Surprising Low-Temperature Domain Wall Fluctuations in Antiferromagnets

33-ID-D,E • XOR/UNI • Materials science, physics, chemistry • Anomalous and resonant scattering (hard x-ray), diffuse x-ray scattering, x-ray reflectivity, surface diffraction, x-ray standing waves, general Diffraction • 3.3-cm Undulator A • Accepting general users

8-ID-E • XOR • Materials science, polymer science, physics • Intensity fluctuation spectroscopy, x-ray reflectivity, x-ray photon correlation spectroscopy, grazing incidence small-angle x-ray scattering • 3.3-cm Undulator A • Accepting general users

Domain formation is inherent in most types of magnetic materials because of their crystal symmetry. In each domain, all of the electron spins are coupled together in a preferential direction, and thermal fluctuations can cause random movement of the boundary walls between domains. In the case of a ferromagnetic material such as iron, this "thermal noise" can be measured by detecting small jumps in the magnetization by using only a tiny coil of wire placed near a sample of the material. But measuring similar fluctuations in antiferromagnetic materials such as chromium (Cr) had not been possible because the magnetic moments of neighboring atoms point in opposite directions, preventing bulk magnetization and making it impossible to detect fluctuations in the domain walls of an antiferromagnet via the use of conventional magnetization probes. Researchers using a beam of coherent x-rays from XOR beamlines 33-ID-D,E and 8-ID-E discovered a way to eavesdrop on the antiferromagnetic domain walls in chromium.

Researchers from Argonne, The University of Chicago, and University College London, employed x-ray photon correlation spectroscopy (XPCS) to exploit the fact that when a disordered material is illuminated by coherent incident radiation, an interference pattern called a "speckle" pattern is observed. This speckle pattern is uniquely determined by the instantaneous spatial distribution of the disorder in the material; if the spatial distribution changes in time, the corresponding speckle pattern will also change, so it is possible to extract information about the dynamics of a disordered system by analyzing the time correlation of one speckle.

It is known that the antiferromagnetism in Cr arises from its conduction electrons, rather than the localized electrons themselves. The electrons surrounding each Cr atom have a magnetization opposite to those of the nearest Cr neighbors. This results in a sinusoidal magnetic structure called a spin density wave (SDW) of wavelength λ = 6 to 8 nm. Although the x-rays could not probe the SDWs directly, each SDW is accompanied by a commensurate electron charge density wave (CDW). The team scattered a coherent beam of x-rays from a Cr sample, and the resulting speckle pattern (Fig. 1) was captured by using a charge-coupled device camera over a period of several hours. The precise appearance of the speckle pattern is related to the arrangement of CDWs in a tiny portion of the sample. By watching how the speckle changed over time, the group was able to observe changes in the antiferromagnetic domains over distances as small as 1 μm. These results cannot be attributed to drift of the x-ray beam, motion of crystalline defects, or other similar experimental artifacts not related to magnetic domain dynamics because the reference speckle sensitive to these motions is stable over at least ~20,000 s, while the speckles related to domain wall structure are completely uncorrelated after 100 s to 3,000 s.

< Fig. 1. By observing changes in the coherent x-ray speckle pattern, researchers can investigate nanoscale dynamics of antiferromagnetic domain walls and observe a crossover from classical to quantum behavior.

In addition, the group observed that domain fluctuations continued, even at temperatures as low as 4K. This result is quite surprising because domain walls are relatively large structures that require a significant amount of thermal energy to move. To account for this unexpected result, the group used measured relaxation times to construct a simple model of electrons hopping across the domain walls, which suggests that at very low temperatures the walls are moving because of quantum tunneling instead of thermal activation.

Antiferromagnetic materials are currently used in read heads for magnetic storage devices, and they show promise for use in spintronic devices, which could make use of both the spin and charge of the electron to process information. However, any future technologies that rely on the precise location of antiferromagnetic domains would be affected by the instability of the antiferromagnetism. The current findings light the way toward engineering stability in these materials; for example, the introduction of defects or impurities in the antiferromagnetic materials would tend to fix the domain locations.

The researchers are now turning their attention to the study of other magnetic materials, including those that can contain both ferromagnetic and antiferromagnetic domains. They also believe that the XPCS technique could be used to study quantum phase transitions in antiferromagnets and to gain insight into ways in which antiferromagnetic nanoparticles might be engineered into a valuable new class of material, one in which magnetization can be switched quickly and with negligible energy loss, ideal for use in high-frequency electronic devices. — *Luis Nasser*

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