

Nanoscale Mapping of Magnetic Orientations with Complex X-Ray Magnetic Linear Dichroism

Marina Raboni-Ferreira^{1,2,3,*}, Benedikt J. Daurer⁴, Jeffrey Neethirajan,¹ Andreas Apseros^{5,6}, Sandra Ruiz-Gómez^{1,7}, Burkhard Kaulich,⁴ Majid Kazemian⁴, and Claire Donnelly^{1,†}

¹Max Planck Institute for Chemical Physics of Solids, 01187 Dresden, Germany

²Gleb Wataghin Institute of Physics, University of Campinas, 13083-859 Campinas, Brazil

³Brazilian Synchrotron Light Laboratory, Brazilian Center for Research in Energy and Materials, 13085-970 Campinas, Brazil

⁴Diamond Light Source, Harwell Science and Innovation Campus, Didcot OX11 0DE, United Kingdom

⁵Laboratory for Mesoscopic Systems, Department of Materials, ETH Zurich, 8093 Zurich, Switzerland

⁶PSI Center for Neutron and Muon Sciences, 5232 Villigen PSI, Switzerland

⁷ALBA Synchrotron Light Source, 08290, Cerdanyola del Valles, Barcelona, Spain



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Compensated magnets are of increasing interest for both fundamental research and applications, with their net-zero magnetization leading to ultrafast dynamics and robust order. To understand and control this order, nanoscale mapping of local domain structures is necessary. One of the main routes to mapping antiferromagnetic order is x-ray magnetic linear dichroism (XMLD), which probes the local orientation of the Néel vector. However, XMLD imaging typically suffers from weak contrast and has mainly been limited to surface-sensitive techniques. Here, we harness coherent diffractive imaging to map the complex XMLD spectroscopically, and identify the phase linear dichroism as a high-contrast, high-resolution mechanism for imaging magnetic order. By applying x-ray spectroptychography to a model sample, we retrieve the full complex XMLD spectrum. Combining this with hierarchical clustering, we resolve the spatial distribution of probed domains by their distinct spectral signatures, providing a robust method for analyzing magnetic configurations with weak signals. Our results show that phase contrast is significantly stronger than the corresponding absorption contrast, offering higher spatial-resolution magnetic imaging. This approach establishes a reliable element- and orbital-sensitive tool for studying compensated magnets.

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Introduction—Compensated magnets are systems with spin arrangements resulting in minimal or net-zero magnetization [1]. These materials are promising due to their intrinsic properties, including being robust to stray magnetic fields, ultrafast spin dynamics in the terahertz range, rapid domain wall motion [2–4], and diverse electronic behaviors [5–9]. Once limited to exchange-coupled pinning layers in ferromagnet-based devices, they now play primary roles in antiferromagnetic (AF) spintronics [2–5], driven by breakthroughs in electrical control of the Néel vector orientation [10–12], recent discoveries of antiferromagnetic topological spin structures (e.g., meron-antimeron pairs [13]), and magnetoelectric effects [14,15].

As AF spintronics advances, applications demand precise control of nanoscale magnetic configurations. Mapping AF domains, identifying pinning centers, and tracking their motion are essential for understanding these systems' response to electrical currents, especially for homogeneous and reversible domain switching [2,16,17]. These demands for nanoscale characterization techniques grow as interest expands to more complex compensated magnets such as altermagnets, which combine the net-zero magnetization of antiferromagnets with the time-reversal symmetry breaking, and some spintronic effects of ferromagnets [18].

Despite their potential, the net-zero magnetization of compensated magnets challenges conventional techniques sensitive to the magnetization or magnetic induction. X-ray magnetic linear dichroism (XMLD) provides a mechanism to probe local Néel vector orientations [19–21]. So far, most studies have relied on surface-specific x-ray photoemission electron microscopy (XPEEM) [22–27]. However, imaging beyond the surface requires transmission-based techniques, where weak contrast and small domain sizes can be challenging. Thus, suitable methods with high sensitivity and spatial resolution are required.

*Contact author: marina.raboniferreira@cpfs.mpg.de

†Contact author: claire.donnelly@cpfs.mpg.de

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Here, we present quantitative high-contrast nanoscale imaging of magnetic orientations using XMLD spectroptychography. By combining complex coherent imaging with an unsupervised machine learning data analysis strategy, we identify low-contrast magnetic domains and demonstrate that phase-linear magnetic dichroic imaging offers higher spatial resolution and signal-to-noise ratio than absorption-based contrast for nanoscale studies of compensated magnets. The high-contrast phase linear dichroism, combined with the potential of diffraction-limited coherent imaging, offers a route to sub-10 nm resolution of ferromagnetic and antiferromagnetic configurations. Moreover, integrating coherent diffractive imaging with advanced computational methods to identify magnetic configurations has promising implications for compensated magnets, key for advancing spintronic applications.

