PHONON ANOMALIES IN HIGH T_c SUPERCONDUCTORS RELATED TO CHARGE STRIPE ORDER

D. Reznik[1,2] , L. Pintschovius[1] , M. Sato[3] , M. Itoh[3] , S. Iikubo[3] , S. Yamada[4]

[1]Forschungszentrum Karlsruhe, IFP, POB 3640, D-76021 Karlsruhe, Germany
[2]Laboratoire Léon Brillouin, CE Saclay, F-91191 Gif-sur-Yvette Cedex, France
[3]Department of Physics, Division of Materials Science, Nagoya University, Nagoya 464-8602, Japan
[4]Institute for Materials Research, Tohoku University, Katahira, Sendai 980-8577, Japan

It is a wideheld belief that the holes doped into the CuO_2 planes of the cuprate superconductors tend to segregate into stripes that separate antiphase antiferromagnetic domains. However, solid evidence for such stripe order was obtained so far only for the particular compound $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ (LNSCO) and the closely related one $La_{1.875}Ba_{0.125}CuO_4$. In these two compounds, nuclear and magnetic superlattice peaks were observed indicative of static stripe order [1]. These compounds are special in that their doping level is about 1/8 and in that their low temperature structure provides a pinning potential for the charge stripes. We note that static stripe order seems to suppress superconductivity and therefore, stripe order is assumed to be dynamic in the superconducting cuprates.

Inelastic neutron scattering may be used to look for signatures of dynamic stripe both in the charge and in the spin channel. Here, we focus on the charge channel. Although neutrons cannot observe directly an inhomogeneous charge distribution, they may do so indirectly by looking at the atomic displacements induced by the inhomogeneous charge. More precisely, they can probe atomic vibrations and those vibrations having a displacement pattern closely related to charge stripe order should manifest themselves by an anomalous behaviour. Since an inhomogeneous charge distribution will modulate the Cu-O bond length, stripe-related phonon anomalies are expected to be strongest in Cu-O bond-stretching vibrations. Several neutron scattering investigations carried out at LLB on a number of doped and undoped high T_c compounds have indeed shown that doping induces pronounced anomalies in just those phonon branches associated with plane-polarized Cu-O bond-stretching vibrations whereas nearly all other modes show little change upon doping [2]. More precisely, doping induces a pronounced frequency renormalization of zone boundary modes in the (100) direction (Fig. 1) and, to a smaller extent, also in the (110) direction.

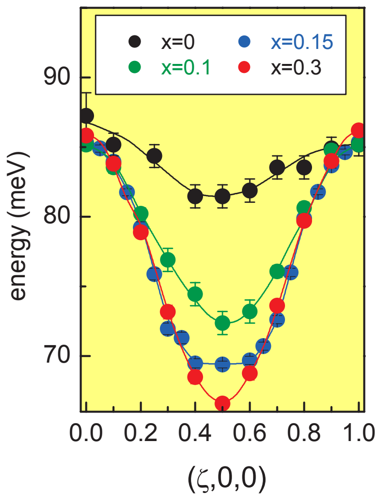

Figure 1. Dispersion of longitudinal Cu-O bond-stretching vibrations along the (100)-direction determined by inelastic neutron scattering at T = 10 K on $La_{2-x}Sr_xCuO_4$ for insulating (x = 0), underdoped (x = 0.1), optimally doped (x = 0.15) and overdoped (x = 0.3) samples.

The doping induced frequency renormalization can certainly seen as evidence of a strong electron-phonon coupling of these modes but on the other hand, it is by no means obvious that this coupling is related to charge-density formation. Experiments carried out recently on the above mentioned stripe-ordered compound LNSCO have allowed us for the first time to establish a clear relationship between a certain phonon anomaly and charge stripe formation : the evidence comes not so much from the phonon dispersion which is intermediate between the curves for x = 0.1 and x = 0.15 shown in Fig. 1 but from the phonon linewidth : the linewidth, which is the most direct measure of the electron-phonon coupling strength, shows a very pronounced peak just at the ordering wave vector q_{CD} = (0.24,0,0) of the charge-density wave [3](Fig. 2). Moreover, the linewidth shrinks considerably on raising the temperature indicating that it is linked to an electronic instability. Last not

