  is an operator annihilating a hole in a Wannier state at the site  $i$  (copper or oxygen), in orbital  $\lambda$ , and with spin  $\sigma$ . We took account of two copper orbitals ( $d_{x^2-y^2}$  and  $d_{z^2}$ ) and one  $p$  orbital ( $p_x$  or  $p_y$ ) on each oxygen site. Among the Coulomb matrix elements, the intra-atomic Hubbard  $U_d(U_p)$  matrix elements for repulsion on one copper (oxygen) orbital with opposite spins, interorbital  $V_d(V_p)$  Coulomb and exchange  $J_d(J_p)$  matrix elements as well as the interatomic parameters of the Coulomb  $V_{pd}$  and exchange  $J_{pd}$  copper–oxygen interactions (which, for simplicity, we assume to be the same for all orbitals). The last term in Eq. (1) describes interatomic copper–oxygen hops with the parameters  $t_{pd}^{x^2-y^2,x} \equiv T_{pd}$  and  $t_{pd}^{z^2,x} = T_{pd}/\sqrt{3}$  and oxygen–oxygen hops with the parameter  $t_{pp}^{x,y} \equiv t_{pp}$ . We denote the charge-transfer energy  $\delta = \varepsilon_p - \varepsilon_{d_{x^2-y^2}}$  and the energy splitting of the  $d$  level in a uniaxial component of the crystal field as  $\Delta_d = \varepsilon_{pz^2} - \varepsilon_{dx^2-y^2}$ .

In the generalized tight-binding method<sup>14</sup> the band structure of the quasiparticles can be calculated, taking account of strong electronic correlations, in two stages: At the first stage the lattice of the  $\text{CuO}_2$  layer is divided into elementary cells and the Hamiltonian inside a cell is diagonalized exactly. The cells can be chosen to be either nonoverlapping ( $\text{CuO}_2$ ) or overlapping ( $\text{CuO}_4$ ), and in the latter case the additional problem of constructing the Wannier functions is solved.<sup>16–18</sup> The multielectronic molecular orbitals  $m = |n, l\rangle$  (where  $n = 0, 1, 2, \dots$  is the number of holes in a cell,  $l$  denotes the collection of all other orbital and spin indices), which are obtained by diagonalizing the Hamiltonian  $H_0$  of a cell, are used to construct the Hubbard operators  $X^{ps} = |p\rangle\langle g|$  of this cell.

At the second stage all intercellular hops and interactions are rewritten exactly in the Hubbard–operator representation, and the Hamiltonian (2) assumes the form

$$\begin{aligned}
 H = & H^{(0)} + H^{(l)} = \sum_{i,m} E_m X_i^{m,m} \\
 & + \sum_{\langle i,j \rangle} \sum_{m_1, n_1} \sum_{m_2, n_2} T_{m_1 n_1}^{m_2 n_2} X_i^{m_1 n_1} X_j^{n_2 m_2}. \quad (3)
 \end{aligned}$$

Here the lattice sites  $i$  and  $j$  refer only to the centers of the clusters (copper atoms).

Various variants of perturbation theory with respect to the intercellular hops are known for the Hubbard model.<sup>15,19–21</sup> In the strong correlations regime they all lead to a quasiparticle band structure that depends on the temperature and carrier density through the occupation numbers  $\langle x^{m,m} \rangle$  of the terms  $E_m$ . The latter can be calculated self-consistently using the equation for the chemical potential

$$\sum_n n \langle X^{n,l;n,l} \rangle = n_h, \quad (4)$$

where  $n_h$  is the hole density per cell,  $n_h = 1 + x$  for  $\text{L}_{2-x}\text{Sr}_x\text{CuO}_4$  and  $n_h = 1 - x$  for  $\text{Pr}_{2-x}\text{Ce}_x\text{CuO}_4$ .

For us the important states are the ground terms with  $n = 0, 1$ , and 2; the vacuum state  $|0\rangle$  with  $n = 0$  corresponds to the  $d^{10}p^6$  configuration. The single-hole state with  $n = 1$  is a superposition of  $d^9$  and  $d^{11}L$  configurations. The main term with spin  $S = 1/2$  and projection  $\sigma = \pm 1/2$  is

$$\begin{aligned}
 |1, \sigma\rangle = & u|0; d_{1\sigma}; 0\rangle - v(|p_x, \sigma; 0; 0\rangle + |0; 0; p_x, \sigma\rangle) / \sqrt{2}, \\
 u^2 = & (1 + \delta/\nu)/2, \quad v^2 = 1 - u^2, \quad \nu^2 = \delta^2 + 8T_{pd}^2. \quad (5)
 \end{aligned}$$

Here  $d_1 \equiv d_{x^2-y^2}$  and the vector  $|\dots; \dots; \dots\rangle$  denotes various multielectronic states of a O–Cu–O cluster.

