CP Violation
and
Three Generations

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§1 Introduction

1930 Dirac

Dirac equation and Antiparticle

W.Pauli

Die Allgemeinen Prinzipien der Wellenmechanik

Handbuch der Physik, Bd.XXIV, Teil 1 (1933)

> kommen müßte. Neuerdings versuchte DIRAC deshalb den bereits von OPPENHEIMER diskutierten Ausweg, die Löcher mit Antielektronen, Teilchen der Ladung $+e$ und der Elektronenmasse, zu indentifizieren. Ebenso müßte es dann neben den Protonen noch Antiprotonen geben. Das tatsächliche Fehlen solcher Teilchen wird dann auf einen speziellen Anfangszustand zurückgeführt, bei dem eben nur die eine Teilchensorte vorhanden ist. Dies erscheint schon deshalb unbefriedigend, weil die Naturgesetze in dieser Theorie in bezug auf Elektronen und Antielektronen exakt symmetrisch sind. Sodann müßten jedoch (um die Erhaltungssätze von Energie und Impuls zu befriedigen mindestens zwei) γ-Strahl-Protonen sich von selbst in ein Elektron und ein Antielektron umsetzen können. Wir glauben also nicht, daß dieser Ausweg ernstlich in Betracht gezogen werden kann.

1964 Christenson, Cronin, Fitch, Turlay

Discovery of CP violation

Matter Dominance

1967 Sakharov

1978 Yoshimura

1978 Ignatiev, Krasnikov, Kuzmin, Tavkhelidze

§2 History of Flavor Mixing

1956 Lee, Yang
1957 Wu
Discovery of Parity Violation

1958 Feynman, Gell-mann
Conserved Vector Current

1960 Gell-Mann, Levy

$$GV_\alpha + GV_\alpha^{(\Delta S=1)} = \frac{G_\mu}{(1+\epsilon^2)^{\frac{1}{2}}} \bar{p}\gamma_\alpha(n+\epsilon\Lambda) + \dots$$

1963 Cabibbo

$$J_\mu = \cos\theta(j_\mu^{(0)} + g_\mu^{(0)}) + \sin\theta(j_\mu^{(1)} + g_\mu^{(1)})$$

1970 Glashow, Illiopoulos, Maiani
GIM Current

1956 Sakata

$$p, \; n, \; \Lambda$$

$\Delta S = \Delta Q$

1959 Gamba, Marshak, Okubo

$$\begin{array}{ccc} p & n & \Lambda \\ | & | & | \\ \nu & e & \mu \end{array}$$

1960 Maki, Nakagawa, Ohnuki, Sakata

Nagoya Model

$$p = (\nu B), \; n = (eB), \; \Lambda = (\mu B)$$

1962 Danby et al.

Discovery of Two Neutrinos

1962

Katayama, Matumoto, Tanaka, Yamada

Maki, Nakagawa, Sakata

Extended Nagoya Model

$$\begin{array}{rcl} p & = & (\nu_1 B) \qquad \nu_1 = \cos\theta \; \nu_e + \sin\theta \; \nu_\mu \\ n & = & (eB) \\ \Lambda & = & (\mu B) \\ p' & = & (\nu_2 B) \qquad \nu_2 = -\sin\theta \; \nu_e + \cos\theta \; \nu_\mu \end{array}$$

1971 Niu et al.

Cosmic Ray Events

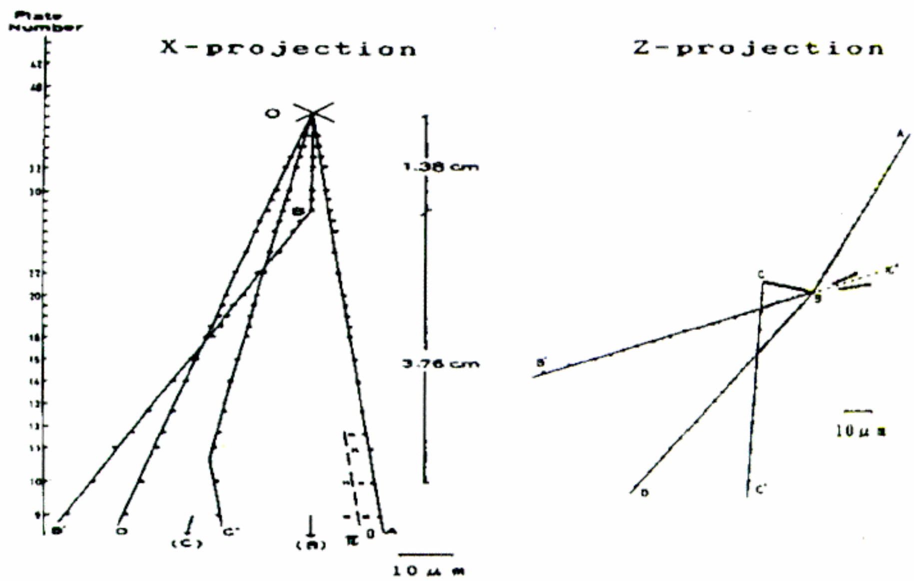


Fig. 1 A pair of charmed particles discovered in 1971.

