How scientists' ability to adapt led to new insights into magnetism

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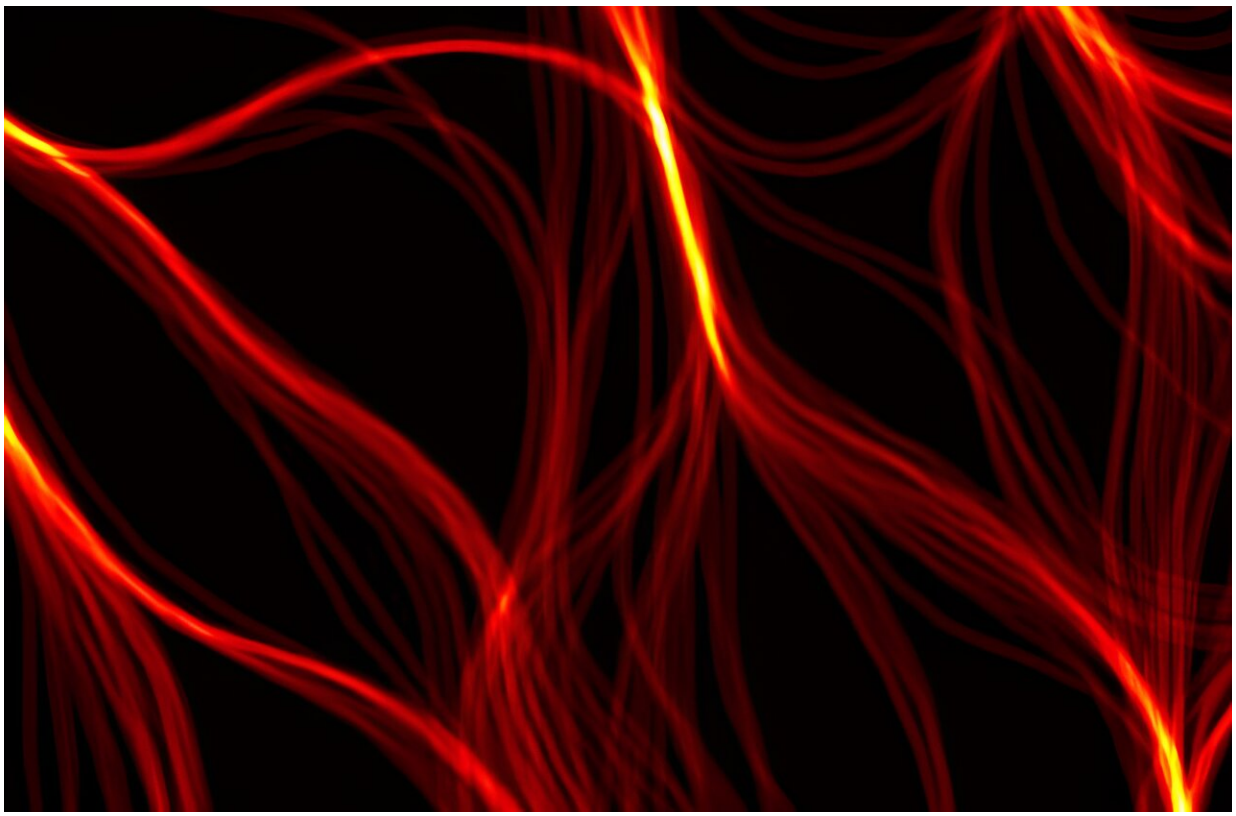

A compilation of where the borders of the magnetic domains accumulated. The brightest areas are the places the domain borders shifted to, again and again. Credit: Brookhaven National Laboratory, Helmholtz-Zentrum Berlin (HZB), the Massachusetts Institute of Technology (MIT) and the Max Born Institute

With time scheduled to use a certain beamline at the National

Synchrotron Light Source-II (NSLS-II), scientists from NSLS-II and their partner institutions faced a challenge. They planned on researching a special type of region in magnetic materials that could be useful for next-generation computers. Regions in magnetic materials—called magnetic domains—determine a material's magnetic properties. The scientists wanted to study how these magnetic domains changed over time under the influence of an outside magnetic field.

But the newly-designed experimental chamber the scientists wanted to use wasn't quite ready yet. Fortunately, the scientists had no lack of subjects they wanted to study.

The NSLS-II team shifted gears to run a very similar experiment on the same subject that could use a different chamber. What they found led to them developing an entirely new technique to take images of magnetic materials in space and time. This technique is now providing detailed insights that have never been possible before.

