CP violation and the third generation of quarks

Nobel Prize in Physics, 2008

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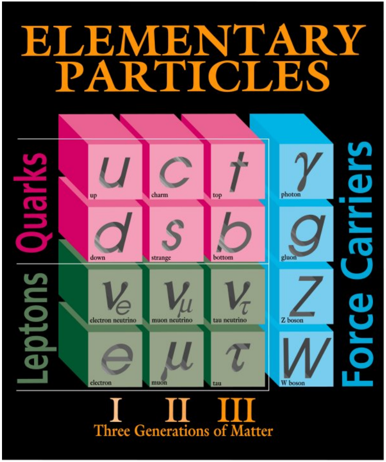
... for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature

TIFR Colloquium, Nov 20, 2008

Contents

Standard model of particle physics: 2008



Fermilab 95-759

- Three families of quarks and leptons
- quarks:
  up charmed top
  down strange bottom
- Mixing between families

Outline

1. Before Kobayashi-Maskawa
   - The status of Particle Physics in 1972
   - The broken symmetry: charge-parity (CP)
2. The insight of Kobayashi and Maskawa
   - Prog. Theo. Phys. 49, 652 (1973)
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3. Testing the Kobayashi-Maskawa predictions
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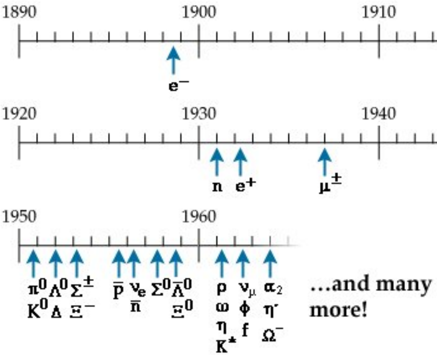
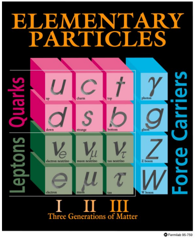
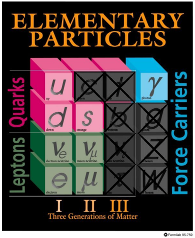
4. Concluding remarks

Known particles in 1972



$$
\begin{array}{rcl}
p & \equiv & uud \\
n & \equiv & udd \\
\pi^+ & \equiv & u\bar{d} \\
\pi^- & \equiv & d\bar{u} \\
\pi^0 & \equiv & (u\bar{u} - d\bar{d})/\sqrt{2} \\
K^+ & \equiv & u\bar{s} \\
K^- & \equiv & s\bar{u} \\
K^0 & \equiv & d\bar{s} \\
\overline{K^0} & \equiv & s\bar{d}
\end{array}
$$





Universality of weak interactions: Cabibbo angle

Interrelated coupling constants:

- (i) muon decay: $g_{e\mu}$
  $\mu^- \to \nu_\mu e^- \bar{\nu}_e$
- (ii) neutron decay : g_{ud}
  $n \to p e^- \bar{\nu}_e \ (d \to u e^- \bar{\nu}_e)$
- (ii) kaon decay: g_{us}
  $K^- \to \pi^0 e^- \bar{\nu}_e \ (s \to u e^- \bar{\nu}_e)$

$$\boxed{|g_{e\mu}|^2 = |g_{ud}|^2 + |g_{us}|^2}$$

Universality:

- There is only one coupling constant, $g = g_{e\mu}$
- *u* quark couples to only one combination of *d* and *s*:

$$d' \equiv \cos\theta_c \cdot d + \sin\theta_c \cdot s$$

- Cabibbo angle θ_c: the first quark mixing angle

N. Cabibbo, “Unitary Symmetry and Leptonic Decays,”
Phys. Rev. Lett. **10**, 531 (1963)

Suppression of flavor-changing neutral currents

- Cabibbo angle unable to explain why
$$\Gamma(K_L \to \mu^+\mu^-) << \Gamma(K^+ \to \mu^+\nu_\mu)$$
- Possible explanation via another “c” quark:
charge $+2/3$, couples to
$$s' \equiv -\sin\theta_c \cdot d + \cos\theta_c \cdot s$$
- The $s \to u \to d$ and $s \to c \to d$ contribution cancel, leading to the suppression of FCNC $s \to d$
- GIM mechanism: existence of the “charmed” quark.

