Local structural distortions and their role in superconductivity in SmFeAsO$_{1-x}$F$_x$ superconductors

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Abstract

EXAFS studies at the As K edge as a function of temperature were carried out in SmFeAsO$_{1-x}$F$_x$ ($x=0$ and 0.2) compounds to understand the role of local structural distortions in superconductivity observed in F-doped compounds. A significant correlation between the thermal variation of local structural parameters such as anion height and superconducting onset is found in the fluorinated compounds. Such a variation in anion height is absent in the non-superconducting compound. An increase in the Fe-As bond distance just below the superconducting onset temperature indicates a similarity between the distortions observed in the high-$T_C$ cuprates and these Fe-based superconductors.

Keywords: superconductivity, EXAFS, iron-based superconductors

(Some figures may appear in colour only in the online journal)

1. Introduction

The discovery of superconductivity in Fe-based systems has initiated a flurry of research activity due to (a) a high superconducting transition temperature ($T_C \sim 50$ K); (b) the similarity in the local structure of Fe in all these Fe-based superconductors; and (c) the similarity of their structure and phase diagrams with those exhibited by cuprates and heavy Fermion superconductors [1]. Structurally, all Fe-based superconductors consist of a stack of Fe-X networks (where X is either a chalcogen or pnictogen ion) separated with or without a spacer layer. Here, the Fe ions form a planar two-dimensional square lattice, and the pnictide or chalcogen ions occupy the centres of these squares, displaced alternatively above and below the plane of the Fe atoms. Again, the stacking can be of various types, like in REOFeAs (RE: rare earth), where the RE layers act as a spacer layer [2, 3], and the Ba ions play the role of spacers in BaFe$_2$As$_2$-type compounds [4], while there are no spacer layers in FeSe-type superconductors [5, 6].

Superconducting $T_C$ shows a considerable enhancement under the influence of hydrostatic or chemical pressure. For example, $T_C$ is enhanced to 43 K when a pressure of 4 GPa is applied to LaFeAsO$_{1-x}$F$_x$ [7]. Similarly, changing the rare-earth ion from La to Sm also leads to an increase in $T_C$ due to the pressure exerted by smaller Sm ions [3]. Superconductivity can also be induced due to the doping of holes or electrons as in the case of Ba$_{1-x}$K$_x$Fe$_2$As$_2$ (hole doping) [4] or in BaFe$_{1-y}$Co$_y$As$_2$ (electron doping) [8], as well as by changing the chalcogen ion as in FeTe$_{1-x}$Se$_x$ [9]. All these results indicate a strong influence of the local structure, especially around the Fe ion on the superconducting interactions in these compounds. Such an influence of local structure has also been reported in high-$T_C$ cuprates and is believed to be intimately connected to the mechanism of superconductivity in these materials [10, 11].

The local structure around Fe atoms has been obtained in different families of Fe-based superconductors as a function of temperature, pressure and chemical substitution [12–15]. In substituted compounds, especially of the type FeSe$_{1-x}$Te$_x$, the
coexistence of phases (FeSe and FeTe) separated over nano-
scopic dimensions has been noticed [16]. Anion height (h),
which is defined as the perpendicular distance between the
plane of anions and the plane of Fe atoms, has emerged as an
important parameter that can be correlated with super-
conductivity in these compounds. Lower values of h directly
influence the hybridization between the Fe 3d bands and the
anion p bands, thereby regulating the nature of the Fermi
surface [17]. EXAFS studies have also revealed that the
application of hydrostatic pressure and/or the modi-
fication of intercalated layers cause sizeable compression of Fe-X
networks (reduction in h) [14, 15]. Such modifi-
cations are known to influence Tc, for example in Ba0.8K0.2Fe2As2 [18].

However, it is still not clear if the local structural dis-
tortions have a role to play in superconductivity. For instance,
it is known that anion height is much smaller in super-
conducting Fe-based compounds as compared to their non-
superconducting counterparts. But does this anion height
change near the onset of superconductivity? Is there any
correlation between local structural distortions in Fe-based
superconductors and other superconducting compounds like
cuprates? In order to seek answers to these questions and to
establish a correlation between local structural distortions and
superconductivity in FeAs-based superconductors, we have
carefully studied As K edge EXAFS as a function of tem-
perature in superconducting (x = 0.2) and non-
superconducting (x = 0) SmFeAsO1−xFx compounds.

