Right-Handed $b$ to $c$ and $u$ Coupling Model and CP Violation

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ABSTRACT

We investigate CP violation in the purely right-handed $b$ quark to $c$- and $u$- quark coupling model under the constraint of right-handed W-gauge boson mass $M_R > 720$ GeV, which is experimentally obtained recently by D0 Collaboration at Fermilab. By using the data on $K_L - K_S$ mass difference, CP violating parameter $\varepsilon$ in the neutral kaon system and $B_d - \bar{B}_d$ mixing, together with the new data of $\frac{\text{Br}(B^-(\rightarrow \psi\pi^-)/\text{Br}(B^- \rightarrow \psi K^-)} = 0.052 \pm 0.024 (\approx |V_{cd}/V_{cs}|^2)$, we can fix all of the three independent angles and one phase of the right-handed mixing matrix $V^R$. Under these constraints, another CP-violating parameter $\varepsilon'/\varepsilon$ and electric dipole moment of neutron are shown to be consistent with the data in our model. The pattern of CP violation in the nonleptonic decay of $B_d(B_s)$ mesons to CP eigenstates is different from that in the Standard Model.

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1. Introduction

The Standard Model of electroweak interactions for quarks and leptons has proved to be increasingly successful by the discovery of top quark by CDF and D0 Collaborations [1].

All of the weak charged currents are postulated to be left-handed (V-A) in the Standard Model. As for the quark currents, among the nine charged currents caused by the Cabibbo-Kobayashi-Maskawa quark mixing [2], those between the first two generations and the diagonal third generation coupling $t \to b$ are known to be left-handed [3, 4]. However, the chirality of the off-diagonal couplings in the $b$-quark decay, $b \to c$ and $b \to u$, is not yet experimentally confirmed to be left-handed. Polarization of $\Lambda_b$ baryon produced in $Z^0 \to b\bar{b}$ decay has recently been measured to be $P_{\Lambda_b} = -0.23 \pm 0.25$ by using the semileptonic decays with charmed hadrons at LEP [5], while it has been predicted to be $P_{\Lambda_b} \approx -0.75$ in a simple model in the framework of the Standard Model.

Since the $SU(2)_L \times SU(2)_R \times U(1)$ gauge model with right-handed charged currents was proposed [6], the mass ($M_R$) of right-handed gauge boson $W_R$ has been studied phenomenologically. Beal, Bander and Soni obtained the constraint $M_R > 1.6$ TeV from the analysis of $K_L - K_S$ mass difference in the left-right symmetric model ($V^R = V^L$) [7], where $V^L$ and $V^R$ are left- and right-handed quark mixing matrices, respectively. After that, Olness and Ebel discovered two types of $V^R$ which enabled to lower the mass $M_R$ to several-hundred GeV by relaxing the constraint $V^R = V^L$ [8]. Langacker and Sanker extended their analysis and showed that the mass can be lowered to 300GeV for the case of right-handed neutrino mass of above 100 MeV for the special form of $V^R$ [9] which is idealized from the types found by Olness and Ebel. Nishiura, Takasugi and Tanaka proposed a model with light $W_R$
in which CP violation in $K \rightarrow \pi\pi$ decay mainly arises from the right-handed interactions, and investigated CP violation in $K$ and $B_{d(s)}$ decays and the electric dipole moment of neutron [10].

In 1992, Gronau and Wakaizumi proposed a purely right-handed $b$ to $c(u)$ coupling model [11] in the framework of $SU(2)_L \times SU(2)_R \times U(1)$ gauge model under the circumstance that the left-handed chirality of these couplings has not yet been confirmed experimentally, and showed that this model is viable within both the experimental precision of $b$ semileptonic decays, $K_L - K_S$ mass difference and $B_d - \bar{B}_d$ mixing and the theoretical uncertainties in the hadronic matrix elements. After that, Hou and Wyler discussed these couplings more generally in their model [12]. Several methods to test the chirality of the $b$ to $c$ coupling have been proposed [13].