X-ray magnetic linear dichroism: When magnetic materials are probed with polarized x-rays near an absorption edge, their scattering and absorption cross sections depend on the orientation between the incident x-ray polarization and the material's magnetic axis. This resonant magnetic scattering (see Appendix A), enables element-selective studies of magnetic configurations. From this, two main contrast mechanisms arise. First, x-ray magnetic circular dichroism (XMCD), which probes net magnetic moments along the beam direction, and is therefore ideal for probing ferro- and ferrimagnets. Second, XMLD is sensitive to the orientation of moments in the plane perpendicular to the beam, making it well-suited for studying both ferromagnetic and antiferromagnetic systems.

Combining XMLD with nanoscale microscopy has revealed key features of compensated magnets, including the response of domains to external stimuli [17,24,28], as well as the structure of domain walls [26,29] and topological structures [13,25]. Most XMLD microscopy has used XPEEM [16,17,24–27,30], which offers surface-sensitive imaging with typically ~ 30 – 50 nm resolution. While transmission-based techniques, like scanning transmission x-ray microscopy [31,32] and Fourier transform holography [33], have been successfully demonstrated, XPEEM remains widely used. This is because it enables surface-sensitive imaging of conductive samples—both bulk and thin films on bulk substrates—with high sensitivity, making it particularly suitable for detecting the typically weak XMLD contrast in a wide range of systems. With growing interest in topological textures and emergent phenomena in new materials like altermagnets [18,27,34], there is growing demand for imaging methods with high contrast, nanoscale spatial resolution, bulk sensitivity, and applicability to materials with diverse electronic properties and under complex *in situ* conditions. To this end, the employment of coherent diffractive imaging (CDI) techniques like x-ray ptychography, which offer prospects of diffraction-limited resolution and high sensitivity, represents another promising yet underexplored opportunity.

X-ray ptychography: X-ray ptychography is a scanning form of CDI that can overcome key limitations of traditional x-ray microscopy approaches—for example, going beyond the limits of x-ray optics to diffraction-limited spatial resolutions [35,36]. Employing robust phase-retrieval algorithms, it reconstructs images from far-field diffraction patterns, recovering the full complex transmission function of an object as $T(E) = A(E)e^{i\phi(E)}$, enabling both amplitude (A) and phase (ϕ) contrast imaging.

Recently, x-ray ptychography has proven to be highly advantageous for magnetic materials, allowing for the imaging of multiferroic spin spirals with high spatial resolution [37], providing high sensitivity for nanoscale imaging of extended systems with hard x-rays [38], which paved the way to vector magnetic tomography [39], and providing single polarization dichroic imaging with multimodal reconstruction methods [40]. Moreover, the use of CDI for the recovery of complex XMCD spectra has enabled the separation of elemental contributions to the sample's magnetic signal [38] and highlighted the benefits of phase XMCD, such as enabling the study of thicker samples that were previously challenging for transmission methods [41]. While highly effective for XMCD, CDI for XMLD remains to be fully explored.

XMLD spectroptychography—To assess the benefits of CDI for magnetic linear dichroism, we map the full complex XMLD signal of a multidomain system with spectroptychography. Experiments were performed at the I08-1 instrument of Diamond Light Source, using a coherent x-ray beam with linear vertical (LVP) or horizontal polarization (LHP). A ~ 1 μm probe was defined at the sample position using a Fresnel zone plate and order sorting aperture [Fig. 1(a)]. Coherent diffraction patterns were collected in the far field on a sCMOS detector by scanning the sample in overlapping spiral paths [Figs. 1(a) and 1(b)] across the Fe $L_{2,3}$ edges. Images were reconstructed using the Python-based framework PtyPy [42].

XMLD spectroptychography was performed on a lithographically patterned permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) microsquare (Appendix C) exhibiting a Landau pattern: a vortex configuration with triangular in-plane ferromagnetic domains induced by shape anisotropy [Fig. 1(c)]. This well-known multidomain configuration represents an ideal test sample for the exploration of XMLD, as XMLD probes spin-axis orientation rather than magnetization direction, which is equally applicable to both ferromagnets and antiferromagnets.

