CP Violation in B Meson Decays in 3- and 4- Generation Models

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Abstract

We investigate the effects of CP violation in nonleptonic decays of neutral B mesons (B_d, B_s) in the Kobayashi-Maskawa model through the quark exchange- and W emission-diagrams for three and four generations. We obtain the result that the CP violating asymmetries for $B_d \to D^+D^-$, $\pi^+\pi^-$ and K^+K^- reach the order of 40% and the number of $b\bar{b}$ quark pairs needed to detect the asymmetries is 10^6-10^8 at 3σ level, and the asymmetries for $B_s \to \bar{D}^0\pi^0$, $D^-\pi^+$, $D^0\pi^0$ and $D^+\pi^-$ reach the order of 20% and the number of $b\bar{b}$ pairs is order of 10^8. The 4th generation hardly enhances the CP asymmetries except for the mode $\bar{b}\to\bar{c}c\bar{s}$ for B_s-decay among the eight "tree diagram" decay modes studied here. The reason for such an effect of the 4th generation is investigated.

In this report, the CP asymmetry in nonleptonic decays of tagged neutral b-flavored mesons is investigated within the framework of the Kobayashi-Maskawa(KM) model[1] through the quark exchange- and W emission-diagrams for three and four generations in the light of the large B_d-$\bar{B}_d$ mixing.[2,3]

The time-integrated CP-violating asymmetry is defined as[4]

$$C_f = \frac{\Gamma(B^0_{phys}\to f) - \Gamma(\bar{B}^0_{phys}\to \bar{f})}{\Gamma(B^0_{phys}\to f) + \Gamma(\bar{B}^0_{phys}\to \bar{f})} \quad , \tag{1}$$

where B^0_{phys} is the physical B^0 meson evolved from a pure B^0 produced at t=0 and $\Gamma(B^0_{phys}\to f)$ is the partial decay rate of B^0_{phys} into the specified final state f. The decay rate can be calculated in the usual way under the B^0-$\bar{B}^0$ mixing[4,5] under the assumption of the box-diagram dominance and no direct CP-violation in the magnitude in pure B^0 and $\bar{B}^0$ decays, and it leads to the following expression,

$$C_f = - \frac{2z\ \mathrm{Im}\Lambda}{2+z^2+z^2\,|x|^2} \quad , \tag{2}$$

where z is the mixing parameter defined by $z=\Delta M/\Gamma$, ΔM and Γ being mass difference and average lifetime of the two mass-eigenstates $|B^0_\pm\rangle$ of B^0-$\bar{B}^0$ system, respectively, x is the ratio of decay amplitude $\bar{A}(\bar{B}^0\to f)$ to $A(B^0\to f)$ and Λ is the product of x and ratio of the mixing coefficients, q/p (where $|B^0_\pm\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$), i.e.

$$x \equiv \frac{\bar{A}(\bar{B}^0 \to f)}{A(B^0 \to f)} \quad , \qquad \Lambda \equiv \frac{q}{p}\, x \simeq \frac{M_{12}}{|M_{12}|}\, x \quad . \tag{3}$$

Using the Wolfenstein parametrization[6] for the KM matrix and the measured value of the B_d-$\bar{B}_d$ mixing,[2,3] $z=0.70\pm0.13$, we calculate the asymmetry, Eq(1), for the modes, $\bar{b}\to\bar{u}u\bar{d}$, $\bar{b}\to\bar{u}c\bar{d}$, $\bar{b}\to\bar{c}u\bar{d}$ and $\bar{b}\to\bar{c}c\bar{d}$ for the B_d decays and for $\bar{b}\to\bar{u}u\bar{s}$, $\bar{b}\to\bar{u}c\bar{s}$, $\bar{b}\to\bar{c}u\bar{s}$ and $\bar{b}\to\bar{c}c\bar{s}$ for the B_s decays.

In the three-generation model, the Wolfenstein matrix is given as follows,

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} , \tag{4}$$

where λ is defined by $\lambda\equiv\sin\theta_C\simeq0.22$ where θ_C is the Cabibbo angle, $A \simeq 1$ is derived from the B-meson lifetime, and a range for the parameters ρ and η is obtained from the conservative limit[7,8] $|V_{ub}/V_{cb}| < 0.16$ and the analysis[9] of ε determined from the data[10] on the kaon system as

$$\rho^2+\eta^2 < 0.53 \quad \text{and} \quad 0.2 \leq \eta \leq 0.7 \ . \tag{5}$$

By using the constraints, Eq.(5), the asymmetry is obtained and summarized in Table I(a) and (b) together with the number of $b\bar{b}$ quark pairs needed to detect the asymmertry at 3σ level.

