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Emergent chirality in the electric polarization texture of titanate superlattices

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Chirality is a geometrical property by which an object is not superimposable onto its mirror image, thereby imparting a handedness. Chirality determines many important properties in nature—from the strength of the weak interactions according to the electroweak theory in particle physics to the binding of enzymes with naturally occurring amino acids or sugars, reactions that are fundamental for life. In condensed matter physics, the prediction of topologically protected magnetic skyrmions and related spin textures in chiral magnets has stimulated significant research. If the magnetic dipoles were replaced by their electrical counterparts, then electrically controllable chiral devices could be designed. Complex oxide BaTiO$_3$/SrTiO$_3$ nano-composites and PbTiO$_3$/SrTiO$_3$ superlattices are perfect candidates, since “polar vortices,” in which a continuous rotation of ferroelectric polarization spontaneously forms, have been recently discovered. Using resonant soft X-ray diffraction, we report the observation of a strong circular dichroism from the interaction between circularly polarized light and the chiral electric polarization texture that emerges in PbTiO$_3$/SrTiO$_3$ superlattices. This hallmark of chirality is explained by a helical rotation of electric polarization that second-principles simulations predict to reside within complex 3D polarization textures comprising ordered topological line defects. The handedness of the texture can be topologically characterized by the sign of the helicity number of the chiral line defects. This coupling between the optical and novel polar properties could be exploited to encode chiral signatures into photon or electron beams for information processing.

Significance

Many natural structures exhibit chirality that is essential to their functional interactions, yet the chiral electronic structures found in condensed matter systems have been primarily limited to magnetic materials. Notably, the electric dipole equivalent of magnetic skyrmions has remained conspicuously elusive. However, recent theoretical predictions and experimental observations of the continuous rotation of electric polarization in titanate superlattices suggest that such complex oxide nanocomposites are ideal candidates for realizing chiral electric dipole configurations. Here we present the results from superlattices of PbTiO$_3$ and SrTiO$_3$ using a combination of resonant soft X-ray diffraction and second-principles simulations. We observe chiral arrays of polar line defects, spontaneously formed by the complex interactions in these artificial superlattices constructed from two nonchiral layers.


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and gradient (or anisotropy) energies forms the curled polar textures (5). X-ray diffraction (XRD) and high-resolution scanning transmission electron microscopy (HR-STEM) confirmed sharp interfaces and coherent atomic layers, as well as highly aligned superlattices of polar cores, both vertically and laterally (Materials and Methods). Within the film plane, the periodic cores of curled polar texture define a lateral repeat direction (designated \([100]_l\) in Fig. 1A, where \(\chi\) denotes the chiral phase) along one of the principal axes of the pseudocubic perovskite cell.

We have performed RSXD (12, 13) on PbTiO\(_3\)/SrTiO\(_3\) superlattices. The soft X-ray wavelengths (~2 nm to 3 nm) are well matched to the periodicity of the lateral modulations in the polar texture, leading to satellites that decorate the 00\(_{\ell}\) diffraction rod (Fig. 1A). Fig. 1B shows a line cut through the lateral satellite peaks in proximity to \(\ell = 0\). Peak positions \((q_{\text{lateral}} = \pm 2q_{\text{lateral}} = \pm 2\pi d_{\text{Lateral}})\) indicate a lateral period equal to that of a pair of counterrotated polar cores, \(d_{\text{Lateral}}\), which is 11.4 nm for \(n = 16\).

By tuning the X-ray energy within the vicinity of resonant electronic transitions from the titanium 2p\(_{\text{1/2}}\) (\(L_1\)) and 2p\(_{\text{3/2}}\) (\(L_2\)) core levels into empty 3p valence states, we directly probe the electronic transitions from the titanium 2p\(_{\text{1/2}}\) (\(L_1\)) and 2p\(_{\text{3/2}}\) (\(L_2\)) core levels into empty 3p \(d\), \(e\), and \(f\) states near the \(L_3\) edge. In X-ray absorption studies of ferroelectric Pb(Zr\(_{0.2}\)Ti\(_{0.8}\))O\(_3\), the same \(t_{2g}\) feature highlights the anisotropy of the polar TiO\(_2\) distortion (14). The resonant behavior in Fig. 1C can be understood (ATS Diffraction) by considering that the supermodulation diffraction peaks are due to anisotropic tensor susceptibility (ATS) scattering (15, 16), driven by periodic rotational patterns of electric polarization in the textured arrays (Fig. S1).