We obtained single-polarization (LVP and LHP) images [Figs. 1(d) and 1(e)], which combine electronic density and magnetic contrast. To isolate the magnetic contribution, we align, normalize, and subtract the two images, generating the XMLD image [Fig. 1(b)], as explained in Appendix D. The XMLD image [Fig. 1(f)] reveals triangular domains with opposite contrast, corresponding to horizontal and

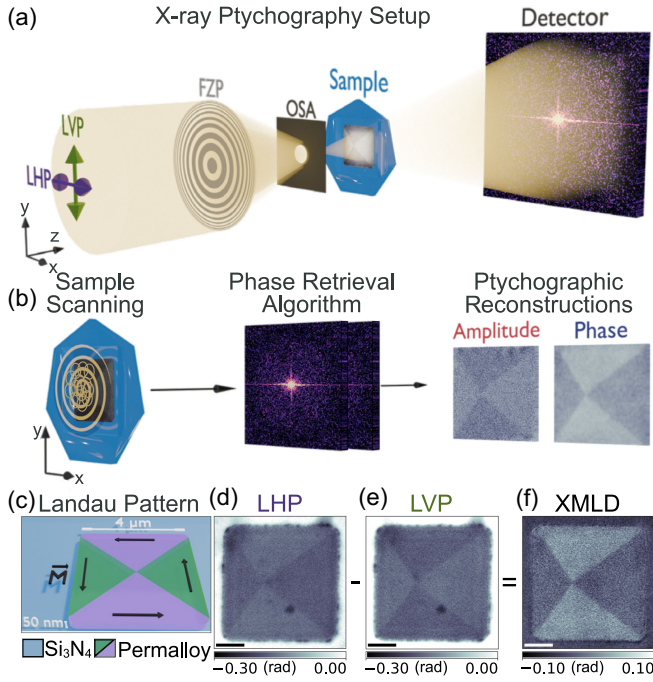


FIG. 1. Dichroic x-ray ptychography setup and XMLD imaging. (a) Schematic of the setup: a coherent x-ray beam with LVP or LHP polarization is focused through a Fresnel zone plate (FZP) and order sorting aperture (OSA) onto the sample, with diffraction patterns captured by the detector. (b) The permalloy thin film on a Si_3N_4 membrane forms a Landau pattern (c) and is scanned in overlapping positions along a spiral path. Each diffraction pattern is processed with an iterative phase retrieval algorithm, yielding phase- and amplitude-contrast images. (d), (e) Subtracting LHP and LVP images yields the XMLD contrast image (f). Scale bar: 1 μm .

vertical in-plane magnetization [Fig. 1(c)], consistent with the expected Landau pattern. The triangular domains meet at a vortex core, slightly shifted due to the presence of a small magnetic field in the setup. The contrast arises from linearly polarized light interacting strongly with magnetization parallel to the polarization direction and weakly with perpendicular magnetization. We next analyze the energy dependence of the magnetic contrast comparing phase and absorption spectra.

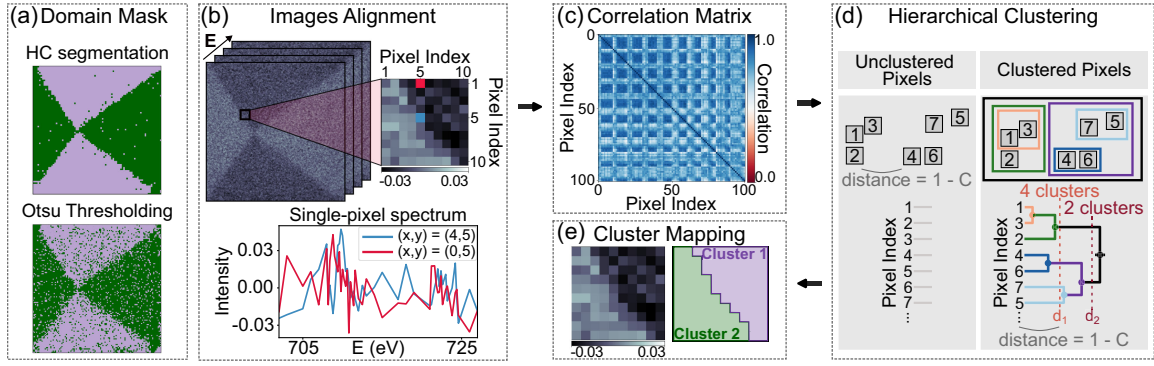
Spectroscopic hierarchical clustering: To extract the energy dependence of the complex dichroism, the identification of domains in the sample is necessary. While for strong signals, domain segmentation is feasible through image thresholding [41] or by leveraging prior knowledge of the sample’s properties, the application to unknown samples, small signals, and/or fewer statistics can be challenging. Here, although the magnetic domains are visually discernible at the $\text{Fe } L_3$ edge [710 eV, Fig. 1(f)], the low contrast and high noise leads to high variability in pixel spectra [Fig. 2(b)], complicating standard segmentation techniques such as Otsu thresholding [lower image in Fig. 2(a)] and requiring a more sophisticated approach.

