of liquids, and it's still a challenge to stabilize the interfaces between a solid electrolyte and solid electrodes that are constantly growing and shrinking.[8] "This is the new kid on the block trying to beat the existing electrolyte," says Yang Shao-Horn of MIT, "and we need to discover the design principles" to explore the possible materials more efficiently than by trial and error. "There is a very small solid-state battery on the market now," notes Yoshino, "but can it be made into a large format suitable for electric vehicles? That still requires a breakthrough in production technology. I think it should be possible, but it will take time."

Another research direction has explored replacing lithium with a cheaper, more abundant working ion, such as sodium, magnesium, or calcium.[9] Sodium is chemically similar to lithium, so many (but not all) of the materials and processes developed for lithium-ion batteries can be adapted for sodium-ion batteries. Calcium and magnesium, on the other hand, would require a whole new set of materials. They're appealing, though, because their ions are doubly charged, so a battery could supply twice as much current for a given number of working ions.

Lithium-ion batteries aren't going away anytime soon. "Even if I came up with a great new battery tomorrow," says Marca Doeff of Lawrence Berkeley National Laboratory, "it would take 10 or 15 years of work to get to where lithium-ion batteries are now. And the goalposts keep moving." But as Shirley Meng of the University of California, San Diego, notes, that's all the more reason for urgency. "Now is the time to worry about resource availability," she says. "If we want to use batteries to store clean energy and combat climate change, we don't have a lot of time."

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Magnetic semimetals host massless quasiparticles

Two materials have an unusual electronic band structure that can support fast, low-dissipation electronic transport.

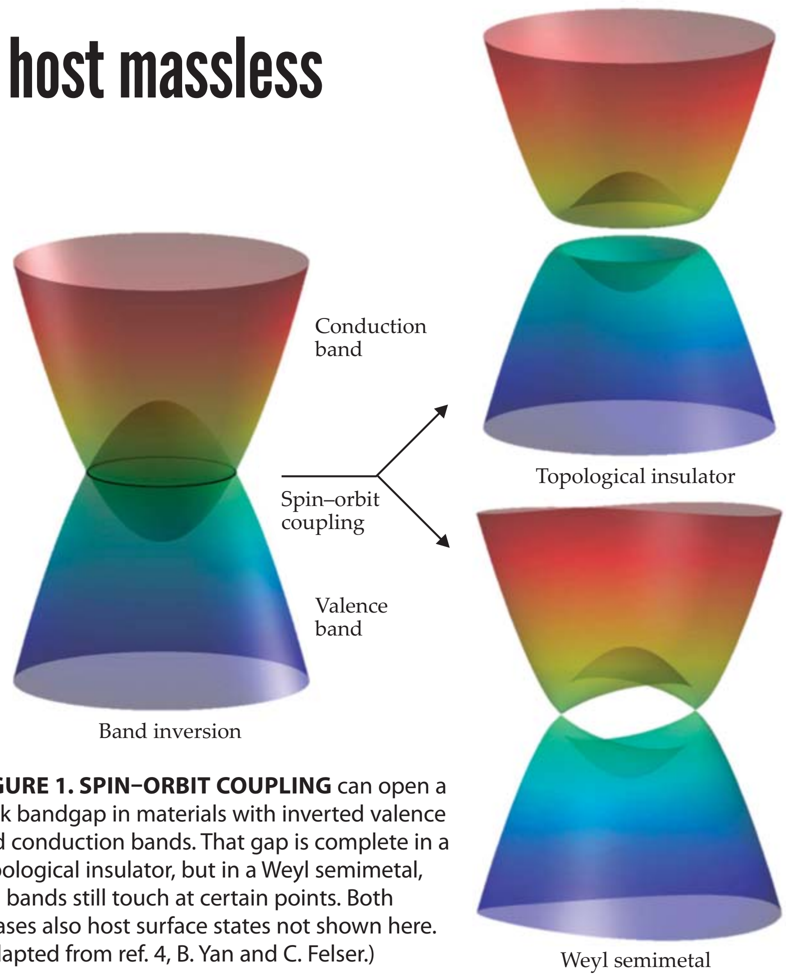

FIGURE 1. SPIN–ORBIT COUPLING can open a bulk bandgap in materials with inverted valence and conduction bands. That gap is complete in a topological insulator, but in a Weyl semimetal, the bands still touch at certain points. Both phases also host surface states not shown here. (Adapted from ref. 4, B. Yan and C. Felser.)

