Overviews on

CP Violation

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① Introduction
② Discovery $K_L \to \pi\pi$
③ Standard KM model. &
Other theories tour
④ Electric dipole moment of n, e, atoms..
⑤ More on kaon CPLEAR, KTEV
⑥ Hyperon decay
⑦ B Physics
~~⑧ Baryogenesis~~ Strong CP θ
⑨ Summary

* Introduction

1956 Parity violation proposed to explain

$\Theta - \tau$ puzzle ($K^+ \to 2\pi, 3\pi$)

→ Lee, Yang

1957, before P violation was confirmed,

Landau proposed to replace "space inversion" (parity) by "combined inversion" (CP)

⟶

He also pointed out that

CP violation $\Longleftrightarrow$ complex coupling constants

⟶

1964 Christensen, Cronin, Fitch, Turlay use K^0 beam to study

① regeneration phenomena

② CP invariance ⟶

③ Neutral current

They found that the long-lived, heavier K_L which regularly decays to 3π can also decay to 2π

92. ON THE CONSERVATION LAWS FOR WEAK INTERACTIONS

A variant of the theory is proposed in which non-conservation of parity can be introduced without assuming asymmetry of space with respect to inversion.

Various possible consequences of non-conservation of parity are considered which pertain to the properties of the neutrino and in this connection some processes involving neutrinos are examined on the assumption that the neutrino mass is exactly zero.

1. Combined Parity

As is well known, the unusual properties of K-mesons have created a perplexing situation in modern physics. The correlation between π-mesons in τ-decay ($K^+ \rightarrow 2\pi^+ + \pi^-$) leads to the necessity of assigning a 0^- state to K^+-mesons. This kind of system, however, cannot decay into two π-mesons ($K^+ \rightarrow \pi^+ + \pi^0$). We are thus faced with the dilemma of either assuming that two different K-mesons exist or that the conservation laws are violated in K-meson decay. In the first case one must then explain the identity of masses (which are equal to within two electron masses) and the near coincidence in lifetime of the θ and τ-decays. One may attempt to explain the equality of K-meson masses by postulating, as Lee and Yang[1] have done, the existence of some hitherto unknown symmetry property of nuclear forces which transforms the τ-meson into a θ-meson. If, however, decay involving a neutrino ($K^+ \rightarrow \mu^+ + \nu$, $K^+ \rightarrow \mu^+ + \nu + \pi^0$, $K^+ \rightarrow e^+ + \pi^0 + \nu$) is considered to be essentially the same for particles of various parity a difference in lifetime related to the different rate of τ and θ-decay (≈ 8 per cent and ≈ 25 per cent) should be anticipated. This discrepancy should be not less than 30–40 per cent, a result which seems to be inconsistent with experiment[2]).

Thus we come to the conclusion that the hypothesis of the existence of two different K^+-mesons is contrary to the experimental facts and the only alternative is to assume that the generally accepted conservation laws are violated in K-decay. Since there is no reason to think that the law of conservation of angular momentum is untenable, we are apparently dealing here with a direct violation of the law of conservation of parity.

L. Landau, On the conservation laws for weak interactions, *Nuclear Physics*, 3, 127 (1957).

Л. Д. Ландау, О законах сохранения при слабых взаимодействиях, *Журнал Экспериментальной и Теоретической Физики*, 32, 405 (1957).

L. D. Landau Conservation laws in weak interactions, *Soviet Phys.-JETP*, 5, 336 (1957).

Л. Д. Ландау, Об одной возможности для поляризационных свойств нейтрино, *Журнал Экспериментальной и Теоретической Физики*, 32, 407 (1957).

L. D. Landau, Possible properties of the neutrino spin, *Soviet Phys.-JETP* 5, 337 (1957).

It might seem at first glance that non-conservation of parity implies asymmetry of space with respect to inversion. If however, complete isotropy of space (conservation of angular momentum) is taken into account this type of asymmetry would seem to be extremely strange and in my opinion a simple rejection of parity conservation would create a difficult situation in theoretical physics. I would like to point out a solution of this problem which consists in the following. As is well known, both the law of conservation of parity and charge conjugation invariance undoubtedly hold in strong interactions. Let us now assume that each of these conservation laws does not hold separately in weak interactions. However, invariance with respect to the set of both operations (which we shall call combined inversion) will be assumed to exist. In combined inversion, space inversion and transformation of a particle into an antiparticle occur simultaneously.

It is easy to see that invariance of the interactions with respect to combined inversion leaves space completely symmetrical, and only the electrical charges will be asymmetrical. The effect of this asymmetry on the symmetry of space is no greater than that due to chemical stereo-isomerism.

On the other hand the law of conservation of parity of charged particles will not hold as the operator of combined inversion does not transform charged particles into themselves.

Furthermore, it is easy to see that the constants characterising the particles and anti-particles (masses, lifetimes) should be identical since, as a result of invariance with respect to combined inversion, all processes involving particles and antiparticles should differ from each other only in regard to space inversion. Graphically speaking, a K^--meson is a mirror reflected K^+-meson.