To segment the magnetic domains, we apply the unsupervised machine learning technique of hierarchical clustering [43], bypassing the need for prior knowledge of the sample and achieving robustness to noise through data correlation. Our approach segregates the regions based on a physical property: the absorption or phase x-ray spectrum of each pixel. As illustrated in Figs. 2(b)–2(e), firstly, all normalized single polarization images are aligned via subpixel registration methods [44,45], ensuring consistent pixel correspondence across different energies [Fig. 2(b)]. Next, each single-pixel spectrum forms a vector, and the vector array is then used to construct a pixel-to-pixel correlation matrix, capturing the degree of similarity (values close to one) or dissimilarity (values approaching zero) between the spectra of individual pixels. In Fig. 2(c), the correlation matrix for a 10×10 pixel region [inset of Fig. 2(b)] is shown. The main diagonal values are one (self-correlation), while squarelike regions of high correlation represent pixels within the same domain, separated by low-correlation elements indicating different domains.

From this correlation matrix, we define a “distance” metric $1 - C$, where C is the correlation value. This value quantifies how each pixel’s spectral behavior differs from others, with higher distances corresponding to pairs of pixels with low correlation. Using the bottom-up hierarchical clustering approach through the linkage method available in SciPy [46], we group the most similar pixels based on the correlation-based metric, progressively clustering pixels with smaller distances (larger correlation) [43] as displayed in Fig. 2(d). Plotting the two clusters with the largest distance—indicating low intercluster correlation but strong intracluster correlation—reveals the perpendicularly oriented magnetic domains of the Landau pattern, as shown in the enlarged region of Fig. 2(e). Applying this approach to the full sample provides a high-fidelity spatial map of magnetic domains and boundaries [Fig. 2(a)], outperforming Otsu thresholding [Fig. 2(a), lower image].

Beyond this mapping of magnetic domains, the principle of hierarchical clustering could be applied to spectroscopic data or hyperspectral imaging in general to identify material phases [47], from oxidation states [48,49] to ferroic order in multiferroics [50], and is compatible with advanced statistical methods such as principal component analysis.

Complex XMLD spectra: Correlation-based hierarchical clustering of the amplitude XMLD image stack yields the domain mask in Fig. 2(a) and enables the extraction of magnetic orientation-specific XMLD spectra (Appendix E). The XMLD ptychography images at eight energies across the $\text{Fe } L_3$ edge are displayed in Fig. 3(a). The corresponding phase (blue circles) and amplitude (red triangles) XMLD spectra at the $\text{Fe } L_3$ and L_2 edges, together with the transmission spectrum (gray), are shown in Fig. 3(b). The amplitude XMLD spectrum [Fig. 3(b)] agrees with literature [22,51], exhibiting the expected signal inversion at L_3 : a dip



at 709.8 eV and a peak at 710.4 eV. The phase spectrum shows a single peak around 710–710.2 eV, where the magnetic contrast is strongest, along with two subtle dips at 709.4 and 710.8 eV. Notably, the phase XMLD spectrum agrees well with the Hilbert transform of the amplitude signal (dashed blue lines), as expected from the Kramers-Kronig relations, highlighting the quantitative capability of phase dichroic ptychography for spectroscopy.

Notably, the XMLD energy dependence contrasts with the XMCD spectra obtained via spectroptychography,

where the phase spectrum exhibits signal inversion, while the amplitude spectrum shows a narrow peak across the L_3 edge [38,41,52]. For XMLD, because the amplitude maxima are offset from the highest absorption (~ 710 eV), good magnetic contrast can be achieved with amplitude-based imaging at higher transmission energies. Finally, phase-contrast XMLD imaging provides sharper features and higher contrast than amplitude, offering a route to higher-resolution imaging of antiferromagnetic structures.

