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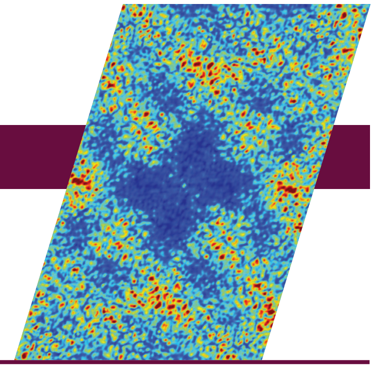
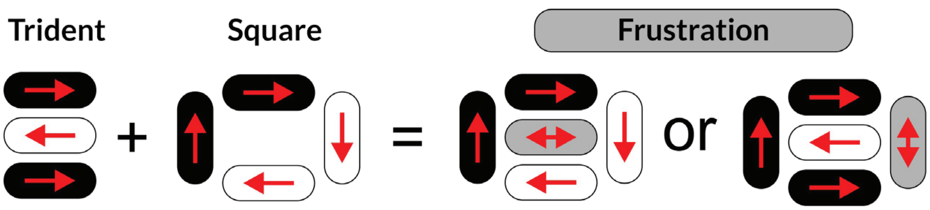
PHYSICAL SCIENCES



Tuning Magnetic Frustration in a Dipolar Trident Lattice



Single-domain nanomagnets can be arranged into trident and square configurations that minimize magnetic interactions with head-to-tail alignments. However, combining the trident and square into a five-magnet block results in at least one "frustrated" nanomagnet (colored gray above) that can point in either of two possible directions—a source of disorder in the system.

Scientific Achievement

Researchers designed and fabricated a nanomagnet array in which competing ("frustrated") magnetic interactions can be directly tuned, enabling detailed studies of the system's properties.

Significance and Impact

Frustrated interactions are key to a wide range of phenomena, from protein folding and magnetic memory to fundamental studies of emergent exotic states.

Geometrical frustration and "spin ice"

When bar magnets are brought together, opposite poles will attract and like poles will repel, and the magnets will arrange themselves accordingly, to minimize energy. However, if the magnets are constrained to a lattice structure where each one has just two possible orientations, some magnets could end up geometrically "frustrated," with neither orientation being lower in energy than the other. The system becomes what's known as a "spin ice," analogous to water ice, which retains intrinsic randomness (residual entropy) even at absolute zero.

Systems incorporating geometrical frustration are fascinating because their hard-to-predict behavior is key to a wide range of phenomena, from protein folding and magnetic memory to the emergence of exotic states of matter. For example, the emergence of magnetic monopole–like excitations in spin ice raises the intriguing possibility of "magnetic-charge" circuitry based on currents of magnetic monopole excitations.

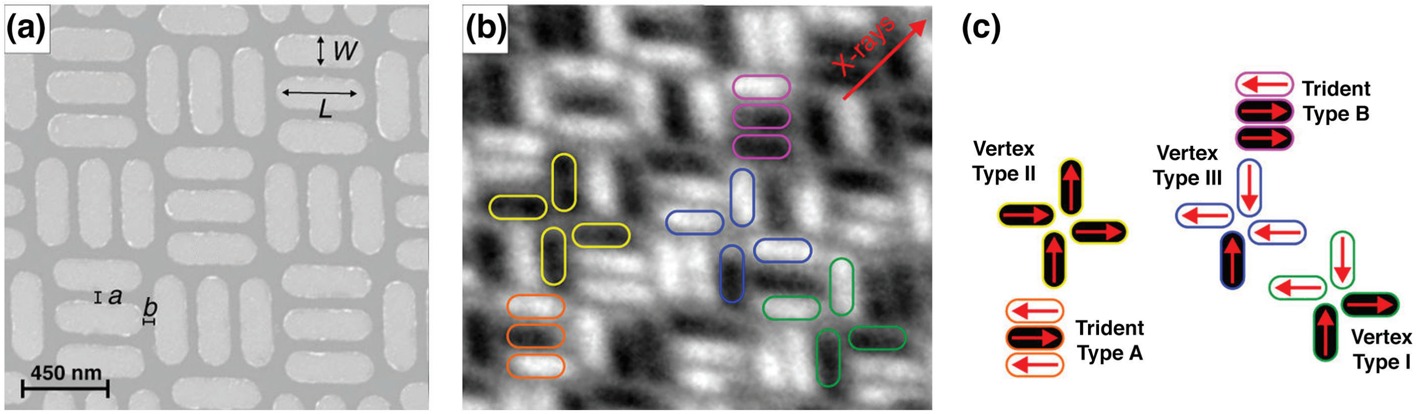
Artificial spin ice systems: the trident

