

# Staging and oxygen ordering in superoxygenated $\text{La}_2\text{CuO}_{4+\delta}$

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As part of an ongoing investigation [1, 2, 3] we have studied an oxygen-doped  $\text{La}_2\text{CuO}_{4+\delta}$  single crystal (named sLSCO\_0\_B) in a four-circle setup on the hard x-ray triple axis diffractometer BW5 at Deutsches Elektronen Synchrotron (DESY). Non-oxygen doped  $\text{La}_2\text{CuO}_4$  undergoes a structural phase transition from a high-temperature tetragonal (HTT) to a low-temperature orthorhombic (LTO) phase due to a tilt of the  $\text{CuO}_6$  octahedra at lower temperatures. In oxygen-doped  $\text{La}_2\text{CuO}_{4+\delta}$  staging peaks around the LTO  $Bmab$  positions  $\mathbf{Q} = (0, \text{odd}, \text{even})$  are believed to reveal a super-periodicity of the tilted  $\text{CuO}_6$  octahedra due to the excess oxygen. The staging peaks have previously been examined by neutrons on the TriCS single crystal diffractometer at the Paul Scherrer Institute (PSI) in Switzerland and are positioned at  $\mathbf{Q} \pm (0, 0, q)$ , where  $q = 2\pi/\lambda_s$  with  $\lambda_s$  being the wavelength of the periodicity.

Figure 1 shows a  $(0, 3, L)$ -scan and a  $(0, K, L)$  grid map around  $(0, 3, 2)$ . [Throughout this report reciprocal vectors are given in the LTO  $Bmab$  notation.] From the scans we conclude that both  $Bmab$ , staging 2 ( $q = 0.5$ ) and staging 4 ( $q = 0.25$ ) peaks are present. The relative intensity of the peaks at BW5 are approximately the same as those measured by neutrons on TriCS, showing that the main contribution must be structural.

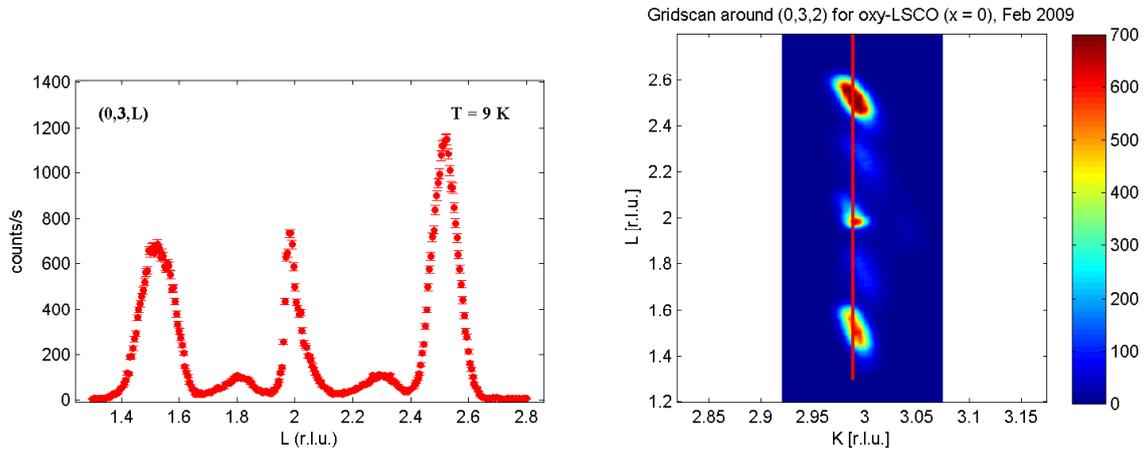


Figure 1:  $(0, K, L)$  grid map (right) and  $(0, 3, L)$  scan (left) around the  $Bmab$  position  $(0, 3, 2)$  at  $T=9 \text{ K}$  (the red line in the grid map depicts the position of the presented  $(0, 3, L)$  scan). Both staging 2 and staging 4 peaks are seen in the measurements.

The neutron investigations at TriCS revealed features at  $(0.05, 0.27, 5.5)$  and  $(0.27, 0.05, 5.5)$  which were speculated to be directly related to the excess oxygen ordering [3, 4]. Hence, the features were named *direct oxygen peaks*. At BW5, a series of long  $L$  scans at  $\mathbf{Q} = (0.05, 0.27, L)$  show a systematic appearance of intensity at every half-integer  $L$ -value (figure 2). These *direct oxygen peaks* persisted to the highest measured temperature of 350K albeit at lower intensity in contrast to [4] where no peak intensity was left at 330K.

