functionalized for sensitivity to certain gases. Further, the sustainability of fibroin is expected to play an important role, as the biodegradable SIO sensors would naturally decompose instead of requiring retrieval. Beyond fibrion, one can foresee a wealth of biologically derived raw materials, such as collagen or cellulose, with engineered functional properties that could lead to sustainably produced optical materials, suitable for a broad range of applications. For example, cellulose-based photonic crystals could potentially be used as a temperature indicator integrated into cups for hot drinks.

Certain challenges still need to be met before SIOs become feasible or fully sustainable in all applications. At present, the time between implantation and the onset of bioresorption of fibroin-based materials depends on the processing methodology, with longer-lived structures requiring non-aqueous processing[10]. Similarly, the logistics of how to functionalize the SIOs for use as high-sensitivity detectors need to be addressed. Yet, the potential advantages of using sustainable materials like fibroin to make photonic crystals — for a variety of applications — ensure that their future will be brighter than ever. ❐

Jennifer M. MacLeod and Federico Rosei are at the Centre for Energy, Materials and Telecommunications, Institut National de la Recherche Scientifique, Varennes, Quebec J3X 1S2, Canada.
e-mail: macleod@emt.inrs.ca; rosei@emt.inrs.ca

References

1. Kim, S. *et al. Nature Photon.* **6,** 818–823 (2012).
2. Gosline, J. M., Guerette, P. A., Ortlepp, C. S. & Savage, K. N. *J. Exp. Biol.* **202,** 3295–3303 (1999).
3. Brown, C. P. *et al. Nanoscale* **3,** 3805–3811 (2011).
4. Joannopoulos, J. D., Villeneuve, P. R. & Fan, S. *Nature* **386,** 143–149 (1997).
6. Altman, G. H. *et al. Biomaterials* **24,** 401–416 (2003).
7. Kim, D. H. *et al. Nature Mater.* **9,** 511–517 (2010).
8. Jain, P. K., Huang, X., El-Sayed, I. H. & El-Sayed, M. A. *Plasmonics* **2,** 107–118 (2007).
9. Sofia, S., McCarthy, M. B., Gronowicz, G. & Kaplan, D. L. *J. Biomed. Mater. Res.* **54,** 139–148 (2001).
10. Wang, Y. *et al. Biomaterials* **29,** 3415–3428 (2008).

MATERIAL WITNESS

WATCHING ICE SPIN

Mechanical analogies for the microscopic world have a distinguished history, perhaps most famously James Clerk Maxwell's vision of the luminiferous ether as a mesh of spinning vortices propelled by "gearwheel particles". J. D. Bernal used bags of ball-bearings to explore atomic random close-packing; for Osborne Reynolds several decades earlier, such a bag of spheres was a model for the fine-grained structure of the entire universe. And chemists have long used macroscopic physical models of molecules to intuit how they move and interlock.

The trick is to identify which elements of the macroscale apply equally to the microscale, where in general a different balance of forces — electrostatic, dispersion, capillary — holds sway. As Bernal understood, packing effects scale because they are purely geometric. The same is true for a macroscopic model of spin orientations described by Mellado *et al.* (*Phys. Rev. Lett.* **109,** 257203; 2012).

The researchers examine frustration arising in certain geometric arrangements of interacting particles. The problem is most easily seen for a two-dimensional array of magnetic spins that display antiferromagnetic interactions, so that adjacent spins aim to point in opposite directions. On a triangular lattice that configuration is impossible for all three neighbours in a unit cell — two neighbouring spins must inevitably be parallel rather than antiparallel.

This means the system has no unique energetic ground state. The same is true for the tetrahedral arrangement of hydrogen bonds in water ice: the number of configurations grows exponentially with system size, precluding a single minimal-energy state even at absolute zero. By analogy, some magnetic materials with a lattice of corner-sharing tetrahedra (the pyrochlore structure) exhibit magnetic frustration and have been christened spin ices.

To understand the relaxation dynamics of such compounds — the collective reorientations of spins as the system explores its rough free-energy landscape — Mellado *et al.* have built a macroscopic analogue of spin ice consisting of a honeycomb lattice of ferromagnetic rods about 2 cm long whose ends converge at (frustrated) three-fold vertices, hinged at their midpoint so that they can rotate vertically to flip their orientation.

When the spins are first oriented vertically by applying a strong magnetic field, and then allowed to relax, there follows a few seconds of 'negotiation' during which all the vertices acquire the various permutations of north–north–south (NNS) and SSN magnetic alignments, with no high-energy NNN or SSS

PHILIP BALL

states. Close video inspection of this relaxation process reveals that it has three stages. In the first ~0.07 s, many spins rotate from vertical to horizontal. Then some spins form head-to-tail linear chains; finally, the remaining spins become horizontal and rotate, then simply oscillate, until the kinetic energy is dissipated.

Such distinct dynamical regimes would be hard to see in microscopic systems — although in any case some of the behaviour, such as viscous dissipation at the hinges, does not translate to atomic-scale spin ice. The macroscopic system is also amenable to manipulation: changing the interaction strength, say, or adding vacancies. The researchers have even created a preliminary three-dimensional tetrahedral version from stacked layers. Regardless of how much of the behaviour applies to microscopic media, these systems look set to exhibit a richness of their own. ❐