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Genesis of Electroweak Unification

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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

Imperial College in 1959

- In 1959 I joined IC theoretical physics group founded in 1956 by Abdus Salam

- 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***?

- Yang & Mills 1954 – SU(2) gauge theory of isospin (also Shaw, student of Salam's)

- Initial interest in strong interactions
  — but calculations impossible

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 (1957), 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) x 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) x 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***?
  — suggested by Nambu by analogy with superconductivity

- But there was a big problem — the **Goldstone theorem**.

Nambu-Goldstone bosons

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

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

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

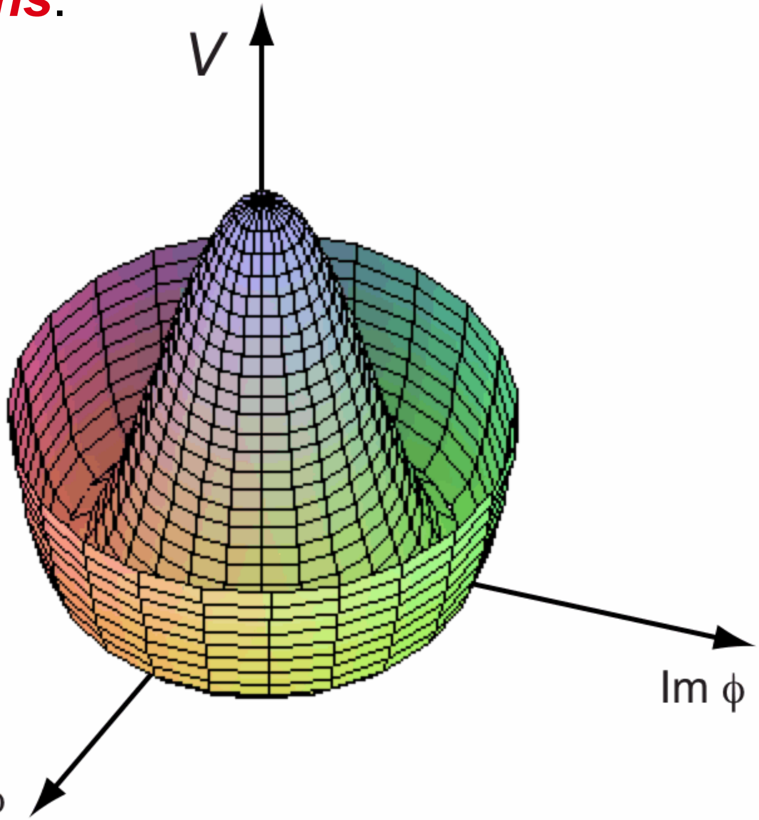
— vacuum breaks symmetry:

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

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

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

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



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

Goldstone theorem

- Proof (Goldstone, Salam & Weinberg 1962): assume

  1. symmetry corresponds to conserved current: $\partial_\mu j^\mu = 0$

  $$\delta\phi(0) = i\varepsilon \int d^3\boldsymbol{x}\,[\phi(0), j^0(0,\boldsymbol{x})]$$

  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 $\dfrac{dQ}{dt} = 0, \quad Q = \int d^3\boldsymbol{x}\, j^0(x)$

- The broken symmetry condition is then $i\langle 0|\left[\phi(0), Q\right]|0\rangle = \eta \neq 0$

- 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 ⇒ zero-mass spin-0 bosons
  - — no such bosons known ⇒ 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):

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

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

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

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

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

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 $\dfrac{dQ}{dt} = 0, \quad Q = \int d^3\mathbf{x}\, j^0(x)$
- 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 $Q = -e^2\eta^2 \int d^3\mathbf{x}\, B^0(x) + \cdots$ 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) x 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.
- 1973: existence of neutral current interactions confirmed at CERN.
- 1979: ***Nobel Prizes*** for Glashow, Salam & Weinberg in 1979 — but Ward was left out (because of the ‘rule of three’?)
- 1983: *W* and *Z* particles were discovered at CERN.
- 1999: ***Nobel Prizes*** for ’t Hooft and Veltman
- 1970s and 1980s: quantum chromodynamics (QCD) developed — so we now have the SU(3) x SU(2) x U(1) standard model.
- 2012: Higgs boson discovered at CERN
- 2013: ***Nobel Prizes*** for Englert and Higgs

I am deeply indebted to:

Abdus Salam

Gerald Guralnik