

History of Electroweak Symmetry Breaking

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Outline

Development of the **electroweak theory**, which incorporates the idea of the **Higgs boson**

— as I saw it from my standpoint in Imperial College

- Physics post WW2
- The aim of electroweak unification
- Obstacles to unification
- Higgs mechanism
- The electroweak theory
- Later developments
- Discovery of the Higgs boson

Imperial College in 1959

- IC theoretical physics group was founded in 1956 by **Abdus Salam**
 - he already had a top-rank international reputation for his work on renormalization
 - in 1959 he became the youngest FRS at age 33.
- I joined also in 1959
- It was very lively, with numerous visitors:
 - Murray Gell-Mann,
 - Stanley Mandelstam,
 - Steven Weinberg, ...



Physics in the 1950s

- After QED's success, people searched for field theories of other interaction (or even better, a unified theory of all of them)
 - also ***gauge theories***?
- Most interest in ***strong interactions*** — there were candidate field theories (e.g. **Yukawa**'s meson theory), but no one could calculate with them because perturbation theory doesn't work if the 'small' parameter is ~ 1 .
- Many people abandoned field theory for ***S-matrix theory***
 - dispersion relations, Regge poles, ...
- In a few places, the flag of ***field theory*** was kept flying
 - Harvard, Imperial College, ...
 - but perhaps weak interactions were more promising?

Symmetries

- Experimenters had found many new particles
 - to bring order to this zoo, we sought (approximate) symmetries
- ***Isospin*** (Heisenberg, Kemmer)
 - SU(2), broken by electromagnetism
 - now seen as a symmetry of two lightest quarks (u , d)
- ***Eightfold Way*** (Gell-Mann, Ne'eman)
 - SU(3) symmetry
 - now seen as symmetry of *three* lightest quarks (u , d , s)
 - broken by whatever gives different mass to quarks of different generations
- These are approximate, ***broken*** symmetries
 - spontaneously broken?

Yang-Mills theory

- First example of a gauge theory beyond QED was the **Yang-Mills** theory (1954), a gauge theory of isospin $SU(2)$ symmetry.
 - same theory also proposed by Salam's student **Ronald Shaw**, but unpublished except as a Cambridge University PhD thesis
 - ultimately not correct theory of strong interactions, but the foundation for all later gauge theories.
- Because isospin is an approximate symmetry, this symmetry must be broken in some way
 - but adding symmetry-breaking terms destroys many of the nice properties of gauge theories
 - could the symmetry be spontaneously broken?

Goal of Unification

- Because of the difficulty of calculating with a strong-interaction theory, interest began to shift to weak interactions
 - especially after **V–A theory**
 - **Marshak & Sudarshan** (1958), **Feynman & Gell-Mann** (1958)
 - they could proceed via exchange of spin-1 W^\pm bosons
- First suggestion of a **gauge** theory of weak interactions mediated by W^+ and W^- was by **Schwinger** (1957)
 - **could there be a *unified* theory of weak and electromagnetic?**
- If so, it must be broken, because weak bosons
 - are massive (short range)
 - violate parity

Solution of Parity Problem

- **Glashow** (1961) proposed a model with symmetry group $SU(2) \times U(1)$ and a fourth gauge boson Z^0 , showing that the parity problem could be solved by a mixing between the two neutral gauge bosons.
- **Salam and Ward** (1964), unaware of Glashow's work, proposed a similar model, also based on $SU(2) \times U(1)$
 - Salam was convinced that a unified theory must be a gauge theory
- **But** in all these models symmetry breaking, giving the W bosons masses, had to be inserted by hand
 - spin-1 bosons with explicit mass were known to be **non-renormalizable**.
- **Big question: could this be a *spontaneously broken symmetry*?**

Spontaneous Symmetry Breaking

- Spontaneous breaking of gauge symmetry, giving mass to the plasmon, was known in super-conductivity. **Nambu** (1960) suggested a similar mechanism could give masses to elementary particles.

