

## NANOMECHATRONICS

## A new twist on a classic experiment

The interplay between angular momentum, electron spin and magnetism at the nanoscale could have applications in spintronics, transducers and actuators, as well as fundamental research.

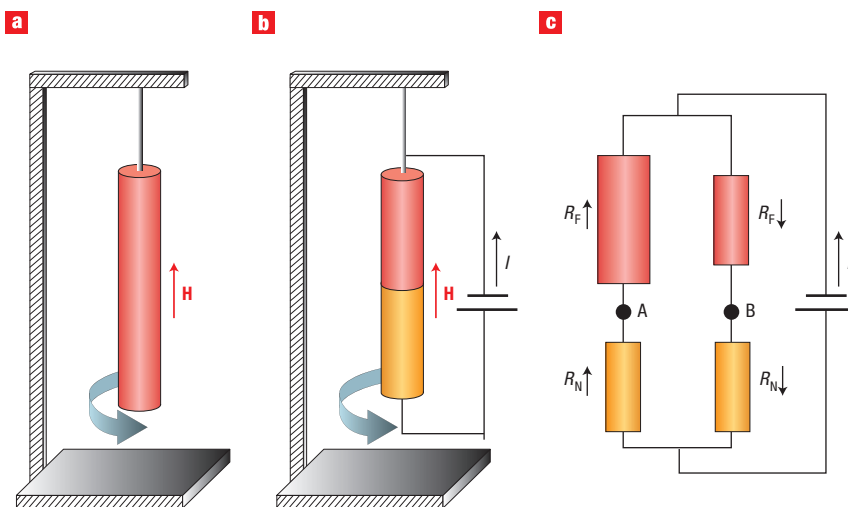
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In 1915, Albert Einstein and Wander Johannes de Haas performed an experiment in which they applied a magnetic field to a cylinder made of ferromagnetic material. This caused the magnetic domains in the cylinder — which had initially all pointed in different directions — to line up. It is helpful to think of the cylinder starting out in an equilibrium state, being placed in a non-equilibrium state by the magnetic field, and then relaxing to a new equilibrium state in which all the magnetic domains point in the same direction. However, the magnetic field also causes the cylinder to rotate. The reason for this is that the origins of magnetism lie in the intrinsic angular momentum or ‘spin’ of the electron. Using an applied magnetic field to force all of the magnetic domains to point in the same direction also changes the angular momentum of the cylinder, so it needs to rotate to conserve the total angular momentum. This experiment is a clear demonstration that electron spin, which is a quantum phenomenon, is very similar to classical angular momentum.

Similar physics is at work in the experiment described by Pritiraj Mohanty and co-workers<sup>1</sup> on page 720 of this issue. Imagine we have a cylinder with a ferromagnetic top half and a non-magnetic bottom half in an applied magnetic field, and that we want to impose the magnetized state of the top half on the bottom half by sending a current through the cylinder (Fig. 1b). As in the Einstein–de Haas experiment, this involves placing something — in this case the non-magnetic bottom half of the cylinder — in a non-equilibrium state, so that it tries to return to its original non-magnetic state. The magnetization induced in the bottom half by the current then relaxes and the cylinder rotates as a whole to conserve angular momentum. However, if we keep sending



**Figure 1** A new twist on the Einstein–de Haas experiment. **a**, A sketch of the original Einstein–de Haas set-up, in which the use of a magnetic field ( $\mathbf{H}$ ) to align the magnetic moments in a ferromagnetic cylinder causes the cylinder to rotate to conserve angular momentum. **b**, A modified Einstein–de Haas experiment, in which the top half of the cylinder is ferromagnetic and the bottom half is non-magnetic. Initially the top half induces a non-equilibrium magnetization of the bottom half by virtue of electric current ( $I$ ) being sent through the cylinder. The relaxation of the non-equilibrium magnetization of the bottom half causes the whole cylinder to rotate to conserve angular momentum. In the experiment of Mohanty and co-workers, the cylinder is a metal nanowire. **c**, The flow of spin and electric charge in **b** can be represented by a model with different resistances (shown as coloured rectangles with areas that are proportional to the resistance) in parallel for the spin-up and spin-down electrons in the ferromagnetic (F) and non-magnetic (N) halves of the cylinder.

current through the system, the end result will be a constant mechanical torque on the cylinder.

In a ferromagnetic material, conduction electrons with spins that point along the magnetization direction (‘spin-up’ electrons) are usually scattered more than electrons with spins against the magnetization direction (‘spin-down’ electrons)<sup>2</sup>. In a non-magnetic metal that is subject to charge bias, however, there is no preferred direction and thus there is no net flow of angular momentum along any direction.

The system can therefore be represented by the currents of spin-up electrons ( $I\uparrow$ ) and spin-down electrons ( $I\downarrow$ ) encountering different resistances in the ferromagnetic half of the cylinder,

but meeting the same resistance as each other in the non-magnetic half (Fig. 1c). One might expect a voltage to be present between points A and B in Fig. 1c, but as we are talking about spin-up and spin-down channels here, this voltage translates into a non-equilibrium magnetization in both halves of the cylinder in the vicinity of the interface. The spin current at the interface can be described as the difference of the currents at A and B.