S. Ogawa

1971-1972

Maki, Maskawa

Hayashi, Kobayashi, Nakagawa, Nitto

Hayashi, Kawai, Matsuda, Ogawa, Shige-eda

etc.

§3-1 Phase factor of CP transformation

ϕ : complex field

$$U_{\rm cp}\ \phi\ U_{\rm cp}^{-1} = e^{i\alpha}\ \phi^*$$

cf.

$$U_{\rm cp}\ \phi^*\ U_{\rm cp}^{-1} = e^{-i\alpha}\ \phi$$

$$U_{\rm cp}^2 = 1$$

- CP conserving case

$$H = g\ \phi\ O + g^* \phi^* O^*$$

for example, $O = \bar{\psi}\psi$

$$U_{\rm cp}\ H\ U_{\rm cp}^{-1} = g\ e^{i\alpha} \phi^* O^* + g^* e^{-i\alpha} \phi\ O$$

where we assumed $U_{\rm cp}\ O\ U_{\rm cp}^{-1} = O^*$

$$g^* = e^{i\alpha}\ g$$

$$\alpha = -2arg.(g)$$

§3-2 Phase Convention

Field redefinition $\phi = e^{i\theta}\tilde{\phi}$

$$H = g\,\phi\,O + g^*\phi^*O^*$$
$$= \tilde{g}\,\tilde{\phi}\,O + \tilde{g}^*\tilde{\phi}^*O^*$$

where

$$\tilde{g} = e^{i\theta}g$$

under $U_{\mathrm{cp}}\,\phi\,U_{\mathrm{cp}}^{-1} = e^{i\alpha}\phi^*$

$$U_{\mathrm{cp}}\,\tilde{\phi}\,U_{\mathrm{cp}}^{-1} = e^{i\alpha}e^{-2i\theta}\tilde{\phi}^*$$

If we choose

$$\alpha = -2arg.(g)$$

$$\theta = -arg.(g)$$

then

$$\tilde{g} = e^{i\theta}g : real$$

$$U_{\mathrm{cp}}\,\tilde{\phi}\,U_{\mathrm{cp}}^{-1} = \tilde{\phi}^*$$

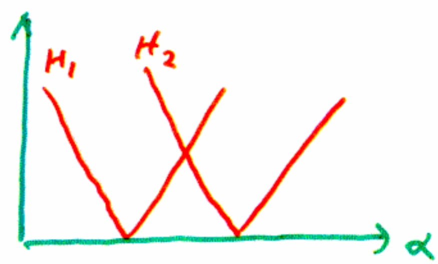
- CP violating case

$$H = g_1 \phi\ O_1 + g_1^* \phi^* O_1^* + g_2 \phi\ O_2 + g_2^* \phi^* O_2^*$$

$$U_{\mathrm{CP}}\ H\ U_{\mathrm{CP}}^{-1} = g_1 e^{i\alpha} \phi^* O_1^* + g_1^* e^{-i\alpha} \phi\ O_1 + g_2 e^{i\alpha} \phi^* O_2^* + g_2^* e^{-i\alpha} \phi\ O_2$$

if $\quad arg.(g_1) \neq arg.(g_2)$

No way to fix α



§3-3 Quark Mixing

$$\begin{pmatrix} u \\ d' \end{pmatrix}, \begin{pmatrix} c \\ s' \end{pmatrix}, \begin{pmatrix} t \\ b' \end{pmatrix}, \cdots$$

$$\longleftarrow n \longrightarrow$$

$$\begin{pmatrix} d' \\ s' \\ b' \\ \vdots \end{pmatrix} = V \begin{pmatrix} d \\ s \\ b \\ \vdots \end{pmatrix}$$

$$H_{cc} = \frac{g}{2\sqrt{2}} W_\mu^+ (\bar{u}, \bar{c}, \bar{t}, \cdots) \gamma^\mu (1 - \gamma^5) V \begin{pmatrix} d \\ s \\ b \\ \vdots \end{pmatrix} + h.c.$$

