Englert and Higgs are awarded the Nobel Prize in Physics

The prize comes in the wake of the much anticipated discovery of the spinless fundamental particle their theoretical work predicted half a century ago.

The Royal Swedish Academy of Sciences has awarded the 2013 Nobel Prize in Physics to François Englert and Peter Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles." The academy's citation goes on to point out, with unaccustomed specificity, that the mechanism "recently was confirmed through the discovery of the predicted fundamental particle by the ATLAS and CMS experiments at CERN's Large Hadron Collider."

Englert and Higgs are emeritus professors, respectively, at the Free University of Brussels in Belgium and the University of Edinburgh in the UK. Figure 1 shows them together at CERN on 4 July 2012, the day the experimental discovery was announced to great acclaim. (See PHYSICS TODAY, September 2012, page 12, and the article by Joe Lykken and Maria Spiropulu on page 28 of this issue.)

The theoretical discovery honored by the prize is generally called the Higgs mechanism. But many experts would prefer the ungainly but arguably fairer name Brout-Englert-Higgs-Guralnik-Hagen-Kibble (BEHGHK) mechanism. Over a period of barely 10 weeks in the summer and fall of 1964, essentially the same seminal argument was submitted to journals by three groups of theorists working quite independently: Englert and the late Robert Brout, an American expatriate, in Brussels;[1] Higgs working alone in Edinburgh;[2,3] and Tom Kibble at Imperial College London with two American postdocs, Gerald Guralnik and Carl Hagen.[4] Scientists have often lamented the canonical three-individual limit of the Nobel science prizes.

The problem the six men were addressing half a century ago was that the quantum field theories that otherwise seemed most promising for understanding the patchwork quilt of particle physics appeared stubbornly to require the production of a kind of massless particle that clearly doesn't exist. Theorists who had not yet given up altogether on quantum field theory were looking for fruitful generalizations of quantum electrodynamics, the spectacularly successful paradigm of locally gauge-invariant field theories.

Prelude

Quantum electrodynamics (QED), the theory of the interaction of electrons with photons, is invariant under rotations of the electron wavefunction's phase that can differ arbitrarily from one spacetime point to another. That "local gauge invariance" requires compensatory changes from point to point in an interacting massless vector (spin-1) boson field, namely the photon field. A profound consequence, then, of the requirement of local gauge invariance is that it mandates, all by itself, the existence of the photon and essentially dictates the character of its interactions as mediator of the electromagnetic force.

Figure 1. François Englert and Peter Higgs at the 4 July 2012 announcement and celebration at CERN of the discovery of the spinless boson their theoretical work had predicted half a century earlier. It was their first face-to-face meeting. (Photo courtesy of CERN.)

In 1954 C. N. Yang and Robert Mills initiated the search for local gauge-symmetry operations more elaborate than the one-dimensional phase rotations of QED—for example, rotations in an internal "isospin" space that expresses a symmetry between protons and neutrons. Local invariance under such higher-dimensional rotations, they argued, might similarly dictate the character of the mediators of the strong nuclear force.

An apparent difficulty with the Yang–Mills program was that its "gauge bosons"—the force-mediating vector bosons dictated by the local gauge invariance—had to be massless like the photon. But the short ranges of the nuclear forces appeared to require massive gauge bosons.

In 1960 Yoichiro Nambu, arguing from analogy with condensed-matter systems, suggested that the vector bosons might acquire the requisite masses by spontaneous symmetry breaking—that is, processes in which an exact symmetry of the Hamiltonian (the energy function) of a system is broken by the system's ground state. (See PHYSICS TODAY, December 2008, page 16.) For example, the ground state of a ferromagnet below its Curie temperature adopts an arbitrary polarization direction in spite of the Hamiltonian's exact rotational symmetry. In particle theory, the asymmetric "ground state" would be the vacuum itself, violating a symmetry of its Hamiltonian.

The following year, Jeffrey Goldstone seemed to squash Nambu's suggestion by proving a theorem that applies to any relativistic quantum field theory that satisfies the usual axioms of such theories: If a continuous (as distinguished from discrete) symmetry of the theory's Hamiltonian is not also a symmetry of the physical vacuum, then the spontaneous symmetry breaking creates one or more massless scalar (spin-0) boson species.

