Eyes on a prize particle

Luis Álvarez-Gaumé and John Ellis

The search for the Higgs boson could soon prove successful. Although the particle bears the name of a single physicist, many more were involved in devising the theory behind it — so which of them should share a potential Nobel Prize?

The story of the Higgs boson begins with symmetry. Physicists are obsessed with the notion of symmetry — it enables them to relate phenomena that may at first sight seem very disparate — and with the notion of symmetry breaking, because many of nature's symmetries are not exact but only approximate or otherwise concealed. One example of an exact symmetry (or rather, exact so far) is Lorentz invariance, which first appeared in Maxwell's equations that unify electricity and magnetism, and was subsequently elevated to a general principle by Einstein in his special theory of relativity. On the other hand, there are two distinct possibilities for breaking a symmetry: either it was never really there at all, because there are parts of the underlying equations that are not symmetric; or the breaking originates not in the equations themselves, but rather in the solution that nature chooses, an option known as spontaneous symmetry breaking or hidden symmetry.

An example of a 'really broken' symmetry is provided by nuclear physics: protons and neutrons experience very similar strong nuclear forces but have different electric charges and slightly different masses. We now understand the small differences in their masses and nuclear forces as being due largely to the small differences between the masses of the two types of quark they contain. On the other hand, an example of 'spontaneous' symmetry breaking is provided by superconductivity: as explained in the theory of Bardeen, Cooper and Schrieffer[1], the photon — which has no mass when propagating freely through space — acquires an effective mass when it tries to penetrate a superconducting material (as discussed earlier by Ginzburg and Landau[2,3]). In free space, the masslessness of the photon is guaranteed by Lorentz invariance and a symmetry known as gauge invariance. This symmetry is still present inside the superconductor, but it is 'hidden' by the condensation of Cooper pairs of electrons, as was discussed explicitly by Anderson[4].

Related ideas were introduced into particle physics by Nambu[5] in 1960, earning him a share in the Nobel Prize for physics finally in 2008. He suggested that the low mass and the low-energy interactions of pions — the lightest nuclear particle — could be understood as a reflection of an approximate 'hidden' symmetry that would have been exact if the quarks they contain were actually massless. In the real world, the masses of the quarks that make up protons, neutrons and pions are much smaller than a typical nuclear mass. Nambu's insight was that, even if the quark masses vanished, the corresponding symmetry would be 'hidden'.

This happens because the light quarks condense in pairs in the vacuum, breaking the symmetry 'spontaneously' much like Cooper pairs of electrons inside a superconductor (Fig. 1). Consequently, the 'hidden' symmetry causes the pions' masses to vanish, in accord with a general theorem proven in 1961 and 1962 by Goldstone, Salam and Weinberg[6,7], and fixes their low-energy couplings to protons, neutrons and each other. A key difference between the cases of superconductivity and Nambu's theory of pions is that the former breaks a 'gauge' symmetry — that is, one whose transformations can be made locally — and the latter breaks a 'global' symmetry, in which the same transformation must be made over all space and time.

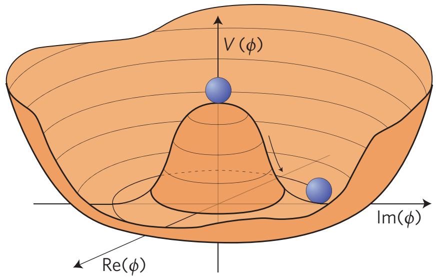

Figure 1 | An effective potential, $V(\phi)$, in the form of a 'Mexican hat' leads to spontaneous symmetry breaking. The vacuum — that is, the lowest-energy state — is described by a randomly chosen point around the bottom of the hat. In a global symmetry, movements around the bottom of the hat correspond to a massless, spin-zero, Nambu–Goldstone boson[5–7]. In the case of a local (gauge) symmetry, as was pointed out by Englert and Brout[8], by Higgs[10] and by Guralnik, Hagen and Kibble[11], this boson combines with a massless spin-one boson to yield a massive spin-one particle. The Higgs boson[10] is a massive spin-zero particle corresponding to quantum fluctuations in the radial direction, oscillating between the centre and the side of the hat in the direction of the arrow.

The mechanism emerges

At this point, theoretical physicists were confronted with massless particles at every turn: an exact gauge symmetry entails a massless boson with one unit of spin, such as the photon; breaking a global symmetry spontaneously spawns a massless spin-zero 'Nambu–Goldstone' boson such as the pion. However, in experimental data there were no candidates for such massless particles, although there were suggestions that massive bosons might mediate the weak interactions responsible for radioactivity.

In 1964, Englert and Brout[8] were the first to show how to kill two birds with one theoretical stone, by combining would-be massless spin-one and spin-zero bosons to obtain massive spin-one particles in gauge theories with either Abelian or non-Abelian symmetry groups. Soon after and independently, Higgs wrote a paper[9] pointing to a loophole in earlier arguments for the existence of massless bosons, and then wrote a second paper[10] using this mechanism to work the same trick as Englert and Brout, for the Abelian case. The final paper in the series, by Guralnik, Hagen and Kibble[11], incorporates a discussion of the relationship of their work to the papers of Englert, Brout and Higgs, again in the Abelian case.

