

# MY LIFE AS A BOSON

## PLAN OF TALK:

### 1) SPONTANEOUS SYMMETRY BREAKING

BCS SUPERCONDUCTIVITY 1957

NAMBU, GOLDSTONE 1961

BROUT & ENGLERT, HIGGS 1964

ELECTROWEAK THEORY 1961

GLASHOW

WEINBERG, SALAM 1967

VELTMAN, 'T HOOFT 1971

### 2) 1972-PRESENT MY LIFE AS A BOSON

OCT 1960 PWH → EDINBURGH LECTURESHIP

JULY 1960 PWH STEWARD AT FIRST  
SCOTTISH UNIVERSITIES SUMMER  
SCHOOL IN PHYSICS

## STUDENTS INCLUDED

DR N CABIBBO ROME

DR S L GLASHOW CERN (NOBEL 1979)

MR D W ROBINSON OXFORD

MR M J G VELTMAN UTRECHT (NOBEL 1999)

("GANG OF FOUR", WHO STAYED UP  
HALF THE NIGHT DISCUSSING  
THEORETICAL PHYSICS)



# EARLY HISTORY OF SSB

## ① FERROMAGNETISM

Heisenberg (1928)

(SSB of continuous symmetry  
⇒ degenerate ground state,  
for infinite volume)

## ② SUPERFLUIDITY (Bose condensate)

Bogoliubov (1947)

(global U(1),  $\psi \rightarrow e^{i\alpha} \psi$ , broken)

## ③ SUPERCONDUCTIVITY (charged Bose condensate)

(a) Landau & Ginzburg (1950)

(Charged spinless particles +  
electromagnetism)

(Unrealistic, so had limited impact)

(b) BCS (1957)

### PARTICLE THEORIES

Heisenberg (1958)

Nonlinear  
spinor theories  
(SSB: global)

Approximations  
not believable!

Schrieffer, 1957  
Chicago seminar  
↓  
Nambu: QFT  
formulation of BCS

Nambu et al (1960)  
Models of SB of SU(2) etc



1960

MODELS OF ELEMENTARY PARTICLES  
FEATURING SPONTANEOUS BREAKING  
OF SYMMETRIES

Y. NAMBU & G. JONA-LASINIO

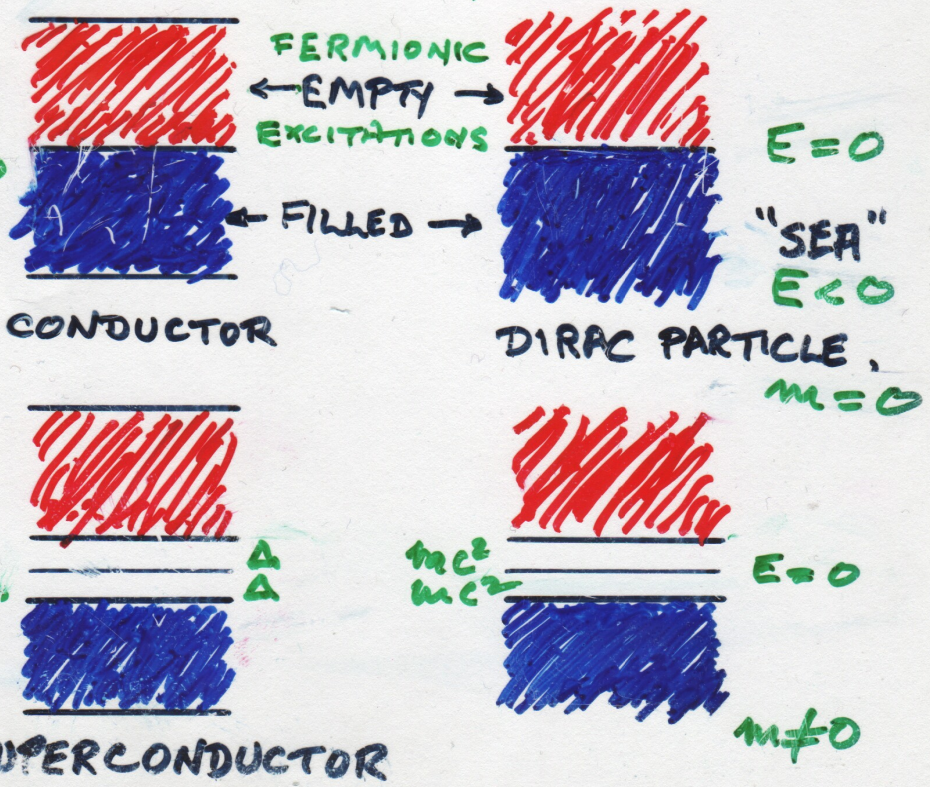
"DYNAMICAL MODEL OF  
ELEMENTARY PARTICLES  
BASED ON AN ANALOGY  
WITH SUPERCONDUCTIVITY"

