Supplemental Material: Nature of the charge density wave excitations in cuprates

J. Q. lin,[1,2,3,4,*] H. Miao,[1,†] D. G. Mazzone,[1] G. D. Gu,[1] A. Nag,[5] A. C. Walters,[5] M. García-Fernández,[5] A. Barbour,[6] J. Pelliciari,[6] I. Jarrige,[6] M. Oda,[7] K. Kurosawa,[7] N. Momono,[8] K. Zhou,[5] V. Bisogni,[6] X. Liu,[2,‡] and M. P. M. Dean[1,§]

[1] *Condensed Matter Physics and Materials Science Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[2] *School of Physical Science and Technology, ShanghaiTech University, Shanghai 201210, China*
[3] *Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*
[4] *University of Chinese Academy of Sciences, Beijing 100049, China*
[5] *Diamond Light Source, Harwell Science and Innovation Campus, Didcot, Oxfordshire OX11 0DE, United Kingdom*
[6] *National Synchrotron Light Source II, Brookhaven National Laboratory, Upton, NY 11973, USA*
[7] *Department of Physics, Hokkaido University, Sapporo 060-0810, Japan*
[8] *Department of Sciences and Informatics, Muroran Institute of Technology, Muroran 050-8585, Japan*

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This document provides additional details of the sample synthesis, sample characterization, temperature-dependent phonon intensity data, and fitting of the RIXS spectra.

SAMPLE SYNTHESIS

$La_{2-x}Sr_xCuO_4$ samples were grown by the traveling-solvent floating-zone method. For each composition, a single feed rod with a length of 20–25 cm was used. After the growth, the first few centimeters of the crystal rod were removed and discarded, while the remainder was annealed in flowing O_2 at 980°C for 1 week. Sample surfaces were prepared by cleaving the samples mechanically to expose a c-axis face. The samples were crystallographically aligned prior to the measurements RIXS using Laue diffraction. During the RIXS measurements themselves, the θ and χ angles were further refined by optimizing the CDW intensity as a function of both angles.

SAMPLE CHARACTERIZATION

The superconducting transition temperatures were determined by magnetization measurements in a 1 mT applied magnetic field (after cooling in zero field) yielding the expected values of T_{SC} = 28, 37, 30, and 10 K, for LSCO12, LSCO17, LSCO21 and LSCO25, respectively. X-Ray diffraction measurements confirmed excellent sample crystallinity with crystal mosaics of the order of 0.02°. The doping level was characterized by angle-resolved photoemssion spectroscopy (ARPES) [1]. The effective doping was determined to be consistent with the Sr concentration via a tight binding fitting of the Fermi surface. The topological change in Fermi surface topology was also observed between LSCO17 and LSCO21. Very similar results have been observed in previous ARPES studies of LSCO [2, 3].

PHONON INTENSITY DEPENDENCE

In Fig. S1 we show that the phonon intensity dispersion is essentially identical at T_c and 100 K.

FITTING OF THE RIXS SPECTRA

In order to illustrate the method and quality of data fitting, we present the fitting result for LSCO17 at low temperature in Fig. S2. The spectra were fitted with a Pseudo-Voigt function for the elastic peak, an anti-symmetric Lorentzian function for the bond-stretching (BS) mode and a linear background, all convoluted with energy resolution. This lineshape is described by 10 parameters, but only 6 parameters are free to vary in the fit. For the Pseudo-Voigt lineshape describing the elastic peak the center, Gaussian vs. Lorentzian fraction and width are fixed by measurements of a graphite elastic reference sample, only the amplitude is free to vary. For the anti-symmetric lorentzian lineshape (Damped Harmonic Oscillator Model) phonon mode, the temperature is fixed, and the center, width and amplitude

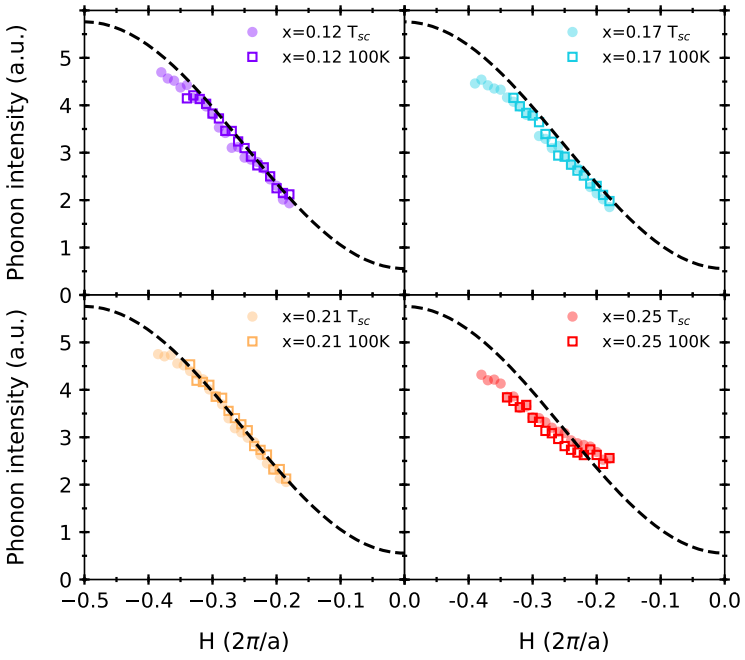

FIG. S1. Phonon intensity as a function of H similar to Fig. 3(c) of the main text, but with the 100 K data overlaid on the low-temperature data and separated onto different panels. This shows that the phonon intensity is the same at T_c and 100 K for all the different dopings.