If such massless, spinless "Goldstone bosons" really existed, they should have been easy to spot. But none have been found. So Goldstone's theorem piled yet another wet blanket on the aspirations of the field theorists. A year later, Philip Anderson, invoking spontaneous symmetry breaking in various condensed-matter systems, offered relief: "The Goldstone zero-mass difficulty [in particle physics] is not a serious one," he suggested, "because we can probably cancel it off against an equal Yang–Mills zero-mass problem."[5] And indeed, the 1964 BEHGHK papers spelled out the mechanism by which Anderson's prescient conjecture is accomplished.

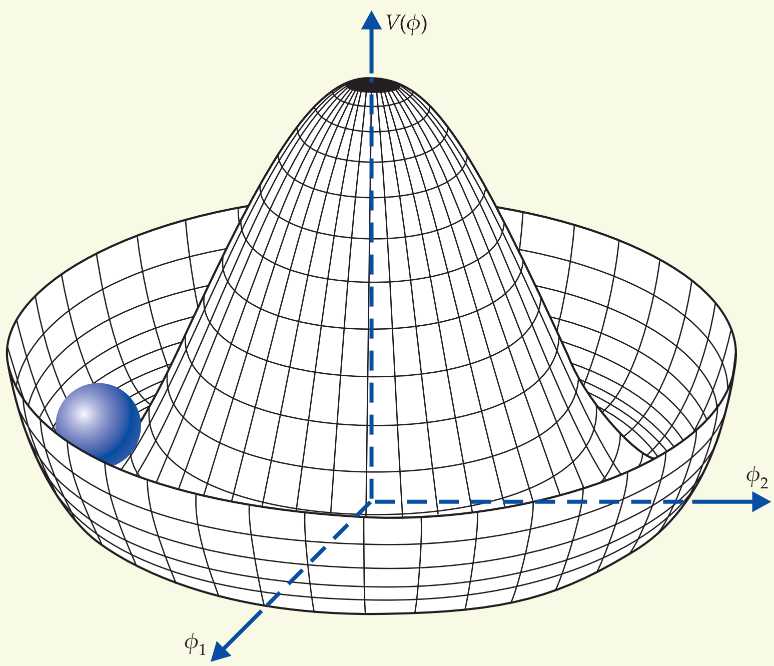

Figure 2. Spontaneous symmetry breaking in a quantum field theory is illustrated by the so-called Mexican-hat shape of the potential-energy density V of a self-interacting complex scalar field ϕ as a function of its real and imaginary parts, ϕ_1 and ϕ_2. Though the potential is symmetrical about the origin, the presumptive vacuum state $\phi = 0$ is not the potential's minimum. So the scalar field (represented by the ball) finds its asymmetric "physical vacuum" state at an arbitrary point in the sombrero's trough.

1964

The three papers that convincingly demonstrated the cancellation mechanism[1,3,4] had differences in formalism, emphasis, elaboration—and submission date. But, coincidentally, all three began with essentially the same illustrative "toy" field theory, "lest the simplicity of the argument be shrouded in a cloud of indices," as the Englert–Brout paper (submitted first, on 26 June) put it.[1]

The toy model, introduced in Goldstone's 1961 paper, was a Lorentz-invariant complex scalar field $\phi = \phi_1 + i\phi_2$ whose self-interaction produces a potential-energy density $V(\phi^*\phi)$ that has the Mexican-hat shape shown in figure 2. The potential function is invariant under rotation about the origin of the complex ϕ plane. But its minimum is *not* at the origin. So the system's physical vacuum, somewhere in the sombrero's trough, spontaneously breaks the Hamiltonian's rotational symmetry.

The complex scalar field, being equivalent to a pair of real scalar fields, has two spinless quanta. Goldstone had shown that the spontaneous symmetry breaking converts the original pair of equal-mass quanta into a very different pair: the troublesome massless Goldstone boson plus another scalar boson with a finite mass that depends on the steepness of the sombrero's trough walls. More generally, Goldstone had proven that in all relativistic field theories obeying the usual axioms, spontaneous symmetry breaking must generate massless scalar bosons.

