Experimental report

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Proposal: **7-01-458**

Council: 4/2017

Title: LSCO+O Cu-O bond-stretching phonons

Research area: Physics

This proposal is a new proposal

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Samples: La1.94Cu0.06O4+y
LaCuO4+y

Instrument	Requested days	Allocated days	From	To
IN8	7	3	05/06/2018	11/06/2018

Abstract:

The mechanism responsible for superconductivity in LSCO and LSCO+O is still unknown. Recently an anomaly in the Cu-O bond-stretching phonon has been observed in optimally doped LSCO. Comparison with ARPES data indicate that this anomaly is connected to a novel charge collective mode which, in turn, may be relevant to the superconductivity mechanism. We propose to study this Cu-O bond-stretching phonon in a LSCO+O single crystal sample which is strongly underdoped with respect to Sr, but has optimal Tc due to the interstitial oxygen.

Giant Phonon Anomaly in LSCO+O

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Inelastic neutron scattering is used to study the Cu-O vibrational mode in oxygen-doped $La_{1.94}Sr_{0.06}CuO_{4+\delta}$ ($T_c = 40\,\mathrm{K}$). Similar to results from optimally doped $La_{1.85}Sr_{0.15}CuO_4$ ($T_c = 35\,\mathrm{K}$), we observe anomalous features in the dispersion in the form of a softening halfway through the Brillouin Zone. This 'giant phonon anomaly' cannot be explained in terms of conventional band theory and is indicative of a coupling to inhomogeneous charge order possibly related to superconductivity. Considering the differences in electronic structure and local environment between Oxygen- and Strontium-doped compounds, we rule out a connection between the phonon anomaly and the specific nature of Sr-dopants in $La_{1.85}Sr_{0.15}CuO_4$. This, in turn, strengthens the argument for a direct correlation between the giant phonon anomaly, dynamic charge order and superconductivity in the cuprates.

I. EXPERIMENTAL

The sample is 2 grams of single crystal $La_{1.94}Sr_{0.06}CuO_{4+\delta}$ grown by the Traveling Solvent Float Zone (TSFZ) method. Oxygen intercalation was performed by wet-chemical methods[1]. The sample is superconducting with $T_c = 40\,\mathrm{K}$, confirmed by magnetization measurements (See supplementary information). All Miller indices are described with reference to the orthorhombic Bmab space group and the sample is aligned in the *a*-*b* plane. Lattice parameters were determined to be $a = b = 5.35\,\text{Å}$, $c = 13.1, \text{Å}$. All measurements presented in this letter were at $T = 5\,\mathrm{K}$.

Neutron scattering experiments were performed on the IN8 Triple-Axis Spectrometer (TAS) at Institut Laue-Langevin, Grenoble. The instrument was configured with a Silicon (311) monochromator in order to achieve the desired q-range and a pyrolitic graphite (002) analyser to get the desired intensity. The detector was an Imaging MultiPlexed Spectrometer (IMPS) allowing for position-sensitive information. The analyser was fixed to a final wavelength $k_\mathrm{f} = 2.226\,\text{Å}^{-1}$ during inelastic scans.

For the bond-stretching phonon, it is desirable to measure in the highest achievable odd-index Brillouin Zone (BZ). We thus measured the phonon in the (5,5,0) BZ by performing constant-$\boldsymbol{q}$ scans with energies between 65 and 90 meV. Due to a strong spurious signal originating from the scattering plane, our sample was tilted by 12 degrees around the (1,1,0) axis.

Representative scans of the experimental data is shown in Figure 1. Due to a strong spurious signal identified as accidental Bragg scattering (A-type)[2] from the (8,4,0) fundamental Bragg peak, the phonon signal is obscured by spurious scattering localized in the region between $\boldsymbol{q} = (4.65, 4.65, 0)$ and $\boldsymbol{q} = (4.75, 4.75, 0)$. By inspection of the pixel-sensitive signal from the IMPS detector, we realized that the spurious signal is spatially separated from the phonon signal, allowing us to subtract the spurious signal using neighbouring channels (see Figure 2).

Figure 1A shows the raw data before background subtraction and Figure 1B shows the reduced data for selected wave vectors. Energy scans were fit to a Damped Harmonic Oscillator (DHO) model[3] with a constant background:

$$S(\boldsymbol{q}, \omega) = I_\mathrm{ph} \frac{1}{\pi \omega_{\boldsymbol{q}}} \frac{\gamma}{(\omega - \omega_{\boldsymbol{q}})^2 + \gamma^2} + I_\mathrm{BG}\,,$$