S. L. Glashow, J. Iliopoulos and L. Maiani,
“Weak Interactions with Lepton-Hadron Symmetry,”
Phys. Rev. D **2**, 1285 (1970)

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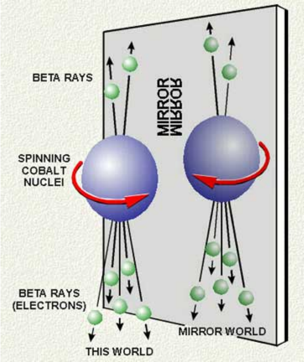
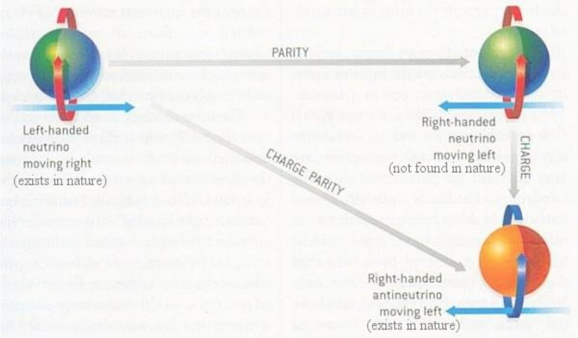
Discovery of parity violation: 1956-57



- Mirror world does not behave the same as the real world
- Theoretical possibility: T.D.Lee and C.N.Yang, Phys. Rev. **104**, 254 (1956)
- Experiments: 1957
  - Wu (^{60}Co)
  - Friedman-Telegdi ($\pi^+ \to \mu^+ \to e^+$)
- Nobel prize 1957: Lee–Yang

Can Charge ⊕ Parity may be conserved ?

Parity: left landed ↔ right handed



- Neutrinos violate parity: they are only left-handed
- But antineutrinos are right-handed !
- Does that mean C and P violations cancel each other to give CP conservation ?

Prediction of CP violation in K decay

$$K^0 \equiv d\bar{s} \qquad \overline{K^0} \equiv s\bar{d}$$

- CP eigenstates:

$$\begin{aligned} K_1 &\equiv (K^0 + \overline{K})/\sqrt{2} \qquad \text{(CP even)} \\ K_2 &\equiv (K^0 - \overline{K})/\sqrt{2} \qquad \text{(CP odd)} \end{aligned}$$

- CP even decay channel: $\pi\pi$
- CP odd decay channel: $\pi\pi\pi$
- CP conservation $\Rightarrow$

$$\begin{aligned} K_1 &\to \pi\pi \text{ short-lived, } K_{\text{Short}} \\ K_2 &\to \pi\pi\pi \text{ long-lived, } K_{\text{Long}} \end{aligned}$$

- Original $K^0 = (K_{\text{Short}} + K_{\text{Long}})/\sqrt{2}$

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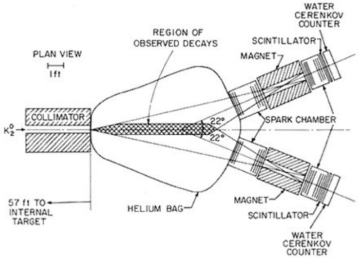
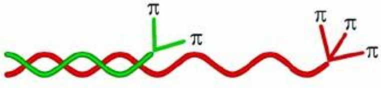
Discovery of CP violation: 1964

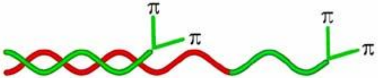
Cronin-Fitch experiment



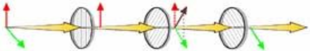
Nobel prize 1980



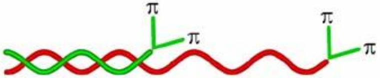
(a) Kaon Mixing



(b) Indirect CP Violation

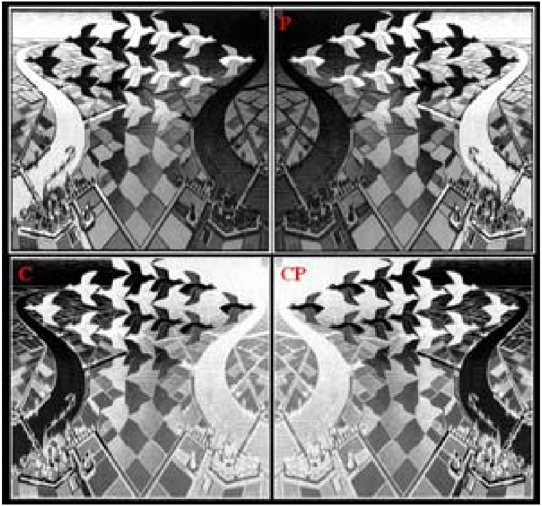


(c) Polarized Light Analogy



(d) Direct CP Violation

Charge-parity violated slightly



“Day and Night”, M.C.Escher

Questions raised by the discovery of CP violation

- Is it small or large ? Is CP an approximate symmetry ?
- Is the symmetry breaking spontaneous ?
- Where does it come from ? Are there extra interactions ?

