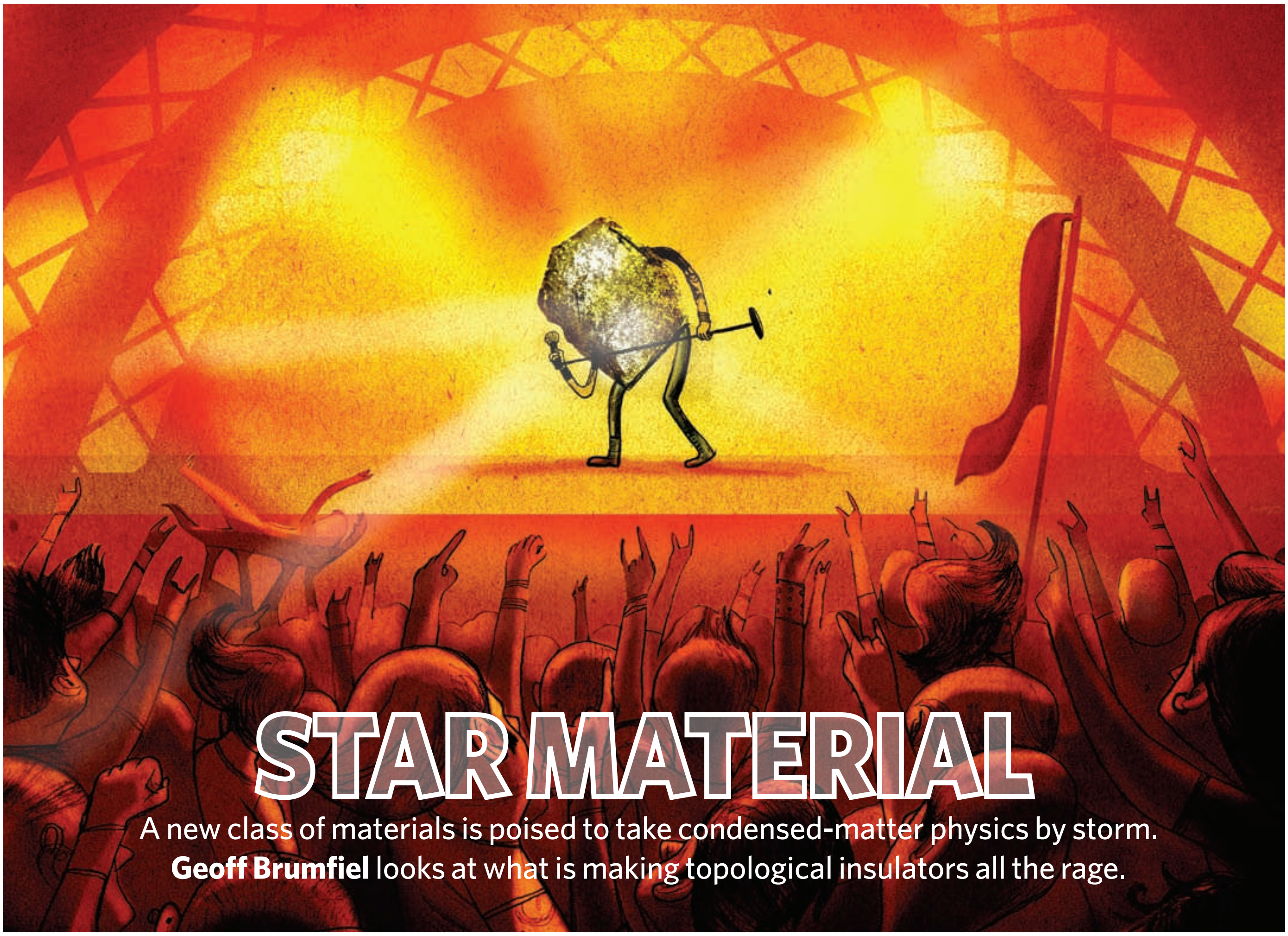


J. BURTON

STAR MATERIAL

A new class of materials is poised to take condensed-matter physics by storm. **Geoff Brumfiel** looks at what is making topological insulators all the rage.

