Hole superconductivity in Arsenic-Iron compounds

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Superconductivity above 25K, and possibly above 40K, has recently been discovered in LaO\textsubscript{1−x}F\textsubscript{x}FeAs and related compounds. We propose that this is another example of the mechanism of hole superconductivity at play. This requires the existence of hole carriers at the Fermi energy, which appears to contradict current observations. We propose that two-band conduction is taking place in these materials, that the negative ion As\textsuperscript{3−} plays a key role, and that superconductivity is non-phononic and driven by pairing and undressing of heavily dressed hole carriers to lower their kinetic energy. We make several predictions of future observations based on our theory.

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I. INTRODUCTION

Arsenic-iron compounds have just joined\textsuperscript{1} the ever-growing number of superconductors that do not appear to conform to the conventional BCS-Eliashberg electron-phonon explanation of superconductivity\textsuperscript{2}. Superconductivity above 25K has been reported in electron-doped LaO\textsubscript{1−x}F\textsubscript{x}FeAs\textsuperscript{3, 4, 5, 6, 7}, in hole-doped La\textsubscript{1−x}Sr\textsubscript{x}OFeAs\textsuperscript{4}, and very recently superconductivity above 40K in electron-doped SmFeAsO\textsubscript{1−x}F\textsubscript{x}\textsuperscript{8} and CeO\textsubscript{1−x}F\textsubscript{x}FeAs\textsuperscript{9}. Eliashberg calculations\textsuperscript{10} based on density functional theory\textsuperscript{11} as well as dynamical mean field theory calculations\textsuperscript{12} appear to rule out the electron-phonon mechanism as the cause of superconductivity in LaO\textsubscript{1−x}F\textsubscript{x}FeAs and related compounds even at 25K. What then is the mechanism responsible for superconductivity? Where will the next high temperature superconductors be found?

The theory of hole superconductivity\textsuperscript{13} provides one possible alternative to answer these questions (many other alternatives have been recently proposed\textsuperscript{11, 12, 14}), based on the same basic principles that we have used to interpret the observed superconductivity in cuprate

\textit{d-wave} superconductivity at play. This requires the existence of hole carriers at the Fermi energy, which appears to contradict current observations. We propose that two-band conduction is taking place in these materials, that the negative ion As\textsuperscript{3−} plays a key role, and that superconductivity is non-phononic and driven by pairing and undressing of heavily dressed hole carriers to lower their kinetic energy. We make several predictions of future observations based on our theory.

Our point of view differs significantly from the prevalent point of view. The prevalent point of view maintains that superconductivity in MgB\textsubscript{2} is fully explained by conventional electron-phonon theory; that superconductivity in the cuprates is driven by electrons in copper d orbitals, and that it has d-wave symmetry at least in the hole-doped case; that in the electron-doped cuprates the dominant carriers are electrons rather than holes; that magnetic fluctuations arising from a strong Hubbard-U repulsion on copper ions drives superconductivity and provide the ‘glue’ for Cooper pairing in the cuprates. For arsenic-iron compounds, a consensus is rapidly growing that (in most compounds) the carriers are electron-like\textsuperscript{1, 2, 4, 5} that they reside in iron d-bands at the Fermi energy\textsuperscript{11, 11, 12}, and that incipient ferromagnetism or antiferromagnetism of electrons in Fe orbitals may drive pairing and superconductivity\textsuperscript{11, 11, 12, 14}. Based on that consensus one would \textbf{not} predict the observations listed in the previous paragraph.

We argue that our point of view on the explanation of high temperature superconductivity is compelling because it relies on a minimal number of unifying assumptions and because it is easily falsifiable, in contrast to the prevalent point of view. (1) Conduction has to occur in substructures (planes) that have excess negative charge. If instead the planes have excess positive charge, or are charge neutral, high temperature superconductivity will not occur. Neither electron-phonon theory nor magnetic-based theories can make such a general prediction. (2) Hole carriers have to exist. Again, neither electron-phonon theory nor magnetic-based theories can make such a general prediction. We made these predictions based on experimental evidence on hole-doped cuprates in 1989. Subsequent observations in electron-doped cuprates and in MgB\textsubscript{2} have been fully consistent with these predictions. Arsenic-iron compounds are the next test of our theory: given the observations to date these compounds could potentially refute it. If they don’t, they will provide additional evidence in its favor.
II. NATURE OF THE CHARGE CARRIERS

