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Towards the Higgs boson: symmetry-breaking particles and the origin of mass in early particle physics

Higgs boson ↔ origin of mass/mass "generation"

↓

Higgs mechanism, i.e. spontaneous breakdown of EW-symmetry

SSB and the Higgs mechanism emerged ca. 1961-64, the EW-model even later, but before that the "origin of mass" was already linked to a particle very similar to the Higgs boson:

> a scalar, neutral particle with a nonzero vacuum expectation value breaking the symmetry of a fundamental Lagrangian and giving rise to particle masses

a look back at some early ideas on symmetry and mass generation - focus on:

- importance of verbal statements: innovations are not just formulas!
- collective character of theoretical research: how individual theorists take over, transform and build upon each other's ideas ("whose idea was it?" unclear!)

The structure of this talk: the many paths to symmetry-breaking

1957 Julian Schwinger

1958 Werner Heisenberg

1959-61 Abdus Salam & John Ward

1961 Yoichiro Nambu & Giovanni Jona Lasinio

1961 Jeffrey Goldstone

1962 Marshall Baker & Sheldon Glashow

ca. 1964 "Higgs mechanism"

1967-68 Salam/Weinberg model

The historical context: mass in early particle physics

up to ca. 1935: mass as a primary factor in determining particle properties

"light particles" = e, ν + antiparticles
"heavy particle" = p, n + antiparticles

+ γ "light quantum" with zero mass - a particle?

ca. 1935-1955: cosmic ray "mesons" - intermediate mass, puzzling properties (μ, π, K...) later even "hyperions" (heavier than p) --> mass is no guide anymore!

---> new particles are described by extending older notions, like isospin

- why do interactions have different conservation properties (e.g. isospin)?
- why are particle masses so different?

possible Lagrangians are written down, with masses and symmetries put in by hand to match phenomena

J. Schwinger "A theory of the fundamental interactions" *AP* (1957)

Key idea: observed masses and interactions derive "dynamically" from a highly symmetrical and massless Lagrangian

"We suppose that the various intrinsic degrees of freedom are dynamically exhibited by specific interactions, each with its characteristic symmetry properties, and that the final effect of interactions with successively lower symmetry is to produce a spectrum of physically distinct particles from initially degenerate states" also mass has a "dynamical origin"

what does "dynamical" mean? properties due to higher order corrections - e.g. not all symmetries of the bare Lagrangian are exhibited "dynamically"

how to implement this idea mathematically? only a very sketchy proposal:

Fields: $\Psi_{(1/2)}$: spinor, isospin doublet (n, p)
$\Phi_{(1)}$: pseudoscalar, isospin triplet (π^-, π^0, π^+)
$\Phi_{(0)}$: scalar, isospin singlet (hypothetical σ-meson)

Why the field $\Phi_{(0)}$? "As a field which is scalar under all operations [...] $\Phi_{(0)}$ has a nonvanishing expectation value in the vacuum"

-----> what is this vacuum expectation value good for?

the interaction and mass terms in the Lagrangian are:

$$g\Phi\Psi\Psi,\quad g''\Phi\Phi\Phi\Phi,\quad -m\Phi\Phi,\quad -\mu\Psi\Psi$$

the Lagrangian should be invariant with respect to a chiral transformation T: how?

choose $\Phi_{(0)} - \mu/g$ (VEV!) as physical field, and set $m=0$

----> $g\Phi\Psi\Psi - \mu\Psi\Psi \rightarrow g\Phi\Psi\Psi$ and the Lagrangian is symmetric!

because of the VEV fermion and boson mass terms will emerge "dynamically"

electro-weak interactions: isospin triplet of massless vector bosons (γ Z^+ Z^-)

"we again use the $\Phi_{(0)}$ field to remove three-dimensional internal symmetries and produce mass for the charged [vector bosons Z]"

[NB: the symmetry is a *global* , not a local gauge symmetry]

Schwinger describes the "dynamical" properties as manifestation of an "unknown physical agency" - he gives no mathematical discussion of "dynamical" effects, but the many ideas in his simple model are very influential

spin-offs: Gell-Mann&Levy's σ-model (1960), Skyrme's non-linear theory (1958-9)

1959-1961: Salam&Ward take up Schwinger's model for EW-interaction and add to it local gauge invariance (following Yang&Mills):

- triplet (γ X^+ Y^-): photon + 2 charged vector bosons as EW-gauge bosons
- the σ-field breaks the local gauge symmetry with its VEV....
- .... giving mass to the charged gauge bosons!

all statements are only backed up by discussions at the level of the Lagrangian, but the connection to dynamical mass generation is strongly stated

1958ff.: Heisenberg & co.: how to get asymmetry from symmetry?

symmetric fundamental equations ---> nonperturbative, non-symmetric solutions

fundamental level: massless spinor fields with symmetric, non-linear interaction

phenomenological level: massive particles, nonsymmetric interactions

how do particle fields arise from the fundamental ones? nonsymmetric vacua v(1), v(2)... actively contribute to the emergence of particle phenomena

“the nonsymmetrical ground level is not properly a vacuum, but rather a “world” state which constitutes the basis for the existence of elementary particles”

when a quantity seems not conserved in a process, the vacuum changes state and "absorbs" it - vacuum/world as "infinite reservoire" of quantum numbers

NB: these is no scalar field with symmetry-breaking vacuum expactation value!

However, Heisenberg was never able to construct a phenomenologically satisfactory model...

meanwhile: BCS theory of superconductivity (1958-59)

„fundamental level"	*vs.*	*„phenomenological level"*
electromagnetism		BCS theory
electrons, nuclei		quasi-particles
local gauge symm. + e- charge cons.		no gauge symm. + no e-charge cons.

