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# Phonons bend to magnetic fields

Valentina Martelli

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Phonons do not carry spin or charge, but they can couple to an external magnetic field and cause a sizable transverse thermal gradient. Experiments suggest that phonon handedness is a widespread effect in magnetic insulators with impurities.

Phonons are quasiparticles associated with lattice vibrations, and they are the dominant heat carriers in insulators because electrons are locked in place. When a magnetic field is applied perpendicular to a heat current, a transverse thermal gradient can be detected. This effect, the thermal Hall effect (THE), has been observed in a growing number of insulators, but the underlying mechanisms that couple phonons to a magnetic field are under debate. Amirreza Ataei and co-workers[1] carried out a systematic study of the THE in the antiferromagnetic material $Sr_2IrO_4$, into which they selectively introduced impurities at different lattice sites. Their work put on firm ground the role of defects in boosting the THE.

When establishing a temperature gradient in a material, heat flows from the hot side to the cold side. If a static external magnetic field is applied perpendicular to this heat current, a sizable transverse temperature gradient can develop, manifesting with one hotter side (Fig. 1a). In a magnetic field, phonons acquire handedness — they become chiral. This effect is the thermal analogue of the well-studied Hall effect, in which a charge flow experiences the Lorentz force under the application of a perpendicular magnetic field.

It has long been known that a transverse thermal signal exists in a material with free electrons. Even in the absence of an external electric field, when free charges move under the effect of a temperature difference, as long as a magnetic field is present, they will experience the Lorentz force and give rise to a transverse temperature gradient. On the other hand, neutral heat carriers such as phonons were expected to produce a negligible effect because they lack degrees of freedom that can be affected by a magnetic field.

The multiferroic $Tb_3Ga_5O_{12}$ was the first insulating material reported to show a THE less than two decades ago[2]. This was followed by the observation in several insulators with a range of quite different characteristics, including cuprates[3], the Kitaev spin liquid candidate $\alpha$-$RuCl_3$ (refs. 4,5), the quantum paraelectric $SrTiO_3$ (ref. 6), and now the antiferromagnetic $Sr_2IrO_4$ (ref. 1). This shows that the THE occurs in various insulating materials, but how do neutral heat carriers couple to a magnetic field and become chiral?

For most of these materials, the microscopic origin of the THE has so far been attributed to phonons through two general coupling mechanisms. They either have an intrinsic origin — phonons couple to a field-sensitive mechanism inherent to the host material — or an extrinsic origin — phonons couple through impurities and defects, which are unavoidable in real samples. In a small number of materials, magnons can also be the heat carriers associated with the observed THE[7]. Finally, one cannot exclude other exotic chargeless excitations, which could themselves be sensitive to magnetic fields. This is, for example, the case for Majorana fermions, which are expected to open a gap in their bands under the effect of a field and show a peculiar signature on the THE. The Kitaev spin liquid candidate $\alpha$-$RuCl_3$ was suggested to host this exotic effect[4], but a consensus on this front is far from being reached[5].