As for CP violation in the purely right-handed $b$ to $c$ coupling model, Gronau investigated CP asymmetry in neutral $B$ meson decays into hadronic CP-eigenstates by giving one phase to $V^R$ and obtained a remarkably different pattern of the asymmetry from that in the Standard Model [14]. Hattori, Hasuike, Hayashi and Wakaizumi proposed a model of purely right-handed $b$ to $c$ coupling together with purely left-handed $b$ to $u$ one with a full number of phases in $V^R$ in order to examine CP violation in neutral kaon system, in neutral $B$ meson decays and electric dipole moment of neutron, and discussed the behavior of the phases [15].

A new lower bound of the right-handed gauge boson $W_R$ has recently been obtained to be 720 GeV by D0 Collaboration at Fermilab [16]. In this paper, under this new circumstance we investigate the model of purely right-handed chirality for both $b$ to $c$ and $b$ to $u$ couplings by giving the most general form to $V^R$, that is, with the three independent angles and all of the necessary phases to study CP violation in neutral $K$ and $B$ systems and the
electric dipole moment of neutron.

In §2, we describe the model and determine some of the parameters in the model by using the data on $K_L - K_S$ mass difference, CP-violating parameter $\varepsilon$ in the neutral kaon system, $B_d - \bar{B}_d$ mixing and the new data on $\text{Br}(B^- \to \psi\pi^-)/\text{Br}(B^- \to \psi K^-) = 0.052 \pm 0.024(\approx |V_{cd}/V_{cs}|^2)$. In §3, we examine another CP violating parameter $\varepsilon'$, electric dipole moment of neutron and CP asymmetries in $B_d(s)$ meson decays into hadronic CP-eigenstates. We present discussions and conclusions in §4.

2. Purely right-handed $b$ to $c(u)$ model

Our model is the purely right-handed coupling model for both $b$- quark to $c$ and $u$ charged currents in the framework of $SU(2)_L \times SU(2)_R \times U(1)$ gauge model, so that the left-handed quark mixing matrix is

$$V^L \simeq \begin{pmatrix} 1 & \lambda & 0 \\ -\lambda & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

where the Wolfenstein parametrization with the Cabibbo angle $\lambda \equiv \sin \theta_c(\simeq 0.22)$ is used. For the right-handed mixing matrix, we take the following most general form with all of the three mixing angles $\theta_{12}, \theta_{13}$ and $\theta_{23},$

$$V^R = \begin{pmatrix} e^{i\alpha}c_{12}c_{13} & -e^{i\beta}s_{12}c_{13} & e^{i\gamma}s_{13} \\ e^{i(\alpha-\gamma)}(s_{12}c_{23}e^{i\delta} - c_{12}s_{13}s_{23}) & e^{i(\beta-\gamma)}(c_{12}c_{23}e^{i\delta} + s_{12}s_{13}s_{23}) & c_{13}s_{23} \\ e^{i(\alpha-\gamma)}(-s_{12}c_{23}e^{i\delta} - c_{12}s_{13}c_{23}) & e^{i(\beta-\gamma)}(-c_{12}s_{23}e^{i\delta} + s_{12}s_{13}c_{23}) & c_{13}c_{23} \end{pmatrix},$$

where $c_{12} \equiv \cos \theta_{12}$, $s_{12} \equiv \sin \theta_{12}$, and etc. As for CP phases, our $V^L$ needs three independent phases from its unitarity up to the overall phase and the most general $V^R$ needs six phases. From these nine phases, five phases can be eliminated by the quark fields, so that four phases survive in our model and we will assign them to $V^R$ as seen in Eq.(2).