Truly neutral particles, that is, particles which are identical to their antiparticles, transform into themselves in combined inversion. Consequently, with respect to these particles combined inversion leads to a law of conservation of combined parity. It should be emphasised that conservable parity is the product of ordinary parity and charge parity of the particles. Evidently, in this sense the π^0-meson is an odd particle; the K_1^0 (θ^0)-meson which decays into 2 π-mesons is an even particle and the K_2^0-meson predicted by Gell-Mann and Pais[3] and recently discovered experimentally[4] is an odd particle. Combined inversion changes the sign of the magnetic field of a photon but does not change that of the electric field. The ordinary parities of electric and magnetic multipoles are reversed for combined inversion.

It is easy to show from the foregoing that despite the absence of ordinary parity the particles cannot possess dipole moments. Indeed, the only vector which can be constructed from ψ-operators for a particle at rest is its spin vector which is even with respect to inversion and odd with respect to charge. It is consequently odd with respect to combined inversion and, in accord with the foregoing regarding the electromagnetic field, it defines only a magnetic but not an electric moment.

Lee and Yang[5]† have shown that non-conservation of parity leads to correlations in a number of hyperon production and decay processes. It can be

† I would like to sincerely thank the authors for sending me a preprint of their paper.

shown that a consequence of invariance with respect to combined inversion is that the weak interaction operators in the Lagrangian contain real coefficients. This circumstance, however, does not appreciably modify the qualitative picture which is obtained in the general case of non-conservation of parity. Therefore asymmetry of hyperon decay with respect to the plane of their creation, which has been predicted by Lee and Yang[3], will also hold in this case.

I would like to express my deep appreciation to L. Okun, B. Ioffe and A. Rudik for discussions from which the idea of this part of the present paper emerged.

2. Properties of the Neutrino

Rejection of the law of conservation of parity entails the possibility of the existence of new properties of the neutrino. The Dirac equation for the case of zero mass splits into two independent pairs of equations. It will be recalled that in the usual theory one cannot confine oneself to a single pair of equations since both pairs transform into each other as a result of space inversion. If, however, we restrict out attention to combined inversion we arrive at the possibility of describing the neutrino by a single pair of equations. In the sense of the usual scheme this would signify that the neutrino is always polarised in the direction of its motion (or in the opposite direction). The polarisation of the antineutrino is correspondingly reversed. According to this model the neutrino is not a truly neutral particle and this agrees with the fact that double β-decay has not been observed experimentally and especially with the results of experiments on induced β-decay. We shall call this kind of neutrino a longitudinally polarised neutrino or briefly a longitudinal neutrino.

In the usual theory the neutrino mass is zero, so to say, accidentally. Thus, account of neutrino interactions automatically leads to the appearance of a definite, albeit vanishingly small, rest mass. The mass of the longitudinal neutrino, on the other hand, vanishes automatically and this situation cannot be altered by the existence of any type of interaction.

The longitudinal neutrino concept appreciably reduces the possible number of types of weak interaction operators. Consider, for example, the decay of a μ-meson into an electron and two neutrinos. In the usual manner we represent the interaction operator as the product of operators consisting of μ-meson and electron ψ-operators on the one hand and ψ-operators of the two neutrinos on the other. For the longitudinal neutrino only one combination can be made from the two neutrino operators—(a scalar with respect to rotation; the operation of ordinary inversion is not applicable), as it is well known that the tensor combination of two identical operators obeying Fermi statistics is equal to zero. In this case two combinations, scalar and pseudo-scalar (in the usual sense of the word), can be constructed for a μ-meson and electron.

If a neutrino and anti-neutrino are emitted in μ-meson decay the situation changes. Only a four-dimensional vector can then be constructed from the longitudinal neutrino and anti-neutrino operators. In this case two combinations —vector and pseudo-vector—can be made from the μ-meson and electron ope-

$|\bar{s}d\rangle$ $\bar{K}^0 = |s\bar{d}\rangle$

The K^0 is characterized by an additive quantum number S conserved in strong and electromagnetic interactions but violated by the weak interaction.
Since S is not a good quantum number K^0 with $S = 1$ mixes with $\bar{K}^0$ with $S = -1$, so one expected the eigenstates to be CP eigenstates

$$
\begin{aligned}
|K_1\rangle &= \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right), \\
|K_2\rangle &= \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right), \\
|\bar{K}^0\rangle &\equiv CP\,|K^0\rangle.
\end{aligned}
$$

The observed eigenstates were K_S (lifetime $\tau_S = 0.9 \times 10^{-10}$ sec) and K_L ($\tau_L = 5.2 \times 10^{-8}$ sec) with $m_L - m_S = 0.48\,\Gamma_S \sim 10^{-5}$eV.
The primary decays were

$$
\begin{aligned}
K_S &\to \pi^+\pi^- \text{ and } \pi^0\pi^0, \\
K_L &\to 3\pi,
\end{aligned}
$$

consistent with the CP assignment $K_S = K_1$ and $K_L = K_2$.
The discovery in 1964 was that K_L also decayed into $\pi^+\pi^-$ with a small branching ratio.