The two-hole states are a superposition of the configurations  $d^8, d^9L$ , and  $d^{10}L^2$ . We write the ground term in the form

$$|2, S\rangle = u_0|d^{10}L^2\rangle + v_0|d^9L\rangle + w_0|d^8\rangle, \quad (6)$$

where the spin is 0 or 1 (crossover between the singlet  $^1A_{1g}$  and the triplet  $^3B_{1g}$  is possible).<sup>22</sup> Strong correlations suppress the weight of the  $d^8$  configuration. For the parameters  $w_0^2 \leq 0, 1$ , which are realistic for oxides, the Zhang–Rice singlet makes the main contribution. In the limit  $U_d \rightarrow \infty$ , neglecting  $w_0$ , the coefficients  $u_0$  and  $v_0$  can be written analytically as

$$\begin{aligned}
 u_0^2 = & (1 - \Delta_0/\nu_0)^2, \quad v_0^2 = 1 - u_0^2, \\
 \Delta_0 = & \delta - V_{pd}, \quad \nu_0^2 = \Delta_0^2 + 8T_{pd}^2.
 \end{aligned}$$

Fermi-type quasiparticles in a strongly correlated system can be determined by analogy with the Landau Fermi-liquid theory as local excitations with energy

$$\Omega(n, l_1, l_2) = E(n + 1, l_1) - E(n, l_2). \quad (7)$$

Intercluster hops lead to dispersion of these quasiparticles. The single-particle (hole) excitation scheme is shown in Fig. 1, where to simplify the figure only the two lowest terms with  $n = 1$  and 2 are shown. Here the numbered arrows enumerate different types of holes: A quasiparticle 1 forms an empty conduction band (in the electronic language) and the quasiparticles 2 and 3 form the valence-band top. For both  $n$  and  $p$  types, there exist hole in-gap states, whose spectral weight is proportional to the carrier density. These holes are denoted by the number 4 for  $n$ -type systems and they are described by a superposition of  $d_{z^2}$  states of copper and the  $a_1$  molecular orbital of oxygen.<sup>23</sup> For  $p$ -type HTSCs the impurity holes are denoted by the number 5 in Fig. 1 and are formed in the ground  $b_1$  orbitals of oxygen.<sup>24</sup>

The spectral weight of quasiparticles is determined by the so-called terminal factor,<sup>25</sup> which for Fermi quasiparticles is the sum of the particles occupying the initial and final states

$$F(l_1, l_2) = \langle X^{n+1, l_1; n+1, l_1} \rangle + \langle X^{n, l_2; n, l_2} \rangle. \quad (8)$$

The occupation numbers themselves are found self-consistently by solving the equation for the chemical poten-

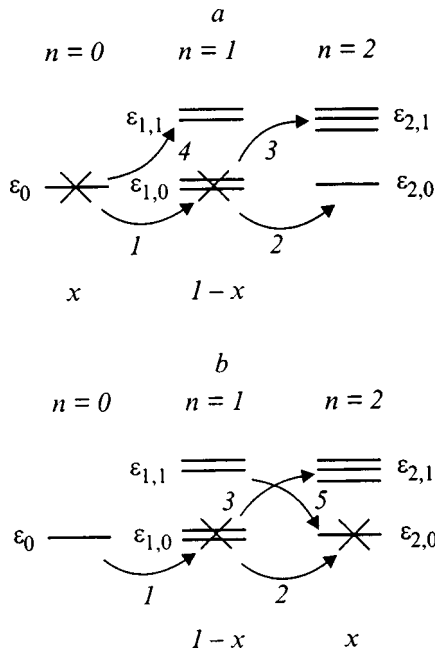


FIG. 1. Scheme of multielectronic terms in various sectors of Hilbert space with  $n=0, 1$ , and  $2$  holes per cell. The cross marks indicate partial filling of different terms for  $n$ -type (a) and  $p$ -type (b) systems. The numbered arrows show the possible Fermi quasiparticles: 1 — conduction-band bottom; 2, 3 — singlet and triplet excitations at the valence-band top; 4, 5 — impurity states for  $n$ - and  $p$ -type systems.

