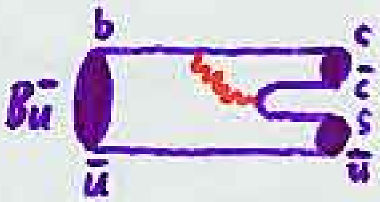
$B \to J/\psi K$ Decays: $\sin 2\beta$, Penguins, New Physics

WIN2002, Christchurch / Zhi-zhong XING, IHEP
Beijing

MacFarlane
Sanda
Stark
Sevior
Masiero

Within the Standard Model

1. $B_u^\pm \to J/\psi K^\pm$ and Direct $\cancel{CP}$



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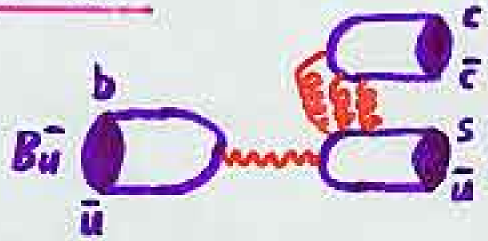


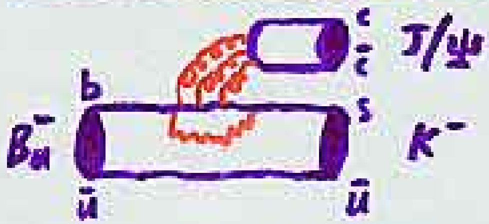
Formfactor suppression:
$\sim i f_B/m_B$
$\sim i\lambda^2$

Dominant amplitude:
CKM factor $\sim \lambda^2$

Annihilation amplitude:
CKM factor $\sim \lambda^4 e^{i\gamma}$

【Lepage & Brodsky 79
Bernabéu & Jarlskog 81】

$\boxed{\text{Direct } \cancel{CP} \sim \lambda^4 \sin\gamma \sim O(10^{-3}) \text{ or smaller}}$ 【Brown, Pakvasa & Tuan 84】



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Penguin/Hairpin amplitudes:

CKM factor $\sim \lambda^2 e^{iO(\lambda^2)}$ $(V_{cb}V_{cs}^*)$

or $\sim \lambda^5 e^{iO(1)}$ $(V_{ub}V_{us}^*)$

QCD-loop suppression:
$\sim \dfrac{a_4 + a_6}{a_2} \sim \lambda e^{iO(1)}$

EW-loop suppression:
$\sim \dfrac{a_8 + a_{10}}{a_2} \sim \lambda^3 e^{iO(1)}$

【Du & Xing 93, Fleischer 93/94】

$\boxed{\text{Direct } \not{CP} \sim \lambda^4 \sim O(10^{-3}) \text{ or smaller}}$ 【He & Soni 97, $c\bar{c}$ color-octet, $\sim 10^{-4}$】

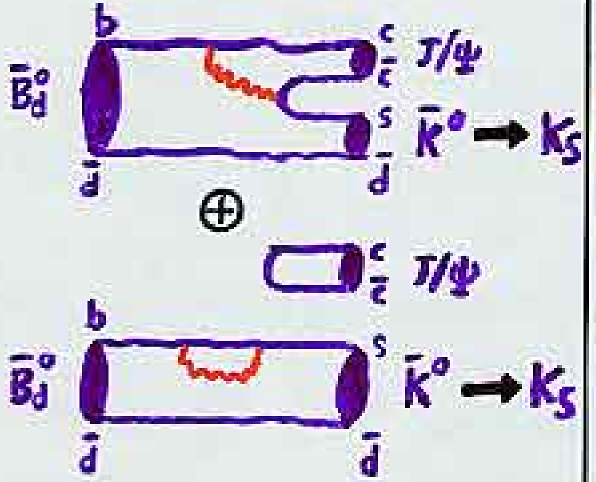
$\boxed{\text{Conclusion}}$ the SM prediction is of $O(10^{-3})$ or smaller. At 10^{-2} EX level, nothing new.

