Artificial 'spin ice' in a geometrically frustrated lattice of nanoscale ferromagnetic islands

D. Kochkov, Y. Kulinich, N. Laracuente, Y. Lao

December 6, 2013

Wang, 1. RF, et al. "Artificial spin icein a geometrically frustrated lattice of nanoscale ferromagnetic islands." Nature 439.7074 (2006): 303-306.

Spin ice is a magnetic material whose spin configurations obey ice rules.

- No single ground energy state
- Exhibits magnetic monopole characteristics
- Frustrated interactions

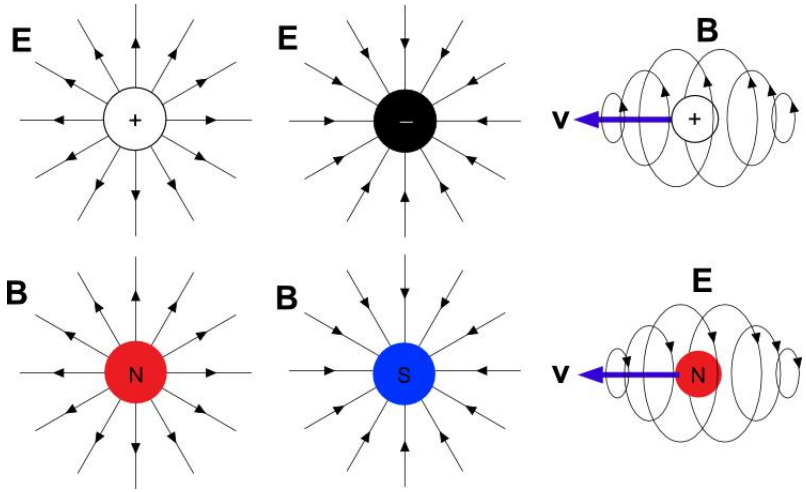


Figure: Electromagnetic Monopoles *en.wikipedia.org*

Figure: Lattice configuration *en.wikipedia.org*

Results
Fabricated magnetic lattice exhibits spin ice behavior

- Fabricated lattice behaves like real spin ice
- Ice rule is applicable for artificial spin ice
- Variations in fabrication allow for the study of spin ice phenomena

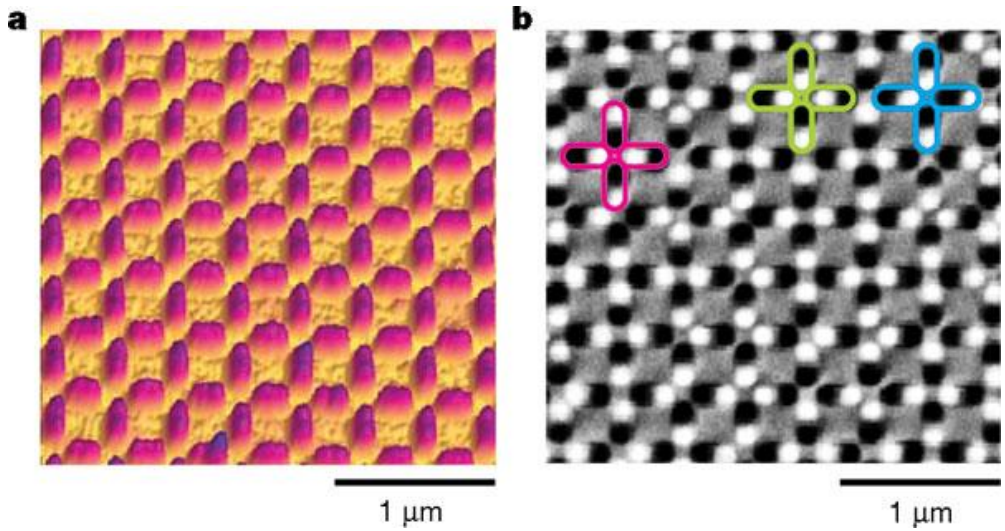


Figure: Resulting fabricated material

Critical Analysis
Object: 2-d Square Lattice

- 2 dimensions
- Fixed size, variable lattice parameters
- Shape anisotropy $\Longrightarrow$ magnetic moment aligned along long axis
- Accessible at room temperature

