

Giant Domain Walls and Intrinsic Heterogeneity in 214 Cuprate Superconductors

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Structural phase transitions generate complex microstructures that often govern material functionality, yet directly resolving their three-dimensional organization in bulk samples remains challenging. Here we employ scanning three-dimensional x-ray diffraction (3DXRD) to resolve the bulk microstructure of $\text{La}_{1.675}\text{Eu}_{0.2}\text{Sr}_{0.125}\text{CuO}_4$, a prototypical 1/8-doped cuprate in which structural and electronic heterogeneity is well established. We reveal remarkably broad tetragonallike domain wall regions within the nominally orthorhombic crystal structure, and, upon cooling to 100 K, a fine microstructure of orthorhombiclike stripes embedded within the tetragonal matrix that has significant consequences for interpreting the interplay between structural and electronic heterogeneity in this class of materials. More broadly, this work establishes 3DXRD as a powerful approach for resolving bulk microstructures and understanding their role in emergent functionality.

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The physical properties of materials are often governed by their microstructure. In ferroelastic and martensitic systems, the accommodation of strain during symmetry-lowering phase transitions generates complex microstructures spanning multiple length scales. Interfaces formed during these transitions can themselves become active elements, hosting properties absent in the surrounding bulk, including enhanced conductivity [1], polarity [2], and ferroelectricity [3], motivating intense interest in understanding and controlling microstructure. Despite its importance, directly visualising bulk microstructure over the relevant length scales remains challenging. Electron microscopy and scanning probe techniques provide high spatial resolution but are generally restricted to surfaces or thin samples, while many bulk probes average over spatial correlations. As a result, establishing how local structural distortions organize into extended three-dimensional microstructures remains an outstanding challenge across a wide range of functional materials.

The consequences of such microstructural heterogeneity are particularly evident in correlated electron materials, where strong coupling between strain, charge, and spin degrees of freedom can amplify the effects of local structural variations. Inhomogeneities, whether structural, electronic, or chemical, can drive phase separation on the nanometer to micrometer scale, with significant consequences for their

properties [4,5]. This is notably observed in the manganites, where the colossal magnetoresistance is believed to be linked to the percolation of a ferromagnetic conducting phase within a charge-ordered antiferromagnetic insulating matrix [6].

High-temperature superconducting cuprates provide another important example in which structural and electronic inhomogeneity are ubiquitous. Their layered perovskite framework supports cooperative rotations and tilts of the CuO_6 octahedra, giving rise to structural phase transitions that are strongly coupled to charge, spin, and superconducting degrees of freedom. This interplay manifests in phenomena including charge stripes [7], nematicity [8], and filamentary superconductivity [9]. A wide range of experimental techniques has revealed evidence for structural and electronic inhomogeneity across multiple length scales. Local structural probes, including pair distribution function analysis [10] and extended x-ray absorption fine structure measurements [11], reveal deviations from the average crystallographic structure, while scanning tunneling microscopy has demonstrated substantial spatial variations in electronic properties [12,13]. Collectively, these studies establish that inhomogeneity is an intrinsic feature of the cuprates. Despite this extensive body of work, the three-dimensional bulk organization of these structural distortions remains unresolved. Bulk probes can reveal local distortions but not their spatial arrangement, while surface-sensitive techniques cannot access the bulk microstructure. Consequently, the interplay between structural and electronic heterogeneity, as well as the effect this has on bulk properties, remains poorly understood.

$\text{La}_{1.675}\text{Eu}_{0.2}\text{Sr}_{0.125}\text{CuO}_4$ (LESCO), a prototypical 1/8-doped cuprate [14,15], provides an ideal model system to

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address this. LESCO exhibits signatures of structural coexistence between the low-temperature orthorhombic (LTO) and low-temperature tetragonal (LTT) phases over a broad temperature range [16], reminiscent of electronic phase separation observed in other highly correlated systems. While these signatures are also evident in several 1/8-doped cuprates, and notably absent in the isostructural band insulator La_2MgO_4 [17], prevailing interpretations and theories often assume a homogeneous structural state underpins both superconducting and charge density wave (CDW) order.