$$K_L \sim K_2 + \varepsilon K_1$$
$$K_S \sim K_1 + \varepsilon K_2$$

ε : CP violation

indirect (mixing) CPX

$$
\begin{tikzcd}
 & \varepsilon K_1 \arrow[dr] & \\
K_L \arrow[ur] \arrow[dr] & & 2\pi\ (\pi^+\pi^-, \pi^0\pi^0) \\
 & K_2 \arrow[ur, "\varepsilon'"'] &
\end{tikzcd}
$$

direct CPX

Experimentally

$$\eta_{+-} \equiv \frac{\langle \pi^+\pi^- | \mathcal{H}_w | K_L\rangle}{\langle \pi^+\pi^- | \mathcal{H}_w | K_S\rangle} = |\eta_{+-}|\, e^{i\phi_{+-}}$$

$$\eta_{00} = \frac{\langle \pi^0\pi^0 | \mathcal{H}_w | K_L\rangle}{\langle \pi^0\pi^0 | \mathcal{H}_w | K_S\rangle} = |\eta_{00}|\, e^{i\phi_{00}}$$

* Describe CP violation in decay

$$A(K^0 \to \pi^+\pi^-) = \frac{1}{\sqrt{3}}\left(A_2 e^{i\delta_2} + \sqrt{2} A_0 e^{i\delta_0}\right)$$

$$A(K^0 \to \pi^0\pi^0) = \sqrt{\frac{2}{3}}\left(-\sqrt{2} A_2 \underbrace{e^{i\delta_2}} + A_0 \underbrace{e^{i\delta_0}}\right)$$

strong phase shifts

$$\left.\begin{matrix} \mathrm{Im}A_0 \\ \mathrm{Im}A_2 \end{matrix}\right) \Rightarrow \text{CP violation}$$

3 CP violation parameters : M' $\mathrm{Im}A_0$ $\mathrm{Im}A_2$

but they are related by a redefinition of phase related the strangeness quantum number

$\Rightarrow$ Only two combinations are physical observables (rephase inv.)

$$\epsilon, \ \epsilon'$$

$\leftarrow$ relative phase betw' mixing and decay

$$\epsilon = \bar{\epsilon} + i\frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}$$

$$\epsilon' = \frac{-1}{\sqrt{2}}\left(\frac{\mathrm{Im}A_0}{\mathrm{Re}A_0} - \frac{\mathrm{Im}A_2}{\mathrm{Re}A_2}\right)\omega e^{i(\delta_2 - \delta_0 + \frac{\pi}{2})}$$

$\hookrightarrow$ relative phase betw' two decay channels

$0.02 \sim \omega = \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0}$ $\Delta I = \frac{1}{2}$ rule.

$$\eta_{+-} \cong \epsilon + \epsilon'$$

$$\eta_{00} \cong \epsilon - 2\epsilon'$$

phase of $\epsilon' \sim e^{i(\frac{\pi}{2} - \delta_0 + \delta_2)} \cong e^{i45^\circ} \cong$ phase of $\bar{\epsilon}$

by accident

* Describe how $K^0 - \bar{K}^0$ (or $D^0 \bar{D}^0$, $B^0 - \bar{B}^0$) mixes

$$i\hbar \frac{\partial}{\partial t} \psi = \mathcal{H} \psi \qquad \text{(in } K^0 - \bar{K}^0 \text{ basis)}$$

$$\mathcal{H} = \hat{M} - \frac{i}{2} \hat{\Gamma} \equiv \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}$$

hermiticity

CPT or CP inv. $\Rightarrow$ $M_{11} = M_{22}$ $\quad \Gamma_{11} = \Gamma_{22}$

T or CP inv. $\Rightarrow$ $\mathrm{Im}\, M_{12} = 0 = \mathrm{Im}\, \Gamma_{12}$

Or in $K_1 - K_2$ basis

$$\mathcal{H} = \begin{pmatrix} m_1 & im' \\ -im'^* & m_2 \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \gamma_1 & i\gamma' \\ -i\gamma'^* & \gamma_2 \end{pmatrix}$$

CPT $\Rightarrow$ m', γ' are real

CP violation in m' and γ' $\qquad m' \gg \gamma'$

$\Rightarrow$

$$K_S = K_1 + \epsilon K_2 \qquad \epsilon = \frac{+i(m' - i\gamma'/2)}{\Delta m - \frac{i}{2}\Delta\Gamma}$$

$$K_L = K_2 + \epsilon K_1$$

For kaon $-\frac{\Delta\Gamma}{2} \cong \frac{\gamma_1}{2} \cong \Delta m \equiv m_2 - m_1 \qquad \Delta\Gamma \equiv \gamma_2 - \gamma_1$

$$\epsilon \cong \frac{1}{\sqrt{2}} e^{i\pi/4} \frac{m'}{\Delta m}$$

ε was measured in 1964. $\sim 2.2 \times 10^{-3}$

Many groups have been trying to measure ε'

by measuring $\left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 \cong 1 + 6\, \mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$

$\cong 1 + 6 \left|\frac{\varepsilon'}{\varepsilon}\right|$

In 1993

	NA31 (CERN)	$\mathrm{Re}\,\frac{\varepsilon'}{\varepsilon} = 23.0 \pm 6.5$	$\cdot 10^{-4}$
	E731 (FNAL)	7.4 ± 5.9	$\cdot 10^{-4}$
1999	KTEV (FNAL)	28.0 ± 4.1	$\cdot 10^{-4}$
	NA48 (CERN)	$18.5 \pm 4.5 \pm 5.8$	$\cdot 10^{-4}$

both groups have more data to be analyzed

Average	20 ± 6	$\cdot 10^{-4}$

$\longrightarrow \varepsilon' \sim 5 \cdot 10^{-6}$

KLOE (DAFNE)

$\Longrightarrow$ Evidence for direct CP violation in K decay

Theory

Landau : CP violation $\longleftrightarrow$ complex couplings

catch : not every complex phase in field theory has physical significance.

many are just fixing convention

$\Rightarrow$ Identify the physically relevant phases

re-phase invariants ....