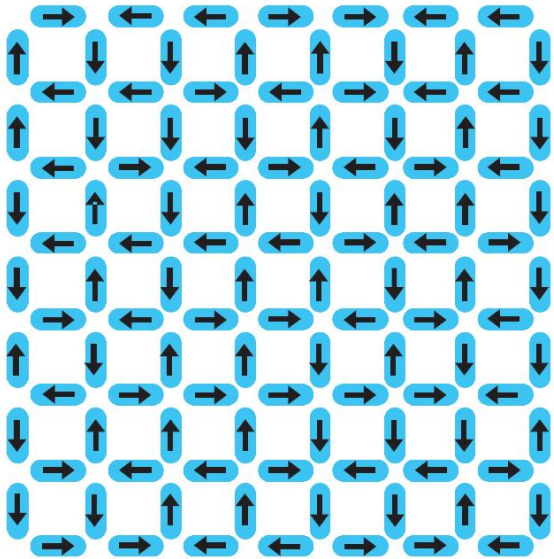


Figure: Artifical of spin ice topology

- Pairs of vertices
- 4 types, 16 multiplicity
- Nondegeneracy present in artificial spin ice not seen in real spin ice

Favourable pair alignments

Unfavourable pair alignments

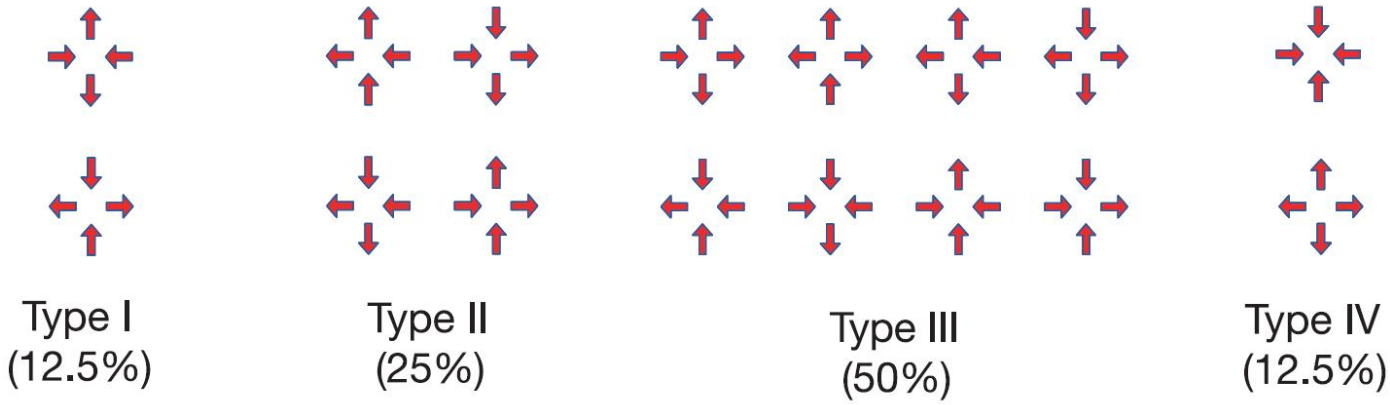


Figure: Topological types

- Fabrication: E-Beam Lithography (Compare with Photolithography)
- Characterization:
  - Atomic Force Microscopy(AFM) $\Longrightarrow$ topology
  - Magnetic Force Microscopy(MFM) $\Longrightarrow$ magnetic phase

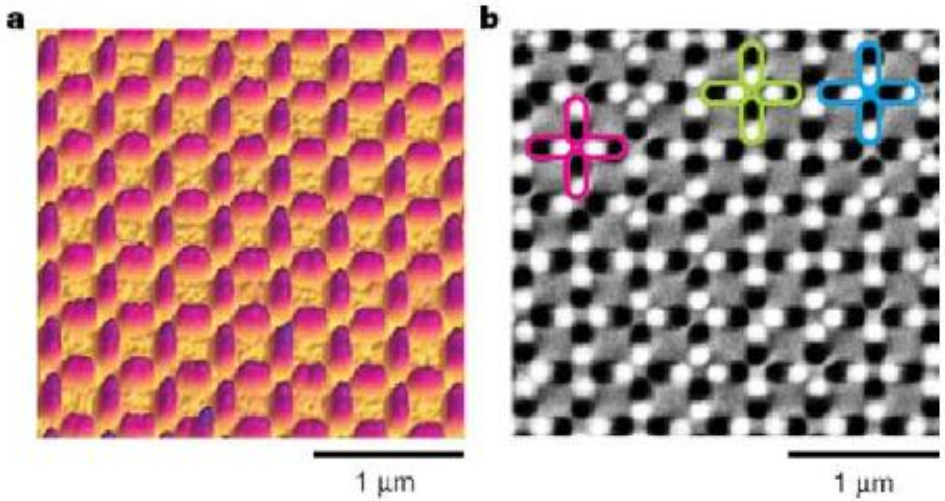


Figure: Lithographically fabricated islands

Critical Analysis
Exhibits Ice Rule or Not?