But Higgs, in the first of his two 1964 papers[2] (submitted 27 July), pointed out that locally gauge-invariant theories ("gauge theories," for short) are the exception. Their predictions are of course Lorentz invariant. But, in essence, the gauge-boson fields they mandate spoil the manifest Lorentz covariance that's a condition of Goldstone's theorem.

That one-page paper in *Physics Letters* was Higgs's response to the assertion by Walter Gilbert—Guralnik's thesis adviser and later a Nobel chemistry laureate for his work in molecular biology—that no Lorentz-invariant theory could possibly violate Goldstone's theorem. Higgs was saving his exposition of the mechanism by which gauge theories avoid Goldstone bosons for a longer follow-up paper. Early in August he sent that one also to *Physics Letters*. But it was rejected, he recalls, as "not the kind of result that called for rapid publication."

So Higgs did some rewriting "to make the point that this sort of theory has experimental consequences," and submitted the revised draft on 31 August to *Physical Review Letters*, which promptly accepted it.[3] But the referee (who turned out to be Nambu) did call his attention to the just-published Englert–Brout paper, of which Higgs had been unaware. So he added a footnote "to the effect that essentially the same thing had already been done by Englert and Brout."

Eating massless scalars

Both papers[1,3] turned Goldstone's toy model theory into a gauge theory by requiring that the Hamiltonian be invariant under phase rotations of the complex ϕ field that vary arbitrarily in spacetime. To that end, a compensating vector-boson gauge field analogous to QED's photon field has to be added to the Hamiltonian.

The combination of spontaneous symmetry breaking and local gauge invariance turns out to create the remarkable synergy Anderson had anticipated. The Goldstone boson mixes with the massless gauge boson in such a way that the former vanishes and the latter acquires mass. That's often described as the photon putting on weight by eating the massless Goldstone boson.

Such a meal doesn't change the count of particle states. Unlike massive spin-1 particles with their three possible spin orientations, the massless photon is restricted by Lorentz invariance to just two: parallel and antiparallel to its velocity. In effect, the vanished spinless Goldstone boson has morphed into the gauge vector boson's third spin state. The other scalar boson survives and keeps the mass it acquired in the symmetry breaking.

Both papers[1,3] then extended the argument to the higher-dimensional symmetry operations of Yang–Mills gauge theories. In such cases, they pointed out, spontaneous symmetry breaking begets a more communal feast: multiple

Goldstone bosons eaten by multiplets of gauge bosons.

The Guralnik-Hagen-Kibble paper independently reached the same conclusions, with special attention paid to the inapplicability of the Goldstone theorem to gauge theories. But it was not submitted until mid-October. "Our paper was unquestionably the last," concedes Kibble good-naturedly, "though we naturally regard our treatment as the most thorough and complete."

The surviving scalar boson

In their zeal to describe the mechanism that simultaneously endows the vector bosons with much-desired mass and exorcises the troublesome Goldstone boson, the 1964 authors paid scant attention to the massive neutral scalar that survives. But it's the boson that eventually instigated the prodigious search that culminated in the heady celebration at CERN 48 years later.

Trying to make his second paper look a bit more relevant for experimenters after its initial rejection, Higgs added that "an essential feature of [this] type of theory . . . is the prediction of incomplete multiplets of scalar and vector bosons."[3] He recalls that "this reference to the so-called Higgs boson would never have appeared in print if *Physics Letters* had accepted the original version." The existence of the massive neutral scalar particle is implicit in the mechanism, but only Higgs gave it even passing attention.

Englert explains: "To begin to think about looking for the [Higgs] boson, we had to wait until the 1964 theory was applied to a realistic physical system" with couplings to fermions (leptons, nucleons, or quarks). Even in such a realistic theory, the mass of the Higgs boson can't be predicted. And without some idea of those couplings, one wouldn't know where to start looking.

