Creation and manipulation of magnetic monopoles in spin ice

Condensed matter near the absolute zero of temperature reveals much exotic physics associated with unusual orders and excitations, with examples ranging from helium superfluidity to magnetic monopoles in the solid materials called "spin ices". The far-from-equilibrium physics of such low temperature states may be even more exotic, yet to access it in the laboratory remains a challenge. We have demonstrated a simple and robust technique, that we call the "magnetothermal avalanche quench", that can be used in the controlled creation of non equilibrium populations of magnetic monopoles in spin ice at millikelvin temperatures.

In 1931, Dirac asserted that if just one magnetic monopole exists, then charge (both electric and magnetic) must be quantized. This was based on a hypothetical conjecture that stretching a magnetic dipole by taking one of the poles out to infinity, would leave behind a magnetic charge, attached to an imaginary string of dipoles for the return flux. Although a "Dirac monopole" has not yet been observed, its classical analogue is believed to occur in certain magnetic systems, the rare earth oxides with the pyrochlore crystal structure, $Dy_2Ti_2O_7$ and $Ho_2Ti_2O_7$ (Dysprosium Titanate and Holmium Titanate).

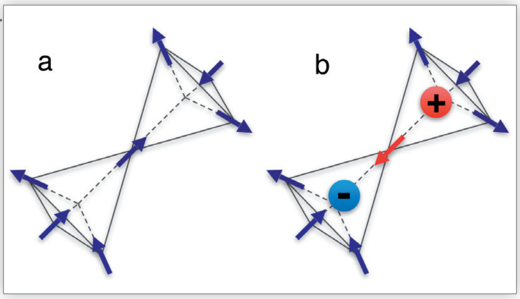

Fig. 1: ***(a)*** *Two corner-sharing tetrahedra of rare earth spins in a pyrochore crystal structure, each obeying the ice rule "two spins point in, two spins point out".*
(b) *Departures from the ice rule create effective magnetic monopoles. The monopoles may occur in adjacent tetrahedra as shown here, or separated.*

These compounds are said to be geometrically "frustrated": They show no magnetic order because the magnetic interactions cannot all be satisfied simultaneously. The magnetic ions in these compounds (the rare earth ions) form a network of corner-sharing tetrahedra, and have a strong magnetic anisotropy: Their magnetic moments align along a <111> axis (a diagonal) of their local tetrahedron. This combined with dipole-dipole interaction gives rise to the "ice rules" (so-called by analogy with the rules for the O-H bonds in water ice). Simply stated, the minimum energy state corresponds to two rare earth spins pointing in and two spins pointing out of each tetrahedron (Fig. 1a).

This 'ice-rule' is equivalent to a divergence-free condition on the total magnetic moment on each tetrahedron, and thus, in analogy with electromagnetism, can be viewed as a vacuum of magnetic charges. In this picture, thermally activated defects, *i.e* three spins in and one out (or vice versa) on a given tetrahedron (Fig. 1b), create a magnetic charge on that tetrahedron, and correspond to an effective magnetic monopole. That is, in the vicinity of the defect, the magnetic field looks like the field of a monopole. The density of these monopoles in zero applied field goes to zero with temperature. Nevertheless it has been shown theoretically that a fast thermal quench could create long-lasting monopole-rich states at low temperature.

In recent measurements of the magnetic moment of $Dy_2Ti_2O_7$ at temperatures <1 K, we have demonstrated the importance of the quench rate on the dynamic properties. In addition, we proposed a new protocol, which we call the magneto-thermal avalanche quench technique, that results in a density of effective monopoles more than an order of magnitude greater than the one generated by the fastest conventional cooling experiments in zero field.

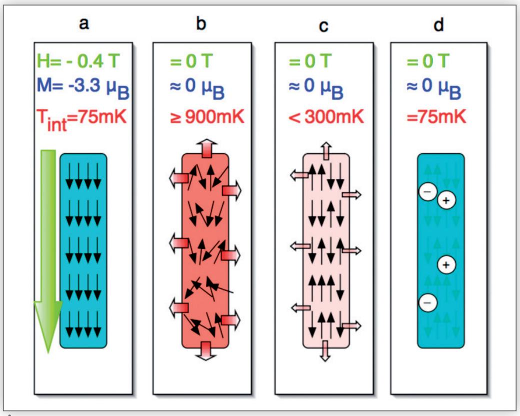

Fig. 2: *The avalanche quench technique. Each tetrahedron has been replaced by an arrow that represents the direction of just one of its apex spins.* ***(a)*** *The magnetism of the sample is first saturated in a high field at low temperature* ***(b)*** *the field is switched off, which heats the sample,* ***(c)*** *the heat is evacuated leaving* ***(d)*** *a large density of defects (monopoles). Signs + and - represent effective magnetic monopoles.*

The trick is to exploit the heat that is created by the magnetic work done on the sample when the field is rapidly changed, which will cause a sudden increase in temperature solely inside the sample. The sample then finds itself at relatively high temperature but connected to the cold thermal bath. The ensuing quench is the most efficient and rapid possible. Our avalanche technique is illustrated in Fig. 2. The sample's magnetization is first saturated in a field of 0.4 Tesla and cooled to 75 mK. Then the field is rapidly switched off and the magnetic Zeeman energy $\Delta M \cdot H$ released (from the spins flipping back towards spin-ice configurations) heats the interior of the sample to approximately 900 mK. This heat evacuates to the still very cold mixing chamber of the helium dilution refrigerator. The sample cools extremely fast, limited only by the thermal conduction to the copper sample holder. The result of the avalanche quench is to freeze-in a very large, non-equilibrium density of monopoles.

In subsequent experiments, we have shown that applying a magnetic field to this non-equilibrium state produces a magnetic current, *i.e.* a current of monopole charges, analogous to an electric-field driven current of + and - electric charges in an electrolyte. Our technique thus opens a path for studies of the intrinsic far-from-equilibrium dynamics of spin ices at low *T*, which is dominated by magnetic monopoles.

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FURTHER READING

"Far-from-equilibrium monopole dynamics in spin ice"
C. Paulsen, M. J. Jackson, E. Lhotel, B. Canals, D. Prabhakaran, K. Matsuhira, S. R. Giblin and S. T. Bramwell
Nature Phys. 10, 135 (2014) ; also see "News & Views" by H.-B. Braun, *Nature Phys.* 10, 88 (2014)