Bulk electronic structures and strong electron–phonon interactions in an electron-doped high-temperature superconductor

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Abstract. We have performed soft x-ray angle-resolved photoemission spectroscopy (ARPES) for the electron-doped high-temperature superconducting cuprates (HTSCs) Nd2−xCexCuO4 (x = 0.075 and 0.15) in order to disclose their genuine bulk electronic structures. Our soft x-ray ARPES has revealed that the bulk-derived nodal ‘kink’ (the abrupt change of the electron velocity in quasiparticle dispersions), being absent in the low-energy ARPES, is clearly observable for the electron-doped superconducting Nd1.85Ce0.15CuO4. This result confirms that the antiferromagnetic spin correlation is suppressed and the electron–phonon interactions are prevailing in the bulk of the electron-doped superconducting Nd2−xCexCuO4 at the optimal doping level. The nodal ‘kink’ behavior is equivalent to that observed in the hole-doped HTSCs. The anisotropic strong electron–phonon interactions seem to be inherent in the HTSCs irrespective of the type of doped carriers.

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1. Introduction

It is generally accepted that collective excitations play essential roles in the superconducting state of the high-temperature superconducting cuprates (HTSCs). Low-\(h\nu\) (photon energy) angle-resolved photoemission spectroscopy (ARPES) studies \[1\] have elucidated the anisotropic ‘kink’ feature (abrupt change of the electron velocity) in the quasiparticle dispersions (QD) for the HTSCs. Since the ‘kink’ will be observed at binding energies corresponding to the collective mode, its observation is regarded as evidence for the strong coupling of the electron with a collective mode. For the hole-doped HTSCs, the ‘kink’ behavior along the nodal \([(0,0)-((\pi,\pi))\)] direction is interpreted as indicating strong coupling with longitudinal optical phonons, because it is observed even for \(\text{La}_{2-x}\text{Sr}_x\text{CuO}_4\) where the magnetic mode does not exist \[2\]–\[4\]. For the electron-doped HTSCs, on the other hand, no ‘kink’ behavior is observed along the nodal direction while the finite ‘kink’ or the antiferromagnetic ‘pseudo-gap’ behavior is seen along the antinodal \([(\pi,0)-((\pi,\pi))\)] and off-nodal directions by low-\(h\nu\) ARPES \[5\]–\[9\]. For both the hole- and electron-doped HTSCs, it is considered that the ‘kink’ behavior along the antinodal and off-nodal directions is depicted by the magnetic excitation mode because the electrons near \((\pi,0)\) are easily coupled to the magnetic mode with a \(Q\) vector of \((\pi,\pi)\) \[7, 10, 11\].

So far, low-\(h\nu\) ARPES results reported for \(\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4\) (NCCO) have shown the suppression of the spectral weight around \(\sim 0.7\pi\) and \(\sim 0.3\pi\) and \(\sim 0.3\pi\) and \(\sim 0.7\pi\) (‘hot spots’ \[11\]–\[13\]), which are located at the intersections between the Fermi surface (FS) and the antiferromagnetic Brillouin zone (AFBZ) boundary. Such suppression has been believed to correspond to the pseudogap in the optical conductivity, which is estimated as \(\sim 200\text{meV}\), and to the peak of the two-magnon Raman scattering \[14\]. It has been considered that the pseudogap in the optical conductivity in the underdoped region, which becomes smeared out for \(x = 0.15\), is related to the evolution of the antiferromagnetic spin correlation \[14\]. The suppression of the spectral weight at the ‘hot spots’, however, is confirmed not only in underdoped antiferromagnetic NCCO, but also in optimally doped superconducting \(\text{Nd}_{1.85}\text{Ce}_{0.15}\text{CuO}_4\) in the low-\(h\nu\) ARPES reported so far \[11\]. Meanwhile, there are several reports claiming strong electron–phonon interactions in the electron-doped HTSCs leading to the ‘kink’ in the scattering rate derived from the optical reflectance \[14\], the softening of a mode in the...
inelastic x-ray scattering [15] and so on. However, there is thought to be no direct evidence for the strong electron–phonon interactions in the electron-doped HTSCs contributing to the superconductivity [16]. In hole-doped HTSCs, on the other hand, the isotope effect [17] and the anisotropic ‘kink’ along the nodal direction in QD [2, 3] are often thought to be directly reflecting the contribution of the electron–phonon interactions to their superconductivity.

