Thermal Imaging of the Thomson Effect

Thermal images of an elusive thermoelectric effect reveal that the effect significantly increases when a magnetic field is applied to the material.

By **Kelly Morrison** and **Fasil Kidane Dejene**

The term "thermoelectric" most commonly pops up when describing how materials convert a temperature difference into an electric current, and vice versa. However, these descriptions often overlook something called the Thomson effect—an additional heating or cooling effect that arises in a conducting material that is subjected to both a charge current and a temperature gradient. Now, Ken-ichi Uchida of the National Institute for Materials Science, Japan, and Tohoku University, Japan, and his colleagues have succeeded in imaging this effect [**1**] and have directly shown the reversal of heating and cooling that it induces in a material. Their results could impact the design of thermoelectric devices in magnetic systems, for example heat switches for spintronics applications [**2**].

Imagine a device made of two materials that are sandwiched together. Raising the temperature of the interface between the two materials induces a potential difference across the device that is proportional to the induced temperature gradient, a phenomenon known as the Seebeck effect (Fig. **1**). The reverse process—heating or cooling of the interface by the flow of a charge current—is called the Peltier effect. The Thomson effect also plays a role in thermoelectric behavior. Often, however, it goes ignored because it is difficult to measure, and, in practice, manifests as a small correction to the analysis of thermoelectric devices [**3**].

The Thomson effect depends both on the temperature gradient and charge current across the material [**4**]. Unlike the Peltier and Seebeck effects, the Thomson effect does not require the presence of two materials—it can also occur in a homogenous slab of one substance. Originally proposed by William Thomson (also known as Lord Kelvin), the Thomson effect links together the Peltier coefficient Π (the heat absorbed/evolved per unit charge) and the Seebeck coefficient S (the voltage generated per unit temperature difference) at any temperature T_0, using $\Pi = ST_0$ and the Thomson coefficient $\tau = S \cdot dS/dT$ [**3**].

For nearly 100 years, scientists have been attempting to directly measure the Thomson effect and its influence on other thermophysical phenomena. But until now, the effect had only been detected indirectly by either comparing Joule heating in a material to heating or cooling due to the Thomson effect as the charge current across the material was decreased [**5**] or by observing the temperature dependence of the Seebeck coefficient [**3**]. The new results from Uchida and his colleagues solve that deficiency, providing the first direct measurements of the effect.

In their experiments, Uchida and co-workers studied the heat absorption and emission in a 3.5-mm-thick slab of a nonmagnetic conductor made of the bismuth-antimony alloy $Bi_{88}Sb_{12}$. Each end of the slab was held at a fixed temperature. At the center of the slab, the team attached a dc heater. This device heated the slab's center, inducing a "bipolar" temperature gradient across the material with both ends being colder than the center. The team then passed through the slab a periodic square-wave current, which weakly modulated the slab's temperature profile. To measure the temperature profile of the slab, the team imaged it with a thermographic camera locked on to the frequency of the square-wave current. The electromagnetic force due to a magnetic field is known to modify the Seebeck and Thomson coefficients, so the team also carried out the same experiments while applying to the

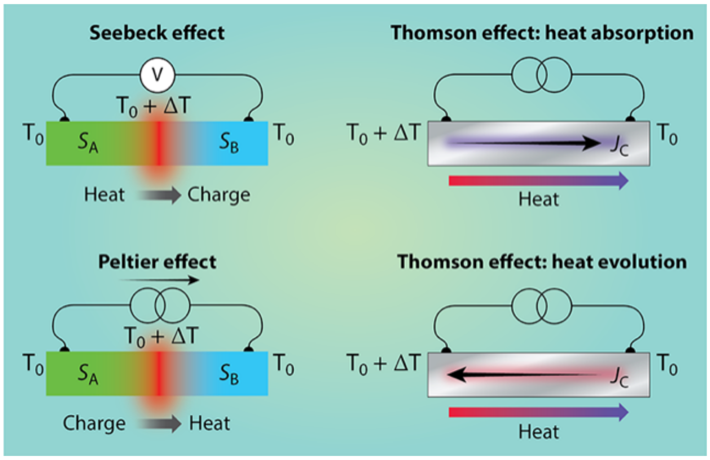

Figure 1: In new experiments, Uchida and colleagues have imaged a thermoelectric effect known as the Thomson effect (right). To do this they had to disentangle the effect from the more commonly known thermoelectric effects, the Seebeck and Peltier effects, as well as from Joule heating. (Left) The Seebeck effect describes the generation of a charge voltage V from a temperature difference ΔT (shown in red) present at an interface between two materials (shown in green and blue) that have different Seebeck coefficients S_A and S_B. The Peltier effect is the heating or cooling of the same system when a charge current J_c flows through the interface. (Right) The Thomson effect is the amount of heat carried by a moving charge per unit temperature increase across a material and it can manifest in a single conducting material (shown in grey). Depending on the relative orientation of the charge and heat currents, heat is either absorbed from or liberated to the surroundings.
Credit: APS/Carin Cain

material a magnetic field of up to 0.9 T in strength.

