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Fourth-generation effect on CP violation in B_d hadronic decays

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Du, Dunietz, and Wu examined CP violation in partial-decay-rate asymmetries of neutral b-flavored mesons in the standard Kobayashi-Maskawa (KM) model. We calculate in the four-generation model the same CP asymmetry in B_d hadronic decays in light of the large B_d-$\bar{B}_d$ mixing obtained by the ARGUS and CLEO Collaborations. The general 4×4 KM matrix proposed by Botella and Chau is used. The effect of the fourth generation on asymmetry is found to be sizable for various mixings of the fourth with the preceding three generations, changing signs of the asymmetry in the modes $\bar{b}\to\bar{u}u\bar{d}$ and $\bar{b}\to\bar{c}c\bar{d}$, and enhancing magnitudes in the modes $\bar{b}\to\bar{u}c\bar{d}$ and $\bar{b}\to\bar{c}u\bar{d}$ from their standard-model predictions.

Du, Dunietz, and Wu[1] formulated a scheme for calculating CP asymmetries in hadronic decays of tagged neutral b-flavored mesons within the framework of the Kobayashi-Maskawa (KM) model with three generations.[2] They found large CP asymmetries due to the sizable B^0-$\bar{B}^0$ mixing in the hadronic final states into which both B^0 and $\bar{B}^0$ can decay under the assumption that those states proceed only through one strong-interaction channel.

In this Brief Report we examine the effects of the fourth generation on the same asymmetry in B_d hadronic decays by using a naive extension of the Du-Dunietz-Wu scheme in light of the large B_d-$\bar{B}_d$ mixing obtained by the ARGUS (Ref. 3) and CLEO (Ref. 4) Collaborations.

The time-integrated CP-violating asymmetry is defined as[1]

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

where B^0_{phys} is the physical B^0 meson evolved from a pure B^0 produced at $t=0$ and $\Gamma(B^0_{\text{phys}}\to f)$ is the partial decay rate of B^0_{phys} into the specified final state f. The decay rate is calculated in the usual way under B^0-$\bar{B}^0$ mixing[5] by assuming the box-diagram dominance and leads to the following expression for C_f:[1]

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

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

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

In order to calculate the asymmetry in four generations, we use one of the general parametrizations of the 4×4 KM matrix proposed by Botella and Chau.[6] This matrix has the advantage of having simple forms in the first row,

$$(V_{ud},V_{us},V_{ub},V_{ub'})=(c_wc_xc_z,c_ws_xc_z,c_ws_ze^{-i\phi_1},s_we^{-i\phi_2})\ ,$$

and in the fourth column,

$$(V_{ub'},V_{cb'},V_{tb'},V_{t'b'})=(s_we^{-i\phi_2},s_vc_we^{-i\phi_3},s_uc_vc_w,c_uc_vc_w)\ ,$$

where $c_w=\cos\theta_w$, $s_w=\sin\theta_w$, and so on, and t' and b' are, respectively, the up and down quarks of the fourth generation. In this parametrization, most of the angles could be easily determined by $b\to u$ decay and b' decays. According to the recent phenomenological analyses with the unitarity relation,[7] $|V_{ub'}|<0.07$, $|V_{cb'}|<0.49$, and $|V_{tb'}|,|V_{t'b'}|<0.999$, so we obtain $s_w<0.07$ and $s_v<0.49$. To see the order of magnitude of these angles, it is convenient to use the Wolfenstein-type parametrization[8] with Cabibbo angle ($\lambda\equiv\cos\theta_C\simeq0.22$);[8] $s_x=\lambda$, $s_y\simeq\lambda^2$, $s_z<\lambda^3$, $s_w<\lambda^2$, and $s_v<2\lambda$.[6]

Using the above-mentioned Botella-Chau parametrization and the measured value of B_d-$\bar{B}_d$ mixing,[3,4] $z=0.70\pm0.13$, we calculate the asymmetry, Eq. (1), for the four quark-level 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.[1]

We take the mode $\bar{b}\to\bar{u}u\bar{d}$ as an example to show the calculation. The relevant products of the 4×4 KM matrix elements are

$$V_{tb}V_{td}^{*}\sim c_u^2 s_x s_y - c_u^2 s_z e^{-i\phi_1} - c_x c_u c_v s_u s_w e^{-i\phi_2} + s_x c_u s_u s_v e^{-i\phi_3}\,,$$

$$V_{t'b}V_{t'd}^{*}\sim c_u c_v s_u s_w e^{-i\phi_2} - s_x c_u s_u s_v e^{-i\phi_3}\,,$$

$$V_{ub}^{*}V_{ud}\sim c_x s_z e^{i\phi_1}\,,$$

where we have used an approximate form for the matrix which satisfies the unitarity relation to the order of λ^3. Then, the dispersive part $M_{12}^{(4)}$ in the four generations is expressed in terms of $M_{12}^{(3)}$ for the three generations as

