K. R. Schubert, TU Dresden
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CP Violation in K and B Meson Decays, an Introduction

Four Types of CP Violation:

I: CPV in Mixing, Re(ε_K), Re(ε_B)

II: CPV in Mixing-Decay Interference, Im(ε_0), sin2β

III: Direct CPV in Decays into one Final State, Re(ε')

IV: Direct CPV in Decays into $\geqslant$ 2 Final States, Im(ε')

Two more examples for Type IV

Type I: CP Violation in Meson-Antimeson Mixing

Only four systems, $\bar{s}d \leftrightarrow s\bar{d}\,,\quad c\bar{u} \leftrightarrow \bar{c}u\,,\quad \bar{b}d \leftrightarrow b\bar{d}\,,\quad \bar{b}s \leftrightarrow b\bar{s}\,.$

Evolution given by Schrödinger equation, $e.g.\quad \psi = \psi_1 K^0 + \psi_2 \overline{K}^0$:

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} = \begin{pmatrix}\mu_{11} & \mu_{12}\\ \mu_{21} & \mu_{22}\end{pmatrix}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}, \qquad \begin{aligned} m_{ij} &= (\mu_{ij} + \mu_{ij}^{+})/2 \\ \Gamma_{ij}/2 &= (\mu_{ij} - \mu_{ij}^{+})/2i \end{aligned}$$

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} = \left[\begin{pmatrix}m_{11} & m_{12}\\ m_{21} & m_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\ \Gamma_{21} & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}$$

Matrix μ_{ik} has 8 real parameters. CPT requires same mass and width for K^0 and $\overline{K}^0$, $m_{11} = m_{22} = m,\quad \Gamma_{11} = \Gamma_{22} = \Gamma.$ $8 \rightarrow 6$.
m_{12} and Γ_{12} describe transitions from $\overline{K}^0$ to K^0 (Gell-Mann & Pais 1955), m_{21} and Γ_{21} from K^0 to $\overline{K}^0$.
Hermiticiy: $m_{21} = m_{12}^{*}\,,\quad \Gamma_{21} = \Gamma_{12}^{*}\,.$
Only 5 parameters are observable, because of arbitrary and unobservable phase rotations.

$K^0 \to K^0 e^{i\Phi}$ and $\overline{K}^0 \to \overline{K}^0 e^{-i\Phi}$ leads to $m_{jj} \to m_{jj}$, $\Gamma_{jj} \to \Gamma_{jj}$, but to $m_{12} \to m_{12} e^{2i\Phi}$, $\Gamma_{12} \to \Gamma_{12} e^{2i\Phi}$ with the same Φ. The 5 observables are: m, Γ, $|m_{12}|$, $\mathrm{Re}(\Gamma_{12}/m_{12})$, $\mathrm{Im}(\Gamma_{12}/m_{12})$.

$i\partial\psi_i/\partial t = \mu_{ik}\psi_k$ has a well-defined solution $\psi(t)$ for each given $\psi(0)$. There are 2 and only 2 states which have a t-independent flavour composition. With $|p|^2 + |q|^2 = 1$:

$$K_S^0(t) = \left(pK^0 + q\overline{K}^0\right) \cdot e^{-\gamma_S t}, \quad \gamma_S = i\, m_S + \Gamma_S/2,$$
$$K_L^0(t) = \left(pK^0 - q\overline{K}^0\right) \cdot e^{-\gamma_L t}, \quad \gamma_L = i\, m_L + \Gamma_L/2.$$

q/p is not an observable, only $|q/p|$. The 5 observables m_S, m_L, Γ_S, Γ_L, $|q/p|$ are given by the 5 parameters of μ_{ik} . Explicit formulae in the literature, an example:

$$\frac{q}{p} = \frac{-2m_{12}^* + i\Gamma_{12}^*}{2|m_{12}| + i|\Gamma_{12}|}$$

Evolution of the 2 states $\psi_K(0)=K^0, \psi_{\overline{K}}(0)=\overline{K}^0$

$$\psi_K(t)=\frac{e^{-\gamma_S t}+e^{-\gamma_L t}}{2}K^0+\frac{q}{p}\frac{e^{-\gamma_S t}-e^{-\gamma_L t}}{2}\overline{K}^0,$$

$$\psi_{\overline{K}}(t)=\frac{e^{-\gamma_S t}+e^{-\gamma_L t}}{2}\overline{K}^0+\frac{p}{q}\frac{e^{-\gamma_S t}-e^{-\gamma_L t}}{2}K^0.$$

With $\Delta m = m_L - m_S$:

$$P(K^0\to K^0)=P(\overline{K}^0\to\overline{K}^0)=\left|\frac{e^{-\gamma_S t}+e^{-\gamma_L t}}{2}\right|^2=\frac{1}{4}\left[e^{-\Gamma_S t}+e^{-\Gamma_L t}+2e^{-(\Gamma_S+\Gamma_L)t/2}\cos\Delta m t\right],$$

equal because of CPT. And:

$$P(K^0\to\overline{K}^0)=\frac{1}{4}\left|\frac{q}{p}\right|^2\left[e^{-\Gamma_S t}+e^{-\Gamma_L t}-2e^{-(\Gamma_S+\Gamma_L)t/2}\cos\Delta m t\right],$$

$$P(\overline{K}^0\to K^0)=\frac{1}{4}\left|\frac{p}{q}\right|^2\left[e^{-\Gamma_S t}+e^{-\Gamma_L t}-2e^{-(\Gamma_S+\Gamma_L)t/2}\cos\Delta m t\right].$$