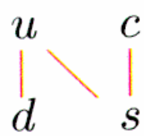
Number of Parameters

$n \times n$ unitary matrix	:	n^2
$n \times n$ orthogonal matrix	:	$\frac{n(n-1)}{2}$
removable phases	:	$2n - 1$

$$n^2 - \frac{n(n-1)}{2} - (2n-1) = \frac{(n-1)(n-2)}{2}$$

- $n = 2$

phase convention

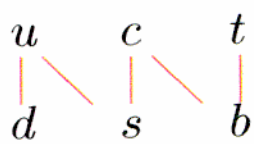


$$\Rightarrow \quad V = \begin{pmatrix} R & \underline{R} \\ * & R \end{pmatrix}$$

$$V = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

- $n = 3$

phase convention



$$V = \begin{pmatrix} R & \underline{R} & \underline{*} \\ * & R & \underline{R} \\ * & * & R \end{pmatrix}$$

parametrization

$$V = \begin{pmatrix} * & \lambda & A\lambda^3(\rho - i\eta) \\ * & * & A\lambda^2 \\ * & * & * \end{pmatrix}$$

$$V=\begin{pmatrix} D_1 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda\frac{D_2+A^2\lambda^4(\rho+i\eta)}{D_1} & D_2 & A\lambda^2 \\ A\lambda^3\frac{D_2-(\rho+i\eta)D_0^2}{D_1D_3} & -A\lambda^2\frac{D_2+\lambda^2(\rho+i\eta)}{D_3} & D_3 \end{pmatrix}$$

where

$$\begin{aligned} D_1 &= \sqrt{1-\lambda^2-A^2\lambda^6(\rho^2+\eta^2)}, \\ D_2 &= \frac{-A^2\lambda^6\rho+\sqrt{D_1^2D_3^2-A^4\lambda^{12}\eta^2}}{1-A^2\lambda^6(\rho^2+\eta^2)}, \\ D_3 &= \sqrt{1-A^2\lambda^4-A^2\lambda^6(\rho^2+\eta^2)}, \\ D_0 &= \sqrt{1-\lambda^2-A^2\lambda^4-A^2\lambda^6(\rho^2+\eta^2)}. \end{aligned}$$

(M.Kobayashi, Progr.Theor.Phys.92(1994),287) other phase conventions

•Kobayashi Maskawa(1973)

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

$$s_i = \sin\theta_i, \quad c_i = \cos\theta_i, \quad i = 1,2,3$$

•PDG (Chau, Keung (1984))

$$V_{PDG} = \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{13}} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta_{13}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta_{13}} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{13}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta_{13}} & c_{23} c_{13} \end{pmatrix}$$

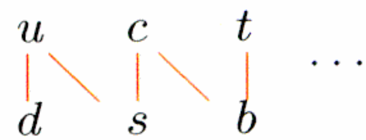
$$s_{ij} = \sin\theta_{ij}, \quad c_{ij} = \cos\theta_{ij}, \quad i,j = 1,2,3$$

$$V_{PDG} = \begin{pmatrix} * & \widehat{\lambda} & \widehat{A}\widehat{\lambda}^3(\widehat{\rho} - i\widehat{\eta}) \\ * & * & \widehat{A}\widehat{\lambda}^2 \\ * & * & * \end{pmatrix}$$

$$\begin{aligned} \widehat{\lambda} &= \lambda \\ \widehat{A} &= A \\ \widehat{\rho} + i\widehat{\eta} &= e^{i\xi}(\rho + i\eta) \end{aligned}$$

$$\xi = O(\lambda^6)$$

• $n \geq 4$



$$V = \begin{pmatrix} R & \underline{R} & \underline{C} & \underline{C} & \cdot \\ C & R & \underline{R} & \underline{C} & \cdot \\ C & C & R & \underline{R} & \cdot \\ C & C & C & R & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \end{pmatrix}$$

$\underline{R}, \underline{C}$: independent parameters

$$\begin{aligned} \text{real part} &: \frac{n(n-1)}{2} \\ \text{imaginary part} &: \frac{(n-1)(n-2)}{2} \end{aligned}$$