1973 : Kobayashi + Maskawa Prog. of Theo. Phys. 49 (73) 652

No CP violation in 2 generation Weinberg model.

$\rightarrow$ need more fields to get complex couplings

① 2 Higgs doublet model

② 3 generation fermion model $\longrightarrow$ Standard Model.

$\longrightarrow$ KM model

In KM model, CPX in the Yukawa couplings

$\rightarrow$ after diagonalization of quark masses

$\rightarrow$ Charge current mixing matrix (3×3)

$\rightsquigarrow$ need all three generations involved in order to achieve CP violation

$\rightsquigarrow$ CP viol disappear if $m_i = m_j$ for u, or d

or if $\theta_i = 0$ for any i

$\rightsquigarrow$ many automatic suppression factors even though the CP phase may not be small.

$\rightsquigarrow$ phenomenologically, the best parametrization is to put the complex phase at the smallest components: $\longrightarrow$ Wolfenstein parametrization

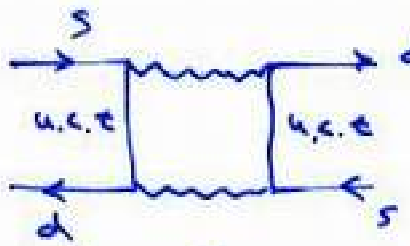
$\longrightarrow$ Chau-Keung parametrization

$\longrightarrow$

In This model

$\epsilon \rightarrow \bar{\epsilon} \rightarrow m'$

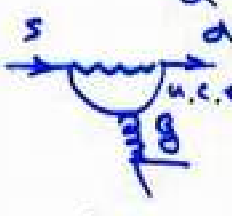
$\Delta S = 2$



+ others

ϵ': $\frac{\mathrm{Im} A_0}{\mathrm{Re} A_0} - \frac{\mathrm{Im} A_2}{\mathrm{Re} A_2}$

$\Delta S = 1$ "penguins"



gluon penguin

electroweak penguin

$$e^{-i\gamma}$$

$$\mathbf{V} = \begin{array}{cc} \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} & \begin{matrix} u \\ c \\ t \end{matrix} \\ \begin{matrix} d & \qquad\qquad s & \qquad\qquad b \end{matrix} & \end{array}$$

$$e^{-i\beta}$$

$\lambda \sim 0.2$

In KM

① $\varepsilon \sim 2.2 \times 10^{-3}$ constrains (ρ, η)

② ε' uncertain : cancellation betw' gluon penguin
& electroweak penguin

$$0.26 \times 10^{-4} \le \frac{\varepsilon'}{\varepsilon} \le 28.8 \cdot 10^{-4}$$

Buras
hep-ph/9908355

$\downarrow$

not very useful in constraining KM parameters

More Theory Tour (Inventing complex couplings)

1973 KM → ① 3 generation fermions

② 2 Higgs doublets

1974 T. D. Lee → Spontaneous CP violation

e.g. 2 Higgs doublet

CP viol. mediated by neutral Higgs exchange

1974 Mohapatra + Pati → extend gauge sector

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

CP viol. mediated by gauge boson W_R exchange

1976 : Weinberg : use discrete symmetry to avoid large flavor changing neutral currents

→ need at least 3 Higgs doublets

CP viol. mediated by charged Higgs exchange

1977 : Branco : Weinberg model with spontaneous CP violation

(Kill the KM mechanism naturally)

1983 : $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model with spontaneous CP violation : (DC and Bigi + Branco + Frere)

Other ideas

* Thirring : CP violation from higher dimension (1972)

* Georgi + Pais : CP violation as a quantum effect. Or. radiative CP violation

→ a pseudo-Goldstone boson

(1974)

→ realistic model using 2 Higgs doublets (1995)

some finetuning are needed

light pseudoscalar escape detection

* CP as a discrete gauge symmetry

: some GUTs example

1992-93 Choi, Kim. Nelson, Kaplan ...

* Many superweak models ($\varepsilon' \simeq 0$) proposed over the years ...

* CP violation in SUSY Standard model

New sources : soft SUSY breaking terms

R symmetry breaking terms.