2. B_d^0 vs $\bar{B}_d^0 \to J/\psi K_S$ on the $\Upsilon(4S)$ resonance

Time-independent $\not{CP}$: 【Xing 95】

$$\not{CP} = \frac{\Gamma(\ell^-, J/\psi K_S) - \Gamma(\ell^+, J/\psi K_S)}{\Gamma(\ell^-, J/\psi K_S) + \Gamma(\ell^+, J/\psi K_S)}$$

$$\approx \frac{2}{1+x^2}\Big[\underbrace{\mathrm{Re}\,\epsilon_K}_{\substack{K^0\text{-}\bar{K}^0 \text{ mixing} \\ \sim 10^{-3}}} - \frac{x^2}{1+|\epsilon_B|^2}\underbrace{\mathrm{Re}\,\epsilon_B}_{\substack{B_d^0\text{-}\bar{B}_d^0 \text{ mixing} \\ \sim 10^{-3}}} - \lambda^2\eta\, \underbrace{\mathrm{Im}\frac{A_t}{A_c}}_{\substack{\text{Direct } \not{CP} \\ \sim 10^{-3}}}\Big]$$



$\boxed{\text{Conclusion}}$ At 10^{-2} EX level, nothing new; at 10^{-3} EX level, something interesting.
(In particular, to test CPT symmetry or $\Delta B = \Delta Q$ rule or other NP)

3. A general analysis 【Fleischer & Mannel 01】

Isospin relations: $\langle J/\psi K^+ | \mathcal{H}_{\rm eff}^{I=0} | B_u^+ \rangle = + \langle J/\psi K^0 | \mathcal{H}_{\rm eff}^{I=0} | B_d^0 \rangle$, $\langle J/\psi K^+ | \mathcal{H}_{\rm eff}^{I=1} | B_u^+ \rangle = - \langle J/\psi K^0 | \mathcal{H}_{\rm eff}^{I=1} | B_d^0 \rangle$

Decay amplitudes:
$$\begin{cases} A(B_u^+ \to J/\psi K^+) = \frac{G_F}{\sqrt{2}}\left[V_{cb}^* V_{cs}\left(A_c^{(0)} - A_c^{(1)}\right) + V_{ub}^* V_{us}\left(A_u^{(0)} - A_u^{(1)}\right)\right] \\ A(B_d^0 \to J/\psi K^0) = \frac{G_F}{\sqrt{2}}\left[V_{cb}^* V_{cs}\left(A_c^{(0)} + A_c^{(1)}\right) + V_{ub}^* V_{us}\left(A_u^{(0)} + A_u^{(1)}\right)\right] \end{cases}$$

where $A_c^{(0)} = A_{cc}^{c} - A_{QCD}^{pen} - A_{EW}^{(0)}$, $A_u^{(0)} = A_{cc}^{u(0)} - A_{QCD}^{pen} - A_{EW}^{(0)}$, $A_c^{(1)} = -A_{EW}^{(1)}$, $A_u^{(1)} = A_{cc}^{u(1)} - A_{EW}^{(1)}$.

4. Determination of $\sin 2\beta$ / $\sin 2\phi_1$

$$\beta \equiv \arg\left(-\frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}}\right) \qquad \omega \equiv \arg\left(-\frac{V_{cs}^* V_{cd}}{V_{us}^* V_{ud}}\right)$$

Indirect ~~CP~~ in B_d^0 vs $\bar{B}_d^0 \to J/\psi K_S$ (penguins neglected)

$B_d^0-\bar{B}_d^0$ mixing b & $\bar{b}$ decays $K^0-\bar{K}^0$ mixing

The measurable : $\mathrm{Im}\left[\frac{q_B}{p_B}\cdot\frac{A(b\to c\bar{c}s)}{A(\bar{b}\to \bar{c}c\bar{s})}\cdot\frac{q_K^*}{p_K^*}\right]$

$\frac{q_B}{p_B}$: $\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$ $\frac{A(b\to c\bar{c}s)}{A(\bar{b}\to \bar{c}c\bar{s})}$: $\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}$

$\frac{q_K^*}{p_K^*}$: $\begin{cases} \dfrac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}} & \text{(box diagram)} \\ \dfrac{V_{us} V_{ud}^*}{V_{us}^* V_{ud}} & (|\epsilon_K| \ll 1) \end{cases}$

【Cohen et al 97】

Then the measurable $= \sin 2\beta$ or $\sin 2(\beta+\omega)$.