In this model, since $b$ quark decay proceeds through the right-handed
charged current $(V+A)$, semileptonic decay $b \rightarrow c l^{-}\bar{\nu}$ is mediated by the right-handed gauge boson $W_R$ and the following relation must be satisfied [11],

$$|V_{cb}^{R}|\sqrt{\beta_g^2 + \zeta_g^2} = |V_{cb}^{SM}|,$$

(3)

where $\beta_g \equiv (g_R/g_L)^2M_L^2/M_R^2$ and $\zeta_g \equiv (g_R/g_L)\zeta, g_L, g_R$, and $M_L, M_R$ being left- and right-handed gauge coupling constants and gauge boson masses, respectively, $\zeta$ the $W_L-W_R$ mixing angle, and $V_{cb}^{SM}$ is the $(cb)$-element of the Kobayashi-Maskawa mixing matrix [2]. $W_R$ has recently been searched for by D0 Collaboration at Fermilab [16] by decays to an electron and a massive right-handed neutrino ($N_R$), $W_R^\pm \rightarrow e^\pm N_R$, and a lower limit of the mass has been obtained as $M_R^2(\equiv (g_L/g_R)M_R) > 720\text{GeV}$ for $m_{N_R} \ll M_R$. An upper limit of $\zeta_g$ is obtained by the phenomenological analysis with the data on both low-energy processes and high-energy processes to be $|\zeta_g| < 0.031$ for light right-handed neutrino [17]. If we use these limits and $|V_{cb}^{SM}| = 0.032-0.048$ [18], the relation of Eq.(3) leads to

$$|V_{cb}^{R}| = |c_{13}s_{23}| > 0.96.$$

(4)

The constraint, $|V_{ub}^{SM}/V_{cb}^{SM}| = 0.08 \pm 0.02$ [19], obtained from the analyses of the lepton energy spectra in $B$ meson semileptonic decays with various theoretical hadronic models is transformed into

$$\left|\frac{V_{ub}^{R}}{V_{cb}^{R}}\right| = \left|\frac{s_{13}}{c_{13}s_{23}}\right| = 0.08 \pm 0.02$$

(5)

in our model, since we assume $m_{\nu_R} < m_b - m_c$, where $m_b$ and $m_c$ are the masses of $b$- and $c$- quark, respectively. From Eqs.(4) and (5), we obtain the following range for the angle $\theta_{13}$ of $V^R$,

$$|s_{13}| \simeq 0.08 \pm 0.02.$$

(6)

Next, in order to fix the remaining two angles $\theta_{12}, \theta_{23}$ and the phase $\delta$, we use experimental data on $B_d - \overline{B}_d$ mixing, $\text{Br}(B^- \rightarrow \psi\pi^-)/\text{Br}(B^- \rightarrow$
ψK−) = 0.052 ± 0.024 obtained recently by CLEO Collaboration [20], $K_L - K_S$ mass difference and CP violating parameter $\varepsilon$ in neutral kaon system.

First of all, $B_d - \overline{B}_d$ mixing is dominantly described in our model by the $W_L - W_R$ box diagram with $c$- and $t$- quark exchanges, depicted in Fig.1. This diagram gives the following mass difference between the two mass-eigenstates in neutral $B_d - \overline{B}_d$ system,

$$\Delta m_{B_d}^{LR}(c, t) = 2 | < B_d | H_{eff}^{LR}(c, t) | \overline{B}_d > |$$

$$= \frac{4G^2 F M_B^2 B}{\pi^2} \left[ \left( \frac{m_B}{m_b + m_d} \right)^2 + \frac{1}{6} \right] \frac{1}{4} f_B^2 B m_B$$

$$\times | V_{ub}^L V_{cd}^L V_{tb}^R V_{td}^R V_{cb}^R | B(x_c, x_t, \beta_g), \quad (7)$$

where $m_{B_d}$, $f_B$ and $B_B$ are the mass, decay constant and bag parameter of $B_d$ meson, respectively, and $m_d$ the $d$- quark mass. $B(x_c, x_t, \beta_g)$ is the $W_L - W_R$ box function with QCD corrections which is formulated by Ecker and Grimus [21] and extended by Nishiura, Takasugi and Tanaka [10], where $x_c \equiv (m_c/M_L)^2$ and $x_t \equiv (m_t/M_L)^2$ for $c$- and $t$- quark mass $m_c$ and $m_t$. The QCD parameter $\Lambda_f$ of the strong-coupling constant $\alpha_s(m^2)$ in $B(x_c, x_t, \beta_g)$ is chosen to be $\Lambda_f = 0.11$ GeV for $N_f = 5$ to reconcile with $\alpha_s(M_Z^2) = 0.122 \pm 0.007$ [19] obtained from the event shape measurements by PEP/PETRA, TRISTAN, LEP, SLC and CLEO. If we substitute $G_F = 1.166 \times 10^{-5}$ GeV, $M_L = 80$ GeV, $f_B \sqrt{B_B} = (0.15 \pm 0.05)$ GeV, $m_{B_d} = 5.28$ GeV, $m_b = 4.5$ GeV, $m_d = 0.01$ GeV, $m_c = 1.5$ GeV and $m_t = 174$ GeV in Eq.(7) and use the data of $\Delta m_{B_d} = (3.36 \pm 0.39) \times 10^{-10}$ MeV [19], we obtain