* Electric dipole moment (edm) is an T-odd P-odd operator.
So assuming CPT $\Rightarrow$ CP violation

Experimentally : edm of n, e, μ, atom

① edm of n $\quad d_n < (6-10)\times 10^{-26}$ e-cm

PRL 82 (99) 904

Source ① d_q (d_u, d_d and maybe d_s) or d_q^c

② CP violating interaction betw' quarks in n

③ Strong CP θ - parameter

* Ignore θ, KM model $\rightarrow$ $d_n \sim 10^{-31} - 10^{-32}$ e-cm

* Many alternative CP violation models give large d_q that contributes to d_n

$\longrightarrow$ strong constraint on models

* Some models even give large contribution at 2-loop level when 1-loop contribution is accidentally suppressed. Barr-Zee

Chang-Keung-Pilaftsis

Experimentally, factor of 2-3 improvement possible

② edm of e^- (upper limit) from limit on atomic edm

$$d_e < 4\times10^{-27}\ \text{e-cm} \quad \text{from Tl atom}$$

Commis (1994)

* If atomic edm ≠ 0, hard to interpret into de, but upper limit is easier assuming no accidental cancellation.
* aided by some nuclear physics enhancement factor ($d(\text{Tl}) < 2\times10^{-24}$ e-cm, enhancement ~600)

One order of magnitude improvement by Commins to announce soon....

* KM model: 4 loop effect $d_e < 10^{-40}$ e-cm
* de is a cleaner constraint on models than dn

③ edm of μ $\qquad d_\mu < 10^{-18}$ e-cm

④ edm of atom

$$d(^{199}\text{Hg}) < 9\times10^{-28}\ \text{e-cm}$$

→ stronger limit on d_q^c than using d_n

CP LEAR (CERN)

$$p\bar{p} \to K^- \pi^+ K^0 \qquad BR \sim 10^{-3}$$
$$\qquad\quad \underbrace{K^+ \pi^-}_{\text{tag}} \underbrace{\bar{K}^0}_{\text{initial}}$$

① tag final kaon $\quad K^0 \to \ell^+ \nu \pi^-$

$$\bar{K}^0 \to \underbrace{\ell^- \bar{\nu} \pi^+}_{\text{tag}}$$

$$A_T = \frac{\text{rate}_0(\bar{K}^0 \to K^0) - \text{rate}_0(K^0 \to \bar{K}^0)}{\text{rate}_0(\bar{K}^0 \to K^0) + \text{rate}_0(K^0 \to \bar{K}^0)} = (6.6 \pm 1.3 \pm 1.0) \cdot 10^{-3}$$

Direct measurement of T violation

② time evolution of asymmetry

$$A_{+-}(t) = \frac{\Gamma(K(t) \to \pi^+\pi^-) - \Gamma(\bar{K}^0(t) \to \pi^+\pi^-)}{\Gamma(K(t) \to \pi^+\pi^-) + \Gamma(\bar{K}^0 \to \pi^+\pi^-)}$$

$$\propto |\eta_{+-}| \cos(\Delta m t - \phi_{+-})$$

$$\Rightarrow |\eta_{+-}| = 2.305 \pm 0.043_{st} \pm 0.031_{sys}\, 10^{-3}$$

$$\phi_{+-} = 43.7 \pm 0.9_{st} \pm 0.6_{sys} \pm 0.4_{(\Delta m)}$$

③ Test CPT

④ Test lost of quantum decoherence

An interesting KTeV observation

$K_L \to \pi^+\pi^-\gamma^*$
$\hookrightarrow e^+e^-$

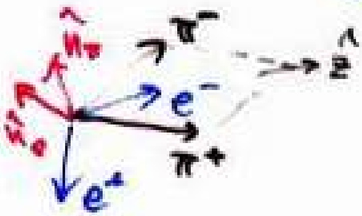
BR ~ 3×10^{-7}

γ^* can be bremsstrahlung (electric multipole, CP+)
or direct M1 emission (magnetic multipole, CP −)

The two modes are roughly the same size and if $\gamma^* \to e^+e^-$ internally, they can interfere.

$\Rightarrow \quad \langle \hat{n}_\pi \times \hat{n}_e \cdot \hat{z} \rangle \neq 0$

CP odd
T odd



define $\sin\phi \equiv \hat{n}_\pi \times \hat{n}_e \cdot \hat{z}$
$\cos\phi \equiv \hat{n}_\pi \cdot \hat{n}_e$

$\Rightarrow \quad \frac{d\Gamma}{d\phi} \sim (-\Sigma_1 \sin 2\phi +$

KTeV measure $A \equiv -\frac{2}{\pi}\Sigma_1 = (13.6 \pm 2.5 \pm 1.2)\%$
(1999)

agree with earlier calculation
Sehgal (1992)

agree with ε

Hyperon decays

Fermilab exp E871 has $2\times10^9\ \Xi^-$ and $\frac{1}{2}\times10^9\ \Xi^+$ → in the process of analyzing CP violation in the data.

$$\Xi^- \to \Lambda\pi^-$$
$$\hookrightarrow p\pi^-$$

$$\Lambda \to p\pi^- \longrightarrow \text{Amp} \sim \underset{\text{S-wave}}{S} + \underset{\text{P-wave}}{P}\,\hat{\sigma}\cdot\hat{q}$$

$B_i \to B_f \pi$

$$\to \frac{d\Gamma}{d\Omega} = \frac{\Gamma}{4\pi}\left\{1 + \alpha\hat{s}_i\cdot\hat{q} + \hat{s}_f\left[(\alpha + \hat{s}_i\cdot\hat{q})\hat{q} + \beta\hat{s}_i\times\hat{q} + \gamma\,\hat{q}\times(\hat{s}_i\times\hat{q})\right]\right\}$$

E871 arrange such that Ξ is unpolarized then

final Λ polarization $\vec{P}_\Lambda = \alpha_\Xi \hat{q}_\Lambda$ (for $\hat{s}_i \sim \vec{P}_\Xi = 0$)