CP symmetry if and only if $|p/q|=1 \quad\Leftrightarrow\quad \mathrm{Im}(\Gamma_{12}/m_{12})=0$

$$\varepsilon_K=\frac{p-q}{p+q},\quad p=\frac{1+\varepsilon_K}{\sqrt{2+2|\varepsilon_K|^2}},\quad q=\frac{1-\varepsilon_K}{\sqrt{2+2|\varepsilon_K|^2}},\quad \frac{p}{q}=\frac{1+\varepsilon_K}{1-\varepsilon_K}.$$

We know (since 1964) that $|p/q| \neq 1$, but very close to 1,

$$\left|\frac{p}{q}\right| = 1 + \frac{2\,\mathrm{Re}(\varepsilon_K)}{1+|\varepsilon_K|^2} \;=\; 1 + 2\,\mathrm{Re}(\varepsilon_K), \quad \mathrm{Re}(\varepsilon_K) << 1.$$

Im ε_K is unobservable. Take it small for <u>simplicity</u> .
Re ε_K<<1 means small phase between Γ_{12} and m_{12} .
Re(Γ_{12}/m_{12}) is negative:

$$\Gamma_{12}/m_{12} = -\left|\Gamma_{12}/m_{12}\right| e^{-i\Phi_m} \quad \Rightarrow \quad \mathrm{Re}(\varepsilon_K) \approx \Phi_m / 4$$

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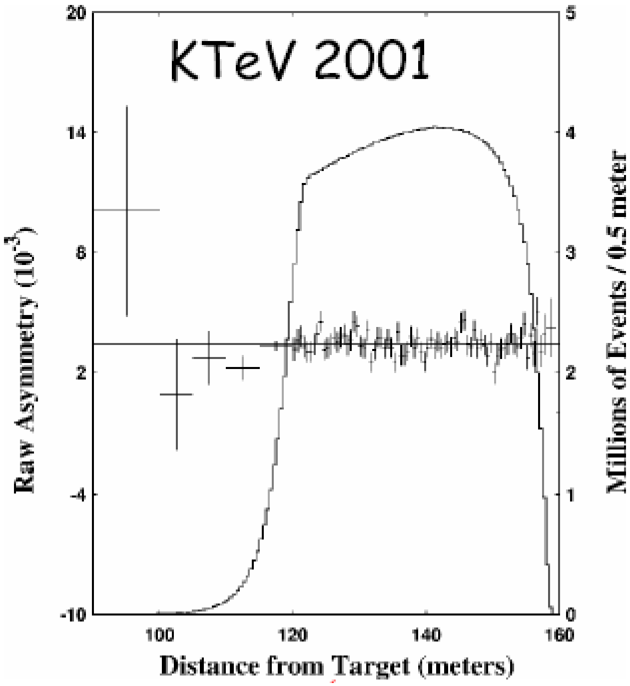
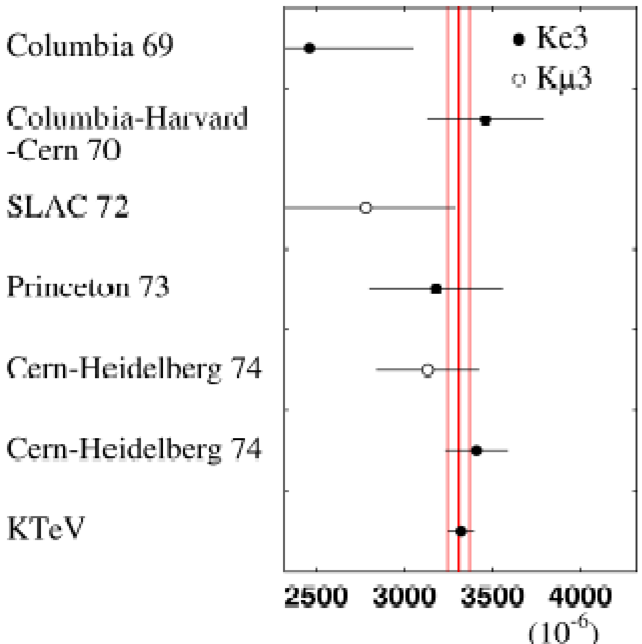
<u>Experimental results:</u> based on $K^0 \to \ell^+, \overline{K}^0 \to \ell^-$:

$$\frac{\Gamma(K_L \to \ell^+ \nu \pi) - \Gamma(K_L \to \ell^- \nu \pi)}{\Gamma(K_L \to \ell^+ \nu \pi) + \Gamma(K_L \to \ell^- \nu \pi)} = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} = (0.327 \pm 0.012)\%.$$ [PDG 2000]

$$\left|p/q\right| = 1.00327 \pm 0.00012\,, \quad \mathrm{Re}(\varepsilon_K) = (1.64 \pm 0.06) \cdot 10^{-3}, \quad \Phi_m = 0.0065 \approx 0.37^0.$$

