Magnetricity and Monopoles

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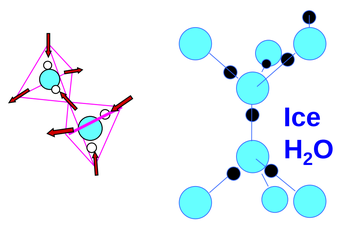
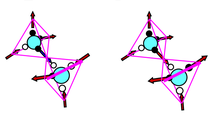
Magnetic Monopoles in Spin Ice

Displacement vectors in water ice →Spin vectors in Spin Ice (Bramwell & Harris 1997)



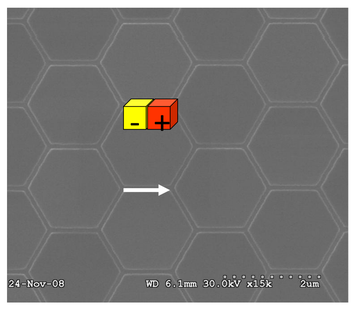
• Spin flips make magnetic monopoles analogous to water ice's ionic defects

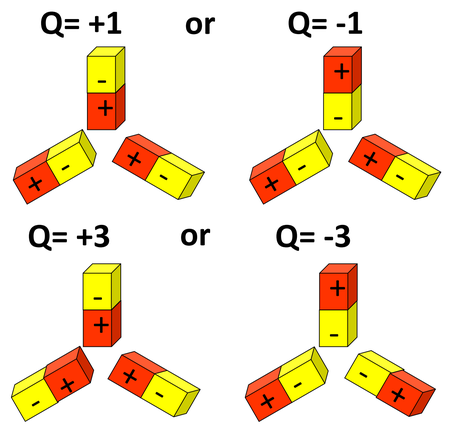
$2H_2O = [H_3O^+ + OH^-] = H_3O^+ + OH^-$



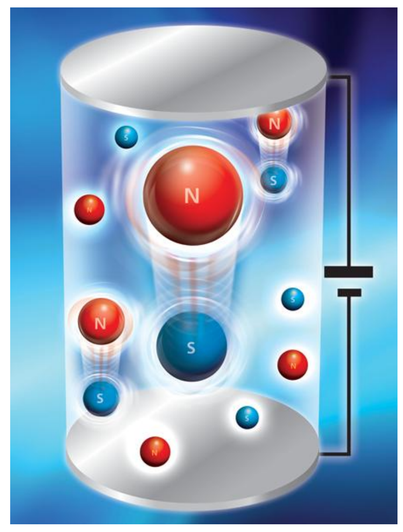
- Spin ice materials like $Ho_2Ti_2O_7$ are simple transparent crystals that include atoms of "rare earth" elements arranged in corner-linked tetrahedra. The atomic magnetic moments or "spins" point into or out of the tetrahedral (arrows).
- Magnetic monopoles - the magnetic version of a charged particle like electrons or protons – have recently been shown to exist in spin ice. We have shown that monopoles form a magnetic version of electricity, or "magnetricity" at very low T.
- We have fabricated arrays of nanomagnets in a spin ice geometry, to create magnetic monopole defects at room temperature

Artificial System: Nanomagnets →atomic spins
•Magnetic charge Q at each vertex in honeycomb
•Q=3 monopole defects

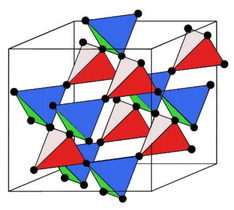




Potential magnetic monopole capacitor?



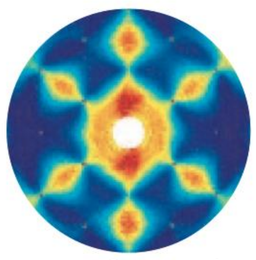
Physics of Bulk Spin Ice Materials



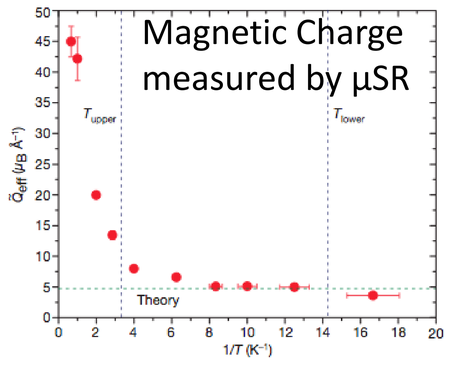
•The spin ice state has been confirmed by neutron scattering to be a vacuum for magnetic charge.