In Λ decay $\quad \frac{4\pi}{\Gamma}\frac{d\Gamma}{d\Omega} = 1 + \alpha_\Lambda \vec{P}_\Lambda\cdot\hat{q} = 1 + a\,\hat{p}_\Lambda\hat{q}_p$

$$a = \alpha_\Lambda\alpha_\Xi \qquad \alpha = 2\frac{\mathrm{Re}(S^*P)}{|S|^2+|P|^2} \quad \text{S-P interference}$$

E871 measure $\frac{a-\bar{a}}{a+\bar{a}} \sim A_\Lambda + A_\Xi$

$$A = -\underbrace{\tan(\delta_{11}-\delta_1)}_{\text{strong phase difference}}\ \underbrace{\sin(\theta^P - \theta^S)}_{\text{weak phase difference}}$$

E871 expect to reach $A \sim 10^{-4}$ to 10^{-5}

Theoretical prediction

	KM	Weinberg C-H model	L-R model
$A(\Lambda)$	$-(1-5)\times10^{-5}$	-2.5×10^{-5}	$-6\cdot10^{-4}$
$A(\Xi)$	$(1-10)\times10^{-6}$	3.8×10^{-5}	$2.6\cdot10^{-6}$

D.C. He & Pakvasa PRL 74 (95)

Also flavor changing squark mixing can give rise to large $A(\Lambda)$ as large as 10^{-3}

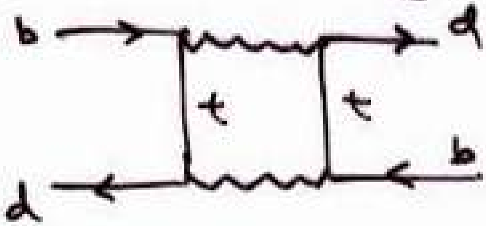
He & Murayama & Pakvasa & Valencia P.R.D (2000)

E871 is analyzing their data now (~ 40% done)

B Physics

* CP violation can naturally be large in B-$\bar{B}$ system : best place to test KM model

* B_d-$\bar{B}_d$ mixing : leading box diagram is top



$$\sim \left(V_{td}^{*} V_{tb}\right)^2 = A^2 \lambda^6 \left(1-\rho+i\eta\right)^2$$
$$= A^2 \lambda^6 \left((1-\rho)^2+\eta^2\right) e^{2i\beta}$$

time dependence of CP asymmetry in decay into a CP eigenstate $CP|f\rangle = \eta_f |f\rangle$ $\quad \eta_f = \pm 1$

$$a_{CP}(t) \equiv \frac{\Gamma(B_q^0 \to f) - \Gamma(\bar{B}_q^0 \to f)}{\Gamma(B_q^0 \to f) + \Gamma(\bar{B}_q \to f)} \qquad q = d, s$$

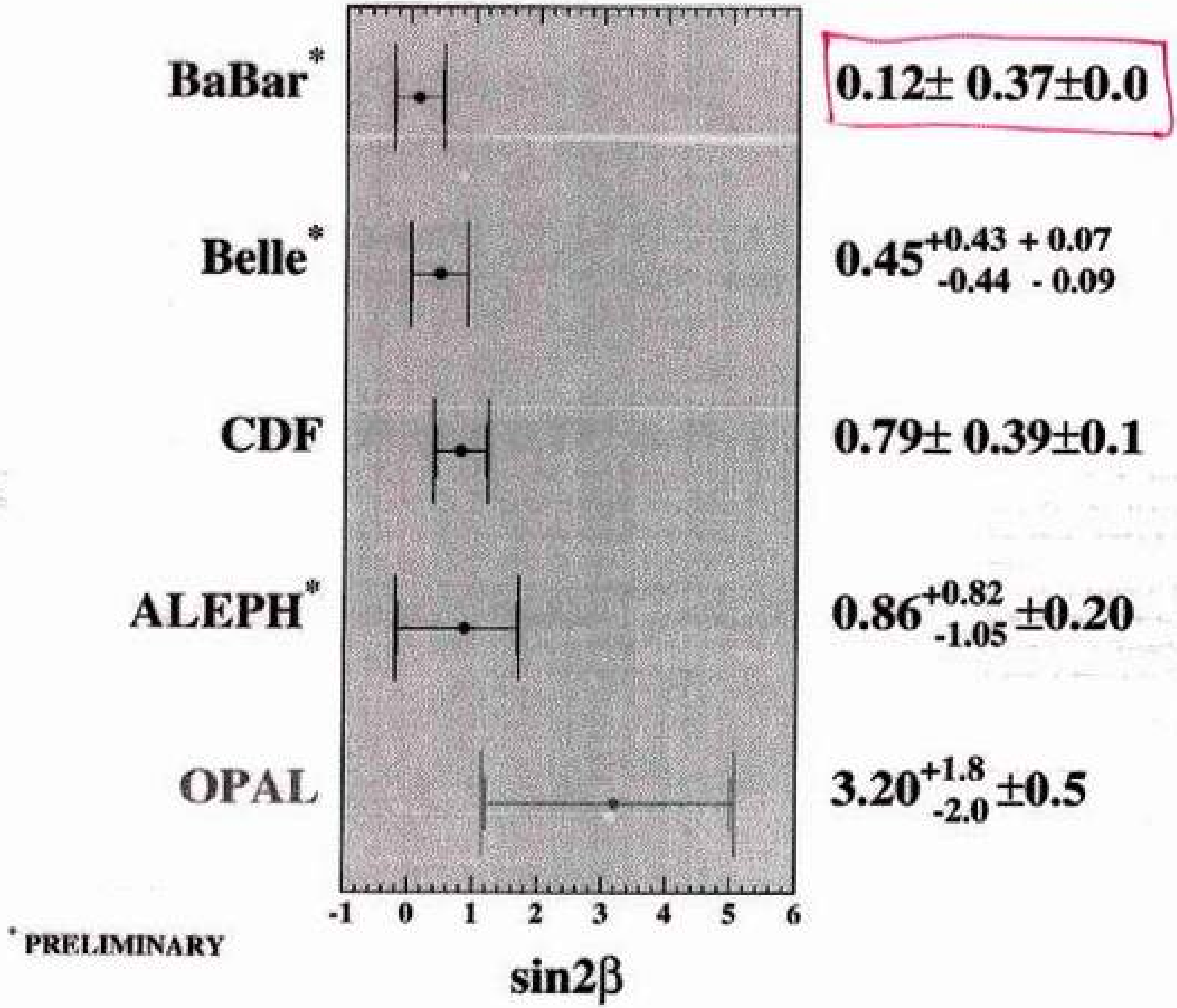
$$\propto A_q^{dir} \cos \Delta m t + A_q^{mix} \sin \Delta m t$$

