Magnetic monopoles in spin ice

Magnetic monopoles in spin ice
Authors: C. Castelnovo, R. Moessner, and SL Sondhi
ArXiv:0710.5515, Nature, **451** (7174):42-45, 2008.

Signature of magnetic monopole and Dirac string dynamics in spin ice
Authors: LDC Jaubert and PCW Holdsworth
ArXiv:0903.1074, Nature Physics, **5**(4):258-261, 2009.

Measurement of the charge and current of magnetic monopoles in spin ice
Authors: ST Bramwell, SR Giblin, S. Calder, R. Aldus, D. Prabhakaran, and T. Fennell
ArXiv:0907.0956, Nature, **461**(7266):956-959, 2009.

Recommendation and Commentary by Leon Balents, KITP, UCSB

Students learn early on in classes that magnets always have both north and south poles; as college undergraduates, this is formulated in Maxwell's equations as div B=0, implying the absence of magnetic monopoles. However, the possible existence of magnetic monopoles has long been entertained amongst theoretical physicists. Dirac postulated the existence of the monopole in 1931 as a means to argue for the quantization of electric charge. Elementary particle physicists have searched unsuccessfully for monopoles, which are at least very rare and probably extremely massive.

Now recent theory and experiments seem to have found a way for magnetic monopoles to emerge in the solid state: a class of frustrated magnetic insulators known as "spin ice". See Ref.[1] for a thorough review of the history and physics of spin ice. In spin ice, realized in – $Dy_2Ti_2O_7$, $Ho_2Ti_2O_7$, $Ho_2Sn_2O_7$ – large rare earth magnetic moments are arranged on a pyrochlore lattice, a network of corner-sharing tetrahedra. The spins are Ising-like, each one pointing along the $\langle 111 \rangle$ axis connecting the centers of the two tetrahedra shared by its site. The predominant interaction between the spins is dipolar, which strongly favors configurations with two spins pointing in and two spins pointing out of each tetrahedron. This is called the "ice rule", by analogy with the position of protons in the tetrahedrally coordinated network of water ice.

The number of spin configurations obeying the ice rules is very large, actually possessing an extensive entropy, which was estimated by Pauling in

1935. In spin ice, there seems to be a fairly wide range of temperature over which the spins adopt these configurations in an egalitarian fashion without any further preference. The residual low temperature entropy representing the fluctuations amongst these states was measured by Ramirez *et al* about a decade ago, in agreement with Pauling's estimate.

Recent work focuses on more detailed consequences of the nearly complete observance of the ice rules. It turns out that though the ice rule constraints are local, they have long-range effects. It has been realized theoretically for some time that, if the ice rules are perfectly obeyed, the spins should exhibit subtle power law correlations, which are mathematically described as a kind of "emergent magnetostatics". This has been observed in the last year in experiment[2]. The most recent development has focused on defects, in which individual tetrahedra violate the ice rules. In the magnetostatic analogy, these are magnetic monopoles. Remarkably, as Castelnovo *et al* showed, they actually behave in many respects as *real* sources of magnetic flux (**M** or **H** rather than **B**), so the name is appropriate. These monopoles are interesting non-local objects: to create one requires flipping a semi-infinite "string" of spins. By local operations on the spins, one can create only neutral monopole–antimonopole pairs. You can think of the monopole as the end of a very floppy thin bar magnet, which, because of the special form of the spin Hamiltonian, can move almost freely once created. Energetically, two monopoles exert $1/r^2$ Coulomb forces on one another, just as electric charges do – though the forces of the monopoles are about 14000 times weaker.

It turns out that magnetic monopoles are eminently observable in experiment. This is because, in their absence, the ice rules states are so highly constrained it is difficult for the spins to move. Instead, spin dynamics at low temperatures seems to predominantly proceed through the fast motion of a dilute set of monopoles, which flip spins behind them as they move. The last two papers highlighted here identify distinct experimental signatures showing that the monopoles are behaving dynamically as a dilute classical plasma' of charged particles. The paper by Jaubert and Holdsworth, two theorists, revisits old experimental data on the magnetization relaxation rate. They identify quasi-Arrhenius behavior with an activation energy given by the energy of a monopole, and not the larger energy of a single spin flip. This observation is similar to the fact that in an intrinsic semiconductor, the conductivity obeys an Arrhenius law with an activation energy given by the energy of a single electron or hole, and not a neutral electron-hole pair, even though neutrality is in fact maintained. Jaubert and Holdsworth also show

how deviations from the Arrhenius law can be understood as arising from the Coulomb forces between monopoles.

Complementing this experimental measure of the monopole's energy, the paper by Bramwell *et al*, provides a measurement of the monopole's magnetic *charge*. The authors translate an old theory of Onsager's for non-linear electric field effects on electrolytes into this magnetic context, and apply it to relate the magnetic field dependence of the spin fluctuation rate to the elementary monopole charge. Using muon spin resonance measurements, they arrive rather strikingly at an estimate for the monopole's charge in agreement with theoretical expectations.

I focused on these two papers because they show the monopoles behave dynamically as particles with magnetic Coulomb charges and otherwise local dynamics. Their non-locality is the focus of several other works which study spin ice in a magnetic field. A magnetic field selects a preferred spin background, revealing the "strings" trailing the monopoles, which can then be seen in neutron scattering experiments[3], [4].

In the future, we can certainly expect more detailed experiments on monopoles in spin ice. It will also be interesting to see if the lessons learned here have any impact on less classical but related materials such as $Tb_2Ti_2O_7$, a "quantum spin ice", and $Pr_2Ir_2O_7$, which seems to be like a spin ice immersed in a Fermi liquid of conduction electrons.

References

[1] Michel J. P. Gingras in C Lacroix, P Mendels, and F. Mila, editors, *Highly Frustrated Magnetism*, in press. $arXiv: 0903.2772v1$.

[2] T. Fennell, et al., Arxiv preprint $arXiv: 0907.0954, 2009$.

[3] DJP Morris, DA Tennant, SA Grigera, B. Klemke, C. Castelnovo, R. Moessner, C. Czternasty, M. Meissner, KC Rule, J.U. Ho?mann, et al. Dirac Strings and Magnetic Monopoles in the Spin Ice $Dy_2Ti_2O_7$, Science, 326(5951):411, 2009.

[4] H. Kadowaki et al., Journal of the Physical Society of Japan, 78(10):103706, 2009. http://arxiv.org/abs/0908.3568.