$$M_{12}^{(4)}=M_{12}^{(3)}\left[1+2\frac{V_{t'd}^{*}V_{t'b}}{V_{td}^{*}V_{tb}}\frac{E(t,t')}{E(t,t)}+\frac{(V_{t'd}^{*}V_{t'b})^2}{(V_{td}^{*}V_{tb})^2}\frac{E(t',t')}{E(t,t)}\right], \tag{4}$$

with

$$M_{12}^{(3)*}/|M_{12}^{(3)}|=V_{tb}^{*}V_{td}/(V_{tb}V_{td}^{*})$$

for the B_d-$\bar{B}_d$ system, where the $E(i,j)$'s are the box function obtained by Inami and Lim.[9] x of Eq. (3) is given by

$$x=\frac{\bar{A}(\bar{B}_d\to f)}{A(B_d\to f)}=\frac{V_{ub}V_{ud}^{*}}{V_{ub}^{*}V_{ud}}\,, \tag{5}$$

where f is $\pi^+\pi^-$, K^+K^-, and $\pi^0\pi^0$. In order to do numerical calculations, we take $s_x=0.22$, $s_y=0.044$, and $0.002\le s_z<0.007$,[7] where the lower limit of s_z comes from the analyses of B_d-$\bar{B}_d$ mixing[10] and of the parameter ϵ of the kaon system,[11] and moreover we take $\pi/2\le\phi_1\le 5\pi/6$.[10,13] The angles s_u, s_v, and s_w occur as two combinations of $s_u s_w$ and $s_u s_v$ in $V_{tb}V_{td}^{*}$ and $V_{t'b}V_{t'd}^{*}$ and these combinations seem to lie around $s_u s_v\approx\lambda^2$ (~ 0.05) and $s_u s_w\approx\lambda^3$ (~ 0.01) as a result of the analyses of B_d-$\bar{B}_d$ mixing in the four-generation model.[12] So, we change $0<s_u s_w<5\times10^{-2}$ and take $s_u s_v$ as 0.01, 0.05, and 0.10. As for the unknown phases, we take $\phi_2=\phi_3=\pm\pi/2$ in order to estimate the maximum contribution of the fourth generation.[13] And we tentatively assume the mass of the t'quark as 200 GeV. In Fig. 1, we show the calculated values of the asymmetry C_f at three

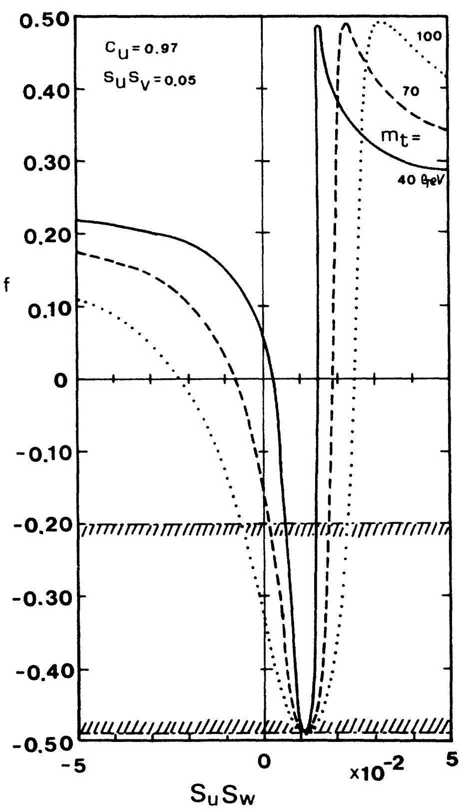

FIG. 1. Asymmetry C_f in $\bar{b}\to\bar{u}u\bar{d}$ mode for $c_u=0.97$, $s_u s_v=0.05$, and $m_t=40$ GeV (solid line), 70 GeV (dashed line), and 100 GeV (dotted line). Here $s_u s_w>0$ (<0) corresponds to the case of $\phi_2=\pi/2$ ($-\pi/2$). The values predicted in the standard model are shown by the hatched region.

