CONDENSED-MATTER PHYSICS

Waves cornered

The experimental discovery of materials known as higher-order topological insulators corroborates theoretical predictions and expands the toolbox for integrated optics and mechanical devices. See Letters p.342 & p.346

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When waves encounter an obstacle, they are typically scattered in all directions. But at the edges of materials called topological insulators, waves are topologically protected, which means that they can propagate in spite of structural imperfections. Two papers in *Nature*, by Serra-Garcia *et al.*[1] (page 342) and Peterson *et al.*[2] (page 346), and a third published on the arXiv preprint server by Imhof *et al.*[3], now report experimental evidence for a new type of topological insulator that supports protected waves at its corners, rather than at its edges. Such materials could find applications in the design of waveguides (structures that restrict wave propagation) and in integrated optics and mechanics. More importantly, they are the first confirmation of a theoretical description that could unify observations previously thought to be unrelated in condensed-matter physics[4].

A good chocolate is hard on the outside, but soft on the inside. Topological insulators are the opposite. The d-dimensional interior (bulk) of a topological insulator is 'hard' in the sense that it will not react to external stimuli at certain frequencies: there is a range of frequencies, known as a gap, at which waves cannot propagate. By contrast, the $(d-1)$-dimensional boundaries not only allow wave propagation, but also guarantee the existence of topologically protected oscillations (modes) at the gap frequencies. Such oscillations are localized in dimension $d=1$, for which the boundaries are points, and propagate along the boundaries in $d>1$ (Fig. 1a).

Crucially, the existence of these protected edge modes can be traced to the physics of the bulk material. One can summarize the mathematical description of wave propagation inside a topological insulator as an intricate knot and that outside it as a simple loop. The knot must be cut at the edges to match the 'untwisted' wave propagation outside. Cutting the knot allows modes that have otherwise forbidden frequencies to be present.

In 2017, the theory of topological insulators was extended[5,6] to include higher-order examples[7–9], such that ordinary topological insulators appear at the first order. A higher-order insulator can be thought of as having a nested topological structure. For example, in second-order topological insulators, the properties of the bulk cause the $(d-1)$-dimensional boundaries to have frequency gaps. However, the boundaries themselves are topological insulators — protected modes are supported on $(d-2)$-dimensional corners or hinges (Fig. 1b). In third-order insulators, the boundaries of the boundaries are topological insulators, and protected modes exist on $(d-3)$-dimensional corners (Fig. 1c). The result of this hierarchical process is more subtle than merely adding together topologically protected edges without the bulk of a higher-order insulator. For instance, in a quadrupole topological insulator (a second-order insulator in dimension $d=2$), there is only one mode in each corner, yet each mode is shared between two edges.

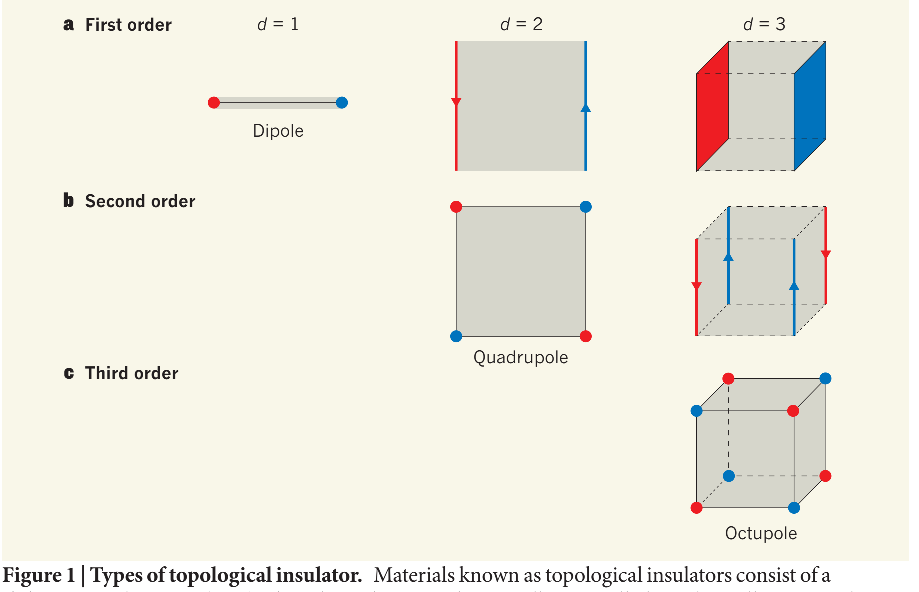

Figure 1 | Types of topological insulator. Materials known as topological insulators consist of a d-dimensional interior (grey) whose boundaries can host oscillations called topologically protected modes (red and blue; the two colours correspond to opposite electric charges). **a**, In first-order topological insulators, modes are localized in dimension $d=1$ (dipole topological insulators), travel along one-dimensional channels in $d=2$ and exist on surfaces in $d=3$. **b**, Three papers[1–3] report evidence for second-order topological insulators in $d=2$ (quadrupole systems), for which modes are localized to corners. Second-order topological insulators do not exist in $d=1$, and modes are supported along one-dimensional hinges in $d=3$. **c**, At third order, the minimum dimension is $d=3$, for which modes exist on corners (octupole topological insulators).