2. Experimental methods

Bulk polycrystalline SmFeAsO and SmFeAsO0.8F0.2 com-
pounds were synthesized by the conventional solid-state
reaction route method via the vacuum encapsulation tech-
nique. The high purity (~99.9%) Sm, As, Fe, FeF3, and Fe2O3
reactants were weighed according to the stoichiometric ratio,
mixed and ground thoroughly using a mortar and pestle. The
weighing and grinding was carried out in a glove box with a <
1 ppm level of oxygen and humidity atmosphere. The mixed
powder was pelletized in a rectangular bar shape and then
encapsulated in an evacuated (10⁻³ Torr) quartz tube. These
sealed quartz tubes embodying the said pellet were heat
treated at 550 °C for 12 h, 850 °C for 12 h and then at 1150
°C for 33 h in continuum, and then the furnace was switched
off and it was allowed to cool naturally. The sintered sample
was obtained by breaking the quartz tube. The as-sintered
sample was black in color and brittle. For transport mea-
surements, the obtained sample is again ground and sealed in
a quartz tube and finally heated for 12 h at 1150 °C with a
slow heating rate to obtain a good compact pellet. Finally, the
samples were furnace-cooled slowly to room tempera-
ture [19].

Phase identification and crystal structure investigation
were carried out using powder x-ray diffraction (Rigaku-
XRD) with Cu-Kα radiation. The lattice parameters are cal-
culated with the help of Rietveld refinement using the
FULLPROF SUITE program [20]. The resistivity measure-
ments were performed by a conventional four-point-probe
method on a quantum design physical property measurement
system (PPMS-140kOe). The DC-magnetization suscept-
bility measurement was performed on a superconducting
sample using a DC magnetometry system (ACMS-Model-
P500) on the same QD-PPMS.

EXAFS measurements at the As K edge were performed
in transmission mode at the BL09C beamline at the Photon
Factory in Japan. EXAFS was scanned from −200 to 1200 eV
with respect to the As K edge energy (11600 eV). Both incident (I₀) and transmitted (I) intensities were measured simultaneously using an ionization chamber filled with appropriate gases. The absorbers were prepared by sprinkling finely ground powder on scotch tape and stacking several such layers to optimize the thickness so that the edge jump (Δμ) was restricted to ≤ 1.

EXAFS data analysis in the k range of 2 to 14 Å⁻¹ and in the R range of 1 to 3.5 Å was performed using the Demeter program [21]. Theoretical amplitude and phase shift functions for different correlations were calculated with FEFF 6.01 [22] using the crystal structure data obtained from room-temperature x-ray diffraction.

3. Results and discussion

Observed and Rietveld-fitted x-ray diffraction (XRD) patterns for polycrystalline SmFeAsO and SmFeAsO₀.₀₁₅F₀₆.₀₂ samples are shown in figure 1. The Rietveld analysis of the room-temperature x-ray diffraction pattern confirmed that all observed reflections could be satisfactorily indexed on the basis of tetragonal crystal structure (space group: P4/nmm), ensuring the phase purity of the studied sample. The Rietveld fitted pattern shows that the studied samples are nearly single phase, except the additional weak peaks (marked with a * in the XRD pattern), and were assigned to the rare-earth oxide and fluoride impurity phases in the F-doped sample. The Rietveld refined structural and fitting goodness parameter, along with the Wyckoff position of the atoms, are shown in table 1. After F substitution, a very small reduction is observed in a, while c reduces significantly. The contraction of c in the SmFeAsO₀.₀₁₅F₀₆.₀₂ sample indicates a successful substitution of F⁻¹ (Rₐ = 1.33 Å) at O²⁻ (R₀ = 1.40 Å) sites. These evaluated values of the lattice parameters of the synthesized samples are close to those reported earlier [23, 24]. It is also clear from the table 1 that the position of the As atom is unaffected in both the samples, whereas the Sm atom shifted along the c-axis, because F⁻¹ substitution (at the O²⁻ site) decreases the negative charge at the O site, thereby increasing the polarization and coulomb interaction between the layers. The contraction of the Sm-As bond length (which is bridging the layers) coupled with a slight increase of the Sm-O bond lengths and bond angles were calculated using the bond valance sum method [26]. The observed structural results are fairly consistent with the reports on other rare-earth substitutions, and indicate the covalent character of the intra-layer chemical bonding due to the smaller covalent radius of fluorine than oxygen [24, 25].

