1967 – "STANDARD" UNIVERSAL V-A THEORY

In conclusion then we have a reasonably well-defined theory of weak interactions which I summarized at the beginning. Were it not for CP-violation we would have no compelling reason to modify the theory. On the other hand the verification of the theory is still quite limited so that there may well be new surprises for us in the conferences to come.

MEANWHILE

S. WEINBERG "A THEORY OF LEPTONS"

SPONT. BROKEN GAUGE THEORY

1970 – GIM : Extension to quarks
required 4th quark

1973 – DISCOVERY OF NEUTRAL CURRENTS.

NEW STANDARD MODEL

NO CP VIOLATION

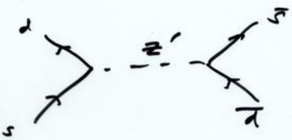
SUPERWEAK IDEA

$K-\bar{K}$ mixing

$$\begin{array}{c|cc} & K & \bar{K} \\ \hline K & M & m' \\ \bar{K} & m' & M \end{array}$$

m' is second-order weak

Small CP-odd contribution to $m \rightarrow \epsilon$



Next we consider a 6-plet model, another interesting model of *CP*-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{weak}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\cos\theta_3 e^{i\delta} \end{pmatrix}. \tag{13}$$

Then, we have *CP*-violating effects through the interference among these different current components. An interesting feature of this model is that the *CP*-violating effects of lowest order appear only in $\Delta S\neq0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

So far we have considered only the straightforward extensions of the original Weinberg's model. However, other schemes of underlying gauge groups and/or scalar fields are possible. Georgi and Glashow's model[4] is one of them. We can easily see that *CP*-violation is incorporated into their model without introducing any other fields than (many) new fields which they have introduced already.

References

1) S. Weinberg, Phys. Rev. Letters **19** (1967), 1264; **27** (1971), 1688.
2) Z. Maki and T. Maskawa, RIFP-146 (preprint), April 1972.
3) P. W. Higgs, Phys. Letters **12** (1964), 132; **13** (1964), 508.
G. S. Guralnik, C. R. Hagen and T. W. Kibble, Phys. Rev. Letters **13** (1964), 585.
4) H. Georgi and S. L. Glashow, Phys. Rev. Letters **28** (1972), 1494.

A. The CKM matrix

In the standard electroweak model, the interactions of the quarks with the charged gauge bosons W are given b

$$g\bar{u}_j V_{jk} \gamma_\lambda (1-\gamma_5) d_k W^\lambda + \text{H.c.} \qquad (3.$$

Here $u_j = (u,c,t)$ are the up-type quarks and $d_j = (d,s,b)$ are the down type. V is the unitary CKM (Cabibbo-Kobayashi-Maskawa) matrix, the 3×3 generalization of the Cabibbo mixing matrix. A convenient parametrization of V due to Maiani (1977) is

$$V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} C_\sigma C_\theta & C_\sigma S_\theta & S_\sigma e^{-i\gamma} \\ -C_\tau S_\theta - C_\theta S_\sigma S_\tau e^{i\gamma} & C_\tau C_\theta - S_\theta S_\sigma S_\tau e^{i\gamma} & C_\sigma S_\tau \\ S_\theta S_\tau - C_\theta C_\tau S_\sigma e^{i\gamma} & -C_\theta S_\tau - C_\tau S_\theta S_\sigma e^{i\gamma} & C_\tau C_\sigma \end{bmatrix}, \qquad (3.$$

ere $C_\theta = \cos\theta$ and $S_\theta = \sin\theta$. As originally noted by bayashi and Maskawa (1973), it is possible by defining phase of the quark fields to eliminate all but one of phases in V. Thus all CP violation in this model de- ds on the phase γ. Experimental data on strange- ticle and B decay rates can determine the magnitudes V_{us}, V_{cb}, and V_{ub}. Given these magnitudes, there is empirical observation (Wolfenstein, 1983) that the cing angles have a hierarchical structure allowing ex- sion in powers of $\lambda = \sin\theta = 0.22$ with

$$\sin\tau = A\lambda^2 , \qquad (3.3a)$$

$$\sin\sigma e^{-i\gamma} = A\lambda^3(\rho - i\eta) . \qquad (3.3b)$$

The analysis of experimental data from decay rates discussed in Sec. III.C is summarized by

$$A = 0.9 \pm 0.1 \quad .81 \pm .03 \qquad (3.$$

$$(\rho^2+\eta^2)^{1/2} = 0.4 \pm 0.2 \quad .38 \pm .04 \qquad (3.$$

where the errors are primarily theoretical.