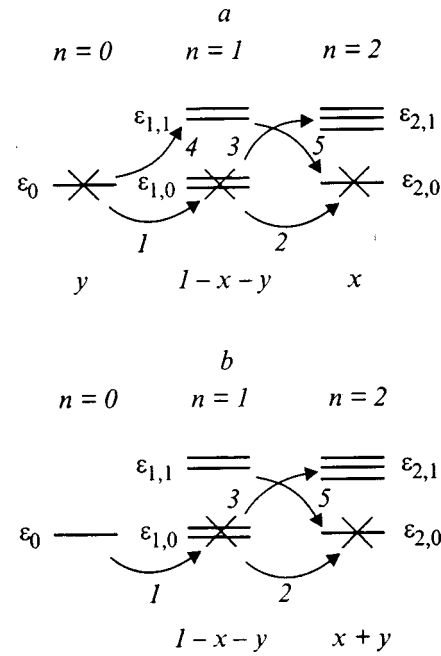


FIG. 2. Change in the quasiparticle spectra in a  $p$ -type  $\text{CuO}_2$  layer due to substitution of zinc (a) and nickel (b) for copper. For Zn there is an additional hole impurity state with  $a_1$  symmetry.

tial (4). These solutions at  $T=0$  in the paramagnetic phase for three cases of interest to us — without doping and with  $p$ - and  $n$ -type doping — are as follows:

1) undoped system,  $n_h = 1$ ,

$$\langle X^{0;0} \rangle = 0, \quad \langle X^{1,\sigma;1,\sigma} \rangle = 1/2, \quad \langle X^{2,0;2,0} \rangle = 0; \quad (9)$$

2)  $p$ -type doping,  $n_h = 1 + x$ ,

$$\langle X^{0;0} \rangle = 0, \quad \langle X^{1,\sigma;1,\sigma} \rangle = (1-x)/2, \quad \langle X^{2,0;2,0} \rangle = x; \quad (10)$$

3)  $n$ -type doping,  $n_h = 1 - x$ ,

$$\langle X^{0;0} \rangle = x, \quad \langle X^{1,\sigma;1,\sigma} \rangle = (1-x)/2, \quad \langle X^{2,0;2,0} \rangle = 0. \quad (11)$$

The structure of the solutions is similar in the antiferromagnetic phase with the spin degeneracy lifted in each sublattice.

**2. CHANGES IN THE ELECTRONIC STRUCTURE DUE TO SUBSTITUTIONS OF ZINC AND NICKEL FOR COPPER**

Each substitution of  $\text{Zn}^{2+}(d^{10})$  for  $\text{Cu}^{2+}(d^9)$  decreases the number of holes by one, so that the hole density, for example, in the system  $\text{La}_{2-x}\text{Sr}_x\text{Cu}_{1-y}\text{Zn}_y\text{O}_4$  is  $n_h = 1 + x - y$ . At the same time the substitution of  $\text{Ni}^{2+}(d^8)$  for  $\text{Cu}^{2+}(d^9)$  increases the number of holes, and in the system  $\text{La}_{2-x}\text{Sr}_x\text{Cu}_{1-y}\text{Ni}_y\text{O}_4$  the hole density is  $n_h = 1 + x + y$ . In other words, from the standpoint of electrical neutrality the substitution of Zn is equivalent to  $n$ -type doping and the substitution of Ni is equivalent to  $p$ -type doping. The small spatial radius of impurity states distinguishes them from mobile carriers formed by doping with  $\text{Ce}^{4+}$  or  $\text{Sr}^{2+}$ .<sup>14</sup>

In the system  $\text{La}_{2-x}\text{Sr}_x\text{Cu}_{1-y}\text{Zn}_y\text{O}_4$  two types of unit cells in the  $\text{CuO}_2$  layer can be distinguished: a) a Sr impu-

rity, giving a hole in the cell, where  $n_h = 2$ , lies above or below the cell; b) instead of a  $\text{CuO}_4$  square we have  $\text{ZnO}_4$  and for this cell  $n_h = 0$ .