In the four-generation model, the effect of the fourth generation occurs only in the mixing coefficients' ratio q/p appearing in Λ, Eq(3). We parametrize the KM elements for the fourth generation as[9,11]

$$(V_{td},\ V_{ts},\ V_{tb},\ V_{tb})=(-\lambda^{n}B(\gamma+i\delta),\ -\lambda^{m}B(\alpha+i\beta),\ -\lambda^{\ell}B,\ 1)\ ,\quad (6)$$

where ℓ, m and n are the exponents for λ. We take tentatively m_t=40 GeV, $m_{t'}$=200 GeV, and n=3, m=2, ℓ=1, A=B=1 and use the range of Eq.(5) for ρ and η and the constraints of $\alpha^2+\beta^2\lesssim 1$ and $\gamma^2+\delta^2\lesssim 1$ which assure the validity of a perturbative expansion in λ of the KM matrix elements. The result of the maximum value for the CP-asymmetry $C_f^{(4)}$ in the four-generation model is summarized in Table II together with the maximum value of $C_f^{(3)}$ for the three generations and the ratio $C_f^{(4)max}/C_f^{(3)max}$.

As can be seen in Table II, the 4th generation hardly enhances the CP asymmetry for the "tree-diagram" modes of B_d and B_s mesons, except for the mode of $\bar{b}\to\bar{c}c\bar{s}$ for B_s decay for which the higher-order term of the KM matrix element V_{cb} in λ affects the CP violation. The reason for this small effect can be understood as follows. If we define the phase of Λ as $e^{i\Psi}=\Lambda/|\Lambda|$, the phase is already very close to $\pi/2$ for the maximum value of $C_f^{(3)}$ in the three generations. For the mode $\bar{b}\to\bar{c}u\bar{d}$, for example, the phase Ψ is as $\sin\Psi$=0.995 for (ρ,η)=(0.7,0.2). Therefore, the 4th generation might at most bring $\sin\Psi$ to its maximum; $\sin\Psi$=1, which would enhance $C_f^{(3)max}$ only by a factor 1/0.995. On the other hand, the mode $\bar{b}\to\bar{c}c\bar{s}$, for which the 4th generation largely affects the asymmetry, has a phase of $\sin\Psi=0.068$ for $\eta=0.7$ which gives the maximum value of $C_f^{(3)}$. Since the phase Ψ is small for this mode, the 4th generation could enhance the asymmetry by a large amount as seen in Table II.

In summary, the CP violating asymmetries for $B_d \to D^+D^-$, $\pi^+\pi^-$, and K^+K^- reach the order of 40% and the number of $b\bar{b}$ quark pairs needed to detect the asymmetry is 10^6-10^8 at 3σ level, and the asymmetries for $B_s \to \bar{D}^0\pi^0$, $D^-\pi^+$, $D^0\pi^0$, and $D^+\pi^-$ reach the order of 20% and the number of $b\bar{b}$ pairs is order of 10^8. Therefore, we may conclude that the CP-violation for these decay modes is possibly observable. The 4th generation hardly enhances the CP asymmetry, except for the mode $\bar{b} \to \bar{c}c\bar{s}$ for B_s-decay. So, it is interesting to observe the CP-asymmetry for the processes $B_s \to D^+D^-$, F^+F^-, and $\Phi\psi$. If the asymmetry larger than 10% is found, it would indicate the existence of "new physics" such as the 4th generation.

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Table I(a). Numerical results of C_f and $N_{b\bar{b}}$.

$B_d - \bar{B}_d$ system

Case	Process	C_f	$N_{b\bar{b}}$
1) $\bar{b} \to \bar{u}u\bar{d}$	$\pi^+\pi^-$ (ex d)	$\lvert C_f \rvert \leq 0.49$	$7.2 \cdot 10^5 \leq N_{b\bar{b}}$
	K^+K^- (ex s)		$7.2 \cdot 10^5 \leq N_{b\bar{b}}$
2) $\bar{b} \to \bar{u}c\bar{d}$	$D^+\pi^-$ (ex d)	$0.004 \leq -C_f \leq 0.122$	$3.0 \cdot 10^7 \leq N_{b\bar{b}} \leq 7.0 \cdot 10^{10}$
	F^+K^- (ex s)		$3.0 \cdot 10^8 \leq N_{b\bar{b}} \leq 7.0 \cdot 10^{11}$
	ψD^0 (ex c)		$2.2 \cdot 10^8 \leq N_{b\bar{b}} \leq 5.0 \cdot 10^{11}$
	$D^0\pi^0$ (ex u)		$3.0 \cdot 10^7 \leq N_{b\bar{b}} \leq 7.0 \cdot 10^{10}$
3) $\bar{b} \to \bar{c}u\bar{d}$	$D^-\pi^+$ (ex d)	$0.001 \leq -C_f \leq 0.022$	$1.6 \cdot 10^8 \leq N_{b\bar{b}} \leq 4.1 \cdot 10^{11}$
	F^-K^+ (ex s)		$1.6 \cdot 10^9 \leq N_{b\bar{b}} \leq 4.1 \cdot 10^{12}$
	ψD^0 (ex c)		$1.1 \cdot 10^9 \leq N_{b\bar{b}} \leq 2.9 \cdot 10^{12}$
	$\bar{D}^0\pi^0$ (ex u)		$1.6 \cdot 10^8 \leq N_{b\bar{b}} \leq 4.1 \cdot 10^{11}$
4) $\bar{b} \to \bar{c}c\bar{d}$	F^+F^- (ex s)	$0.10 \leq C_f \leq 0.49$	$3.7 \cdot 10^9 \leq N_{b\bar{b}} \leq 4.0 \cdot 10^{11}$
	D^+D^- (ex d)		$3.7 \cdot 10^7 \leq N_{b\bar{b}} \leq 4.0 \cdot 10^9$