The temperature dependence of normalized resistivity (ρ/ρ₀₀₀) for the SmFeAsO and SmFeAsO₀.₀₁₅F₀₆.₀₂ samples are shown in figure 2. The temperature-dependent resistivity ρ(T) curve of the undoped SmFeAsO sample shows an anomaly behavior at around ~150 K. It exhibits a semiconducting behavior above the said temperature, and suddenly the resistivity becomes metallic in nature at lower temperatures. This peculiar behavior is a coupled result of the crystal-lographic phase transition from the tetragonal P4/nmm to the orthorhombic Cmma space group around T ~150 K, and the occurrence of static spin density wave (SDW) instability like

| Table 1. The Rietveld refined structural data of SmFeAsO and SmFeAsO₀.₀₁₅F₀₆.₀₂ samples with space group P4/nmm |
| Sample | SmFeAsO | SmFeAsO₀.₀₁₅F₀₆.₀₂ |
|--------|---------|-------------------|
| Lattice parameters | a Å | 3.937(2) | 3.926(2) |
| | c Å | 8.491(8) | 8.460(4) |
| | V Å³ | 131.637 | 130.417 |
| Wyckoff positions | x | y | z | x | y | z |
| Sm 2c | 0.25 | 0.25 | 0.1371(1) | 0.25 | 0.25 | 0.142(6) |
| Fe 2b | 0.75 | 0.25 | 0.5 | 0.75 | 0.25 | 0.5 |
| As 2c | 0.25 | 0.25 | 0.661(5) | 0.25 | 0.25 | 0.660(2) |
| O/F 2a | 0.75 | 0.25 | 0 | 0.75 | 0.25 | 0 |
| Bragg R-factor χ² | 2.22 | 4.61 |
| | 2.02 | 3.07 |

| Table 2. Selected bond lengths and bond angles in SmFeAsO and SmFeAsO₀.₀₁₅F₀₆.₀₂. |
| Bond distance/angle | SmFeAsO | SmFeAsO₀.₀₁₅F₀₆.₀₂ |
| Sm-As | 3.2669 | 3.3287 |
| Sm-O | 2.2871 | 2.3042 |
| Fe-As | 2.3997 | 2.3958 |
| O-Sm-O | 118.80 | 116.85 |
| As-Fe-As | 109.13 | 108.84 |

| Δμ |
|---|
| 1|

The occurrence of static spin density wave (SDW) instability like...
magnetic ordering of the Fe spins at a slightly lower temperature of \(~140\) K [27, 28]. This feature disappears in the F-doped SmFeAsO_{0.8}F_{0.2} sample. The resistivity in the F-doped sample is metallic in nature above the superconducting transition temperature \(T_c(\rho = 0) \sim 49\) K. The increasing metallic behavior of the F-doped sample indicates that the charge-carrier density increases in the conduction plane. The superconducting transition width, \(\Delta T_c(T - T_{c\text{onset}})(\rho = 0)\), is found to be \(\Delta T_c \sim 2.9\) K. The normal state resistivity shows linear dependence on temperature for the studied SmFeAsO_{0.8}F_{0.2} sample [29, 30].

The bulk superconductivity in the studied SmFeAsO_{0.8}F_{0.2} sample is also confirmed by the DC magnetization measurements. The DC magnetic susceptibility versus temperature plot for the superconducting SmFeAsO_{0.8}F_{0.2} sample in both zero-field-cooled (ZFC) and field-cooled (FC) situations at \(H = 10\) Oe are shown in the inset of figure 2. Superconductivity sets in below 50 K, as evidenced from the negative susceptibility in both the ZFC and FC condition. The slight difference in onset transition temperature obtained from resistivity \(\rho(T)\) and magnetization \(M(T)\) is due to the threshold for transport measurements. The transport measurement is through the percolation path and hence is lower in comparison to the bulk diamagnetic response. The difference between the ZFC and FC curves suggests that the material has a fairly large flux pinning force, resulting in the trapping of magnetic flux under the field cooling condition.