Cells where Sr and Zn act simultaneously are unimportant. In the first place such an encounter is unlikely because  $x$  and  $y$  are small and in the second place compensation of  $p$ - and  $n$ -type doping occurs in such cells.

The change in the density of states in the lightly doped case ( $x \ll 1, y \ll 1$ ) can be easily followed in Fig. 2, which shows the quasiparticle scheme for the spatially averaged picture. Here the occupation numbers of the terms are

$$\begin{aligned} \langle X^{0;0} \rangle &= y, \quad \langle X^{1,\sigma;1,\sigma} \rangle = (1-x-y)/2, \\ \langle X^{2,0;2,0} \rangle &= x. \end{aligned} \quad (12)$$

The change in the density of states as a result of within-gap states is

$$\delta N(E) \sim y \delta(E - \epsilon_{1,1} + \epsilon_0) + x \delta(E - \epsilon_{2,0} + \epsilon_{1,1}). \quad (13)$$

Here the second term is associated with  $b_1$  impurity states, which merge with the valence-band top as the hole density increases, forming a band responsible for superconductivity. The first term in Eq. (13) is due to holes with  $a_1$  symmetry. These are impurity states, which lie beyond the edge of the ground band with  $b_{1-}$  symmetry. According to Ref. 15, the presence of such a state could be the reason for the strong resonance scattering in the unitary limit. Hops between  $\text{CuO}_4$  clusters give, as is well known, narrow Hubbard bands with a typical width of less than 0.5 eV.<sup>20</sup> Since the band widths are small, here we neglect the dispersion of the bands and analyze not the entire density of states but only the impurity part, i.e. the part proportional to the hole density.

In the case of Ni substitution for Cu with  $n_h = 1 + x + y$ , the solution of the self-consistency equation for the chemical potential is

$$\begin{aligned}\langle X^{0;0} \rangle &= 0, & \langle X^{1,\sigma;1,\sigma} \rangle &= (1 - x - y)/2, \\ \langle X^{2,0;2,0} \rangle &= x + y.\end{aligned}\quad (14)$$

In this case, as one can see from Fig. 2b, the electronic structure is formed by the same quasiparticles as in the absence of Ni in Fig. 1b. The main doping-induced change in the density of states is

$$\delta N(E) \sim (x + y) \delta(E - \varepsilon_{2,0} + \varepsilon_{1,1}). \quad (15)$$

As a result, the substitution of Ni for Cu leads primarily to a renormalization of the density of states without any qualitative changes to it.

Conversely, in  $n$ -type superconductors the substitution of Ni for Cu changes the density of states substantially. Let us consider the system  $\text{Pr}_{2-x}\text{Ce}_x\text{Cu}_{1-y}\text{Ni}_y\text{O}_4$ . The superconductivity and electrical properties of the single crystals have been investigated in Refs. 10, 26, and 27. Here the average Hall density is  $h_h = 1 - x + y$ . For cells with Cu impurity  $h_h = 0$ , while for  $\text{NiO}_4$  squares  $h_h = 2$ . The solution of Eq. (4) is

$$\begin{aligned}\langle X^{0;0} \rangle &= x, & \langle X^{1,\sigma;1,\sigma} \rangle &= (1 - x - y)/2, \\ \langle X^{2,0;2,0} \rangle &= y.\end{aligned}\quad (16)$$

Hole quasiparticles are formed by the same excitations as in Fig. 2a. The change in the density of states as a result of the impurity states is

$$\delta N(E) \sim x \delta(E - \varepsilon_{1,1} + \varepsilon_0) + y \delta(E - \varepsilon_{2,0} + \varepsilon_{1,1}). \quad (17)$$

In this case Ni forms an impurity state with  $b_1$  symmetry. This state is split from the conduction band bottom and can lead to a strong scattering of current carriers. For  $n$ -type systems Zn impurity plays a passive role, just as Ni for  $p$ -type systems. Moreover, as shown in Ref. 27, Zn does not dissolve  $n$ -type single crystals.