For B^0 mesons: $\mathrm{Re}(\varepsilon_B) = (1 \pm 3 \pm 4) \cdot 10^{-3}.$ [BABAR 2001]





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$$\mathrm{Re}(\varepsilon_K) = (1.64 \pm 0.06) \cdot 10^{-3}$$ [PDG 2000]

$$\mathrm{Re}(\varepsilon_K) = (1.661 \pm 0.037) \cdot 10^{-3}$$ [KTeV 2001]

Type II: CPV in Interference between Mixing and Decays

$$\begin{tikzcd} K^0 \arrow[rr] \arrow[dr] & & f \\ & \overline{K}^0 \arrow[ur] & \end{tikzcd} \qquad \begin{tikzcd} \overline{K}^0 \arrow[rr] \arrow[dr] & & f \\ & K^0 \arrow[ur] & \end{tikzcd}$$

For this type, f is a CP eigenstate, CP f = η_f f.

First example: f = $\pi\pi$, I=0, η_f = +1.

$$<2\pi, I=0|T|K^0> = A_0 \,, \quad <2\pi, I=0|T|\overline{K}^0> = \overline{A}_0 \,.$$

[up to common normalization factor]

Decay rates N from states ψ_K and $\overline{N}$ from $\psi_{\overline{K}}$:

$$N(t) = \left| \frac{e^{-\gamma_S t} + e^{-\gamma_L t}}{2} A_0 + \frac{q}{p} \frac{e^{-\gamma_S t} - e^{-\gamma_L t}}{2} \overline{A}_0 \right|^2 ,$$

$$\overline{N}(t) = \left| \frac{e^{-\gamma_S t} + e^{-\gamma_L t}}{2} \overline{A}_0 + \frac{p}{q} \frac{e^{-\gamma_S t} - e^{-\gamma_L t}}{2} A_0 \right|^2 .$$

Introducing $\boxed{r_0 = \frac{q\,\overline{A}_0}{p\,A_0}}$ where r_0 - in contrast to q/p and $\overline{A}_0/A_0$ - is observable in modulus and phase, we obtain:

$$N(t)=\frac{|A_0|^2|1+r_0|^2}{4}\cdot\left|e^{-\gamma_S t}+\frac{1-r_0}{1+r_0}e^{-\gamma_L t}\right|^2 ,$$

$$\overline{N}(t)=\frac{|A_0|^2|1+r_0|^2}{4}\cdot\left|\frac{p}{q}\right|^2\cdot\left|e^{-\gamma_S t}-\frac{1-r_0}{1+r_0}e^{-\gamma_L t}\right|^2 .$$

Using $\boxed{\frac{1-r_0}{1+r_0}=\varepsilon_0 \quad\Leftrightarrow\quad \frac{1-\varepsilon_0}{1+\varepsilon_0}=r_0}$ we obtain for $a=(\overline{N}-N)/(\overline{N}+N)$:

$$a(t)=\frac{-2e^{-(\Gamma_S+\Gamma_L)t/2}\cdot\left[\mathrm{Re}(\varepsilon_0)\cos\Delta mt+\mathrm{Im}(\varepsilon_0)\sin\Delta mt\right]}{e^{-\Gamma_S t}+|\varepsilon_0|^2e^{-\Gamma_L t}} \qquad \varepsilon_0=\frac{\langle 2\pi,I=0|T|K_L\rangle}{\langle 2\pi,I=0|T|K_S\rangle}$$

$a(t)=0$ for $r_0=+1$ and $r_0=-1$. CPV $\Leftrightarrow$ $r_0 \neq \pm 1$. Three reasons:

$$\boxed{r_0=\frac{q\overline{A}_0}{pA_0}=\left|\frac{q}{p}\right|\cdot\left|\frac{\overline{A}_0}{A_0}\right|\cdot e^{-2i\phi_0}}$$

(1) $|q/p|\neq 1$, CPV in mixing,

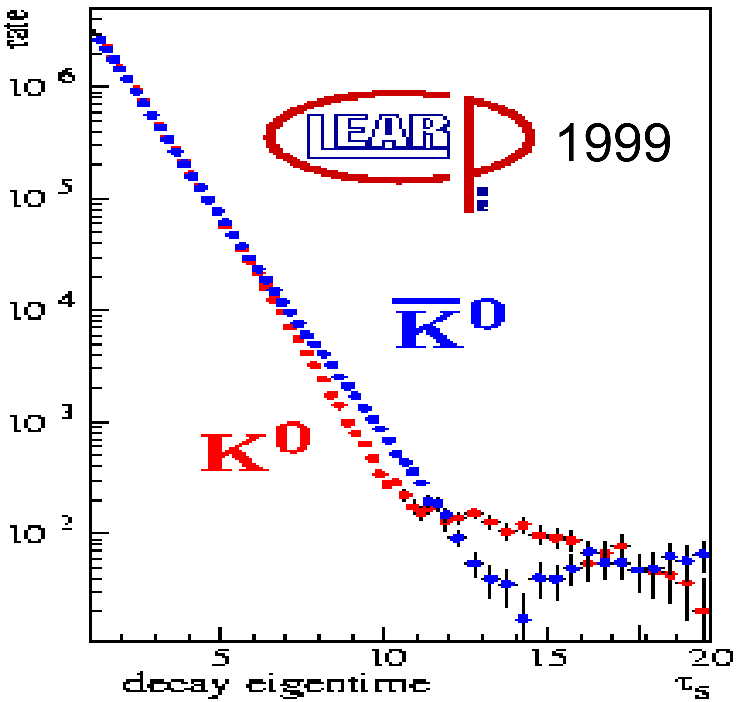
(2) $|\overline{A}_0/A_0|\neq 1$, CPV in decay, here forbidden because of CPT,

