Large response of charge stripes to uniaxial stress in La$_{1.475}$Nd$_{0.4}$Sr$_{0.125}$CuO$_4$

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The La-based ‘214’ cuprates host several symmetry breaking phases including superconductivity, charge and spin order in the form of stripes, and a structural orthorhombic-to-tetragonal phase transition. Therefore, these materials are an ideal system to study the effects of uniaxial stress onto the various correlations that pervade the cuprate phase diagram. We report resonant x-ray scattering experiments on La$_{1.475}$Nd$_{0.4}$Sr$_{0.125}$CuO$_4$ (LNSCO-125) that reveal a significant response of charge stripes to uniaxial tensile-stress of ∼0.1 GPa. These effects include a reduction of the onset temperature of stripes by ∼50 K, a 29 K reduction of the low-temperature orthorhombic-to-tetragonal transition, competition between charge order and superconductivity, and a preference for stripes to form along the direction of applied stress. Altogether, we observe a dramatic response of the electronic properties of LNSCO-125 to a modest amount of uniaxial stress.

Cuprate high-temperature superconductors may be the quintessential example of a strongly correlated quantum system, featuring a complex interplay between broken symmetry states, often referred to as intertwined orders [1, 2]. This rich interplay is evident in the charge order (CO) state: a periodic modulation of charge that is intertwined with superconductivity, magnetism, the crystal structure, and nematicity (four-fold $C_4$ to two-fold $C_2$ symmetry breaking [3]). These various links between ordered states and CO are perhaps most clearly observed in the ‘214’ family of La-based cuprates. (i) CO and magnetism emerge intertwined in the form of stripes. (ii) The stripes are $C_2$ symmetric, with their orientation alternating by 90° between adjacent CuO$_2$ planes [4]. (iii) The stripes are strongly pinned to the low temperature tetragonal (LTT) crystal structure, which stabilizes the alternating pattern [5, 6]. (iv) Finally, the stabilization of stripes occurs in concert with the suppression of three-dimensional (3D) superconductivity, which results from a frustration of the Josephson coupling between adjacent CuO$_2$ layers [7, 8]. Determining how all these ordered states are interconnected is a major challenge in the field of high-temperature superconductivity.

There are different methods to tune the intertwined orders in the cuprates. Typically, a magnetic field [9, 10], chemical doping [11], or pressure [12] are used to adjust the relative strengths of the ordered states. For instance, the application of 1.85 GPa of hydrostatic pressure to La$_1.875$Ba$_{0.125}$CuO$_4$ decouples the LTT and CO phases, suppressing the former while allowing the latter to survive with an onset temperature of 35 K [13]. However, controlling the rotational symmetry of the correlations in the CuO$_2$ planes requires a tuning parameter that couples directionally to the electronic degrees of freedom. This can be achieved with the uniaxial application of pressure, or stress, which has recently become the focus of several cuprate studies. For example, recent experiments on YBa$_2$Cu$_3$O$_{y+y'}$ indicate that attaining uniaxial strain around 1% can modify the inter-layer interaction of the CO and its coupling to acoustic phonons [14, 15]. In the ‘214’ family, uniaxial stress has repeatedly been shown to increase the onset temperature of superconductivity [16–19]. A small value of uniaxial stress, approximately 0.05 GPa, dramatically increases the onset of 3D superconductivity in La$_{1.885}$Ba$_{0.115}$CuO$_4$ (LBCO-115) from 6 K to 32 K [19]. Remarkably, the same application of uniaxial stress also reduces the onset of spin stripe order from 38 K to 30 K. These opposing effects between superconductivity and spin stripes highlight the importance of uniaxial stress experiments to the study of intertwined orders. Still, diffraction experiments that directly measure the effects of uniaxial stress on charge stripe order and the LTT structure in the
La-based cuprates have not been reported.

Here we report a Cu-L$_3$- and O-K edge resonant x-ray scattering (RXS) study of CO and the LTT structure in La$_1.475$Nd$_0.4$Sr$_{0.125}$CuO$_4$ (LNSCO-125) under the influence of modest uniaxial stress, approximately 0.1 GPa, applied along the $a$ axis of the LTT structure (i.e., along the Cu-O bond direction). We first performed a detailed zero-stress control experiment on LNSCO-125, where we observed CO correlations above the onset of stripes near 70 K and detectable up to at least 150 K. Upon introducing uniaxial tensile-stress, the onset of the LTT phase ($T_{\text{LTT}}$) is reduced by 29 K, from 63 K to 34 K. Additionally, the onset of stripe order decreases by approximately 50 K, from $\approx T_{\text{LTT}} + 12$ K in the absence of strain to $\approx T_{\text{LTT}} - 9$ K in the presence of strain. This overall shift is larger than the one observed for $T_{\text{LTT}}$, which likely reflects the competition between CO and superconductivity. An additional offset of approximately 6 K is observed between the onset of charge stripes along the $a$ and $b$ directions. Despite the effects of stress on the LTT and the charge stripe phases, we find no appreciable modification of the high-temperature CO correlations. Altogether, our experiments not only show that a small amount of uniaxial stress triggers responses from the various intertwined orders, they also establish uniaxial stress as a powerful tool to control the electronic properties of LNSCO-125.

