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C. R. Physique 8 (2007) 970–972
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The mystery of the Higgs particle/Le mystère de la particule de Higgs

Prehistory of the Higgs boson

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1. Origins in condensed matter physics

A Higgs boson is a particle whose existence is predicted in a class of quantum field theories in which a symmetry under a Lie group of transformations of the fields is spontaneously broken by an asymmetric vacuum state. It is a quantum of certain excitations of the order parameter.

Such spontaneous symmetry breaking was first proposed as a feature of theories of elementary particles in 1960, but it has a much longer history in the context of condensed matter theory. The earliest relevant example is ferromagnetism, as explained by Heisenberg [1] in 1928; an array of electron spins with nearest-neighbour interactions which favour energetically parallel over antiparallel configurations has a ground state in which all the spins are aligned in some direction, thus breaking the rotational symmetry of the dynamics.

Another example, which comes closer to the kind of symmetry breaking which is of interest in particle physics, is superfluidity. In 1947 Bogoliubov [2] studied Bose condensation of an infinite system of neutral spinless bosons with short-range repulsive two-body interactions. Such a condensate is characterised by a 'macroscopic wave function' (the order parameter) which is complex; its modulus squared is a measure of the observable condensate density, but its argument (which is unobservable) is arbitrary, thus breaking the symmetry of the dynamics under rotations of the boson wave functions in the Argand diagram. The short-range interactions are represented in the second-quantised Hamiltonian by a term proportional to the square of the particle density, that is, to a quartic in the components of the scalar quantum field.

A third example, which became the model for theories in particle physics, is superconductivity. In 1950, Ginzburg and Landau [3] showed that the phenomenon could be understood as a consequence of Bose condensation of electrically-charged spinless bosons: at the time there seemed to be no candidates for such bosons among the known constituents of a metal or alloy. It was only after Cooper had shown how pairs of electrons could bind to form spinless composite bosons that the theory of superconductivity, in the form proposed by Bardeen, Cooper and Schriefer [4] in 1957, became viable. The Ginzburg–Landau theory thereby acquired the status of an effective theory, valid in circumstances where the compositeness of the Cooper pair could be neglected.

In common with superfluidity, the macroscopic wave function of the condensate responsible for superconductivity breaks the symmetry of the dynamics under rotations in the Argand diagram, but now, because the bosons are charged, this symmetry is the one which generalises to the gauge invariance of electrodynamics.

The BCS energy gap in the fermion spectrum is proportional to the modulus of the condensate wave function; the existence of excitations in which this quantity is no longer constant but has a wavelike space-time dependence was first extracted from BCS theory by Littlewood and Varma [5] in 1981, as the explanation of a puzzling feature of the Raman spectrum of superconducting $NbSe_2$, measured the previous year by Sooryakumar and Klein [6].

1631-0705/$ – see front matter
doi:10.1016/j.crhy.2006.12.006

2. Spontaneous symmetry breaking in particle physics

It was Nambu [7] who in 1960 first proposed relativistic models inspired by BCS theory as a means of generating fermion masses in elementary particle physics. His idea was that the energy gap between a single-fermion state and the filled negative-energy Dirac states should be generated by a scalar condensate, as in BCS theory, where the filled energy bands are the analogue of the Dirac 'sea'. The existence of such a condensate would break the symmetry of the model under a Lie group which, in particle physics, would be a non-Abelian group containing the $U(1)$ group associated with electric charge conservation as a subgroup.

Although BCS theory was Nambu's inspiration, the hadronic models which he proposed lacked the local gauge invariance of their prototype. It soon became clear that, both in these models and those (featuring elementary scalar fields) studied by Goldstone [8] (1961), spinless zero-mass excitations (Goldstone bosons) always existed. The connection between spontaneous symmetry breaking and Goldstone bosons in relativistic theories was formally proved by Goldstone, Salam and Weinberg [9] in 1962. The experimental evidence against the existence of such particles in the real world cast doubt on the viability of Nambu's ideas.