$$| V_{td}^R | = | e^{i\delta} s_{12} s_{23} + c_{12} c_{23} s_{13} | = 0.08 - 0.41, \quad (8)$$

where we used Eq.(4) for $| V_{cd}^R |$. As for $\beta_g$, we will take $M_R^g = 750$ GeV to be compatible with the experimental limit $M_R^g > 720$ GeV [16] hereafter in this paper.
Next, we obtain from the data on the ratio of two nonleptonic decay branching ratios $R \equiv \text{Br}(B^- \to \psi\pi^-)/\text{Br}(B^- \to \psi K^-)$ [20] the following constraint on the angles,

$$R \approx \left| \frac{V_{cd}^{R} e^{i\delta} - c_{12} s_{13} s_{23}}{c_{12} c_{23} e^{i\delta} + s_{12} s_{23}} \right|^2 = 0.052 \pm 0.024. \quad (9)$$

As for $K_L - K_S$ mass difference $\Delta m_K$, three box diagrams depicted in Fig. 2 contribute in our model. The diagram of Fig. 2(a) is the same as the one in the Standard Model and gives the following expression to $\Delta m_K$.

$$\Delta m_{K}^{LL}(c,c) = 2 \text{Re} < K^0 | H_{eff}^{LL}(c,c) | K^0 > = \frac{G_F^2 M_s^2}{6 \pi^2} f_K^2 B_K m_K \text{Re}[ (V_{cs}^{L} V_{cd}^{L*})^2 ] \eta_{cc}^{LL} S(x_c), \quad (10)$$

where $m_K$, $f_K$, and $B_K$ are the mass, decay constant and bag parameter of the kaon, respectively, $\eta_{cc}^{LL}(\sim 0.7)$ the QCD correction factor, and $S(x_c)$ is the Inami-Lim box function [22]. If we put $f_K = 0.16$ GeV and the theoretical range $B_K = \frac{1}{3} - 1.5$ in Eq. (10), we obtain

$$\Delta m_{K}^{LL}(c,c) = (\frac{1}{3} - 1.5) \times 2.22 \times 10^{-12}\text{MeV}. \quad (11)$$

The diagrams of Figs. 2(b) and 2(c) give the following expressions,

$$\Delta m_{K}^{LR}(c,c) = 4 \frac{G_F^2 M_s^2 \beta_g}{\pi^2} \left[ \left( \frac{m_K}{m_s + m_d} \right)^2 + \frac{1}{6} \right] \frac{1}{4} f_K^2 B_K m_K \text{Re}[ (V_{cs}^{R} V_{cd}^{R*})^2 ] \eta_{tt}^{RR} S(x_t^R), \quad (12)$$

$$\Delta m_{K}^{RR}(t,t) = \frac{G_F^2 M_s^2 \beta_g}{6 \pi^2} f_K^2 B_K m_K \text{Re}[ (V_{ts}^{R} V_{td}^{R*})^2 ] \eta_{tt}^{RR} S(x_t^R), \quad (13)$$

where $x_t^R \equiv (m_t/M_R^2)^2$. If we take the $s$-quark mass $m_s = 0.2$ GeV and QCD correction factor $\eta_{tt}^{RR} \simeq 0.7$ in Eqs. (12) and (13), the following contributions are obtained,

$$\Delta m_{K}^{LR}(c,c) = (\frac{1}{3} - 1.5) \times 59.0 \times \text{Re}(V_{cs}^{R} V_{cd}^{R*}) \times 10^{-12}\text{MeV}, \quad (14)$$