Photoemission spectroscopy (PES) is very powerful to directly probe electronic structures of solids. However, the high surface-sensitivity of low-$h\nu$ PES has often prevented one from probing genuine bulk electronic structures [18]–[20]. For quasi-two-dimensional electron systems such as HTSCs, it has long been thought that the electronic structures of the top (or surface) conducting layer are equivalent to those of the bulk layers, which are responsible for the superconductivity. High-$h\nu$ core-level PES studies [21]–[26], however, recently suggested that the electronic structures of the bulk CuO$_2$ layers, in particular for optimally doped Nd$_{1.85}$Ce$_{0.15}$CuO$_4$, are noticeably different from those of the surface CuO$_2$ layer, which are mainly detected by low-$h\nu$ ARPES [6, 8, 22]. High-$h\nu$ ARPES [23, 24] is therefore essential for directly revealing the bulk QD.

In this paper, we demonstrate by means of bulk-sensitive high-$h\nu$ ARPES that the electron–phonon interactions are strong enough along the nodal direction in the bulk of optimally electron-doped Nd$_{1.85}$Ce$_{0.15}$CuO$_4$, even though the electron–phonon coupling is suppressed in the underdoped region. Our results imply that the effect of anisotropic electron–phonon interactions is ‘universal’ in the HTSCs.

2. Experimental

High-$h\nu$ ARPES and angle-integrated PES of single crystals of Nd$_{2-x}$Ce$_x$CuO$_4$ ($x = 0.075$ and $0.15$) [27] were performed at SPring-8 BL25SU [28] by using a GAMMADATA-SCIENTA SES-200 electron energy analyzer. The energy resolution was set to either 200 (for the FS mapping as later shown in figure 4) or 100 meV (for the ARPES along the high-symmetry lines as shown in figures 2 and 3). The momentum resolution parallel (perpendicular) to the analyzer slit was set to $\pm 0.02 (\pm 0.03)$ Å$^{-1}$. The emission angle for ARPES was approximately set to normal to the sample surface. The energy resolution for the angle-integrated Cu 2p core-level PES was set to be better than $\sim 350$ meV. Clean surfaces were obtained by cleaving the sample in situ at the measuring temperature of 20 K. The base pressure was $3.0 \times 10^{-8}$ Pa.

3. Surface and bulk electronic structures probed by soft x-ray PES for quasi-two-dimensional Nd$_{1.85}$Ce$_{0.15}$CuO$_4$

It has been widely believed that the electronic structures are similar in the bulk and at the surface in the case of quasi-two-dimensional systems, for instance, HTSCs. Recently, hard x-ray PES has, however, revealed a noticeable difference of the electronic structures between the bulk and the surface [29]. Soft x-ray PES is useful enough to estimate both the contributions of the topmost and the bulk layers in PES spectra [23] by changing the emission angle $\theta$ from the normal, resulting in a change of the probing depth. We have performed Cu 2p core-level PES in order to confirm that the electronic structures derived from the surface’s topmost layer are remarkably different from those in the bulk even for quasi-two-dimensional Nd$_{1.85}$Ce$_{0.15}$CuO$_4$. 

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Figure 1. (a) Angle-integrated PES spectra of the Cu 2p core-level for different detection polar-angles ($\theta$). The Shirley-type background is subtracted from the spectra. The energy resolution was set to $\sim 350$ meV at $h\nu = 1504$ eV. (b) The ‘Bulk’ and ‘Surface’ PES spectra derived from the PES spectra at $\theta = 0$ and 60$^\circ$. (c) A schematic view of the definition of the ‘Surface’ and ‘Bulk’ in (b). (d) The spectra given by the weighted sum of the ‘Bulk’ and ‘Surface’ spectra.