At room temperature, LESCO adopts the LTO ($Bmab$) phase, characterized by rotations of the CuO_6 octahedra about the $[100]$ axis, as shown in Fig. 1(a). This distortion transforms as irreducible representation $X_3^+(a;0)$, with respect to the high-temperature tetragonal (HTT, $I4/mmm$, $F4/mmm$ in the basis of LTO) phase. Upon cooling to approximately 160 K, LESCO undergoes a first-order phase transition from LTO to the LTT ($P4_2/ncm$) phase, in which the octahedra rotate about $[110]$ and $[1\bar{1}0]$, with alternating layers rotating in opposite senses. This is described by $X_3^+(a;a)$. The notation follows representation theory, or “symmetry-mode analysis,” describing distorted structures as a high-symmetry parent structure plus symmetry-adapted distortions. This provides a direct microscopic description of the order parameters and can be

obtained using software such as ISODISTORT [18,19]. The absence of a direct group-subgroup relationship between LTO and LTT necessitates a region of phase coexistence. However, the persistence of this down to at least as low as 10 K in LESCO and isostructural $\text{La}_{1.875}\text{Ba}_{0.125}\text{CuO}_4$ (LBCO) suggests a coupling to electronic phase separation related to an intrinsic competition between superconductivity and CDW order at this doping level. While CDW order is believed to suppress bulk superconductivity [7], in-plane superconducting correlations may persist [20,21]. In the LTO phase, charge stripe alignment across layers enables bulk superconducting coherence, but in the LTT phase, the octahedral rotations pin charge stripes and induce a 90° rotation between adjacent layers, frustrating interlayer Josephson coupling [22,23]. Similar frustrations may occur at structural domain walls, where the sense of the octahedral rotations reverses, inducing corresponding charge stripe rotations. Therefore, a detailed understanding of the microstructure at the domain level appears essential for accurately measuring and controlling superconductivity.

To directly resolve this complex microstructure, we used scanning three-dimensional x-ray diffraction (3DXRD) [24,25] at ID11, ESRF [26], allowing spatially resolved characterisation of LTO- and LTT-like structural domains in the bulk from 300 to 100 K. This method contrasts with techniques like transmission electron microscopy (TEM),