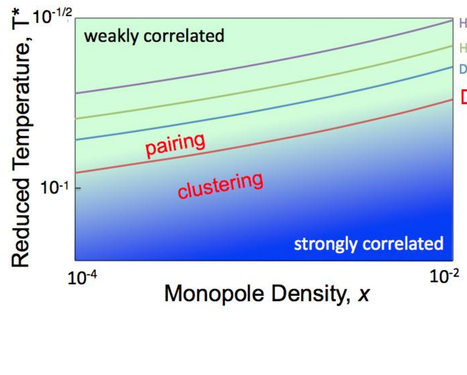
•Magnetic monopoles live in this vacuum. They are analogous to water's ionic defects.

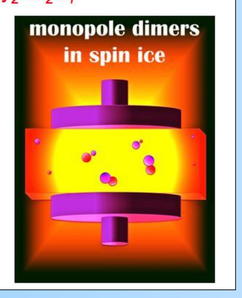
•Different spin ice materials have different monopole concentrations. High pressure has been used to create a new spin ice, $Dy_2Ge_2O_7$ with the highest monopole concentration yet discovered.



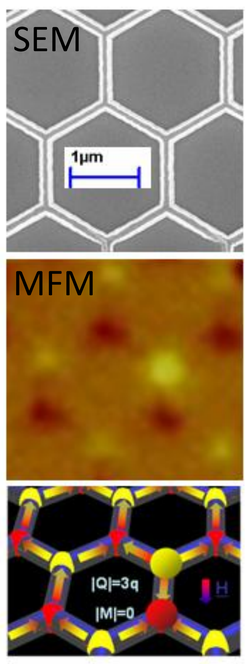
Neutron Scattering







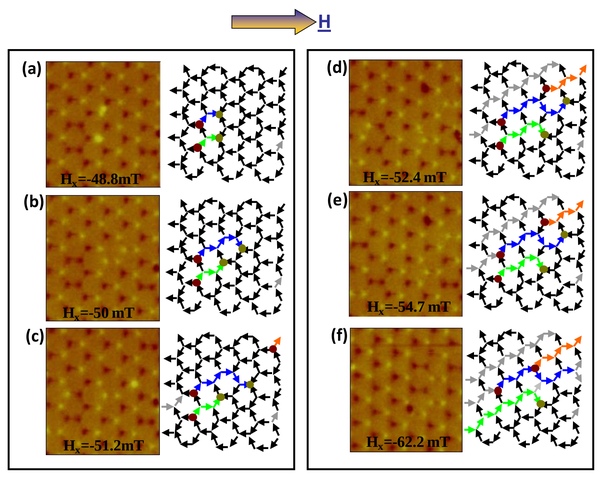
Monopoles in Artificial Spin Ice Nanostructures



•Scanning electron micrograph of the cobalt honeycomb nanostructure.

•Magnetic force micrograph showing a negatively charged magnetic monopole defect (bright yellow). The ice rule in the planar structure gives trapped magnetic charge of alternating sign at the other vertices seen a weak yellow (negative) and red (positive) contrast.

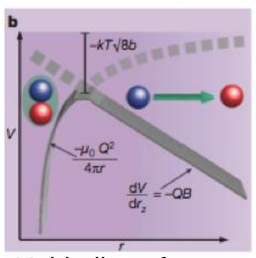
• Schematic of the magnetic spins (arrows) and charges spheres after formation of a pair of oppositely charged monopole defects (large spheres).