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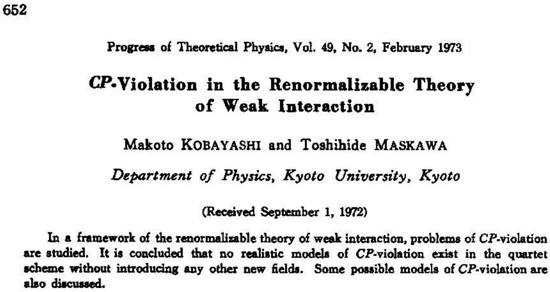
The paper and the authors



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Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

What the paper is about

- Consider various ways of putting (u_L, d_L, c_L, s_L) and (u_R, d_R, c_R, s_R) as doublets or singlets of $SU(2)_{\mathrm{weak}}$ (4 = 2+2, 4=2+1+1 or 4 = 1+1+1+1 ?)
- Experimental data ⇒
  - (u_L, d_L) have to form a doublet: isospin symmetry
  - (c_L, s_L) must also form a doublet: FCNC suppression
- Now, how can one get CP violation ?

CP violation and complex coupling

- CP violation: $A(X \to Y) \neq A(\overline{X} \to \overline{Y})$

- If all amplitudes are real, $|A(X \to Y)|^2 = |A(\overline{X} \to \overline{Y})|^2$
- CP violation possible if complex numbers involved in

$$\begin{aligned}|A(X \to Y)|^2 &= |A(X \to w \to Y) + A(X \to z \to Y)|^2 \\ |A(\overline{X} \to \overline{Y})|^2 &= |A(\overline{X} \to \overline{w} \to \overline{Y}) + A(\overline{X} \to \overline{z} \to \overline{Y})|^2\end{aligned}$$

- CP violation ⇒ Amplitudes complex ⇒ Couplings complex

Two generations of quarks are not enough

- The mixing matrix between up-type and down-type quarks has to be a 2×2 unitary matrix

$$\mathcal{L} \propto (\overline{u_L}, \overline{c_L}) \begin{pmatrix} \cos\theta e^{i\phi_1} & \sin\theta e^{i\phi_2} \\ -\sin\theta e^{i\phi_3} & \cos\theta e^{i(\phi_2+\phi_3-\phi_1)} \end{pmatrix} \begin{pmatrix} d_L \\ s_L \end{pmatrix}$$

- Can change three relative phases of quarks to get rid of all three complex phases ϕ_1, ϕ_2, ϕ_3

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- Mixing matrix real $\Rightarrow$ no CP violation

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- Mixing matrix real ⇒ no CP violation

Paremeter counting for two generations

- 2×2 complex matrix $\Rightarrow$ 4 real + 4 imaginary quantities

- Unitarity $U^\dagger U = \mathbb{I}$: 3 real and 1 imaginary conditions
- 1 real and 3 imaginary parameters left

- Can choose the 3 relative phases between quarks to get rid of the 3 imaginary parameters
- The mixing matrix is completely real

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Three generations work

- 3×3 matrix $\Rightarrow$ 9 real + 9 imaginary quantities
- Unitarity $U^\dagger U = \mathrm{I}$: 6 real and 3 imaginary conditions
- 3 real and 6 imaginary parameters left
- Can choose the 5 relative phases between quarks to get rid of 5 imaginary parameters
- In addition to 3 real parameters (Euler angles of rotation), one imaginary quantity is unavoidable
- Mixing matrix complex $\Rightarrow$ CP violation may be present

$$\begin{pmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{pmatrix}$$

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Flavor basis vs. mass basis

$$U' \equiv \begin{pmatrix} u \\ c \\ t \end{pmatrix} , \quad D' \equiv \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Charged current in the basis of flavor eigenstates:

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \overline{U'_L} \gamma^{\mu} D'_L W^{+}_{\mu} + h.c.$$

- Charged current in the basis of mass eigenstates:

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \overline{U_L} \gamma^{\mu} (V^{\dagger}_{UL} V_{DL}) D_L W^{+}_{\mu} + H.c.$$

V_{UL}, V_{DL}: unitary matrices that change the basis

- Coupling between U_L and D_L: $(g/\sqrt{2}) V_{CKM}$

$$V_{CKM} \equiv V^{\dagger}_{UL} V_{DL}$$

V_{CKM} is the Cabibbo-Kobayashi-Maskawa (CKM) matrix

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Predictive power of the CKM mechanism

- A third family of quarks exists (never suspected before)
- All CP violation can be described in terms of a single complex number: Jarlskog invariant $J \equiv s_1 s_2 s_3 c_1^2 c_2 c_3 s_\delta$

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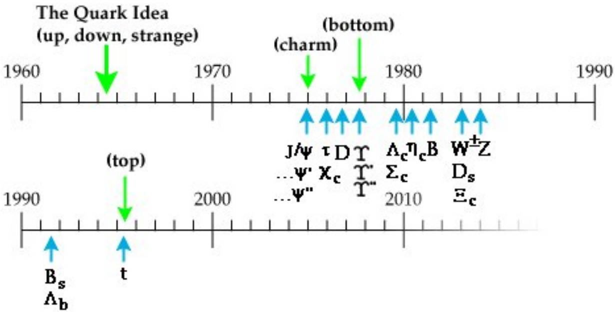
Experimental discovery of the third generation



- Discovery of τ: 1976
- $\Upsilon, B, B_s, \lambda_b$ contain b quark
- Top quark: 1995
- The last element, ν_τ, discovered in 2000.