Although real three-dimensional examples of spin ice exist, advanced fabrication techniques enable researchers to design two-dimensional versions that provide greater control over key parameters and are simpler to study. Over the past 12 years, square- and hexagon-based artificial spin ice systems have been investigated extensively, but new geometries exhibiting a higher degree of spin frustration at low temperatures was needed. In this work, researchers came up with an interesting new design: the dipolar trident lattice.

Taking advantage of state-of-the-art electron-beam lithography available at the Molecular Foundry, the researchers created a pattern consisting of tridents that are tiled perpendicularly to each other. Because the nanomagnets couple via dipolar magnetic fields, the system is called a dipolar trident lattice. With full control of the lattice parameters—nanomagnet length *(L)*, nanomagnet width *(W)*, the distance between nanomagnets within a trident *(a)*, and the distance between trident blocks *(b)*—the researchers sought to tune the degree of geometrical frustration in the system.

ALS Beamline 11.0.1 reveals frustration

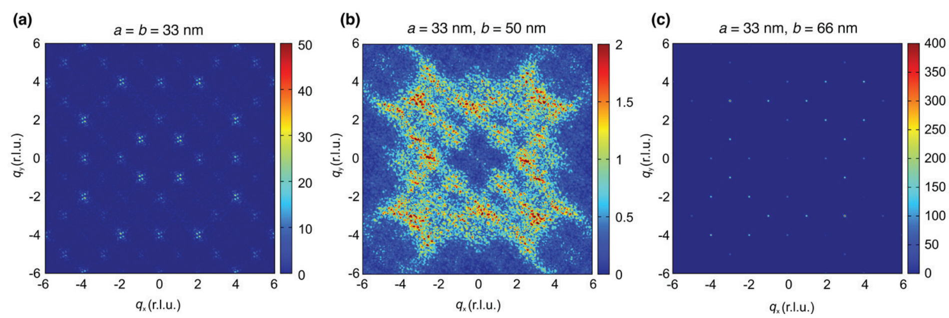
The lattices were visualized at the photoemission electron microscope (PEEM3) at ALS Beamline 11.0.1, using x-ray magnetic circular dichroism (XMCD) at the Fe L_3 edge to show magnetic contrast. The degree of frustration in the system was quantified by looking at the mix of vertex and trident types for different values of the ratio *b/a*. The researchers found that a phase with no clear preference for any vertex or trident type (i.e. a disordered phase) occurred at a *b/a* value of 1.5.



(a) Scanning electron microscope image of a dipolar trident lattice ($L = 450$ nm, $W = 150$ nm, $a = b = 50$ nm). (b) Photoemission electron microscopy (PEEM) image. Dark regions have magnetizations pointing toward the x-ray propagation vector (red arrow); bright regions point in the opposite direction. (c) Examples of the two lattice motifs relevant to this discussion: tridents and vertices. Colored outlines are keyed to corresponding patterns in panel (b). The two motifs can be divided into several types, each with higher or lower energies depending on the magnetic configuration. In order of increasing energy, the types are: tridents—A, B, and C (not shown); vertices—I, II, III, and IV (not shown).

To explore whether this behavior persists at low temperature, the researchers repeated the experiment (with slightly different lattice parameters) at $T = 150$ K. Although long-range order was observed for b/a values of 1 and 2, the array remained disordered for $b/a = 1.5$. Magnetic scattering patterns calculated from the XMCD data provided strong evidence that the researchers were indeed able to tune the lattice between two long-range ordered phases and a highly disordered intermediate phase, down to 150 K.

However, the true ground state of the lattice, where maximum spin frustration is achieved, is still an open question. It will require future work involving experimental developments—such as the improvements in light-source quality associated with the ALS Upgrade (ALS-U) project—as well as advances in theory.



Magnetic scattering patterns calculated from XMCD data for various lattice parameters. While relatively sharp peaks indicative of long-range order are seen in (a) and (c), the diffuse patterns in (b) indicate highly disordered configurations.

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