Temperature dependent local Cu-O displacements from underdoped to overdoped La-Sr-Cu-O superconductor

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Abstract. We have studied doping evolution of the temperature dependent local Cu-O displacements in the La$_{2-x}$Sr$_x$CuO$_4$ superconductor by polarized Cu K-edge extended X-ray absorption fine structure (EXAFS) measurements. While temperature dependent Debye-Waller factor of the Cu-O bonds, measuring the local Cu-O displacements, shows an anomalous increase at low temperature for the underdoped single crystals, we do not find such a dependence for the case of the overdoped system. The results, which are discussed in the light of recent angle resolved photoemission measurements, provide an evidence for some important correlation between the doping dependent electron-lattice interaction, the charge inhomogeneities and the local Cu-O displacements in the copper oxide superconductors.

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1 Introduction

Even though character of the superconducting order parameter in the copper oxides with charge 2e remains intact, the electron-lattice interaction, fundamental basis for the superconductivity in metals, is given minor importance in the models for their superconductivity. Further complications are also due to the self-organization of various degrees of freedom, related to the charge, spin and lattice excitations at a mesoscopic length-scale, the phenomena which has been a point of recent debate [1]. However, recent experiments appear to support a key role of the superconductivity, but also in the low temperature orders, such as the stripe ordering [2–10].

The main experiments used to probe local displacements in the copper oxides are the pair distribution function (PDF) analysis of neutron and X-ray diffraction, extended X-ray absorption fine structure (EXAFS) and ion channeling [2–7]. Although the techniques have their own limitations to determine quantitative atomic displacements, there is a qualitative agreement on the experimental results obtained by these techniques. Recent technical developments, combining with high brilliance X-ray synchrotron radiation sources, allows the EXAFS spectroscopy, a fast (∼10$^{-15}$ s) and local (∼5-6 Å) probe [11], to determine the quantitative and directional atomic displacements.

Here we have exploited the polarized Cu K-edge EXAFS, with high k-resolution, to study the local Cu-O displacements as a function of doping. La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) is one of the simplest systems among the copper oxides and hence been chosen as a model system for the present work. The added advantage is that a wide range of hole doping could be achieved by variation of the chemical substitution (Sr content). The temperature dependent distribution of the local and instantaneous lattice distortions (dynamic and static) is measured by the correlated Debye-Waller factor (DWF) of the Cu-O bonds. The DWF shows an anomalous temperature dependence for the underdoped and optimally doped systems, while we do not find such a temperature dependent change for the overdoped case. The anomalous change appears to depend on the electron-lattice interaction, that decreases with increasing the Sr concentration.

2 Experimental

Cu K-edge X-ray absorption measurements were made on a series of La$_{2-x}$Sr$_x$CuO$_4$ single crystals ($x = 0.105, 0.13, 0.15, 0.20$) of size ∼3×2×0.5 mm$^3$, grown by travelling solvent floating zone (TSFZ) method. The samples show sharp superconducting transitions at the temperatures 28 K, 32 K, 36 K and 29 K respectively with the increasing Sr concentration. The X-ray absorption measurements were performed at the beamline BL13B of the Photon Factory, Tsukuba. The Synchrotron radiation...
emitted by a 27-pole wiggler source at the 2.5 GeV Photon Factory storage ring was monochromatized by a double crystal Si(111) monochromator and sagittally focused on the samples, mounted in a closed cycle refrigerator. The measurements were made in the grazing incidence geometry with plane polarized light falling parallel to the Cu-O-Cu bonds. This geometry was ascertained by monitoring the $1s \rightarrow 3d_{x^2-y^2}$ quadrupole transition in the absorption spectra [12]. The absorption spectra were recorded by detecting the Cu Kα fluorescence photons using a 19-element Ge X-ray detector array [13]. The sample temperature was controlled and monitored within an accuracy of $\pm 1$ K.

X-ray absorption measurements at several temperatures were repeated at the BM29 of the European Synchrotron Radiation Facility (ESRF), Grenoble where the synchrotron radiation emitted by a Bending magnet was monochromatized by a double crystal Si(311) monochromator. As our standard experimental approach, several absorption scans were collected to limit the noise level to the order of $10^{-4}$. Standard procedure was used to extract the EXAFS signal from the absorption spectrum [11], followed by the correction of the signal for the X-ray fluorescence self-absorption effects [14] before the analysis. Further details on the experiments and the data analysis could be found in our earlier publications [6,7,12].

3 Results and discussion

Figure 1 shows the Fourier transforms of the EXAFS oscillations (weighted by $k^2$) measured on the underdoped (La$_{1.895}$Sr$_{0.105}$CuO$_4$) and the overdoped (La$_{1.8}$Sr$_{0.2}$CuO$_4$) samples at several temperatures. The EXAFS oscillations (weighted by $k^2$) at representative temperatures are shown as inset. The Fourier transforms (FTs) were performed between $k_{\text{min}} = 3$ Å$^{-1}$ and $k_{\text{max}} = 17$ Å$^{-1}$ using a Gaussian window. The FTs are not corrected by the phase shifts due to photoelectron back-scattering and represent the raw experimental data. The first peak in the Fourier transform corresponds to the in-plane Cu-O bonds, while the doublet structure at $\sim 3$–4 Å is due to the Cu-La(Sr) and...