The magnitude of the Fourier transform of EXAFS recorded at room temperature in the two compounds is presented in figure 3. The data exhibits a prominent peak at about \(2\) Å, corresponding to the nearest neighbor As-Fe correlation. Two smaller humps corresponding to As-Sm, As-O and As-As correlations can be seen in the range 3 to 4 Å. The data in the range 1 to 4 Å was fitted to these three correlations. In order to reduce the number of fitting parameters and to extract all important anion heights \(h\), these correlations were expressed in terms of a geometric relation based on the lattice parameter \(a\) and \(h\). A good fitting was obtained in both \(R\) and \(k\) space, as can be seen in figure 3. The values of the parameters obtained from the fitting are presented in table 3.

EXAFS studies on isostructural F-doped and undoped LaFeAsO compounds have a reported anomaly in the mean

![Figure 3](image)

**Figure 3.** Magnitude of the Fourier transform of \(k^2\) weighted \(\chi(k)\) recorded at room temperature in the (a) SmFeAsO and (b) SmFeAsO_{0.8}F_{0.2} samples.
and R (Å)

bands, there is also a difference in the concentration of 
upturn was identified, indicating the presence of 
structural anomalies around the superconducting transition. In 
figure 4, the temperature variation of $\sigma^2$ for the nearest 
neighbor As-Fe is presented. The $\sigma^2$ value shows a decrease 
with temperature, consistent with the Debye-type behavior. While a monotonic decrease seems to be present, as in the 
case of non-superconducting SmFeAsO, a clear upturn, 
peaking at 56 K, is seen in the values of $\sigma^2$ in the case of the 
SmFeAsO$_{0.4}$F$_{0.2}$ compound. The temperature at which $\sigma^2$ 
exhibits a peak correlates well with the $T_{C_{onset}}$ temperature 
observed in resistivity. This is consistent with the observations 
reported in [12]. In the case of the LaFeAsO sample, the 
upturn was identified with a characteristic temperature $T^*$, 
which was more than twice the $T_{C_{onset}}$. In the case of the 
SmFeAsO$_{0.4}$F$_{0.2}$, the upturn occurs at about 80 K, which is 
about 1.4 times the $T_{C_{onset}}$ temperature. In high-$T_c$ superconductors, $T^*$, which corresponds to the appearance of a 
pseudogap-like phase, is about 1.5 T. Further, in the present 
case, it may be noted that apart from a change in the rare-earth ion, 
which would affect the hybridization between Fe 3d and As 4p bands, there is also a difference in the concentration of F. Fluorine doping in the compound studied here is about 20%, while in [12] it was only 7%. F doping is believed to introduce holes in the hybridized Fe-As band, and hence our sample will be overdoped with holes as compared to LaFeAsO$_{0.93}$F$_{0.07}$. In the phase diagrams presented for other 
superconductor families like cuprates, the characteristic 
temperature $T^*$ decreases with increasing hole doping in CuO planes [31].

The deviation of $\sigma^2$ from the expected Debye behavior in 
superconducting SmFeAsO$_{0.4}$F$_{0.2}$ suggests the presence of 
dynamical distortions, appearing as split Fe-As bonds in 
EXAFS, as the temperature is decreased below $T^*$ to 
approach the superconducting transition. Such a splitting has 
also been proposed in F-doped LaFeAsO material [12].

Anion height ($h$) is considered to be an important parameter 
for superconductivity in Fe-based compounds as it is 
directly related to the hybridization between Fe 3d and As 4p 
bands. The higher the hybridization, the greater the mobility 
of holes, thereby suppressing the antiferromagnetic interactions 
and ushering in superconductivity. Therefore, $h$ is 
smaller in the case of compounds exhibiting superconductivity 
as compared to their non-superconducting counterparts. A similar observation is made in F-doped and 
undoped SmFeAsO samples. In the undoped sample, $h$ was 
found to be approximately 1.37 Å, while in its 
superconducting variant $h \approx 1.364$ Å.