- **Nambu and Jona-Lasinio** (1961) proposed a specific model

$$\mathcal{L}_{\text{int}} = g[(\bar{\psi}\psi)^2 - (\bar{\psi}\gamma_5\psi)^2] \quad \psi \rightarrow e^{i\alpha}\psi \quad \text{exact, but chiral symmetry}$$
$$\psi \rightarrow e^{\alpha\gamma_5}\psi \quad \text{spontaneously broken by } \langle \bar{\psi}\psi \rangle \neq 0 \Rightarrow m_\psi \neq 0$$

- Model has a **massless pseudoscalar**, identified with pion
 - N & J-L suggested chiral symmetry was not quite exact even before spontaneous symmetry breaking, hence pion has a small mass

Spontaneous Symmetry Breaking

- Particle physics exhibited many approximate symmetries
 - natural to ask: could they be ***spontaneously*** broken?
- Spontaneous symmetry breaking
 - when the ground state or vacuum state does not share the symmetry of the underlying theory
 - ubiquitous in condensed matter physics
- Often there is a high-temperature symmetric phase, and a critical temperature below which the symmetry is spontaneously broken
 - **crystallization** of a liquid breaks rotational symmetry
 - so does Curie-point transition in a **ferromagnet**
 - gauge symmetry is broken in a **superconductor**
- **But** there was a big problem — the **Goldstone theorem**.

Nambu-Goldstone bosons

- Spontaneous breaking of a continuous symmetry \Rightarrow existence of massless spin-0 **Nambu-Goldstone bosons**.

- e.g. **Goldstone model** $\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi - \mathcal{V}$

$$\mathcal{V} = \frac{1}{2} \lambda (\phi^* \phi - \frac{1}{2} \eta^2)^2$$

— vacuum breaks symmetry:

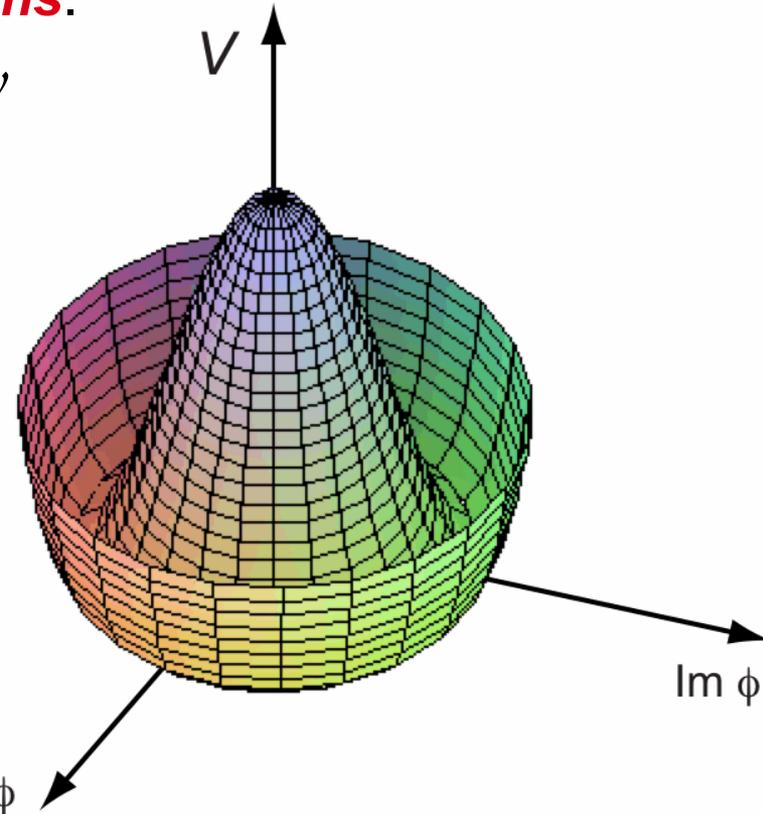
$$\langle 0 | \phi | 0 \rangle = \frac{\eta}{\sqrt{2}} e^{i\alpha} \quad \text{— choose } \alpha = 0$$