The inelastic mean free path of photoelectrons (IMFPP) is typically estimated as $\sim 5$ and 11–15 Å at the kinetic energies of photoelectrons ($E_k$) of 55 and 400–700 eV, respectively [30]. Figure 1(a) shows the angle-integrated PES spectra of the Cu 2p core-level for different detection polar-angles ($\theta$) of the emitted photoelectrons with $E_k \sim 530–570$ eV at $h\nu = 1504$ eV, where the acceptance angle is about $\pm 5^\circ$. The surface sensitivity of the PES spectra increases with $\theta$. In addition to a broad peak centered at 933 eV, a shoulder structure is observed at 931–932 eV in figure 1(a). The relative intensity of the shoulder structure to the broad peak is clearly reduced with increasing $\theta$, namely with increasing surface sensitivity. The spectral weight of the ‘Bulk’ component in the PES spectra can then be estimated as

$$\exp \left[ -\frac{s}{\lambda(E_k) \cos \theta} \right],$$

where $s = 6.035$ Å and $\lambda(E_k \sim 570$ eV) = 14.5 Å are the thickness of the ‘Surface’ as assumed in figure 1(c) (the distance between the Nd(Ce)-O layers) and the IMFPP [30] at the kinetic energy $E_k$. We have deconvoluted the Cu 2p core-level spectra for the polar angles $\theta = 0^\circ$
Figure 2. (a) ARPES intensity plot for Nd$_{1.85}$Ce$_{0.15}$CuO$_4$ measured at $h\nu = 500$ eV along the antinodal direction. (b) QD along the antinodal direction estimated from the high-$h\nu$ ARPES. The filled circles and the thin dotted line correspond to the peak positions of the momentum distribution curves (MDCs) in (a) and the bare QD which are used to estimate the real part of the electron self-energy as displayed in the inset. (c) and (e) Intensity plots along the nodal direction at $h\nu = 500$ and 460 eV, respectively. (d) and (f) QD along the nodal direction, where the green and blue shaded areas represent the binding energy region of 50–80 meV, where the ‘kink’ was observed.

4. Strong electron–phonon contribution to the quasiparticle dispersion: nodal ‘kink’ and suppressed antinodal ‘kink’ behavior

The high-$h\nu$ ARPES-intensity plots along the antinodal and nodal directions at $h\nu = 500$ eV are displayed in figures 2(a) and (c), respectively. The anisotropy of the ‘kink’ behavior revealed...
by the high-\(h\nu\) ARPES is in striking contrast to that reported by low-\(h\nu\) ARPES [5]. No clear ‘kink’ is observed in our high-\(h\nu\) ARPES for \(\text{Nd}_{1.85}\text{Ce}_{0.15}\text{CuO}_4\) along the antinodal direction as shown in figures 2(a) and (b), although an antinodal ‘kink’ was suggested by the low-\(h\nu\) ARPES for NCCO [5]. It has recently been suggested that the antinodal ‘kink’ behavior is related to the antiferromagnetic ‘pseudo-gap’ at the ‘hot spots’ for NCCO [6]. Stronger antiferromagnetic ‘pseudo-gap’ and ‘hot spot’ effects are reported in the other electron-doped HTSC, \(\text{Sm}_{1.86}\text{Ce}_{0.14}\text{CuO}_4\) [9]. It is found that the quasiparticle effective mass near the Fermi level \((E_F)\) is most strongly enhanced in the close vicinity of the ‘hot spot’ due to the opening of the antiferromagnetic ‘pseudo-gap’ for those electron-doped HTSCs. Such an enhancement of the quasiparticle effective mass near \(E_F\) is gradually suppressed due to their movement away from the ‘hot spot’ toward \((\pi, 0)\) [6]. Neither the antiferromagnetic ‘pseudo-gap’ behavior nor the near-\(E_F\) quasiparticle mass enhancement are clearly seen along the antinodal direction by our high-\(h\nu\) ARPES in figures 2(a) and (b), which implies that both effects are weak in the bulk. Nevertheless, from the experimental point of view, it remains slightly unclear at present whether both the effects are really negligible along the antinodal direction in the bulk. The suppression of the spectral weight at the ‘hot spots’ is described in chapter 5.