$$A_q^{mix} = \frac{2\,\mathrm{Im}\, \xi_f^q}{1 + |\xi_f^q|^2}$$

mixing phase

$$\xi_f^{q=d} = -\eta_f\, e^{-i2\beta} \left(\frac{A(\bar{B}_q \to f)}{A(B_q \to f)} \right) \rightarrow \text{decay phase} \times 2$$

$$A_{q=d}^{mix} \sim -\eta_f \sin\left(2(\beta - \phi_f)\right)$$



BaBar*
0.12± 0.37±0.0
Belle*
$0.45^{+0.43}_{-0.44}{}^{+0.07}_{-0.09}$
CDF
0.79± 0.39±0.1
ALEPH*
$0.86^{+0.82}_{-1.05}\pm0.20$
OPAL
$3.20^{+1.8}_{-2.0}\pm0.5$
-1 0 1 2 3 4 5 6
* PRELIMINARY
sin2β

Ali + London
hep-ph/0002167

Table 1: *Data used in the CKM fits*

Parameter	Value
λ	0.2196
$\lvert V_{cb}\rvert$	0.0395 ± 0.0017
$\lvert V_{ub}/V_{cb}\rvert$	0.093 ± 0.014
$\lvert\epsilon\rvert$	$(2.280 \pm 0.013) \times 10^{-3}$
ΔM_d	$(0.473 \pm 0.016)\ (ps)^{-1}$
ΔM_s	$> 14.3\ (ps)^{-1}$
$\overline{m_t}(m_t(pole))$	(165 ± 5) GeV
$\overline{m_c}(m_c(pole))$	1.25 ± 0.05 GeV
$\hat{\eta}_B$	0.55
$\hat{\eta}_{cc}$	1.38 ± 0.53
$\hat{\eta}_{ct}$	0.47 ± 0.04
$\hat{\eta}_{tt}$	0.57
$\hat{B}_K$	0.94 ± 0.15
$f_{B_d}\sqrt{\hat{B}_{B_d}}$	215 ± 40 MeV
ξ_s	1.14 ± 0.06

In the fit, we allow ten parameters to vary: $\bar{\rho}$, $\bar{\eta}$, A, m_t, m_c, η_{cc}, η_{ct}, $f_{B_d}\sqrt{\hat{B}_{B_d}}$, $\hat{B}_K$, and ξ_s. The allowed (95% C.L.) $\bar{\rho}$-$\bar{\eta}$ region is shown in Fig. 1. The triangle drawn is to facilitate our discussions, and corresponds to the central values of the fits, $(\alpha, \beta, \gamma) = (93^\circ, 24^\circ, 63^\circ)$.

The CP angles α, β and γ can be measured in CP-violating rate asymmetries in B decays. These angles can be expressed in terms of $\bar{\rho}$ and $\bar{\eta}$. Thus, different shapes of the unitarity triangle are equivalent to different values of the CP angles. Referring to Fig. 1, the allowed ranges at 95% C.L. are given by

