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The road of gaining mass for gauge boson: interpretation of Nobel Prize in physics 2013

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The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs with no surprise "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider". This partially settles down the story concerning the discovery of "God particle".

Within subatomic scale, the smallest constituents of matter physicists known now are quarks, leptons, gauge particles which mediate interaction forces and newly discovered Higgs boson. The works of the Nobel Prize in physics 2013 mainly refer to the origin of mass of gauge particles; historically they were born due to a combined solution for two distinctive problems on massless particles.

During 1960s, physicists already knew that our nature is governed by four kinds of interactions: gravitation, electromagnetism, the weak interaction and the strong interaction. At subatomic scale, gravitation is so weak that physicists usually ignore its effects. While for electromagnetism, a systematic description in terms of quantum field theory (QFT) is already set up at that time, i.e. quantum electrodynamics (QED) or U(1) abelian gauge theory. The remaining two interactions are found at play within the nucleus and act only over a very short range. The theories describing them all met with serious theoretical difficulties, and this leads to a general mistrust in QFT. Only during and after 1970s, the issue of strong interaction gradually became clear which we will not discuss further in this paper. For the weak interaction, physicists found that the underlying theory of famous phenomenological V-A theory could be a non-abelian gauge field theory, except an extra requirement that gauge particles of the theory must be massive, just like original Yukawa's proposal that pions——the mediator of the strong nuclear force are massive. Unfortunately, the gauge symmetry of non-abelian gauge theory prohibits the massive gauge boson. If we artificially add in a mass term by hand into the theory, the basic gauge symmetry is violated and the theory becomes non-renormalizable due to the mass-induced extra bad ultraviolet behavior for the gauge particle propagator. This gauge symmetry required massless gauge particle is the first distinctive problem on massless particle mentioned at the end of last paragraph. It is the main difficulty faced with newly born non-abelian gauge theory, which leads to criticism of Wolfgang Pauli (Nobel Prize, 1945), since no such particle was known and such a particle would mediate a long range force instead of the short-range force of the strong and weak interactions. From present point of view, put in theory by hand the gauge particle mass results in an explicit violation of gauge symmetry. The way to get rid of it is to change to a spontaneous violation of gauge symmetry which exhibits in gauge boson as that the mass of it is not artificially put into theory by hand, instead spontaneously generates within theory itself. This mechanism of the mass generation is just the origin of gauge particle mass. How to practically realize spontaneous gauge symmetry breaking? Or how to spontaneously generate gauge particle mass? Before the work of Englert, Brout and Higgs, physicists did not know.

Before the work of Englert, Brout and Higgs in 1964, investigation of spontaneous symmetry breaking independently evolved in another track in parallel to the research of the origin of mass of gauge particle. Y. Nambu (Nobel

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Prize 2008) had previously shown that the BCS ground state has spontaneously broken gauge symmetry and then extended ideas from superconductivity to particle physics. In QFT, physicists found a theorem—Goldstone theorem which states that spontaneous breaking of continuous symmetry will lead to massless particle or so called Goldstone boson. As long as the spontaneous breaking of continuous symmetry happen, there will be massless particle showing up in the physical spectrum. This is the second distinctive problem on massless particle mentioned at the end of the second paragraph, since we do not find such kind massless particles in reality.

Concerning the first massless problem, Schwinger [1] asked the question if a massive gauge field always comes together with a massless scalar. In 1962 Anderson [2] took up Schwinger's problem and discussed it in a model of a charged plasma. He concluded that 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. Anderson's ideas were not pursued much by particle physicists, because he had neither identified a flaw in the proof of Goldstone theorem, nor discussed explicitly any relativistic model. Instead, they try hard to improve Goldstone theorem into a relativistically invariant theory. The result was that these kind efforts always met with flaws. Finally until 1964, three group of physicists independently published four journal papers which realized relativistic version of Anderson's idea as a combined solution for two distinctive problems on massless particles.

