EUROPEAN SYNCHROTRON RADIATION FACILITY

INSTALLATION EUROPEENNE DE RAYONNEMENT SYNCHROTRON

ESRF

Experiment Report Form

The double page inside this form is to be filled in by all users or groups of users who have had access to beam time for measurements at the ESRF.

Once completed, the report should be submitted electronically to the User Office via the User Portal:

https://wwws.esrf.fr/misapps/SMISWebClient/protected/welcome.do

Reports supporting requests for additional beam time

Reports can be submitted independently of new proposals – it is necessary simply to indicate the number of the report(s) supporting a new proposal on the proposal form.

The Review Committees reserve the right to reject new proposals from groups who have not reported on the use of beam time allocated previously.

Reports on experiments relating to long term projects

Proposers awarded beam time for a long term project are required to submit an interim report at the end of each year, irrespective of the number of shifts of beam time they have used.

Published papers

All users must give proper credit to ESRF staff members and proper mention to ESRF facilities which were essential for the results described in any ensuing publication. Further, they are obliged to send to the Joint ESRF/ ILL library the complete reference and the abstract of all papers appearing in print, and resulting from the use of the ESRF.

Should you wish to make more general comments on the experiment, please note them on the User Evaluation Form, and send both the Report and the Evaluation Form to the User Office.

Deadlines for submission of Experimental Reports

- 1st March for experiments carried out up until June of the previous year;
- 1st September for experiments carried out up until January of the same year.

Instructions for preparing your Report

- fill in a separate form for each project or series of measurements.
- type your report, in English.
- include the reference number of the proposal to which the report refers.
- make sure that the text, tables and figures fit into the space available.
- if your work is published or is in press, you may prefer to paste in the abstract, and add full reference details. If the abstract is in a language other than English, please include an English translation.

	Experiment title: Measuring the momentum-dependent electron-phonon coupling strength in Bi-based superconducting cuprate via ultrahigh resolution RIXS	**Experiment number**: HC-1838
Beamline: ID 32	**Date of experiment**: from: 24 Feb. 2016 to: 01 Mar 2016	**Date of report**:
Shifts: 18	**Local contact(s)**: Nicholas Brookes	*Received at ESRF:*

Names and affiliations of applicants (* indicates experimentalists):

* Dr. Wei-Sheng Lee, SLAC National Accelerator Lab., Menlo Park, USA

* Dr. Makoto Hashimoto, SLAC National Accelerator Lab., Menlo Park, USA

Prof. Thomas Devereaux, SLAC National Accelerator Lab., Menlo Park, USA

Prof. Z. X. Shen, Stanford University

* Prof. Giacomo Ghiringhelli, Physics Department, Politecnico di Milano

* Prof. Lucio Braicovich, Physics Department, Politecnico di Milano

* Dr Yingying Peng, Politecnico di Milano

* Dr. Laura Chaix, SLAC Nation Accelerator Lab., Menlo Park, USA

Report:

During this beamtime, we performed high-resolution resonant inelastic x-ray scattering (RIXS) measurements at the Cu L_3-edge on double-layered cuprates, $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212). A heavily underdoped sample with a T_c of 45 K was measured to investigate phonon excitations and their interplay with the underlying charge density wave (CDW) state.

The spectrometer was set at 149.5° geometry to maximize the momentum-transfer for the momentum-dependence measurements. We have also set the energy resolution to ~ 40 meV, in order to clearly resolve the phonon excitations, with reasonable data acquisition efficiency (~ 2 hours per spectrum including the overhead). The polarization was set to vertical (*i.e.* σ-polarization) to maximize the scattering cross section from charges and phonons. We have obtained high quality and high resolution data along the (0,0)-(1,0) direction that allows to reveal new aspects of the RIXS phonon cross-section.

Figure 1 shows the overview of our main results demonstrating the high quality of our data. In close examination of the intensity in the quasi-elastic region as a function of momentum (Fig. 1c), we observe the signature of a CDW diffraction peak centred at Q_{CDW} ~ 0.3 *r.l.u.* This confirms the existence of the CDW state in the underdoped Bi2212, previously reported by resonant diffraction and STM [1]. Importantly, a branch of phonon excitations with an energy scale of ~ 0.06 eV can be clearly resolved. According to the literature, it corresponds to the bond-stretching (BS) phonons [2]. While the properties of the BS phonon