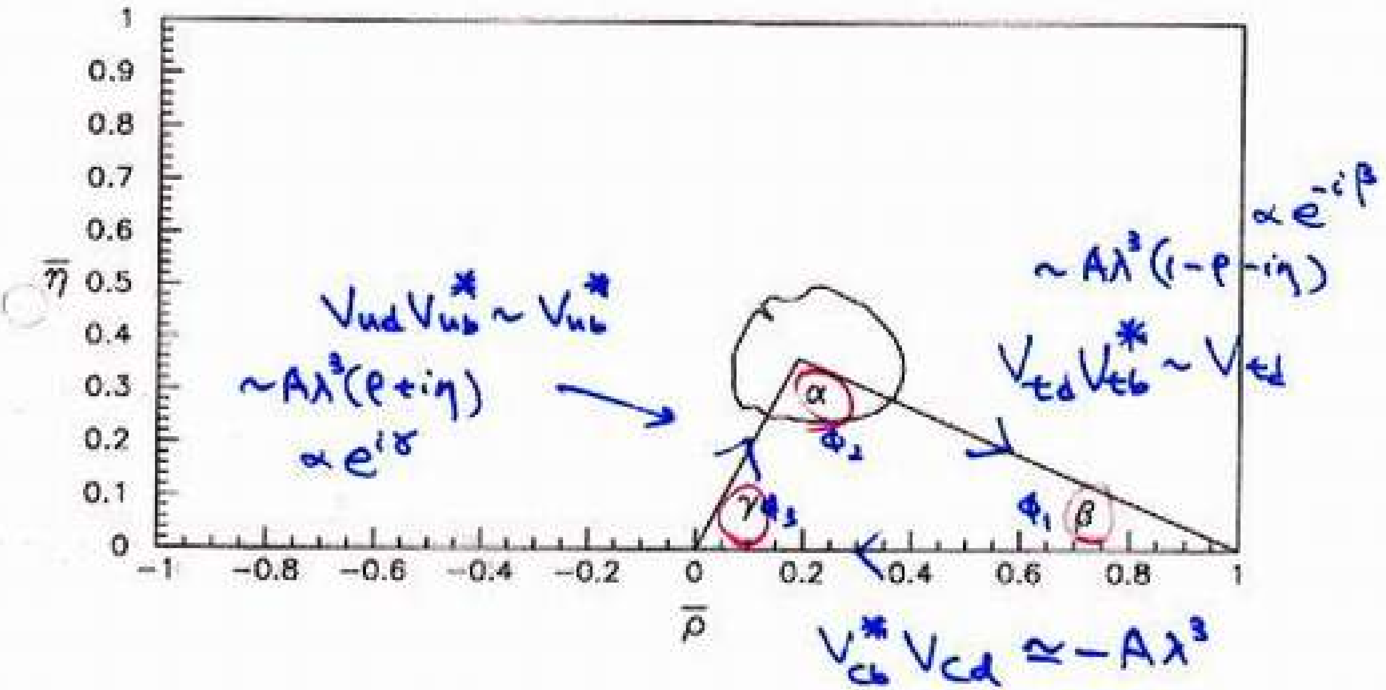
$$75^\circ \leq \alpha \leq 121^\circ \ , \quad 16^\circ \leq \beta \leq 34^\circ \ , \quad 38^\circ \leq \gamma \leq 81^\circ \ , \qquad (12)$$

or, equivalently,

$$-0.88 \leq \sin 2\alpha \leq 0.50 \ , \ \boxed{0.53 \leq \sin 2\beta \leq 0.93 \ ,} \ 0.38 \leq \sin^2\gamma \leq 0.98 \ . \quad (13)$$

Unitary triangle of KM

$f_{B_d}\sqrt{\hat{B}_{B_d}} = 215 \pm 40$ MeV, $B_K = 0.94 \pm 0.15$



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

For $B_d \to J/\psi\, K_S$

$b \to c\bar{c}s \longrightarrow \phi_f = 0$

tree dominated

$\Rightarrow$ through $A^{\text{mix}} \to$ measure $\sin 2\beta$

☆ CDF, LEP (Aleph, OPal), Belle, Babar had measured $\sin 2\beta$ $\xRightarrow{\text{data}}$

☆ Current theoretical best fit give roughly $\underset{\text{fit}}{\Longrightarrow}$

$$0.53 \le \sin 2\beta \le 0.93$$

Babar gives $0.12 \pm 0.37 \pm 0.0$

* If $\sin 2\beta|_{exp} <$ global fit

where can the new physics be imbedded ?

* How to measure angle γ ? $\underset{\gamma}{\Rightarrow}$

① $B_s \bar{B}_s$ mixing CDF $\to \Delta M(B_s)$

② $B^0 \to \pi^+\pi^-$

$K\pi$

$B^0 \to \rho\pi$

In $B \to \pi\pi$ $\quad b \to u\bar{u}d$

If only tree graph contributes to decay

then $$A^{mix}_{q=d}(\pi^+\pi^-) = -\sin(-2(\beta+\gamma))$$

mixing decay

However, unfortunately, penguin graph also give important contribution, and Penguin have different weak phase as well as strong phase.

$\longrightarrow$ need to control the penguin

$\longrightarrow$ Isospin analysis (Gronau, London, Rosner ...

3 modes $\pi^+\pi^-$, $\underbrace{\pi^0\pi^0}_{\text{hard}}$ & $B^+ \to \pi^+\pi^0$

Alternative

use $B \to \rho\pi$

$B \to K\pi$

Summary.

* The experimental activities related to CP violation is making progress on almost all front
  - ✓ EDM
  - ✓ hyperon decays
  - ✓ kaon decays
  - ✓ B decays → CDF, CLEO
    Belle, Babar
    maybe
    LHCB, BTeV

* Hopefully some surprising result arises from some corner

  Otherwise, the B data will continue to put strong constraint on theories beyond SM.