whether the charge-carrier and excited-state densities required to overcome all loss processes can be reached not only by optical excitation — as demonstrated by Mathews and Sum — but also by carrier injection from electrodes. However, the perovskites' low onset threshold for optically pumped ASE in combination with their high gain coefficient and superior stability, as well as the facile solution-processing at low temperatures, are certainly prerequisites for the development of a new generation of low-cost lasers. ❐

Frédéric Laquai is at the Max Planck Research Group for Organic Optoelectronics, Max Planck Institute for Polymer Research, Ackermannweg 10, D-55128 Mainz, Germany.
e-mail: laquai@mpip-mainz.mpg.de

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OXIDE HETEROSTRUCTURES

Thin spin ice under investigation

It is now possible to fabricate high-quality thin films of spin ice materials. At higher temperatures, they exhibit the hallmarks of a regular spin ice, but at lower temperatures their physics deviate significantly from the properties observed in the bulk.

Oleg Petrenko

Over the past few years the study of spin ice has undergone a remarkable transformation. Immediately after its introduction in 1997, when it was used as an analogy to describe the magnetic properties of the pyrochlore system $Ho_2Ti_2O_7$ (ref. 1), spin ice was recognized as an intriguing model of a magnetic system with competing interactions, a so-called frustrated magnet (Fig. 1a). The subsequent observation of a zero-point entropy[2], the realization that the excitations above its ground state (the so-called magnetic Coulomb liquid) are best described as point-like defects that behave as magnetic monopoles[3,4] and the identification of associated currents termed 'magnetricity'[5] have elevated spin ice to the point where it has become a fascinating topic of investigation in its own right.

The rise in interest in spin ice has certainly been helped by the connection its properties have with a diverse range of phenomena in physics. However, the growth of high-quality single crystals of pyrochlore magnets such as $Ho_2Ti_2O_7$ and $Dy_2Ti_2O_7$ has been crucial in aiding these conceptual developments. In this regard, one important aspect that has not been examined in detail is the feasibility of fabricating these materials in the form of thin films (Fig. 1b). Writing in *Nature Communications* and in *APL Materials*, two independent research groups report the synthesis of single-crystal epitaxial films of $Dy_2Ti_2O_7$ on non-magnetic $Y_2Ti_2O_7$ substrates[6] and $Ho_2Ti_2O_7$ on yttria-stabilized ZrO_2 substrates[7].

Beyond the seemingly remote prospect of manipulating monopoles in possible spintronic devices, the thin-film form of spin ice should provide an interesting platform for the study of fundamental effects. If the analogy between the magnetic moments in spin ice compounds and the proton displacement vectors in water ice is to hold, thin spin ice is bound to exhibit remarkable properties. One only needs to consider the slipperiness of water ice as an example: an unrealistic model assuming a thin layer of ice melting under pressure has been invoked as an explanation for almost a century, but in fact many of the specific properties of water ice surfaces (such as molecular disorder, enhanced diffusivity, surface charges and conductivity) are still awaiting a full theoretical description[8].

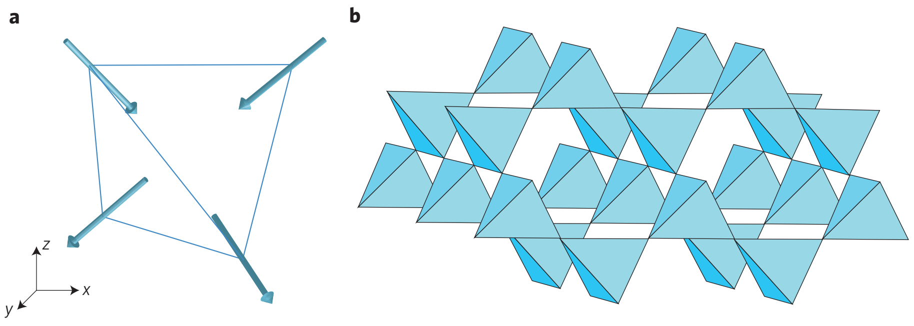

Figure 1 | Pyrocholore structure of spin ice. **a**, Corner-sharing tetrahedra forming the main building block of the structure. The arrows denote the orientation of the spins in this magnetic system, which is along the <111> axes. The spins also satisfy the 'two in two out' rule, which constrains them to a ground state in which two spins are always pointing within a tetrahedron, and two spins are pointing out. **b**, Network of corner-sharing tetrahedra in a thin-film geometry, as fabricated by Bovo and colleagues[6] and Leusink and co-workers[7].