The Hall coefficient has been measured in polycrystalline samples of $LaO_{1-x}F_xFeAs$ by Zhu et al.\cite{1}, Chen et al.\cite{2}, Sefat et al.\cite{3}, and Yang et al.\cite{4}. In all cases it is found to be negative and weakly temperature dependent, becoming more negative as the temperature decreases. However, in a multi-band situation, the Hall coefficient will generally exhibit temperature dependence due to the different temperature dependent of the mobilities in the different bands. So measurement of a negative Hall coefficient certainly does not imply absence of hole carriers. For an isotropic two band model with electron and hole carriers of densities $n_e$ and $n_h$ the Hall coefficient is

$$R_H = -\frac{1}{n_e e c} \frac{1 - (n_h/n_e)(\mu_h/\mu_e)^2}{1 + (n_h/n_e)(\mu_h/\mu_e)^2}$$  \hspace{1cm} (1)$$

and will be negative if the mobility of the dressed hole carriers ($\mu_h$) is much smaller than that of the electron carriers ($\mu_e$), as we expect. However, we expect that in-plane transport will start being dominated by hole carriers as the temperature is lowered and the hole mobility increases. Just as in the case of electron-doped cuprates\cite{21}, we expect that measurement of the in-plane Hall coefficient in single crystal samples as the temperature is lowered will show a trend towards zero and a change in sign to positive before the onset of superconductivity.

Simple valence counting indicates that the $La^{3+}O^{2-}$ unit donates one electron to the $Fe^{2+}As^{3-}$ unit, so the substructure where the conduction is expected to occur has one extra electron per $FeAs$ unit. This is similar to the cuprates, where there are two extra electrons per $CuO_2$ unit in the plane donated by the off-plane atoms, and to $MgB_2$ which has one extra electron per $B$ atom in the $B^-$ plane donated by the off-plane $Mg^{2+}$ ion. Thus, the first requirement for high temperature superconductivity in our theory is clearly satisfied. The reason negatively charged substructures are helpful is because they give rise to large orbital relaxation effects when a hole travels through such a structure, which is the mechanism that leads to pairing of hole carriers in our model.

In the absence of doping, the compound $LaOFeAs$ exhibits superconductivity with $T_c$ around $3K$\cite{1}. When $O$ is substituted by $F$, electrons are added to the $FeAs$ plane, and $T_c$ increases above $25K$. It has very recently been reported\cite{2} that upon substituting $La$ by $Sr$, which would correspond to hole doping, superconductivity with $T_c \sim 25K$ also occurs, namely in $(La_{1-x}Sr_x)OFeAs$ with $x \sim 0.13$. How can this apparent electron-hole ‘symmetry’ be understood within the theory of hole superconductivity?

Fig. 1 shows the generic $T_c$ versus hole concentration dependence in the model of hole superconductivity. We assume that this band originates in direct overlap of $As$ $p$-orbitals. The undoped material is proposed to correspond to the underdoped regime where this band is almost full and $T_c$ is almost zero. Hence the hole-doped case ($Sr$ substituting for $La$) is easy to understand: for each $Sr$ substituting $La$, one hole gets added to the $As$ band and $T_c$ increases up to the maximum in Fig. 1. The electron-doped case ($F$ substituting for $O$) is less straightforward: we need to assume that as electrons are added both electrons and holes are doped to the $Fe$-$As$ planes. This would parallel the scenario that we proposed for the electron-doped cuprates\cite{21}.

Schematically, as shown in Fig. 2, when an electron is added to the $Fe - As$ plane, we assume it goes onto the $Fe^{2+}$ ion. It will repel neighboring $As^{3-}$ ions and push one electron into another neighboring $Fe^{2+}$. The net result would be that for each electron added to the $Fe - As$ plane, two $Fe^{2+}$ ions get converted into $Fe^+$ and one $As^{3-}$ ion turns into $As^{2-}$. Thus electron doping creates added electron carriers in a $Fe$ band, and added hole carriers in a purely $As$ band, which would drive the system superconducting just like in the case of electron-doped cuprates.