---> asymmetry from symmetry!

1960 - Nambu uses methods of QFT (and Heisenberg's) to formally argue:

symmetric equation (EM) --(nonpert. effects)--> nonsymmetric solution (BCS)
with „hidden symmetry" (no symmetry-breaking!)

1961 - Nambu&Jona Lasinio: analogy: superconductivity ↔ strong interactions

electrons, nuclei ↔ hypoth. massless fermions (Heisenberg!)
EM-gauge symmetry ↔ chiral symmetry
↓ (through non-perturbative effects)
quasi-particles ↔ massive nucleons

Sketchy nonperturbative computations + superconductivity as exemplar:
perturbative vacuum vs. nonperturbative vacuum
other than Heisenberg: a "superselection rule" forbids transition between vacua

1961 Salam: Nambu's model as a possibility to implement the symmetry breaking between electromagnetic and weak interactions in the Salam/Ward proposal

many other authors, too, are attracted by the idea of getting asymmetry from symmetry through nonperturbative, "dynamical" effects....

1962 Baker/Glashow: "spontaneous breakdown of elementary particle symmetry"
the term "spontaneous" is introduced here for the first time

“Should not the complexities of the phenomena of elementary particle physics arise from a “simple” fundamental theory? [...] It is conceivable that the field equations may be highly symmetric expressions, while their solutions may reflect the asymmetries of nature. This is the philosophy we adopt in this paper [...] We propose that a nonperturbative behaviour characterizes all the interactions to which elementary particles are subject. Mass is completely dynamical; mass splittings and 'approximate symmetries' result from nonsymmetric solutions to a fully symmetric Lagrangian theory
[Conclusion:] we have shown the possibility that the fundamental interactions can generate themselves from a 'bootstrap mechanism' in a theory where the bare coupling constants vanish"

however, spontaneous symmetry breaking is not as easy as it seems....

1961 Goldstone: "Field theories with 'superconductor' solutions"

Schwinger's scalar field (with VEV) as a phenomenological manifestation of nonperturbative effects deriving from a (nonspecified) fundamental Lagrangian

some complex computations.... and "a symple model" (the Goldstone potential!)

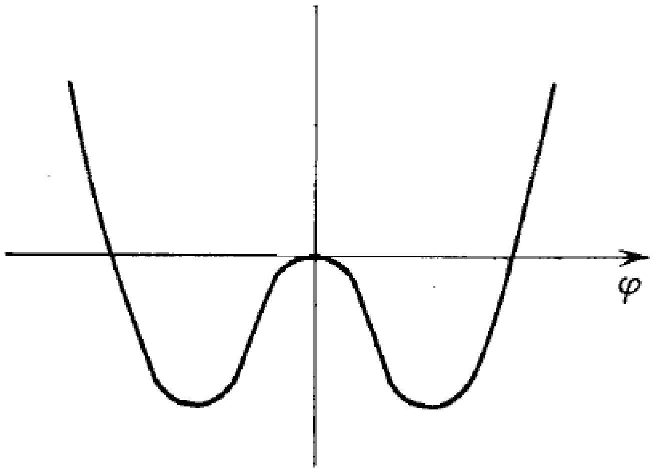

Fig. 7.

gives the number of particles. When $\mu_0^2 < 0$, this approach will not work. However, if $\lambda_0 > 0$, the function

$$\frac{\mu_0^2}{2}\varphi^2 + \frac{\lambda_0}{24}\varphi^4 ,$$

is as shown in Fig. 7.

The classical equations

$$(\Box^2 + \mu_0^2)\varphi + \frac{\lambda_0}{6}\varphi^3 = 0 ,$$

the “Goldstone theorem”:

scalar field + “double-well” potential, ---> VEV gives rise to different asymmetrical minima/vacua and masses.... and to a massless scalar!

...is the Goldstone theorem valid also for local gauge symmetry?

1964-66: Anderson, Brout, Englert, Guralnik, Hagen, Higgs, Kibble, Schwinger...

show how the scalar can spontaneously break local gauge symmetry without Goldstone bosons!

they give no mathematical argument why the "spontaneous" breakdown is different from the explicit one, but their results motivate Weinberg and Salam in their proposals for a spontaneously broken gauge theory of EW-interactions:

Salam (1968): *"[masses are introduced] more gently than a brutal addition and subtraction of mass terms [...] let the vector mesons interact with a set of scalar particles and let them acquire physical masses by assuming self-consistently that these scalar particles possess nonzero vacuum expectation values"*

Weinberg (1967) *"Is this model renormalizable? We usually do not expect so, but [our vector bosons] get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning"*

The proof for renormalizability - will be delivered only in 1971 by Gerhard 't Hooft - yet the verbal argumentations had been enough to lead Weinberg ans Salam to propose their model

the many paths to symmetry breaking...

1957 Schwinger: unique vacuum, scalar field with nonzero VEV breaks the symmetry

1958 Heisenberg: non perturbative, nonsymmetric vacua break symmetry, transitions between vacua occur

1959-61 Salam/Ward: the scalar breaks local gauge invariance

1961 Nambu/Jona Lasinio: non-perturbative vacuum and “hidden” symmetry (like BCS!), no transitions between vacua

1961 Goldstone: nonsymmetric vacuum and scalar with VEV as "black-box" for non-perturbative effects

1962 Baker&Glashow: "spontaneous" symmetry breaking

["Higgs mechanism"]
1967-68 Salam/Weinberg model

more details in: A. Borrelli, EJPH 40 (2015): 1-52