Nobel Prize 2008

Krzysztof A. Meissner

Warszawa, 26.11.2008

Winners

Yoichiro
Nambu
1/2

Makoto
Kobayashi
1/4

Toshihide
Maskawa
1/4

Nobel Committee Announcement

- Y. Nambu:
  “for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics” (1960)
- M. Kobayashi and T. Maskawa:
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- Nambu: 1964 (with Han) quark color
  1970 string theory (after Veneziano formula)

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- SSB – ferromagnetism (Heisenberg, 1928)
- Nambu – global SSB in particle physics
  (chiral symmetry $\leftrightarrow$ superconductivity)
  talk at Purdue in 1960 by Jona-Lassinio (!)
- pions almost massless
- pions as bound states
  (4 years before quarks!)

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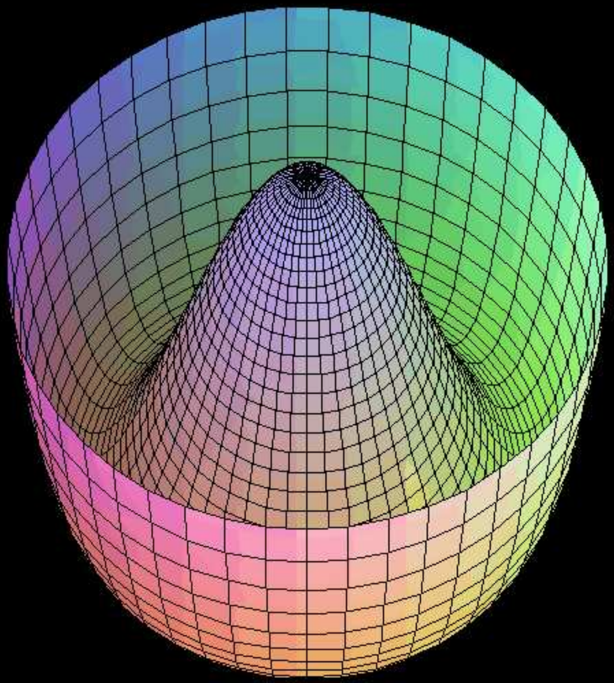
- SSB of local (gauge) symmetry $\Rightarrow$
  Brout-Englert-Higgs mechanism
  massive gauge bosons

Example of local symmetry SSB

Complex scalar field + QED ($D_\mu = \partial_\mu - 2\mathrm{i}eA_\mu$)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - D_\mu\varphi^\dagger D^\mu\varphi - \frac{\lambda}{4}(\varphi^\dagger\varphi - v^2)^2$$



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- $\varphi \to e^{2\mathrm{i}e\alpha}(v + h/\sqrt{2}), \quad A_\mu \to A_\mu + \partial_\mu \alpha$
- $\Rightarrow$ massive photon A_μ and one real field h

$$\begin{aligned}\mathcal{L} \;=\; & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - 4e^2v^2A_\mu A^\mu \\ & -\frac{1}{2}\partial_\mu h\partial^\mu h - \frac{\lambda}{2}v^2h^2 + \text{interactions}\end{aligned}$$

- $m_A = 2\sqrt{2}ev, \quad m_h = \sqrt{\lambda}v$

Superconductivity

Coupling a current j_μ to the A^μ part ($\partial_\mu A^\mu = 0$):

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - 4e^2 v^2 A_\mu A^\mu - j_\mu A^\mu$$

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- quantization of flux (Abrikosov vortices):

$$2e \oint \vec{A} \cdot \mathrm{d}\vec{l} = 2\pi n \quad \Rightarrow \int \vec{B} \cdot \mathrm{d}\vec{S} = \frac{\pi n}{e}$$

Leptons and quarks of the SM

Leptons L^i	E^i	N^i	Quarks Q^i	U^i	D^i
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L ,$	$e_R,$	ν_{eR}	$\begin{pmatrix} u \\ d \end{pmatrix}_L ,$	$u_R,$	d_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L ,$	$\mu_R,$	$\nu_{\mu R}$	$\begin{pmatrix} c \\ s \end{pmatrix}_L ,$	$c_R,$	s_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L ,$	$\tau_R,$	$\nu_{\tau R}$	$\begin{pmatrix} t \\ b \end{pmatrix}_L ,$	$t_R,$	b_R

Lepton-Higgs and Quark-Higgs interactions

- Yukawa part of the Standard Model

$$\overline{L}^i \gamma^\mu D_\mu L^i + \ldots + \overline{Q}^i \gamma^\mu D_\mu Q^i + \ldots +$$
$$\left(\overline{L}^i \Phi Y^E_{ij} E_j + \overline{Q}^i \Phi Y^D_{ij} D_j + \overline{Q}^i \epsilon \Phi^* Y^U_{ij} U_j + \mathrm{h.c}\right)$$

where $\Phi = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$

- Y^U_{ij}, Y^D_{ij} a priori arbitrary complex matrices

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- experimentally $v \approx$ 174 GeV.
- $g_i v \Rightarrow$ masses of gauge bosons
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- if $v = 0$ (no SSB) all fundamental particle massless (but strongly coupled bound particles like proton presumably still massive)

Cabibbo-Kobayashi-Maskawa matrix

- any complex matrix can be decomposed as

$$Y = K_1^\dagger M K_2$$

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- one can use unitary rotations of Q, U and D to put

$$Y_{ij}^U = M^U, \quad Y_{ij}^D = K_m^D M^D$$

M^U and M^D real diagonal, K_m^D – CKM matrix

$\frac{n(n-1)}{2}$ angles, $\frac{(n-1)(n-2)}{2}$ phases

Explicit form of CKM matrix

$$\begin{pmatrix} c_{12}c_{13}, & s_{12}c_{13}, & s_{13}e^{-\mathrm{i}\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{\mathrm{i}\delta}, & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{\mathrm{i}\delta}, & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{\mathrm{i}\delta}, & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{\mathrm{i}\delta}, & c_{23}c_{13} \end{pmatrix}$$

$c_{ij} = \cos(\theta_{ij}),\ s_{ij} = \sin(\theta_{ij})$, θ_{12} Cabibbo angle

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$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot F_{\mathrm{T}} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot F_{\mathrm{T}}^{*} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $F_{\mathrm{T}} = \mathrm{diag}\left(1, e^{-\mathrm{i}\delta}, e^{\mathrm{i}\delta}\right)$

Experimental values

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{ts} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9742 & 0.226 & 0.0036 \\ 0.226 & 0.9733 & 0.0041 \\ 0.0087 & 0.041 & 0.99913 \end{pmatrix}$$

The errors are $\approx$ the last displayed digit.

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The phase independently of the parametrization in the form of the Jarlskog invariant J:

$$\mathrm{Im}\left[V_{ij}V_{kl}V_{il}^*V_{kj}^*\right] = J(\delta_{ij}\delta_{kl} - \delta_{il}\delta_{kj})$$

Experimentally, $J = (3.0 \pm 0.2)\cdot 10^{-5}$

CP violation

- Kobayashi and Maskawa noticed that the phase (corresponding to explicit CP breaking) is possible starting from 3×3 matrices – "prediction" of at least 6 quarks
- CP breaking originally seen in s quark systems (K mesons) – prediction of CP breaking in b quark systems (now measured)

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- in 1972 only 3 quarks (u, d, s) and 3 leptons (e, μ, ν) were known

CP violation in cosmology

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- the amount of CP violation in CKM matrix too small to explain this asymmetry – needed other sources!

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  when repaired after explicit breaking...