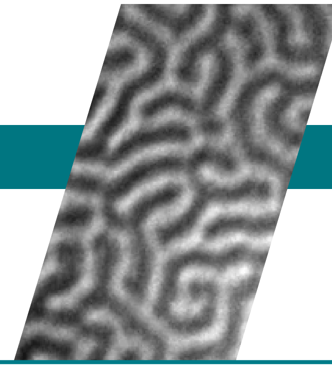
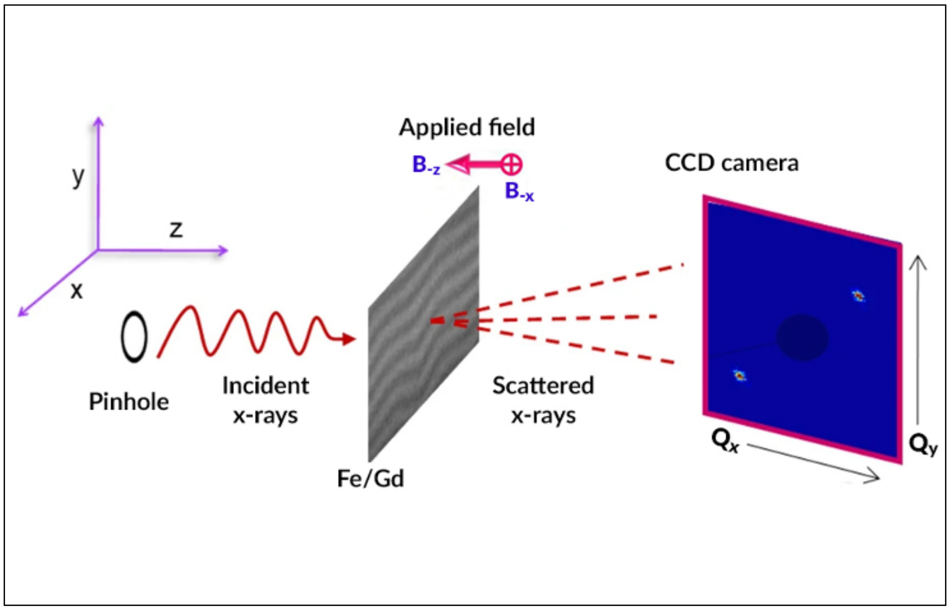
ADVANCED LIGHT SOURCE



MATERIALS SCIENCES

A Novel Staircase Pattern in Spin-Stripe Periodicity



Schematic of the experiment's x-ray scattering geometry. The sample was an iron/gadolinium (Fe/Gd) multilayer in a variable applied magnetic field. A pinhole was used to establish transverse coherence of the x-ray beam, and a CCD camera captured resonant soft x-ray scattering patterns.

Scientific Achievement

At the Advanced Light Source (ALS), striped patterns of spins in a magnetic thin film were found to evolve, under an applied magnetic field, in steps reminiscent of a structure known as the "Devil's Staircase."

Significance and Impact

Such studies are valuable for understanding competing interactions at the atomic level for applications such as magnetic sensors and spintronic devices.

Devilishly complex systems

The "Devil's Staircase" is a peculiar mathematical function that rises continuously but has no slope (i.e., its derivative is zero almost everywhere). This is because it consists of "runs" (flat sections) connected by "rises" that are fractal: each contains successively smaller copies of the main step, to the infinitesimal limit. Similar structures have emerged in phenomena ranging from earthquakes to charge density waves—systems characterized by competing pressures that result in periods of stability punctuated by short bursts of activity.

Here, researchers report the observation of novel staircase patterns in the evolution of spin-stripe domains in an iron/gadolinium (Fe/Gd) multilayer system.

Theoretical modeling that builds on the measurements revealed which of the competing atomic-level interactions in this system is the dominant cause of the staircase structure. The findings help unravel the complex interplay of forces affecting spins in systems relevant to applications in magnetic sensing, information storage, and spintronics.