Thus, we propose that a ‘minimal’ model to describe superconductivity in $As - Fe$ compounds has to contain two bands: a hole band derived from $As$ $p$ orbitals (for example $p_z$ orbitals forming $\pi$-bonds) and a band involving $Fe$ $d$ orbitals, as shown schematically in Fig. 3. We expect the $As$ band to be very narrow because of the band narrowing effect due to orbital relaxation. Furthermore, its bandwidth will increase with hole doping (this effect is not shown in Fig. 3\cite{13}). Upon hole doping the Fermi level will move down, adding holes to (removing electrons from) both the $As$ and $Fe$ bands (Fig. 3b)). Upon electron doping however there should also be a relative shift of the position of the two bands, with the $As$ band moving up in energy and the $Fe$ band moving down...
in energy, as shown in Fig. (3c), resulting in hole doping of the As band and additional electron doping of the Fe band.

This band shift results self-consistently from the self-doping process discussed in connection with Fig. (2): as electrons are pushed out from $As^{3-}$ ions onto $Fe^{2+}$ ions, the (negative) carriers in the $Fe$ band feel a higher electric potential from the more positively charged As ions and hence their energy is lowered. Conversely, the carriers in the As band feel a lower electric potential because the $Fe$ ions have become more negatively charged, hence their energy is raised. This results in the relative band shifts shown in Fig. (3c). For this process to take place requires the 'charge transfer gap' (the energy cost in transferring an electron from $As^{3-}$ to the neighboring $Fe^{2+}$, leaving behind a hole in arsenic ($As^{2-}$)).

![Diagram of electron doping](image)

**FIG. 2:** Schematic depiction of how holes are created by electron doping. The electron added to $Fe^{2+}$ repels an electron from $As^{3-}$ to the neighboring $Fe^{2+}$, leaving behind a hole in arsenic ($As^{2-}$).

Thus we propose that a rigid band model is approximately valid for the case of hole doping of $As-Fe$ planes in these structures (except for the neglected band expansion effect) but is qualitatively wrong for electron doping.

**III. TWO-BAND SUPERCONDUCTIVITY**

Our model for the arsenic-iron compounds utilizes two bands, one of primarily arsenic character, and the other of primarily iron character, as depicted in Fig. (3). The reduced Hamiltonian to describe such a model, following Suhl et al. [22], is

$$ H = \sum_{k\sigma} (\epsilon_k^a - \mu) a_{k\sigma}^\dagger a_{k\sigma} + \sum_{k\sigma} (\epsilon_k^d - \epsilon_0 - \mu) d_{k\sigma}^\dagger d_{k\sigma} + \sum_{kk'} V_{kk'}^{aa} a_{k\uparrow}^\dagger a_{-k\downarrow}^\dagger a_{-k'\downarrow} a_{k'\uparrow} + \sum_{kk'} V_{kk'}^{dd} d_{k\downarrow}^\dagger d_{-k\uparrow}^\dagger d_{-k'\uparrow} d_{k'\downarrow} + \sum_{kk'} V_{kk'}^{ad} (a_{k\uparrow}^\dagger a_{-k\downarrow}^\dagger d_{k'\downarrow} d_{k'\uparrow} + d_{k\downarrow}^\dagger d_{-k\uparrow}^\dagger a_{-k'\uparrow} a_{k'\downarrow}). \quad (2) $$

As discussed in Ref. [19] we retain the simplest interband interaction, and in what follows adopt a constant interband potential: $V_{kk'}^{ad} = V_{ad}$. We have used a hole notation, so that the $a^\dagger$ and $d^\dagger$ operators correspond to hole creation operators in the As and Fe band, respectively, and similarly for the annihilation operators. We adopt a flat density of states for both bands, each with bandwidth $D_i$. The single particle energies are measured from the center of each band, and the Fe band is shifted by an amount $\epsilon_0$ with respect to the As band.