When Paul Dirac introduced his famous equation for relativistic fermions in 1928, he aimed to describe one well-known particle: the electron. Shortly thereafter, Hermann Weyl observed that the equation has a special solution when the mass is set to zero. The so-called Weyl fermions embodied by that solution would be charged, like electrons, but being massless, they would travel faster and with less energy dissipation. The particles would also be chiral, like neutrinos, with each one's handedness depending on whether its spin is aligned or antialigned with its momentum. Those features make Weyl fermions appealing candidates for use in electronic and spintronic devices.

No such elementary particle has yet been found. However, in 2015 three groups of researchers identified the first Weyl semimetal (WSM), tantalum arsenide, which hosts quasiparticles—collective excitations of electrons—with the properties of Weyl fermions.[1] A WSM must have a broken symmetry, and in TaAs, it's inversion symmetry. Researchers, however, have continued searching for materials, particularly ferromagnetic materials, that instead rely

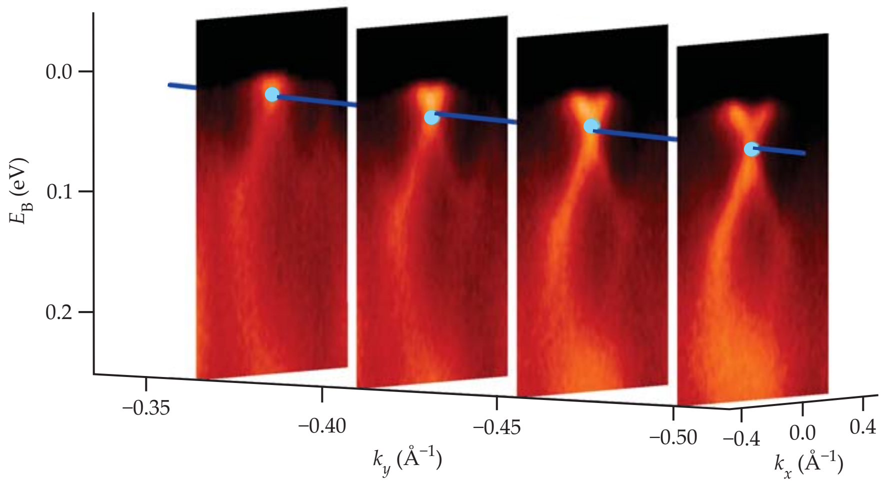

FIGURE 2. A NODE LINE APPEARS in angle-resolved photoemission spectroscopy measurements of Co_2MnGa. Slices of data showing binding energy E_B as a function of the momentum component k_x display linear bands and their points of intersection (light blue), key components of a Weyl semimetal's band structure. The features persist for a range of momenta k_y, so the points form a nodal line (blue). (Adapted from ref. 3.)

on broken time-reversal symmetry. Tying a WSM crystal's properties to magnetism, which can be adjusted using temperature changes or external fields, makes them potentially tunable.

Three new papers provide experimental evidence for magnetic WSMs. Yulin Chen's team at Oxford University and Haim Beidenkopf's team at the Weizmann Institute of Science, together with collaborators,[2] presented studies of $Co_3Sn_2S_2$, and Zahid Hasan's group at Princeton University[3] looked at Co_2MnGa. The works identify important features in the electronic structures of both materials' bulk and surface states.

Electronic underpinnings

The secret to a WSM's behavior is in its band structure, which has similar origins to that of a topological insulator.[4] In both cases, interactions cause the conduction and valence bands to invert near the Fermi surface. Spin–orbit coupling then opens a gap between them, as illustrated in figure 1. In topological insulators, it opens a bandgap throughout the bulk. (See PHYSICS TODAY, April 2009, page 12.) But in a WSM, the valence and conduction bands still touch at a set of points.

