Fragmentation of magnetism

In physics as in chemistry, it is well known that matter can become ordered, as for example in a crystalline solid, when cooled to sufficiently low temperature. There also exist systems that remain disordered in the manner of a gas or a liquid, even at the lowest temperatures accessible experimentally. What is much more rare, if ever observed, is a state of matter that would be both ordered and disordered everywhere in the system, *i.e.* that would be both solid and liquid for example.

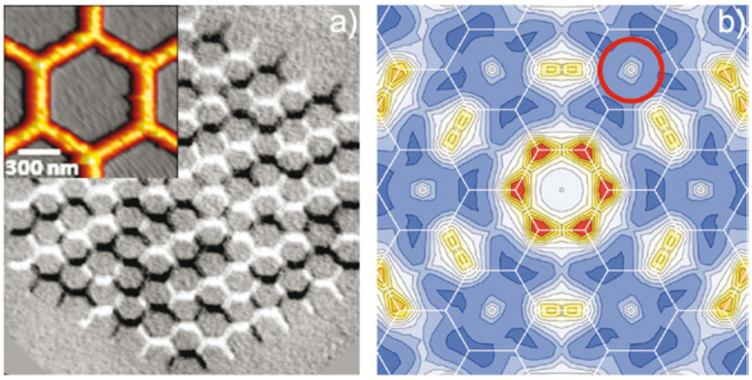

***Fig. 1**: **(a)** Magnetic image (10µm x 11µm) of a honeycomb array of ferrimagnetic-alloy nanomagnets with size approx. 500x100x10 nm³), obtained with a photoemission electron microscopy technique at the ELETTRA facility. The black and white contrast gives the local direction of the magnetization (pointing left or right) within each individual nanomagnet. nset (top left): Topographic image obtained with an Atomic Force Microscope.*

***(b)** Representation in reciprocal space of the magnetic phase reconstructed mathematically (a Fourier transform) from the real space image shown in (a). The diffuse background, associated with the magnetic disorder, appears in yellow. Six Bragg peaks (one of them indicated by a red circle) are also visible. The coexistence of this diffuse background and the Bragg peaks demonstrates the coexistence of magnetic order and disorder here, i.e. "fragmentation" of magnetism.*

Such a phase, simultaneously liquid and solid, can be observed in a magnetic "meta-material". We emphasize here that we are not considering a magnetic equivalent of a glass of water containing ice cubes, which would be, simply, a system presenting a coexistence of two phases, physically separated and out of thermodynamic equilibrium. Instead, what we mean is a magnetic equivalent of a glass of water that would be liquid and ice everywhere in the glass, at any time.

It is difficult to get a mental representation of such a system and it may be convenient to visualize it, not in real space, but in reciprocal space. Indeed, if we could achieve a diffraction pattern of such an exotic state of matter, we would observe two features simultaneously. This pattern would present very intense points in some specific regions of the reciprocal space, called Bragg peaks, associated with the existence of a periodic arrangement and reflecting the symmetry of the solid. But this diffraction pattern would also show a diffuse background signal, associated with the disorder present in the system. It is important to stress once more that these two characteristics of the diffraction pattern would be representative of a state of matter at thermodynamic equilibrium.

In a collaboration with the Nanospectroscopy beamline staff at the ELETTRA synchrotron radiation facility (Trieste), researchers of the Institut NÉEL and the Jean Lamour Institute (at Nancy) have fabricated a magnetic meta-material that exhibits all the characteristics of such an exotic state of matter. This magnetic meta-material is just an array of nanomagnet bars arranged on a lattice having a honeycomb-type hexagonal geometry. When the size of these nanomagnets is carefully chosen, their individual magnetization can be in two states, and in two states only, aligned left or right along the long axis of the bars. We can then shake the system of magnets (using a magnetic field or the temperature) to bring it into a magnetic state that minimizes its configurational energy.

When the state resulting from this process is imaged in real space, the magnetic configuration (the arrangement of left or right orientations of the individual magnets) seems, essentially, disordered. Looking at it more carefully, a trained eye could find some periodic, magnetic patterns (see Fig. 1a). Sometimes, but not everywhere ! This is why it is useful to visualize the resulting magnetic configuration in reciprocal space (Fig. 1b). When doing so, the corresponding "diffraction" pattern shows a coexistence of Bragg peaks and a diffuse background, thus indicating that the system is both ordered and disordered. The challenge is then to demonstrate that this is not a coexistence of two out-of-equilibrium phases, but a state of matter that is both liquid and solid, everywhere in the lattice, at thermodynamic equilibrium.

A detailed analysis of the magnetic configuration reveals that the system acts as if each individual nanomagnet of the lattice was split into two distinct components. For this reason, we say that the magnetism is "fragmented": an internal degree of freedom (the magnetization of the nanomagnets) is somehow cut into two pieces, resulting in a collective phase which is at the same time ordered and disordered, solid and liquid, at thermodynamic equilibrium.

This exotic state of matter is not specific to our artificial magnetic structures: we have also observed it in a bulk compound synthesized chemically. Achieving complete, fine tuning of this fragmentation of magnetism is now an ultimate goal. It would provide new opportunities to understand, realize and control new states of condensed matter, be they artificial or not.

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FURTHER READING...

"Fragmentation of magnetism in artificial kagome dipolar spin ice"
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