Strikingly, the diffraction peaks of the polar texture exhibit pronounced X-ray circular dichroism (XCD), with intensity differing on the order of ~20% when the circular polarization of incident X-rays is reversed. XCD in resonant diffraction peaks can contain contributions from a number of mechanisms, including chiral motifs (17), scattering from ordered magnetic moments (18), and dynamical effects (19–21). The antisymmetric XCD signal in Fig. 1B is a hallmark of chirality in magnetic materials such as those with chiral domain walls (18). However, no magnetism is expected nor found in the \(d^0\) configuration of PbTiO\(_3\)/SrTiO\(_3\) superlattices. Rather, XCD here must be generated by a chiral rotation of electric polarization within the textured arrays (Fig. 2), as is expected for ATS diffraction peaks from chiral structures (16, 22–24). In these materials, the polarity of the XCD signal reverses when either the chirality of the crystal structure or the direction of the diffraction vector is independently inverted. The latter is observed in Fig. 1B by reversal of the lateral component of the diffraction vector, \(q_{\text{lateral}}\), and Fig. 1D shows evidence of the former.

One must also consider dynamical effects in resonant X-ray scattering, such as the refraction and polarization rotation of both incident and diffracted X-rays, which have been shown in antiferromagnetic ordering diffraction peaks to produce significant XCD in addition to the XCD expected from kinematical models (19–21). The kinematical scattering amplitude is the Fourier transform of the material’s effective electronic density, directly linked to the ordered state being studied (13). The results of dynamical effects also reveal information about material properties, but are strongly

**Fig. 1.** Self-organized arrays of electric polarization textures in (PbTiO\(_3\)/SrTiO\(_3\)) \(_n\) superlattices exhibit a chiral RSXD pattern. (A) These polar arrays produce diffraction satellites that decorate the specular reflection along the lateral direction, \([100]_l\), for X-rays tuned near the titanium \(L_2\) edge. Specular scattering plane is shown in blue. Red and blue helices illustrate opposing circular polarizations of incident X-rays. Sample azimuth is indicated by \(\Phi\). (B) (Upper) Line cut of scattered intensity versus lateral momentum transfer \((q_{\text{lateral}})\) using right- (red) and left-circularly (blue) polarized X-rays for \(n = 16\). (Lower) XCD is the difference in intensity for the two helicities. (C) (Upper) Resonance profiles through the titanium \(L_2\) edges at \(q_{\text{lateral}} = \pm q_{\text{lateral}}\) for both X-ray helicities (red and blue) and (Lower) their XCD (green) for \(n = 14\). Fluorescence excitation spectrum (black curve in upper) shows electronic states similar to that of Pb\(_{0.6}\)Z\(_{0.4}\)Ti\(_{0.8}\)O\(_{1.4}\) (14). (D) Map of XCD intensity at \(q_{\text{lateral}} = \pm q_{\text{lateral}}\) across an \(n = 14\) sample. Regions of positive (negative) XCD indicate where chiral polar arrays have positive (negative) helicity.
dependent on the particular geometry of each diffraction experiment (25). However, these components can be principally distinguished via their azimuthal dependence, in particular by the reversal (or not) of XCD. We now demonstrate that the azimuthal pattern of XCD (Fig. 3A) measured in the $q_{\text{mt}} = 2q_{\text{pair}}$ diffraction peaks from PbTiO$_3$/SrTiO$_3$ superlattices is indicative of the chiral electric dipole configuration in the textured arrays, and that it is also distinct from that of other systems whose XCD is dominated by dynamical effects. Finally, we have also confirmed that XCD is essentially negligible (XCD of Ordered Phases, Fig. 4, and Fig. S2) in thinner (PbTiO$_3$)$_n$/(SrTiO$_3$)$_n$ superlattices (e.g., $n = 4$), which have no curled polar structure but which still possess periodic arrays of ferroelectric $a$ domains that exhibit resonant diffraction peaks (Phase Coexistence). Thus, the dramatic difference in XCD between samples with and without curled polar textures directly points to the chiral structure of the arrays, rather than dynamical effects, as the primary origin of XCD.