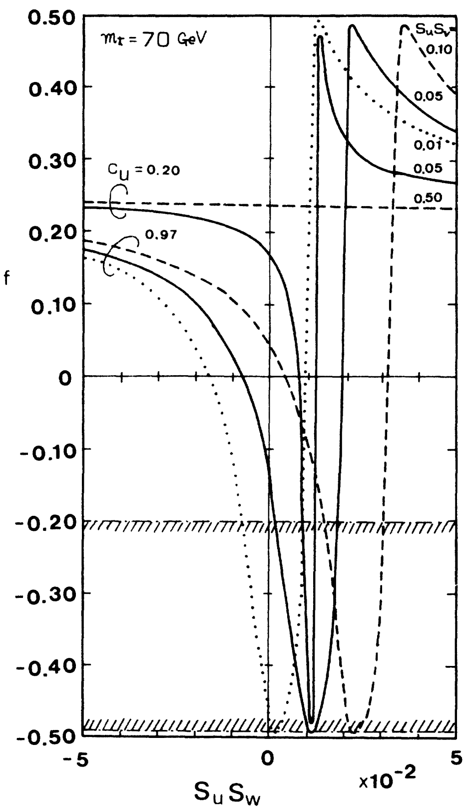

FIG. 2. $s_u s_v$ dependence of C_f in $\bar{b}\to\bar{u}u\bar{d}$ mode for $s_u s_v=0.01$ (dotted line), 0.05 (solid line), and 0.10 (dashed line) for $c_u=0.97$, and $s_u s_v=0.5$ (solid line) and 0.20 (dashed line) for $c_u=0.20$. The top-quark mass is taken as $m_t=70$ GeV.

values of top-quark mass; $m_t = 40$, 70, and 100 GeV for $c_u = 0.97$ and $s_u s_v = 0.05$ for the mode $\bar{b} \to \bar{u}u\bar{d}$, and in Fig. 2 we show the $s_u s_v$ and c_u dependences of the asymmetry for $m_t = 70$ GeV. In these figures, $s_u s_w > 0$ (<0) and $s_u s_v > 0$ (<0) correspond to $\phi_2 = \pi/2$ ($-\pi/2$) and $\phi_3 = \pi/2$ ($-\pi/2$), respectively. In Fig. 2, the case of $s_u s_v < 0$ gives the similar behavior of C_f to that for $s_u s_v > 0$ and is not depicted there. The case of $c_u = 0.20$ corresponds to the nondiagonal mixing between the third and fourth generations and does not give so different $s_u s_v$ dependence of C_f from the diagonal mixing case ($c_u = 0.97$) for not too large a value of $s_u s_v$. In these figures, the values of C_f for three generations (=standard KM model) are also shown as $-0.49 < C_f \leq -0.20$ by a hatched region, which are obtained from the range of s_z and ϕ_1. From these results, one can see that the effect of the fourth generation is remarkable, especially changing the sign of the asymmetry or reducing the magnitude, but not enhancing the absolute magnitude from the standard-model (SM) value.

For the other three modes, we give the results in Fig. 3 for $\bar{b} \to \bar{u}c\bar{d}$ ($B_d \to D^+\pi^-$, F^+K^-, $\psi D^0, D^0\pi^0$), in Fig. 4 for $\bar{b} \to \bar{c}u\bar{d}$ ($B_d \to D^-\pi^+$, F^-K^+, $\psi\bar{D}^0$, $\bar{D}^0\pi^0$), and in Fig. 5 for $\bar{b} \to \bar{c}c\bar{d}$ ($B_d \to D^+D^-$, F^+F^-, $D^0\bar{D}^0$). In these cases, another combination of the angles occurs as $s_v s_w$,

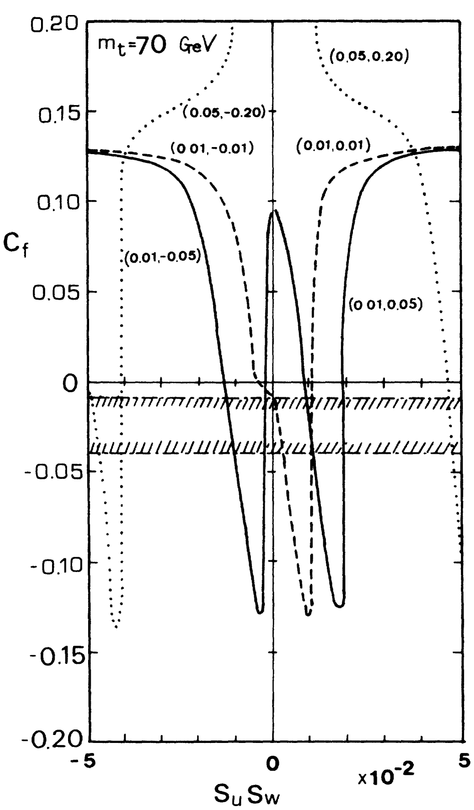

FIG. 3. Asymmetry C_f in $\bar{b} \to \bar{u}c\bar{d}$ mode for $(s_v s_w, s_u s_v) = (0.01, \pm 0.01)$ given by the dashed line, $(0.01, \pm 0.05)$ by the solid line, and $(0.05, \pm 0.20)$ by the dotted line. The values predicted in the standard model are shown by the hatched region. $m_t = 70$ GeV is taken.