Beyond the Standard Model

1. "Normal" New Physics in $B_d^0-\bar{B}_d^0$ Mixing

(A) Typical Examples (Nir-Quinn Plot 92, see below)

(B) A Generic Parametrization : $M_{12} = M_{12}^{SM} + M_{12}^{NP}$ with $|M_{12}| = \frac{1}{2}\Delta M$

$$\begin{Bmatrix} M_{12}^{SM} \\ M_{12}^{NP} \\ M_{12} \end{Bmatrix} = \begin{Bmatrix} R_{SM}\, e^{i2\beta} \\ R_{NP}\, e^{i2\theta} \\ 1 \;\; e^{i2\phi} \end{Bmatrix} \frac{\Delta M}{2}$$

Solution : $R_{NP} = -R_{SM}\cos 2(\theta-\beta) \pm \sqrt{1 - R_{SM}^2 \sin^2 2(\theta-\beta)}$ 【Sanda & Xing 97】

 【 Nir-Quinn Plot 92 】

Model	CKM Unitarity	$B-\bar{B}$ Mixing	SM Predictions for A^{CP}
SM		t W W t	
Four Quark Generations	$V_{td}V_{tb}^*$	t′	Modified
Multi-Scalar with NFC (General)		ϕ^+	Unmodified
(+ SCPV)		No New Phases	All Asymmetries Vanish
Z-Mediated FCNC	U_{db}^*	Z	Modified
LRS		W_R Small	Unmodified
SUSY (General)		$\tilde{g}$ $\tilde{q}_L,\tilde{q}_R$ $\tilde{q}_L,\tilde{q}_R$ $\tilde{g}$	Modified
(Minimal)		$\tilde{g}$ $\tilde{q}_L$ $\tilde{q}_L$ $\tilde{g}$ No New Phases	Unmodified
"Real Superweak"		Real	Modified for B_d Unmodified for B_s

Figure 4 New physics effects on *CP* asymmetries in neutral B decays (48). The second column describes whether unitarity of the three-generation CKM matrix is maintained (a *triangle*) or violated (a *quadrangle*). The third column gives an example of a new contribution to the mixing. Unless otherwise mentioned, the contribution could be large and carry new phases.

More inputs (e.g. from Masiero's talk)

Indirect ~~CP~~ measurable (B_d^0 vs $\bar{B}_d^0 \to J/\psi K_S$): $\sin 2\phi = R_{SM} \sin 2\beta + R_{NP} \sin 2\theta$

Deviation from the SM: **Illustration**

($\sin 2\beta = 0.75 \pm 0.06$, Caravaglios et al 00)

$$\boxed{\frac{\sin 2\phi}{\sin 2\beta} = R_{SM} + R_{NP} \frac{\sin 2\theta}{\sin 2\beta}}$$

$$= \begin{cases} 0.79 \pm 0.26 & \text{BaBar 01} \\ 1.32 \pm 0.30 & \text{Belle 01} \end{cases}$$ (1σ?)

(Can we calculate R_{SM} accurately?
$R_{SM} = \frac{1}{6\pi^2 \Delta M} G_F^2 B_B f_B^2 M_B m_t^2 \eta_B F(z) |V_{tb} V_{td}|^2$)

(C) What does $\sin 2\phi = \sin 2\beta$ mean? New Physics may be there!

The possible values of θ : $\tan 2\theta = \tan 2\beta$ or $\tan 2\theta = \tan 2\beta \frac{R_{SM}-1}{R_{SM}+1}$

【Xing 01】 trivial ? Non-trivial !

Conclusion: more accurate SM prediction and more measurements required.