A similar half-integer  $L$  dependence was observed at  $(2 + \delta_q, 2 + \delta_q, L)$  and  $(4 + \delta_q, 4 + \delta_q, L)$  for  $\delta_q \simeq 0.17$  as shown in figure 3. Since the superoxygenated  $\text{La}_2\text{CuO}_{4+\delta}$  system contains incommensurate (IC) anti-ferromagnetism (AF) below 40K with characteristic peaks at  $\delta_H \sim \delta_K \sim 1/8$  around the AF positions, the observed peaks are possibly the charge ordering peaks which are expected in the so-called stripe model which has proven to be applicable to other high- $T_c$  cuprates such as  $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$  and  $\text{La}_{1.875}\text{Ba}_{0.125}\text{CuO}_4$ . In these striped materials, however, superconductivity is strongly suppressed whereas in superoxygenated  $\text{La}_2\text{CuO}_{4+\delta}$  it is even above optimal for the oxygen-stoichiometric La-(Sr,Ba)-Cu-O system.

It is therefore of high interest to investigate the possible charge ordering peaks in our system further and elucidate the relation to the incommensurate magnetism. Furthermore both the suspected *charge ordering peaks* and the *direct oxygen peaks* seem to persist at all measured temperatures 9-350K and a more detailed study of the temperature dependence and further search for related features is required.

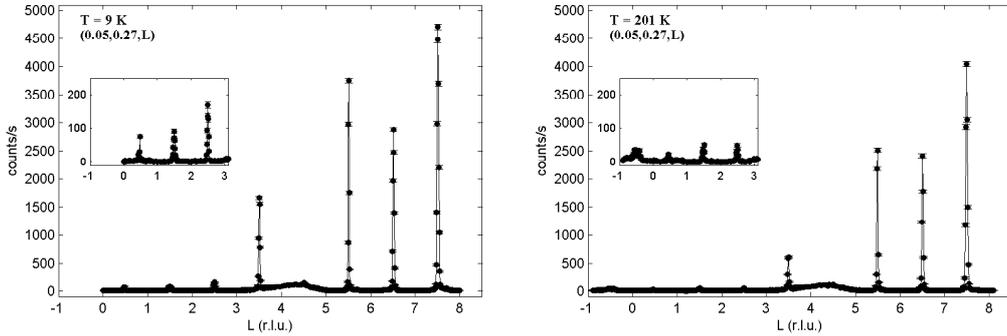


Figure 2: Long L scan at the direct oxygen position  $(0.05, 0.27, L)$  at  $T=9$  K and  $T=201$  K. Features appear at half-integer values. Insets show a close-up of the region from  $L=-1$  to 3.

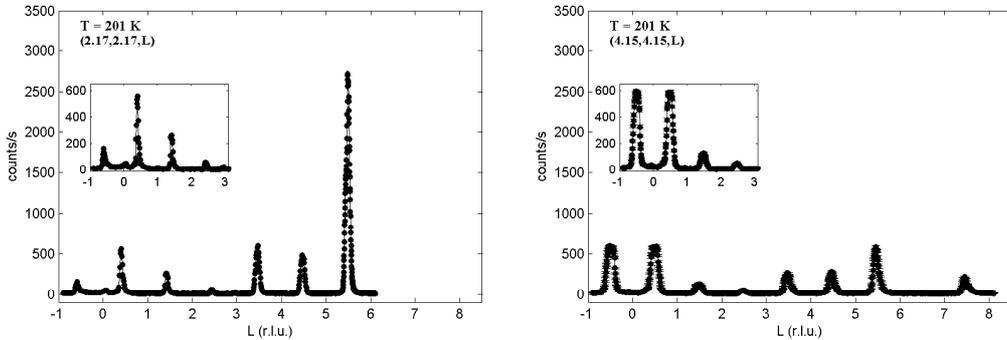


Figure 3: Long L scan at the suspected charge ordering positions  $(2.17, 2.17, L)$  and  $(4.17, 4.17, L)$  at  $T=210$ K. Features appear at half-integer values. Insets show a close-up of the region from  $L=-1$  to 3.

## References

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