When symmetry breaks down

Electroweak-symmetry breaking: solving the riddle of how symmetry is broken may determine the future direction of particle physics.

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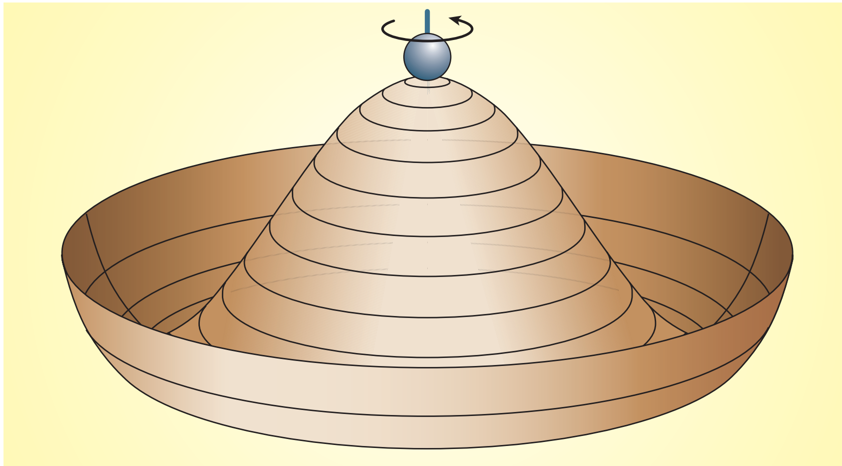
Our prehistoric ancestors did not need any modern equipment to detect the effects of what we now call the electromagnetic interactions. Light is pretty obvious in everyday life, and other electromagnetic effects, such as static electricity, lightning bolts and the magnetic properties of some rocks, such as lodestone, were well known in ancient days.

But it takes quite a bit of modern technology to discover even the existence of the weak interactions — let alone to understand them. We first became aware of weak interactions with the discovery of radioactivity in 1896. Some radioactive nuclei decay by emitting 'β-particles', which we now understand as energetic electrons. Such nuclear β-decay is the most accessible window into the weak interactions, and was the only one available until the middle of the last century, when cosmic ray detectors, nuclear reactors and particle accelerators arrived on the scene.

Electricity, magnetism and light once seemed to be three different topics. Their unified understanding, obtained in the nineteenth century, led scientists to describe them collectively as 'electromagnetic' phenomena.

Electromagnetism seems a good deal more obvious than the weak interactions. But in our modern understanding, which is based on something called the 'standard model' of particle physics, the two are perfectly in parallel. For example, electromagnetism is described by Maxwell's equations, and the weak interactions are described by a quite similar, albeit nonlinear, set of equations (called the Yang–Mills equations). To give another example, an elementary particle called the photon is the basic quantum unit of electromagnetism, and similar particles called *W* and *Z* bosons are the basic quantum units of weak interactions. Because of this close relationship between electromagnetic and weak interactions, modern particle physicists refer to them collectively as the 'electroweak' interactions.

If weak interactions are so similar to electromagnetism, why do they appear so different in everyday life? According to the standard model, the key is 'symmetry breaking'. Even if the laws of nature have a symmetry — in this case, the symmetry between electromagnetism and weak interactions, or between the photon and the *W* and *Z* bosons — the solutions of the equations may lack that symmetry.



Spoiling the spin: when the ball rolls down the slope, it will break the symmetry of the hat.

For example, in a liquid, an atom is equally likely to move in any direction in space — there are no preferred coordinate axes. But if we cool the liquid until it freezes, a crystal will form, which has distinguished axes. All directions in space are equally possible as crystal axes, but when the liquid freezes, some distinguished axes will always emerge. The symmetry between the different directions in space has been lost or 'spontaneously broken'.

Similarly, according to the standard model, just after the 'Big Bang' there was a perfect symmetry between the photon and the *W* and *Z* bosons. At the high temperatures that then existed, electromagnetism and the weak interactions were equally obvious. But as the Universe cooled, it underwent a phase transition, somewhat analogous to the freezing of a liquid, in which the symmetry was 'spontaneously broken'. The *W* and *Z* bosons gained masses, limiting the weak interactions to nuclear distances and putting their effects out of reach of the unaided eye. The photon remained massless, as a result of which electromagnetic effects can propagate over human-scale distances (and beyond) and are obvious in everyday life.