What about the properties of thin spin ice? In their bulk form, both $Ho_2Ti_2O_7$ and $Dy_2Ti_2O_7$ display highly anisotropic and characteristic magnetization behaviour under an applied field. For different directions of the field, the magnetization saturates quickly at well-defined fractions of the total moment, in full agreement with the spin ice model in which the moments are constrained to point along the local <111> directions (Fig. 1a). For the thicker films, both sets of authors performed an extensive magnetic characterization, and their results suggest that bulk spin ice behaviour is observed down to temperatures of about 2 K (refs 6,7). Bovo *et al.*[6] also performed careful magnetic susceptibility measurements for their thinner samples. In this case, they found good agreement with bulk measurements at higher temperatures, but significant deviations on cooling.

Perhaps the most intriguing observation so far is that in the $Dy_2Ti_2O_7$ films the magnetic entropy recovered at low temperatures amounts to $R\ln 2$ (where R is the universal gas constant), the full value expected for an effective spin-1/2 system, rather than to the celebrated value of $R(\ln 2 - 1/2\ln(3/2))$, which corresponds to the Pauling entropy observed[2] in bulk $Dy_2Ti_2O_7$ (and famously measured by Giauque and Stout in water ice in the 1930s[9]). This observation prompts Bovo and colleagues to argue that the third law of thermodynamics, violated in bulk spin ice materials, is restored in thin films[6]. They suggest the most likely cause for this may be the strain induced by the lattice mismatch between the spin ice film and its substrate.

Whether or not strain is indeed the cause of this phenomenon remains to be proven, but there is no doubt that the fact that a new field for addressing a series of probing questions is now well and truly open. Apart from the important but perhaps more mundane issues concerning the quality of the thin films and the influence of the substrate on their properties, some of the more interesting questions the works of Bovo *et al.*[6] and Leusink *et al.*[7] raise are: What is the ground state of a monolayer-thick spin ice? Can the spin ice films be properly thermally equilibrated even at the lowest temperatures on a timescale of typical experiments? Are monopole dynamics different on the surface and can they be manipulated? Can any links to the growing body of work on artificial spin ice[10] be made? Doubtless there will be surprises, but these issues will keep researchers busy in the field of magnetism and beyond. ❐

Oleg Petrenko is at the Department of Physics, University of Warwick, Coventry CV4 7AL, UK.
e-mail: O.Petrenko@warwick.ac.uk

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MATERIAL WITNESS

STELLAR METALLURGY

PHILIP BALL

The recent detection of a fingerprint in the polarization of the cosmic microwave background radiation, apparently left by primordial gravitational waves triggered by an inflationary epoch in the universe's expansion after the Big Bang, has been hailed as the kind of discovery that comes only once every few decades. Although such phenomena seem a very long way from the science of materials, the ongoing search for a direct detection of gravitational waves produced in violent astrophysical events certainly is not.

Candidate sources for these waves include rotating neutron stars with 'mountains' on their surface — small deviations from perfect rotational symmetry of the high-density crust, which would excite and radiate gravitational waves. The higher the mountains, the stronger the waves. How high the mountains are — and we're talking inches here — depends on the strength of the crust.

The crust's materials properties could also play a role in understanding other phenomena. For example, 'star quakes' produced by magnetic stresses that deform and ultimately crack the crust of magnetized neutron stars have been proposed as a possible explanation for gamma-ray flares seen in 2004 from SGR 1806-20, an object thought to be a neutron star in the Sagittarius constellation[1].

Whereas a neutron star's deep interior is thought to be essentially a neutron fluid, the crust contains the nuclei of neutron-rich atoms immersed in an electron gas and permeated by a superfluid of free neutrons. The nuclei have been long assumed to form a body-centred cubic (bcc) lattice, and on this basis the strength of the crust has previously been estimated to be around 10 billion times that of steel[2]. That study modelled the ultradense fabric of neutron stars much like the crystal lattice of a metal, complete with dislocations (albeit mostly squeezed out by the intense pressure).

Now Kobyakov and Pethick extend the metallurgical picture further, and in doing so they revise our view of the material properties of the crust of a neutron star[3]. They argue that the interstitial neutron fluid between the nuclei acts like a second component of an alloy, and has the effect of creating an attraction between the nuclei that renders the bcc lattice unstable to a phase transition, in a manner analogous to the phase separation of an alloy through spinodal decomposition[4].

Although it isn't possible from this stability analysis alone to calculate what structure the phase transition will produce, the nature of the most unstable mode suggests a doubling of the unit cell, which Kobyakov and Pethick interpret as perhaps leading to a phase analogous to a ferroelectric such as barium titanate (but without actual ferroelectricity). This would be likely to increase the crust's breaking strain, and also to alter the thermodynamic and transport properties relevant to star quakes and other phenomena. There are evidently, then, implications for astrophysics and gravitational-wave detection. But in the application of methods developed for metallurgy to these exotic and barely imaginable materials, there is also an illustration of the unity in condensed-matter physics. ❐

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