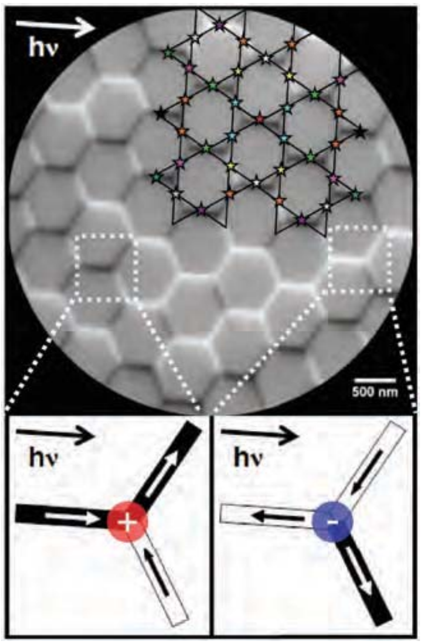
Emergent magnetic charge crystal in artificial dipolar spin ice

Using nanofabrication processes, we have synthesized a mesoscopic assembly of interacting nanomagnets, with statistical properties quantitatively described by an Ising-like spin Hamiltonian. This artificial realization of a spin model has been imaged in real space using a synchrotron-based magnetic imaging technique. The magnetic configurations we obtain after demagnetizing the spin assembly fit well with predictions from Monte Carlo simulations. In particular, we observe the emergence of a phase where spins fluctuate while classical magnetic charges, associated with these spins, crystallize. This phase was predicted theoretically, but never observed experimentally. Our results open the way to the investigation of a wide variety of classical spin models within the concept of the "lab on a chip".

The property called "frustration" arises when all the pairwise interactions in a system cannot be satisfied at the same time, because of a system's symmetry, geometry or topology. In some cases, frustration effects lead to an extensively degenerate ground state, i.e a low temperature manifold built with a large number of configurations with identical energy. Pauling's description of the low-temperature proton disorder in water ice was perhaps the first example of frustration in condensed matter physics, and remains the paradigm. In recent years, a new class of magnetic compounds has been characterized in which the disorder of the magnetic moments at low temperatures is analogous to the proton disorder in water ice, hence the name "spin ice".

Recently, this correspondence between water ice and its magnetic equivalents has been pushed even further with the realization of artificial, two dimensional analogs of spin ice models using nanofabrication techniques. Using lithography techniques, we have made geometrically frustrated arrays of nanomagnets on a kagome lattice, i.e. a lattice of triangles sharing their corners on which the nanomagnets are located (see Figure). The magnetic configuration of each nanomagnet is then determined by X-ray PhotoEmission Electron Microscopy (XPEEM). Due to their elongated shape, magnetization within the nanomagnets can only point along the long axis of the elements. These pseudo spins can also be considered as magnetic dipoles, which allows one to map any spin configuration onto a magnetic charge configuration, the charge at each vertex of the honeycomb lattice being the sum of the pole signs (south = -1, north = +1) of each spin of the kagome lattice participating in the vertex.

A major property of the effective spin Hamiltonian is that, at low temperatures, frustration constrains the spin configurations on each triangle of the kagome lattice such that two spins point inward in the triangle and one outward, or two spins point outward and one inward. This property, also called the "ice rule", is equivalent to constraining the magnetic charge on each vertex of the honeycomb lattice to be equal to plus or minus 1. Combining Monte Carlo simulations and XPEEM magnetic imaging of these artificial arrays, we found an important result. Contrary to what was thought until now, the long range dipolar interaction between the nanomagnets can not be neglected, and actually drives the physics we observe. This result has profound consequences: while the main interest for frustrated compounds arises from the massive degeneracy of their ground state, this degeneracy is fully lifted when long range, dipolar interactions are included in the model.



XPEEM magnetic image of an artificial array of nanomagnets with typical dimension 500x80x10 nm³. The direction of the incoming x rays is indicated by the arrow hν. Black and white contrast is then observed according to the sign + or - of the magnetization component along this x ray direction, as sketched in the two panels below the image. The spin state of each nanomagnet, and thus the magnetic charge carried by each vertex, is measured. The partly superimposed dots highlight the nodes of the kagome lattice.

Understanding whether or not these long range interactions influence the local spin configuration in artificial arrays of nanomagnets is thus essential, especially because these networks are often considered as a playground to study magnetic frustration effects on a mesoscopic scale. To demonstrate this result, we compared predictions from dipolar spin ice models and our experimental observations. In particular, as the system reaches low-energy spin configurations, it goes through a (predicted) phase transition where spins fluctuate while the magnetic charges at the vertex crystallize to form a perfectly ordered pattern of alternating +1 and −1 magnetic charges. The "beauty" of our work was to observe the emergence of the phase in which the magnetic charges crystallize.

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FURTHER READING

ARTIFICIAL KAGOME ARRAYS OF NANOMAGNETS: A FROZEN DIPOLAR SPIN ICE
N. Rougemaille, F. Montaigne, B. Canals, A. Duluard, D. Lacour, M. Hehn, R. Belkhou, O. Fruchart, S. El Moussaoui, A. Bendounan, and F. Maccherozzi
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