On the other hand, the striking nodal ‘kink’ is observed by high-\(h\nu\) ARPES, here in the QD at 50–80 meV and 0.46–0.49 \(\text{Å}^{-1}\) (figure 2(d)), although no clear ‘kink’ at 50–80 meV has been detected by low-\(h\nu\) ARPES. Insets of figures 2(b) and (d) show the energy dependence of the real part of the self-energy derived from the QD at \(h\nu = 500\) eV. Although no significant feature is observed in the inset of figure 2(b) along the antinodal direction, a clear feature is observed in the inset of figure 2(d) near the nodal ‘kink’. This energy for electron-doped \(\text{Nd}_{1.85}\text{Ce}_{0.15}\text{CuO}_4\) (50–80 meV) is close to those of the kinks reported for several families of hole-doped HTSCs. The nodal ‘kink’ in figures 2(c) and (d) for the electron-doped \(\text{Nd}_{1.85}\text{Ce}_{0.15}\text{CuO}_4\) is similar to those [2, 3, 16] observed for the hole-doped HTSCs with respect to both \(k\)-direction and energy scale. The nodal ‘kink’ feature was also observed in the high-\(h\nu\) ARPES spectra at different \(h\nu\) (= 460 eV) as shown in figures 2(e) and (f) beyond the statistic fluctuation as recognized in the inset of figure 2(f). Therefore, the nodal ‘kink’ observed here for high-energy excitations is neither due to any possible extrinsic effect nor due to matrix element effects, but due to an intrinsic effect, being a characteristic of bulk \(\text{Nd}_{1.85}\text{Ce}_{0.15}\text{CuO}_4\). The presence (absence) of the nodal (antinodal) ‘kink’ in QD observed by the present high-\(h\nu\) ARPES is much different from the results of low-\(h\nu\) ARPES so far reported for NCCO [5, 6].

First, the electron–phonon coupling is considered as an origin of the ‘kink’ behavior, while other scenarios are also proposed for the ‘kink’ behavior. The electron–phonon coupling constant \(\lambda\) estimated from the low-\(h\nu\) ARPES results for optimally doped NCCO is definitely smaller than that for the hole-doped HTSC families, suggesting that the superconducting mechanism for the HTSCs depends on the type of the doped carriers [16]. However, the bulk \(\lambda\) is estimated here as \(\sim 1.2–1.6\) for \(\text{Nd}_{1.85}\text{Ce}_{0.15}\text{CuO}_4\) in a way similar to that in [2] by assuming a bare band shown in figure 2(d). This value is comparable to \(\lambda\) for the hole-doped HTSCs with a similar carrier concentration [2]. Our results have thus revealed that the electron–phonon coupling intensity for the electron-doped \(\text{Nd}_{1.85}\text{Ce}_{0.15}\text{CuO}_4\) is not smaller than those in the hole-doped HTSCs [2] in the superconducting phase, implying that the existence of the anisotropic nodal ‘kink’ behavior is inherent in the HTSCs irrespective of the type of doped carriers.

There have been several reports supporting a strong electron–phonon contribution to the superconductivity in the electron-doped HTSCs in the following respects. (i) The ‘kink’ in the scattering rate derived from optical reflectance lies in a similar energy region to our ‘kink’...
and is assigned to electron–phonon coupling [14]. (ii) The inelastic x-ray scattering reported by d’Astuto et al [15] suggests that the softening of a mode at ~55–75 meV is ascribable to the oxygen half-breathing mode as reported for the hole-doped HTSCs. (iii) The neutron scattering reported by Kang et al has revealed changes with doping in the generalized phonon density of structures around 70 meV [31]. (iv) While the nodal ‘kink’ energy of 50–80 meV estimated from our high-hν ARPES is much smaller than the energy of ~200 meV for the pseudogap in the optical conductivity [14] associated with the antiferromagnetic spin correlation model, it corresponds well to the characteristic energy of the electron–phonon interactions. Therefore, the antiferromagnetic spin correlation [14] cannot be the leading candidate for the origin of the nodal ‘kink’ behavior here. The nodal ‘kink’ reported here is consistently understandable with the other bulk-sensitive results mentioned above [14, 15, 31]. It is possible that the surface electronic structures deviated much from the bulk could induce the stability of the antiferromagnetism in the surface region even for optimally doped NCCO. Then, the electron–phonon interactions would be masked at the surface. There can be another possible scenario [32] as the s and d wave superconductivity coexists in HTSCs, whereas the contribution from the s wave superconductivity is suppressed at the surface. The superconductivity gap symmetry in the bulk cannot be resolved, however, in the present high-hν ARPES due to the limited energy resolution.