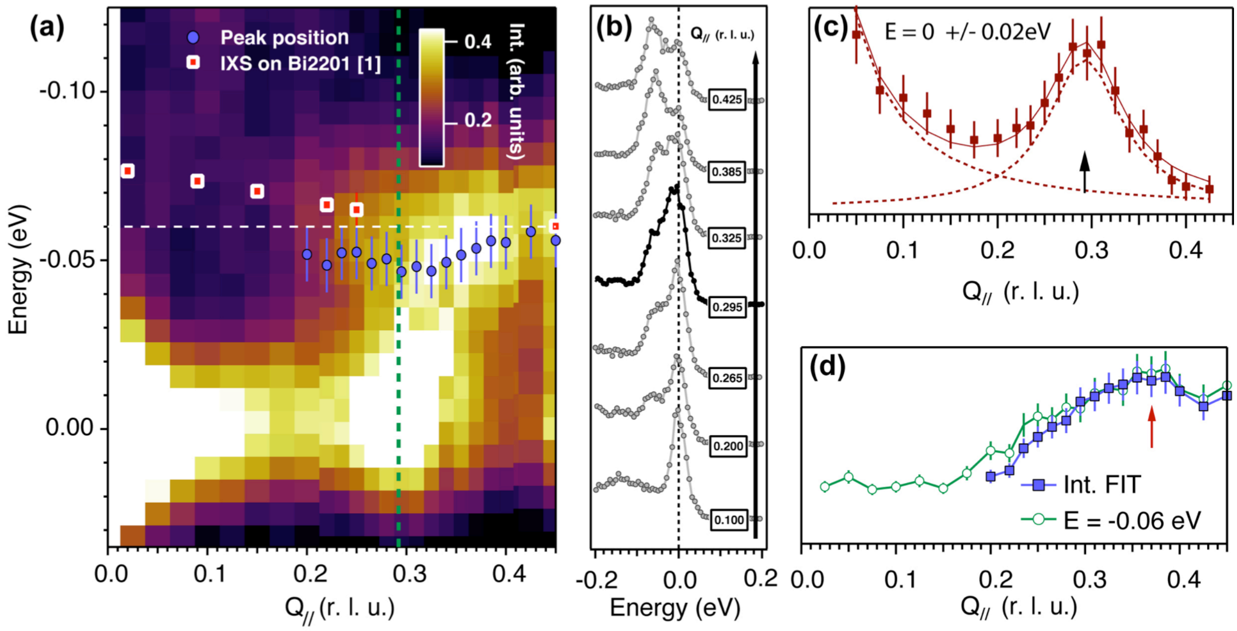

Figure 1: (a) RIXS intensity map of the underdoped Bi2212 as function of projected in-plane momentum-transfers ($Q_{//}$) and energy loss (y-axis). The fitted phonon peak position is shown by blue markers. As a comparison, the dispersion of the bond-stretching phonon of Bi2201 obtained via non-resonant IXS is also superimposed [1]. The green dashed line indicated the position of Q_{CDW}. (b) Waterfall plot of energy loss spectra at selected momentum positions. (c) Intergrated intensity in the quasi-elastic region (within the energy window of E = 0 ± 0.02 eV) as a function of $Q_{//}$. (d) Momentum distribution of the phonon intensity obtained by a cut at E = - 0.06 eV (white dashed line in (a)) and the fitted phonon intensity.

in cuprates have been intensively investigated in previous works, we observed several important new aspects arising from the RIXS process: (1) The phonon energy exibits a weak softening near the CDW wavevector. (2) The momentum distribution of the phonon intensity is negligible near the zone center, but increases when approaching the zone boundary. (3) The phonon intensity reaches a maximum before the zone boundary. These observations are distinct from the phonon cross section observed via inelastic neutron scattering and non-resonant inelastic x-ray scattering, highlighting the fact that the RIXS phonon cross-section reflects the electron-phonon coupling strength, not merely the phonon self-energy [3].

Currently, we have finished the data analysis and are working on a manuscript for publication [4]. This manuscript will also include theoretical calculations to elucidate the influence of the CDW on the RIXS phonon cross section. The theory suggests that the non-monotonic momentum distribution of the RIXS phonon intensity is due to the intersection of the bond-stretching phonons with the CDW excitations. Thus, this phonon anomaly can serve as a way to reveal characteristics of the underlying CDW excitations. This information is difficult to probe by other techniques and can provide new insight into the nature of the CDW in cuprates. It is of great interest to investigate the doping evolution of this phonon anomaly throughout the phase diagram, as will be proposed in the next cycle.

Reference:

[1] R. Comin and A. Damascelli, Resonant x-ray scattering studies of charge order in cuprates, *Ann. Rev. of Cond. Matt. Phys.* **7**, 369 (2016).

[2] J. Graf *et al.*, Bond Stretching Phonon Softening and Kinks in the Angle-Resolved Photoemission Spectra of Optimally Doped $Bi_2Sr_{1.6}La_{0.4}CuO_{6+\delta}$ Superconductors, *Phys. Rev. Lett.* **100**, 227002 (2008)

[3] T. P. Devereaux *et al.,* Directly characterizing the relative strength and momentum dependence of electron-phonon coupling using resonant inelastic x-ray scattering, arXiv: 1605.03129 (2016), accepted in Phys. Rev. X.

[4] L. Chaix, Y. Peng, M. Hashimoto, Y. He, S. Chen, K. Kummer, N. Brookes, L. Braicovich, G. Ghiringhelli, B. Moritz, S. Ishida, Y. Yoshida, H. Eisaki, Z.-X. Shen, T. P. Devereaux, W.-S. Lee, Anomalous RIXS phonon cross-section induced by CDW excitations in underdoped cuprate. In preparation.