Turn your phonon

Heat travelling down a thermal gradient may be significantly deflected by a magnetic field via the magnetic degree of freedom in multiferroic materials.

It is well known that metals can be heated by eddy currents induced by a changing magnetic field, and that magnetic materials can be cooled via spin disorder due to field removal, but the use of a magnetic field to deflect a flow of heat is less well explored. This thermal Hall effect (Fig. 1a) has traditionally been considered very small in insulating materials that are poor conductors of both heat and electricity, but on this issue, T. Ideue et al. demonstrate considerable improvements in a fashionable class of insulator that is ‘multiferroic’ by virtue of possessing electrical and magnetic order.

In a multiferroic material, the immobile distribution of valence electrons is virtually a requirement for the formation of an electrical polarization, but the resulting lack of metallicity is essentially incompatible with the presence of a magnetization, and so multiferroic materials are rare. In addition to the ongoing search for materials with polarizations and magnetizations that are both large, there are beautiful demonstrations of magnetoelastic coupling between these two order parameters. For example, an applied electric field can produce dramatic changes of magnetization in the boracite Ni$_3$B$_7$O$_{13}$I (ref. 3), and an applied magnetic field can produce dramatic changes of polarization in the manganite TbMnO$_3$ (ref. 4).

The natural focus on the magnetic and electrical properties of multiferroic materials has somewhat inevitably come at the expense of a fullsome consideration of their thermal properties, although there is now some interest in multicaloric materials where magnetic and electric fields are both used to control phase transitions that result in cooling. Ideue et al. also explore the thermal properties of a multiferroic material, but take (Zn,Fe)$_2$Mo$_3$O$_8$ on a less travelled path at room temperature. Their order-of-magnitude improvement in the thermal Hall effect of an insulator arises because the heat flowing through the lattice is strongly modified by via the magnetization of the material.

The concept of ‘heat flow’ is very well established, but this is very unfortunate because heat is technically defined as a flow of energy. A flow of heat therefore describes—nonsensically—a flow that flows. Microscopically, thermal energy in materials is manifested as lattice vibrations, whose modes may be described in terms of hypothetical particles known as ‘phonons’. Fortunately, there is no logical conflict when describing a flow of phonons, and in the thermal Hall effect reported by Ideue et al., the phonons turn away from the main path as they travel because they couple with the magnetization.

The thermal Hall effect is reminiscent of its much better known electrical analogue, where a magnetic field deflects an electrical current flowing through a semiconductor to produce a transverse voltage (the Hall effect, Fig. 1b). The Hall voltage provides information about the nature and density of the charge carriers, and is widely used for magnetic field-sensing. For metals, a significant transverse voltage can arise if the electric current is replaced by a flow of heat. This Nernst effect arises because electrons carry both charge and heat, but like the thermal Hall effect, its strength is limited in materials with low thermal conductivity.

Could the large thermal Hall effect in (Zn,Fe)$_2$Mo$_3$O$_8$ be useful? This set of materials conducts heat relatively well for an insulator, and could in principle be operated as a magnetically operated heat switch. This inspires the idea of applications in thermal logic circuits, or in heat...
pumps based on caloric materials where it is necessary to control cyclical flows of heat (the magnetic fields required for this are already present in magnetocaloric cooling\textsuperscript{7}, while electrocaloric cooling\textsuperscript{7} could perhaps benefit from an electrically insulating heat switch to help avoid electrical breakdown). That said, enthusiasm for any prospective applications would need to be tempered by the knowledge that the thermal Hall effect in metals is considerably larger\textsuperscript{8}.

Returning to the core interest that lies behind multiferroics, one is led to ask about the role of the electrical polarization of (Zn,Fe)\textsubscript{2}Mo\textsubscript{3}O\textsubscript{8} in the thermal Hall effect. Ideue \textit{et al.} find that the answer is not straightforward, as might be anticipated given the complex nature of the crystals. In future, the polarization could be monitored or controlled using a voltage, yielding a complex phase space linking the magnetic, thermal and electrical degrees of freedom.

Overall, (Zn,Fe)\textsubscript{2}Mo\textsubscript{3}O\textsubscript{8} provides an interesting addition to the renascent field of phononics\textsuperscript{6}. A relatively large thermal Hall effect can be dialled up using a magnetic field, and it remains to be seen whether this can be mimicked using an electric field, or exploited for any application. Similar studies in other multiferroic materials could now be forthcoming, and the more general trend of combining multiple degrees of freedom should keep all of us busy for a long time to come.

**Fig. 1. Magnetic control of phonons and charge.** \textit{a}, In the thermal Hall effect, a perpendicular magnetic field $\mathbf{H}$ modifies the sample magnetization (not shown), thus deflecting phonons as they flow in response to a thermal gradient (phonons represent lattice vibrations and carry heat). This results in a transverse difference of temperature $\Delta T$. \textit{b}, In the Hall effect, a perpendicular magnetic field deflects electrons as they flow in response to an electric field. This results in a transverse voltage $\Delta V$. If the charge carriers are holes (missing electrons) then the deflection is reversed.

Xavier Moya and Neil D. Mathur are in the Department of Materials Science, University of Cambridge, Cambridge CB3 0FS, UK. xm212@cam.ac.uk, ndm12@cam.ac.uk