The helical polarization structure depicted in Fig. 2A and its inherent broken mirror symmetry along $q_{\text{mt}}$ will produce a resonant ATS diffraction pattern whose peaks, $q_{\text{mt}} = q_{\text{helix}} = 2\pi/d_{\text{helix}}$ ($d_{\text{helix}}$ is the period of the helix), have opposite XCD, similar to Fig. 1B. The twofold symmetry of the helix implies that its diffraction pattern after a 180° rotation is indistinguishable from the diffraction pattern of the original orientation. Notably, however, because $q_{\text{mt}}$ is fixed to the sample (by construction), the peak with positive dichroism in the original orientation is located at $q_{\text{mt}} = q_{\text{helix}}$, whereas, after rotation, it is located at $q_{\text{mt}} = -q_{\text{helix}}$. We observe similar behavior from the PbTiO$_3$/SrTiO$_3$ polar arrays, as seen in Fig. 3.

Fig. 3A shows that, for a single diffraction spot with $q_{\text{mt}} = q_{\text{pair}}$, XCD is large and positive (red) across a range of azimuths, $\phi_{\text{pot}}$ near +90°. XCD in that same spot is strongly negative (blue) for $\phi_{\text{pot}}$ near −90°, and, in between these extremes, the XCD tends toward zero at $\phi_{\text{pot}}$ near 0° or 180°. Similar azimuthal patterns were measured for multiple diffraction spots from the polar arrays (Materials and Methods), and have been overlaid in Fig. 3A to highlight this commonality via judicious selection of the origin, $\phi_{\text{pot}} = 0°$. Here the azimuth, $\phi_{\text{pot}}$, has been defined for each diffraction spot, to measure the in-plane projection of its scattering vector relative to the projection of incident X-rays onto the sample surface (dashed green line in Fig. 3B). The cartoon in Fig. 3B illustrates the data in Fig. 3A, to emphasize that either diffraction spot exhibits positive XCD (red disk) when its in-plane scattering vector is +90° from the dashed green reference line. This condition is fulfilled for $q_{\text{mt}} = +q_{\text{pair}}$ (thick black arrow, parallel to [100]$_X$) in Fig. 3B, Left and also by a 180° azimuthal rotation of the sample for $q_{\text{mt}} = -q_{\text{pair}}$ (thick gray arrow, antiparallel to [100]$_X$) in Fig. 3B, Right. For a fixed sample orientation, however, the mirrored diffraction spots ($q_{\text{mt}} = 2q_{\text{pair}}$) have XCD with opposite polarity, as in Fig. 1B. Indeed, the inversion of XCD polarity with reversal of $q_{\text{mt}}$ persists at all azimuths, as deduced from Fig. 3A, and is a defining feature that points toward the chiral origin of this XCD signal.

This azimuthal pattern of XCD in the polar array diffraction spots is functionally similar to that of the ideal electric polarization helix. In the reference frame of the diffractometer, this twofold rotation of the sample results in a similar (albeit not identical) XCD diffraction pattern from the polar texture. An immediate implication of this XCD pattern is that the electric polarization of the chiral array must possess a broken mirror symmetry along $q_{\text{mt}}$, with an additional restriction that the electric polarization texture must be considerably unchanged by a 180° azimuthal rotation. These constraints extracted from experimental results help to identify the most likely candidate structures calculated from second-principles atomistic simulations, which are discussed in Calculation of Polarization Textures.

The XCD pattern of PbTiO$_3$/SrTiO$_3$ superlattices is not perfectly antisymmetric with respect to azimuth, largely because the magnitude is smaller for azimuths with negative XCD. This indicates that the chiral arrays do not perfectly mimic the ideal helix in their polarization configuration. This might arise, in part, due to a skewing of the atomic positions, which leads to a systematic asymmetric offset (i.e., buckling) of the polar core positions, as seen in Fig. S3. Skewed profiles of periodic structures are well known to produce asymmetric intensity in the mirrored diffraction spots of, e.g., surface gratings made of patterned lines with asymmetric cross-section (26). Dynamical effects might also partially contribute to the XCD signal, causing it to deviate from an idealized antisymmetric azimuthal pattern. In studies where dynamical modulation of dichroism [either XCD or X-ray linear dichroism (XLD)] in the diffraction peaks was found to be significant (20, 21), the azimuthal patterns possess twofold symmetry or else mirror symmetry that deviates only slightly from twofold symmetry (Fig. S4). This is in stark contrast to the inversion of XCD polarity that we observe with a 180° azimuthal rotation.

