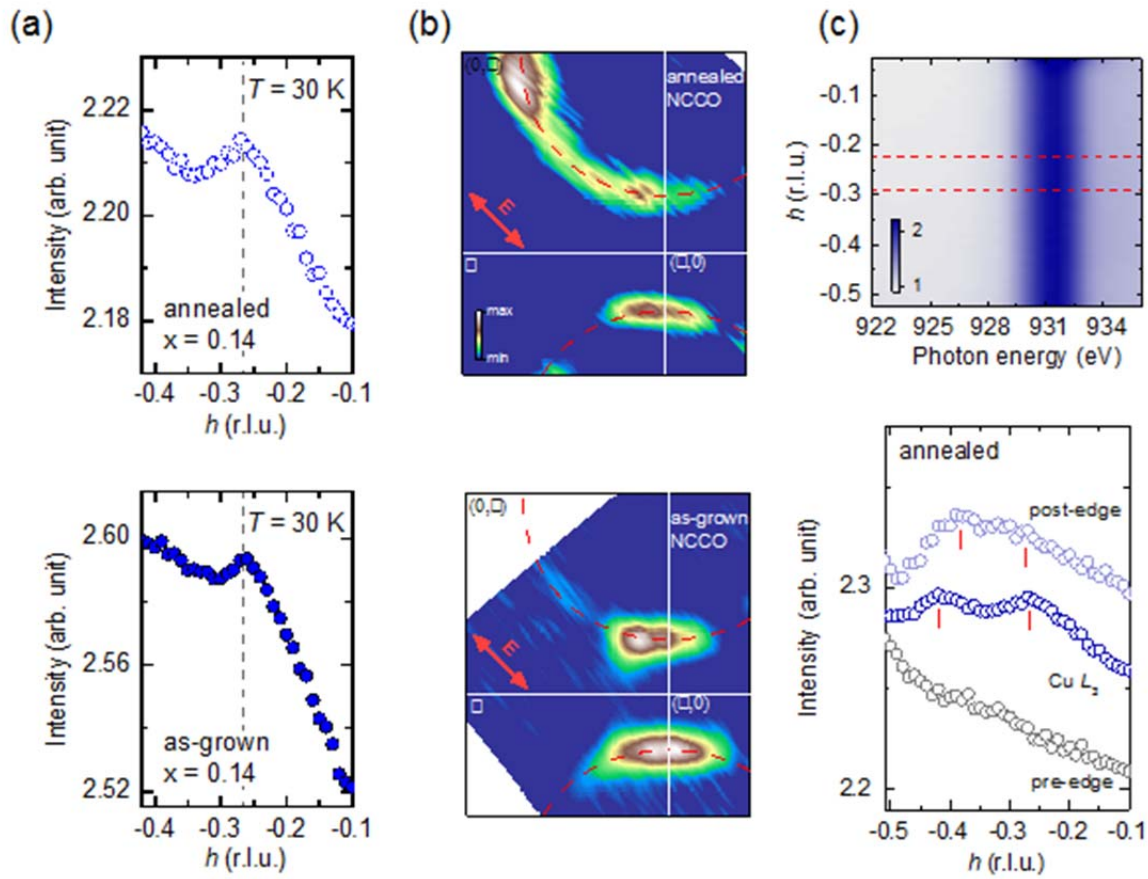
Questioning the Universality of the Charge Density Wave Nature in Electron-doped Cuprates

Since the discovery of unconventional high-temperature superconductivity (HTSC) in cuprates, one of the central questions in high T_c research is the nature of the “normal state” which develops into HTSC. As one of the pursuits of normal state properties, the recent observation of charge density wave (CDW) order is expected to shed light on the nature of the competing phases in high T_c cuprates. For this reason, CDW order in hole-doped cuprates has been actively studied by various experimental techniques such as neutron and x-ray scattering, scanning tunneling microscopy (STM), nuclear magnetic resonance (NMR), quantum oscillation, and ultrasound experiments. Among those techniques, x-ray scattering uniquely characterizes the spatial arrangement and strength of the charge density wave. This is because the scattering signal directly measures the periodicity of the density wave and its correlation. Moreover, the resonant soft x-ray scattering (RSXS) technique at the Cu L_3-edge – where the photon energy is tuned to about 930 eV – has been extensively utilized to detect very weak CDW signals in hole-doped cuprates. As a consequence, the CDW feature is well characterized for hole-doped cuprates.

More recently, Cu L_3-edge RSXS has been used to study an electron-doped cuprate, $Nd_{2-x}Ce_xCuO_4$ [1,2]. These studies reveal CDW order, with the putative CDW peak occurring at an in-plane wavevector of q ~ 1/4. This CDW behavior resembles that of the hole-doped cuprates and suggested CDW phenomena could be a universal property of all high-T_c cuprates. Nevertheless, many of characteristic behaviors of the CDW in $Nd_{2-x}Ce_xCuO_4$ differ from those of hole-doped cuprates. Naturally, the strong implication of the presence of a CDW phenomenon in both hole- and electron-doped cuprates calls for a systematic investigation of this topic.

