QUANTUM PHYSICS

Information on heat

Keith Schwab

There is a fundamental quantum limit to heat flow, just as there is to electric current. This limit is independent of what carries the heat, and could also have a role in an unexpected quarter: information theory.

In the past 20 years, physicists have learnt a tremendous amount about the transport of matter and energy through devices small enough for quantum effects to come into play. One surprising fact that has emerged is that the rates of transport in such devices, expressed for example by their electronic or thermal conductance, have simple quantum-mechanical limits. On page 187 of this issue, Meschke *et al.*[1] extend this principle to heat conduction by photons. Although the result will certainly have practical ramifications for the engineering of ultra-sensitive detectors, sensors and microelectronic refrigerators, the physics behind it hints at more fundamental truths.

The experimental trail leading to this point starts in 1988, when two groups independently demonstrated[2,3] the quantization of electron transport through a single 'ballistic' channel in which the electron's movement is impeded only negligibly by scattering. The conductance of such a channel (the inverse of its resistance) was found to vary in discrete steps of size $2e^2/h$, where e is the electron charge and h is Planck's constant. This quantum of electrical conductance has a value of around $7.8 \times 10^{-5}\ \Omega^{-1}$ in conventional units. In small systems, such as a single channel, that have only one way for electrons to propagate (one 'mode of conduction'), it also represents the maximum value of the conductance.

This first demonstration of quantized electronic transport was a *tour de force* of cryogenics, microelectronics and materials science. Since then, the phenomenon has been observed in thousands of situations: in larger, mesoscopic devices, in atomic point contacts and break junctions, in single molecules, nanotubes and so on. It has become an example of what physicists love, and strive for, most: a prediction of complete generality. Without specifying any of the material details, such as the structure of electronic bands or the density, one can estimate the electronic conductance of any quantum-scale device.

Experimental evidence that the transport of thermal energy is also quantized dates back to 1999. Then, Michael Roukes and I demonstrated[4] that the movement of heat through discrete, freely suspended mechanically vibrating channels approached a previously predicted maximum rate[5] for each independent vibrational mode — longitudinal, transverse and torsional — of the structure. This universal rate is the quantum of thermal conductance, G_Q, and comes in units of $\pi^2 k_B^2 T/3h$. Here, k_B is Boltzmann's constant and T is the prevailing temperature; the exact maximum rate of heat transport through a quantum device therefore increases linearly with temperature.

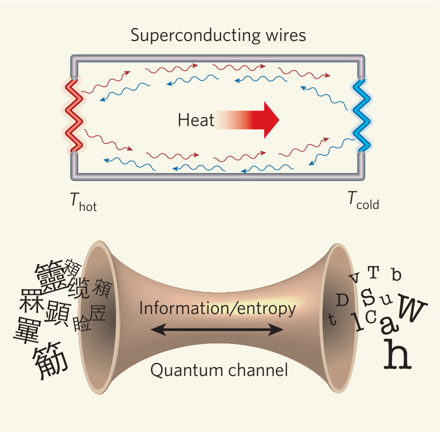

Figure 1 | Information is power. In Meschke and colleagues' experiments[1] on quantized heat transfer by photons, two resistors of different temperatures radiate thermal voltage noise. Net power and entropy flow from hot to cold at the maximum possible rate. Because entropy and information are fundamentally related[9], this exchange of noise is analogous to classical information transfer over a quantum channel in which both parties encode information on the particles they exchange. The fact that heat transport has a universal quantum limit that is independent of the type of particle exchanged might therefore be the result of a similar principle that underlies information exchange.

The mechanical vibrations that transported the heat in this case are called phonons, and are analogous to the quantized vibrations of the electromagnetic field — better known as photons. With photons, the channels of conduction are the propagating electromagnetic modes of a transmission line or of an optical waveguide such as a single-mode fibre-optic cable.