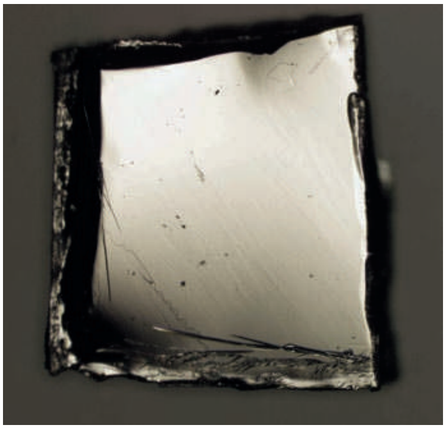
For a brief time in Portland, Oregon, this past spring, thousands of physicists moved from session to session at the annual March meeting of the American Physical Society (APS) on the lookout for the next big thing.

It was a talent search not unlike the one that unfolds every night in the bars and converted dance halls of Portland's famous music scene, where locals listen for the next big sound. The physicists' quest is a lot harder, though. Trends in music come and go, but the disciplines that dominate the APS March meeting — such as optics, electronics and condensed-matter physics — are rooted in the original theories of quantum mechanics, which were more-or-less completed in the 1930s. When it comes to describing how light and matter behave, only a few phenomena have emerged since then to become the physics equivalent of superstars.

At this year's APS meeting, however, the hallways were filled with talk of a promising newcomer — an eccentric class of materials known as topological insulators. The most striking characteristic of these insulators is that they conduct electricity only on their surfaces. The reasons are mathematically subtle — so much so that one physicist, Zahid Hasan of Princeton University in New Jersey, tried to explain the behaviour using 'simpler' concepts such as superstring theory. ("It's awfully beautiful stuff," he said reassuringly.) Yet the implications are rich, ranging from practical technology for quantum computing to laboratory tests of advanced particle physics.

Hence the excitement. It is still too early to say whether topological insulators are the next big thing. But physicists are auditioning various formulations of the insulators in their labs, eager to determine whether the material can live up to its many promises.

A topological insulator sounds simple enough — a block of material that lets electrons move along its surface, but not through its inside. In fact, it is far from straightforward. Ordinary metals conduct electrons all the way through, whereas ordinary insulators don't conduct electrons at all. A copper-plated block of wood conducts only on the surface, but that is two materials, not one. The idea of a topological insulator is so strange that for a long time, physicists had no reason to believe that such a material would exist.



Electrons move along the surface of, but not through, topological insulators such as bismuth selenide.

J. SEO/P. ROUSHAN/A. YAZDANI

Quantum dance

Things changed in 2004, when Charles Kane, a theoretical physicist at the University of Pennsylvania in Philadelphia, was studying sheets of carbon called graphene. Kane's calculations suggested that electrons would move through this one-atom-thick material in a way that reminded him of the quantum Hall effect: a phenomenon first observed in 1980. This effect occurs when electrons are confined to thin films of certain materials, subjected to large electric and magnetic fields, and cooled to within just a fraction of a degree above absolute zero. At that point, the ordinarily chaotic motion of the electrons gives way to a more orderly collective behaviour governed by quantum mechanics. The transition shows up in the laboratory as a series of discrete quantum steps in the capacity of the material to conduct electricity.

What Kane and his group saw in their graphene calculations wasn't exactly the same as the quantum Hall effect. Even so, further analyses showed that there might be other thin-film materials with similar behaviour. This time there would be no need for huge external magnetic fields or ultra-low temperatures to get the electrons moving in unison. Such a material would produce the magnetic field from the nuclei of its own atoms — possibly even at room temperature.

These coordinated electrons would mostly end up just spinning in place. Intriguingly, however, those at the edge of the thin film would be forced to skip along the boundary. The net result would be that thin samples would conduct electricity along the edge — and only along the edge — but in separate quantum steps, similar to those seen in the quantum Hall effect[1].

The work of Kane and his colleagues got noticed almost immediately. Joel Moore, a theorist at the University of California, Berkeley, and his co-workers built on Kane's calculations to show that three-dimensional blocks of material would also display quantum effects[2], although the way electrons moved along the surface would be more complex than in the flat sheet used by Kane. Moore also gave the materials a new name. They were originally termed "novel Z_2 topological invariants" by Kane, in reference to the quantum-mechanical properties that cause the electrons to skip along the edge. "We got tired of typing that out, so we called it a 'topological insulator'," says Moore. "I don't know that that term is particularly explanatory, but at least it's short."

