ACOUSTICS

Negative refraction without reflection

At the interface between two facets of an artificial crystal, sound waves can be transmitted in the opposite direction to that expected, and undergo no reflection. Such wave behaviour could have many applications. SEE LETTER P.61

BAILE ZHANG

Waves change direction when they pass from one medium to another — a phenomenon called refraction. This effect underlies most optical lenses and instruments, and is widely found in acoustics when an acoustic beam behaves like an optical beam. In general, some of the waves are reflected during the refraction process. On page 61, He *et al.*[1] report an impressive demonstration of a previously unobserved refraction phenomenon. They show that, in a certain artificially engineered material, an acoustic beam can be refracted in the opposite direction to that seen in ordinary materials, without reflection. The authors' findings could lead to improved control of waves in electronic and photonic systems.

When an acoustic or optical ray strikes the interface between two different media, part of its energy passes through the interface to form a refracted ray (Fig. 1a). The remaining energy reflects from the interface to produce a reflected ray. In nature, the incident and refracted rays are always on opposite sides of the normal — an imaginary line perpendicular to the interface. But, in theory, this need not be the case.

In 1968, the Russian physicist Victor Veselago considered a hypothetical material that has a negative refractive index[2]. A refractive index describes how waves propagate in a medium, and is positive in all conventional materials. Veselago showed that the way in which refraction usually occurs could be reversed in a negative-index material: the refracted ray could emerge on the same side of the normal as the incident ray (Fig. 1b).

Although intriguing, negative refraction did not trigger much attention, and was considered impossible for more than 30 years because it was thought that negative-index materials could not exist. The situation changed in 2000, when the British physicist John Pendry made a shocking prediction[3]: that negative refraction could be used to make a lens that could focus light more tightly than is normally possible. He also identified a practical way to construct negative-index materials in the lab using artificial structures. Such materials, now generally referred to as metamaterials, stimulated research into concepts such as invisibility cloaking[4] that had previously existed only in science fiction.

In the years since Pendry's work, the pursuit of negative refraction has led to developments in optics, acoustics, plasmonics (the study of how light interacts with electrons in metals) and even graphene-based electronics[5]. Versions of negative refraction have been realized in each of these areas. However, the phenomenon is generally accompanied by reflection, which is often undesirable. In many cases, such as in experiments involving the refraction of electrons through an interface[5], reflection can even dominate negative refraction.

The property of reflection immunity is not found in natural optical materials for light. However, it does occur in exotic phases of matter known as topological quantum matter, for quantum-mechanical electronic waves. A well-studied example is the topological insulator, which is an electrical insulator in its interior, but conducts electricity on its surface through electronic waves called topological surface states. Such states are able to propagate unidirectionally — they bypass obstacles and defects, rather than being reflected.

He and colleagues' demonstration was directly inspired by another emerging topological quantum matter: the Weyl semimetal[6]. The topological surface states in this material cannot propagate in all directions; propagation is confined to a certain range of directions, which connect to form what are known as Fermi arcs[6]. Because the limited range of propagation directions does not include the direction in which reflection would normally occur, reflection is forbidden (Fig. 1c).

In their experiment, He *et al.* used an artificial crystal that is an acoustic analogue of the Weyl semimetal. They found that, at the interface between two adjacent facets of the crystal, airborne acoustic waves could undergo negative refraction without reflection. The authors' results represent the first realization of negative refraction for topological surface states.

There are a few limitations of the work. For instance, the refraction does not occur in a flat plane, contrary to the common impression of refraction. Moreover, the interface scatters some of the acoustic waves into the crystal's interior, resulting in energy loss. Nevertheless, the demonstration opens the door to many exciting opportunities for further research.

The immediate question is whether He and colleagues' refraction phenomenon could be realized in optical systems for light and condensed-matter systems for electrons. Another question, which will be of interest to both optical and condensed-matter physicists, is how to engineer the range of propagation directions — and, in turn, the Fermi arcs — to achieve greater control of negative refraction. In this sense, the authors' work provides the first practical use of Fermi arcs, which are currently being enthusiastically explored in condensed-matter systems[7,8] and in optical structures called photonic crystals[9].

The refraction phenomenon could also find widespread use in acoustics. For example, the combination of negative refraction and zero reflection could lead to improved resolution in ultrasonic imaging and testing. Moreover, acoustic waves are used in biomedical microfluidic devices to trap, sort and deliver cells and drug particles. Reflection-free acoustic waves are strongly desirable in such applications, because reflections at the interfaces and sharp corners of microfluidic channels are currently a huge limitation to device efficiency.

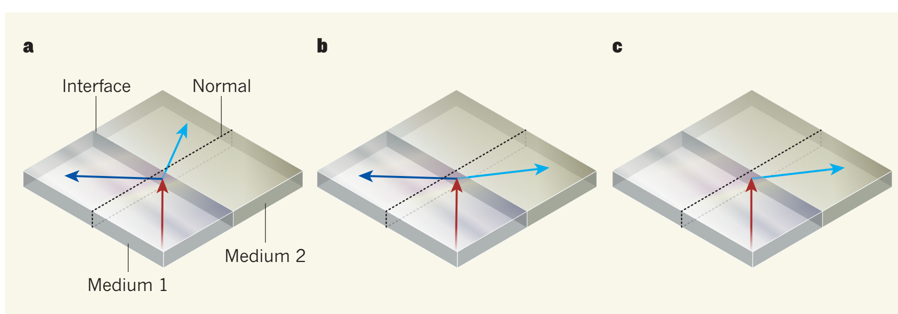

Figure 1 | Comparison of refraction phenomena. **a**, In conventional refraction, when an acoustic or optical ray (red) hits the interface between two different media, a reflected ray (dark blue) and a refracted ray (light blue) are produced. The incident and refracted rays exist on opposite sides of the normal — an imaginary line perpendicular to the interface. **b**, In negative refraction, the refracted ray emerges on the same side of the normal as the incident ray. **c**, He *et al.*[1] report a previously unobserved type of refraction for acoustic rays, in which not only are the incident and refracted rays on the same side of the normal, but also there is no reflected ray. (Figure adapted from ref. 1.)