Our current analysis focuses on the general trend that positive XCD is observed at positive azimuths, while negative XCD is measured at negative azimuths. Other features of the azimuthal pattern in Fig. 3A could be manifestations of dynamical effects (Azimuthal XCD and Chirality), including fine intensity modulations and a notable imbalance of intensity between the azimuthal lobe of positive XCD and the lobe with negative XCD. Regardless, these two primary lobes of XCD with opposite polarization are clearly visible in the azimuthal pattern, even though some regions of the azimuthal circle are inaccessible due to geometrical constraints of the experimental setup. Based on this distinct azimuthal pattern, we can rule out dynamical effects as the principal source of XCD in the polar array diffraction spots. Also, in the absence of magnetic order, we conclude that XCD in these diffraction patterns is primarily the result of a chiral configuration of electric polarization in the curled textures of PbTiO$_3$/SrTiO$_3$ arrays.

Calculation of Polarization Textures

To ascertain more specifically the structure that produces the observed XCD signal, we have performed second-principles
Superimposed onto this curled polar texture, we observe the condensation of a robust polarization component along the axial direction of the polar cores (29, 30), [010], that triggers the appearance of chiral geometries (Fig. S6). Simulations at low temperature (10 K) predict the stabilization of enantiomers where the axial component points in opposite directions at the center of the clockwise and counterclockwise cores (Fig. 5 A and C). Our second-principles calculations also find an achiral structure, where the axial component is parallel throughout the structure (Fig. S8). The difference in energy between these configurational states is small. This therefore requires that we look at these calculated results within the context of our experimental data to identify the most likely ground states. Furthermore, ab initio calculations do not overtly include the consequence of finite size effects, because of the periodic boundary conditions used. The net component of polarization along [010], in the achiral structure would lead to polarization charges at the surfaces of a real sample, destabilizing this achiral state with respect to the chiral geometries. Polar reconstructions at the lateral surfaces by mobile carriers are unlikely because the superlattices are highly insulating. Even though we cannot rule out all screening mechanisms that might help stabilize achiral textures, we emphasize that only the chiral polar textures are compatible with the experimental XCD results presented earlier. The calculated chiral structures are stable up to higher temperatures, where a transition toward dynamically changing polar textures is predicted (Fig. S7).

The helicity density (31), defined as \( H = \int \vec{p} \cdot (\nabla \times \vec{p}) d^3r \), and the sign of this scalar field, \( \gamma = \text{sign}(H) \), allow an unambiguous classification of the handedness of a given polar core (Fig. 5 D–F), and its volume integral over the clockwise and anticlockwise pair defines the overall chirality of the system. The handedness is identical for both cores in Fig. 5 A, leading to a net positive helicity (Fig. 5 G), and positive XCD for positive \( \phi_{\text{spot}} \) in Fig. 3 A. Spatial agreement between Fig. 5 G and the azimuthally robust polarization texture (averaged for \( \Phi = 0 \) and \( 180^\circ \) in Fig. 3 C) identifies the helicity of alternating polar cores as the primary source of XCD. Within the central PbTiO\(_3\) layers of these chiral arrays, the electric polarization forms a helical structure (Fig. S1) similar to Fig. 2A. In this context, the helicity number simultaneously describes the handedness of the individual cores and the handedness of the collective helical rotation within each layer (Helicity of Calculated Polarization Textures).

The polarization texture in Fig. 5 C is a mirror image of Fig. 5 A, with opposite handedness, net negative helicity, and an XCD signal that must be opposite in sign. Both enantiomers coexist as macro-scale domains in the XCD map shown in Fig. 1 D. The axial components of polarization in Fig. 5 could potentially be visible in planar view HR-STEM or dark-field transmission electron microscopy (TEM) images. In practice, however, variations in the strength and orientation of the axial polarization as a function of depth act to dilute the signal below detection limits (Fig. S8).