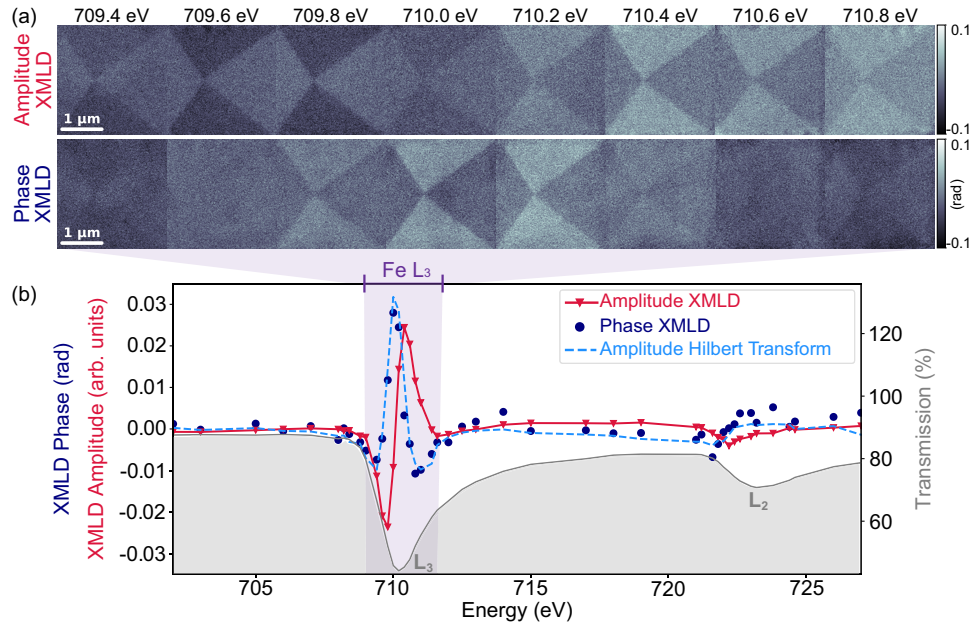


FIG. 3. Energy-dependent XMLD ptychography and complex spectrum of the Landau pattern. (a) XMLD images at the Fe L_3 edge (709.4–710.8 eV) showing amplitude (top) and phase (bottom) contrast, highlighting the magnetic domains. (b) Spectra at the Fe L_3 and L_2 edges: amplitude transmission spectrum (gray), phase XMLD spectrum (blue circles), amplitude XMLD spectrum (red triangles), and the Hilbert transform of the amplitude (blue dashed) yielding the phase signal.

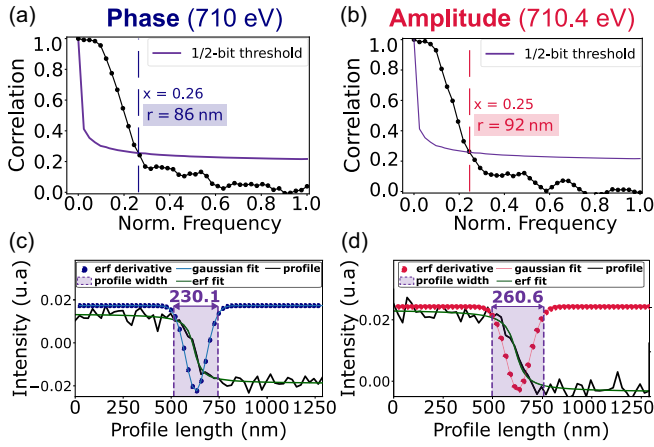


FIG. 4. Spatial resolution analysis at peak contrast energies for phase (blue, 710 eV) and amplitude (red, 710.4 eV) XMLD imaging. (a),(b) Fourier ring correlation with a 1/2-bit threshold, yielding resolutions of ~ 88 nm for phase and ~ 92 nm for amplitude. (c),(d) Average intensity profile perpendicular to a domain boundary (black), with an error-function fit (dark green) and corresponding derivatives (circles); a Gaussian is fitted to the derivative, and domain boundary widths are defined as the full width at 10% of the Gaussian minimum. Panels (c) and (d) show examples for a single domain boundary; all boundaries were analyzed.

Resolution and contrast analysis: Having identified the potential of phase XMLD imaging, we evaluated the spatial resolution of phase and amplitude XMLD at their respective peak contrast energies, 710 and 710.4 eV, using Fourier ring correlation with a 1/2-bit threshold [53]. As shown in Figs. 4(a) and 4(b), the phase XMLD images achieved 86 nm and the amplitude XMLD images 92 nm resolution, with the phase contrast slightly outperforming the amplitude contrast. Intensity profiles across all domain boundaries yield average domain wall widths of 217(11) nm (phase) and 257(33) nm (amplitude) from 10% Gaussian fits [Figs. 4(c) and 4(d)], confirming sharper phase boundaries. Thus, using both analysis methods, the spatial resolution of the phase XMLD consistently surpassed that of the amplitude XMLD signal.