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$$\Delta m^R_{K}(t, t) = \left( \frac{1}{3} - 1.5 \right) \times 77.8 \times \text{Re}[(V^R_{td}V^R_{td})^2] \times 10^{-12}\text{MeV}. \quad (15)$$

From the requirement that the sum of the three contribution, Eqs.(11), (14) and (15), gives the experimental value of $\Delta m_K$ [19], we obtain the following constraint,

$$\Delta m_K = \Delta m^{LL}_K(c, c) + \Delta m^{LR}_K(c, c) + \Delta m^{RR}_K(t, t) = (3.491 \pm 0.009) \times 10^{-12}\text{MeV}. \quad (16)$$

Finally, CP-violating parameter $\varepsilon$ in the neutral kaon system is given by

$$\varepsilon = e^{i\pi/4}(\varepsilon_m + \frac{1}{\sqrt{2}}\xi_0),$$

where $\varepsilon_m$ is the contribution from the $K^0 - \bar{K}^0$ mixing, $\varepsilon_m = \text{Im}M_{12}/\text{Re}M_{12}$, $M_{12}$ being the mass matrix of $K^0 - \bar{K}^0$ system, and $\xi_0$ is the contribution from decay dynamics, $\xi_0 = \text{Im}A_0/\text{Re}A_0$, $A_0$ being the decay amplitude of $\bar{K}^0 \to \pi\pi$ for the isospin $I = 0$ state of the two pions. As seen in the next section, $\xi_0/\sqrt{2}$ is about $-0.05 \times 10^{-3}$ and constitutes only 2% of the experimental value of $\varepsilon$ in our model, so that we can neglect the contribution from $\xi_0$ for the discussion of $\varepsilon$. The contributions to $\varepsilon_m$ come from the two diagrams of Figs.2(b) and (c) as follows,

$$\varepsilon^{LR}(c, c) = \frac{\text{Im} < K^0|H^{LR}_{eff}(c, c)|\bar{K}^0 >}{\sqrt{2}\Delta m_K} = \frac{2G^2_FM^2_L\beta_g}{\sqrt{2}\pi^2\Delta m_K} \left[ \left( \frac{m_K}{m_s + m_d} \right)^2 + \frac{1}{6} \right] \frac{1}{4}f^2_KB_Km_K \times \text{Im}(V^L_{cs}V^{L*}_{cd}V^R_{td}V^{R*}_{cd})B(x_c, x_c, \beta_g), \quad (17)$$

$$\varepsilon^{RR}(t, t) = \frac{G^2_FM^2_L\beta_g}{12\sqrt{2}\pi^2\Delta m_K} f^2_KB_Km_K \text{Im}[(V^R_{td}V^R_{td})^2] \eta^{RR}_{tt}S(x^R_t). \quad (18)$$

When we calculate the two quantities of Eqs.(17) and (18) with the data $\Delta m_K = (3.491 \pm 0.009) \times 10^{-12}\text{MeV}$, we obtain

$$\varepsilon^{LR}(c, c) = 5.94 \times \text{Im}(V^R_{cd}V^{R*}_{cd}), \quad (19)$$
\( \delta RR(t, t) = 7.84 \times \text{Im}[(V^R_{ts}V^R_{td})^2]. \)  

Therefore, we get the following constraint by summing the contributions of Eqs. (19) and (20) and using the data on \( \varepsilon \) [19],

\[
\frac{\varepsilon}{e^{i\pi/4}} = \epsilon^{LR}(c, c) + \epsilon^{RR}(t, t) = (2.28 \pm 0.02) \times 10^{-3}.
\]  

(21)

This constraint involves three phases \( \alpha, \beta \) and \( \delta \) of \( V^R \) as can be seen in Eq.(2). The discussion of another CP-violating parameter \( \varepsilon' \) in the next section will give us a relation between the two phases, \( \alpha - \beta = \pi \). So, the constraint of Eq.(21) fixes the phase \( \delta \).

