After a Weyl

Like London buses, you wait for a Weyl then a few come along at once.

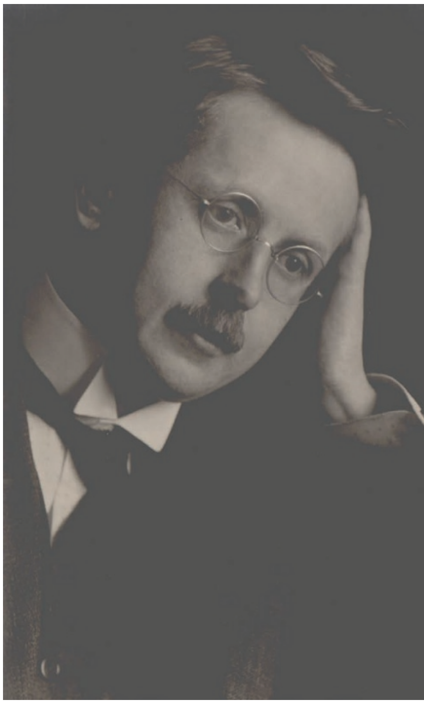
A little over three years ago, physicists were celebrating the discovery of the Higgs boson — the elementary particle that helps others acquire mass. First proposed in 1964, this 40-year search was met with jubilation in the particle physics community, and was followed by a Nobel Prize soon after. But one particle that has eluded this community for 85 years has now been discovered in both solid state and photonic crystals. Could these discoveries help to realize the fermion set: Dirac, Weyl and Majorana?

Although the Higgs ensured bosons were a topic of conversation in recent years, fermions are now firmly back on people's lips. All currently observed elementary particles fall into one of these two classes, depending on their spin: fermions have half-integer spin; bosons integer. The term fermion was coined by Paul Dirac, after Enrico Fermi, who in 1928 came up with the equation that describes the behaviour of electrons in the relativistic regime. In doing so, Dirac predicted the existence of antimatter, and provided a description for all particles that are now known as Dirac fermions.

Just one year after the publication of the Dirac equation, however, Hermann Weyl (pictured) realized that a different type of fermion would arise if the mass was zero. Not long after this prediction, it looked like massless Weyl fermions could actually help to explain an important problem in particle physics: the conservation of energy, momentum and spin in beta decay.

Scientists had observed for many years that the transformation from a proton into a neutron resulted in the emission of an electron, but the energies involved didn't add up. Wolfgang Pauli postulated the existence of a new particle in 1930, which would help to explain the missing energy. Such a particle had to be neutral, so was given the name neutrino, and was thought to be massless. Many therefore assumed it to be a Weyl fermion. Detailed experiments in the late 1950s and 60s, however, showed that neutrinos could oscillate between different flavours, requiring them to have non-zero masses. It therefore looked like Weyl fermions may not feature in the real world.

The lack of Weyl particles did not deter the condensed-matter physics community, however. Excitations in certain systems can behave analogously to elementary particles. A well-known example is represented by the relativistic particles in graphene, which behave as two-dimensional Dirac fermions. Could this be extended to three dimensions? A paper in 2011 suggested that this might be possible, and that Weyl fermions could exist in crystals of a family of exotic materials known as pyrochlore iridates[1].



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Alongside these condensed-matter efforts, a 2013 paper suggested that Weyl points could also be realized in photonic crystals[2]. This was surprising for a number of reasons: firstly, photons are bosons, so this is a non-fermionic system; secondly, Weyl fermions had escaped the physics communities for over 80 years, and it now looked like there was a race!

For the condensed-matter physicists, two papers earlier this year provided increased optimism, predicting Weyl behaviour in a class of much simpler materials that do not have inversion centres, such as TaAs, TaP, NbAs and NbP (refs 3,4). The Weyl state in such materials was not expected to be dependent on magnetic ordering or require fine-tuning of the chemical composition.

Within six months of these publications, these predictions have now been realized experimentally[5,6]. But, not to be outdone, Weyl points were concurrently observed in photonic crystals[7]. So an 85-year search finally came to an end, with Weyl points reported in several systems, by a number of groups.

In this issue of *Nature Physics*, three papers on pages 724, 728 and 748, cement these earlier findings, and confirm that Weyl physics has entered the realm of condensed-matter physics. A Commentary by B. Andrei Bernevig on page 698 discusses the predictions from earlier this year, what it means to be Weyl-like in a crystal, and what is next for researchers working with Weyl semimetals. A Research Highlight on page 703 also discusses the observation of Weyl nodes in a photonic crystal.

Beyond the fact that these are fascinating observations, like electrons in graphene, or photons in vacuum, Weyl quasiparticles obey relativistic laws of motion and have non-trivial topological properties, giving them some protection against scattering. So, like their two-dimensional cousins, Weyl materials provide much promise for electronic applications. These observations also open the door to three-dimensional topological photonics, and could help develop a range of devices, such as high-power single-mode lasers.

But there is another type of fermion that has yet to be mentioned. In 1937, Ettore Majorana realized that a third fermion could exist, which would have mass but that would be its own antiparticle. Like Weyl fermions, it is not known if Majorana fermions actually exist in nature. And also like Weyl fermions, neutrinos look to be the most likely candidate for Majorana fermions in the particle-physics world, but this is still to be settled. Condensed-matter physicists have provided tantalizing evidence for analogous Majorana-like excitations in recent years, however[8,9]. Are we on the verge of completing the fermion set? ❐

References

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Correction

In the Editorial 'After a Weyl' (*Nature Physics* **11,** 697; 2015), the author name in ref. 2 was incorrect, it should have been Lu, L. Corrected in the online versions 8 September 2015.