### 3. DISCUSSION

Oxygen nonstoichiometry can also be a source of  $p$ -type carriers in  $n$ -type systems even in the absence of Ni. The complicated temperature dependence of the Hall constant  $R_H(T)$ , which changes sign from negative to positive with decreasing  $T$ ,<sup>28</sup> indicates the coexistence of two types of carriers. As shown in Ref. 10, the substitution of Ni for Cu destroys the balance between the electrons and holes, and even for  $y > 0.7$  at.% the Hall constant becomes positive at all temperatures. Our conclusion that the hole density increases when Ni is substituted is in qualitative agreement with experiment.<sup>10</sup>

Since the residual resistance is formed by carrier scattering at the same impurity levels, it is obvious that the suppression of  $T_c$  is proportional to the changes in the residual resistance  $\rho_{res}$  and it follows from our calculations for  $p$ -type HTSCs that  $\rho_{res}(\text{Zn}) \gg \rho_{res}(\text{Ni})$ . We also wish to comment on the universal dependence  $T_c(\rho_{res})$ , found for different 214 and 123 systems with Zn substituted for Cu and with

different hole densities.<sup>11</sup> It is important that universality occurs for lightly doped systems and breaks down for optimally and heavily doped systems. In lightly doped systems holes are in regions with antiferromagnetic short-range order. The size of these regions is of the order of  $\xi_{AFM}$ . Diamagnetic substitution for the  $\text{Cu}^{2+}$  spin destroys the equivalence of the sublattices and a magnetic moment from the uncompensated sublattice appears near the impurity  $\text{Zn}^{2+}$ . This moment has been observed experimentally.<sup>29,30</sup> Hole scattering with spin flip by such a defect will suppress superconductivity, just as in the BCS theory.<sup>31</sup> If it is assumed that scattering with spin flip in lightly doped samples is the main mechanism for the suppression of  $T_c$ , then we arrive at the two conclusions that 1) both  $T_c$  and  $\rho_{res}$  are determined by the same parameters so that there is a universal dependence  $T_c(\rho_{res})$  and 2)  $\text{Ni}^{2+}$  impurity gives diamagnetic substitution with probability  $u_0^2$  so that for  $T_c$  and  $\rho_{res}$  a relation of the form (1) should hold:

$$\frac{dT_c(\text{Ni})}{dx} \bigg/ \frac{dT_c(\text{Zn})}{dx} = \rho_{res}(\text{Ni})/\rho_{res}(\text{Zn}) = u_0^2. \quad (18)$$

For optimally and heavily doped systems the situation is more complicated because for them  $\xi_{AFM}$  is small and the assumption that spin scattering plays a dominant role is incorrect. Potential scattering  $\Gamma_N$  here predominates over spin scattering  $\Gamma_S$ . The relative contributions of these mechanisms are different for each hole density and the function  $T_c(\rho_{res})$  is no longer universal. Analysis of the suppression of  $d_{x^2-y^2}$  type superconductivity in Y-123 with Zn substituted for Cu led<sup>32</sup> to the conclusion that  $\Gamma_S/\Gamma_N \ll 0.1$ . Potential scattering by Ni impurities in  $p$ -type systems is much weaker than for Zn, since it is not of a resonant character. Conversely, in the  $n$ -type case a resonant character can occur and gives record high suppression of  $T_c$ .

In closing, we note that our goal was to relate the observed differences in Zn- and Ni-substituted systems of both  $p$  and  $n$  type to the changes occurring in the electronic structure. We showed that, based on a multielectronic approach taking account of strong electronic correlations, differences indeed arise at the microscopic level: For  $p$ -type systems the Zn impurities form an impurity level with symmetry different from that of the valence band top while Ni impurities do not; for  $n$ -type systems even the Ni impurity forms a level with symmetry different from that of the conduction-band bottom.

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<sup>1</sup>J. M. Tarascon, L. H. Greene, P. Barboux, W. R. Mckinnon, G. W. Hull, T. P. Orlando, K. A. Delin, S. Foner, and E. J. McNiff, Phys. Rev. B **36**, 8393 (1987).

<sup>2</sup>J. Clayhold, N. P. Ong, P. H. Hor, and C. W. Chu, Phys. Rev. B **38**, 7016 (1988).

<sup>3</sup>G. Xiao, M. Z. Cieplak, J. Q. Xiao, and C. L. Chien, Phys. Rev. B **42**, 8752 (1990).

<sup>4</sup>K. Ishida, Y. Kitaoka, N. Ogata, T. Kamino, K. Asayama, J. R. Cooper, and N. Athanassopoulou, J. Phys. Soc. Jpn. **62**, 2803 (1993).