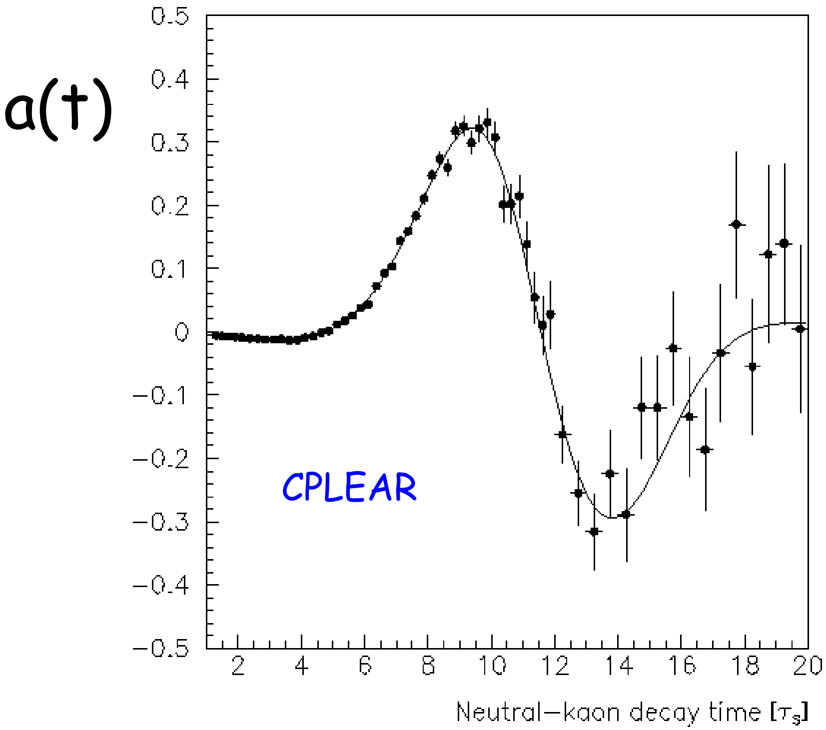
(3) $\Phi_0 \neq n\pi/2$, CPV in mix.-dec. interference.

$$r_0=\left|\frac{q}{p}\right|e^{-2i\phi_0}=\left[1-2\,\mathrm{Re}(\varepsilon_K)\right]\left[1-2i\phi_0\right],\quad \varepsilon_0=\frac{1-r_0}{1+r_0}=\mathrm{Re}(\varepsilon_K)+i\phi_0 ,$$

$$\mathrm{Re}(\varepsilon_0)=\mathrm{Re}(\varepsilon_K),\quad \mathrm{Im}(\varepsilon_0)=\phi_0 .$$

$\pi^+\pi^-$ Results from CPLEAR: $\eta_{+-} = (2.27 \pm 0.02) \cdot 10^{-3} \cdot e^{i(43.3\pm 0.5)^0} \approx \varepsilon_0$





$$a(t) = \frac{N(\overline{K}^0 \to \pi^+\pi^-) - N(K^0 \to \pi^+\pi^-)}{N(\overline{K}^0 \to \pi^+\pi^-) + N(K^0 \to \pi^+\pi^-)} = \frac{-2|\eta_{+-}| e^{-(\Gamma_S+\Gamma_L)t/2} \cos(\Delta m \cdot t - \varphi_{+-})}{e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t}}$$

$$= \frac{-2e^{-(\Gamma_S+\Gamma_L)t/2} \cdot [\mathrm{Re}(\varepsilon_0)\cos\Delta m t + \mathrm{Im}(\varepsilon_0)\sin\Delta m t]}{e^{-\Gamma_S t} + |\varepsilon_0|^2 e^{-\Gamma_L t}}$$

Two types of CPV seen, I: $\mathrm{Re}(\varepsilon_0) = \mathrm{Re}(\varepsilon_K)$, II: $\mathrm{Im}(\varepsilon_0) = \Phi_0$.

(In this description,
Re(ε_0)=Φ_m/4 from the phase between Γ_{12} and m_{12},
and Im(ε_0)=Φ_0 from the phase between q/p and $\bar{A}_0/A_0$
seem to be unrelated.
But K phenomenology tells us Im(ε_0)/Re(ε_0) = $2\Delta m/\Gamma_S$.
Why this relation?