Table I(b). Numerical results of C_f and $N_{b\bar{b}}$.

$B_s - \bar{B}_s$ system

Case	Process	C_f	$N_{b\bar{b}}$
1) $\bar{b} \to \bar{u}u\bar{s}$	$\pi^+\pi^-$ (ex d)	$\lvert C_f \rvert \leq 0.19$	$2.4 \cdot 10^8 \leq N_{b\bar{b}}$
	K^+K^- (ex s)		$2.4 \cdot 10^8 \leq N_{b\bar{b}}$
2) $\bar{b} \to \bar{u}c\bar{s}$	$D^0\phi$ (ex c)	$0.05 \leq C_f \leq 0.19$	$1.8 \cdot 10^8 \leq N_{b\bar{b}} \leq 8.8 \cdot 10^9$
	F^+K^- (ex s)		$9.1 \cdot 10^8 \leq N_{b\bar{b}} \leq 4.4 \cdot 10^{10}$
	$D^+\pi^-$ (ex d)		$9.1 \cdot 10^7 \leq N_{b\bar{b}} \leq 4.4 \cdot 10^9$
	$D^0\pi^0$ (ex u)		$9.1 \cdot 10^7 \leq N_{b\bar{b}} \leq 4.4 \cdot 10^9$
3) $\bar{b} \to \bar{c}u\bar{s}$	$D^0\phi$ (ex c)	$0.05 \leq C_f \leq 0.18$	$1.8 \cdot 10^8 \leq N_{b\bar{b}} \leq 8.5 \cdot 10^9$
	F^-K^+ (ex s)		$8.8 \cdot 10^8 \leq N_{b\bar{b}} \leq 4.3 \cdot 10^{10}$
	$D^-\pi^+$ (ex d)		$8.8 \cdot 10^7 \leq N_{b\bar{b}} \leq 4.3 \cdot 10^9$
	$\bar{D}^0\pi^0$ (ex u)		$8.8 \cdot 10^7 \leq N_{b\bar{b}} \leq 4.3 \cdot 10^9$
4) $\bar{b} \to \bar{c}c\bar{s}$	D^+D^- (ex d)	$0.004 \leq C_f \leq 0.014$	$6.4 \cdot 10^9 \leq N_{b\bar{b}} \leq 3.0 \cdot 10^{11}$
	F^+F^- (ex s)		$6.4 \cdot 10^{11} \leq N_{b\bar{b}} \leq 3.0 \cdot 10^{13}$
	$\phi\psi$ (ex c)		$9.2 \cdot 10^8 \leq N_{b\bar{b}} \leq 4.3 \cdot 10^{10}$

Table II. The effects of 4th generation.
$B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ systems

Case	$C^{(3)}_{fmax}$	$C^{(4)}_{fmax}$	$\lvert C^{(4)}_f / C^{(3)}_f \rvert$
1) $\bar{b} \to \bar{u}u\bar{d}$	0.491	0.491	1.000
2) $\bar{b} \to \bar{u}c\bar{d}$	-0.~~085~~ 122	-0.~~108~~ 123	1.~~273~~ 008
3) $\bar{b} \to \bar{c}u\bar{d}$	-0.0216	-0.0217	1.005
4) $\bar{b} \to \bar{c}c\bar{d}$	0.491	0.491	1.000
1) $\bar{b} \to \bar{u}u\bar{s}$	0.192	0.192	1.000
2) $\bar{b} \to \bar{u}c\bar{s}$	0.185	0.185	1.000
3) $\bar{b} \to \bar{c}u\bar{s}$	0.181	0.181	1.000
4) $\bar{b} \to \bar{c}c\bar{s}$	-0.0136	-0.192	14.17