A WSM's band structure is similar to a three-dimensional version of graphene. In both materials the dispersion relation is linear around the bands' contact points, so low-energy electron excitations travel at a constant speed set by the dispersion relation's slope. Having a constant speed that doesn't depend on energy makes the excitations effectively massless. But that doesn't mean they travel at the speed of light—they are still about two orders of magnitude slower than photons.

In graphene, the points at which the valence and conductance bands meet are degenerate because the system is invariant under both inversion and time-reversal symmetry (see the article by Andre Geim and Allan MacDonald, PHYSICS TODAY, August 2007, page 35). Known as Dirac points, they describe excitations of both chiralities, so the momentum and spin can be either parallel or antiparallel. But in a WSM, the presence of a broken symmetry lifts that degeneracy and splits the Dirac points into pairs of Weyl nodes with opposite chirality.

A WSM that breaks inversion symmetry but preserves time-reversal symmetry must have at least four Weyl nodes because time reversal flips the signs for both momentum $\mathbf{k}$ and spin $\mathbf{s}$. If $(\mathbf{k},\mathbf{s})$ describes a Weyl node, then under time reversal, so does $(-\mathbf{k},-\mathbf{s})$. But those have the same chirality, so $(\mathbf{k},-\mathbf{s})$ and $(-\mathbf{k},\mathbf{s})$ with opposite chirality must also be included to maintain zero net chirality. If, instead, inversion symmetry is preserved and time-reversal symmetry is broken, there can be just two Weyl nodes. Inversion symmetry changes only the sign of the momentum, so the inversion-symmetric points $(\mathbf{k},\mathbf{s})$ and $(-\mathbf{k},\mathbf{s})$ already have opposite chirality. Therefore, to produce

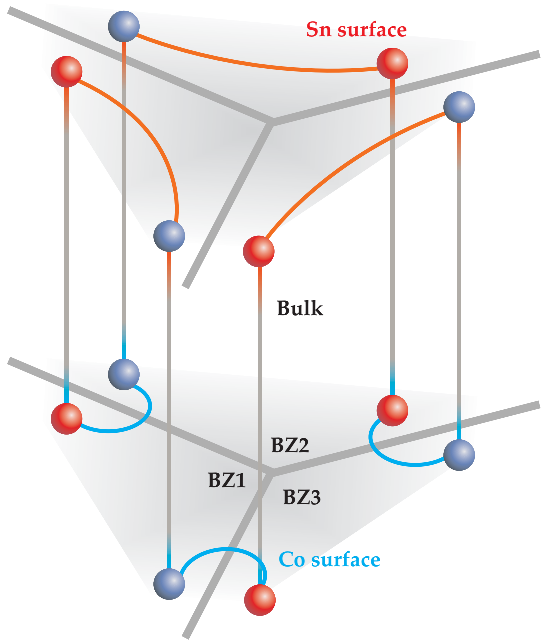

FIGURE 3. THE SURFACE TERMINATION of the Weyl semimetal $Co_3Sn_2S_2$ determines the connectivity of the Weyl points (blue and red dots) by surface Fermi arcs (blue and red lines). A crystal cleaved to reveal a tin surface (top) has pairs of Weyl points that are connected within the same Brillouin zone (BZ), whereas if it has a cobalt surface (bottom), the Weyl points are connected between adjacent Brillouin zones. (Adapted from ref. 2, N. Morali et al.)

the simplest WSM with only two Weyl nodes—which would be ideal for studying the underlying physics—the material must break time-reversal symmetry.

Weyl nodes in crystal momentum space behave like magnetic monopoles in real space. If an electron made a closed loop around a magnetic monopole, its wavefunction would acquire a nonzero phase. A Weyl node does the same thing. Like a vector sliding along the surface of a mobius strip, the wavefunction's failure to regain its initial state reflects the nontrivial curvature and topology of the underlying space. (See the article by Joseph Avron, Daniel Osadchy, and Ruedi Seiler, Physics Today, August 2003, page 38.) Weyl nodes serve as sources and sinks of so-called Berry curvature, and they are associated with nonzero values of a topological invariant known as the Chern number. The topological nature of the Weyl points makes them appealing for electronic applications because it protects the surface states. Perturbations don't change the underlying topology, so the states aren't destroyed by moderate deformations or impurities.