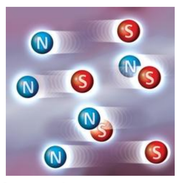


The flow of magnetic charge:
•Mobile defects have effective charge ±2q (Domain wall).
• Positive and negative charged defects move in opposite directions.
• "String" of head-tail dipoles created with defects at the ends.

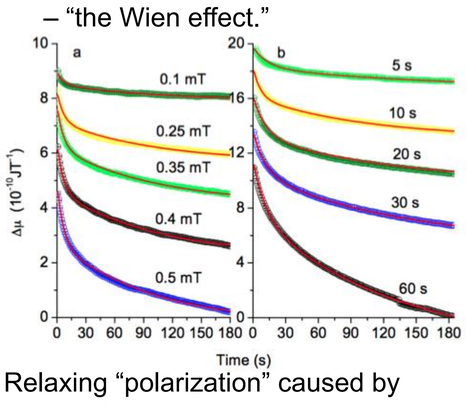
Field Control - Magnetricity

Bulk





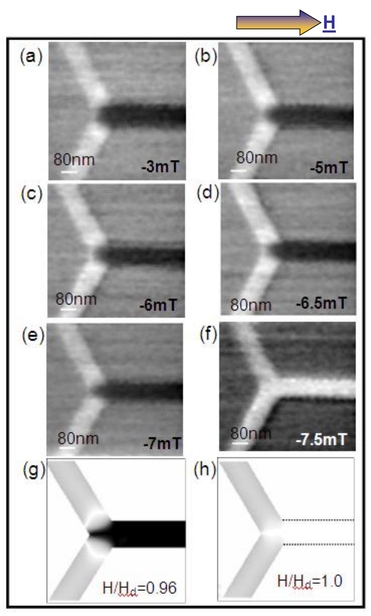
Unbinding of monopole pairs – "the Wien effect."



Relaxing "polarization" caused by monopole currents

Nanostructures

Monopole defects under magnetic pressure



STXM at ALS

Coulomb blockade of two magnetic charges at the same vertex

(a-f) Scanning Transmission Xray Micrograph of a -3q monopole defect.

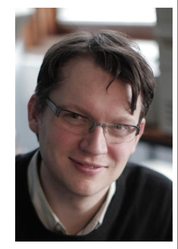
(g-h) Micromagnetic simulations of a -3q monopole defect in field close to depinning field H_d.

Key Publications

- T. Fennell, *et al*…; S. T. Bramwell *Science*, **326** 415-417 (2009)
- S. T. Bramwell, S. R. Giblin, S. Calder, *et al*. *Nature*, **461** 956-959 (2009)
- S. Ladak, D. Read, G.K. Perkins, L.F.Cohen, W.R. Branford *Nature Physics* **6**, 359 (2010)
- S. R. Giblin, S. T. Bramwell, *et al. Nature Physics* **7**, 252-258 (2011)
- S. Ladak, D. Read, L.F.Cohen, T. Tyliszczak, W. R. Branford, *NJP* **13,** 023023 (2011).
- H.D. Zhou, S.T. Bramwell *et al*. *Nature Comm.* **2,** 478 1483 (2011)
- S. Ladak , D. Read, L.F.Cohen, W. R. Branford, *NJP* **13** 063032 (2011).

LCN team

- Academics in charge: Steve Bramwell (UCL) and Will Branford (Imperial)
- UCL team: S.T. Bramwell, T. Fennell, D. F. McMorrow, R. Aldus, S. Calder, J.A. Bloxsom, A. Harman-Clarke, L. Bovo.
- Imperial team: W. R. Branford, S. Ladak, D. Read, G.K. Perkins, K. Zeissler, S. K. Walton, A.M. Gilbertson and L.F. Cohen



Acknowledgements

EPSRC Engineering and Physical Sciences Research Council
The Leverhulme Trust
RESEARCH COUNCILS UK
U.S. DEPARTMENT OF ENERGY
THE ROYAL SOCIETY
NEUTRONS FOR SCIENCE
EUROPEAN SCIENCE FOUNDATION
Science & Technology Facilities Council ISIS