(D) Other Approaches (e.g., effective field theory with dim-6 operators; numerical simulations)

2. "Exotic" New Physics (An Example)

If the geometry of space-time is noncommutative, i.e. $[x_\mu, x_\nu]_\star = i\theta_{\mu\nu} \neq 0$ then new ~~CP~~ effects may be manifest at low energy scales (e.g. at the scale $\Lambda \equiv \theta^{-1/2} \leq 2$ TeV). In the noncommutative standard model, the parameter θ itself is the source of ~~CP~~. At the field theory level, it is the momentum-dependent phase factor appearing in the theory which gives ~~CP~~. Experimentally, a signal for noncommutative geometry here is the

momentum-dependent CKM matrix : 【Hinchliffe & Kersting 01】

$$\bar{V}(p,p') = \begin{pmatrix} V_{ud}e^{i\chi_{ud}} & V_{us}e^{i\chi_{us}} & V_{ub}e^{i\chi_{ub}} \\ V_{cd}e^{i\chi_{cd}} & V_{cs}e^{i\chi_{cs}} & V_{cb}e^{i\chi_{cb}} \\ V_{td}e^{i\chi_{td}} & V_{ts}e^{i\chi_{ts}} & V_{tb}e^{i\chi_{tb}} \end{pmatrix}$$

where $\chi_{ab} \equiv p_a^\mu \theta_{\mu\nu} p_b'^\nu$ for $\begin{cases} a = u, c, t \\ b = d, s, b \end{cases}$

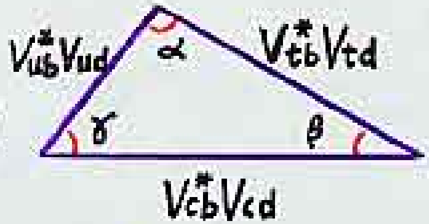
Note: $e^{i\chi_{ab}} \approx 1 + i\chi_{ab}$ in the perturbative limit.

Unitarity ?

The normalization relations keep valid
The orthogonal relations become invalid

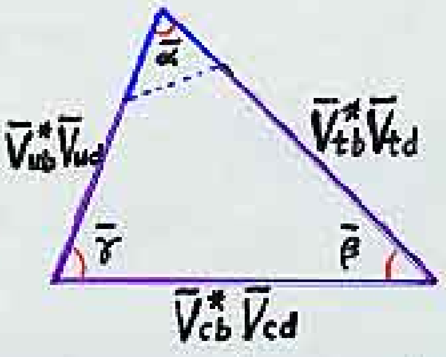
$$\bar{V}_{ub}^* \bar{V}_{ud} + \bar{V}_{cb}^* \bar{V}_{cd} + \bar{V}_{tb}^* \bar{V}_{td} = V_{ub}^* V_{ud} e^{i(\chi_{ud}-\chi_{ub})} + V_{cb}^* V_{cd} e^{i(\chi_{cd}-\chi_{cb})} + V_{tb}^* V_{td} e^{i(\chi_{td}-\chi_{tb})} \neq 0$$

C-geometry



- Angle relations: $\begin{cases} \bar{\alpha} = \alpha + (\chi_{td} + \chi_{ub} - \chi_{tb} - \chi_{ud}) \\ \bar{\beta} = \beta + (\chi_{cd} + \chi_{tb} - \chi_{cb} - \chi_{td}) \\ \bar{\gamma} = \gamma + (\chi_{ud} + \chi_{cb} - \chi_{ub} - \chi_{cd}) \end{cases}$

NC-geometry



- Sum: $\bar{\alpha} + \bar{\beta} + \bar{\gamma} = \alpha + \beta + \gamma = \pi$ 【Xing 02】

(Fake deviation of $\bar{\alpha} + \bar{\beta} + \bar{\gamma}$ from π was improperly remarked by HK 01)

- Indirect ~~CP~~ measurable in B_d^0 vs $\bar{B}_d^0 \to J/\psi K_S$: $\sin 2\beta \Rightarrow \sin 2\bar{\beta}$ $\Big\langle$ large ? / small ?

To interpret BaBar/Belle inconsistency ?

A lot of Phenomenology with a lot of subtlety (~~CP~~ from strong & electromagnetic interactions)

Concluding Remark