Expanding V in powers of λ to order λ^3, we see th the matrix has the simple form

$$V = \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} . \qquad (3.6)$$

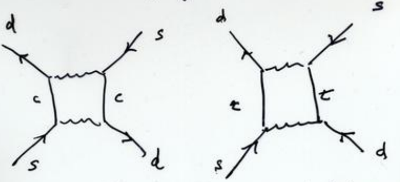
We have chosen a phase convention (that is, a definition of the phases of quark fields) in Eqs. (3.2) and (3.6) such that V is manifestly CP invariant to order λ^2, and CP

The CP-violating part of the $(K^0\text{-}\bar{K}^0)$ mass m: be calculated (Ellis *et al.*, 1976) from the seco box diagram (Fig. 2). The result of the calculatio and Lim, 1981; Buras *et al.*, 1984), includin corrections (Gilman and Wise, 1983; Buras *et a* Flynn, 1990), is well represented for $m_t > m_w$ by

$$\epsilon e^{-i\theta} = 3.4 \times 10^{-3} A^2 \eta B \left[1 + 1.3 A^2 (1-\rho) \left(\frac{m_t}{m_w} \right. \right.$$

$K - \bar{K}$ mixing $\not{CP}$

Due to new physics at a high scale?



$\Delta m_K \sim \lambda^2$

CP Violation

$\sim A^4 \lambda^{10} \cdot \mathrm{Im}\,(1-\rho+i\eta)^2$

$\sim A^4 \lambda^{10} \sin 2\beta$

$\approx 10^{-6} \lambda^2$

CP History

1964 – $\epsilon = 2 \times 10^{-3}$

CP violation in $K-\overline{K}$ mix

1993-2003 $\epsilon' = 4 \times 10^{-6}$

CP in K decay amplitude

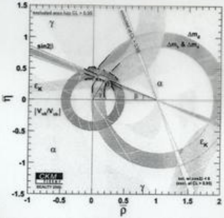
2001 - 2006 $\sin 2\beta = 0.7$

CP in $B-\overline{B}$ mixing

2004 -2006 $A(B \to K^{\pm}\pi^{\mp}) = -0.1$

CP in B decay amplitude

The $(\bar\rho, \bar\eta)$ Plane



Inputs:

- $|V_{ud}|$, $|V_{us}|$
- $|V_{cb}|$
- γ
- α
- Δm_d
- Δm_d & Δm_s
- $|\varepsilon_K|$
- $|V_{ub}|$, BR($B \to \tau\nu$)
- $\sin 2\beta$

$$\bar\rho = .195 \begin{smallmatrix} +.044 \\ -.110 \end{smallmatrix}$$

$$\bar\eta = .326 \begin{smallmatrix} +.058 \\ -.030 \end{smallmatrix}$$

ν Mixing Matrix

$$\approx \begin{pmatrix} -\sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & \theta_{13} e^{i\delta} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ +\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix}$$

$$\theta_{13} < 0.2$$

Reactor + Long Baseline experiments:

$$\theta_{13} \to 0.05$$

LESSONS FROM THE PAST

FITCH-CRONIN

EXPERIMENTALISTS CAN
IGNORE THEORY AND

WEINBERG

THEORISTS CAN
IGNORE EXPERIMENT AND

KOBAYASHI-MASKAWA

THE NEW PHYSICS AT
A HIGH MASS SCALE
MAY NOT BE VERY HIGH