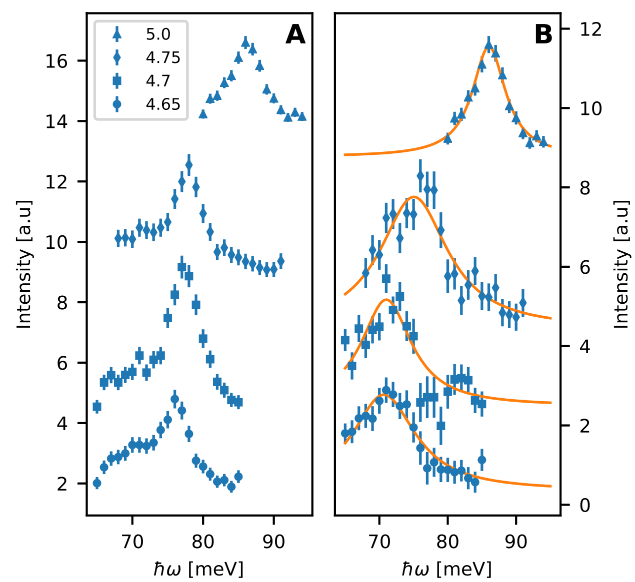

FIG. 1. **(A):** Raw data at selected wavevectors as obtained without background subtraction from neighbouring channels. The peaks at roughly $\approx 78\,\mathrm{meV}$ is a consequence of spurious scattering as described in the text. The data at $\boldsymbol{q} = (4.65, 4.65, 0), (4.7, 4.7, 0), (4.75, 4.75, 0)$ has been scaled by a factor of $\frac{1}{2}$ for clarity as the spurious signal is strong compared to the phonon. **(B)**: Data reduced as described in the text for $\boldsymbol{q} = (4.65, 4.65, 0), (4.7, 4.7, 0), (4.75, 4.75, 0)$ and raw data for $\boldsymbol{q} = (5, 5, 0)$. No data was scaled, showing that the intensity of the reduced data originates from the phonon. Solid lines are fits to a DHO model.

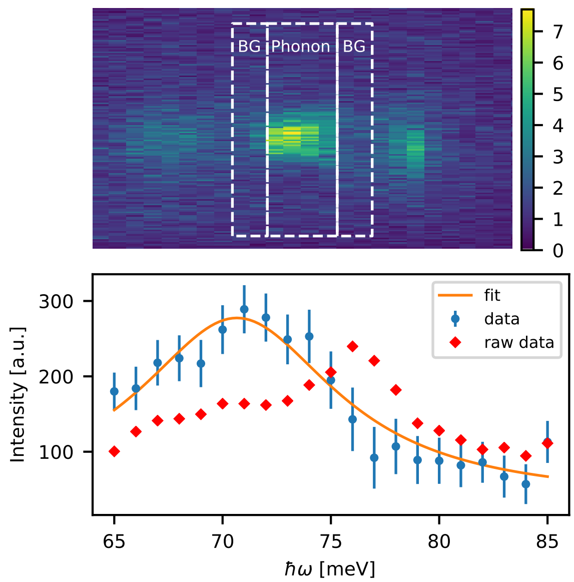

FIG. 2. Illustration of the data reduction performed using the IMPs detector. **Top**: Summed raw data from an energy scan at $q = (4.65, 4.65, 0)$. The dashed lines denote the regions of interest used in the data reduction. The geometry of the instrument ensures that the desired phonon scattering will occur in the 'Phonon' ROI. **Bottom**: Corresponding raw (diamonds) and reduced (circles) data. The raw data is obtained by only considering the 'Phonon' ROI, while the reduced data is obtained by subtracting the intensity from the two 'BG' ROIs. The solid line is a fit to a DHO lineshape.

where I_{ph} is the phonon intensity, $\omega_{\boldsymbol{q}}$ the phonon energy at wave vector $\boldsymbol{q}$, γ the phonon linewidth and I_{BG} the background intensity.

II. RESULTS

The measured dispersion is shown in Figure 3 along with a normal dispersion found by fitting the measured zone center ($h = 0$) and edge ($h = 0.5$) to a cosine function of the form $\alpha \cos(2\pi h) + \beta$. Figure 3B shows the anomaly amplitude for $La_{1.94}Sr_{0.06}CuO_{4+\delta}$ ($T_c = 40\,\mathrm{K}$), $La_{1.85}Sr_{0.15}CuO_4$ ($T_c = 35\,\mathrm{K}$)[4] and $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ (insulating, static stripe ordered)[4].

III. CONCLUSION

In conclusion, we have measured the giant phonon anomaly in $La_{1.94}Sr_{0.06}CuO_{4+\delta}$ and confirmed the existence of a giant phonon anomaly roughly halfway through the zone at $\boldsymbol{q} = (0.3, 0.3, 0)$ consistent with results from optimally doped $La_{1.85}Sr_{0.15}CuO_4$. Due to this result being from a microscopically distinct sample, we confirm the electronic nature of the phonon anomaly. A direct connection to superconductivity is still hypothetical, but we believe these results strengthens the hypothesis.

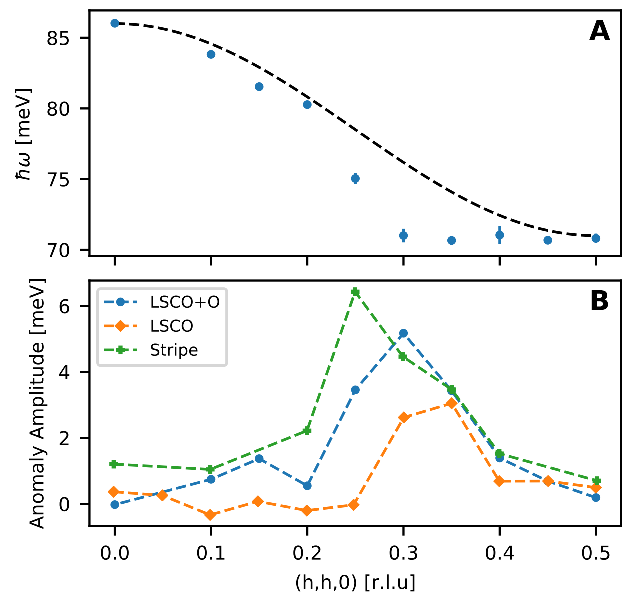

FIG. 3. **(A)**: Dispersion of the LO phonon obtained from the peak positions of individual spectra. Dashed line is the 'normal' dispersion as described in the text. All data was obtained at $T = 5\,\mathrm{K}$. **(B)**: Difference between normal and measured dispersion in $La_{1.94}Sr_{0.06}CuO_{4+\delta}$ (LSCO+O), $La_{1.85}Sr_{0.15}CuO_4$ (LSCO) and $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ (Stripe)

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