All of the constraints obtained above, Eqs.(4), (6), (8), (9), (16) and (21), can lead to a solution of the three angles \( \theta_{12}, \theta_{13}, \theta_{23} \) and one phase \( \delta \) of \( V^R \),

\[
s_{12} \equiv \sin \theta_{12} = -0.152, \quad s_{13} = 0.09, \quad s_{23} = 0.975, \quad \sin \delta = 0.0345,
\]

\[
c_{12} \equiv \cos \theta_{12} = 0.988, \quad c_{13} = 0.996, \quad c_{23} = 0.22, \quad \cos \delta = -1.0.
\]  

(22)

If we substitute the solution of Eq.(22) with \( \alpha - \beta = \pi \) into \( V^R \), we obtain the following solution of \( V^R \),

\[
V^R = \begin{pmatrix}
  e^{i\alpha}0.984 & -e^{i\alpha}0.151 & e^{i\gamma}0.09 \\
  e^{i(\alpha-\gamma)}(-0.033e^{i\delta} - 0.0867) & -e^{i(\alpha-\gamma)}(0.217e^{i\delta} - 0.0133) & 0.971 \\
  e^{i(\alpha-\gamma)}(0.148e^{i\delta} - 0.0196) & -e^{i(\alpha-\gamma)}(-0.963e^{i\delta} - 0.0030) & 0.219
\end{pmatrix}.
\]  

(23)

This solution is quite close to the type II of \( V^R \) among the four forms discussed by Langacker and Sanker [9], which are idealized from the two solutions obtained by Olness and Ebel [8] by reconciling the left-right symmetric model to \( K_L - K_S \) mass difference. So, the solution of the three angles of Eq.(22) could be regarded as a unique solution with a small range coming from the experimental errors and the theoretical uncertainties in the hadronic matrix elements.

According to the solution of \( V^R \) in Eq.(23), the quantities dealt with in
this section acquire the following values,

\[
\left| \frac{V_{ub}^R}{V_{cb}^R} \right| = 0.093, \quad \Delta m_{B_d} = 3.43 \times \left( 1 + 0.78 - 0.56 \right) \times 10^{-10} \text{MeV},
\]

\[
\Delta m_K = \Delta m_{K}^{LL}(c,c) + \Delta m_{K}^{LR}(c,c) + \Delta m_{K}^{RR}(t,t)
\]

\[
= \left( \frac{1}{3} - 1.5 \right) (2.22 - 0.72 + 2.02) \times 10^{-12} = \left( \frac{1}{3} - 1.5 \right) \times 3.52 \times 10^{-12} \text{MeV},
\]

\[
\varepsilon_K = 2.27 \times 10^{-3}, \quad \frac{\text{Br}(B^+ \rightarrow \psi \pi^-)}{\text{Br}(B^+ \rightarrow \psi K^-)} = 0.053, \quad (24)
\]

where the large errors in \( \Delta m_{B_d} \) come from the large uncertainty in \( f_B \sqrt{B_B} = (0.15 \pm 0.05) \text{GeV} \).

3. CP violation

In this section we study "direct" CP-violating parameter \( \varepsilon' \) in the neutral kaon system and the electric dipole moment of neutron in our model. In addition, we analyze CP violation in the nonleptonic decay of \( B_d \) and \( B_s \) mesons into CP-eigenstates, comparing with that in the Standard Model.

"Direct" CP-violating parameter \( \varepsilon' \) arising from the decay dynamics in neutral kaon system is expressed as follows,

\[
\varepsilon' = \frac{1}{\sqrt{2}} e^{i(\xi_2 + \delta_2 - \delta_0)} \frac{\text{Re}A_2}{\text{Re}A_0} (\xi_2 - \xi_0), \quad (25)
\]

where \( A_{0,2} \) are the transition amplitudes for \( K^0 \rightarrow \pi \pi (I = 0, 2), \xi_{0,2} \equiv \text{Im}A_{0,2}/\text{Re}A_{0,2} \), and \( \delta_{0,2} \) are the strong interaction phase shifts. This quantity \( \varepsilon' \) has been measured and there are two controversial results from two groups; \( \varepsilon' / \varepsilon = (2.0 \pm 0.7) \times 10^{-3} \) from CERN [23] and \( \varepsilon' / \varepsilon = (0.74 \pm 0.52 \pm 0.29) \times 10^{-3} \) from Fermilab [24]. Although these two results are different from each other by two standard deviations, both measurements would show that \( \varepsilon' / \varepsilon \) is at the level of \( 10^{-4} - 10^{-3} \).