Topological acoustics is therefore a promising research field that not only can produce phenomena that are difficult to realize in other physical systems, but could also bring about transformative technologies. ■

Baile Zhang *is in the Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371, Singapore.*
e-mail: blzhang@ntu.edu.sg

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NATURE

50 Years Ago

The prospect of beer by the litre for British drinkers came a step closer last week. Mr Anthony Wedgwood Benn, the Minister of Technology, announced that the United Kingdom is to adopt the metric system of measurement by 1975 — the target date already accepted by British industry for its timetable … The industrial change is going ahead fast … but the non-industrial sector of the economy and the general public have been lagging behind … It is "imperative" for the planning of the change in the general sectors of the economy to be put in hand; if this is not done, "the dynamism of the industrial change will be lost" … The cost-effectiveness of metrication is not … likely to be known until it is a fact. So far, certainly, hunch has played a greater part than has sober analysis of the situation.
From *Nature* 3 August 1968

100 Years Ago

… Finally, there is the personal use of insecticidal preparations as aids to the primitive method of getting rid of [lice] — now referred to as "chat"-hunting … [T]he preparation should be of quick action and easy of application to clothing, and its issue should be as general and comprehensive as that of food … [P]astes are more economical and convenient than powders; fluids are out of the question. Crude "unwhizzed" naphthalene, produced by coke-oven plants, affords the most effective base, and may be conveniently mixed into paste form by the addition of soft soap or some grease, such as vaseline, in the proportion of 10 to 20 per cent … When it is necessary to use an anti-lice preparation on a hair-clad surface the use of vaseline, to which has been added ½ per cent. of veratrine dissolved in 5 per cent. of benzene, may be recommended.
From *Nature* 1 August 1918

METABOLISM

An unexpected trigger for calorie burning

The molecule succinate, which is a product of metabolism, promotes heat production and therefore calorie burning in brown fat in mice. This discovery could have implications for combating obesity in humans. SEE LETTER P.102

SHENG HUI & JOSHUA D. RABINOWITZ

There are two ways to lose weight: eat less to reduce the number of calories available for metabolism by the body, or burn more calories, for example through exercise. On page 102, Mills *et al.*[1] identify a molecule produced during nutrient metabolism that, surprisingly, induces calorie burning. This metabolite, succinate, activates energy expenditure in brown fat. Remarkably, supplementing the drinking water of mice with succinate can prevent the animals from gaining weight.

Brown fat is different from the white fat that builds up around our waistlines. Whereas white fat acts as an energy reserve, brown fat specializes in heat generation, and is essential for mammals to maintain their body temperature in the cold[2]. Brown-fat cells contain smaller lipid droplets than do white-fat cells, and have many more organelles called mitochondria[3], which enable brown fat to generate heat.

In mitochondria, a metabolic pathway called the TCA cycle breaks down nutrients such as glucose, lactate and fat into carbon dioxide, using the energy stored in the nutrients to generate high-energy electrons. These electrons are used to pump protons (hydrogen ions, H^+) out of the interior matrix of the mitochondrion into the space between the organelle's inner and outer membranes, thereby converting the energy into a proton gradient. Normally, protons re-enter the mitochondrial matrix through a membrane-spanning protein complex called the proton ATPase. This complex uses the energy stored in the proton gradient to convert ADP molecules into energy-carrying ATP molecules, and thereby generates most of the body's usable energy. But in brown fat, protons pass through another protein, uncoupling protein 1 (UCP1). This transporter uncouples the process of crossing the mitochondrial membrane from that of ATP production, effectively wasting the proton gradient's energy as heat (reviewed in ref. 4).

This capacity of brown fat to dissipate calories as heat has attracted much attention, in the hope of activating the process to combat obesity[5]. To do this, it is necessary to know what switches on calorie burning by brown fat. At the macroscopic level, the main answer is exposure to cold. At the mechanistic level, it has been proposed that the brain senses cold and sends signals to brown fat through a process mediated by proteins called β-adrenergic receptors[2]. But drugs that activate these receptors have not been successful in curbing obesity[6]. Thus, there is intense interest in finding new pathways that activate heat generation in brown fat.

Mills *et al.* began by searching for metabolites that are selectively abundant in brown fat, and whose concentration in this tissue increases during cold exposure. Their survey identified succinate, one of the metabolic intermediates of the TCA cycle.

The TCA cycle is generally assumed to be a cell-intrinsic process in which most intermediates are trapped in the mitochondrial matrix. Thus, most succinate is consumed by the same cell that produces it. Some succinate, however, makes its way into the bloodstream. The authors provide evidence that a key trigger for the release of succinate may be muscle activity, because shivering in response to cold increased blood succinate levels in mice.

To trace the fate of succinate circulating in