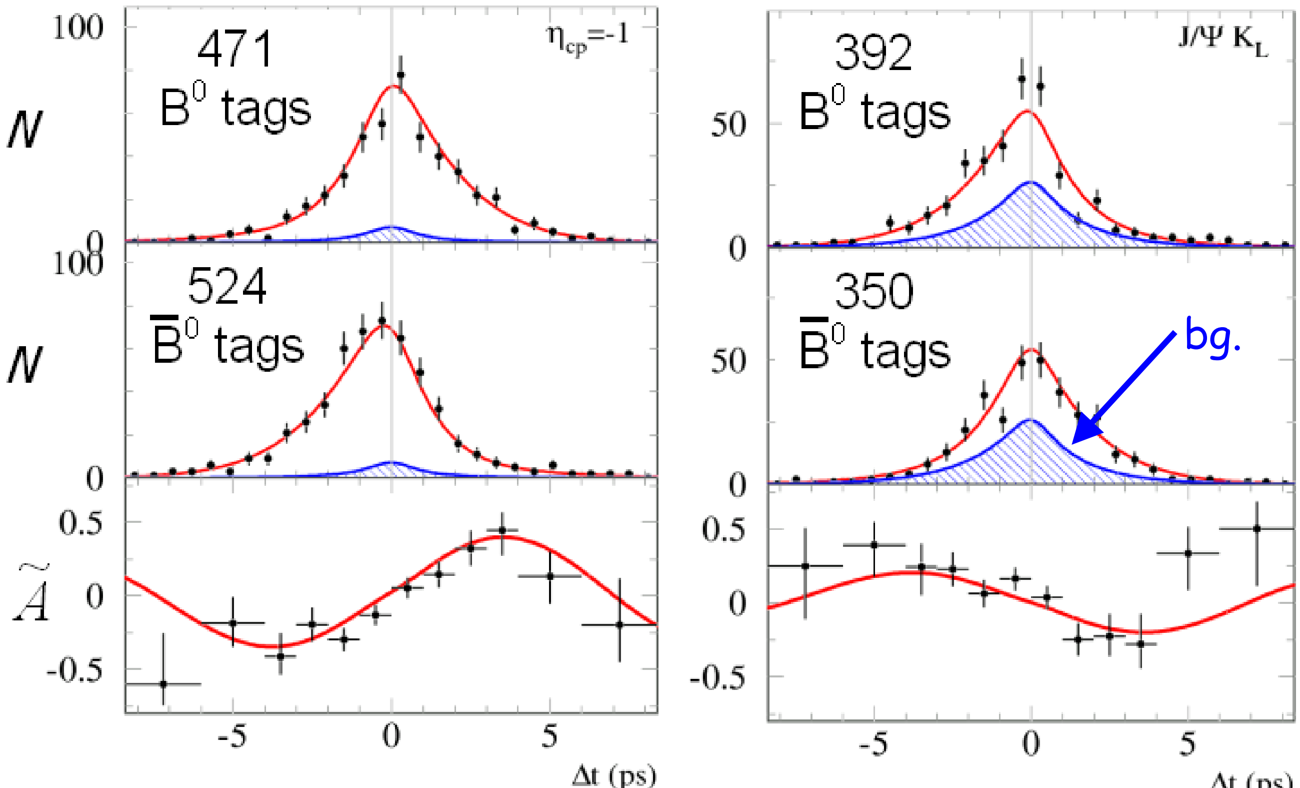
Completely different from the D^0, B^0, B_s case,
this originates in the dominance of one K^0 decay channel:

$$r_0 = \frac{q}{p}\cdot\frac{\overline{A}_0}{A_0} = \frac{-2m_{12}^* + i\Gamma_{12}^*}{2|m_{12}| + i|\Gamma_{12}|}\cdot\frac{\Gamma_{12}}{|\Gamma_{12}|}\quad \textit{because of p.3 and}$$

$$\Gamma_{12} = k\cdot\overline{A}_0 A_0^*, \Gamma_{11} = k\cdot A_0 A_0^* = \Gamma_S/2 = -\Delta\Gamma/2 = |\Gamma_{12}|.$$

$$\Gamma_{12} = -|\Gamma_{12}/m_{12}|\cdot(1 - i\Phi_m)m_{12}\ (p.5) \Rightarrow r_0 = 1 - \frac{2i\Phi_m}{2 + i|\Gamma_{12}/m_{12}|}, \varepsilon_0 = \frac{1-r_0}{1+r_0} = \frac{i\Phi_m}{2 + i\Gamma_S/\Delta m}.)$$

Second example for Type-II CPV: $B^0,\bar{B}^0 \to c\bar{c}K$



$\sin 2\beta = 0.76 \pm 0.10$ $\sin 2\beta = 0.73 \pm 0.19$

$\boxed{\sin 2\beta = 0.75 \pm 0.09 \pm 0.04}$

[03/02]

World average = 0.78 ± 0.08

$$r_{\psi K} = \left(\frac{q}{p}\right)_B \frac{\overline{A}_{\psi K}}{A_{\psi K}}$$

with |q/p|=1 and |Ā/A|=1, but with a relative phase 2β between Ā/A and q/p.