§4 Remarks

- Subsequent development

1974 Discovery of the J/Ψ particle

1975 Discovery of the τ lepton

1976 Pakvasa, Sugawara, P.R. D14,305
1976 Maiani, P.L. 62B,183
1976 Ellis, Gaillard, Nanopoulos, N.P. B109,213

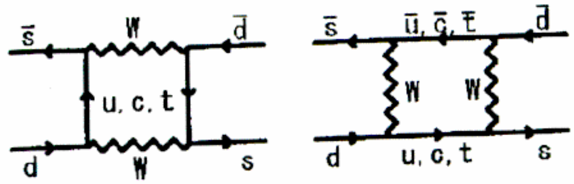
1977 Discovery of the Υ particle

1982 Discovery of W and Z

1994 Discovery of the t-quark

$$|K_L\rangle = \frac{1}{\sqrt{2}}\{(1+\epsilon)\,|K^0\rangle + (1-\epsilon)\,|\bar{K}^0\rangle\}$$

$$\epsilon \approx \frac{1}{2}\frac{i\mathrm{Im}M_{12}}{M_{12} - \frac{i}{2}\Gamma_{12}}$$



$$|\epsilon| \approx \frac{G_F^2 m_W^2 B_K F_K^2 m_K}{6\sqrt{2}\pi^2 \Delta m}\eta A^2\lambda^6[-E(x_c)\eta_c + E(x_c, x_t)\eta_{ct} + A^2\lambda^4(1-\rho)E(x_t)\eta_t]$$

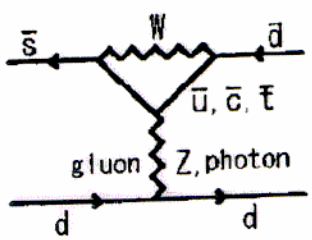
$$x_c = m_c^2/m_W^2, \; x_t = m_t^2/m_W^2$$

$\eta_c, \eta_{ct}, \eta_t$: QCD correction factors

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \epsilon + \epsilon'$$

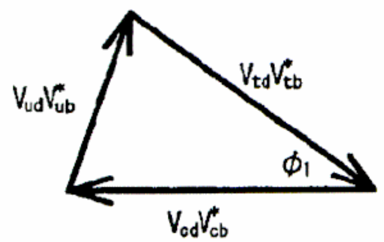
$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \epsilon - 2\epsilon'$$

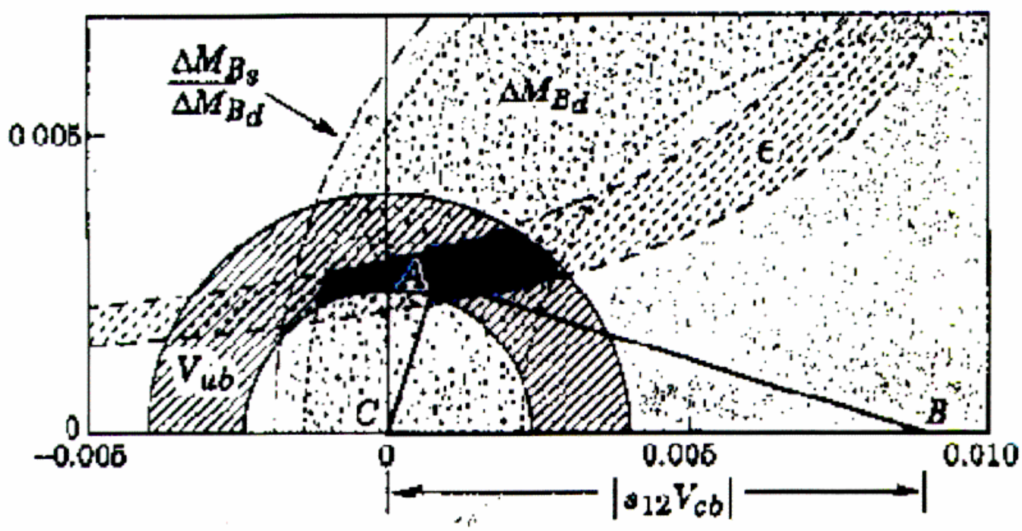
$$\sqrt{2}\epsilon' \approx i e^{i(\delta_2 - \delta_0)}\mathrm{Im}\frac{A_2}{A_0}$$



Unitarity Triangle

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$





(Review of Particle Physics, PDG)

Recent results on ϵ'

$$\begin{aligned} \mathrm{Re}(\epsilon'/\epsilon) &= (28.0 \pm 4.1) \times 10^{-4} \quad \text{KTeV} \\ \mathrm{Re}(\epsilon'/\epsilon) &= (18.5 \pm 7.3) \times 10^{-4} \quad \text{NA48} \end{aligned}$$

Large CP asymmetry

- suppressed in $K_L \to \pi + \pi$ decay
- can be seen in B-meson decay

Asymmetric B-factory

- SLAC
- KEK

$$B_d(\bar{B}_d) \to J/\psi + K_S$$

$$\begin{array}{ccccccccc} B & & \to & & f & & \bar{B} & & \to & & f \\ & \searrow & & \nearrow & & \neq & & \searrow & & \nearrow & \\ & & \bar{B} & & & & & & B & & \end{array}$$

Future

- origin of the Higgs couplings
- possible relation to baryogenesis