We further investigate the origin of this difference in spatial resolution by calculating the signal-to-noise ratio (SNR) of the phase and amplitude XMLD images (Appendix F), finding that the phase contrast exhibits SNR up to $\sim 46\%$ higher than amplitude at the L_3 edge, reflecting a stronger change in the real part of the refractive index experienced by the linearly polarized x-ray traversing the sample. According to Poisson statistics (SNR approximately scaling as $\sqrt{N}$), roughly twice as many amplitude-based images are required to achieve a comparable SNR at these energies. Consequently, at peak contrast energies, images optimized for phase contrast (710 eV) deposit a dose of $D = 1.79 \times 10^{10}$ Gy onto the sample [54], whereas amplitude contrast (709.6 eV) with equivalent SNR

deposits $D = 2.68 \times 10^{10}$ Gy, suggesting phase-contrast XMLD as a dose-efficient imaging mechanism.

Finally, while single-polarization reconstructions were found to have a spatial resolution of ~ 48 nm, the spatial resolution of the magnetic contrast here (~ 86 – 92 nm) does not match the highest XMLD resolutions reported in literature (30–80 nm [17,25,27,29,30]). This is not a fundamental limitation of the method itself, but rather reflects the practical constraints of this initial experiment. The spatial resolution of x-ray ptychography depends on several factors, including the coherent flux, the sample scattering cross section, the detector dynamic range, the highest accessible scattering vector (Q), and the exposure time. With the advent of fourth-generation synchrotrons, detectors with improved dynamic range [37], and the use of multiple repetitions per energy or scan point [38], XMLD ptychography could approach single-digit nanometer spatial resolution. In such cases, the higher SNR and spatial resolution of the phase XMLD could enable significant advances in imaging antiferromagnetic domain configurations.

Conclusion and outlooks—We have established x-ray magnetic linear dichroic spectroptychography, harnessing linear dichroism and coherent diffractive imaging for high-quality imaging of in-plane ferromagnetic domains. With hierarchical clustering, we perform a physics-informed segmentation of the domains with no prior knowledge of the sample and extract high-quality complex XMLD spectra, recovering the known amplitude spectrum, and mapping the phase XMLD spectrum. Remarkably, we find that phase XMLD imaging provides sharper features, higher spatial resolution, and up to $\sim 46\%$ higher signal-to-noise ratio compared to amplitude XMLD. These features, combined with additional approaches, e.g., measurements with multiple in-plane linear polarizations beyond vertical and horizontal [17,30], establish XMLD spectroptychography as a sensitive tool for investigating a wide range of systems, including complex magnetic structures with heterogeneous domain boundaries and nontrivial spin-axis orientations.

Although demonstrated on a ferromagnet, our results show magnetic contrast governed by the XMLD spectral behavior at the Fe $L_{2,3}$ edges, where strong signals translate directly into high-contrast images. This provides a solid foundation for future applications to compensated magnets with strong XMLD signals, particularly metallic antiferromagnets (e.g., FeRh [55] and FeMn [56]), which display XMLD spectral features similar to permalloy.

The use of hierarchical clustering in this method enables detailed analysis of nanoscale spectral features, which could be applied to the spectroscopic analysis of more intricate magnetic textures or to domain selection based on time- or polarization-dependent contrast changes. As a photon-in photon-out technique, ptychography is particularly well-suited for *in situ* measurements [57–59], including experiments under applied magnetic fields and currents, such as tracking domain evolution under external stimuli

[60]. Moreover, as a transmission-based technique, it opens the door to higher-dimensional imaging such as tomography. For instance, the power of the phase XMLD ptychography could be combined with linear dichroic orientation tomography [61] to provide high spatial resolution tomography of antiferromagnets, mapping three-dimensional antiferromagnetic configurations in real space.

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Data availability—The data and code that support the findings of this article are openly available [62].

