Spontaneous symmetry breaking

J.Iliopoulos

Higgs Hunting 2012

LAL, July 18-20, 2012

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Higgs Taming 2012

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THE STANDARD MODEL IS COMPLETE

Contents

Brief Historical Remarks

Two words of caution:

- Never read old papers with to-day's knowledge
- Beware of changes in notation and terminology

Brief Historical Remarks I.

- Spontaneous Symmetry Breaking

  -A critical point

  -Instability of the symmetric solution

  -The ground state is degenerate $\Rightarrow$ Massless excitations

  -The origins go back to 19th century Classical Mechanics

Brief Historical Remarks I.

- Spontaneous Symmetry Breaking

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- Spontaneous Symmetry Breaking in the presence of Gauge Interactions

Brief Historical Remarks II.

- Two parallel stories

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- The Theory of Superconductivity

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- The Gauge Theories of Elementary Particles

Brief Historical Remarks II.

- Two parallel stories
- The Theory of Superconductivity
- The Gauge Theories of Elementary Particles
- They developed independently and often ignored each other

Spontaneous Symmetry breaking in the Theory of Superconductivity

- L.D. Landau and B.L. Ginzburg JETP **20** (1950) 1064

$$\Delta\vec{A} = \ldots\ldots + \frac{4\pi e^2}{mc^2}|\Psi|^2\vec{A} \quad \Rightarrow \quad \vec{A}(x) \sim \vec{A}(0)e^{-x/\lambda}$$

Note: no-one in the subsequent list refers to this paper

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- P.W. Anderson Phys. Rev. **112** (1958) 1900 ; **110** (1958) 827

  "Random Phase Approximation in the Theory of Superconductivity"

  In BCS $\Rightarrow$ Mass gap, + Longitudinal waves

  From the Abstract : "The theory.... is gauge invariant *to an adequate degree throughout.*"

Spontaneous Symmetry breaking in the Theory of Superconductivity

- P.W. Anderson Phys. Rev. **130** (1963) 439

  "Plasmons, Gauge invariance and Mass"

  Shows that BCS exemplifies Schwinger's programme.

  From the Abstract : "Schwinger has pointed out that the Yang-Mills vector boson (*He only considers Abelian theories*) ......does not necessarily have zero mass.....We show that the theory of plasma oscillations is a simple non-relativistic example exhibiting all of the features of Schwinger's idea."

Spontaneous Symmetry breaking in the Gauge Theories of Elementary Particles. Early attempts

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- Julian Schwinger Phys. Rev. **125** (1962) 397

  "Gauge Invariance and Mass"

  $\Pi_{\mu\nu}(q) = \Pi(q^2)\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right) \qquad \Pi(0) \neq 0 \Rightarrow m \neq 0$

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- Julian Schwinger Phys. Rev. **128** (1962) 2425

  "Gauge Invariance and Mass II"

  The Schwinger Model (2-d QED)

  Note: No references to superconductivity

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- In fact, Schwinger had understood the connection earlier.

  From Feynman's Summary Talk at the Aix-en-Provence Conference on Elementary Particles, Sept. 14-20 1961:

  "…..Since gauge invariance is usually believed to imply that the mass [of the gauge bosons] is zero, the first prediction of these theories ….. is disregarded. Schwinger pointed out to me however, that one can use gauge invariance to prove that the mass of the real photon is equal to zero, only if one assumes that in the complete dressed photon, there is a finite amplitude to find the undressed one."

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- M. Lévy Phys. Lett. **7** (1963) 36 ; Nucl. Phys. **57** (1964) 152

  Non-local, gauge invariant, QED with a massive photon

Spontaneous Symmetry breaking in the Gauge Theories of Elementary Particles. Early attempts

- On the one hand we had Goldstone Theorem : Sp. Sym. Br. $\Rightarrow$ A massless particle.

  On the other we had Anderson's non-relativistic counter example.

  Could we find relativistic analogues?