The first such realistic gauge theory was Steven Weinberg's 1967 unification of electromagnetism with the weak nuclear force. He posited a doublet of self-interacting scalar fields that spontaneously breaks the Hamiltonian's "weak-isospin" symmetry between neutrinos and electrons, thus endowing the electron with mass.[6] The symmetry breaking also makes three of the theory's four gauge bosons massive, as one wants for the mediators of the weak interactions; but it leaves the photon massless.

The Weinberg model, like its 1964 progenitors, predicted the existence of a massive neutral scalar boson—the Higgs. Its mass, M_H, was still unpredictable. But its couplings to other particles could now be predicted as a function of M_H.

"Even then," recalls Englert, "a search would still have been premature. A proof of the electroweak model's renormalizability [its freedom from unmanageable infinities] didn't come until 1971. And then there was a long period of experimental tests of the model's more precise predictions. As the standard model of particle physics and its testing evolved, the [Higgs] boson eventually became its last missing piece and therefore the experimenters' highest priority." And because M_H turned out in the end to be 135 times the proton's mass, the discovery had to wait for CERN's Large Hadron Collider, which started doing physics only four years ago.

In the standard model, coupling to the scalar boson's ubiquitous field is responsible not only for the masses of the three vector bosons, $W^\pm$ and Z^0, that mediate the weak interactions, but also for the masses of all the fundamental fermions (leptons and quarks) except the neutrinos. Within the standard model's purview, the tiny neutrino masses that became evident in the 1990s have no explanation.

The laureates

François Englert was born in Brussels to Jewish parents in November 1932. After the Germans invaded Belgium in May 1940, the seven-year-old boy was concealed with false identity papers in a succession of orphanages until the Allied liberation in the autumn of 1944.

In 1955 Englert graduated from the Free University of Brussels as an electrochemical engineer. But he stayed on to work toward a PhD in physics under the supervision of Jules Géhéniau, a mathematician and quantum theorist who had been a student of Louis de Broglie.

After completing his thesis, "The behavior of a small quantum system immersed in a weakly dissipative medium," in 1959, Englert came to the US as a postdoc of Brout, a professor at Cornell University doing mostly condensed-matter theory. Their enduring friendship and collaboration "began already at our very first meeting," at the Ithaca airport. Two years later Brout left Cornell to join Englert on the Free University's physics faculty. Their conversion to particle theory grew out of their interest in spontaneous symmetry breaking in condensed-matter systems. Brout, a native New Yorker, became a citizen of Belgium, where he died in 2011 (see his obituary by Englert, PHYSICS TODAY, August 2011, page 63).

Peter Higgs was born in 1929 in Newcastle upon Tyne on England's northeast coast. His father was a sound engineer for the BBC. As a teenager at Cotham Grammar School in Bristol, Peter was inspired by reading about the work of one of the school's alumni—Paul Dirac.

All of Higgs's university training was at King's College London. His doctoral supervisor was theoretical chemist Charles Coulson. After finishing his thesis, "Some problems in molecular vibrations," in 1954, Higgs first came to the University of Edinburgh as a senior research fellow. Then after various academic posts in London, he returned permanently to Edinburgh in 1960.

The story of his involvement with spontaneous symmetry breaking, as amusingly recounted in a 2010 talk entitled "My Life as a Boson,"[7] begins inauspiciously with the 1960 Scottish Universities Summer School in Physics. The fledgling faculty member's assignment as the summer school's wine steward was subverted by a youthful "gang" of future architects of the standard model—among them, Nicola Cabibbo, Sheldon Glashow, and Martinus Veltman. He would have learned much from their discussions late into the night, had the gang not kept him at bay so they could make free with the wine he was supposed to be guarding.

The following year Higgs was drawn seriously into the subject by the attempts of Nambu and others to apply spontaneous symmetry breaking to the strong interactions. Not until Weinberg's 1967 paper did it become clear that Nambu's seminal ideas had largely been applied to the wrong class of interactions.

Surprisingly, Englert and Higgs had never met before the 2012 discovery announcement and celebration at CERN. They would have met eight years earlier, had Higgs attended the ceremony in Jerusalem awarding them and Brout, jointly, the 2004 Wolf Prize in Physics.

Bertram Schwarzschild

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