$$\text{and set } \phi = \frac{1}{\sqrt{2}} (\eta + \varphi_1 + i\varphi_2)$$

$$\mathcal{V} = \frac{1}{2} \lambda \eta^2 \varphi_1^2 + \text{cubic and quartic terms}$$

$$\text{So } m_1^2 = \lambda \eta^2, \quad m_2^2 = 0 \quad (\text{Goldstone boson})$$

- This was believed **inevitable** in a relativistic theory



Goldstone theorem

- Proof (**Goldstone, Salam & Weinberg 1962**): assume
 1. symmetry corresponds to conserved current: $\partial_\mu j^\mu = 0$
$$\delta\phi(0) = i\varepsilon \int d^3\mathbf{x} [\phi(0), j^0(0, \mathbf{x})]$$
 2. there is some field ϕ whose vev is not invariant: $\langle 0 | \delta\phi | 0 \rangle \neq 0$, thus breaking the symmetry
- Now $\partial_\mu j^\mu = 0$ would seem to imply $\frac{dQ}{dt} = 0$, $Q = \int d^3\mathbf{x} j^0(x)$
- The broken symmetry condition is then $i\langle 0 | [\phi(0), Q] | 0 \rangle = \eta \neq 0$
- But if Q is time-independent, the only intermediate states that can contribute are **zero-energy** states which can only appear if there are **massless particles**.

Impasse

- In a *relativistic* theory, there seemed no escape
 - spontaneous symmetry breaking \Rightarrow zero-mass spin-0 bosons
 - no such bosons known \Rightarrow no spontaneous symmetry breaking
 - models with explicit symmetry breaking were clearly non-renormalizable, giving infinite results
- **Weinberg** commented:
 - ‘*Nothing will come of nothing; speak again!*’ (King Lear)
- In 1964 **Gerald Guralnik** arrived at Imperial College as a postdoc
 - a student of **Walter Gilbert**, who had been a student of **Salam**
 - he had been studying this problem, and already published some ideas about it
 - we began collaborating, with another US visitor, **Richard Hagen**
 - we (and others) found the solution.

Higgs mechanism

- The argument **fails** in the case of a ***gauge theory***
 - Englert & Brout (1964), Higgs (1964), Guralnik, Hagen & TK (1964)
- Higgs model (gauged Goldstone model):

$$\mathcal{L} = D_\mu \phi^* D^\mu \phi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \mathcal{V}$$

$$D_\mu \phi = \partial_\mu \phi + ieA_\mu \phi \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad \mathcal{V} = \frac{1}{2} \lambda (\phi^* \phi - \frac{1}{2} \eta^2)^2$$

Again set $\phi = \frac{1}{\sqrt{2}} (\eta + \varphi_1 + i\varphi_2)$ $B_\mu = A_\mu + \frac{1}{e\eta} \partial_\mu \varphi_2$ $F_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$

$$\mathcal{L} = \frac{1}{2} \partial_\mu \varphi_1 \partial^\mu \varphi_1 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \lambda \eta^2 \varphi_1^2 + \frac{1}{2} e^2 \eta^2 B_\mu B^\mu + \text{cubic terms ...}$$

Thus the massless gauge and Goldstone bosons have combined to give a massive gauge boson.

But: there is more to it.