We discuss now the competition between the electron–phonon coupling and the spin correlation along the nodal direction in both superconducting and antiferromagnetic phases. The energy distribution curves (EDCs) for \( x = 0.075 \) and 0.15 are integrated around the Fermi wave vector \( (k_F) \) and \((0,0)\) (4.1% of the half of the Brillouin zone (BZ) along the nodal direction) at \( h\nu = 500 \text{ eV} \) in figure 3(a). The EDCs near \((0,0)\) are shown as reference for discussing the intrinsic spectral shape near the \( k_F \) point beyond the background spectral shape. The spectral weight around \( k_F \) is drastically suppressed for \( x = 0.075 \) compared with that for \( x = 0.15 \). In the difference spectra between the near-\( k_F \) and near-\((0,0)\) spectra in figure 3(b), the intensity for \( x = 0.075 \) decreases monotonically from 200 meV toward \( E_F \), consistently with the pseudogap in the optical conductivity for \( 0 \leq x \leq 0.125 \). Such a pseudogap behavior is not seen for \( x = 0.15 \) in figure 3(b). These results have revealed that the electron–phonon coupling overwhelms the antiferromagnetic spin correlation in the superconducting bulk NCCO with \( x = 0.15 \) along the nodal direction. Our result for \( x = 0.075 \) suggests, on the other hand, that the antiferromagnetic spin correlation is certainly playing important roles in the antiferromagnetic phase in the underdoped region. The behavior of the quasiparticle spectral weight revealed here near \( E_F \) along the nodal direction (even though broadened by the instrumental resolution) is similar to the doping dependence of the pseudogap in the optical conductivity for \( 0 \leq x \leq 0.15 \). This scenario is consistent with the report that both the pseudogap in the optical conductivity and the two-magnon peak in the Raman scattering spectra are not discerned for \( x = 0.15 \) in the superconducting phase, but are seen for \( x \leq 0.125 \) in the antiferromagnetic phase [14].

5. FS mapping by high-hν ARPES

The near-\( E_F \) ARPES-intensity plot for \( x = 0.15 \) at \( h\nu = 500 \text{ eV} \) is shown in figure 4(a) indicating a hole-like FS centered at \((\pi, \pi)\). The \( k_F \)’s estimated from the EDCs and momentum distribution curves (MDCs) are shown in figure 4(b) by black full circles with error bars. Since the \( k_z \) dependence of the FS topology was recently found for Ca-doped Sr$_2$RuO$_4$ [33], a typical layered compound, the measurement of Nd$_{1.85}$Ce$_{0.15}$CuO$_4$ was additionally performed.
Figure 3. (a) EDCs integrated around $k_F$ (near $(\pi/2, \pi/2)$) and $(0, 0)$ for $x = 0.15$ and 0.075 of Nd$_{2-x}$Ce$_x$CuO$_4$. The $(0, 0)$ spectra are shown for reference purposes. The thick and thin black solid lines correspond to the smoothed EDC near $(0, 0)$ of the raw data shown by empty circles and rectangles for $x = 0.15$ and 0.075 of Nd$_{2-x}$Ce$_x$CuO$_4$, respectively. (b) Difference spectra between the raw EDCs around $k_F$ and those around $(0, 0)$ reflecting the intrinsic bulk spectral weight near $E_F(k_F)$. The shaded area emphasizes the pseudogap of $\sim 200$ meV in the EDC around $k_F$ for $x = 0.075$ and the coherent state developed in the region from $\sim 200$ meV to $E_F$ for $x = 0.15$.