Since $h$ was a parameter in the model used to fit the 
EXAFS data, its variation as a function of temperature, in 
both superconducting and non-superconducting samples, is 
shown in figure 5. In the case of non-superconducting samples, $h$ shows a slight increase in temperature from about 
1.37 Å at 300 K to 1.377 Å at 50 K. The exact opposite behavior is noted in the superconducting sample. Here, $h$ 
remains nearly constant down to about 80 K and then starts 
decreasing with a minimum at 56 K followed by a local 
maximum at about 52 K. As in the case of MSRD, the

### Table 3. Selected bond lengths in SmFeAsO and SmFeAsO$_{0.4}$F$_{0.2}$.

| Temperature | Bond × coordination number | SmFeAsO | SmFeAsO$_{0.4}$F$_{0.2}$ |
|-------------|-----------------------------|---------|--------------------------|
| 300 K       | As—Fe × 4                   | 2.391(3) | 0.006 (1)               |
|             | As—Sm × 4                   | 3.243(7) | 0.008 (2)               |
|             | As—O × 4                    | 3.30(7)  | 0.007 (3)               |
|             | As—As × 4                   | 3.89(1)  | 0.021 (5)               |
|             | As—As × 4                   | 3.93(1)  | 0.021 (5)               |
| 100 K       | As—Fe × 4                   | 2.392(3) | 0.003 (1)               |
|             | As—Sm × 4                   | 3.256(7) | 0.007 (2)               |
|             | As—O × 4                    | 3.31(3)  | 0.008 (3)               |
|             | As—As × 4                   | 3.88(1)  | 0.011 (1)               |
|             | As—As × 4                   | 3.91(1)  | 0.011 (1)               |
| 60 K        | As—Fe × 4                   | 2.392(3) | 0.003 (1)               |
|             | As—Sm × 4                   | 3.261(7) | 0.007 (2)               |
|             | As—O × 4                    | 3.31(4)  | 0.007 (1)               |
|             | As—As × 4                   | 3.88(1)  | 0.010 (1)               |
|             | As—As × 4                   | 3.92(1)  | 0.010 (1)               |
| 50 K        | As—Fe × 4                   | 2.392(2) | 0.003 (1)               |
|             | As—Sm × 4                   | 3.227(7) | 0.006 (1)               |
|             | As—O × 4                    | 3.24(4)  | 0.004 (3)               |
|             | As—As × 4                   | 3.88(1)  | 0.012 (1)               |
|             | As—As × 4                   | 3.92(1)  | 0.012 (1)               |

In the case of non-superconductors, $\sigma^2$ increases with increasing hole doping in CuO planes [31].
minimum in variation of $h$ corresponds with the onset of superconducting transition. This behavior of $h$ is akin to the behavior of the width of the Cu-O peak in the neutron radial distribution function (RDF) analysis in high-T$_c$ superconductors [32]. Such a variation has been interpreted to indicate the presence of microscopic inhomogeneity below T$^\star$. The anomaly in the temperature dependence of $\sigma^2$, which begins at about 80 K (figure 4), also supports electronic instability beginning at this temperature. This clearly indicates the role of lattice distortions in superconductivity in Fe-based superconductors.

The present results indicate an intimate connection in the mechanism of superconductivity in Fe-based superconductors and that proposed in cuprates. It may also be mentioned here that a similarity between these two families of superconductors also exists in their phase diagrams, the close proximity of superconductivity to antiferromagnetic order, and the presence of a spin resonance peak in the superconducting region, indicating the unconventional nature of superconductivity. In cuprates, EXAFS studies performed using polarized x-ray on bulk single-crystal samples or single-crystalline thin films have clearly shown a splitting ($\sim$0.1 Å) in Cu-O bond distances [33]. Below T$^\star$, the planar Cu-O bonds undergo dynamical elongation, creating charge-rich and charge-poor domains. In order to observe the presence or absence of such domains in Fe-based superconductors, more detailed experiments preferably on bulk single crystals are required. However, in figure 6, we present the variation of nearest neighbor As-Fe and As-As bond distances in the superconducting compound as obtained from our EXAFS analysis. It can be seen that while the variation of the As-As distance is nearly temperature-independent, a very weak increase is noticed in the Fe-As distance. This small increase suggests a close proximity in the mechanism responsible for superconductivity in these Fe-based compounds and other families of superconductors-like cuprates.

4. Conclusions

In summary, this paper reports temperature-dependent As K edge EXAFS studies in superconducting SmFeAsO$_{0.8}$F$_{0.2}$ and non-superconducting SmFeAsO compounds. Local structural parameters like anion height, As-Fe bond distance and the mean square disorder in the As-Fe bond distance of the fluorinated compound exhibit anomalous variation near the...
superconducting onset temperature. Such a variation in these parameters is absent in the non-superconducting compound. Furthermore, the increase in the Fe-As bond distance just below the superconducting onset temperature indicates a similarity in the distortions observed in high-T$_c$ cuprates and these Fe-based superconductors.