The three current papers report experimental evidence for higher-order topological insulators. More specifically, they identify the topologically protected corner modes associated with quadrupole insulators. The authors achieved this feat using artificial structures called metamaterials, which are engineered to have properties not found in nature[10].

Serra-Garcia *et al.* obtained the required topological structure by tuning the vibrational excitations of connected vibrating plates. Peterson *et al.* used coupled light-trapping devices known as microwave resonators. Finally, Imhof *et al.* used a network of electrical components (capacitors and inductors) that were linked to one other. All three teams showed that the corner modes of their topological insulators exist at frequencies not permitted in the bulk — a clear indication that such modes originate from the bulk's topology. Peterson and colleagues went a step further by explicitly demonstrating the robustness of the corner modes to deformation of the edges.

The theoretical prediction of higher-order systems rests on a generalization of electric dipole moments to multipole moments that are quantized (having only specific discrete values)[5,6]. Whereas conventional topological insulators are related to dipoles, higher-order insulators are related to quadrupoles, octupoles, and so on. This theory has been corroborated by the authors' experimental realizations of quadrupole systems. However, the experiments did not directly measure the responses of the topological insulators to electromagnetic fields, which would prove whether or not a quantized quadrupole moment is present. Such higher-order-bulk responses could be measured in electronic systems, in which higher-order insulators were demonstrated earlier this year[4]. Future work could also extend the theoretical formalism to general external fields, rather than solely electromagnetic fields.

In terms of potential applications, it is not yet clear whether higher-order topological modes localized to corners or hinges have practical advantages over their conventional counterparts. For instance, higher-order topological insulators rely on the existence of crystal symmetries that typically limit the robustness of the edge modes. Moreover, it has been shown that protected modes can also be localized to points or lines of dimensionality lower than $(d-1)$ in ordinary topological insulators that have material defects[11–14].

Finally, one can speculate about such systems beyond third order — in other words, beyond the octupole moment. However, these are difficult to realize because of the unfortunate lack of spatial dimensions in our everyday world. Possible ways of overcoming this difficulty include resorting to 'synthetic' dimensions provided by internal degrees of freedom (such as the oscillation modes of a resonator), or artificially enhancing the connectivity of crystal lattices using long-range links[15].

The authors' experimental evidence for higher-order topological insulators illustrates the rapid transition from theoretical proposals to experimental realizations in current research on topological materials. We expect the next few years will be the time for such materials to prove their engineering worth. ■

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IMMUNOLOGY

Melanin triggers antifungal defences

Melanins are enigmatic pigments that have many roles, and the melanin in pathogenic fungi can aid host infection. Identification of a mammalian protein that recognizes melanin now reveals an antifungal defence pathway. SEE LETTER P.382

ARTURO CASADEVALL

Most organisms produce numerous varieties of the highly diverse dark pigments known as melanins, which are among the last remaining biological frontiers with the unknown. These polymer molecules can act in protective or harmful ways, in biological functions as diverse as providing protection against DNA-damaging ultraviolet radiation[1] to bolstering fungal cell-wall strength[2]. Melanins bolster microbial virulence[3], including that of many disease-causing fungi. The presence of melanin can trigger an immune response in the infected organism[4], but how this occurs was unknown. On page 382, Stappers *et al.*[5] report the identification of a protein that can recognize a type of melanin produced by the fungus *Aspergillus fumigatus*. Their finding illuminates the immune-system response to a fungal infection that can be lethal in people who have a suppressed immune system, such as those who have undergone transplantation surgery[6].

Melanin pigments are stable free radicals, and, in animals and fungi, they are produced in membrane-bound organelles known as melanosomes, which shield the cell cytoplasm from the potentially damaging free-radical reaction needed for melanin production. They are insoluble and resistant to degradation by acids. These striking characteristics probably explain why their structures are difficult to analyse and are not fully understood. Host immune cells can trigger potentially damaging cell-signalling pathways in fungi. But such attacks can be neutralized by fungal melanin, which also reduces susceptibility to antifungal drugs[3].

Human disease caused by fungi of the genus *Aspergillus* is called aspergillosis. If a

50 Years Ago

Like many other museums of its type, the Museum of Comparative Zoology has teaching and curatorial responsibilities, expeditions are organized to build up collections, and staff travel to study collections in other museums. Research conducted in the museum covers a wide range of topics — evolution, behaviour, ecology, zoogeography, physiology and biochemistry and taxonomy. Almost all the research produces results of interest to the evolutionist. One interesting find during the year was the discovery of a fossil insect from Cretaceous amber from New Jersey. This is the oldest known ant and is apparently virtually a missing link between ants and wasps. The presence of worker characteristics in these insects is evidence of the existence of social Hymenoptera as far back as about 100 million years.
From *Nature* 16 March 1968

100 Years Ago

An announcement in the daily Press states that whale-meat furnished the principal article of food at a luncheon given in New York by the American Museum of Natural History to demonstrate the possibilities of whale-meat for home consumption, in order that the beef thus saved might be sent by America to relieve the scarcity prevailing among the Allies in Europe … Unfortunately, we can do little to assist in this saving, for the whales in our home-waters cannot be "fished", since neither ships nor men are available for the purpose … It is to be hoped, however, that the fullest possible use will be made of the carcasses of the various species of Cetacea stranded around our coasts. Of course, no great quantity of meat would thus be obtained, but locally it should form a very welcome addition to the scanty meat rations now of necessity prevailing.
From *Nature* 14 March 1918