SOLID-STATE PHYSICS

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Enabled by recent advances in symmetry and electronic structure, researchers have observed signatures of unconventional threefold degeneracies in tungsten carbide, challenging a longstanding paradigm in nodal semimetals.

Benjamin J. Wieder

Take a single layer of graphite and you get graphene, a material whose structural and electronic properties allow diverse applications ranging from biosensing to electrical engineering. Try and explain graphene's properties using solid-state physics, and you get an equation similar to one otherwise seen in discussions of cosmology and colliders: the Dirac equation. In the decade following graphene's discovery, all materials of this kind, known as 'nodal semimetals', were named and categorized assuming a one-to-one correspondence between the low-energy electronic behaviour of crystalline solids and the equations of high-energy particle physics, leading to the classification of a wide variety of chemical compounds as Dirac or Weyl semimetals. Now, writing in Nature Physics, Jun-Zhang Ma and colleagues' present experimental evidence in tungsten carbide, Ma et al. provide some insight into the natural simplicity of graphene. By observing electronically relevant threefold nodal degeneracies and surface Fermi arcs in tungsten carbide, Ma et al. provide some of the first experimental support for the growing body of imaginative proposals for unconventional semimetals with topological electronic character.

In both particle physics and nodal semimetals, the possible energies of a particle or quasiparticle are determined by its momentum. This is known as a dispersion relation. When a particle has no mass, the solutions of its dispersion relation come together and meet in a degenerate nodal point. In high-energy physics, the structure of this dispersion relation and the degree of its degeneracy are determined by the fundamental symmetries of nature, such as charge conjugation, parity inversion and time reversal. Conversely, as recognized since the 1970s, the dispersion relation of a crystalline solid is instead more accurately described by the mathematical representations of its spatial symmetries. With the advent of computers powerful enough to perform large-scale numerical calculations of the electronic structures of real materials, researchers have only recently begun to link this abstract mathematical characterization to nodal points in known chemical compounds. In turn, this fuelled a rediscovery of the group theory underlying the connection between symmetry and dispersion, culminating this past year in a complete symmetry-based characterization of all possible electronic structures in nonmagnetic crystals.

Among the proposals for unconventional nodal quasiparticles, the notion of a threefold electronic degeneracy was perhaps the most unexpected. Electrons are fermions, or particles with half-integer spin. Fermions are known to come in degenerate states twisted into loops, chains and hourglasses, or meeting in unexpected multiples of three. Materials candidates accompanying these proposals were identified so readily that one might even question how exotic unconventional semimetals really are. Rather, it was possible that we had all just been a bit spoiled by the simplicity of graphene. By observing electronically relevant threefold nodal degeneracies and surface Fermi arcs in tungsten carbide, Ma et al. provide some of the first experimental support for the growing body of imaginative proposals for unconventional semimetals with topological electronic character.

### Fig. 1 | Dispersion relations for electronic bands as a function of crystal momentum (k).

- **a.** The dispersion relation for a 3D Dirac nodal degeneracy. A Weyl fermion has the same dispersion, but with half the degeneracy.
- **b.** For three arbitrary singly degenerate bands, two independent parameters ($\lambda_{1,2}$) must be fine-tuned to get a threefold degeneracy.
- **c.** A three-component spin-1 Weyl fermion has linear dispersion and single degeneracy in all three directions.
- **d.** A three-component band-inversion fermion, conversely, has a twofold degenerate line in one direction, and can be considered an intermediary between Dirac and Weyl fermions.
pairs under time-reversal symmetry, and so it was assumed that the nodal degeneracies of massless condensed-matter quasiparticles should manifest in multiples of two: either as twofold degenerate Weyl fermions, with broken time-reversal or parity symmetry, or fourfold degenerate Dirac fermions, with time-reversal and parity symmetry (Fig. 1a). Under this paradigm, states with broken symmetries could be fine-tuned to meet in multiples of three, but would have no reason to do so in real materials (Fig. 1b).

Ma et al. provide experimental evidence of this second kind of threefold fermion at energies relevant to transport in tungsten carbide. They also observe relatively robust Dirac-type Fermi arc surface states in this material. However, while these surface arcs are topological in a sense, they are more of a remnant of band inversion in this material, and are not unique to, or necessarily linked to, the particular threefold fermions observed in tungsten carbide. An experimental realization of the topological Fermi arcs necessitated by condensed-matter spin-1 Weyl fermions still remains elusive.

However, the future is very bright for materials discovery and engineering towards this end. Exploiting these advances in symmetry and electronic structure, researchers have just recently proposed the presence of closely related topological surface states and doubled threefold fermions in readily synthesizable crystals in the RhSi family. Given the immense number of known crystalline compounds still uninvestigated for nodal fermions, other ideal materials candidates will surely follow. With the availability of new search algorithms guided by crystal symmetry and fuelled by twenty-first-century computing power, solid-state physics may soon reach an era in which the unconventional has become commonplace.

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TURBULENCE

Ultimate evidence for the ultimate regime

The ultimate regime of turbulence has been observed, more than half a century after its first prediction. Inspiration for achieving this technical feat came from the imperfections of an everyday pipe.

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Heat, mass and momentum are readily mixed by turbulence, but a quantitative description of this mixing process is still lacking, despite more than a 100 years of research, even as it has been driven by the imperatives of industrial and commercial application. There are many theories, of course, but most fundamental theories describe turbulence in some extreme limit. That is, they live in the world of ultimate regimes. Writing in Nature Physics, Xiaojue Zhu and co-workers have now achieved, experimentally and numerically, an ultimate turbulent state that corresponds precisely to the upper limit of transport, first predicted by Robert Kraichnan in 1962 (ref. 2). Their success hinges crucially on using wall roughness to drive the turbulence, thereby achieving a state where the effects of the Reynolds number are no longer important.

The Reynolds number is the parameter for describing turbulence. Formally, it gives the order of magnitude of the inertial force compared to the viscous force in the equations of motion. But it can also be interpreted as the ratio of the largest turbulent eddies (the size of the apparatus) to the smallest ones where dissipation occurs (the Kolmogorov scales).

To appreciate the role of the Reynolds number, consider the flow through a long, smooth pipe. At Reynolds numbers less than $10^4$, the flow is laminar and steady. When the Reynolds number exceeds this value, the flow transitions to a turbulent state because viscous forces are no longer able to damp disturbances. But the state of the turbulence continues to depend on the Reynolds number. For example, the non-dimensional pressure drop (the friction coefficient) along the pipe decreases further, and the turbulence itself also continues to change. In particular, the near-wall motions continue to demonstrate a dependence on viscosity, whereas the motions in the bulk of the flow do not.

Even as the Reynolds number approaches very large values (> $10^7$), these changes persist with no sign of ceasing. Hence, there is no regime that is independent of the Reynolds number, and the ultimate state only exists in the limit of an infinite Reynolds number. Indeed, theories such as Andrey Kolmogorov’s prediction that the energy spectrum scales as a power law with an exponent of $–5/3$ (ref. 3), or the underlying turbulent cascade arguments made by Lewis Richardson, strictly apply only in the infinite Reynolds number limit, and so their applicability to finite Reynolds-number problems is always in question.

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