CHIRAL SYMMETRY (ACTING ON  
MASSLESS FERMIONIC FIELDS)  
SPONTANEOUSLY BROKEN BY  
ASYMMETRIC VACUUM  $\Rightarrow$   
FERMIONS HAVE  $m \neq 0$

$\langle \phi \rangle_0 \neq 0 : \phi \sim \bar{\psi}\psi$  (COMPOSITE)

ANALOGY

FERMI SURFACE:  $E_0$





1960

J. GOLDSTONE

FIELD THEORIES WITH  
"SUPERCONDUCTOR" SOLUTIONS $\langle \underline{\phi} \rangle_0 \neq 0$  : ELEMENTARY SCALARS  $\underline{\phi}$   
(i.e. ELEMENTARY BOSONS)

"WINE BOTTLE" POTENTIAL

 $V(\phi) \Rightarrow$  SSB  
(like Landau-Ginzburg theory)

1960

V. WEISSKOPF, CORNELL SEMINAR  
(RECALLED BY ROBERT BROUT)

"PARTICLE PHYSICISTS ARE SO  
DESPERATE THESE DAYS  
THAT THEY HAVE TO BORROW  
FROM THE NEW THINGS  
COMING UP IN MANY-BODY  
PHYSICS — LIKE BCS.  
PERHAPS SOMETHING  
WILL COME OF IT."



THE GOLDSTONE THEOREM

NAMBU & JONA-LASINIO, WHO BROKE CHIRAL  $SU(2) \times SU(2)$  IN A MODEL WITH ELEMENTARY  $\begin{pmatrix} p \\ n \end{pmatrix}$ , FOUND A MASSLESS TRIPLET OF BOUND STATE  $(\pi^+, \pi^0, \pi^-)$ .

GOLDSTONE MADE THE GENERATION OF MASSLESS SCALARS INTUITIVELY OBVIOUS IN MODELS WITH ELEMENTARY SCALARS:

GOLDSTONE BOSONS ( $m=0$ ) ARE EXCITATIONS AROUND THE TROUGH OF THE WINE-BOTTLE POTENTIAL.

1962 THEOREM FORMALLY PROVED BY GOLDSTONE, SALAM & WEINBERG "BROKEN SYMMETRIES"

IN A MANIFESTLY LORENTZ-INVARIANT QFT, IF THERE IS A CONTINUOUS SYMMETRY UNDER WHICH THE LAGRANGIAN IS INVARIANT, THEN EITHER THE VACUUM STATE IS ALSO INVARIANT UNDER THE SYMMETRY OR THERE MUST EXIST SPINLESS PARTICLES OF ZERO MASS



1963-64

CAN ONE EVADE THE  
GOLDSTONE THEOREM?

1963

P.W. ANDERSON POINTED OUT THAT IN A SUPERCONDUCTOR THE GOLDSTONE MODE BECOMES A MASSIVE "PLASMON" MODE DUE TO ITS ELECTROMAGNETIC INTERACTION, AND THAT THIS MODE IS JUST THE LONGITUDINAL PARTNER OF TRANSVERSELY POLARIZED ELECTROMAGNETIC MODES, WHICH ARE ALSO MASSIVE. (MEISSNER EFFECT!)

ANDERSON CONTINUED,  
"THE GOLDSTONE ZERO-MASS DIFFICULTY IS NOT A SERIOUS ONE, BECAUSE WE CAN PROBABLY CANCEL IT OFF AGAINST AN EQUAL YANG-MILLS ZERO-MASS PROBLEM"

**BUT** (a) HE DIDN'T DISCUSS  
THE THEOREM

(b) HE DIDN'T DISCUSS  
ANY RELATIVISTIC  
MODEL



1964 HOW TO EVADE GOLDSTONE'S THEOREM

GSW PROOF INVOLVES COMMUTATOR

$i [\hat{\Phi}, \hat{\Phi}_1] = \hat{\Phi}_2$  (1)

$\hat{\Phi} = \int d^3x \hat{j}_0(\underline{x}, t)$  (GENERATOR)

AND  $\partial_\mu \hat{j}^\mu = 0$  (2) (INVARIANCE OF  $\hat{\mathcal{I}}$ )

MANIFEST LORENTZ INVARIANCE  $\Rightarrow$   
4D FOURIER TRANSFORM OF

$\langle i [\hat{j}_\mu(x), \hat{\Phi}_1(y)] \rangle_0$

HAS FORM  $k_\mu (\text{sign } k^0) \rho(k^2)$  [ $\rho = 0$  FOR SPACELIKE  $k$ ]

(2)  $\Rightarrow k^2 \rho(k^2) = 0 \Rightarrow \rho = C \delta(k^2)$

(1)  $\Rightarrow C = 2\pi \langle \hat{\Phi}_2 \rangle_0 \neq 0$  (ASYMMETRIC VACUUM)

MARCH 1964

A. KLEIN & B.W. LEE

FOR (E.G.) SUPERCONDUCTOR, F.T. HAS MORE GENERAL FORM

$k_\mu \rho_1(k^2, n \cdot k) + n_\mu \rho_2(k^2, n \cdot k)$

WHERE  $n_\mu (= (1, 0, 0, 0))$  SPECIFIES REST FRAME OF IONIC BACKGROUND.