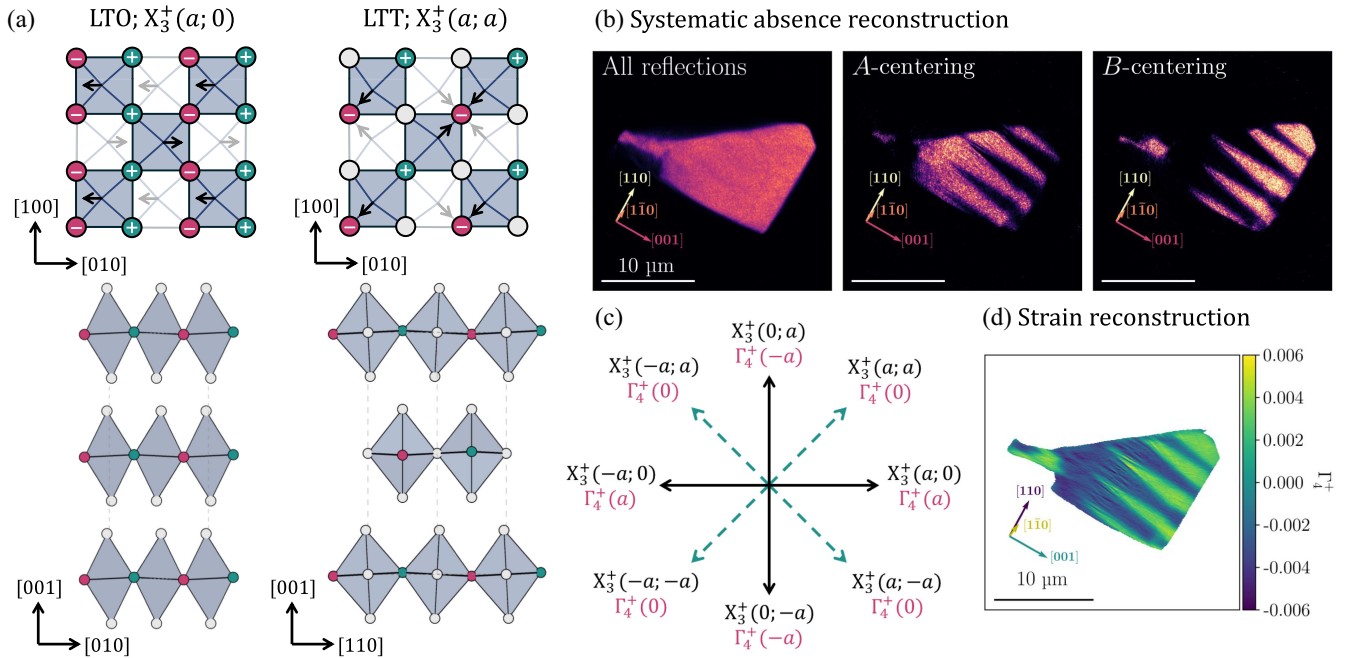


FIG. 1. (a) Representation of the LTO (left) and LTT (right) structures, with A-site cation omitted for clarity. Oxygens are shown in teal and magenta, indicating whether they are above and below the CuO_2 planes, respectively. In LTO, the sense of the distortion propagates along $[010]$, with all layers aligned. In LTT, the sense of the distortion propagates along alternating diagonals, with a 90° rotation, from $[110]$ to $[1\bar{1}0]$, between adjacent layers. (b) 300 K reconstruction of the sample from all reflections and filtered by A- and B-centered systematic absences, revealing twin domains. (c) Order parameter map indicating X_3^+ propagation direction with black as LTO and teal as LTT. (d) 300 K strain reconstruction based on Γ_4^+ showing strong correlations with the systematic absence map. Axes are given with respect to the LTO and LTT basis.

which typically only provide surface-sensitive information, as it instead offers a cross section through the bulk. Similarly to conventional single crystal x-ray diffraction, the full diffraction signal is collected. This contrasts with many alternative x-ray and electron imaging techniques that measure from only specific reflections. In the resulting dataset, the position of each reflection is characterized by its scattering angle (2θ) and azimuthal angle (η), which is then related to its spatial origin within the sample through the rotation angle (ω) and sample translation (y). The additional measurement of the sample translation distinguishes 3DXRD from conventional single crystal diffraction, where only angular dimensions are recorded. Using the full diffraction signal indexed on a $5.35 \times 5.35 \times 13.2$ Å unit cell, the shape of the slice through the crystal can be tomographically reconstructed [Fig. 1(b)]. A more insightful view of the underlying twin domain structure emerges by performing the reconstruction using only a subset of reflections. The two orthorhombic twin domains, related by a fourfold rotation about the c axis, have different systematic absence conditions relative to the lattice used to index all observed reflections. They correspond to either an A - or B -centered lattice, characterized by general reflection conditions $k + l = \text{even}$ or $h + l = \text{even}$, respectively. This distinction arises from the orientation of the octahedral tilting, as illustrated in Fig. 1(c). Reflections where $h, k, l = \text{even}$ are excluded in filtering. This clearly resolves a micron-scale domain structure composed of interlocking A - or B -centered regions, oriented parallel to $[001]$ and perpendicular to $[110]$ and $[1\bar{1}0]$, likely forming continuous sheets in the out-of-plane direction. The $[001]$ direction is approximately 2° out of the plane of the image, which may account for the triangular shape of the domains if the sheets are not of a constant thickness throughout the crystal.

As the LTT structure emerging at lower temperature lacks general systematic absence conditions to differentiate it from the LTO domains, contrast was instead achieved through variation in the ferroelastic strain, Γ_4^+ , that acts as a secondary order parameter of the octahedral tilting, X_3^+ . Iterative reconstructions based on the spatial distribution of the local average unit cell parameters [27] (further details provided in Supplemental Material [28]) were recovered in Fig. 1(d). The strong correlation between the systematic absence reconstruction [from reflection intensities, Fig. 1(b)] and the strain reconstruction [from peak positions, Fig. 1(d)] provides robust validation of our approach. Given its superior resolution (10^{-4} [36]) relative to systematic intensity errors, we focus our subsequent analysis on strain reconstructions. This provides a level of detail generally hard to achieve with techniques like TEM over such large length scales.