Between 1962 and 1964 a debate developed in the literature about whether the Goldstone theorem could be evaded. Anderson [10] (1963) pointed out that in a superconductor the Goldstone mode (excitations of the argument of the condensate wave function) becomes a massive mode because of its electromagnetic coupling and provides a longitudinal partner for the pair of transversely polarised electromagnetic modes, which are also massive. (This was the first account of what has become known as the 'Higgs mechanism'.) He remarked that, in elementary particle theories, "*the Goldstone zero-mass difficulty is not a serious one, because we can probably cancel it off against an equal Yang–Mills zero-mass problem*". His contribution to the debate did not receive the attention that it deserved from particle theorists such as myself, mainly because he had neither identified a flaw in the proof of the Goldstone theorem, nor discussed explicitly any relativistic model.

The resolution of this difficulty finally came in July 1964, when I realised that theories with a local gauge invariance fail to satisfy one of the axioms (manifest Lorentz covariance) on which the 1962 proof of the Goldstone theorem depends. (The realisation was triggered by my acquaintance with Schwinger's papers on gauge invariance [11].) A short paper, outlining my contention that the Goldstone theorem could be evaded in gauge theories, was published subsequentially in Physics Letters [12].

By the end of July 1964 I had also written down the simplest field-theoretic model which substantiated my contention; this is now known as the Higgs model, but I later learned that it is just a relativistic version of Ginzburg–Landau theory, of which I was unaware at the time. Unfortunately, my second short paper was rejected by Physics Letters. (I was told later by a colleague who had been at CERN when it was received by the local editor that it had not been thought by those who read it to have any relevance to particle physics.)

It was in the course of revising this rejected paper, before submitting it to Physical Review Letters, that I added a paragraph drawing attention to some characteristic signatures of spontaneously broken gauge theories. In particular, I pointed out that there are always massive scalar excitations, which remain after the Goldstone modes of the symmetry-breaking scalar multiplet have combined with some of the gauge fields to provide the longitudinal components of massive vector bosons. These scalar excitations have become known as Higgs bosons.

My revised paper was accepted by Physical Review Letters [13], but the referee drew to my attention a paper which had been received a month earlier. This was the paper by Englert and Brout [14] (based on research which had preceded mine), which discussed the 'Higgs mechanism' in much greater generality than mine had done. Our papers were somewhat complementary; Englert and Brout had studied the tree approximation to the vector field propagator in spontaneously broken gauge theories by Feynman diagram methods, whereas I had started from classical Lagrangian field theory.

When I met Nambu for the first time twenty years later, he revealed that he had been the referee of both papers. He also drew my attention to the fact that an example of the BCS analogue of the Higgs boson had been found a few years earlier [5,6].

3. Higgs bosons in realistic theories

Brout and Englert and I all wasted a considerable amount of effort trying, without success, to apply our ideas to the breaking of hadronic flavour symmetries, as Nambu had done before us: they were the fashionable kind of symmetry to break in the sixties.

Progress came only when, in 1967, Weinberg [15] and Salam [16] independently realised that the prime candidate for spontaneous symmetry breaking was the $SU(2) \times U(1)$ group of Glashow's model [17] of leptonic electroweak interactions. A few years passed before 't Hooft's completion (1971) [18] of Veltman's programme for the renormalisation of Yang–Mills' theories gave theorists confidence in the viability of the new electroweak theory and other theories of this type.

By the 1972 High-Energy Physics Conference at Fermilab, 't Hooft's work had triggered an outbreak of theoretical activity, exploring alternative spontaneously broken gauge theories of electroweak and other interactions. The rapporteur of the session on theory of weak interactions, B.W. Lee [19], attached my name to many aspects of this kind of theory, especially to 'Higgs mesons'. (The contribution of Englert and Brout was mentioned only in passing.)

4. The beginning of the search

Within a few years, thanks largely to the discovery of weak neutral currents in 1973, interest among experimentalists in tests of electroweak theory became intense. During the planning of LEP, designed to produce the Z and $W^{\pm}$ vector bosons and to perform precision tests of the theory, a paper appeared which gently encouraged experimentalists not to neglect to look out for a Higgs boson. Ellis, Gaillard and Nanopoulos [20] concluded:

> "*We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm, and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons 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.*"

So the search began.

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