at $h\nu = 460$ eV with different $k_z$. The results are shown in figures 4(c) and (d). In figures 4(b) and (d), the FS topology fitted to the $h\nu = 55$ eV ARPES are added [34]. It is found that the shape of the FS resolved at $h\nu = 500$ and 460 eV is not as different as theoretically suggested [34]. Although its shape is rather circular, noticeable deviation from the FS at $h\nu = 55$ eV is recognized near the antinodal direction [13, 34]. Namely, $k_F$ is closer to the $(-\pi, 0)$-$(\pi, 0)$ and $(0, -\pi)$-$(0, \pi)$ axes in the high-$h\nu$ ARPES, when the center of gravity of the $k_F$ distribution is taken into account. For further discussions, however, higher resolutions with respect to the energy and wave number are required. Still it is very clear that the FS shape is much different from the square-like FS shape along the AFBZ boundary reported by Claesson et al [35] at $h\nu = 400$ eV after symmetrization. The results in figures 4(a)–(d) are raw data measured over the full BZ without any symmetrization procedure. In figures 4(c) and (d), the spectral weight is not fully suppressed in the $k$ region corresponding to the ‘hot spots’ in the lower part of the BZ, implying that the suppressed spectral weight on the ‘hot spots’ could be due to matrix element effects and/or the difference in $k_z$.

6. Conclusions

We have carried out soft x-ray ARPES for the electron-doped HTSCs Nd$_{2-x}$Ce$_x$CuO$_4$ ($x = 0.075$ and 0.15) at $h\nu = 500$ eV. Our high-$h\nu$ bulk-sensitive ARPES results have revealed a bulk-originated nodal ‘kink’ derived from the electron–phonon coupling in electron-doped
Figure 4. (a) ARPES-intensity plot integrated within 100 meV around $E_F$ for Nd$_{1.85}$Ce$_{0.15}$CuO$_4$ at $h\nu = 500$ eV. It should be noted that this intensity plot is raw data (not symmetrized). The character of the FS observed by our high-$h\nu$ ARPES is hole-like centered at $(\pi, \pi)$, consistently with that from low-$h\nu$ ARPES. (b) The $k_F$s plot estimated from the EDCs and MDCs in (a). The solid blue, dashed green, and solid red lines correspond to the symmetry lines in momentum space, the AFBZ boundary, and the FS contour fitted to the ARPES intensity plot at $h\nu = 55$ eV by the tight-binding model with same parameters given in [34], respectively. The deviation of the red FS curves from the FSs presented here is clear around $(\pi, 0)$. (c) ARPES-intensity plot integrated within 100 meV around $E_F$ for Nd$_{1.85}$Ce$_{0.15}$CuO$_4$ at $h\nu = 460$ eV. (d) The $k_F$s plot estimated from the EDCs and MDCs in (c). (e) A schematic view of the Fermi surface for Nd$_{1.85}$Ce$_{0.15}$CuO$_4$.
Nd$_{1.85}$Ce$_{0.15}$CuO$_4$. This result confirms that the electron–phonon interactions prevail in the bulk but are suppressed at the surface in electron-doped superconducting Nd$_{1.85}$Ce$_{0.15}$CuO$_4$. The nodal ‘kink’ behavior is equivalent to that observed in hole-doped HTSCs. The doping dependence of the spectral weight near $E_F$ in the nodal EDCs suggests that the electron–phonon interactions overwhelm the spin correlation in the superconducting bulk Nd$_{1.85}$Ce$_{0.15}$CuO$_4$, even though the spin correlation is certainly playing some important roles in the antiferromagnetic phase in the underdoped region. The electron–hole symmetry in the HTSCs is confirmed with respect to the nodal ‘kink’ behavior due to the electron–phonon coupling.