$r_{\psi K} = -\,e^{-2i\beta}$. (minus-sign is the CP eigenvalue of J/ψ K_S.)

$$\varepsilon_{\psi K} = \frac{1-r_{\psi K}}{1+r_{\psi K}} = \frac{1+e^{-2i\beta}}{1-e^{-2i\beta}} = \frac{1}{i\cdot\tan\beta}, \quad \mathrm{Re}(\varepsilon_{\psi K}) = 0, \quad \mathrm{Im}(\varepsilon_{\psi K}) = -\cot\beta\,.$$

$$a(t) = \frac{N(\overline{B}^0 \to J/\psi K_S) - N(B^0 \to J/\psi K_S)}{N(\overline{B}^0 \to J/\psi K_S) + N(B^0 \to J/\psi K_S)} = \frac{-2e^{-(\Gamma_S+\Gamma_L)t/2}\cdot\left[\mathrm{Re}(\varepsilon_{\psi K})\cos\Delta m t + \mathrm{Im}(\varepsilon_{\psi K})\sin\Delta m t\right]}{e^{-\Gamma_S t} + |\varepsilon_{\psi K}|^2 e^{-\Gamma_L t}}$$

$$\Delta m \to \Delta m_B, \quad \Gamma_L \to \Gamma_H, \quad \Gamma_S \to \Gamma_L, \quad \Gamma_L = \Gamma_H \quad \Rightarrow$$

$$a(t) = \frac{+2\cot\beta\cdot\sin\Delta m_B t}{1+\cot^2\beta} = \sin 2\beta\cdot\sin\Delta m_B t.$$

There is only Type II in this asymmetry and not I+II as in K →ππ.

$$\sin 2\beta = 0.8 \quad \Rightarrow \quad \varepsilon_{\psi K} = -2i \; or \; -\frac{i}{2}.$$

Type III: Direct CPV in Decays into one Final State

$$A = \langle f | T | B^0 \rangle, \ \overline{A} = \langle \bar{f} | T | \overline{B}^0 \rangle, \quad CPV \Leftrightarrow |\overline{A} / A| \neq 1$$

$CPT \ \ requires \ :$

$$A = a \cdot e^{i\varphi} \cdot e^{i\delta} \quad \Rightarrow \quad \overline{A} = a \cdot e^{-i\varphi} \cdot e^{i\delta} \quad \Rightarrow \quad |\overline{A} / A| = 1$$

$Way \ out \ : two \ amplitudes \ \ contribute \ \ to \ the \ same \ \ final \ \ state \, ,$

$$A = A_1 + A_2 \ , \quad A_j = a_j \cdot e^{i\varphi_j} \cdot e^{i\delta_j} \ , \quad \overline{A} = \overline{A}_1 + \overline{A}_2 \quad \Rightarrow$$

$Rates$

$$|A|^2 = a_1^2 + a_2^2 + 2 \cdot a_1 a_2 \cdot \cos(\varphi_1 - \varphi_2 + \delta_1 - \delta_2)$$

$$|\overline{A}|^2 = a_1^2 + a_2^2 + 2 \cdot a_1 a_2 \cdot \cos(-\varphi_1 + \varphi_2 + \delta_1 - \delta_2)$$

$$|\overline{A}|^2 - |A|^2 = 4 \cdot a_1 a_2 \cdot \sin(\varphi_1 - \varphi_2) \cdot \sin(\delta_1 - \delta_2)$$

$CPV \ \ requires \quad \varphi_1 - \varphi_2 \neq 0 \quad \underline{and} \quad \delta_1 - \delta_2 \neq 0.$

This type of CPV is not yet seen in B decays.

What about K decays? ε'?

„Definition“ of ε‘: $$\frac{\langle \pi^+\pi^- | T | K_L \rangle}{\langle \pi^+\pi^- | T | K_S \rangle} = \varepsilon_0 + \varepsilon', \quad \frac{\langle \pi^0\pi^0 | T | K_L \rangle}{\langle \pi^0\pi^0 | T | K_S \rangle} = \varepsilon_0 - 2\varepsilon',$$

$$\frac{\left|\langle \pi^+\pi^- | T | K_L \rangle\right|^2 \Big/ \left|\langle \pi^+\pi^- | T | K_S \rangle\right|^2}{\left|\langle \pi^0\pi^0 | T | K_L \rangle\right|^2 \Big/ \left|\langle \pi^0\pi^0 | T | K_S \rangle\right|^2} = 1 + 6 \cdot \mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon_0}\right).$$

NA48, Eur.Phys.J.C22(2001)231: $\mathrm{Re}(\varepsilon'/\varepsilon_0) = (15.3 \pm 2.6) \cdot 10^{-4}$

KTeV, LP @ Rome 2001: $\mathrm{Re}(\varepsilon'/\varepsilon_0) = (20.7 \pm 2.8) \cdot 10^{-4}$

WA: $\mathrm{Re}(\varepsilon'/\varepsilon_0) = (17.2 \pm 1.8) \cdot 10^{-4}$

$$A_0 = \langle \pi\pi, I = 0 | T | K^0 \rangle, \quad A_2 = \langle \pi\pi, I = 2 | T | K^0 \rangle,$$

$$\varepsilon' = \frac{i}{\sqrt{2}} \frac{a_2}{a_0} e^{i(\delta_2 - \delta_0)} \sin(\varphi_2 - \varphi_0)$$

This is non-zero even with δ_2-δ_0=0, so it is not Type III.