An achiral dipolar thin film

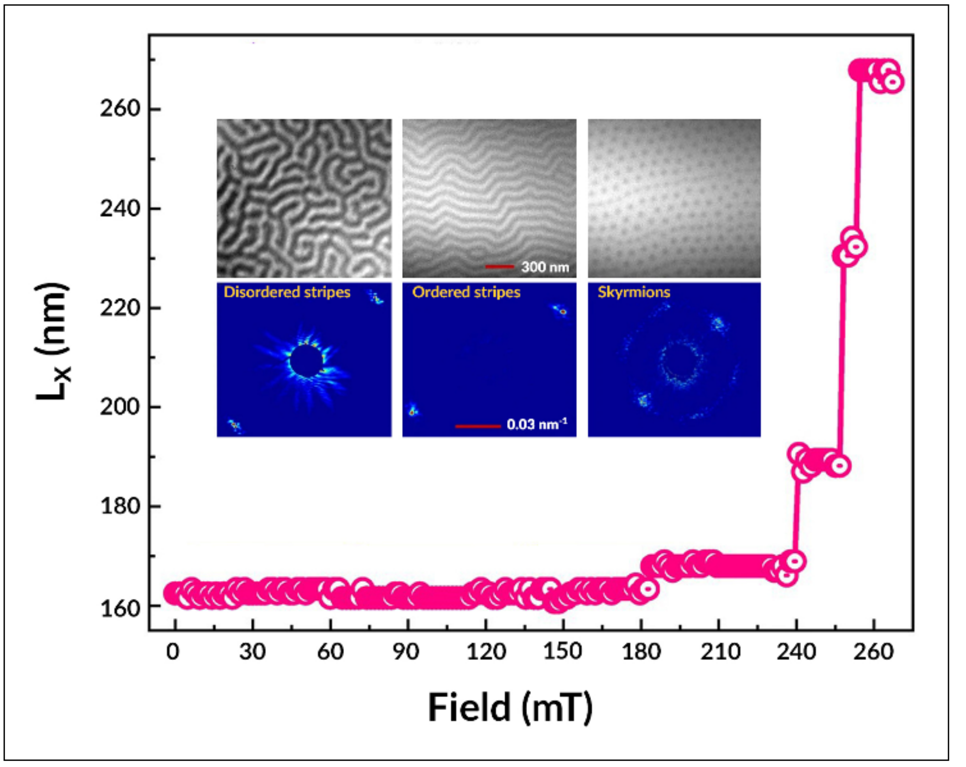
The study's samples consisted of thin films with alternating Fe and Gd layers—a magnetic dipole (spin) system with inversion symmetry and no net chirality. The system exhibits a perpendicular magnetic anisotropy, in which spins align perpendicular to the surface. Thus, the competing interactions include the anisotropy, dipolar interactions (long-range magnetic-field interactions between spins), and exchange interactions (short-range quantum-mechanical interactions).

With these characteristics, Fe/Gd forms achiral stripe phases (ordered and disordered) and skyrmion phases (at higher temperatures and applied magnetic fields). The stripe phases consist of majority domains, where the majority of the spins in the material are aligned in one direction, and minority domains, where the remaining spins are aligned in the opposite direction. Only a limited number of studies have been done on the evolution of achiral magnetic phases and their underlying mechanisms in materials with the above characteristics.

Puzzling out the pattern

In this work, researchers used coherent resonant soft x-ray scattering (RSoXS) at ALS Beamline 12.0.2.2 to study stripe-phase evolution as a function of perpendicular magnetic fields at different temperatures. The coherent beam enhances sensitivity to subtle structural changes in the magnetic domains. From the data, it's possible to extract information about stripe periodicity (the distance between neighboring stripes of the same spin alignment) and the strength of the magnetic order. The data revealed that the stripe periodicity jumps by steps that increase in integer multiples of 7 nm, a value that's close to twice the parameter (exchange length) that governs domain-wall width (≈ 3.2 nm).

According to complementary theoretical simulations, as the applied field increases, enhancement of the majority stripe width is counterbalanced by the minimum minority stripe width, which in turn is governed by the exchange length of the system. The competing tendencies cause a local readjustment of the domain sizes: the pressure exerted on minority domains leads to their local annihilation and domain readjustment. The model indicated that the origin of the staircase pattern lies in the anisotropy effect, because even if exchange and dipole interactions are present, no steps appear in the absence of anisotropy. Overall, the study provides valuable insights and further impetus to study magnetic spin textures, both from an experimental and theoretical viewpoint.



Inset: X-ray microscopy (top row) and scattering (bottom row) images of the sample's magnetic phases: disordered stripes, ordered stripes, and skyrmions. Frame: Graph of the periodicity of the ordered stripe domains (T = 85 K) as a function of applied field. As the field increases, the parameter evolves in a stepwise fashion.

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Publications: A. Singh, J. Li, S.A. Montoya, S. Morley, P. Fischer, S.D. Kevan, E.E. Fullerton, D.-X. Yao, T. Datta, and S. Roy, "Periodicity staircase in a centrosymmetric Fe/Gd magnetic thin film system," *npj Quantum Mater.* **9**, 2 (2024), doi:10.1038/s41535-023-00613-3.

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