The single crystals were synthesized by floating zone and previously characterized by means of resonant x-ray scattering and magnetometry [20]. LNSCO-125 hosts several classic features of La-based cuprates near 1/8 hole doping. In the low temperature orthorhombic (LTO) phase, the CuO$_6$ octahedra tilt about an axis parallel to the [110] direction, which is 45° from the Cu-O bond direction. At lower temperatures, in the LTT phase, the CuO$_6$ octahedra tilt about axes parallel the Cu-O bond directions [21, 22]. Importantly, in the LTT phase the tilt axis alternates between [100] and [010] through consecutive CuO$_2$ planes, Fig. 1(a). Thus, while the LTT is a globally tetragonal phase, it is actually two-fold $C_2$ symmetric within each CuO$_2$ plane, which provides a natural motif to stabilize the stripe order.

Previous RXS experiments on LNSCO-125 indicate the appearance of stripe order at approximately $T_{\text{LTT}}$ [24]. Our detailed RXS experiments show that the peak at $q_{\parallel} = q_{\text{CO}} = 0.23$ r.l.u (reciprocal lattice units) survives at high temperatures, above $T_{\text{LTT}}$, albeit with much lower intensity when compared to the low-temperature signal. Figure 1(b) shows the temperature evolution of the CO peak at $q_{\text{CO}}$ in LNSCO-125, showing a clear and rapid enhancement below $T_{\text{LTT}} = 63$ K. However, the data also show that correlations at $q_{\text{CO}}$ persist even for $T > T_{\text{LTT}}$ and continue to decrease with increasing temperature. It is difficult to determine the onset temperature for these correlations, but we still observe a clear evolution of the peak at $q_{\text{CO}}$ between 80 K and 200 K, Fig. 1(c), which is better visualized by subtracting the 300 K curve, Fig. 1(d).

It is important to note that since our RXS experiments are done in energy-integrated mode, the high-temperature peak at $q_{\text{CO}}$ may originate from both elastic (static) and inelastic (dynamic) correlations. In fact, high-temperature dynamic CO signals have recently been observed in many cuprates, including other La-based systems [25, 26]. While it may be tempting to assign the same rotational symmetry of the charge stripes to the high-temperature correla-

![FIG. 1. (a) A diagram depicting the CuO$_6$ octahedral tilts in both the LTO and LTT phases. In the LTO phase, neighboring octahedra tilt in opposite directions (clockwise and counter-clockwise) along the [110] direction. In the LTT phase, adjacent CuO$_2$ layers have orthogonal tilts along the [100] and [010] directions. (b) Temperature dependence of the CO peak in LNSCO-125. Sharp peaks corresponding to charge stripes are observed below 65 K in the LTT phase. The gray dashed line is a polynomial fit of the high-temperature background curve measured at 300 K. (c) RXS scans in the LTO phase showing broad peaks corresponding to CO correlations. (d) Lorentzian fits of the background-subtracted curves shown in (c).]
A striking consequence of $\sigma \neq 0$ in our experiments on LNSCO-125 is the dramatic reduction of $T_{\text{LTT}}$ from 63 K to 34 K, Fig. 2(b). This is directly seen in our experiments via apical O-K edge RXS measurements of the (001) Bragg peak (in Miller index notation), whose resonant cross-section is an increasing function of the octahedral tilts in the LTT phase [24]. We can understand the reduction of $T_{\text{LTT}}$ as a consequence of uniaxial stress, which spoils the global tetragonality of the LTT phase. Although it still emerges at low temperatures, our experiments unveil a remarkable response of the LTT structure in LNSCO-125 to the application of uniaxial stress.

In principle, uniaxial stress could result in the transition of the macroscopic crystal into a mixed LTO/LTT phase or a decrease in the LTT octahedral tilt angle, as hypothesized from measurements of the magnetic properties of LBCO-115 [19]; neither effect is resolved in our experiments. First note that the intensity of the (001) Bragg peak, whose cross-section is an increasing function of the octahedral tilt angle, appears unchanged by $\sigma$ at 10 K. This indicates that, within the LTT phase, the structure is unaffected by stress. Second, the LTO-LTT transition remains sharp with non-zero $\sigma$, which suggests that the stressed sample enters the LTT phase in a rather uniform fashion. While the uniformity of the strain field on the sample may vary between different uniaxial strain setups, our experiments do not provide evidence of a mixed phase or reduced octahedral tilts in the LTT phase [24]. We can understand the reduction of $T_{\text{LTT}}$ as a consequence of uniaxial stress, which spoils the global tetragonality of the LTT phase. Although it still emerges at low temperatures, our experiments unveil a remarkable response of the LTT structure in LNSCO-125 to the application of uniaxial stress.