Meanwhile, Shoucheng Zhang at Stanford University in Palo Alto, California, and his team were researching what types of real material could be topological insulators. In most materials, Zhang realized, the link between electrons and nuclei is too weak to create a topological-insulating behaviour. But the link gets stronger as the nuclei get heavier. In 2006, Zhang predicted that one material in particular, a crystal made of the heavy elements mercury and tellurium, would be able to do the trick[3]. And within a year, Laurens Molenkamp, a physicist at the University of Würzburg in Germany, and his group had grown a thin layer of mercury telluride crystal and showed that its conductance hopped from one quantum value to the next along the edge of the sample[4].

The experiment by Molenkamp proved that the theorists were onto something, but by itself it didn't cause much excitement. Mercury telluride crystals are difficult to obtain — they have to be grown one layer at a time using a laborious process known as molecular beam epitaxy — and they are not pure topological insulators because they conduct some electricity on their inside.

New compounds based around bismuth, which are simple to make and cheap to work with, have caused the field to take off. "What got so many talks at the March meeting was the bismuth-based compounds," says Hasan. "Anybody can grow them, you can buy them off the shelf, and you don't need a high-purity crystal to see the topological effects."

Those effects go beyond the way electrons move on the surface. For example, all electrons are spinning in a quantum mechanical way. Usually, the spins are constantly knocked about by random collisions and stray magnetic fields. But spinning electrons on the surface of a topological insulator are protected from disruption by quantum effects (for more, see page 323). This could make the materials beneficial for spin-related electronics, which would use the orientation of the electron spin to encode information, thereby opening up a whole new realm of computer technology.


N. SHANNON

"There's something about many-particle quantum mechanics that causes perfection to emerge out of imperfection."
— Joel Moore

Mathematical mimicry

Researchers also believe that the collective motions of electrons inside topological insulators will mimic several of the never-before-seen particles predicted by high-energy physicists. Among them are axions, hypothetical particles predicted in the 1970s; magnetic monopoles, single points of north and south magnetism; and Majorana particles — massless, chargeless entities that can serve as their own antiparticles.

This mimicry is not entirely surprising. Almost by definition, collective electron motions can be described by just a handful of variables obeying simple equations, says Frank Wilczek, a Nobel-prizewinning particle physicist at the Massachusetts Institute of Technology in Cambridge. "There are only a few kinds of equations that you can write down that are really simple," he says. So topological-insulator theorists and particle physicists have almost inevitably ended up in the same place.

Majorana particles could prove particularly useful for practical quantum computing. The idea is to perform calculations using the laws of quantum mechanics, which could make computers much faster than the normal variety at certain tasks such as code-breaking. But the fragile quantum states essential to their operation are easily destroyed by jolts from the outside environment. Majorana particles would spread quantum information across particles, making them far more resistant to interference, says Kane. If Majorana particles could be harnessed on the surface of a topological insulator, "this would be big", he says.

The wealth of calculations, experiments and applications offered by topological insulators, together with their availability, have given the field a white-hot status at the moment — as has a certain thirst for glory. Two variations of the quantum Hall effect have won their discoverers Nobel prizes, and some researchers think that a Nobel awaits whoever can contribute the most to the growing field. "I'm not thinking about that at this point," says Kane, but the competitiveness has forced him to ensure that others are aware of his work. "I sort of feel like if I don't assert myself, then I'm going to get buried," he says.

Yet trips to Stockholm are some way off. Although samples of topological insulators are now easy to get hold of, most still contain impurities that cause them to conduct electricity on the inside, disrupting the states on the surface. Getting things perfect remains more of an art than a science. Furthermore, some of the sought-after effects will require topological insulators to be combined with more common materials. To create Majorana particles, for example, topological insulators will have to merge with superconductors. Many experiments on how best to do that are under way.

The results of these studies will determine whether topological insulators are more than a one-hit wonder. Regardless, says Moore, there is an undeniable appeal in how the collective behaviour of electrons can lead to so many wonderful things. "There's something about many-particle quantum mechanics that causes perfection to emerge out of imperfection," he says. "That's somewhat cheering as far as our everyday lives are concerned." ■

Geoff Brumfiel is a senior reporter for *Nature* based in London.

1. Kane, C. L. & Mele, E. J. *Phys. Rev. Lett.* **95,** 146802 (2005).
2. Moore, J. E. & Balents, L. *Phys. Rev. B* **75,** 121306 (2007).
3. Bernevig, B. A., Hughes, T. L., Zhang, S.-C. *Science* **314,** 1757–1761 (2006).
4. König, M. *et al. Science* **318,** 766–770 (2007).

See News & Views, page 323, and Letters, page 343.