The intraband potentials are assumed to have identical form; we adopt the form from Ref. [13]:

$$ V_{kk'}^{ii} = U_i + K_i \left( \frac{\epsilon_k}{D_i/2} + \frac{\epsilon_{k'}}{D_i/2} \right) + W_i \frac{\epsilon_k}{D_i/2} \frac{\epsilon_{k'}}{D_i/2}, \quad (3) $$

where $U_i$ corresponds to the on-site repulsion, $K_i$ the
modulated hopping, and $W_i$ the nearest-neighbor repulsion. These interactions lead to a BCS ground state that is superconducting, and an (s-wave) order parameter with the form

$$\Delta_i(\epsilon) = \Delta_i^m(\epsilon_i - \frac{\epsilon}{D_i/2}), \quad (4)$$

as found previously $[13, 19]$. Further details are available in these references.

The generic behavior of $T_c$ as a function of doping was already displayed in Fig. (1). The existence of interactions in two bands (instead of a single band) does not alter the behavior of $T_c$ in any significant manner. For simplicity we chose the nearest neighbor repulsion equal to zero for calculations in this paper; in Fig. (1) $U_a = 5$ eV, $K_a = 1.86$ eV, and $U_d = K_d = 0$. The magnitude of $T_c$ is of course determined by the relative strength of the interactions; it is noteworthy that with our choice the interaction is effectively repulsive everywhere in the band (see Fig. 8 of Ref. [13]).

In Fig. (4) we show the result of self-consistent calculations of the gap, as a function of temperature. We chose parameters as in Fig. (1), with a hole concentration corresponding to the maximum $T_c$. Note that the gap is determined by minimizing the energy dispersion relation. Provided we are not too close to the band edges (as is the case here) the result is

$$\Delta_{ai} = \Delta_i(\mu + \epsilon_i^c) \left(1 + \left(\frac{\Delta_i^m}{D_i/2}\right)^2\right)^{1/2}. \quad (5)$$

In Fig. (4) these are plotted for the As band (solid, red curve) and the Fe band (dashed, green curve). They both display the generic BCS gap temperature dependence; clearly the As band drives the superconductivity, and the Fe superconducts only because of interband interactions. A generic feature is that the zero temperature gap ratio is larger (smaller) than the weak coupling BCS result for the As (Fe) gap.

The gaps can most readily be measured in tunneling experiments. In Fig. (5) we plot the expected $dI/dV$ vs. sample voltage, for the same parameters as in Fig. (4). In (a) we used underlying electronic densities of states which were identical for both the As and the Fe bands. The presence of two gaps is readily apparent in the figure, especially at low temperatures. The relative sizes of the gaps are unknown at present. Here, they were determined by our choice of no intraband interactions in the Fe band, but of course some (presumably repulsive) interactions exist, and this would decrease the smaller gap in comparison to the large one.

In Fig. (5b) we show results for the same parameters as in (a), except that we have included an extra degeneracy in the Fe band (by a factor of 3). This is expected from naive considerations of the orbital degeneracy in Fe vs. As. Note that this effect alters the relative weight of the coherence peaks associated with the smaller gap compared to the peaks associated with the larger gap. In either case the two gap structure should be evident in the tunneling. Finally, note that the larger gap coherence peaks display an asymmetry; injecting holes into the sample (negative bias) results in a higher coherence peak than removing holes (positive bias) $[18]$ (note that we reversed our sign convention from our older references to conform with experimental practice). This asymmetry of universal sign is a direct consequence of the form of the order parameter, Eq. (4).

**IV. THE KEY ROLE OF $As^{3−}$**

In the theory of hole superconductivity the atomic charge parameter $Z$, where ($Z = 2$) is the charge of the negatively charged ion when the relevant band is full, plays a key role $[20]$. As $Z$ decreases the degree of orbital relaxation when a hole is added to the negative ion increases, causing an increase in the pairing interaction strength arising from hopping renormalization as well as a decrease in the effective on-site repulsion. Both of these effects contribute to a higher $T_c$. For the classes of materials discussed here $MgB_2$ corresponds to $Z = 1$ (charge of $B^+$), the cuprates to $Z = 0$ ($O^0$) and the $Fe−As$ materials to $Z = −1$ ($As^{3−}$). Thus, the latter class of materials has the potential of yielding the highest $T_c$‘s. This was explicitly predicted in ref. $[28]$ where we remarked: “Even stronger hole dressing and higher $T_c$’s would be expected in a structure with even smaller $Z$ – for example, if one managed to make a material with $N^{3−}$ planes doped with some holes ($Z = −1$).”