Among the calculated, spatially resolved symmetry-adapted strain, only Γ_4^+ uniquely exhibits a pronounced stripelike pattern (see Appendix A). The evolution of Γ_4^+

upon cooling [Figs. 2(a) and 2(b)] provides critical insight into the LTO to LTT transition. From 300 to 140 K, the A -centered LTO domain gradually dominates to accommodate the growing ferroelastic strain, leading to a marked asymmetry in the Γ_4^+ distribution [Fig. 2(b)]. However, before the minority domain is fully consumed, the increasing magnitude of X_3^+ , inherently coupled to Γ_4^+ , triggers the first-order transition to LTT [17]. This behavior, occurring near the critical octahedral tilting amplitude for T_C , is not a coincidence but instead suggests a structural basis underlying the suppression of superconductivity in the composition-doping phase diagram of this material class [16]. At 120 and 100 K, the overall microscale variation in Γ_4^+ appears to be lost, consistent with a more homogeneous LTT structure. However, analysis of the absolute strain magnitude $|\Gamma_4^+|$ [Fig. 2(c)] uncovers crucial submicron variation at all temperatures, reminiscent of tweed domain structures [37].

At 300 K, within the nominally LTO phase, our $|\Gamma_4^+|$ strain map reveals unusually wide, domain wall-like regions with near-zero strain. These features are not atomic-scale defects, but extended regions approximately 150 nm thick and separated by 0.5–2 μm (see Fig. S6 and Table S1 in Supplemental Material [28]). This length scale is orders of magnitude larger than typical ferroelastic or ferroelectric domain walls. Consequently, these structures challenge the more conventional understanding of what we would view as a domain wall or as microscopic coexisting phases with distinct symmetry. Instead, the observed walls are effectively extended LTT-like regions coexisting within an LTO matrix [38,39]. Their substantial thickness could even give rise to coherent scattering signals observable as distinct phases in conventional XRD, offering a natural explanation for the phase coexistence reported in LESCO and related cuprates [16,40,41]. However, we note that the ability to resolve distinct structures does not just depend on the coherence of the order parameters within the material, but also on the resolution of the instrument and coherence of the radiation source measuring them.

Considering Fig. 1(c), we construct a microscopic model for the evolution of the tilt order parameter across these domains. The strain profile shows a smooth transition from positive to negative Γ_4^+ through extended regions where Γ_4^+ approaches zero. This behavior is consistent with a continuous rotation of the tilt, for example, a sequence such as $X_3^+(a;0)|X_3^+(a;a)|X_3^+(0;a)$. Between the LTO domains and the LTT domain wall center, the octahedral tilt gradually changes direction, potentially passing through a region that can be described with $Pccn$ symmetry, which is a common subgroup of LTO and LTT. A microscopic (crystallographic) picture for these possible domain evolutions is given in Supplemental Material [28]. The presence of local tetragonal character is consistent with early structural studies on related cuprates [42–45], which suggest that ideally sharp orthorhombic twin walls are