- Plot the excess of each type of vertex versus spacing
- Spacing controls the interactions
- Small spacing $\Longrightarrow$ more ice rule vertices
- Characteristics
  1. Exhibits ice rules
  2. Not fully at ground state

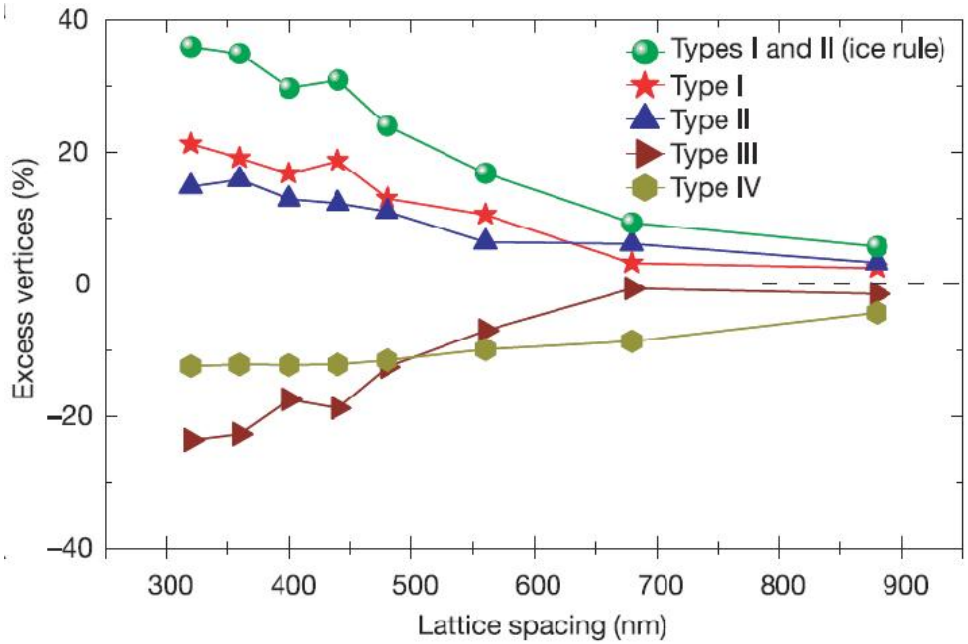


Figure: Main result

This is the first 'artificial' spin ice that has been fabricated.

Spins of individual materials tough to probe while simultaneously leaving system unaltered.

- Real vs artificial spin ice

Solution: create frustrated system where individual elements can be probed.

- Topic of current investigation

Previously done

- Arrays of superconducting rings
- Interacting moments are trapped flux quanta

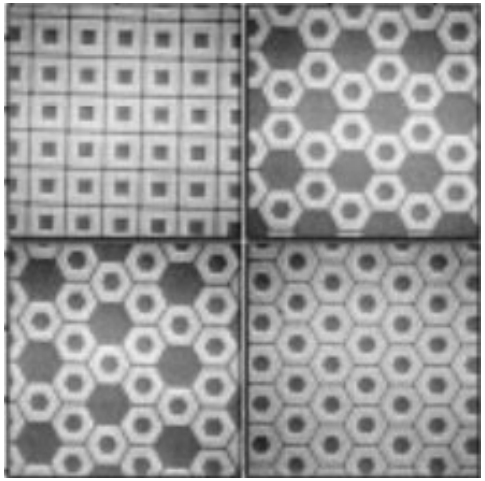


Figure: *Davidovic et. al. 1996, PRL*

New results

- Arrays of interacting single-domain ferromagnetic islands
- Moments intrinsic. (Not from external field)

Advances in lithography allow flexibility in design of such ferromagnetic islands.

Allow accessibility at room temperature, improvement over previous results ($\approx 1.16K$).