NSLS-II is a Department of Energy (DOE) Office of Science user facility at Brookhaven National Laboratory. It's a synchrotron light source that provides X-ray beams 10 billion times brighter than the sun. The beams reveal staggering levels of detail in materials. They allow scientists to examine how particles move at the nanoscale level (a strand of DNA is 2.5 nanometers wide). Some of the beamlines can take up to 100 images per second.

Back in 2018, the team originally wanted to use a newly developed instrument for the Coherent Soft X-ray Scattering (CSX) beamline at NSLS-II. They hoped to examine how skyrmions in a magnetic material interact with external stimuli within an external magnetic field. (Skyrmions are a type of magnetic domain.)

With the chamber unavailable, the NSLS-II team slightly shifted the focus of their experiment. With X-rays in a different chamber on the same beamline, they could investigate similar materials under different conditions. They wanted to enhance the effect of thermal motion (random motion induced by temperature) on conventional magnetic domains.

The researchers took a series of images of the magnetic domains at fixed temperatures. Connecting these images together created a short movie, like a flipbook. It showed the thermal motion of the magnetic domains in equilibrium conditions.

The results showed something unexpected. The magnetic domains gave the impression of dancing in a repetitive way around certain configurations.

The result was so intriguing that the researchers wanted to know more about what they saw. To extract meaningful knowledge from the "dance" of the domains, they realized that they needed to develop a whole new technique.

Developing a new scientific technique is far from easy. First, the scientists took an even closer look at the data from NSLS-II. They knew somewhere in all of that data were the details about how and why the magnetic domains moved the way they did.

But before they could do that, they needed to separate out the weak signal coming from magnetic domains from all of the information brought out by the X-rays.

Once they had the information on the magnetic domains' configurations, they compared the still images from NSLS-II to each other. They needed to match similar ones together. While the immense amount of data NSLS-II collects can be a strength, here it created yet another challenge.

There were nearly 30,000 images! It was far too many for a person to sort through. The scientists developed yet another algorithm to tackle it.

As a result of these years of work, the team developed an entirely new machinery and algorithm for taking images of magnetic domains. This was needed because many of the changes in magnetic materials are only visible if you take direct images. But until this point, scientists weren't able to do so. There was always a trade-off between how detailed the image was and how often you were taking images to create the "movie" of the material. Previous techniques ended up with "movies" that were too noisy or too blurry.

The NSLS-II team used their expertise in X-ray techniques to lead the development of a new technique that solved this conflict. The team named it coherent correlation imaging. As the authors said in a paper published in *Nature*, the new technique revealed "the breadth of unexpected physics hidden in fluctuating states of matter."

With this new technique in hand, the team could interpret the data. The black and white images they took showed the magnetic domains as blobs with uneven borders. Running the images like a movie, the scientists saw that the borders of some of the domains moved back and forth. But the borders of others stayed almost completely still.

The team realized that what they were seeing was an example of magnetic "pinning." Scientists already knew pinning was a property of magnetic materials. However, this was the first time it was possible to see the pinning in such detail. These details revealed how the pinning affected the configuration of magnetic domains and their repetitive dance.

The magnetic domains called skyrmions generally act like balls on a flat surface. The random energy of atoms and molecules, like gusts of wind, cause the domains to move around the surface. Pinning creates bumps and valleys on that flat surface. There are some sites that act like valleys, where the magnetic domains are more likely to "roll" into. There are other sites that act like hills that the domains can't pass over.

What the scientists were seeing were the borders of the magnetic domain swaying back and forth but limited in their configuration by these hills and valleys. The borders that moved quite a bit weren't constrained. In contrast, the borders that hardly moved were surrounded by these hill sections that repulsed them. The image above is a compilation of where the borders of the magnetic domains accumulated. The brightest areas are the places the domain borders shifted to again and again. The limited number of configurations available made the system randomly repeat the magnetic configurations available over and over. It was like shuffling steps in a repetitive dance.

Coherent correlation imaging not only allowed the scientists to see these shifts for the first time but also figure out why they were happening. This information is essential for figuring out how to control skyrmions—the eventual purpose of the original study more than six years ago. Skyrmions can be used in a way that mimics human short-term memory, which could be important for artificial intelligence.

But the applications for coherent correlation imaging go far beyond skyrmions. This technique may be useful for all sorts of research into phase transitions in materials. For magnetic domains, coherent correlation imaging has implications for future electronics and beyond.

In the end, the research team turned an unexpected challenge into a big step forward for materials research.

More information: Christopher Klose et al, Coherent correlation imaging for resolving fluctuating states of matter, *Nature* (2023). DOI:

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