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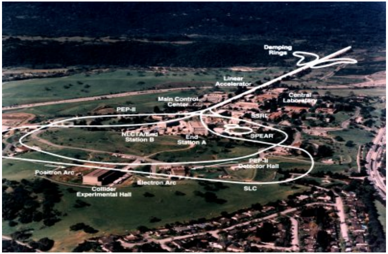
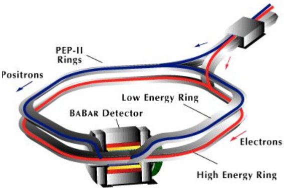
B factories: $B \equiv \bar{b}u, \bar{b}d, \bar{b}s, \bar{b}c, \quad \overline{B} \equiv \bar{u}b, \bar{d}b, \bar{s}b, \bar{c}b$



Babar (SLAC, USA)

BELLE (KEK, Japan)



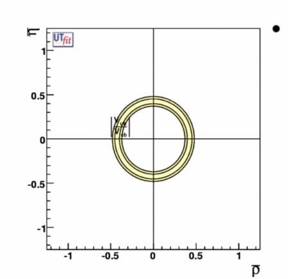
$$\boxed{e^+e^- \rightarrow B\overline{B} \rightarrow \text{decayproducts}}$$

Wolfenstein parametrization of the CKM matrix

$$
\begin{aligned}
V_{CKM} &= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \\
&= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)
\end{aligned}
$$

- λ: Cabibbo angle
- η: the imaginary component of V_{CKM}
- η/ρ large $\Rightarrow$ CP violation is large, not approximate

More and more stringent tests of the CKM mechanism



- Semileptonic decay $B \to D\ell\nu$

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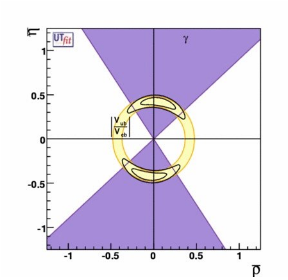
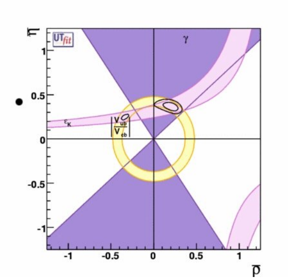


- Semileptonic decay $B \to D\ell\nu$
- “Charmed” decays $B \to DK$

More and more stringent tests of the CKM mechanism



- Semileptonic decay $B \rightarrow D\ell\nu$
- “Charmed” decays $B \rightarrow DK$
- CP violation in K mesons

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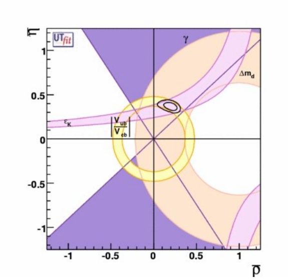

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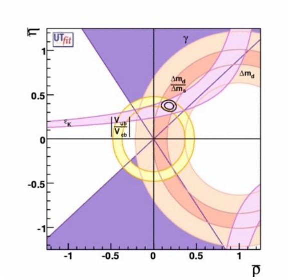

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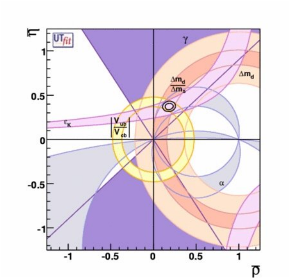
More and more stringent tests of the CKM mechanism



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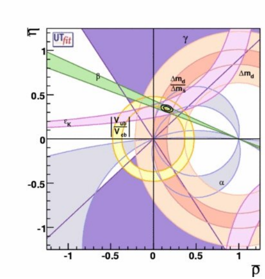

- Semileptonic decay $B \to D\ell\nu$
- “Charmed” decays $B \to DK$
- CP violation in K mesons
- ΔM in B_d–$\overline{B_d}$ system
- ΔM in B_s–$\overline{B}_s$ system
- Decays to π and K
- CP asymmetry in $B \to J/\psi K_S$

Concluding remarks

- No deviation from the CKM predictions has been observed
- Constrains many new physics models
- Future expts: LHC (ATLAS, CMS, LHC-b), super-B factory
- CP violation required for baryon asymmetry, but the CKM is not enough, so there will be life beyond CKM
- The successful prediction of Kobayashi and Maskawa still inspiring theoretical as well as experimental research