Most aspects of the standard model have been abundantly tested by experiment. For instance, the magnetic moment of the electron is measured down to the twelfth significant figure, with results that are in beautiful agreement with theory. Many predicted properties of the *W* and *Z* bosons have been verified to three or four digits. Most recently, the mechanism by which the standard model violates the symmetry between matter and antimatter has been tested in laboratories in California and Japan.

The one facet of the standard model that we have not yet been able to test experimentally is perhaps the most basic: how is the symmetry broken? However, we have a pretty clear idea of where such information can be found. Just as one can use atomic masses and binding energies to estimate the melting points of crystals, one can use the *W* and *Z* masses and other observed properties of elementary particles to estimate the high temperature or energy that particle accelerators need to achieve to explore electroweak-symmetry breaking. According to these estimates, electroweak-symmetry breaking may be in reach of the world's most powerful accelerator, the Tevatron at Fermilab in Chicago, and should certainly be in reach of the Large Hadron Collider (LHC), the new accelerator that is projected to go online in 2007 at CERN, the European particle-physics laboratory near Geneva.

What do we expect to find? In the original (and textbook) version of the standard model, the key to electroweak-symmetry breaking is an entity called the Higgs particle. At high temperatures, Higgs particles, like other particles, move at random. But as the Universe cools, Higgs particles combine into a 'Bose condensate', an ordered state in which many particles share the same quantum wave function, leading — in the case of helium — to superfluidity. The electroweak symmetry is broken by the 'direction' of the Bose condensate (in an abstract space that describes the different particle forces) in roughly the same way that in a crystal, the rotational symmetry is broken by the directions of the crystal axes. Although this proposal is simple and fits the known facts, it is unlikely to be the whole story. A seemingly artificial adjustment of parameters is needed to make the Higgs particle mass small enough for the model to work.

Numerous proposed alternatives solve this particular problem, although they introduce puzzles of their own. One idea, motivated by a phenomenon that occurs in superconductors, is that the Higgs particle arises as a bound state. This would solve the problem of getting its mass right, but also requires a host of new particles and forces, which have not yet been observed. They should be detectable at the LHC. So far, models of this type have run into a great deal of difficulty, but maybe nature knows tricks that human model builders do not.

A more radical idea is 'supersymmetry', a new symmetry structure of elementary particles in which quantum variables are incorporated in the structure of space-time. The new symmetry prevents the particle interactions that would make the Higgs particle mass too big but, again, predicts a host of additional new particles that might be discovered at the LHC, and perhaps at the Tevatron.

Supersymmetry is one idea about electroweak-symmetry breaking that has had really convincing successes. A relation between different particle interaction rates based on supersymmetry is well confirmed experimentally. Moreover, our most interesting attempts at a more complete unification of the forces of nature ('grand unified theories' and 'string theory') really only work if supersymmetry is assumed. On the other hand, supersymmetric models raise numerous perplexing questions to which human model builders do not yet have convincing answers. If supersymmetry is confirmed, then learning how nature dealt with those questions will probably give us crucial clues about a deeper understanding of nature.

Other ideas about electroweak-symmetry breaking go even further afield. One line of thought links this problem to extra dimensions of space-time, subnuclear in size, but observable at accelerators. This approach is probably a long shot, but the pay-off would be huge — discovering extra dimensions could give us the chance for direct experimental tests of the quantum nature of gravity and black holes.

Finally, another line of thought links electroweak-symmetry breaking to the dark energy of the Universe, which astronomers have discovered in the past few years by observing that the expansion of the Universe is accelerating. From this point of view, one tries to relate the relative smallness of the Higgs particle mass to the smallness of the dark energy. One approach is the anthropic principle, according to which the dark energy and the Higgs particle mass take different values in different parts of the Universe, and we inevitably live in a region in which they are small enough to make life possible. If so, many other properties of the Universe that we usually consider fundamental — such as the mass and charge of the electron — are probably also environmental accidents. Although I hope that this line of thought is not correct, it will inevitably become more popular if experiment shows that electroweak-symmetry breaking is governed by the textbook standard model with a Higgs particle and nothing else.

As yet, none of these theoretical proposals about electroweak-symmetry breaking are entirely satisfying. Hopefully, by the end of this decade, experimental findings at the Tevatron and the LHC will set us on the right track. But the diversity and scope of ideas on electroweak-symmetry breaking suggests that the solution to this riddle will determine the future direction of particle physics. ■

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FURTHER READING

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