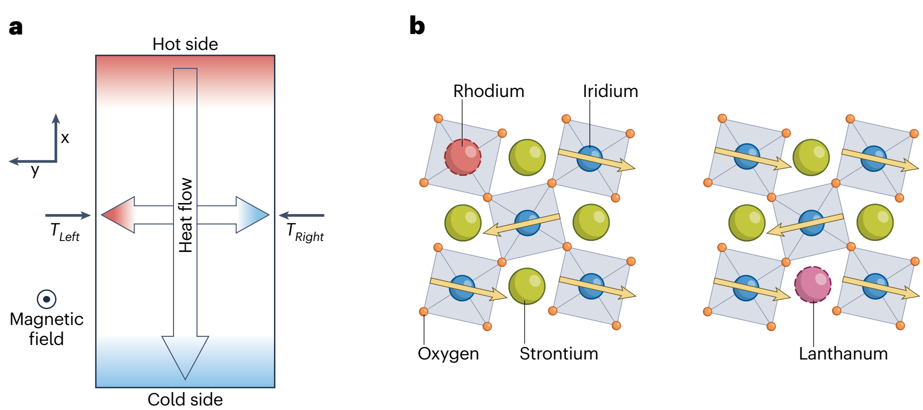


**Fig. 1 | Thermal Hall effect in $Sr_2IrO_4$. a**, In a thermal Hall effect experiment, heat flows from a hot (red) to a cold (blue) side. In the presence of a magnetic field, a transverse gradient (measured by a temperature on the left side, $T_{Left}$, and a temperature on the right side, $T_{Right}$) is observed in many insulators, meaning that chargeless carriers acquire handedness. **b**, A sketch of a portion of the unit cell of $Sr_2IrO_4$. The yellow arrows represent the spins that give the antiferromagnetic (AFM) character in a portion of the unit cell (the full antiferromagnetic structure of $Sr_2IrO_4$ can be found in ref. 10). When impurities are increasingly added in a magnetic environment (Rh→Ir, red circle), the THE intensifies, peaks and then vanishes together with the antiferromagnetic suppression. By contrast, when the substitution is for an atom that is not responsible for the magnetism (La→Sr, magenta circle), the THE is 30 times less intense.

In this context, Ataei and co-workers bring timely new evidence to the debate. They investigated crystals of $Sr_2IrO_4$, an antiferromagnetic insulator, in which iridium gives the crystal its magnetic character (Fig. 1b). They studied the THE in two series of increasingly doped $Sr_2IrO_4$. They discovered that by substituting rhodium into the spin-carrying iridium site, the THE first increases at low doping, reaches a maximum and finally decreases before vanishing at the critical doping that suppresses the antiferromagnetic order. A similar feature is observed when lanthanum is substituted into the non-magnetic strontium site, but the effect is 30 times less intense. Having ruled out the contribution of electrons and magnons, the team was able to attribute the effect to phonons.

This careful work shows that phonons couple to the magnetic field through impurities when placed in a magnetic environment. The presence of the foreign atom effectively acts as a scattering centre for phonons, giving them chirality and boosting the effect. This result, in agreement with a recent theoretical scenario[8], supports the idea that the THE could be a much more common effect in materials with magnetic texture and unavoidable disorder. It does not imply that exotic chargeless excitations cannot contribute to the THE (as for instance in the highly debated case of $\alpha$-$RuCl_3$), but that phonons coupled to impurities in a magnetic environment might have a prominent role.

While Ataei and co-workers' work adds a relevant piece of evidence to the evolution of the THE in one class of insulators, fundamental questions on the underlying coupling mechanisms generating the THE and on the universality of this phenomenon remain to be answered. A recent investigation reported the THE of black phosphorus[9], an elemental insulator in which no magnetic order, no ionic bonds, no structural transitions, nor any other previously scrutinized mechanism could explain the record THE except for the anisotropy of the charge distribution across the lattice. Searching for the minimal conditions to observe the THE in simpler structures may be a promising route to advance the fundamental understanding of this phenomenon. The thermal Hall angle — that is, the ratio between transverse and longitudinal gradient — in analogy to the Hall angle, was phenomenologically shown[9] to display a universal scaling across a variety of materials, pointing to a more general underlying mechanism yet to be explained.

The more we understand about the THE, the more likely it is to become an effective tool to study quantum materials and exotic excitations, in analogy to the Hall effect, which is widely employed to characterize metallic states. On the experimental end, besides exploring new materials, the next frontier may include additional strategies such as studying the THE under strain or under the reduction of dimensionality in properly selected compounds to isolate further contributions to the transverse gradient.

**Valentina Martelli**
Present address: Laboratory for Quantum Matter under Extreme Conditions, Institute of Physics of the University of São Paulo, São Paulo, Brazil.
e-mail: valentina.martelli@usp.br

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## Competing interests

The author declares no competing interests.