The advance made by Meschke and colleagues[1] is to demonstrate for the first time the quantized conduction of heat by photons. In their experiment, two microscopic electronic resistors exchanged heat through random thermal voltage fluctuations transmitted through two superconducting wires. With some clever use of further superconducting circuitry, the authors could switch the electrical conduction channel on and off, and thus expose the thermal connection between the two resistors brought about by the photons emitted and absorbed by them both. The authors show that the rate of heat exchange between the two resistors in this case is given simply by G_Q.

Thus, like the quantum of electrical conductance, G_Q is very general, and independent of the nature of the material connection between two heat reservoirs. Nor does it depend on the type of particle that carries the heat: the same G_Q is the limit for the conductance of heat by electrons, phonons, photons, gravitons, you-name-it-ons. Thus, G_Q is universal in a much deeper sense[6–8] than the quantum of electrical conductance, which depends on the quantum statistics of the particles; that is, whether they are bosons, fermions or something in between, such as the 'anyons' that crop up in certain two-dimensional systems.

A further connection that might seem somewhat surprising at first glance is that the quantum limit for heat transport is intimately related to the maximum classical information capacity of a single quantum channel (Fig. 1). This connection rests on a deep relationship between information and entropy, which was established by Claude Shannon in 1948 (ref. 9) and has been investigated by many authors over four decades[10]. One of the more interesting treatments[5] made explicit the connection between maximum heating and cooling rates through both fermionic and bosonic channels on the one hand, and maximum data rates on the other. Although the maximum data rates of fermionic and bosonic channels differ, there has been speculation[11] that a deeper underlying principle might exist that could be used to extract a universal statement about information capacity from the truly universal nature of thermal transport in one dimension. This connection reinforces the emerging view of the basic nature of information in fundamental physics[12].

Cast in this light, the work of Meschke and colleagues[1] is of more fundamental importance than just investigating the behaviour of microscopic resistors exchanging heat. What they have demonstrated is two resistors babbling to each other using thermal voltage noise. As these resistors are near-perfect 'black-body' radiators, they emit and absorb radiation fields of maximum entropy, and so — according to Shannon's work[9] — maximum information content. The authors have proved that this information can be carried by particles of very different natures: photons do just as well as phonons. In this spirit, I look forward to the day when a measurement of the thermal conductance through a channel of anyons in a quantum Hall fluid demonstrates the extraordinary, universal nature of G_Q. ■

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EARTH SCIENCE

Isotopic hide and seek

Francis Albarède

Isotopes formed by the decay of radioactive nuclei provide evidence of how Earth was shaped in its infancy. But some decay products seem to be hidden — a finding that will revitalize a debate about Earth's interior.

It is thought that Earth formed, along with the rest of the Solar System, from the gravitational collapse of a huge cloud of gas. But what were the processes that turned the resulting ball of rubble into a planet endowed with a metallic liquid core, a thick viscous mantle and a thin continental crust? Some clues may be found by measuring the abundance of neodymium isotopes in volcanic rocks, as reported by Boyet and Carlson in *Earth and Planetary Science Letters*[1]. Their results illuminate the early dynamics of Earth's interior and provide fresh insight into the structure and flow of the modern mantle.

Many short-lived radioactive elements were created in the events that accompanied the formation of the Solar System. These elements — or rather, the isotopically distinctive products of their radioactive decay — provide clues about the processes involved in planetary accretion and development. In the final stages of Earth's formation, differentiation processes distributed its constituent minerals and metals between the core, mantle and crust. This resulted in the separation of radioactive nuclides from the products of their decay, so that isotope compositions of the daughter elements in modern-day minerals attest to the separation of vapour, melts and solid phases in the newborn planet.

For example, samarium (Sm) decays to produce neodymium (Nd); both of these elements are found in mantle silicates. Variations of neodymium-isotope abundances in terrestrial rocks are useful for dating melt segregation in the mantle. Most earth scientists are familiar with the decay of ^{147}Sm into ^{143}Nd, a process with a half-life of 106 billion years. This decay is used as a chronometer and as a tracer of material exchange between mantle and crust. But with such a long half-life it cannot provide a detailed picture of the dawn of geological times. In contrast, the much shorter half-life of ^{146}Sm decay to ^{142}Nd (103 million years) is comparable to the timescale of early planetary processes and so is well suited to investigating the dynamics of newborn Earth.