Band structure calculations using density functional theory (DFT) place the bands arising from $As$ p-orbitals around 3eV below the Fermi energy $[11]$, while the bands crossing the Fermi energy arise from $Fe$-d orbitals. How-
adding a hole to the undoped compound may put holes into a pure As band.

What about the electron-doped case? First, it requires a structure where the Madelung energy of $\text{As}^{3-}$ and $\text{Fe}^{2+}$ is similar, as in the case of electron-doped cuprates\[22\]. Furthermore, the same orbital relaxation effect discussed above will make it easier for an electron doped onto a $\text{Fe}^{2+}$ ion to repel an electron out of a neighboring $\text{As}^{3-}$ ion and create a hole in it. Thus, just like in the case of electron-doped cuprates\[22\], adding electrons to the conducting planes would result in twice as many electrons added to an electron band and holes induced in the hole band arising from the negative ions. By not properly taking into account the local orbital relaxation of the $\text{As}^{-3}$ ions, DFT would miss this effect and predict that only electron carriers are created upon electron doping.

Finally, we have argued that high $T_c$ superconductivity is favored when hole propagation occurs in substructures (planes) that are highly negatively charged\[16\]. Assume the valence states in the $\text{Fe} − \text{As}$ planes corresponded instead to $\text{Fe}^{3+} − \text{As}^{3-}$ ions, i.e. a charge neutral structure. In that case the $\text{Fe} − \text{As}$ bond would be more covalent and the electrons would be located less on the negative ions and more on the covalent bond, the effect of orbital relaxation in the negative ion would be reduced, and we would not expect high $T_c$ superconductivity. Using this argument we predicted that superconductivity would not occur in LiBC$_3$, as had been predicted from electron-phonon theory\[29\], and indeed none has been found\[30\].

### V. Predictions

Our point of view leads to the following predictions for future experimental observations:

- **Hall coefficient:** In the hole-doped samples, positive Hall coefficient has been measured, in accordance with expectations\[7\]. In electron-doped samples, all measurements of Hall coefficient reported so far have been for polycrystalline samples and yielded a negative Hall coefficient\[8, 9, 10, 11\]. However, for transport in the $a − b$ plane in single crystal samples we predict that a positive Hall coefficient will be measured at low temperatures at least in the doping range where $T_c$ is highest. Further-
more even in regimes where the Hall coefficient is negative, then there should be evidence of two-band conduction and that hole carriers start to dominate the transport as the temperature is lowered, as is found in electron-doped cuprates.[23]

- Tunneling: our theory predicts tunneling asymmetry of universal sign,[13] (larger peak for negatively biased sample) arising from the hole band. In fact, point contact tunneling experiments already have shown this asymmetry.[24]. For tunneling in the ab plane we expect that evidence for two-band superconductivity, as seen in $\text{MgB}_2$[25], will be seen, at least in the electron-doped materials. For the smaller gap we do not expect asymmetry in the tunneling peaks.

- Isotope effect: we predict a positive isotope effect in $T_c$ for As substitution but no isotope effect for Fe or O substitution[16]. A more difficult experiment would be to measure the tunneling characteristic for As substitution; then a direct identification of the large gap coherence peak with As could be made. Our model also predicts a positive isotope effect in the superfluid weight (inverse penetration depth squared) due to the effective mass reduction (increase in hoppings amplitude) upon pairing. (This effect was first predicted by the bipolaronic theory of superconductivity)[21]. However, in a multi-band situation if the superfluid weight is dominated by carriers in the electron band this effect may be difficult to detect.

