What is the Ontological Status of the Higgs Boson?

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The International School of Subnuclear Physics, Erice, Italy, 29th June, 2013

I. Introduction

The observation of a vanilla boson:

“Vanilla” suggests:

The scientifically creative **discovery** can be reasonably taken to be made by theoreticians in the 1960s, yet

confirmed by the LHC data recently

The “massive” (?) scalar boson

Goldstone: Nuovo Cimento 19:154(1961)

Eglert & Brout (EB):

PRL 13:321 (1964)

Higgs: PRL 13:508 (1964)

Guralnik, Hagen & Kibble (GHK):

PRL 13:585 (1964)

Higgs: PR 145:1156 (1966)

Kibble: PR 155:1554 (1967)

Weinberg: PRL 19:1264 (1967)

Julian Schwinger on fields and particles

"The observed physical world is the outcome of the dynamical play among underlying primary fields, and the relationship between these fundamental fields and the phenomenological particles can be comparatively remote, in contrast to the immediate correlation that is commonly assumed." (PR 125:397;1962)

So our attention should be shifted from the boson itself to **the incorporation of the scalar field into the structure of the electroweak theory.**

It is **the incorporation** wherein lies the scientific creativity.

The incorporation was the result of three lines of development:

(1) Broken symmetry manifested in a degenerate vacuum;

(2) scalar field theory with a broken symmetry solution; and

(1) the mechanism for gauge boson to be massive.

II. Broken symmetry and degenerate vacuum

- Pierre Curie: “When effects show a certain asymmetry, this asymmetry must be found in the auses which give rise to them.” (1894)
- Luigi Radiati rejected Curie’s idea as logically incorrect ad in ovious contrdiction with empirical evidence, and asserted that spontaneous breakdown of symmetry explicitly contradicts it.” (1987)
- Lev Landau: “The solutions of th equtions will possess lower symmetry than the equations themselves, “ but “this is more a program than a theory. The program is magnificent, but it must still be carried out. I believe this will be the main task of theoretical physics.”

Heisenberg

The degenerate vacuum: (*Proc. of Int. Con. on HEP*, 119;1958)

The degenerate vacuum “is the basis for the symmetry breaking.” (*Proc. of Int. Con..on HEP,* 1960).

Heisenberg’s idea of a degenerate vacuum was influential; but he never reached a satisfactory understanding of the origin, mechanism and physical consequences of broken symmetry

Nambu's physical realization of Heisenberg's idea

- The vacuum is the condensate of the charged pairs of fermion-antifermion, not gauge invariant, thus degenerate.
- The existence of the massless bound states is the logical consequence of gauge invariance.
- His model is not renormalizable.

PR 117:648 (1960); PR 122:345(1961)

III. Scalar field theory with a broken symmetry solution

Goldstone's physical realization of Heisenberg's idea:

- Renormalizable model (1961).
- Fundamental scalar boson field.
- The self interaction of the boson field + certain conditions →
  - broken symmetry solution and degenerate vacuum, and
  - Massless boson.

Goldstone theorem

A broken symmetry solution to a theory with a continuous symmetry (in terms of conserved current and conserved charge) entails a massless particle, the Goldstone boson.

Key to the proof: Lorentz invariance.

J. Goldstone, A. Salam and S. Weinberg, PR 127:965 (1962).

IV. Mechanisms for gauge bosons to acquire mass

Schwinger's strategy for gauge bosons to acquire mass (1962):

- "The general requirement of gauge invariance no longer seems to dispose of this essentially dynamic question."

- When the gauge field is strongly coupled with a symmetry current, it might not be massless if its vacuum polarization tensor possesses a ***pole*** at light-like momenta

Schwinger and broken symmetry

- Both **the pole** itself, which is connected with the nonvanishing vacuum expectation value of a field and **its consequence** of giving photon a mass, were closely related with broken symmetry although the notion was not invoked.

- **The scalar nature of the pole makes it open to the interpretation that it is a consequence of primary scalar fields' vacuum expectation value**.

Anderson's connecting Schwinger to Goldstone (PR 130:439; 1963)

Plasmon **vindicates** Schwinger's insight:

Nambu's massless collective mode is converted into massive plasmon by interacting with the electromagnetic field.

"The **only mechanism** for giving the gauge field mass is the degenerate vacuum type of theory."

"The Goldstone zero-mass difficulty is not a seious one, because we can probably **cancel** it off against an equal Yang-Mill zero mass problem."

Anderson: ideas and real physics

Ideas: the first to associate Schwinger’s mechanism with broken symmetry and the Goldstone theorem.