are free. For the linear background, we use a function $f(x) = b$ for $x < 0$ and $f(x) = a * x + b$ for $x > 0$, a and b are free parameters. Prior to computing the final fit, we performed an initial fit in which the elastic energy was allowed to vary, which we used to shift the spectra in energy such that the exact elastic energy is exactly zero. Typical values for the reduced chi-squared statistic are 1.6.

* jiaqilin@bnl.gov
† Present address: Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
‡ liuxr@shanghaitech.edu.cn
§ mdean@bnl.gov

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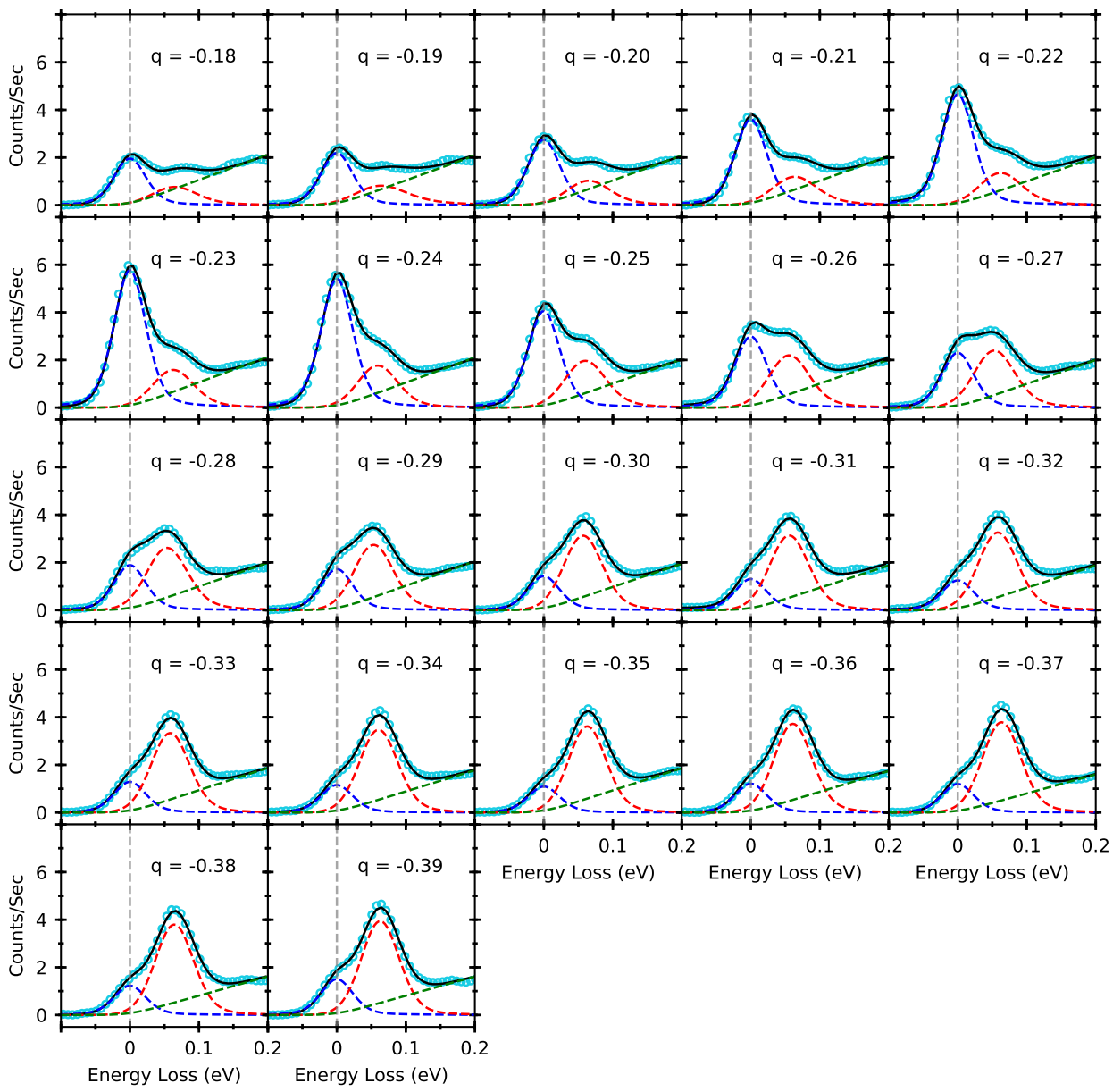

FIG. S2. Fitting results for LSCO17 at $T = T_{SC}$. The data is represented by cyan dots and the fit is shown as a black line. Blue, red and green dashed lines represent the elastic line, phonon mode and background components, respectively. Different panels show spectra at the reciprocal space location denoted in the top right of the plot $(q, 0, L)$, as described in the main text.