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References

[1] Scalapino D J 2012 Rev. Mod. Phys. 84 1383
[2] Kamihara Y, Watanabe T, Hirano M and Hosono H 2008 J. Am. Chem. Soc. 130 3296
[3] Ren Z A et al 2008 Chin. Phys. Lett. 25 2215
[4] Sefat A S, Jin R Y, McGuire M A, Sales B C, Singh D J and Mandrus D 2008 Phys. Rev. Lett. 101 117004
[5] Mizuguchi Y, Hara Y, Deguchi K, Tsuda S, Yamaguchi T, Takeda K, Kotezawa H, Tou H and Takano Y 2010 Supercond. Sci. Technol. 23 054013
[6] Okabe H, Takeda N, Horigane K, Muranaka T and Akimitsu J 2010 Phys. Rev. B 81 205119
[7] Takahashi H, Igawa K, Arii K, Kamihara Y, Hirano M and Hosono H 2008 Nature 453 376
[8] Chu J-H, Analytis J G, Kucharczyk C and Fisher I R 2009 Phys. Rev. B 79 014506
[9] Liu T J et al 2009 Phys. Rev. B 80 174509
[10] Billinge S J L, Kwei G H and Takagi H 1994 Phys. Rev. Lett. 72 2282
[11] Saini N L, Lanzara A, Oyanagi H, Yamaguchi H, Oka K and Ito T 1997 Phys. Rev. B 55 12759
[12] Zhang C J, Oyanagi H, Sun Z H, Kamihara Y and Hosono H 2008 Phys. Rev. B 78 214513
[13] Iadecola A, Agrestini S, Filippi M, Simonelli L, Fratini M, Joseph B, Mahajan D and Saini N L 2009 EPL 87 26005
[14] Joseph B, Iadecola A, Pur I, Simonelli L, Mizuguchi Y, Takano Y and Saini N L 2010 Phys. Rev. B 82 020502
[15] Granado E et al 2011 Phys. Rev. B 83 184508
[16] Saini N L 2013 Sci. Technol. Adv. Mater. 14 014401
[17] Subedi A, Zhang L, Singh D and Du M 2008 Phys. Rev. B 78 134514
[18] Rotter M, Tegel M and Johrendt D 2008 Phys. Rev. Lett. 101 107006
[19] Awana V P S, Pal A, Vajpayee A, Kishan H, Alvarez G A, Yamaura K and Takayama-Muromachi E 2009 J. Appl. Phys. 105 07E316
[20] Rodriguez-Carvajal J 1993 Physica B 192 55
[21] Ravel B and Newville M 2005 J. Synchr. Rad. 12 537
[22] Zubirsky S I, Rehr J J, Ankudinov A, Albers A C and Eller M J 1995 Phys. Rev. B 52 2995
[23] Hadjiev V G, Iliev M N, Sasmal K, Sun Y Y and Chu C W 2008 Phys. Rev. B. 77 220505
[24] Martinelli A, Ferretti M, Manfrinetti P, Palenzona A, Tropeano M, Cimberte M R, Ferdegghini C, Valle R, Putti M and Siri A S 2008 Supercond. Sci. and Tech. 21 095017
[25] Nomura T, Kim S W, Kamihara Y, Hirano M, Sushko P V, Kato K, Takata M, Shluger A L and Hosono H 2008 Supercond. Sci. Technol. 21 125028
[26] Brese N E and Keefe M O 1991 Acta Cryst. B 47 192
[27] Chen G F, Li Z, Wu D, Li G, Hu W Z, Dong J, Zheng P, Luo J L and Wang N L 2008 Phys. Rev. Lett. 100 247002
[28] Pal A, Mehdì S S, Huyan M and Awana V P S 2013 Sol. State Sci. 15 123
[29] Zhi-An R et al 2008 Chin. Phys. Lett. 25 2215
[30] Meena R S, Pal A, Kumar S, Rao K V R and Awana V P S 2013 J. Supercond. Nov. Magn. 26 2383
[31] Oyanagi H, Zhang C, Tsukada A and Naito M 2008 J. Phys.: Conf. Series 108 012038
[32] Mustre de Leon J, Conradson S D, Batistic I and Bishop A R 1990 Phys. Rev. Lett. 65 1675
[33] Zhang C Z, Oyanagi H and Lee C H 2008 Physica C 468 898