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Condensed-matter physics

Light makes atoms behave like electromagnetic coils

Carl P. Romao & Dominik M. Juraschek

Microscopic magnetic fields form in non-magnetic materials when light makes the atoms rotate. A similar macroscopic effect has long been known, but proof of its atomic equivalent could give rise to ultrafast data processing. **See p.534 & p.540**

Many electronic devices require precise control of the intrinsic angular momentum of electrons — their 'spin', a property that can point either up or down. Future computers will probably also rely on spin, and their effectiveness will depend on how fast the spins can be flipped. Modern technologies achieve such switching using current-induced magnetic fields on a timescale of nanoseconds, but ultrashort laser pulses could, in theory, flip spins a million times faster, in a matter of femtoseconds. On pages 534 and 540, respectively, Basini *et al.*[1] and Davies *et al.*[2] report that laser pulses can be used to make the atoms in a material orbit around their positions in a crystal lattice, inducing magnetic fields that could aid rapid spin switching.

Magnetizing an object by applying a magnetic field can make it rotate — a phenomenon known as the Einstein–de Haas effect[3]. This is because the spins in the constituent material initially point in different directions, and the field magnetizes the material by making most of its spins point in the same direction, thereby changing the total angular momentum of the system. But the laws of physics dictate that momentum is always conserved, and this requirement results in a rotation of the sample.

This much has been known for more than a century[3], but it wasn't until a decade ago that physicists proposed that collective circular atomic vibrations, known as chiral phonons, could have a key role in the mechanism on ultrashort timescales[4,5]. These vibrations have an inherent chirality (or handedness) because the circular motions of atoms create a helical pattern as a phonon propagates through the material. Experiments soon confirmed that chiral phonons are indeed involved in the Einstein–de Haas effect: demagnetizing a magnetic material by means of a high-intensity laser pulse was shown to induce chiral phonons and mechanical strain[6,7].

The flip side of the Einstein–de Haas effect is that manually rotating a disordered magnetic material can generate a magnetization inside the material (Fig. 1a), a phenomenon, known as the Barnett effect[8], which was first described in the same year that the Einstein–de Haas effect came to light. Basini *et al.* and Davies *et al.* revisited the Barnett effect to investigate whether chiral phonons could also lead to magnetization. The teams studied different materials, and both found spectroscopic evidence that chiral phonons produce a macroscopic magnetization arising from the circular motions of atoms — giving rise to a phenomenon that can be thought of as a phonon Barnett effect (Fig. 1b).

Basini *et al.* used an approach called a pump–probe experiment, in which laser pulses are used to excite (or 'pump') phonons in a material, and then a second set of pulses 'probes' the material's response. The authors excited chiral phonons in strontium titanate, a non-magnetic insulator, using light that was circularly polarized, meaning that its electromagnetic field rotated in a plane perpendicular to its direction of motion. They then measured the extent to which the polarization of femtoscale probe pulses was rotated when these pulses interacted with the induced magnetization of the strontium titanate. The team found that a transient magnetization developed on a timescale of a few picoseconds (1 ps is 10^{-12} seconds), corresponding roughly to the lifetime of the excited phonons.

Davies *et al.* also performed pump–probe experiments, using circularly polarized pump pulses to generate chiral phonons in non-magnetic insulating substrates made from synthetic sapphire and a silicate-based

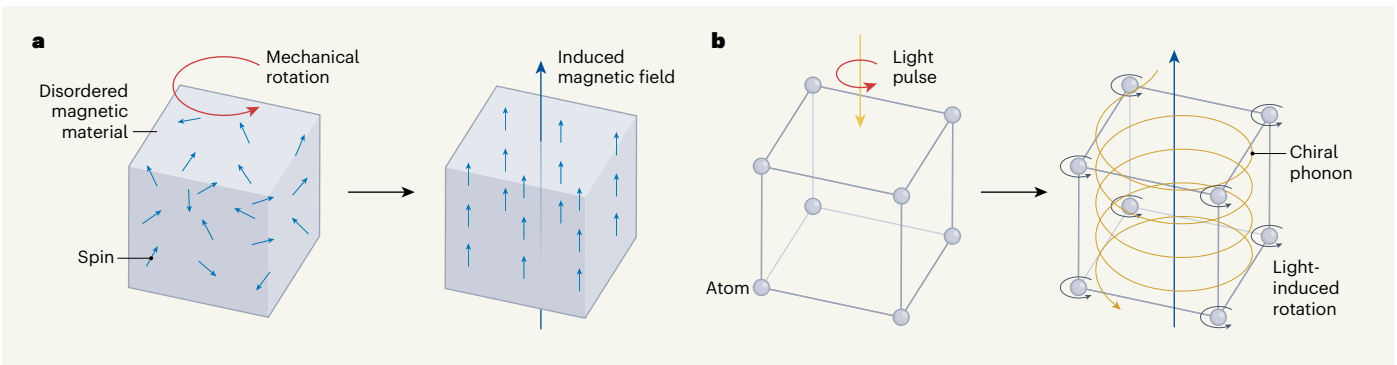

Figure 1 | Magnetic fields on atomic length scales. a, Rotating a disordered magnetic material can make the intrinsic angular momenta (spins) of its electrons align, resulting in a magnetization inside the material, which is known as the Barnett effect[8]. **b**, Basini *et al.*[1] and Davies *et al.*[2] showed that a similar effect can also occur on an atomic scale: light pulses that are circularly polarized (meaning their electromagnetic field rotates in a plane perpendicular to their direction of motion) can make the atoms in a non-magnetic material form collective circular vibrations called chiral phonons. These circular motions induce microscopic magnetic fields in a way that is reminiscent of the mechanism by which an electric current in a coil of wire generates a magnetic field. The resulting atomic-scale fields could be used to increase the rate at which spin states are flipped in electronic devices and computers.