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References

[1] Damascelli A, Hussain Z and Shen Z-X 2003 Rev. Mod. Phys. 75 473
[2] Lanzara A et al 2001 Nature 412 510
[3] Zhou X J et al 2003 Nature 423 398
[4] Terashima K, Matsui H, Sato T, Takahashi T, Kofu M and Hirota K 2007 Phys. Rev. Lett. 99 017003
[5] Armitage N P et al 2003 Phys. Rev. B 68 064517
[6] Matsui H, Terashima K, Sato T, Takahashi T, Wang S-C, Yang H-B, Ding H, Uefuji T and Yamada K 2005 Phys. Rev. Lett. 94 047005
[7] Matsui H, Terashima K, Sato T, Takahashi T, Fujita M and Yamada K 2005 Phys. Rev. Lett. 95 017003
[8] Matsui H, Takahashi T, Sato T, Terashima K, Ding H, Uefuji T and Yamada K 2007 Phys. Rev. B 75 224514
[9] Park S R, Roh Y S, Yoon Y K, Leem C S, Kim J H, Kim B J, Koh H, Eisaki H, Armitage N P and Kim C 2007 Phys. Rev. B 75 060501
[10] Shen Z-X and Schrieffer J R 1997 Phys. Rev. Lett. 78 1771
[11] Armitage N P et al 2002 Phys. Rev. Lett. 88 257001
[12] Armitage N P et al 2001 Phys. Rev. Lett. 86 1126
[13] Armitage N P et al 2001 Phys. Rev. Lett. 87 147003
[14] Onose Y, Taguchi Y, Ishizaka K and Tokura Y 2004 Phys. Rev. B 69 024504
[15] d’Astuto M, Mang P K, Giura P, Shukla A, Ghigna P, Mirone A, Braden M, Greven M, Krish M and Sette F 2002 Phys. Rev. Lett. 88 167002
[16] Shen Z-X, Lanzara A, Ishihara S and Nagaosa N 2002 Phil. Mag. B 82 1349
[17] Gweon G-H, Sasagawa T, Zhou S Y, Graf J, Takagi H, Lee D-H and Lanzara A 2004 Nature 430 187
[18] Sekiyama A, Iwasaki T, Matsuda K, Saitoh Y, Onuki Y and Suga S 2000 Nature 403 396
[19] Sekiyama A et al 2004 Phys. Rev. Lett. 93 156402
[20] Suga S et al 2005 J. Phys. Soc. Japan 74 2880
[21] Taguchi M et al 2005 Phys. Rev. Lett. 95 177002
[22] Kondo T, Takeuchi T, Kaminski A, Tsuda S and Shin S 2007 Phys. Rev. Lett. 98 267004

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[23] Sekiyama A et al 2004 Phys. Rev. B 70 060506
[24] Yano M, Sekiyama A, Fujiwara H, Saita T, Imada S, Muro T, Onuki Y and Suga S 2007 Phys. Rev. Lett. 98 036405
[25] Suga S et al 2004 Phys. Rev. B 70 155106
[26] Tsunekawa M et al 2005 J. Electron Spectrosc. Relat. Phenom. 144–147 541
[27] Tokura Y, Takagi H and Uchida S 1989 Nature 337 345
[28] Saitoh Y et al 2000 Rev. Sci. Instrum. 71 3254
[29] Taguchi M et al 2005 Phys. Rev. B 71 155102
[30] Powell C J, Jablonski A, Tilinin I S, Tanuma S and Penn D R 1999 J. Electron Spectrosc. Relat. Phenom. 98–99 1
[31] Kang H J, Dai P, Mandrus D, Jin R, Mook H A, Adroja D T, Bennington S M, Lee S-H and Lynn J W 2002 Phys. Rev. B 66 064506
[32] Harshman Dale R, Kossler W J, Wan X, Fiory Anthony T, Greer A J, Noakes D R, Stronach C E, Koster E and Dow John D 2004 Phys. Rev. B 69 174505
[33] Uruma M, Sekiyama A, Fujiwara H, Yano M, Fujita H, Imada S, Muro T, Nekrasov I A, Maeno Y and Suga S 2007 Preprint arXiv:0711.2160v1
[34] Markiewicz R S, Sahrakorpi S, Lindroos M, Lin Hsin and Bansil A 2005 Phys. Rev. B 72 054519
[35] Claesson T, Månson M, Dallera C, Venturini F, Nadaï C De, Brookes N B and Tjernberg O 2004 Phys. Rev. Lett. 93 136402