- Pressure effect: our theory predicts increased $T_c$ as the distance between As ions in the plane decreases, hence a positive pressure coefficient for in-plane pressure. For pressure perpendicular to the planes the $T_c$ dependence on pressure should be weak and could be of either sign.[13]

- Optical sum rule violation: we predict optical spectral weight transfer from high frequencies to the zero frequency $\delta$-function as the system is cooled into the superconducting state, with the effect being largest in the underdoped regime[20].

VI. HOW TO GET HIGHER $T_c$S

The theory of hole superconductivity yields simple prescriptions to search for higher $T_c$ materials, which we summarize here.

- Holes conducting through an almost filled band arising from direct overlap of orbitals of negative ions are essential. The more negatively charged the ion is, the better, so triply negatively charged anions in the fifth column (N, P, As, Sb, Bi) are best.

- Neither magnetic fluctuations nor d-electrons are needed, as illustrated by the case of $\text{MgB}_2$. Hence the same structure with e.g. Cd$^{2+}$ ions instead of Fe$^{2+}$ ions could potentially yield high $T_c$.

- Negatively charged planes or other substructures where hole conduction occurs. The larger the negative charge the better. Hence if Fe$^{2+}$ could be replaced by a monovalent positive ion $T_c$ should be greatly increased.

- As small a distance between negative ions as possible. This could be achieved by various off-plane substitutions with atoms of smaller size.

VII. DISCUSSION

Our interpretation of the origin of superconductivity in arsenic-iron compounds differs substantially from other proposed explanations, and we certainly cannot argue at this point that experiments provide compelling support for our point of view over others. However, one strength of our approach is that it makes very definite predictions, and past experience shows that these predictions are often confirmed much later. Examples are our prediction of the existence of hole carriers in electron-doped materials (1989)[22], of tunneling asymmetry of universal sign (1989)[13], of apparent optical sum rule violation and color change (1992)[22], and of hole carriers in $\text{MgB}_2$ (early March 2001)[16]. Except for the latter that was confirmed only a few days later, the first three predictions were confirmed many years later, and in the intervening years experiments appeared to be at odds with these predictions.

On the other hand, some predictions of our theory have not been experimentally confirmed, for example the prediction of positive pressure effect on $T_c$ in $\text{MgB}_2$[16]. This can be understood by hypothesizing that other effects in addition to reduction of the distance between atoms, such as charge transfer between different parts of the system, dominate when pressure is applied.

The greatest strength of our approach however is that it provides a unified point of view to understand superconductivity in all materials. As the number of distinct classes of superconducting materials increases, a new parameter regime opens up as a testing ground for theories. It becomes increasingly unlikely that a different mechanism is required for each new class. As in other fields (e.g. particle physics) one instead searches for unifying ideas that explain a particular phenomenon in a variety of classes. As we have argued here, the Iron-Arsenic compounds provide yet another class in which our proposal can be put to the test.