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Within the same experiment we can also track the temperature dependence of the charge order in the stressed LNSCO-125 crystal, which is summarized in Fig. 3(a). A consequence of uniaxial stress is the reduction of the onset temperature of charge stripes by 50 K, which is larger than the change of 29 K observed for $T_{\text{LTT}}$. If the only effect of uniaxial stress was the suppression of $T_{\text{LTT}}$, one might have expected the same change to occur for the onset of charge stripes. However, the additional shift of 21 K suggests that one should also consider interactions with additional intertwined orders, such as superconductivity. Uniaxial stress on the order of 0.05 GPa has been shown to increase $T_c$ by 8 K in LNSCO-120 and by 10 K in LBCO-115 [16, 19], showing that superconductivity is enhanced in tandem with the suppression of the LTT phase. Additionally, cuprates that lack a similar structural transition, such as Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ and YBa$_2$Cu$_3$O$_{6+y}$, exhibit competition between superconductivity and CO [9, 29, 30]. Together, the suppression of the LTT phase and the enhancement of superconductivity would account for the larger suppression of the onset of stripes, relative to the suppression of $T_{\text{LTT}}$.

In addition to the effects on stripe order due to its intertwining with the LTT phase and superconductivity, uniaxial stress may also directly influence the pinning of stripes along $a$ and $b$. For example, given the $C_2$ symmetry of stripe order, one may expect that a finite $\sigma$ in the absence of an LTT phase would cause the onset temperatures of stripes along $a$ and $b$ to split. Indeed, this split is resolved by our detailed temperature dependent RXS measurements, Fig. 3(a). This is seen more clearly by directly comparing the RXS data along the two directions, Figure 3(b), which shows that at 23 K the peak along $a$ (parallel to the applied stress) has already entered the charge stripe phase, while the peak along $b$ is still very similar to the peak in the high-temperature phase – compare to the 35 K data. Eventually, at 15 K the two signals approach the same saturation value, which may indicate that the LTT structure has suppressed the effects of $\sigma \approx 0.1$ GPa at this temperature. Nevertheless, our observations show that uniaxial stress can be used to pin the direction of stripes in the CuO$_2$ plane.

While our measurements show a delicate balance between charge stripes, superconductivity and structural distortions, a direct effect of uniaxial stress on the high-temperature CO correlations is not clearly observed in our data. Just above the onset of charge stripe order, the intensities of the RXS peaks at $q_{\text{CO}}$ are indistinguishable between the stressed and control samples. We also do not resolve a clear difference between the CO correlations along $a$ and $b$ in the stressed sample – for example see the 35 K data in Fig. 3(b). Figure 3(a) suggests that the onset of CO correlations at high-temperatures may be impacted by the application of stress along $a$. However, there are several complications that prevent us from reaching that conclusion with any reasonable confidence. First, as mentioned above, the CO correlations evolve very slowly with temperature, which makes the assignment of an onset temperature difficult. Second, the stress produced by our apparatus is temperature dependent and we estimate a 3 to 5 fold decrease in the applied stress from 34 K to 200 K. Third, the comparison of small RXS peaks between the stress and control samples can be influenced by variations in the fluorescence background, which is sensitive to sample surface condi-
tions. The effects of uniaxial stress to the high-temperature correlations will likely require experiments that tune the stress at a fixed temperature. Altogether, we cannot conclude the observation of any direct coupling between uniaxial stress and high-temperature CO correlations.

Our experiments demonstrate the complex relationship between uniaxial stress, charge stripes and the low-temperature tetragonal structure in LNSCO-125. Increasing $\sigma$ from zero to 0.1 GPa causes a simultaneous reduction in the onset temperatures of both the LTT phase and charge stripes, as well as a temperature splitting in the formation of charge stripes along the $a$ and $b$ directions. Additionally, the effects of superconductivity need to be included to describe our observations, with the competition between superconductivity and charge order together with the enhancement of $T_c$ under uniaxial stress serving as a natural explanation for the additional suppression of the onset of stripe order with respect to $T_{C_{\text{LTT}}}$. Furthermore, we find that larger stress may be necessary to cause significant changes to the high-temperature CO correlations. Nevertheless, the relatively small amount of stress necessary to tune the electronic properties of the La-based cuprates near $1/8$ hole-doping is quite remarkable. For example, strain on the order of 1.0% is necessary to modify the properties of charge order in YBa$_2$Cu$_3$O$_{6+y}$ [15] or to shift the superconducting transition by 2 K in Sr$_2$RuO$_4$ [31, 32]. While achieving 1.0% strain may be quite challenging and difficult to reproduce, 0.05% or even smaller is clearly sufficient to alter the electronic properties of LNSCO-125, which opens new opportunities for switchable devices and precision detectors at the current frontier of technology.

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