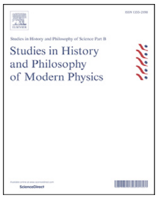
Studies in History and Philosophy of Modern Physics 62 (2018) 36–44

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

journal homepage: www.elsevier.com/locate/shpsb



Beyond the hypothesis: Theory's role in the genesis, opposition, and pursuit of the Higgs boson

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ARTICLE INFO

Article history:
Received 23 September 2016
Received in revised form
12 May 2017
Accepted 24 May 2017
Available online 8 June 2017

Keywords:
Higgs boson
Standard model
Theoretical particle physics
Scientific discovery

ABSTRACT

The centrally recognized theoretical achievement that enabled the Higgs boson discovery in 2012 was the hypothesis of its existence, made by Peter Higgs in 1964. Nevertheless, there is a significant body of comparably important theoretical work prior to and after the Higgs boson hypothesis. In this article we present an additional perspective of how crucial theory work was to the genesis of the Higgs boson hypothesis, especially emphasizing its roots in Landau's theory of phase transitions and subsequent theoretical work on superconductivity. A detailed description is then given of the opposition to the Higgs boson hypothesis by many researchers, giving evidence to its speculative nature. And finally, it is discussed the importance of theory work in the decades after the hypothesis in order to make possible the experimental discovery of the Higgs boson.

1. Introduction

The Higgs boson was postulated in 1964 by the theorist Peter Higgs (Higgs, 1964a) and then discovered in 2012 by experimentalists after a multi-decade herculean construction project at CERN to find it (Aad et al., 2012; Chatrchyan et al, 2012). The works of Higgs (Higgs, 1964a,b), along with Brout and Englert's simultaneous work (Englert & Brout, 1964), are widely recognized as the central theoretical achievements in the Higgs boson discovery narrative. This is appropriate, but there are comparably important works prior to the Higgs boson hypothesis and after the Higgs boson hypothesis that enabled the discovery.

The primary goal of this paper is to elucidate the contributions of the theoretical physics community to the Higgs boson hypothesis and to its later discovery. Of course, it goes without saying that experimental work was crucial, not just for the discovery data announced in 2012, but also through the knowledge attained in prior experiments and the skillful design of the discovery detectors Atlas and CMS. Instead, this article focuses on providing a somewhat comprehensive view of the theoretical physics contributions. It is hoped that this contribution adds to and complements the many other historical analyses of the Higgs boson (Borrelli, 2015; Brown, Brout, Cao, Higgs, & Nambu, 1997; Close, 2013; Karaca, 2013; Massimi & Bhimji, 2015). In particular, we give a more complete picture of the opposition to the Higgs hypothesis in the theory community, showing how that opposition was connected to the early understanding of phase transitions in the condensed matter community, and we give a more complete picture of the work subsequent to the Higgs boson hypothesis that was crucial for the discovery of the Higgs boson.

The discussion begins with an historical discussion of particle physics relevant for the context in which the Higgs boson hypothesis was formulated (sec. 2). After that a more focused discussion is given to theoretical physics efforts in the pre-hypothesis decades that gave rise directly to the Higgs boson hypothesis (sec. 3). The Higgs boson hypothesis was met with both acceptance and loathing by the community. The antipathy by which it was held by some is described in sec. 4, which is intended to impart to the reader how uncertain and speculative the Higgs boson was viewed by many even up to the moment its discovery was announced. To discover the Higgs boson in experimental data required a tremendous amount of theoretical work, not just in making the hypothesis, but also after the hypothesis was initially articulated. The diverse and extensive theoretical physics efforts required for success of the entire endeavor is discussed in sec. 5. Conclusions are summarized in the final section.

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http://dx.doi.org/10.1016/j.shpsb.2017.05.004
1355-2198/

2. Context of the Higgs hypothesis

The known universe of visible matter, including our bodies, the earth, the sun, and every physical phenomenon we have ever seen in a laboratory is accounted for by the Standard Model (SM) of elementary particle physics. This theory says that there exist electrons, neutrinos, up-quarks and down-quarks as matter particles, which interact (i.e., experience forces) by the exchange of photons (electricity and magnetism), $W^\pm$ and Z bosons (the "weak interaction") and gluons (the "strong interaction"). In addition to these particles there exists a second and a third family of matter particles that are exactly the same as the electrons, neutrinos, up-quarks and down-quarks in every way, except their masses are different. These particles include the charm, strange, top and bottom quarks, and the muon and tau leptons and their corresponding neutrinos.

The top quark was the last of these elementary particles to be discovered. Fermilab outside of Chicago took the honors of discovery in 1995 (Abachi et al, 1995; Abe et al, 1995), and to this day it is the heaviest known elementary particle with mass of approximately 173 GeV. It is near the mass of a Tungsten atom, which is not elementary and is made up of more than 550 quarks bound together in its constituent protons and neutrons.