This discovery of chirality in PbTiO\(_3\)/SrTiO\(_3\) superlattices stemming from helicity of the modulated polar arrays is of profound fundamental importance and poses new lines of inquiry. The most exciting discovery is the design of an emergent chirality into a material using arrays of blocks that do not inherently exhibit chirality. In contrast to other chiral crystals with a well-defined handedness that cannot be changed, such as \( \alpha \)-quartz, here it should be possible to switch between the two energy-degenerate enantiomers. Such control could be intrinsically affected by a yet unrealized electrical analog to the Dzyaloshinskii–Moriya interaction, or extrinsically by electrically poling the cores of the chiral textures on a local scale to reverse their axial components. By extension, one might also control optical (32) or magnetic (33, 34) properties of other materials coupled to the polar textures. Additionally, there is reason to believe that these chiral structures could posses a negative index of refraction (28), applicable in tunable frequency oscillators and filters for communication devices.

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Fig. 3. Rotational symmetry of chiral polar arrays observed in azimuthal pattern of XCD. (A) XCD intensity plotted versus azimuth, \( \phi_{\text{spot}} \), for each diffraction spot from the polar arrays. Red circles indicate XCD > 0; blue squares indicate XCD < 0. Filled markers were measured at \( n_a = 3 \); hollow markers were measured at \( n_a = 4 \). Gray regions show experimentally inaccessible sample geometries. (B) Diffraction patterns for two sample orientations (separated by 180° azimuthally) exhibit similar XCD (red and blue circles) relative to the scattering geometry: \( \Phi = 0^\circ \) (Left) and \( 180^\circ \) (Right). Curved arrows indicate \( \phi_{\text{spot}} \); green arrow, measured from the in-plane projection (dashed green arrow) of the incoming X-rays. Sample is depicted with counter-rotated polarization cores (small black arrows) and alternating axial polarization (green and magenta) domains. (C) Polarization structure is averaged over both orientations in the (010), cross-section. These polar cores possess a chiral texture that is robust versus a twofold rotation. Error bars in A represent uncertainty in fitting the XCD spectra at each azimuth (Azimuthal XCD Measurements).
Deposition and Structural Characterization of Thin Film Superlattices. Superlattices of \((\text{SrTiO}_3)_n/(\text{PbTiO}_3)_n\) were synthesized on \(\text{DyScO}_3\) (110) substrates by pulsed laser deposition. Here \(n\) refers to the thickness in unit cells of respective materials oriented along the [001]pc (pseudocubic) direction, defined relative to the orthorhombic substrate as [001]pc // [110]O; [100]pc // \(\frac{1}{2}C_22\frac{1}{2}110\); and [010]pc // [001]O. Superlattice films were grown to a total thickness of 100 nm and were monitored throughout using Reflection High Energy Electron Diffraction (RHEED) in situ characterization; they exhibited Frank–van der Merwe growth mode. Various characterization techniques such as XRD, Rutherford back scattering (RBS), and TEM were employed to ensure structural and chemical homogeneity of superlattice films (5).

Detecting Chirality by RSXD. Synchrotron-based resonant diffraction experiments were performed at the Advanced Light Source, using the scattering endstation at beamline 4.0.2. Polarization and photon energy of the X-ray source

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**Fig. 4.** Resonance profiles for \((\text{PbTiO}_3)_n/(\text{SrTiO}_3)_n\) superlattices through the titanium L\(_3\) edge at (A) \(q_{\text{lateral}} = +q_{\text{pair}}\) for \(n = 14\) and (B) \(q_{\text{lateral}} = +q_{\text{domain}} = +2\pi d_{\text{domain}}\) for \(n = 4\), where \(d_{\text{domain}} \approx 70\) nm. (Upper) The polarization-averaged diffraction intensity (red) for both X-ray helicities, and (Lower) XCD (green). Insets show planar view HR-STEM images of (A) an array of polar cores ordered along [100], (horizontal scale bar: 50 nm) and (B) an array of ferroelectric \(a\) domains ordered along [110], (horizontal scale bar: 200 nm). Superlattices with chiral polar arrays exhibit strong XCD in A that is characteristic of the chiral arrangement of electric polarization in the texture. In superlattices with smaller layer thickness, the polarization arranges into periodic \(a\) domains only, with no chiral structure and correspondingly negligible XCD.