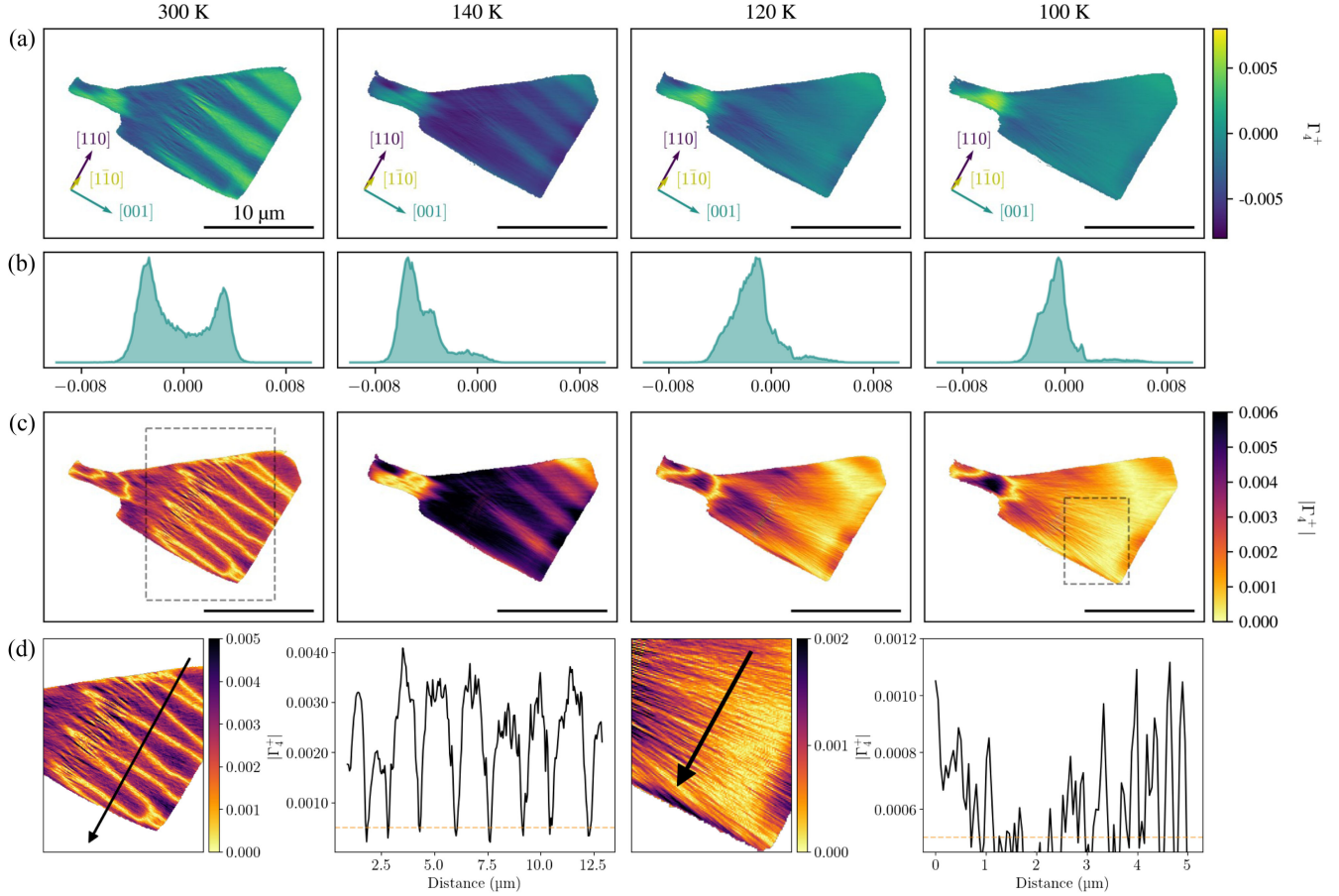


FIG. 2. (a) Spatially resolved maps of Γ_4^+ at 300, 140, 120, and 100 K, illustrating the temperature evolution of the structural domains. (b) Histograms of Γ_4^+ at corresponding temperatures, showing the transition from bimodal at 300 K to a more homogeneous but still asymmetric distribution at 100 K. (c) Maps of the absolute strain magnitude $|\Gamma_4^+|$ with (d) showing enhanced maps and line profiles, revealing broad LTT-like features within the LTO phase at 300 K and subtle LTO-like filaments within the LTT phase at 100 K. The spatial resolution of our reconstructions is at least 70 nm, based on the determined strain resolution of the experiment of 2×10^{-4} ; see Supplemental Material [28].

unlikely because they would require the CuO_6 octahedra to tilt abruptly in orthogonal directions, resulting in a high interfacial energy. Instead, extended boundaries are expected, in which the tilt pattern gradually transitions from orthorhombic to tetragonal at the wall center. TEM measurements on LBCO estimated the width of these tetragonal regions to be around 100 Å, while neutron diffraction indicated larger values of a few hundred Å based on superstructure peak broadening [42]. Consistently, Landau-type free-energy models for LBCO predict that the central region of such walls should adopt LTT-like character rather than revert to the HTT phase [46].

Anomalously wide and structurally coherent walls have been increasingly recognised in ferroic materials, but not widely discussed in superconducting materials. In $\text{Ca}_3\text{Ti}_2\text{O}_7$, infrared nanospectroscopy revealed 60–100 nm wide ferroelastic walls, attributed to a gradual rotation of the octahedral tilt and rotation order parameters [29]. Similarly, Néel-like ferroelectric domain walls, where

the polarization rotates rather than vanishes, have been predicted and observed in systems such as BaTiO_3 [47,48]. These examples support a broader understanding of wide domain boundaries as intrinsic structural features that can serve as functionally active elements [49,50].