PERHAPS THIS COULD HAPPEN IN TRULY RELATIVISTIC CASE?

JUNE 1964 W. GILBERT No!

JULY 1964 P.W.H. YES! —

BUT ONLY IF GAUGE FIELD  $A_\mu$  IS COUPLED TO THE CURRENT



## 1964 ACCIDENTAL BIRTH OF A BOSON

- Th. 16 July Phys. Rev. Letters (22 June), containing Gilbert's paper reaches Edinburgh.
- F. 24 July Broken Symmetries, Massless Particles and Gauge Fields (P.W.H.) sent to Physics Letters editor at CERN.
- ACCEPTED
- F. 31 July Broken Symmetries and the Masses of Gauge Bosons (P.W.H.) sent to Physics Letters editor at CERN.
- REJECTED
- August Paper revised by adding (inter alia)  
 "It is worth noting that an essential feature of this type of theory is the prediction of incomplete multiplets of scalar and vector bosons"
- 31 August Revised paper received by Physical Review Letters.
- ACCEPTED
- Referee (Nambu) draws to attention of PWH the paper by J. Engler & R. Brout, Broken Symmetry and the Mass of Gauge Vector Mesons (received by Phys. Rev. Letters 22 June, published 31 August)



SEPTEMBER 1965 - JUNE 1966

At University of North Carolina,  
Chapel Hill.

SEP. - NOV. Phys. Rev. paper (1966) written.

JAN. 1966 Response from Dyson

MAR. 15 Princeton (Institute) seminar

MAR. 16 Harvard seminar

Reactions: Before { Hepp  
Coleman (1979)

After { Weightman  
Glashow

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$SU(2) \times U(1)$  electroweak model  
— why I had missed  
hearing about it in 1960:

SUSSP 1960



1967 (AUTUMN)

S. WEINBERG

THEORY OF LEPTONS

A. SALAM (LECTURES AT  
IMPERIAL COLLEGE)

1970

VELTMAN & 'T HOOFT RENORMALIZATION  
OF PURE Y.M.

1971

G. 'T HOOFT

RENORMALIZATION OF  
YANG-MILLS THEORIES  
WITH MASSES  
GENERATED BY SSB  
IN SCALAR FIELD SYSTEM

1972

INTERNATIONAL H.E.P.  
CONFERENCE AT  
FERMILAB:

B.W. LEE REPORTS ON  
RENORMALIZABLE  
ELECTROWEAK MODELS,  
ETC

1973

NEUTRAL CURRENTS  
DISCOVERED

1974

CHARMONIUM, - - -  
( $J/\psi$ )



↑  
1975  
DESIGN  
AND  
BUILDING  
OF  
LEP  
↓

J. ELLIS, M.K. GAILLARD, P.V. NANOPoulos

"A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON"

" We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm, and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up."

1989

J. GUNION, H. HABER, G. KANE & S. DAWSON "THE HIGGS HUNTER'S GUIDE"

" The success of the Standard Model has been astonishing. The central problem today in particle physics is to understand the Higgs sector "



1989-99

PRECISION MEASUREMENTS  
AT LEP ON Z BOSON,  
ETC  $\Rightarrow$  BOUNDS ON  
LIKELY  $m_H$  (FROM  
OCCURRENCE OF  $\ln m_H$   
IN 1-LOOP RADIATIVE  
CORRECTIONS).

TOP QUARK  
DISCOVERED

(1993-94)

 $\Downarrow$ 

1995

$m_H < 219$  GeV at 95%  
confidence level  
(most favoured value, 96 GeV,  
near exclusion limit, 95 GeV,  
established by 1998 searches)

July 1999 - November 2000

LEP 200's last run.

Summer 2000 (at about 207 GeV)

$m_H$  up to 114 GeV EXCLUDED  
{ Indications of H at about 115 GeV?

(2001 Backgrounds found to be worse  
than had been realised)

March 2001 Improved Tevatron starts up  
(luminosity poor)

2004

new  $m_T$  measurements  $\Rightarrow$   
most favoured  $m_H = 117$  GeV;  
 $m_H < 251$  GeV at 95% confidence level