The mechanism proposed by Englert and Brout, by Higgs, and by Guralnik, Hagen and Kibble was spontaneous breaking of the gauge symmetry associated with the massless spin-one boson (the so-called gauge boson) via a condensate in the vacuum, taken in these works to be an elementary scalar field. Speaking picturesquely, the Nambu–Goldstone boson is 'eaten' by a gauge boson to become its third, longitudinal, polarization state, thereby giving it a mass. Initially, this idea met with considerable disbelief and scepticism, or at best indifference.

In 1967 and 1968, however, this mechanism was incorporated by Weinberg[12] and Salam[13] in a unified theory of electromagnetism and the weak interactions based on a non-Abelian gauge theory, in papers that also attracted little attention for a while (although Weinberg's seems to be the first paper in which it is shown that matter particles can also acquire their masses from spontaneous symmetry breaking). All this changed in 1971 and 1972, when the resulting model of particle physics was shown by 't Hooft and Veltman[14,15] to be a calculable quantum theory, and the floodgates of theoretical interest and experimental verification soon opened. Subsequently, many experiments have verified the predictions of this 'standard model' with high accuracy. Weinberg and Salam shared the Nobel Prize in physics with Glashow in 1979, and 't Hooft and Veltman shared it in 1999.

The particle, too

So, where does the Higgs boson fit into these developments? In a consistent quantum theory, when you fix the value in the vacuum of a Englert–Brout–Higgs–Guralnik–Hagen–Kibble-style condensate, you must also consider the quantum fluctuations in its magnitude: see the arrow in Fig. 1. These may be represented as a massive scalar particle (not to be confused with a massless Nambu–Goldstone boson), as was pointed out by Higgs in the second of his two 1964 papers[10]. Englert and Brout were aware that such a particle should exist, but did not explore it in their paper, whereas Guralnik, Hagen and Kibble commented that it would be massless and decouple in their simplified model. So this particle has become known as the 'Higgs boson'.

Since then, the standard model has passed many experimental tests with flying colours, and although there is plenty of circumstantial evidence for the existence of the Higgs boson, no direct evidence has been found. However, the standard model would not make mathematical sense without the Higgs boson — or something very much like it — so attention has focused increasingly on the search for this missing ingredient as a key proof of the underlying theory. In a paper[16] co-authored by one of us, the apologetic and cautious final words read, "we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up." Still, a quest for the Higgs boson, akin to that for the Holy Grail, has been triggered.

The agreement of many high-precision experimental data with predictions of the standard model is possible only if the Higgs boson, or whatever replaces it, has an effective mass lower than about 180 GeV (ref. 17). (For comparison, the proton mass is 0.94 GeV.) Searches at CERN's Large Electron–Positron collider, which was shut down at the end of 2000, may have caught a glimpse of the Higgs boson, but the only definite result was that it must have a mass of at least 114.4 GeV (ref. 18). More recently, searches at the Fermilab's Tevatron collider have excluded the existence of a Higgs boson with mass between 158 and 175 GeV (ref. 19), and the sensitivity of their searches is improving continuously. Meanwhile, experiments have started at CERN's Large Hadron Collider, and should be able to discover the Higgs boson, whatever its mass. The net is closing in on it — if indeed the Higgs boson exists!

For the moment, this must be regarded as an open question. Perhaps there is some Higgs-ish object, but its existence would raise so many issues that theorists are actively considering alternatives. Maybe it is composite, like the Cooper pairs in superconductivity, or like the quark–antiquark condensates and pions of the strong nuclear interactions? Or perhaps the electroweak symmetry can be broken in a different way, such as by boundary conditions in some extra dimension of space?

A big deal

Why should anybody care? Particle physicists certainly should, because their standard model is nonsensical without the Higgs boson, and it could be the first in a whole unseen zoo of 'elementary' spin-zero particles. Cosmologists should also care, because something resembling the Higgs boson (possibly even the Higgs itself) could have been responsible for the period of inflationary cosmological expansion that the Universe is thought to have experienced early in its history, and because the dark energy that is now accelerating the expansion of the Universe is in danger of receiving a grotesquely large contribution from the Higgs, or whatever condensate replaces it. Moreover, its existence bears philosophically upon physicists' concepts of symmetries and their breaking.

Clearly, then, discovering the Higgs boson would be a big deal. Even though its existence is not guaranteed, it would have many ramifications within and beyond particle physics. The discovery would be prizeworthy indeed, but who should get the credit? In 1997, the European Physical Society honoured Englert, Brout and Higgs — respectively, the authors of the first 1964 paper[8] (the only one of the three to consider the non-Abelian case used in the standard model) and the proponent of the unseen boson[10]. On the other hand, in 2010 the American Physical Society honoured Englert, Brout and Higgs together with Guralnik, Hagen and Kibble — the authors of the final paper in the 1964 revolution — with its Sakurai Prize (already won by Nambu in 1994).

As for the big one, it is well known that the rules of the Nobel Prize restrict the awarding committee to honouring at most three individuals. With the prospective theoretical nominees already numbering more than that — not to mention the thousands of experimentalists engaged in the search for the Higgs boson — the Nobel Prize committee could soon be facing a difficult decision. It's one that we would rather not call. ❒

Luis Álvarez-Gaumé and John Ellis are in the Theory Division, CERN, CH-1211 Geneva 23, Switzerland; John Ellis is also in the Theoretical Physics and Cosmology Group, Department of Physics, King's College London, London WC2R 2LS, UK.
e-mail: luis.alvarez-gaume@cern.ch, john.ellis@cern.ch

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