**Exploring thermally-induced states in square artificial spin-ice arrays**

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Intrinsic frustration phenomena are widely found in natural systems, as it is the case of water ice with the existing frustration on the hydrogen and oxygen atoms [1]. Another example of naturally occurring frustration is observed in rare-earth alloys, where magnetic frustration is present among the magnetic moments of the rare earth ions due to the crystal geometry of the material. For this reason, these systems are called ‘spin-ice’ systems [2]. Spin-ice physics can be conveniently studied by means of the so-called artificial spin-ice systems, which are arrays of magnetic nanoislands fabricated in different geometries inducing the spin-ice frustration in a 2D system [3,4]. We present a methodology to explore experimentally the formation of thermally-induced long range ground-state ordering in artificial spin-ice systems [5]. Our novel approach is based on the thermalization of a square artificial spin-ice array of elongated ferromagnetic nanoislands made of a FeNi alloy characterized by a Curie temperature about 100K lower than that of Permalloy (Ni81Fe19), which is commonly used for this kind of investigations. The drop of M(T) when the sample is heated close to its Curie temperature, reduces the shape anisotropy barrier of each island and allows us to bring the artificial spin-ice pattern above the blocking temperature of the islands, thus “melting” the spin-ice system, without damaging the sample. The magnetization configuration resulting by the thermal excitation of the islands and the frustrated dipolar interactions among them, can be then imaged by magnetic force microscopy or any other kind of magnetic microscopy imaging after cooling down the sample back to room temperature. The nanomagnets have dimensions of 300x100x25nm, with a lattice parameter of 380nm. We obtained thermal demagnetized states similar to the as-grown magnetization states obtained in [4], and compared them to the demagnetized configurations obtained applying a sample-rotating in-plane magnetic field demagnetization protocol [6] by using Magnetic Force Microscopy, as can be observed in Fig.1. After applying an in-plane rotating field demagnetization protocol to our artificial spin-ice pattern, we obtain short-range ground state spin-ice ordering. Nevertheless, when applying our thermal demagnetization protocol we find long-range ground state spin-ice ordering with a substantial energy reduction of the remanent magnetization state in a repeatable fashion.

### References

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**Figures**

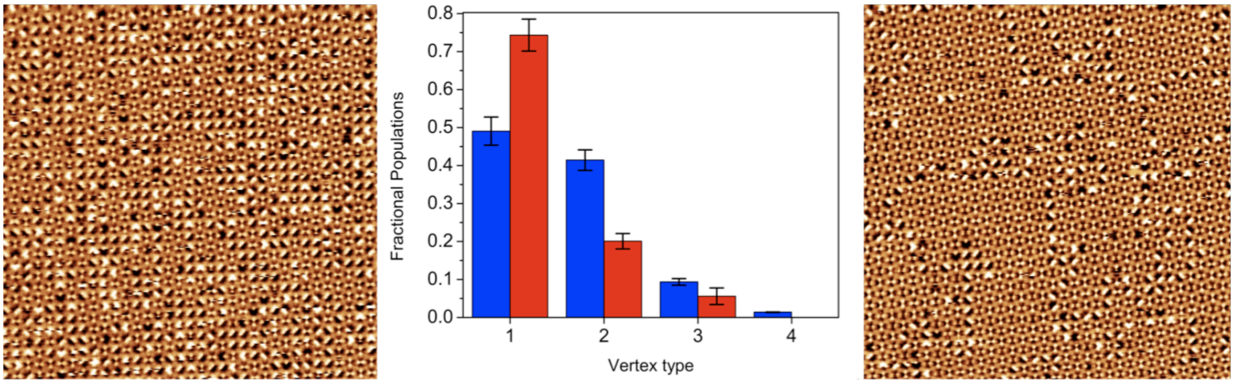


Fig.1: magnetization states after applying a sample-rotating in-plane magnetic field demagnetization protocol (left) and after melting the artificial spin-ice pattern over its blocking temperature (right), and a graphic of the vertex type populations (1-less energetic, 4-most energetic) obtained with the field demagnetization protocol (blue) and the thermal demagnetization protocol (red).