How did the top quark achieve such a high mass compared to, for example, the electron, which is more than 340,000 times lighter? How does the top quark attain mass at all? For that matter, how do any of the elementary particles attain mass? The answer that we know today is that a scalar boson exists – the Higgs boson – that has a background field value everywhere in space, and that other particles couple to this "vacuum expectation value" of the field (Wells, 2009). The mass of a particle, such as the top quark or the electron, is directly proportional to its interaction strength with the vacuum expectation value. The top quark couples the strongest and therefore has the heaviest elementary particle mass (mass of top quark is 173 GeV), then the Z boson (mass 91 GeV), then $W^\pm$ (mass 80 GeV), etc. down to the mass of the electron (mass 0.0005 GeV), and further down to the neutrinos below 10^{-10} GeV.

The question of how elementary particles get their mass had no good leads for quite some time even after the basics of forces and particles were surmised. For example, Glashow's 1961 study (Glashow, 1961), which is widely credited to be the first paper to articulate how the elementary particles and forces come together in a unified way, was cited in the 1979 Nobel Prize (The Nobel Foundation, 1979) as the earliest paper of the "theory of the unified weak and electromagnetic interaction between elementary particles" (i.e., electroweak sector of the Standard Model). In that work the author did not have a good explanation for how masses come about. Instead he allowed the theory to break symmetries (i.e., retain only a "partial symmetry"). For example, the author states that "the part of the Lagrange function bilinear in the field variables which produces masses of the elementary particles need not be invariant under a partial-symmetry," and that "the masses of [the gauge bosons] are as yet arbitrary" (Glashow, 1961). In other words, symmetry breaking masses are merely put in by hand. This idea would have broken down as a useful explanation in time once sufficient experimental precision was obtained, but that precision was not available until the 1980s-1990s well after the Higgs hypothesis was formulated.

It was not until the later work of Weinberg in 1967 (Weinberg, 1967) and Salam in 1968 (Salam, 1968) that connection was made between the theory of matter and forces with the spontaneous symmetry breaking insights of Higgs (Higgs, 1964a,b; Higgs, 1966) and others (Englert & Brout, 1964; Guralnik, Hagen, & Kibble, 1964; Kibble, 1967). Weinberg realized that a Higgs boson scalar field with a background vacuum expectation value could give mass to all the elementary particles. In Weinberg's original paper he made this explicit by constructing a lagrangian that included all the matter particles

> "plus a spin-zero doublet $\varphi = (\varphi^0\ \varphi^-)$ [Higgs boson] whose vacuum expectation value will break $\overrightarrow{T}$ $[SU(2)_L$ gauge group generators] and Y [hypercharge gauge group generator] and give the electron its mass" (Weinberg, 1967).

The Glashow-Weinberg-Salam (GWS) theory, as it came to be known, was now before the world to consider. Except for some important details, which also required deep theoretical insight, especially with regards to the strong interaction (Wilczek, 1982, 2003), the structure of the SM was contained in these papers. In particular the hypothesis of a Higgs boson giving mass to all the elementary particles was clearly articulated. It was not immediately known if the hypothesis was correct. Indeed, it took over four decades to know that. And during that time there were many skeptics. Let us consider the challenges the scientific community had to this hypothesis and through this gain an understanding of how provocative the speculation was and how important the discovery of the Higgs boson has been in the history of science. But first, let us delve into the pre-Higgs world that set the groundwork for the hypothesis of the Higgs boson that was to come later.

3. Genesis of the Higgs hypothesis

Landau's seminal 1937 paper (Landau, 1937) should be considered the first identifiable pre-cursor theory to the Higgs boson. Landau was in search of a way to characterize phase transitions in matter in a systematic way using thermodynamic potentials. He realized that the order parameter of a second-order phase transition – the quantity that changes when a state goes from one phase to the next (e.g., total magnetization when transitioning to a ferromagnetic) – is very small near the phase transition boundary. This calls out for a Taylor series expansion of the free energy near the transition point. For example, the "Landau potential" can be written (Landau & Lifshitz, 1980) as

$$\Phi(P,T,\eta) = \Phi_0(P,T) + A(P,T)\eta^2 + B(P,T)\eta^4 \tag{1}$$

where P is the pressure, T the temperature, η the order parameter, and A and B are thermodynamics functions of pressure and temperature. For fixed pressure the Landau potential may take the approximate form

$$\Phi(T) = \frac{a}{2}(T - T_c)\,\eta^2 + \frac{b}{4}\eta^4 \tag{2}$$

where a, b and T_c are positive constants. Minimizing this free energy leads to the solution $\eta(T) = 0$ when $T > T_c$ and $\eta(T) = a(T_c - T)/b$ when $T < T_c$. Thus, there is a critical temperature T_c below which the phase transition has taken place. At zero temperature the order parameter has the value $\eta_0 = aT_c/b$.

The Landau free energy has been extremely useful in the history of physics, and played a central role in the development of many types of phase transitions witnessed. For example, the theory of superconductivity was elucidated by the application of Landau's theory of phase transitions to the superconducting state (Ginzburg & Landau, 1950). The order parameter η in that case is the number of superconducting charge carriers in the material. In ferromagnetism the order parameter is the magnetization of the material. At high temperatures the magnetic dipoles in a substance are not aligned and thermal fluctuations do not allow any non-zero values of the magnetization, but as the temperature drops, and thermal fluctuations become less destructive to the formation of a more