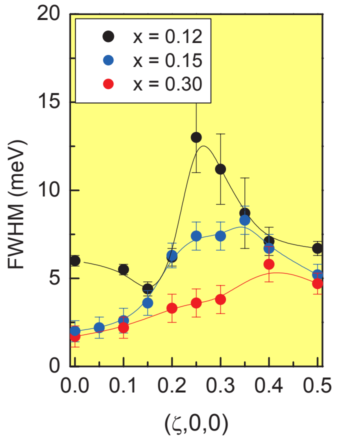

Figure 2. Resolution-corrected linewidths of Cu-O bond-stretching phonons along the (100)-direction observed on an optimally doped (x = 0.15) as well on an overdoped (x = 0.30) sample of LSCO at T = 10 K. The data for x = 0.12 were taken on LNSCO showing static stripe order with a wave vector q = (0.24,0,0).

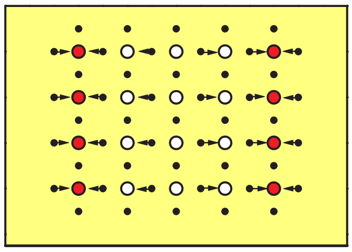

Figure 3. Displacement pattern of the anomalous bond-stretching phonon with wave vector q = (0.25,0,0). Only the displacements in the CuO_2 plane are shown which are the dominant ones. The atoms highlighted in red are those where dynamic charge accumulation is favored by the displacements of the oxygen atoms

least, the displacement pattern of the anomalous mode is such that it favors dynamic charge accumulation on every fourth row of atoms as is observed in the static stripe pattern (Fig. 3). We note that a careful investigation of the next lower phonon branch with bond-bending character did not reveal any anomaly, in line with the fact that the displacement pattern of these phonons is unrelated to charge-density wave formation.We emphasize that the anomaly under discussion occurs in a high frequency branch at about 60 meV whereas practical all phonon anomalies observed previously in other compounds were found in low frequency branches. A notable exception is the extremely large linewidth observed recently for a high frequency mode (about 60 meV) in the 40 K classical superconductor MgB_2. The strength of the phonon anomaly in LNSCO is somewhat surprising in view of the fact that the charge order related superlattice peaks are extremely weak and hence, only a small fraction of an elementary charge seems to be pinned to the static stripes. We presume that much larger charges are involved in strong fluctuations which persist below the charge ordering temperature.

The results obtained on LNSCO allow us to look for precursor effects of charge stripe formation in compounds which do not develop any static order. Inspection of Figs. 2 shows that the behavior in $La_{1.85}Sr_{0.15}CuO_4$ is indeed reminiscent of that observed in LNSCO indicating that optimally doped LSCO is still close to a charge stripe instability. On the other hand, no such precursor effects are observed in overdoped LSCO [4] in line with the general belief that overdoped cuprates behave essentially like ordinary metals.

The question remains whether or not the tendency towards stripe order is restricted to LSCO. Extensive investigations of the magnetic excitations in the prototypical high T_c compound $YBa_2Cu_3O_{7-x}$ have not led to a generally accepted conclusion. We note that we recently embarked on a detailed study of the phonons in optimally doped $YBa_2Cu_3O_{6.95}$ [5] and that we did find pronounced precursor effects of charge stripe order [6]. In this case, the evidence came primarily from the anomalous temperature dependence of certain phonon modes whereas the line broadenings are difficult to measure because of strong hybridization of bond-stretching phonons with other phonon modes. Nevertheless, it is safe to say that the effects observed in optimally doped YBCO resemble those found in the static stripe compound LNSCO. This indicates that the tendency towards stripe order is not a peculiarity of the LSCO system.

References

[1] J. M. Tranquada et al., Nature 375,561 (1995).

[2] For a review, see L. Pintschovius and W. Reichardt, in “Neutron Scattering in Layered Copper-Oxide Superconductors”, A. Furrer Ed.,Phys. and Chem. of Materials with LowDimensional Structures, Vol. 20, Kluwer Academic, Dordrecht 1998, p.165

[3] L. Pintschovius, D. Reznik, M. Itoh, S. Iikubo and M. Sato, manuscript in preparation.

[4] L. Pintschovius, D. Reznik, K. Yamada, manuscript in preparation.

[5] L. Pintschovius, D. Reznik, et al., Phys. Rev. B 69, 214506 (2004).

[6] L. Pintschovius, D. Reznik, et al., cond-mat/0308357