So far, the ^{146}Sm–^{142}Nd chronometer has found its most valuable application in the study of magma oceans — envelopes of liquid silicate that hug newborn planets. The abundances of ^{142}Nd in 3.8-billion-year-old rocks from Isua in Greenland are higher than those in chondrite meteorites, which are made from the same raw materials as Earth and the other rocky planets. Samarium and neodymium are 'refractory' elements, which survived the harsh conditions found in the newborn Solar System. Their relative proportions in Earth must therefore be the same as for chondrites. The 'excess' of ^{142}Nd, compared with chondrites, in the Isua basaltic rocks is evidence of a very early melting event (the formation of magma oceans) that concentrated ^{142}Nd in certain regions of the newly created mantle[2,3].

The modern terrestrial mantle and continental crust also display excesses of ^{142}Nd compared with chondrites. This geochemical feature can only be explained if the mantle is the solid residue of an ancient slurry. To balance the books, the excess of ^{142}Nd in these regions must be paired with a deficit in another complementary material that is derived from the liquid part of the slurry. But this ^{142}Nd-deficient material is conspicuously missing from the geological record. Boyet and Carlson have previously argued[4] that this component probably took the form of a primordial crust, which sank down to the core–mantle boundary very early in Earth's history. The case for a missing reservoir, distinct from the familiar mantle, has also been made based on the abundances of the heavier neodymium isotope ^{143}Nd in Archaean rocks[5] (which are more than 2.7 billion years old) and of hafnium in oceanic basalts[6]. But the ^{142}Nd anomalies raise an additional useful point — that the absent material was segregated in the lower mantle during the first tens of millions of years of Earth's history.

The quest for the hidden reservoir commenced with studies on oceanic basalts derived from deep mantle material[7]. But now Boyet and Carlson[1] present high-precision ^{142}Nd abundance data from carbonatites and diamond-bearing kimberlites — volcanic rocks that are thought most probably to originate from the deepest parts of the mantle. They report that none of these rocks shows a deviation of ^{142}Nd abundances from the modern terrestrial value. This suggests that the rocks do not originate from a ^{142}Nd-deficient reservoir or, at the very least, that the contribution of such deep-seated material is not detectable.

The authors[1] review different interpretations of their data. They first examine the possibility that Earth's composition may not be chondritic; this could be true if atomic nuclei weren't created in a uniform distribution throughout the nebula from which the Solar System formed. A recent paper[8] suggests that at least one process of nucleosynthesis in supernovae could lead to uneven isotopic abundances of some elements. But the isotopic distributions of nearly all the elements are the same in other planets, which makes it very difficult to justify non-chondritic abundances of samarium and neodymium for Earth.

So, if the neodymium isotope compositions of magmas reflect those of their source mantle, the conclusion from Boyet and Carlson's data is inescapable: some lower-mantle material with a ^{142}Nd-deficit exists, untapped by deep magmas and separate from the convective flow field of the upper mantle. This ^{142}Nd-deficient material may be locked up in the so-called D″ layer of the lower mantle, which sits on top of the core–mantle boundary. Or perhaps it resides in a deep reservoir resembling the abyssal layer that is proposed to exist at a depth of about 1,600 kilometres[9], although this layer has so far evaded detection[10]. Of course, it could simply be that the kimberlites and carbonatites analysed by Boyet and Carlson were contaminated on their way to Earth's surface, masking the modest ^{142}Nd deficit inherited from their source region[7].

Several models for the structure and dynamics of the mantle have been proposed over the years, including the theory that two separate mantle layers exist, each with its own convection patterns. This theory seemed inconsistent with emerging seismic evidence and went out of favour. But thanks to Boyet and Carlson's studies[1], layered mantle convection may now be knocking at the back door, as this could explain why deep reservoirs have become segregated from upper mantle regions. The authors have revitalized this fundamental debate — and the arguments look set to continue for years to come. ■

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