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**Fig. 5.** Second-principles calculations of electric polarization textures and their topological properties for \(n = 10\). (A–C) Three different local minima, degenerate in energy. Each texture contains a pair of counterrotated cores yet has different chiral properties. Black arrows indicate the local dipoles, projected onto the (010) plane. A large axial component of the polarization along \(\pm [010]_x\), represented by the green and magenta domains, is observed. (D–F) Simplified cartoon with cylinders representing the cores and arrows that show their rotational and axial polarization components. A right-hand rule reveals the chirality of each cylinder. By curling one’s fingers in the direction of polar rotation around the core, the thumb points (anti-)parallel to the axial polarization for a (left-) right-handed core. (G–I) Maps of helicity. When the handedness of the two cores is the same, the system as a whole is chiral and the enantiomers can be distinguished by the sign of the integrated helicity \(\langle \mathcal{H} \rangle\). Results obtained at temperature of 10 K.
were tuned by an elliptically polarizing undulator. Intensity of X-rays scattered by the sample were measured using an in-vacuum CCD, and background dark counts were subtracted with an out-of-plane modulation. The CCD detector was also used to record X-ray absorption spectra via fluorescence (RSXD Measurements) and monitor small shifts in the diffraction peak position as a function of photon energy due to dynamical scattering effects (RSXD Peak Shifts and Fig. S9).

Resonance profiles were measured by tuning the photon energy through the titanium $L_{2,3}$ edges ($-450$ eV to $470$ eV), while sample and detector angles were adjusted to maintain the Bragg condition for each energy. The satellite features have an out-of-plane modulation (284:2166 × for the polarization-averaged curve).Photon energy was fixed at the most intense feature in the resonance profile, identified as having $f_{g}$ character ($-456.5$ eV).

All measurements were performed with nearly 100% circularly polarized X-rays. Data were collected in pairs, with helicity of the circular polarization reversed for each energy (resonance profiles) or momentum vector (reciprocal space line cuts). XCD (RSXD Measurements) was calculated as the difference of the scattered intensity for the two helicities; subtraction was performed after normalizing the scattered intensities.

Azimuthal data in Fig. 3A were collected from three diffraction spots, two of which were $q_{\text{azimuth}} = q_{\text{lateral}}$ for the primary ordering direction, [100]/[001] (Azimuthal XCD Measurements and Fig. S10 A–C). The third diffraction spot was $q_{\text{azimuth}} = q_{\text{lateral}}$ for the secondary ordering direction, [100]/[110]. The sample azimuth (b) was adjusted to vary the azimuth ($\phi_{\text{sample}}$) of each scattering vector direction in Fig. S10 D–F. XCD resonance profiles were collected at each azimuth, then normalized and fitted by a reference spectrum (Azimuthal XCD Measurements).

The chirality map in Fig. 1D displays the XCD measured in the primary diffraction spot, $q_{\text{azimuth}} = q_{\text{lateral}}$ with $\phi_{\text{sample}}$ fixed near +90°. XCD intensity was recorded at fixed diffraction geometry while scanning the sample, with the effect of rattering the X-ray beam across the surface of the sample.

Second-Principles Simulations of PbTiO$_3$/SrTiO$_3$ Superlattices. The superlattice potentials are identical to those used in ref. 28. We include in-plane lattice distortions of $0.2^\circ$ and $0.3^\circ$, to minimize the underestimate of the lattice constant due to the well-known overbounding error of the local density approximation, which is the first-principles theory used to compute the parameters of our model, an external expansive hydrostatic pressure of ~11.2 GPa is imposed.

For computational feasibility, we have focused on a simulation supercell made from a periodic repetition of 2$n^* 
 \times 2\times 2n^*$ elemental perovskite unit cells, sufficient to mimic the supercell size of the two-dimensional array. We solved the models by running Monte Carlo simulations typically comprising 10,000 thermalization sweeps, followed by 40,000 sweeps to compute thermal averages. We ran Monte Carlo simulated annealing down to very low temperatures to perform structural relaxations and find the ground state or metastable solutions. Additional details of the simulation parameters and the resulting structures are discussed in Second-Principles Calculations.

Local polarizations are derived from a linear approximation of the product of the Born effective charge tensor times the atomic displacements from the reference structure positions divided by the volume of the unit cell. From the complex polarization texture, we can compute the helicity density as proposed by Moffatt (31). A detailed description of the helicity calculations and the polar texture chirality is found in Helicity of Calculated Polarization Textures.

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