At t=0, the CPLEAR states are pure K^0 or $\overline{K}^0$.
Is there CPV in $\pi^+ \pi^-$ decays before $K^0 \overline{K}^0$ mixing starts?

$$\left|\pi^+\pi^-\right\rangle = \left(\sqrt{2}\cdot\left|\pi\pi, I=0\right\rangle + \left|\pi\pi, I=2\right\rangle\right)/\sqrt{3}$$

$$\left\langle\pi^+\pi^-\left|T\right|K^0\right\rangle = \left(\sqrt{2}\cdot a_0 e^{i\delta_0} e^{i\varphi_0} + a_2 e^{i\delta_2} e^{i\varphi_2}\right)/\sqrt{3}$$

$$\left\langle\pi^+\pi^-\left|T\right|\overline{K}^0\right\rangle = \left(\sqrt{2}\cdot a_0 e^{i\delta_0} e^{-i\varphi_0} + a_2 e^{i\delta_2} e^{-i\varphi_2}\right)/\sqrt{3}$$

$$a_{+-} = \frac{\left|\left\langle\pi^+\pi^-\left|T\right|\overline{K}^0\right\rangle\right|^2 - \left|\left\langle\pi^+\pi^-\left|T\right|K^0\right\rangle\right|^2}{\left|\left\langle\pi^+\pi^-\left|T\right|\overline{K}^0\right\rangle\right|^2 + \left|\left\langle\pi^+\pi^-\left|T\right|K^0\right\rangle\right|^2}$$

$$= \sqrt{2}\,\frac{a_2}{a_0}\sin\left(\delta_2-\delta_0\right)\sin\left(\varphi_2-\varphi_0\right) = -2\,\mathrm{Re}\left(\varepsilon'\right)$$

Re(ε‘) is Type-III CPV,
direct CPV in decays into one final state.

Im(ε‘) is different, I call it Type-IV CPV:

$$\mathrm{Im}\left(\varepsilon'\right) = \frac{a_2}{\sqrt{2}\cdot a_0}\cos\left(\delta_2-\delta_0\right)\sin\left(\varphi_2-\varphi_0\right)$$

Type IV: Direct CPV in Decays into two Final States

$$\varepsilon' = \frac{\eta_{+-} - \eta_{+-}}{3} = \frac{\langle \pi^+\pi^- | T | K_L \rangle \langle \pi^0\pi^0 | T | K_S \rangle - \langle \pi^0\pi^0 | T | K_L \rangle \langle \pi^+\pi^- | T | K_S \rangle}{3 \langle \pi^+\pi^- | T | K_S \rangle \langle \pi^0\pi^0 | T | K_S \rangle}$$

$\pi^+\pi^-$ and $\pi^0\pi^0$ are two physically different states.

$$\varepsilon' = \frac{\langle \pi\pi, I=2 | T | K_L \rangle \langle \pi\pi, I=0 | T | K_S \rangle - \langle \pi\pi, I=0 | T | K_L \rangle \langle \pi\pi, I=2 | T | K_S \rangle}{\sqrt{2} \cdot \langle \pi\pi, I=0 | T | K_S \rangle^2}.$$

$$\varepsilon' = \frac{\langle \pi\pi, I=2 | T | K^0 \rangle \langle \pi\pi, I=0 | T | \overline{K}^0 \rangle - \langle \pi\pi, I=0 | T | K^0 \rangle \langle \pi\pi, I=2 | T | \overline{K}^0 \rangle}{p \cdot 2\sqrt{2} / q \cdot \langle \pi\pi, I=0 | T | K^0 \rangle^2}$$

$$= \frac{A_2 \overline{A}_0 - A_0 \overline{A}_2}{p \cdot 2\sqrt{2} / q \cdot A_0^2} = \frac{i}{\sqrt{2}} \frac{a_2}{a_0} e^{i(\delta_2 - \delta_0)} \sin(\varphi_2 - \varphi_0).$$

$$\mathrm{Im}(\varepsilon') = \frac{a_2}{\sqrt{2} \cdot a_0} \cos(\delta_2 - \delta_0) \sin(\varphi_2 - \varphi_0)$$