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- A. Klein and B.W. Lee Phys. Rev. Lett. **12** (1964) 266

  Does Spontaneous Breakdown of Symmetry Imply Zero-Mass Particles?

  M. Baker, K. Johnson, B.W. Lee Phys. Rev. **133 B** (1964) 209

  Broken Symmetries and Zero-Mass Bosons

Spontaneous Symmetry breaking in the Gauge Theories of Elementary Particles. Early attempts

- W. Gilbert Phys. Rev. Lett. **12** (1964) 713

  "Broken Symmetries and Massless Particles"

  A no-go Theorem !!

  Sp. Sym. Br. $\Rightarrow \ \exists \ A \qquad < 0|[Q, A]|0 > \ \neq \ 0 \qquad (1)$

  $\mathcal{A}_\mu(k) = \int d^4 x e^{ikx} < 0|[j_\mu(x), A(0)]|0 >= k_\mu F(k^2) \qquad (2)$

  by Lorentz invariance and $F(k^2) \neq 0$ by (1)

  But $\quad k^\mu \mathcal{A}_\mu = 0 \quad \Rightarrow \quad k^2 F(k^2) = 0 \quad F(k^2) \sim \delta(k^2) \quad \Rightarrow$

  A massless particle

  In a non-relativistic theory (2) does not hold.

  Problem: Find the error!

Spontaneous Symmetry breaking in the Gauge Theories of Elementary Particles. The solution

- F. Englert and R. Brout Phys. Rev. Lett. **13** (1964) 321

  The solution as we know it to-day, using elementary scalar fields.

  Some remarks on the possibility of dynamical symmetry breaking.

  Abelian, Non-Abelian and chiral models are considered.

  The motivation was mainly centred in strong interactions.

  References include SSB (Nambu *et al*), Schwinger and Sakurai.

Spontaneous Symmetry breaking in the Gauge Theories of Elementary Particles. The solution

- P. Higgs Phys. Lett. **12** (1964) 132

  Explicit example answering Gilbert's objection. The Abelian model in the Coulomb gauge.

  References include SSB, Klein+Lee and Gilbert

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- P. Higgs Phys. Rev. Lett. **13** (1964) 508

  Explicit example of the Abelian model. Discussion of the $SU(3)$ Sakurai model for strong interactions.

  Explicit connection between would-be Goldstone modes and longitudinal polarisations of the massive vector bosons.

  Connection with superconductivity.

  References include Goldstone, Anderson, Brout+Englert, Sakurai.

Spontaneous Symmetry breaking in the Gauge Theories of Elementary Particles. The solution

- G.S. Guralnik, C.R. Hagen and T.W.B. Kibble Phys. Rev. Lett. **13** (1964) 585

  Detailed discussion of the Abelian model. Explicit counting 3=2+1.

  Vague connection to superconductivity. No references.

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- S. Weinberg Phys. Rev. Lett. **19** (1967) 1264

  The Synthesis: The Englert-Brout-Higgs mechanism in the electroweak interactions. The same mechanism gives masses to the fermions.

The Hunting is over. Taming of the beast

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- Need for a dedicated collider??

Do we understand the Physics?

- In the old approach to Particle Physics you start from the observed Particles and try to guess their interactions.

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- Gauge theories contain three independent worlds:

  The gauge bosons and their dynamics are determined by the Geometry

  The fermions are arbitrary, but their dynamics is not.

  The scalars are completely arbitrary. Their masses are unstable Why??

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- Supersymmetry. The scalars complete the massive vector supermultiplet.

  We do not know the breaking.
- Could the scalars become also geometrical?

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- Question: Is there a space on which Internal symmetry transformations act as Diffeomorphisms?

- Answer: Yes, but it is a space with non-commutative geometry.

  A space defined by an algebra of matrix-valued functions

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  Not in the Standard Model. New rules?
- Connection with String Theory?

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- **TODAY WE ARE CELEBRATING**