At 100 K, within the CDW phase, the microstructure evolves markedly. Deviations from ideal tetragonal symmetry emerge as fine striplike orthorhombic features on the 100–200 nm scale, repeating with a similar periodicity. These may be interpreted as nanoscale inclusions of the LTO phase embedded within the LTT matrix, likely forming to minimize the elastic energy associated with antiphase boundaries related to the octahedral tilt orientation $[\text{X}_3^+(a; a)\text{X}_3^+(-a; a)]$. While similar behavior has been reported previously in LBCO, where electron microscopy revealed a fine mixture of domains with orthorhombic and tetragonal character with sizes of ≥ 300 Å that persisted well below the LTO and LTT transition to 10 K [51,52], the likely significance of this with respect to interpreting the

bulk properties of these materials has apparently been overlooked in the preceding three decades. Additionally, their regular spatial distribution and morphology, along with the lack of correlation between Γ_4^+ and $\Gamma_1^+(1)$, confirm that they are not artifacts from chemical inhomogeneities but rather reflect an intrinsic and robust microstructure.

From the observed strain profiles, only negative Γ_4^+ is present at 100 K, which constrains the domain configurations. The absence of positive Γ_4^+ implies that the domain sequences must be of the form $X_3^+(-a; a)|X_3^+(0; a)|X_3^+(a; a)$ or $X_3^+(-a; -a)|X_3^+(0; -a)|X_3^+(a; -a)$. These LTO-like inclusions may locally disrupt the CDW-stabilizing LTT tilt pattern, constraining the CDW correlation length and potentially explaining why it does not fully saturate in LESCO [53], and suggesting that similar mesoscale heterogeneity could influence CDW correlations in other members of the cuprate family that exhibit comparable pseudosymmetry. Such fine structural heterogeneity likely actively shapes CDW order and may provide filamentary pathways for localized or lower-dimensional superconductivity [54–56]. Recent studies have emphasized the importance of structural domain walls, particularly those associated with LTO-like distortions, in governing the formation and stability of CDW order in cuprates more broadly [57]. However, a detailed description of the underlying microstructure has so far remained elusive. The present results help address this gap, suggesting that fine structural heterogeneity may provide a natural framework for the microscopic coexistence of CDW order, superconductivity, and even antiferromagnetic order [58,59].

Our interpretation follows the established association of CDW order occurring within the LTT phase and superconductivity within the LTO phase in 214 cuprates; however, direct spatial correlation between structure and electronic response remains an important open problem. We emphasize that the present work is focused on resolving the bulk microstructure. Given the correlation length associated with SC and CDW order parameters is in the region of 2–15 nm in cuprates, we anticipate that the symmetry breaking associated with the domain wall structures shapes the competition between SC and CDW, rather than being shaped by it. Put another way, the SC or CDW order parameters will feel the domain wall symmetry as “bulk.” However, as ferroelastic strains are decreased, the domain wall energy and width, generally having a quadratic dependence on this [60], will fall rapidly. Reductions in the LTO transition temperatures and, hence, ferroelastic strains are evident across the 214 cuprates, where they are strongly influenced by tolerance factor, variance, and doping effects [61].

The 214s are far from the only cuprates expected to exhibit such domain wall structures. Indeed, a symmetry analysis of all aristotypical parent structures of the main cuprate superconductors reveals a striking amount of generality, all being based on $4/mmm$ symmetry (see

Appendix B). For the purposes of our current discussion, it is helpful to divide them into two classes.

Class (A) contains the 214s and the majority of high- T_C compounds. Given that the symmetry breaking strains transform as the same representation of the parent structure, and the parent structures will have both similar elastic constants and low-energy twin planes, we would predict our result to be general in this class, while noting the discussion above on the scaling of domain wall widths. The variation of calculated Γ_4^+ strains and, therefore, expected domain sizes appears to range from 7×10^{-3} in LESCO to 3×10^{-3} in TI-2201 [62] all the way down to 3×10^{-4} in Bi-2223 [63]. This class is also likely to be a relevant description to a broad range of electronic materials with layered perovskite structures, including high-pressure superconductors $\text{La}_3\text{Ni}_2\text{O}_7$ [64–66], which can exhibit complex structural phase transitions driven by octahedral rotations and tilting.