Gauge modes

- Field equations

$$\partial_\mu F^{\mu\nu} = j^\nu = -e^2 \eta^2 B^\nu + \dots$$

are also satisfied for **any** φ_2 so long as $B_\mu = A_\mu + \frac{1}{e\eta} \partial_\mu \varphi_2 = 0$
(gauge invariance of original model)

- To tie down not only B_μ but also A_μ and φ_2 , we need to impose a gauge condition:
- With $B_\mu = 0$ the **Coulomb gauge** condition $\partial^k A_k = 0$ requires $\varphi_2 = 0$ (or constant)
- However the **Lorentz gauge** condition $\partial^\mu A_\mu = 0$ only requires that φ_2 satisfy $\partial^\mu \partial_\mu \varphi_2 = 0$
 - in this manifestly covariant gauge, the Goldstone theorem **does** apply, but the Goldstone boson is a pure gauge mode.

How is the Goldstone theorem avoided?

- Proof assumed that $\partial_\mu j^\mu = 0$ implied $\frac{dQ}{dt} = 0$, $Q = \int d^3\mathbf{x} j^0(x)$
- But this is only true if we can drop a surface integral at infinity:

$$\frac{dQ}{dt} = \int d^3\mathbf{x} \partial_0 j^0(x) = -\int d^3\mathbf{x} \partial_k j^k(x) = -\int dS_k j^k(x)$$

- This is permissible in a manifestly Lorentz-invariant theory (e.g. Lorentz-gauge QED), because commutators vanish outside the light cone — but not in Coulomb-gauge QED
- When the symmetry is spontaneously broken, the integral $Q = \int d^3\mathbf{x} j^0(x)$ **does not exist** as a self-adjoint operator, e.g. in Higgs model $Q = -e^2\eta^2 \int d^3\mathbf{x} B^0(x) + \dots$ diverges. [GHK]
- Distinct degenerate vacua belong to distinct orthogonal Hilbert spaces carrying **unitarily inequivalent representations** of the commutation relations — **a defining property of spontaneous symmetry breaking**

Electroweak unification

- The three papers on the Higgs mechanism attracted very little attention at the time.
- By 1964 both the mechanism and Glashow's (and Salam and Ward's) $SU(2) \times U(1)$ model were in place, but it still took three more years to put the two together.
- I did further work on the detailed application of the mechanism to symmetries beyond $U(1)$ (1967) — how symmetry breaking pattern determines numbers of massive and massless particles. This work helped, I believe, to renew Salam's interest.
- Unified model of weak and electromagnetic interactions of leptons proposed by Weinberg (1967)
— essentially the same model was presented independently by Salam in lectures at IC in autumn of 1967 and published in a Nobel symposium in 1968 — he called it the *electroweak theory*.

Later developments

- Salam and Weinberg speculated that their theory was **renormalizable**. This was proved by **Gerard 't Hooft** in 1971 — a *tour de force* using methods of his supervisor, **Tini Veltman**, especially **Schoonship**.
- In 1973 the key prediction of the theory, the existence of neutral current interactions — those mediated by Z^0 — was confirmed at CERN.
- This led to the **Nobel Prize** for **Glashow, Salam & Weinberg** in 1979 — but **Ward** was left out (because of the ‘rule of three’?) — **'t Hooft** and **Veltman** gained their Nobel Prizes in 1999.
- In 1983 the W and Z particles were discovered at CERN.
- In the 1970s and 1980s the gauge theory of strong interactions, **quantum chromodynamics (QCD)** was developed, a gauged $SU(3)$ — so we now have the **$SU(3) \times SU(2) \times U(1)$ standard model**.

The Higgs boson

- In 1964, the *Higgs boson* had been a very minor and uninteresting feature of the mechanism
 - the key point was the *Higgs mechanism* for giving the gauge bosons masses and escaping the massless Goldstone bosons.
- But after 1983 it started to assume a key importance as the *only missing piece* (bar the top quark) of the standard-model jigsaw. The standard model worked so well that the boson (or something else doing the same job) more or less **had** to be present.
- Two great collaborations, *Atlas* and *CMS* have over a 20-year period designed, built and operated marvellous detectors.
- Result: *discovery of the Higgs in 2012*
 - and Nobel Prizes for *Englert* and *Higgs* in 2013

I am deeply indebted to:



Abdus Salam



Gerald Guralnik