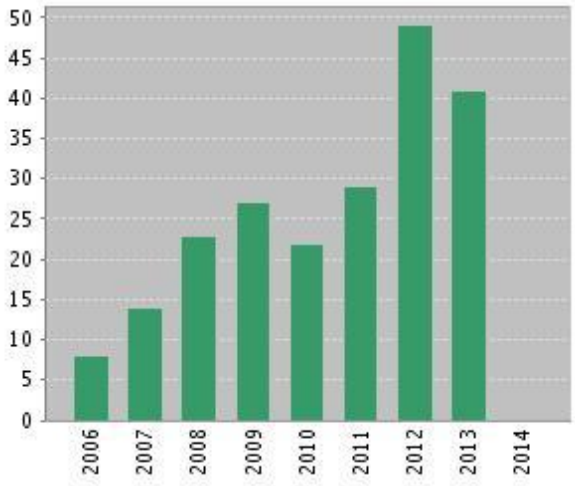
Studies of these islands show that pairwise dipolar interactions are significant.

Frustration effects important if lattice fabricated with frustrated geometry.

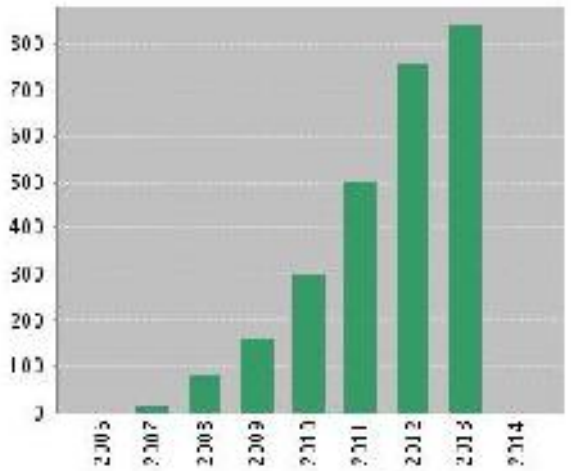
- 206 citations in Web of Knowledge
- 209 citations in Scopus
- 277 citations in Google Scholar
- According to Web of Knowledge, this is the 1st paper for the topic artificial spin ice ever published!

Figure: *Web of Knowledge, 2013*

[Citation Report]



[Citations of Citation]



Citation Analysis

Magnetic Monopoles, Order and Biomaterials Top 5 Citing in Web of Knowledge

1. 

2. Signature of magnetic monopole and Dirac string dynamics in spin ice (Jaubert, L. D. C. et al 2009)
3. A "Star" antiferromagnet: A polymeric iron(III) acetate that exhibits both spin frustration and long-range magnetic ordering (Zeng, Yan-Zhen et al. 2007)
4. Biomorphic mineralization: From biology to materials (Fan, Ton-Xiang et al. 2009)
5. Direct observation of magnetic monopole defects in an artificial spin ice system (Ladak, S. et al. 2010)

Citation Analysis
Has the Ability to Make Spin Ice Changed the Subfield?

- Spin ice was discovered in 1997 (Wikipedia citation) now a major topic in condensed matter.
  - Geometrical Frustration in the Ferromagnetic Pyrochlore Ho2Ti2O7M. J. Harris, S. T. Bramwell, D. F. McMorrow, T. Zeiske and K. W. Godfrey, Phys. Rev. Lett., Vol. 79, p. 2554 (1997)

Citation Analysis

But not a perfect record... Correction Issued in 2007

During the field treatment of the samples prior to measurement, the magnetic field was switched in polarity with each step down in magnitude while the sample was being rotated within the magnetic field. A more detailed description of the field treatment can be found in ref. 1.

http://www.nature.com.proxy2.library.illinois.edu/nature/journal/v446/n7131/full/nature05607.html

Does not appear to negate the impact of this paper.

- The article presents novel methods to investigate frustrated systems.
- First fabricated spin ice like systems
- The paper had a significant impact on condensed matter physics.
- The article is well written and easy to follow

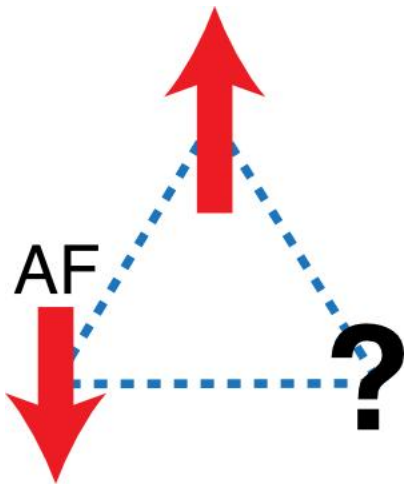


Figure: Triangular Frustration *en.wikipedia.org*