Physics: the connection was tenuous:

-- The plasmon case connects Schwinger’s strategy of gauge field acquiring mass through interacting with other field to the broken symmetry;

-- but the physics for the symmetry-breaking came from **Nambu’s bound states rather than Goldstone’s primary scalar field.**

-- His **nonrelativistic** examples did not meet the Goldstone theorem’s requirement of Lorentz invariance, and thus **cannot be used to evade the logical force of the theorem**

F. Englert and R. Brout (1964)

- They directly interpreted **the Goldstone boson**, in lowest order perturbative calculation of the vacuum polarization loop for the gauge field, as the physical base for **Schwinger's pole**, which gives mass to the gauge boson.
- It is a **real breakthrough in physics** in terms of **understanding the symbiotic nature** of Goldstone's scalar system and the gauge system

F. Englert and R. Brout (1964)

Wrong claim: “the symmetry is broken through the gauge fields themselves”,

while actually it is broken through the self-interactions of the scalar field.

Peter Higgs (1964)

His understanding of the **symbiotic nature** of the gauge system and Goldstone’s scalar system, **within Schwinger’s framework** of field-current coupling:

“as a consequence of this **coupling**, the spin one quanta of some of the gauge fields **acquire mass**; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons **when the coupling tends to zero**.”

Peter Higgs: Induced symmetry breakdown (1966)

When the scalar system, whose symmetry is broken, is (Yukawa-) coupled with a spinor system which contains **no additional mechanism for symmetry breaking**, the symmetry breaking in the scalar system ***breaks*** the symmetry of the spinor system

The Yukawa coupling, which induced the symmetry breaking in the spinor system, is **the mechanism for “massless” fermions to “obtain” mass.**

Peter Higgs and the hierarchical structure of the EW system

- At the most fundamental level, the degenerate vacuum is constituted by the self-interaction of the scalar system **alone**.
- The scalar system is in a symbiotic relation with the system of gauge fields through the gauge coupling, which fixes the EW dynamics, but contributes nothing to the constitution of the degenerate vacuum.
- The primary fermion system lives in the world built up from the degenerate vacuum as a consequence of its Yukawa coupling with the scalar system.

G. S. Guralnik, C. R. Hagen and T. W. B. Kibble (1964)

Lorentz invariance is the key to the Goldstone theorem. So,

in the Coulomb gauge, no Goldstone bosons;

in the Lorentz gauge, Goldstone bosons are logical consequence of broken symmetry, but are physically irrelevant: they are just the non-physical gauge degrees of freedom.

G. S. Guralnik, C. R. Hagen and T. W. B. Kibble (1964): A Problem

When the scalar system's symmetry is broken, in the **Coulomb gauge formulation,** the massless excitations must occur, as Goldstone observed, this "is the new way the original symmetry expresses itself."

These cannot be the Goldstone boson.

But then,

what are they?

V. The ontological status of the massive boson

Last year this time this place, Peter Higgs reminded me that, at the 1992 SLAC conference on the history of particle physics, I asked him:

What is the ontological status of the massive boson?

The Schwinger-Kibble sysem

A non-decomposable single physical entity: the symbiotic structure of the scalar-vector field complex described by the analytically separable mathematical structure.

But,

no mathematical separation of this complex would have any physical meaning.

What God has joined together, let no man put asunder.

Hermann Minkowski declared (1908):

“Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.”

Similarly, we may say:

Goldstone’s scalar system and Glashow’s gauge system are doomed to fade away into mere shadows, and only the symbiotic scalar-vector field complex is the non-decomposable independent physical entity in the EW part of the physical world, aside from the fermion system.

Conceptual difference within the scalar-vector field-complex

Conceptually, the spatial is different from the temporal, even though the only reality is spacetime.

Similarly, the scalar aspect (the massive scalar boson) is different from the vector aspect (the massive vector bosons) of the scalar-vector field-complex, although they are just different manifestations of a single physical entity, having no separate existence.

The conceptual structure of the complex.

The scalar field: (1) its self-coupling is the mechanism for symmetry breaking; (2) its gauge coupling with the gauge fields underlies the physical constitution of the massive gauge bosons; and (3) its Yukawa coupling underlies the constitution of massive fermions, which is responsible for flavor physics, CKM matrix and CP violation, and the weak scale.

The gauge fields: (1) their gauge coupling dictates the EW interactions; but (2) the gauge coupling contributes nothing to symmetry breaking and other parameters.

The fermion fields live on the degenerate vacuum through the Yukawa coupling, and thus is less fundamental.

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The massive boson is the quantum excitation of the scalar moment of the scalar-vector field complex, which can be observationally registered when it is in interactions with other field quanta in the EW part of the physical world, but is physically tightly connected with the other excitations of the whole complex, including the gauge bosons.

Implications of the symbiotic view of the field complex

What God has joined together, let no man put asunder. One example:

If one wishes to take the Higgs boson out of its EW context, e.g., to associate it with the inflaton or dark energy, he has to take the whole package and examine the effects of the W-bosons and the Z-boson in the new context.

This will put very severe constraints on the pursuit.

But it will also give great predictive power to the pursuit.