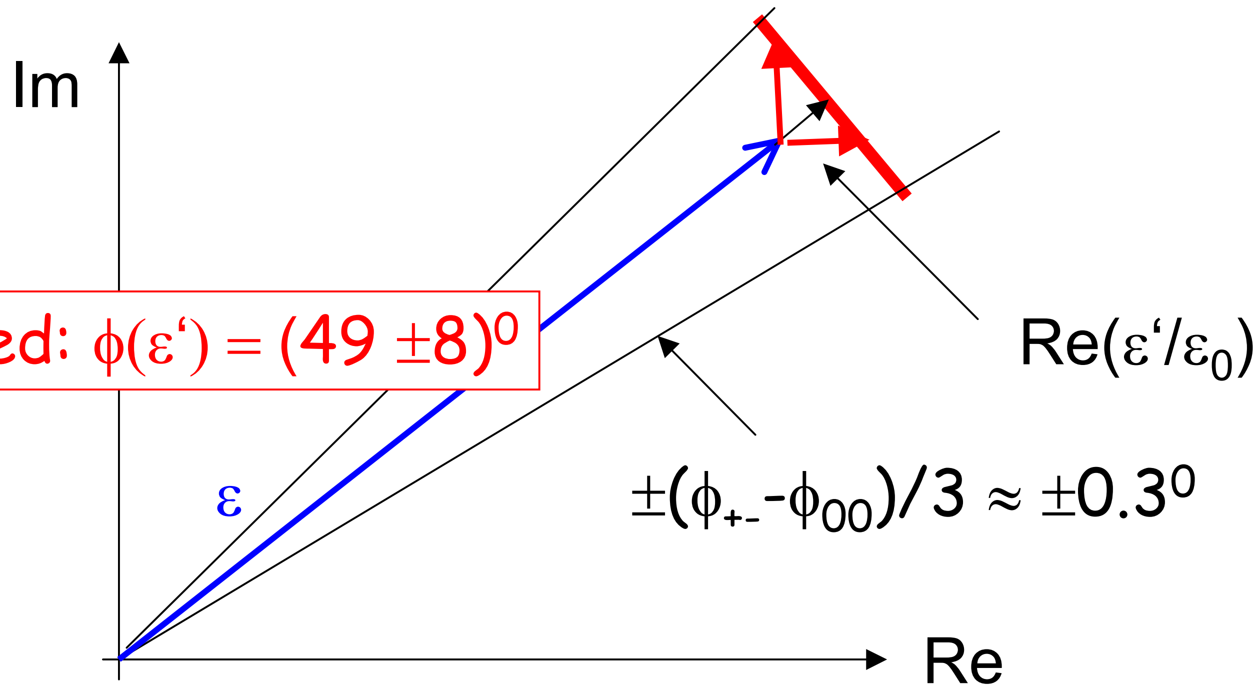
Type IV is $\neq 0$ even if $\delta_2 = \delta_0$; it requires two (or more) different final states.

This was using „Kaon language“. In „Beon language“:

$$r_{+-} = \frac{q\bar{A}_{+-}}{pA_{+-}} = \frac{1-\eta_{+-}}{1+\eta_{+-}} = 1 - 2\varepsilon_0 - 2\varepsilon' ,$$

$$r_{00} = \frac{q\bar{A}_{00}}{pA_{00}} = \frac{1-\eta_{00}}{1+\eta_{00}} = 1 - 2\varepsilon_0 + 4\varepsilon' .$$

Experimentally we do not know much on $\mathrm{Im}(\varepsilon')/\mathrm{Re}(\varepsilon')$:



Expected: $\phi(\varepsilon') = (49 \pm 8)^0$

Two more Examples for Type-IV CPV

1. Listening to L. Wolfenstein yesterday, the weak phase difference between $A(B^0\to\pi\pi)$ and $A(B^0\to\psi K)$:

Because of large expected effect, the quotient is better here than the difference as in Im(ε'),

$$r_{\pi\pi} = \frac{q\bar{A}_{\pi\pi}}{pA_{\pi\pi}}, \quad r_{\psi K} = \frac{q\bar{A}_{\psi K}}{pA_{\psi K}}, \quad \frac{r_{\pi\pi}}{r_{\psi K}} = \frac{\langle \pi\pi|T|\bar{B}^0\rangle\langle \psi K|T|B^0\rangle}{\langle \pi\pi|T|B^0\rangle\langle \psi K|T|\bar{B}^0\rangle}.$$

If this double quotient is different from 1 or -1,
e. g. $e^{2i(\beta+\alpha)}$ as expected in the Standard Model,
this is direct CPV of type IV, two final states involved.

2. Discussing with N. Sinha and R. Sinha at FPCP-2002, and using a B^+ B^- asymmetry in order to show that Type IV has nothing to do with q/p:

$$B^+ \to \left(D^{*0} \ or \ \overline{D}^{*0}\right)\rho^+ \ , \quad B^- \to \left(D^{*0} \ or \ \overline{D}^{*0}\right)\rho^-$$

These vector-vector modes contain 3 final states. Angular distributions $d\Gamma/d\cos\theta_1 d\cos\theta_2 d\phi$ contain P- and CP-violating terms:

$$d\Gamma/d\phi = A + B\cos\phi + C\sin\phi + D\sin 2\phi,$$

$$C(B^+) + C(B^-) = \text{const} \cdot J \cdot \sin\gamma \cdot \cos(\delta_1 - \delta_2)\ .$$

Conclusion:

In laboratory experiments with K and B mesons, we have observed CP violation from four different origins:

in Mixing, $\mathrm{Re}(\varepsilon_K)$, phase $\Delta\phi$ between m_{12} and Γ_{12} ,
in Mixing-Decay Interference, $\mathrm{Im}(\varepsilon_0)$, $\sin 2\beta$,
$\Delta\phi$ between q/p and $\bar{A}/A$,
in Decays into one Final State, $\mathrm{Re}(\varepsilon')$,
$\Delta\phi$ and $\Delta\delta$ between A_1 and A_2 ,
in Decays into $\geqslant 2$ Final States, $\mathrm{Im}(\varepsilon')$,
$\Delta\phi$ between A_1 and A_2 and no $\Delta\delta$.

There are more than these four, in addition to J (quartet), Standard Model CPV has many octets, decuplets ... of CKM matrix elements.