glass–ceramic composite. They showed that these phonons could switch the magnetization of a thin film of gadolinium iron cobalt — a magnetic alloy — that was placed on top of the substrate. The direction of magnetization depended on the handedness of circular polarization of the exciting laser, indicating that the chirality of the phonons was preserved as they made their way through the substrate and into the thin film. Although different in nature, the two investigations both demonstrate that the angular momentum of phonons induced by circular laser pulses is intimately tied to macroscopic magnetization.

Both sets of authors excited chiral phonons in insulating, non-magnetic materials to ensure that any magnetic effects they observed came from the phonons, rather than from direct interactions between light and spin. In simple terms, the materials' magnetization can be thought of as the result of the atoms behaving like tiny electromagnetic coils. Passing an electric current through a coil of wire generates a magnetic field, and this is essentially what happens in these non-magnetic materials, albeit on an atomic scale. The pump pulses excite the materials' ions to rotate, generating a circular current that resembles a miniature electromagnetic coil, which in turn induces magnetization.

The magnetic field can be quantified by a magnetic moment carried by the chiral phonon. Staggeringly, Basini *et al.* estimated the strength of the phonon magnetic moments to be on the scale of one-tenth of the magnetic moment of the electron, which is about 10,000 times larger than that predicted[9], suggesting that more complex physics is at play than was previously thought. This creates an interesting distinction between strontium titanate and magnetic systems such as erbium orthoferrite[10] or cerium trifluoride[11–13], in which chiral phonons create magnetic moments that have strengths spanning various ranges, up to that of the electron. In those cases, the phonon-induced magnetization can be understood in terms of the way that the phonons couple to unpaired electron spins and to partially filled orbitals.

The authors' measurements of the phonon Barnett effect are therefore indicative of intriguing new physics, but they also pose questions and challenges for theoretical predictions and future experiments. For example, the physical mechanisms that are responsible for the connection between phonon angular momentum and magnetization in these non-magnetic materials are yet to be determined. Davies *et al.* showed that the induced magnetic field of chiral phonons can affect magnetic order far away from the point at which the phonons are created, suggesting that there are non-local mechanisms at play, and also that chiral phonon transport needs to be better understood. How the angular momentum propagates through the crystal and how far it travels are therefore issues worthy of investigation.

Theories as to why the induced magnetic fields are larger than predicted have already started to appear[14,15]. These ideas will need to be examined carefully with further spectroscopic experiments, especially those involving electron scattering and X-ray scattering. Such methods are able to track the motion of the atoms directly[16], and will be necessary to fully understand the dynamics of the crystal lattice and the emergent magnetization.

By inducing magnetization in non-magnetic compounds using chiral phonons excited by light, Basini *et al.* and Davies *et al.* have provided a means of generating and controlling magnetic order in a wide range of materials. Their approaches are immediately applicable to simple crystalline materials as well as to heterostructures made from thin layers of different compounds that have been stacked together. Furthermore, the methods could also be extended to molecular systems. The work therefore creates an avenue for 'chiral phonomagnetism' that could lead to fresh approaches to magnetization-based electronics and computing.

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Structural biology

A bitter taste receptor activated in surprising way

Antonella Di Pizio

The sensing of bitter taste results from the complex interplay of many chemical cues and a range of receptors. It emerges that this complexity might be built-in even at the level of individual receptors. **See p.664**

More than 1,000 bitter-tasting compounds are recognized by a repertoire of 26 membrane proteins called the type-2 taste receptors (TAS2Rs), also known as the bitter taste receptors[1,2]. Our understanding of how such chemically diverse compounds activate these receptors at the molecular level has been hindered by a lack of structural data for the receptors. On page 664, Kim *et al.*[3] report a breakthrough in this field: cryo-electron microscopy structures of the human bitter taste receptor TAS2R14. The structures suggest that different molecules modulate the receptor's function at two distinct regions of the receptor, and that dual binding at these regions leads to complete activation.

TAS2Rs belong to the superfamily of G-protein-coupled receptors (GPCRs). In humans, around 800 GPCRs mediate communication between cells and the extracellular environment. When an agonist molecule binds at the extracellular region of a GPCR, the receptor undergoes dynamic conformational changes that enable it to bind to a G protein inside the cell, thereby initiating downstream signalling. The ligand-binding and activation mechanisms of several GPCRs are emerging from experimentally obtained structures of receptors in their inactive and active states[4], but structures of bitter taste receptors have been limited to just one example[5].

The TAS2R14 protein studied by Kim *et al.* binds to most known TAS2R agonists[6], and is present both in the mouth and in numerous other human tissues[7]. The authors report two structures of the receptor in the agonist-bound active state, in complex with one of two