In this study, the researchers carefully examined the CDW phenomenon in the electron-doped cuprate $Nd_{2-x}Ce_xCuO_4$, using complementary experimental techniques, including the RSXS setup at SSRL Beam Line 13-3 and angle-resolved photoemission spectroscopy (ARPES) at Beam Line 5-2. The research team measured both superconducting and non-superconducting $Nd_{1.86}Ce_{0.14}CuO_4$ (NCCO) samples to scrutinize the effect of superconductivity on the CDW. It is worth noting that the superconductivity in NCCO is achieved through a post-annealing process of the as-grown crystal (*i.e.*, non-superconducting NCCO) – because the annealing process enables superconductivity through the suppression of anti-ferromagnetism.

In the RSXS experiments, the researchers found the quasi two-dimensional reflection at in-plane wavevector, q = 0.26 ~ 1/4 r.l.u. in the superconducting NCCO [see Fig. 1a (top)] as previously reported. Since the CDW order in hole-doped cuprates exhibits inside superconducting phase, this reflection was taken as the evidence for a CDW order in NCCO. Surprisingly, this investigation exhibits a similar reflection at the same q position in the non-superconducting NCCO [see Fig. 1a (bottom)]. In addition to the same peak position for the two samples, their temperature dependencies, such as the peak intensity and width (*i.e.*, correlation length), are remarkably similar. These similarities clearly indicate that the CDW order at q ~ 1/4 in electron-doped cuprate NCCO is uncorrelated with superconductivity and quite different from the CDW phenomena in hole-doped cuprates.



Additionally, ARPES experiments were performed on the same crystals that had been examined by RSXS (see Fig. 1b). Since the Fermi (Arc) instability has been proposed as the origin of the CDW, a direct comparison between ARPES and RSXS results from the same crystals are very important to verify such a proposal. If this proposal is right, the nesting vector in a Fermi-surface derived from ARPES is expected to match the scattering wave vector of the CDW measured by RSXS, as was suggested in previous scattering studies [1,2]. However, from the comparison of Fermi-surfaces of superconducting and non-superconducting NCCO, it was found that the magnitudes of the nesting vector were noticeably different while the scattering wave vectors of the reflections are identical. This result indicates that the Fermiology is uncorrelated with the CDW order. Instead, the difference in the nesting vectors could be explained by either a pseudogap or a antiferromagnetic correlation change by an annealing process. In this context, the combined RSXS and ARPES result strongly suggest that the putative CDW reflection is not of the same CDW order observed in hole-doped cuprates.

Finally, in order to understand the origin of this superconductivity-insensitive reflection in NCCO, a photon energy dependence study of RSXS (see Fig. 1c) was carried out. Like the temperature dependences, the photon energy dependences in both superconducting and non-superconducting NCCO crystals are nearly identical. Interestingly, an additional pronounced feature at q ~ 0.4 at the Cu L_3 resonant energy was observed. Moreover, the peak position changes to q ~ 0.39 while the main peak at q ~ 0.26 shifts to ~ 0.27. This peak shifting behavior is consistent with the inelastic contribution which is distinct from the previously observed static CDW phenomena in hole-doped cuprates. To reveal the exact nature of the scattering reflection in electron-doped NCCO, high-resolution resonant inelastic x-ray scattering studies should be carried out in future work.

In summary, the research team performed a comprehensive investigation of the putative CDW reflection in electron-doped cuprate NCCO using RSXS and ARPES techniques. Their findings from RSXS demonstrate that the reflection observed in NCCO at q ~ 1/4 is not analogous to the CDW observed in the hole-doped cuprates. The ARPES measurements show no connection between the Fermiology and the observed scattering reflection in this system. Finally, the results of this study do not support a strong link between CDW behavior and superconductivity in the whole cuprate family. Further studies utilizing multimodal experimental methods like that of H. Jang *et al.* will be important to understanding the role of CDW order in the cuprate family of superconductors.

References

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Primary Citation

H. Jang, S. Asano, M. Fujita, M. Hashimoto, D. H. Lu, C. A. Burns, C.-C. Kao and J.-S. Lee, "Superconductivity-Insensitive Order at *q* ~ 1/4 in Electron-doped Cuprates", *Phys. Rev. X* **7**, 041066 (2017) doi: 10.1103/PhysRevX.7.041066

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SSRL is primarily supported by the DOE Offices of Basic Energy Sciences and Biological and Environmental Research, with additional support from the National Institutes of Health, National Institute of General Medical Sciences.