While LESCO provides an important model system, the broader significance of this work lies in the experimental approach. Scanning 3DXRD enables direct visualization of bulk microstructural heterogeneity with a level of detail that has not previously been accessible across such length scales. More generally, any phase transition that may be considered as ferroelastic or coelastic [67] can be imaged using our implementation of scanning 3DXRD, provided the length scales of domain structures are upward of 70 nm. This includes martensitic transitions, where strain is the primary order parameter and typically of a very large magnitude, as well as almost all structural and magnetic phase transitions where strain (symmetry breaking or symmetric) invariably couples to the primary order parameter. Resolving these structures in three dimensions provides new opportunities to quantitatively link microstructure and mesostructure to macroscopic properties.

Unfortunately, direct tomographic mapping of weak CDW reflections is beyond current 3DXRD capabilities, but advances in beamline technology and methods could enable sub-100-nm bulk mapping of structure and CDW order. This presents a pathway for establishing direct, spatially resolved structure-electronic correlations, which would significantly advance our understanding of competing orders in complex oxides. Beyond diffraction techniques, the observed complexity of these microstructural features highlights the need for local probe techniques capable of resolving electronic behavior on comparable length scales. While conductive atomic force microscopy (cAFM) shows promise for certain materials, in LESCO we found that anion migration currently prevents reliable interpretation. Spatially resolved spectroscopic techniques such as nano-ARPES may also provide clues to the extent of electronic heterogeneity; however, these are also inherently surface sensitive. More broadly, the results underscore that establishing the intrinsic bulk structure is essential for interpreting electronic properties in systems

with competing orders. This is particularly important in ferroelastic materials, where strain fields can relax at free surfaces, meaning that surface-sensitive probes may not directly reflect bulk behavior. Bulk-sensitive structural characterization is, therefore, complementary and necessary for a complete understanding of electronic measurements.

Ultimately, direct visualization of bulk microstructural heterogeneities prompts a reevaluation of how material structure is conceptualized. Increasingly, such variations in ferroic materials are seen not as simple interfaces but as potentially functional components [68]. This raises a philosophical question: should we consider these extensive heterogeneities as distinct coexisting phases, or instead hold a more holistic view of material structure in which the interplay of continuous and discrete structural variations governs macroscopic properties? New experimental techniques, such as scanning 3DXRD demonstrated here, will be instrumental in capturing the high-resolution structural data necessary to confront this challenge, enabling a more nuanced understanding of complex materials.

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Data availability—The data that support the findings of this article are openly available [26]; embargo periods may apply.

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End Matter

Appendix A: Spatially resolved symmetry-adapted strain—Figure 3 shows the spatial variation of the symmetry-adapted strain with respect to the $I4/mmm$ aristotype and associated histograms at 300 K. Among these, Γ_4^+ is unique in exhibiting a pronounced, stripelike

pattern, directly aligned with the orthorhombic twin structure. In contrast, the other strain modes show only subtle spatial deviations, most notably in $\Gamma_1^+(2)$, which corresponds to an elongation of c , and $\Gamma_5^+(b)$, associated with a shearing between c and the ab plane. We note