By locking on to this periodic temperature change, the team was able to separate out heat changes caused by the Peltier and Thomson effects from those arising from a constant (dc) Joule heating. The team then carried out the same experiments with the heater off, something that allowed them to separate the Thomson and Peltier effect contributions. Further confirmation that they had isolated the Thomson effect came from the observation that the measured effect increased linearly with an increasing charge current density and temperature gradient, a behavior predicted by Thomson's models.

In the absence of the magnetic field, the team's thermal images show that the slab has a temperature modulation that switches direction at the slab's center, as expected for the Thomson effect. When the field was turned on, they observed a 90.3% increase in the amplitude of these temperature modulations. This high value makes the magnetic-Thomson coefficient comparable with the material's Seebeck coefficient and is significantly higher than the corresponding magnetic-field-induced changes in both the material's thermal and electric conductivities (8.3 and 19.4%, respectively) and its Seebeck coefficient (20.5%).

The enhancement of the Thomson coefficient when a magnetic field is applied indicates a potential improvement of the cooling efficiency of the material. This behavior could be used to create magnetic cooling devices in which the Thomson effect compensates for Joule heating [**3**].

The technique that the team used could also be applied to study other thermoelectric effects in magnetic materials, such as the spin-Thomson effect—another elusive thermoelectric phenomenon [**2**]. Scientists have demonstrated the existence of spin-dependent thermoelectric effects, whose control parameters, along with a charge current and a temperature current, include an additional degree of freedom: individual electron spin or collective spin excitations known as magnons. Spin-analogs of the Seebeck and Peltier effects have been studied in metallic and in insulating magnetic systems [**6**] and are the basis of the emergent field of "spin caloritronics." It could therefore be interesting to apply this technique to spin-caloritronic experiments to see if the spin-Thomson effect is present in the devices studied in earlier works [**7–9**]. Such an effect could have a huge impact on spin-caloritronic devices, as it could provide a pathway towards designing programmable heat current switches or valves.

Finally, since other thermoelectric effects have so-called Onsager reciprocal processes [**10**]—the Peltier effect is the reciprocal of the Seebeck effect, for example— the new results beg the question of whether there is a reciprocal, inverse-Thomson effect. Does a temperature gradient emerge that is parallel or antiparallel to the flow of charge current when a local heat absorption or evolution occurs in a thermoelectric material? Designing an experimental system to test the inverse-Thomson effect will be difficult but not impossible.

Recent advances in techniques, such as scanning probe thermometry, for example, could allow researchers to locally probe the inverse-Thomson effect by introducing localized heating or cooling at the nanoscale.

Kelly Morrison: Department of Physics, Loughborough University, Loughborough, United Kingdom

Fasil Kidane Dejene: Department of Physics, Loughborough University, Loughborough, United Kingdom

REFERENCES

1. K. Uchida *et al.*, "Observation of the magneto-Thomson effect," **Phys. Rev. Lett. 125, 106601 (2020).**
2. I. A. Starkov *et al.*, "Spin analogs of thermo-magnetoelectric phenomena for heat switches," **J. Magn. Magn. Mater. 496, 165949 (2020).**
3. V. Giaretto *et al.*, "The elusive Thomson effect in thermoelectric devices. Experimental investigation from 363 K to 213 K on various Peltier modules," **Metals 10, 291 (2020).**
4. D. K. C. MacDonald, **Thermoelectricity: An Introduction to the principles (Dover Publications, Inc., New York, 2006).**
5. J. Young, "The Thomson effect in copper, iron, and carbon steels," **Proc. Phys. Soc. London 37, 145 (1924).**
6. K. Uchida *et al.*, "Spin Seebeck insulator," **Nat. Mater. 9, 894 (2010).**
7. L. J. Cornelissen *et al.*, "Long-distance transport of magnon spin information in a magnetic insulator at room temperature," **Nat. Phys. 11, 1022 (2015).**
8. L. Gravier *et al.*, "Spin-dependent Peltier effect of perpendicular currents in multilayered nanowires," **Phys. Rev. B 73, 052410 (2006).**
9. A. Boehnke *et al.*, "Large magneto-Seebeck effect in magnetic tunnel junctions with half-metallic Heusler electrodes," **Nat. Commun. 8, 1626 (2017).**
10. H. B. Callen, "The application of Onsager's reciprocal relations to thermoelectric, thermomagnetic, and galvanomagnetic effects," **Phys. Rev. 73, 1349 (1948).**