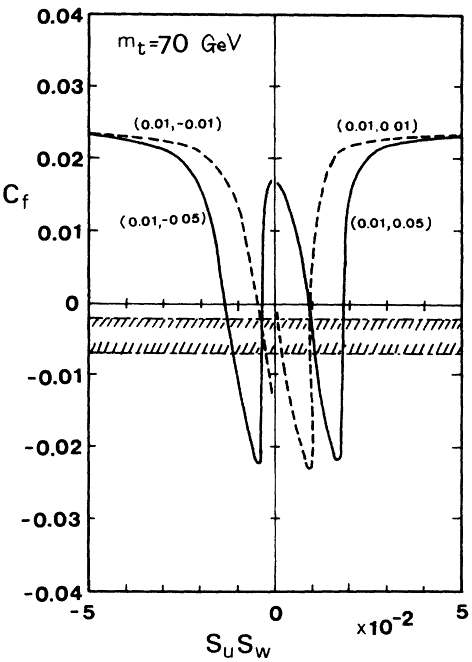

FIG. 4. Asymmetry C_f in $\bar{b} \to \bar{c}u\bar{d}$ mode for $(s_v s_w, s_u s_v) = (0.01, \pm 0.01)$ given by the dashed line and $(0.01, \pm 0.05)$ by the solid line. The values predicted in the standard model are shown by the hatched region. $m_t = 70$ GeV is taken.

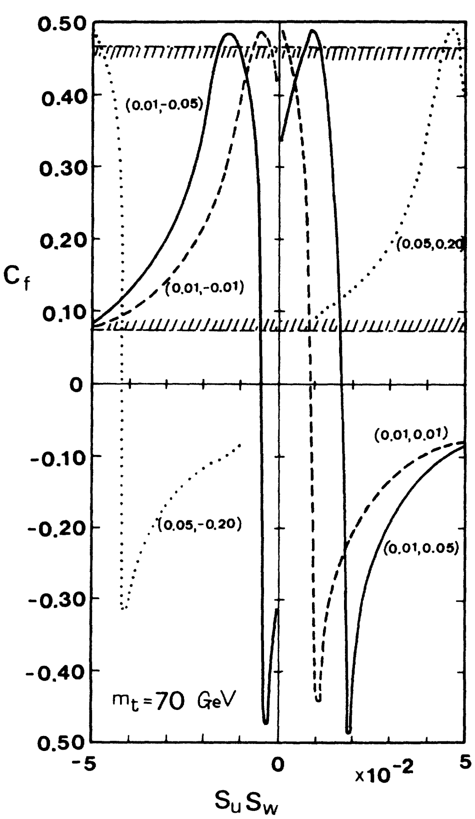

FIG. 5. Asymmetry C_f in $\bar{b} \to \bar{c}c\bar{d}$ mode; legend the same as in Fig. 3.

and we change $s_u s_w$ in the region $0 < s_u s_w < 5\times 10^{-2}$ and take $s_v s_w = 0.01$, 0.05 and $s_u s_v = 0.01$, 0.05, 0.20. When we take $s_v s_w$ as positive, both $s_u s_w$ and $s_u s_v$ must be either positive or negative. The result from the three-generation model is also shown in the figures ($-0.039 < C_f^{(3)} \leq -0.008$ for $\bar{b}\rightarrow\bar{u}c\bar{d}$, $-0.007 < C_f^{(3)} \leq -0.002$ for $\bar{b}\rightarrow\bar{c}u\bar{d}$, and $0.075 \leq C_f^{(3)} < 0.467$ for $\bar{b}\rightarrow\bar{c}c\bar{d}$). And, we have taken the top-quark mass as $m_t = 70$ GeV, since the m_t dependence of C_f is not as strong in the region $40 \leq m_t \leq 100$ GeV, as can be seen in Fig. 1. From these results, we can see that the effect of fourth generation is also remarkable and even enhances the magnitude from the standard-model values for the modes $\bar{b}\rightarrow\bar{u}c\bar{d}$ and $\bar{b}\rightarrow\bar{c}u\bar{d}$.

In conclusion, the effect of fourth generation on *CP* asymmetry C_f in B_d hadronic decays is sizable for the reasonable mixings of fourth generation to the former three generations, which are obtained from the analyses of B_d-$\bar{B}_d$ mixing in the four-generation model. For example, if we find a change of sign of C_f in $B_d\rightarrow D^+D^-$ from its standard-model value of $(0.08 \leq C_f^{(3)} < 0.48)$ by doing experiments, or if we find an enhancement of C_f in $B_d\rightarrow D^-\pi^+$, $\bar{D}^0\pi^0$, $\psi\bar{D}^0$ from its standard-model value $(C_f^{(3)} \sim -1\%)$, it could possibly indicate the existence of a fourth generation.

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