Another hallmark of a WSM is the appearance of spin-polarized surface states. In momentum space, the states appear as lines, known as surface Fermi arcs (SFAs), that connect surface projections of pairs of Weyl points with opposite chirality. The SFAs are confined to the surface of the material by the topology of the band structure.

Hunting for quasiparticles

The researchers suspected that the materials they were investigating could be WSMs because they belong to a long list of candidates suggested by previous numerical and experimental studies. Clinching the case entailed looking for telltale features in the materials' band structures—Weyl nodes with linear dispersions and SFAs. To find bulk Weyl points, the groups led by Hasan and Chen turned to angle-resolved photoemission spectroscopy (ARPES). The technique, which both groups used to identify the WSM TaAs in 2015, involves bombarding the materials with x rays of various energies and measuring the energies and momenta of the ejected photoelectrons at different escape angles. The end product is a map of the distribution of electron binding energies in reciprocal, or momentum, space. In both materials, the ARPES data uncovered linear bands meeting near the Fermi energy. In $Co_3Sn_2S_2$, they meet at six individual points; because of a degeneracy in Co_2MnGa, they instead form a nodal line, as shown in figure 2.

Although ARPES is a surface technique, the photons penetrate deeply enough that bulk electron states predominate. Nevertheless, both groups clearly saw surface states connecting the Weyl points. In $Co_3Sn_2S_2$, the states appeared as lines connecting Weyl nodes, and in Co_2MnGa, as a drumhead-like plane bounded by a nodal line. Because surface states are restricted to a two-dimensional boundary in real space, they should also manifest as 2D features in momentum space. Indeed, both groups confirmed that the states remained unchanged when the momentum varied in the normal direction.

A large Berry curvature has been linked to a particularly large anomalous Hall effect,[5] so Hasan's team turned to that behavior to confirm the topological nature of the surface states in Co_2MnGa. After measuring a conductivity of 1530 ohm^{-1} cm^{-1}, similar to what had previously been seen in $Co_3Sn_2S_2$, the researchers compared their data with a known scaling relation to pin down the source of the effect. The data's functional form and a model's quantitative fit parameters pointed to a large Berry curvature, rather than electron-scattering processes, as the source of the enhanced anomalous Hall effect.

Instead of looking for the Weyl points, Beidenkopf and coworkers focused solely on the surface states. They used scanning tunneling spectroscopy, in which a voltage is applied between a metal tip and the surface of interest to map the electron density across the surface. Although the technique can't look beyond the surface at the bulk Weyl nodes, its high resolution helped the researchers uncover how the nodes' connectivity depends on which atoms are at the surface.

A $Co_3Sn_2S_2$ crystal can be cleaved to reveal three chemically distinct faces, and each face led to different surface states. With the tin termination, SFAs connected Weyl points within the same Brillouin zone (see figure 3). However, with cobalt termination, the SFAs connected pairs of points in adjacent Brillouin zones. For the sulfer-terminated surface, the researchers could not infer the SFA connectivity because the surface potential caused the states to overlap with other metallic bands. The unique band structure of each of the surfaces provides a knob for tuning the material's electronic properties.

There's still more to learn about WSMs that break time-reversal symmetry. "Their topological classification is directly affected by their magnetic ground state," says Beidenkopf. "Therefore, their magnetic phase diagram gives rise to a rich topological phase diagram that can now be explored." For practical applications, Co_2MnGa may have an edge: It's ferromagnetic at room temperature, with a Curie temperature of 690 K, whereas $Co_3Sn_2S_2$ is ferromagnetic only below 175 K. If WSMs find applications in future electronic and spintronic technologies, that difference will likely make Co_2MnGa the more desirable candidate.

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