The first paper is on Phys. Rev. Lett. by Englert and Brout in Université Libre at Bruxelles of Belgium [3]. They started with an abelian gauge theory coupled to a complex scalar field which can be decomposed into two independent real scalars, i.e. scalar electrodynamics. They found that if for some reasons, one scalar field corresponding exciting Higgs boson happens to have Bose–Einstein condensate, there emerge two new interaction terms in the model: the first one is a pure gauge boson mass term, the second one is a coupling term where a longitudinal part of gauge field goes over to the other scalar field corresponding exciting Goldstone boson, and vice versa. The second term produces two important effects: one effect is that the field exciting Goldstone boson or Goldstone field can transfer into longitudinal part of gauge field, since they couple to each other. This explains the Anderson's idea that the two massless particle problems cancel each other, since the Goldstone boson field is transferred into the longitudinal component of the gauge boson. Originally, like the photon field, massless gauge field has no longitudinal component; now it receives the longitudinal component transferred from Goldstone boson field and changes into a massive gauge particle. This is the famous Higgs mechanism (now change to call BEH mechanism) which is the kernel part of Nobel Prize in physics 2013. Particle physicists commonly say that gauge field has "eaten up" Goldstone boson to gain mass. In fact, for spontaneously gauge symmetry breaking triggered by spontaneous gauge particle mass generation, at one hand to gain mass for gauge particle needs a longitudinal degree of freedom which is not possessed in original massless situation. On the other hand spontaneous breaking of gauge symmetry produces a redundant massless degree of freedom, they are just complimentary and the second term just provides the coupling to push two degree of freedoms transfer into each other. Another effect of the second term is that it can improve the ultraviolet behavior of the gauge particle propagator by cancelling some bad contribution from the first pure gauge boson mass term. This improvement is the key for the renormalizability of the theory, although at that time, physicists do not know how to check the renormalization property of the theory at all. The pity result is that Englert and Brout focused their studies on the Higgs mechanism, and ignore to discuss the detail behavior of another scalar field that excite Higgs boson. This is one important reason that the nomenclature of this famous particle does not have the names of Englert and Brout.

The second paper is on Phys. Lett. [4] by Higgs who pointed out the flaw of Goldstone theorem which set up the symmetry basis for the origin of the gauge particle mass. In a following paper on Phys. Rev. Lett. [5], he studied the same model as Englert and Brout and explicitly wrote down a redefined gauge field which has eaten up the Goldstone boson and gain mass. More importantly, he gave the equation of motion for the scalar field that excites Higgs boson. The fact that Higgs derived an explicit expression for the bare mass of this field has led the particle to the name "Higgs boson". Up to this stage, all necessary constituents are complete: two degree of freedoms of the scalar field, one generates Bose–Einstein condensate at one hand and excites Higgs boson on the other hand; another one as Goldstone boson transfers into the longitudinal part of gauge boson to make it massive. These two degree of freedoms relate intrinsically, since they transform each other by original U(1) gauge symmetry. Although the gauge symmetry now is broken, the connection of them still implicitly exists. Due to this reason, some particle physicists like to mention the phrase of "the symmetry is hidden", rather than the standard "the symmetry is spontaneously broken". It is worth to mention that, the manuscript of the second paper of Higgs was firstly submitted to Phys. Lett. After rejection by the editor, he resubmitted it to Phys. Rev. Lett. and got published due to the encouragement and support of Nambu who was the referee of the paper.

At last in 1964, Guralnik, Hagen and Kibble published their paper on Phys. Rev. Lett. [6], which discussed essentially the same model as the one by Englert and Brout and by Higgs. They showed carefully and in detail how Goldstone's theorem is violated and reached the same conclusions as previous authors. Furthermore, two 19-year old undergraduates, Migdal and Polyakov, did the similar work [7], but they had to struggle for about a year to get permission to submit their paper to a journal, since the leading scientists of the time in the Soviet Union did not support their work.

In later years, physicists made more careful discussions on relevant theories. In 1967 Steven Weinberg finally tied the pieces together and built up the theory of electroweak unification. In 1971,'t Hooft further proved that gauge theory with spontaneous symmetry breaking is renormalizable which sets the solid foundation of the whole theory. In this theory of electroweak unification, the scalar field not only spontaneously breaks the gauge symmetry and generates mass for gauge particles mediating weak interaction, but also marvelously takes up the role of generating masses for all quarks and leptons. The scalar field then is responsible for generating masses of all elementary particles and becomes the key of the origin of mass. The theory of electroweak unification in combined with the later developed quantum chromodynamics for strong interaction become the present day standard model of particle physics.

Since its foundation in 1970s, until now, standard model experienced more and more precision checks by various experiments. As the last discovered particle in the standard model, Higgs boson is the excitation of the fundamental scalar field which directly connects masses of all elementary particles. It has extremely special role among all elementary particles and got the nick name of "God particle". Unfortunately, the mass of the Higgs boson is a free parameter in standard model and its couplings to other particles are very weak, which makes the experiments searching it very difficult. That is why physicists spent so much time to finally discover it. It is worth mentioning that, many Chinese physicists joined in the ATLAS and CMS experiments and made their own contributions to the search of Higgs particle and other frontier researches of particle physics. Now particle physicists around world are continuing works on Higgs boson to investigate its properties more precisely and deeply. Chinese particle and accelerator physicists are actively investigating the possibility of building a huge "Higgs factory" in China. Physicists hope to check standard model more carefully and strive hard to find new physics phenomena beyond standard model.

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