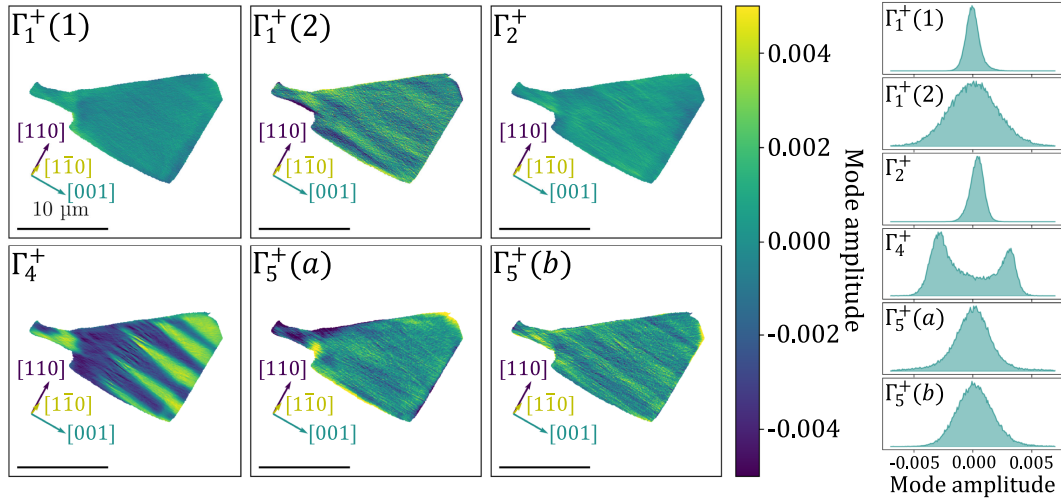


FIG. 3. Spatially resolved maps and associated histograms of symmetry-adapted strain modes at 300 K. Note the bimodal distribution of Γ_4^+ , unique in capturing the twin domain structure. $\Gamma_1^+(1)$ corresponds to an in-plane symmetric expansion or contraction, while $\Gamma_1^+(2)$ is a uniform strain along c . Γ_2^+ is an in-plane shear strain. Γ_4^+ is the orthorhombic strain. $\Gamma_5^+(a)$ and $\Gamma_5^+(b)$ describe shear strains between the ab plane and c axis.

that the small spatial variation in $\Gamma_5^+(b)$, most likely arising from strain localized at the domain walls, may provide an explanation for the apparent subtle monoclinic distortion reported in LSCO and LBCO [69,70]. This distribution is broader than some of the other minor modes (Fig. S3 in Supplemental Material [28]), but the magnitude of these spatial variations remains roughly 3 times smaller than that of Γ_4^+ , the dominant orthorhombic strain. The corresponding histograms reinforce these observations: Γ_4^+ exhibits a clear bimodal distribution reflecting the alternating strain in the twin domains, with negative and positive peaks corresponding to the A and B domains, and a central region showing the gradual transition across the domain wall. By comparison, the other strain modes show uniform distributions centred around zero, consistent with the stable or weakly varying distortions. These can be well modeled by a single pseudo-Voigt distribution and would, for example, give rise to anisotropic peak broadening due to sample microstrain in powder XRD. This symmetry-based decomposition reveals that Γ_4^+ uniquely captures the structural signature of the octahedral tilting.

Appendix B: Symmetry analysis of the main cuprate superconductor families—Class (A) contains 214s (e.g., LSCO, LSCO, LBCO), the Bi-12n[$n + 1$] ($\text{Bi}_2\text{Sr}_2\text{CuO}_6$, $\text{BiSr}_2\text{CaCu}_2\text{O}_8$, $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$), and Tl-12n[$n + 1$] ($\text{Tl}_2\text{Ba}_2\text{CuO}_6$, $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$, $\text{Tl}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$), for

which a parent structure with symmetry $I4/mmm$ can be found. Examples in the literature for all families exist in which structural distortions, corresponding to CuO_2 plane tilting (transforming as X_3^+ or X_4^+), are reported. These distortions couple to symmetry breaking strains along a direction lying between the O-Cu-O planes (the Γ_4^+ strain channel).

Class (B) $\text{Hg}_{12n}[n + 1]$ ($\text{HgBa}_2\text{CuO}_4$, $\text{HgBa}_2\text{CaCu}_2\text{O}_6$, $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_8$) and YBCO ($\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$) have a $P4/mmm$ parent aristotype. Here, where observed, symmetry breaking seems to be predominantly associated with anion ordering, which couples to symmetry breaking strains lying along the Cu-O bonds (Γ_2^+ strain channel).

For class (B), it may also be fruitful to investigate these using scanning 3DXRD, but we would anticipate the most striking contrast would be in Γ_2^+ spatially resolved strains. We note also that strains in YBCO are typically large, and of the order 0.01, suggesting a larger field of view may be required. Indeed, twin domains can be viewed optically in YBCO where they are many microns in size, and procedures exist for detwinning them under uniaxial compression [71]. On the other hand, symmetry breaking in $\text{HgBa}_2\text{CuO}_4$ has been interpreted as nanoscale correlations of atomic displacements [72], with no reported macroscopic strains [73], suggesting the length scales of any structural heterogeneity are well below the intrinsic limit of the technique.