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End Matter

Appendix A: X-ray resonant magnetic scattering—The energy-dependent x-ray scattering and absorption cross sections of magnetic materials depend on the relative orientation of the magnetic axis to the incident polarization. This is described by the resonant magnetic scattering factor $f(E, \mathbf{r})$ for dipole-allowed transitions [63,64],

$$f(E, \mathbf{r}) = \underbrace{f_c(E)(\boldsymbol{\epsilon}_f^* \cdot \boldsymbol{\epsilon}_i)}_{\text{Charge}} - i \underbrace{f_m^{(1)}(E)(\boldsymbol{\epsilon}_f^* \times \boldsymbol{\epsilon}_i) \cdot \mathbf{m}(\mathbf{r})}_{\text{Circular Dichroism}} + \underbrace{f_m^{(2)}(E)(\boldsymbol{\epsilon}_f^* \cdot \mathbf{m}(\mathbf{r}))(\boldsymbol{\epsilon}_i \cdot \mathbf{m}(\mathbf{r}))}_{\text{Linear Dichroism}}. \quad (\text{A1})$$

Here, $\boldsymbol{\epsilon}_i$ and $\boldsymbol{\epsilon}_f$ are the incident and outgoing polarization vectors, $\mathbf{m}(\mathbf{r})$ is the magnetization vector, and f_c , $f_m^{(1)}$, and $f_m^{(2)}$ are scattering factors. From

Eq. (A1), XMCD is sensitive to net magnetization $[\mathbf{m}(\mathbf{r})]$ along the beam direction. In contrast, XMLD probes the spin-axis orientation ($\langle m^2 \rangle$) perpendicular to the beam, making it sensitive to magnetic structure in both antiferromagnetic and ferromagnetic systems.

Appendix B: X-ray ptychography experimental setup and images reconstruction—The x-ray ptychography experiments were performed at the I08-1 beamline of Diamond Light Source. A Fresnel zone plate of 333 μm diameter and 70 nm outermost zone width, together with a 25 μm order sorting aperture, focused the beam to a spot of approximately 1 μm at the sample. The sample was scanned in a spiral pattern using piezoelectric stages. At each position, diffraction patterns were recorded with 40 ms exposure using a sCMOS detector (EUV-Enhanced GSENSE400 BSI, Axis Photonique Inc.) with 2048×2048 pixels of 11 μm size, placed 72 mm downstream. Images were cropped to 1024×1024 pixels

and binned to 512×512 , yielding an effective pixel size of $22 \mu\text{m}$. Measurements were taken at 52 energies across the Fe L_3 and L_2 edges with linear horizontal and vertical polarizations. Reconstruction was performed using PtyPy [42] with relaxed average alternating reflection, and maximum likelihood algorithms, each run for 2000 iterations, and a fixed pixel size of 22.611 nm for all energies.

Appendix C: Sample—The 50 nm -thick permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) film was fabricated by e-beam lithography, dc magnetron sputtering and lift-off on a Si_3N_4 transparent membrane. The patterned structure was a square with lateral dimensions of $4 \mu\text{m}$, responsible for inducing the desired shape anisotropy displayed in Fig. 1(c).

Appendix D: Ptychography images normalization—Before calculating the XMLD, all single-polarization images (LHP or LVP) were aligned using subpixel registration methods [44]. Phase-contrast images were corrected for a linear phase ramp. All images were normalized by the background intensity, defined as the average value of a region of interest (ROI) without the sample, according to Eqs. (D1) and (D2), ensuring quantitative spectral information,

$$A_{\text{NORM}} = \frac{A_{\text{sample}}}{A_{\text{background}}}, \quad (\text{D1})$$

$$\phi_{\text{NORM}} = \phi_{\text{sample}} - \phi_{\text{background}}. \quad (\text{D2})$$

The amplitude and phase XMLD images were then computed as the difference between LHP and LVP images, as in Eqs. (D3) and (D4),

$$A_{\text{XMLD}} = \ln(-A_{\text{NORM}}^{\text{LHP}}) - \ln(-A_{\text{NORM}}^{\text{LVP}}), \quad (\text{D3})$$

$$\phi_{\text{XMLD}} = \phi_{\text{NORM}}^{\text{LHP}} - \phi_{\text{NORM}}^{\text{LVP}}. \quad (\text{D4})$$

Appendix E: XMLD spectra calculation—Using the segmentation mask from hierarchical clustering [Fig. 2(a)], we extract domain-specific spectra by analyzing each cluster. The steps for obtaining the complex XMLD spectra are outlined in Figs. 5(a)–5(c). First, we calculate the x-ray transmission spectra by integrating intensities across each domain and polarization separately [Fig. 5(a)]. Next, we compute the difference between the transmission spectra of each domain, yielding the single-polarization spectra shown in Fig. 5(b), which highlight the absorption contrast between regions with perpendicular magnetization. Finally, the XMLD spectrum is defined as the difference between LHP and LVP spectra, producing a signal with a sharp change at the L_3 edge [Fig. 5(c)]. The spectra in Figs. 5 and 3 are shown in arbitrary units but can be

