Thermal Hall effect in a paramagnet

Thermal Hall conductivity in the frustrated pyrochlore magnet $Tb_2Ti_2O_7$
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Recommendation and Commentary by Leon Balents, KITP, UCSB

The Hall effect – the development of a transverse voltage in response to an applied electric current in the presence of a magnetic field – has proven an exquisitely powerful tool in studying the quantum physics of electrons. Apart from commonplace applications as a means of measuring carrier density in semiconductors, it appears over and over again in fundamental physics studies: probing topology and correlations in the integer and fractional Hall regimes, revealing remarkable effects of spin textures in metallic magnets via the anomalous Hall effects, etc. Sadly, insulators are largely left out of this profitable enterprise.

Insulators, if they harbor local moments, are still influenced by magnetic fields, but cannot transport electrical current. Instead, one may look to the *thermal* Hall effect, in which a transverse temperature gradient is produced in response to a heat current in the presence of a magnetic field. This can be measured in conductors too, and is particularly interesting in superconductors since the condensate itself carries no entropy. Hence it cannot transport heat, and quasiparticles are largely frozen out at low temperature by the superconducting gap; therefore only special low energy quasiparticles and/or vortices contribute. In magnetically ordered insulators, one may imagine a thermal Hall effect due to spin waves – a magnon Hall effect. This has indeed been observed in the the insulating ferromagnet $Lu_2V_2O_7$ and appears consistent with a semiclassical model of magnon dynamics taking into account the so-called anomalous velocity. The latter gives a contribution to the magnon velocity determined by the Berry curvature of magnon wavefunctions.

What about systems without quasiparticles? This is a heavily debated and active topic in the context of non-Fermi liquid metals, such as cuprates at optimal doping, near certain quantum phase transitions, or at high temperature, where the Landau quasiparticle picture breaks down. The analogous magnetic system is a spin liquid, in which there is no influence of any magnetic order, and the excitations are unrelated to magnons. There we may ask about thermal transport without quasiparticles. The thermal Hall effect can be particularly valuable, because the lattice dominates the diagonal thermal conductivity at most temperatures, but is not expected to give any significant thermal Hall signal. The theoretical suggestion by Katsura, Nagaosa, and Lee[1] that a large thermal Hall effect can be a signature of fermionic spinons has stimulated experimental investigations, though the proposed effect has not been found so far. Spin liquids however are rare, thermal Hall effect measurements are difficult, and the understanding of both is sparse, so there is plenty of room for more study.

Hirschberger *et al* report, in the highlighted paper, on striking observations of a significant thermal Hall effect in $Tb_2Ti_2O_7$, an insulating rare earth compound with magnetic Tb^{3+} ions occupying a pyrochlore lattice of corner-sharing tetrahedra. $Tb_2Ti_2O_7$ is one of a family of related compounds which display a diverse range of frustrated magnetism of rare earth ions. Some of these behave quite classically, but others show pronounced exchange-induced quantum dynamics with characteristic energies of order 1-10K. $Tb_2Ti_2O_7$ fits into the latter category. It has been considered as an example of "quantum spin ice", and is particularly interesting as it seems to avoid long-range order down to millikelvin temperatures. The ground state of quantum spin ice has been suggested theoretically under some conditions to be a novel type of spin liquid, which adds to the interest in $Tb_2Ti_2O_7$.

Remarkably, Hirschberger *et al* find a substantial thermal Hall signal in $Tb_2Ti_2O_7$ even at temperatures above 100K. This far exceeds the magnetic interaction scales in $Tb_2Ti_2O_7$, and so the system must be regarded as an unusual paramagnet. However, there is a lot of interesting physics in $Tb_2Ti_2O_7$ on this scale. The Tb^{3+} ion has a large J=6 spin, split by crystal field effects to a doublet ground state, which can be regarded as an effective S=1/2 spin. However, the first excited doublet is at a low energy of about 20K, so the population of these states may change wildly in this temperature range. Hirschberger *et al* find that the thermal Hall effect grows with lowering temperature down to about 15K, below which there is some saturation of the low field effect. At lower temperature, the non-linear curve of thermal Hall conductivity versus field evolves with temperature. This change of behavior around 15K seems to coincide with the excitation scale out of the ground doublet, so perhaps it is indicative of the true effective spin-1/2 quantum regime. At temperatures below 2-3K, the Hall effect is suppressed above a field of 1-2T, which suggests that polarization of the spins destroys whatever delicate state can sustain a thermal Hall conductivity in the most quantum regime.

There is clearly a lot to be understood here, and amongst various measurements of quantum spin ice materials, the thermal Hall measurements of $Tb_2Ti_2O_7$ seem to reveal particularly striking features. There are more questions than answers. Are any of the observations related to the quantum spin ice model? Is it important that Tb^{3+} is a non-Kramers (integer spin) ion, which can couple strongly to the lattice? The experiments find that both the diagonal thermal conductivity and thermal Hall coefficient (slope of thermal Hall conductivity versus field) are linear in temperature below about 1K, which the authors' suggest might be related to neutral fermion excitations. These are not expected in the usual theory of quantum spin ice[2], but this may not apply to $Tb_2Ti_2O_7$. Both more theoretical work on thermal Hall effects in paramagnetic insulators, and further experimental studies extended to other frustrated pyrochlore magnets are much needed to help move forward to answer these questions.

References

[1] Hosho Katsura, Naoto Nagaosa, and Patrick A Lee. Theory of the thermal hall effect in quantum magnets. *Physical review letters*, 104(6):066403, 2010.

[2] Lucile Savary and Leon Balents. Coulombic quantum liquids in spin-1/2 pyrochlores. *Physical review letters*, 108(3):037202, 2012.