MAGNETIC MONOPOLES

Quenching the fire in spin ice

The density of monopoles in spin ice can be enhanced by rapid cooling. After the creation of significant numbers of monopoles, magnetization measurements show that, much like charges in an electric field, monopoles can be driven by a magnetic field.

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Just over a hundred years ago Pierre Curie speculated about the magnetic currents produced by magnetic charges — little did he know that magnetic monopoles would one day play a role in condensed matter physics. In contrast to their free-space counterparts — which have eluded detection in particle physics — these monopoles only exist confined within frustrated magnets known as spin ice. Arising as defects, monopoles can roam more or less freely through the crystal, interacting with their siblings via a Coulomb force. So far, the majority of experiments have detected signatures of these monopoles in thermal equilibrium in the spin ice phase around 600 mK, where their density is too low to test their response to an applied magnetic field — one of their most defining features. Now, writing in *Nature Physics*, Carley Paulsen and co-authors have found a way around this problem. Using a single crystal of Dy$_2$Ti$_2$O$_7$, they succeeded in producing a non-equilibrium population of magnetic monopoles. Controlling their density they were able to demonstrate that monopole currents are the primary mechanism of magnetization relaxation in spin ice systems.

Spin ice inherits its name from water ice because the low-energy spin configuration of an elementary tetrahedron in the rare-earth titanates is governed by the same ‘two-in, two-out’ rule that dictates the positions of the four hydrogen atoms surrounding an oxygen atom in frozen water. For spin ice, the origin of the ice rule can be traced back to the dipolar interaction between the rare-earth spins. Flipping a single spin in a spin ice state results in the creation of a monopole–antimonopole pair in two adjacent tetrahedra. Once created, this pair can easily be separated without further violation of the ice rules, merely at the expense of the Coulomb interaction.

When monopoles move they leave a one-dimensional path of overturned spins in their wake, and, as first noticed by Ivan Ryzhkin, they are thus very effective agents for magnetization relaxation. Ryzhkin proposed a phenomenological law, similar to Drude’s simple relaxational model for electric conductivity, where the speed of the monopoles is proportional to the applied magnetic field. As a result, the time derivative of the magnetization is expected to be proportional to both the density of monopoles and the strength of the applied magnetic field.

To produce a significant number of monopoles, Paulsen *et al.* had to cool their sample rapidly from high temperature, and they employed the clever idea of an ‘avalanche quench’ to achieve the highest cooling rates. Instead of controlling the temperature via the mixing chamber of the dilution refrigerator, a comparatively sluggish procedure, they heated the sample ‘from within’ by triggering a magneto-thermal avalanche. In response to a sudden field change, the Zeeman energy cannot be efficiently carried away by the heat bath. As a result, a ‘reaction front’ of magnetization reversal rides through the sample in the wake of a heat front, resembling the process of flame propagation. This quickly heats the sample from 75 mK to 1 K, but as the heat production is restricted to the small sample of a few cubic millimetres, it can

Figure 1 | A rapid quench creates a non-equilibrium population of monopoles (red) and antimonopoles (blue). The more rapid the quench, the greater the number of monopoles. The monopoles move in the direction of an applied field, whereas the antimonopoles move against it. In their wake, both monopoles and antimonopoles leave a one-dimensional path of magnetic moments aligned in the direction of the applied field. Thus, monopoles are the primary agents for magnetizing the sample. Top: A monopole moves from one tetrahedron to the next by flipping the magnetic moment of a rare-earth ion into the direction of the magnetic field.
subsequently be rapidly cooled by contact with the mixing chamber held at 200 mK.

After this sophisticated quenching protocol, resulting in a state of zero magnetization, Paulsen et al. subjected their sample to a weak external magnetic field of 5 mT. Keeping the temperature at 300 mK, they made the striking discovery that the rate of resurgence of the magnetization indeed depends on the cooling history. The faster the quench, the faster the magnetization increases. At the same time, their Monte Carlo simulations of both a vertex model and dipolar spin ice showed that the monopole density increases with the quenching rate. Hence, the observations support Ryzhkin’s prediction that magnetic monopoles respond to magnetic fields like electric charges do to electric fields. These results also demonstrate that the fastest magnetization relaxation rates are observed when the monopole density is highest, a relationship that is also reported for artificial spin ice, which is a metamaterial analogue of the present system.

The increase of the defect concentration with increasing quenching rate can be understood qualitatively. At sufficiently high temperature, all 2^8 spin configurations in a tetrahedron are nearly equally populated — eight of which correspond to simple monopoles. If a quench were to occur instantly, the result would be a monopole concentration of 50%. However, simulations and experiments show it to be only at the level of a few per cent, indicating a strong annihilation of monopoles and antimonopoles during cooling. Indeed, such pairs are likely to find each other by virtue of their mutual Coulomb attraction. The longer the cooling takes, the more likely this will happen. It is therefore surprising that not all pairs annihilate. Earlier simulations indicate the robust survival of ‘non-contractible’ monopole–antimonopole pairs that are nearest neighbours yet cannot be simply annihilated by a single spin flip. Indeed, in some cases Paulsen et al. also observed a two-stage relaxation of the magnetization, which could be an indication of the annihilation of ‘trivial’ monopole–antimonopole pairs at short timescale and the longer-term survival of non-contractible pairs. This is aided by the fact that relaxation below 600 mK becomes exceedingly slow and non-equilibrium states are very long lived.

The striking observations by Paulsen et al. not only confirm pioneering theoretical work3,5,8, but also inspire the pursuit of new questions: How does the topology of the spin network affect the mobility of the monopoles beyond the existence of the non-contractible pairs? How is the monopole mobility influenced by quantum fluctuations? The work by Paulsen et al. is therefore an exciting step in the exploration of monopoles in spin ice systems far from thermal equilibrium. These results put monopoles on an equal footing with other topological defects in magnetism10, such as skyrmions and domain walls, which are both good candidates for data storage technologies.

Although the low temperatures required for experiments in spin ice seem to be challenging for such applications, the insight gained here might inspire the investigation of similar phenomena in artificial spin ice that can indeed be manipulated at room temperature.

Finally, it should be emphasized that the quenching of topological defects from a high-temperature symmetric phase into a phase with broken symmetry is a familiar phenomenon in physics. Known as the Kibble–Zurek mechanism, it has been used to describe systems ranging from the early hot, dense universe to liquid crystals and it is exciting to see spin ice joining this club.

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References

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