Given the similarities between the Einstein–de Haas experiment and the experiment of Mohanty and co-workers, one may question the gap of almost 100 years between the experiments. Typically, things are not as simple as they seem, and the answer lies in the estimate of the mechanical torque. To maximize

this torque, the non-magnetic part of the cylinder can be made larger than the spin-diffusion length, which means that the electrons eventually ‘forget’ their initial spin direction, as occurs in the most recent experiment.

As each electron has an angular momentum of  $\hbar/2$ , where  $\hbar$  is Planck’s constant divided by  $2\pi$ , we can use the conservation of angular momentum to calculate the torque generated in the non-magnetic part of the cylinder: we find that  $T = \hbar(I\uparrow - I\downarrow)/2e$ , where  $e$  is the charge of the electron. If we design the device so that  $I\uparrow$  is much larger than  $I\downarrow$ , then the spin current ( $I\uparrow - I\downarrow$ ) and the charge current ( $I\uparrow + I\downarrow$ ) through the circuit can be made comparable. A current of 1 A flowing through the structure will, therefore, produce an estimated torque of  $10^{-16}$  N m, which is more than 10 orders of magnitude smaller than the torque in the original Einstein–de Haas experiment.

Mohanty and co-workers are able to achieve unprecedented sensitivity to

torque by replacing the cylinder with a metal nanowire that is 300 nm wide, 50 nm thick and about 5  $\mu\text{m}$  long, and by making use of the fact that the sensitivity of mechanical systems increases as they are made smaller. The experiments were carried out in a magnetic field of 16 tesla and the rotation of the nanowire was detected by measuring the magnetomotive force it exerted on a conducting coil that was attached to the wire via an insulator (see Fig. 2 of ref. 1).

Just as the Einstein–de Haas experiment led to new ways of measuring the gyromagnetic ratio<sup>3</sup> (the magnetization divided by angular momentum), the experiment of Mohanty and co-workers will provide an alternative way of measuring polarization in ferromagnetic metals. Until now, such measurements have usually been performed with a superconducting point contact, providing valuable information about the electron band responsible for polarization in ferromagnets<sup>4</sup>. There are also likely to

be applications of this approach in the design of transducers for experiments in microfluidics and on biological systems<sup>5</sup>, as well as actuators for nanomotors<sup>6</sup> and other nano-electromechanical systems.

Spintronics has already been tremendously successful, especially with magnetic random access memory, and mechanical systems may one day be used as building blocks for computers<sup>7,8</sup>. Devices that combine both spintronics and nanomechanics are still some way off, but the work of Mohanty and colleagues paves the way into this unexplored realm.

#### References

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## NANOMATERIALS

# The ins and outs of thermal expansion

Most materials expand when they are heated, but some contract instead. A record value of this effect — known as negative thermal expansion — has now been observed in magnetic nanocrystals.

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**C**ontrolling the mechanical properties of functional materials is a major challenge in materials science. Industries such as aerospace and telecommunications demand seamless performance across a range of temperature and pressure conditions, and the eventual hope is that effects such as thermal expansion might be constrained or indeed eliminated altogether. On page 724 of this issue, Xu-Guang Zheng and co-workers<sup>1</sup> at Saga University, AIST and the RIKEN Spring-8 Center, all in Japan, describe how thermal expansion in magnetic materials can be controlled, and even reversed, by varying the particle size. In fact they observe negative thermal expansion (NTE) effects that are many times stronger than the positive thermal

expansion effects seen in most ‘normal’ materials. By combining NTE materials (which shrink when they are heated) with normal materials (which expand on heating), it should be possible to produce composites with tailored temperature-dependent characteristics, including zero thermal expansion.

In general materials shrink when they are cooled because atomic vibrations are reduced at lower temperatures — atoms push less strongly against their neighbours, and so the distance between them decreases. In rare cases, however, particular atomic arrangements can mean that the only way to reduce vibrational motion is to force some distances to increase. The archetypal example of this counterintuitive behaviour is zirconium tungstate: the Zr–O–W linkages in this material become increasingly linear at low temperatures as the amplitude of the oxygen vibrations decreases<sup>2</sup> (Fig. 1a). The zirconium and tungsten atoms are

forced apart in the process, and this leads to NTE.

Zheng’s group also report NTE, but what makes their discovery so interesting is that the effect they observe is four times stronger than that seen in zirconium tungstate. Moreover, it arises from a fundamentally different physical process. Whereas NTE in zirconium tungstate is driven by vibrational motion, it seems to be linked to magnetostriction — the process by which magnetic interactions can influence crystal dimensions — in the materials studied by the Japanese team.

The metal atoms in each of the three compounds studied — CuO, MnF<sub>2</sub> and NiO — have electronic configurations that give rise to non-zero magnetic moments. At high temperatures, the orientation of these moments fluctuates quickly and essentially randomly. Neighbouring metal atoms are, therefore, just as likely to experience a magnetic attraction as they are a repulsive force. On cooling, however,