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[1] Y. Kamihara, T. Watanabe, M. Hirano and H. Hosono, J. Am. Chem. Soc. 130, 3296 (2008).
[2] "Superconductivity", ed. by R.D. Parks, Marcel Dekker, New York, 1969.
[3] Xiyu Zhu, Huan Yang, Lei Fang, Gang Mu, Hai-Hu Wen, arXiv:0803.1288 (2008).
[4] G. F. Chen, Z. Li, G. Li, J. Zhou, D. Wu, J. Dong, W. Z. Hu, P. Zheng, Z. J. Chen, J. L. Luo, N. L. Wang, arXiv:0803.0128 (2008).
[5] Athena S. Sefat, Michael A. McGuire, Brian C. Sales, Rongying Jin, Jane Y. Howe, David Mandrus, arXiv:0803.2528 (2008).
[6] Huan Yang, Xiyu Zhu, Lei Fang, Gang Mu, Hai-Hu Wen, arXiv:0803.0623 (2008).
[7] Hai-Hu Wen, Gang Mu, Lei Fang, Huan Yang and Xiyu Zhu, arXiv:0803.3603 (2008).
[8] X. H. Chen, T. Wu, G. Wu, R. H. Liu, H. Chen, D. F. Fang, arXiv:0803.3021 (2008).
[9] G. F. Chen, Z. Li, D. Wu, G. Li, W. Z. Hu, J. Dong, P. Zheng, J. L. Luo, N. L. Wang, arXiv:0803.3790 (2008).
[10] L. Boeri, O.V. Dolgov and A.A. Golubov, arXiv:0803.2703 (2008).
[11] D.J. Singh, and M.H. Du, arXiv:0803.0429 (2008).
[12] K. Haule, J. H. Shim and G. Kotliar, arXiv:0803.1279 (2008).
[13] J.E. Hirsch and F. Marsiglio, Phys. Rev. B 39, 11515 (1989); Physica C 162-164, 591 (1989); J.E. Hirsch, Jour.Phys.Chem. Solids 67, 21 (2006) and references therein.
[14] Kazuhiko Kuroki, Seiichiro Onari, Ryotaro Arita, Hidetomo Usui, Yukio Tanaka, Hiroshi Kontani, Hideo Aoki, arXiv:0803.3325 (2008); Fengjie Ma, Zhong-Yi Lu, arXiv:0803.3286 (2008); Chao Cao, P. J. Hirschfeld, Hai-Ping Cheng, arXiv:0803.3236 (2008); I.I. Mazin, D.J. Singh, M.D. Johannes, M.H. Du, arXiv:0803.2740 (2008).
[15] F. Marsiglio and J.E. Hirsch, Phys. Rev. B 41, 6435 (1990).
[16] J.E. Hirsch, Phys. Lett. A282, 392 (2001); J.E. Hirsch and F. Marsiglio, Phys.Rev. B 64, 144523 (2001).
[17] J.E. Hirsch and F. Marsiglio, Physica C 331, 180 (2000); J.E. Hirsch, Phys. Rev. B 62, 14487 (2000).
[18] F. Marsiglio and J.E. Hirsch, Physica C 159, 157 (1989).
[19] J.E. Hirsch and F. Marsiglio, Phys.Rev. B 43, 424 (1991).
[20] J.E. Hirsch and F. Marsiglio, Phys. Rev. B 62, 15131 (2000).
[21] Wu Jiang, S. N. Mao, X. X. Xi, Xiuguang Jiang, J. L. Peng, T. Venkatesan, C. J. Lobb, and R. L. Greene, Phys.Rev.Lett. 73, 1291 (1994); P. Fournier, X. Jiang, W. Jiang, S. N. Mao, T. Venkatesan, C. J. Lobb, and R. L. Greene, Phys.Rev. B 56, 14149 (1997); Y. Dagan and R.L. Greene, Phys.Rev. B76, 024506 (2007).
[22] J.E. Hirsch and F. Marsiglio, Phys. Lett. A 140, 122 (1989); J.E. Hirsch, Physica C 243, 319 (1995).
[23] R. S. Gonnelli et al, Supercond. Sci. Technol. 16, 171 (2003); M. Javarone et al, Physica C 385, 215 (2003); P. Martinez-Samper et al, Physica C 385, 233 (2003); G. Karapetrov et al, Physica C 388-389, 141 (2003).
[24] Y. Ohta and S. Maekawa, Phys. Rev. B 41, 6524 (1990).
[25] H. Suhl, B.T. Matthias, and L.R. Walker, Phys. Rev. Lett. 3, 552 (1959).
[26] J.E. Hirsch, Phys. Rev. B 48, 3327, 9815 (1993); Phys. Rev. B 65, 184502 (2002).
[27] Lei Shan, Yonglei Wang, Xiyu Zhu, Gang Mu, Lei Fang, Hai-Hu Wen, arXiv:0803.2405 (2008).
[28] J.E. Hirsch, Phys. Rev. B 67, 035103 (2003).
[29] H. Rosner, A. Kitaigorodsky and W.E. Pickett, Phys.Rev.Lett. 88, 127001 (2002).
[30] A.M. Fogg, J.B. Claridge, G.R. Darling and M.J. Rossseinsky, cond-mat/0304662, ChemInform Vol. 34, Issue 35, Aug. 4, 2003.
[31] A.S. Alexandrov, Physica C 363, 231 (2001).
[32] J.E. Hirsch, Physica C 199, 305 (1992); Physica C 201, 347 (1992).