- <sup>5</sup>T. Hotta, *J. Phys. Soc. Jpn.* **62**, 274 (1993).
- <sup>6</sup>P. J. Hirschfeld and N. Goldenfeld, *Phys. Rev. B* **48**, 4219 (1993).
- <sup>7</sup>L. P. Gor'kov, *JETP Lett.* **40**, 1155 (1984).
- <sup>8</sup>J. Sugiyama, H. Yoshikawa, H. Hidaka, T. Sakurai, H. Yamauchi, and S. Tanaka, *Phys. Rev. B* **42**, 803 (1990).
- <sup>9</sup>B. Jayaram, H. Chen, and J. Callanway, *Phys. Rev. B* **52**, 3742 (1995).
- <sup>10</sup>M. Brinkmann, H. Bach, and K. Westerholt, *Phys. Rev. B* **54**, 6680 (1996).
- <sup>11</sup>Y. Fukuzumi, K. Mizuhashi, K. Takenaka, and S. Uchida, *Phys. Rev. Lett.* **76**, 684 (1996).
- <sup>12</sup>Yu. B. Gaididei and V. M. Loktev, *Phys. Status Solidi B* **147**, 307 (1988).
- <sup>13</sup>S. G. Ovchinnikov and I. S. Sandalov, *Physica C* **161**, 607 (1988).
- <sup>14</sup>S. G. Ovchinnikov, *Fiz. Tverd. Tela (St. Petersburg)* **37**, 3645 (1995) [*Phys. Solid State* **37**, 2007 (1995)].
- <sup>15</sup>D. Poilblanc, D. J. Scalapino, and W. Hanke, *Phys. Rev. Lett.* **72**, 884 (1994).
- <sup>16</sup>F. C. Zhang and T. M. Rice, *Phys. Rev. B* **37**, 3759 (1988).
- <sup>17</sup>S. V. Lovtsov and V. Yu. Yushankhai, *Physica C* **179**, 159 (1991).
- <sup>18</sup>R. Raimondi, J. H. Jefferson, and L. F. Feiner, *Phys. Rev. B* **53**, 8774 (1996).
- <sup>19</sup>W. Brenig, *Phys. Rep.* **251**, 153 (1995).
- <sup>20</sup>S. G. Ovchinnikov, *Usp. Fiz. Nauk* **167**, 1043 (1997).
- <sup>21</sup>V. N. Loktev, *Fiz. Nizk. Temp.* **22**, 3 (1996) [*Low Temp. Phys.* **22**, 1 (1996)].
- <sup>22</sup>V. A. Gavrichkov and S. G. Ovchinnikov, *Fiz. Tverd. Tela (St. Petersburg)* **40**, 184 (1998) [*Phys. Solid State* **40**, 163 (1998)].
- <sup>23</sup>S. G. Ovchinnikov, *Fiz. Tverd. Tela (St. Petersburg)* **36**, 2950 (1994) [*Phys. Solid State* **36**, 1569 (1994)].
- <sup>24</sup>S. G. Ovchinnikov, *Ferroelectrics* **144**, 91 (1993).
- <sup>25</sup>R. O. Zaitsev, *Zh. Éksp. Teor. Fiz.* **70**, 1100 (1976) [*Sov. Phys. JETP* **43**, 575 (1976)].
- <sup>26</sup>M. Brinkmann, T. Rex, M. Stief, H. Bach, and K. Westerholt, *Physica C* **269**, 76 (1996).
- <sup>27</sup>M. Brinkmann, T. Rex, H. Bach, and K. Westerholt, *J. Cryst. Growth* **163**, 369 (1996).
- <sup>28</sup>Z. Z. Wang, T. R. Chien, N. P. Ong, J. M. Tarascon, and E. Wang, *Phys. Rev. B* **43**, 3020 (1991).
- <sup>29</sup>G. Xiao, A. Bakhshai, M. Z. Cieplak, Z. Tesanovic, and C. L. Chien, *Phys. Rev. B* **39**, 315 (1989).
- <sup>30</sup>S. T. Ting, P. Pernambuco-Wise, J. E. Crow, and E. Manousakis, *Phys. Rev. B* **46**, 11772 (1992).
- <sup>31</sup>A. A. Abrikosov and L. P. Gor'kov, *Zh. Éksp. Teor. Fiz.* **39**, 1781 (1960) [*Sov. Phys. JETP* **12**, 1243 (1961)].
- <sup>32</sup>L. S. Borkowski and P. J. Hirschfeld, *Phys. Rev. B* **49**, 15404 (1994).

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