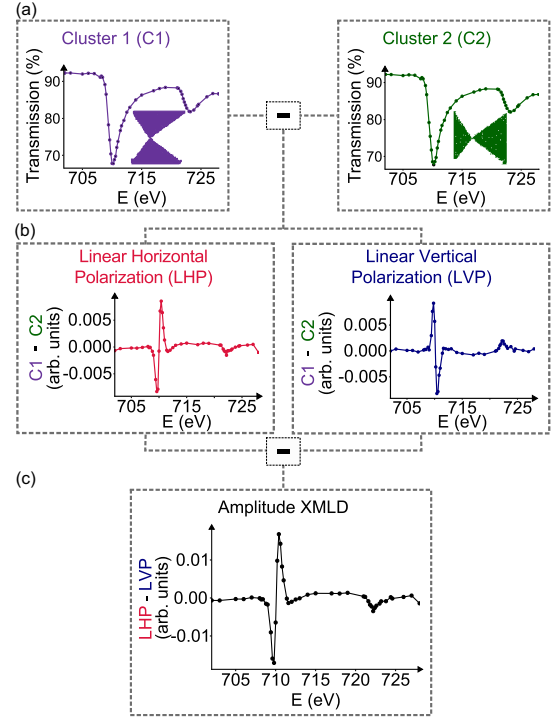


FIG. 5. Steps from the domain mask to XMLD spectrum. (a) Transmission spectra obtained per domain (cluster) and polarization using the hierarchical clustering mask. (b) The difference between these spectra displays the absorption contrast between the magnetic domain regions; this is done separately for LHP and LVP. (c) XMLD spectrum is defined as the difference between LHP and LVP spectra.

expressed as percentages via Eq. (E1), yielding Fig. 6. This shows that phase contrast gives a higher XMLD signal ($\sim 7.1\%$) than amplitude contrast ($\sim 2.7\%$).

$$I_{\text{XMLD}}(\%) = \left(\frac{I_{\text{LHP}} - I_{\text{LVP}}}{I_{\text{LHP}} + I_{\text{LVP}}} \right) \times 100. \quad (\text{E1})$$

Appendix F: Signal-to-noise ratio calculation—We calculate the SNR of the XMLD images as the ratio of the averaged signal to the standard deviation of the

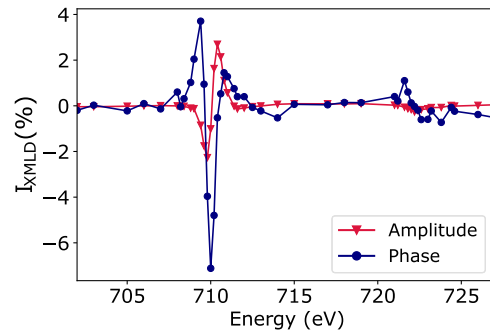


FIG. 6. Complex XMLD spectra for phase contrast (blue circles) and amplitude contrast (red triangles), in percent according to Eq. (E1).

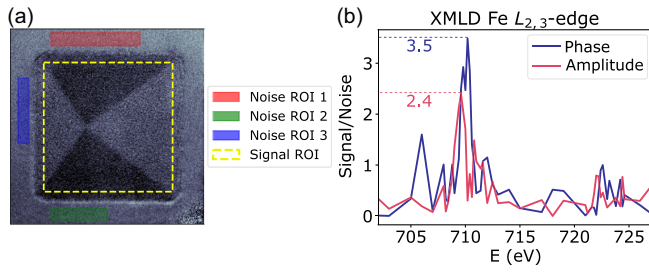


FIG. 7. Real-space SNR analysis. (a) ROIs used for signal and noise estimation: background ROIs for noise (solid boxes) and sample ROI for signal (dashed yellow contour). (b) SNR as a function of energy for amplitude (red) and phase (blue) contrast. Dashed lines indicate maximum SNR values for each contrast.

noise. To estimate the noise, we selected three distinct ROIs within areas of the image that do not contain the sample (i.e., the background). The noise level was approximated by calculating the standard deviation of pixel intensities within these ROIs. These regions were carefully chosen to avoid edges and image artifacts, particularly those observed near the field-of-view boundaries, such as in the lower right corner of Fig. 7, which vary depending on the energy. The SNR, shown in Fig. 7(b), is plotted for amplitude (red) and phase (blue) as a function of energy. The phase SNR peaks at approximately 3.5 at 710.2 eV, while the maximum amplitude SNR of approximately 2.4 occurs at 709.6 eV.