In our model, potential contributions to \( \varepsilon' \) are the eight diagrams shown in Fig.3. Imaginary parts of the amplitudes come from the last five diagrams.
By using the calculational procedure with the QCD corrections given by Ecker and Grimus [21], we obtain the following magnitudes of each amplitude corresponding to the eight diagrams in Fig.3 by use of $V^L$ in Eq.(1) and $V^R$ in Eq.(2); $\text{Re}A_0 \simeq 5.05 \times 10^{-5}$ MeV and $\text{Re}A_2 \simeq 3.14 \times 10^{-5}$ MeV for $W_L$-exchange tree diagram (Fig.3(a)), $(\text{Re}A_0, \text{Im}A_0) \simeq (-0.043 \cos(\beta - \alpha), 0.043 \sin(\beta - \alpha)) \times 10^{-5}$ MeV and $(\text{Re}A_2, \text{Im}A_2) \simeq (-0.023 \cos(\beta - \alpha), 0.023 \sin(\beta - \alpha)) \times 10^{-5}$ MeV for $W_R$-exchange tree diagram (Fig.3(b)), $\text{Re}A_0 \simeq 31.0 \times 10^{-5}$ MeV for $W_L$-loop penguin diagram (Fig.3(c)), $(\text{Re}A_0, \text{Im}A_0) \simeq (-0.428-0.02 \cos \delta) \cos(\beta - \alpha)-0.026 \sin \delta \sin(\beta - \alpha), (0.428-0.024 \cos \delta) \sin(\beta - \alpha)-0.026 \sin \delta \cos(\beta - \alpha)) \times 10^{-5}$ MeV for $W_R$-loop penguin diagram (Fig.3(d)), $(\text{Re}A_0, \text{Im}A_0) \simeq (0.007 \cos(\lambda - \alpha) - 0.317 \cos(\lambda - \alpha + \gamma - \delta) - 0.833 \cos(\lambda - \alpha + \gamma), -0.007 \sin(\lambda - \alpha) + 0.317 \sin(\lambda - \alpha + \gamma - \delta) + 0.833 \sin(\lambda - \alpha + \gamma)) \times 10^{-5}$ MeV for $W_L-W_R$ mixing penguin diagram (Fig.3(e)), $(\text{Re}A_0, \text{Im}A_0) \simeq (-0.005 \cos(\lambda - \beta) + 0.459 \cos(\lambda - \beta + \gamma - \delta) - 0.028 \cos(\lambda - \beta + \gamma), -0.005 \sin(\lambda - \beta) + 0.459 \sin(\lambda - \beta + \gamma - \delta) - 0.028 \sin(\lambda - \beta + \gamma)) \times 10^{-5}$ MeV for $W_R-W_L$ mixing penguin diagram (Fig.3(f)), $(\text{Re}A_0, \text{Im}A_0) \simeq (13.6 \cos(\lambda - \alpha), -13.6 \sin(\lambda - \alpha)) \times 10^{-5}$ MeV and $(\text{Re}A_2, \text{Im}A_2) \simeq (-1.18 \cos(\lambda - \alpha), 1.18 \sin(\lambda - \alpha)) \times 10^{-5}$ MeV for $W_L-W_R$ mixing tree diagram (Fig.3(g)), and $(\text{Re}A_0, \text{Im}A_0) \simeq (-9.46 \cos(\lambda - \beta), -9.46 \sin(\lambda - \beta)) \times 10^{-5}$ MeV and $(\text{Re}A_2, \text{Im}A_2) \simeq (0.82 \cos(\lambda - \beta), 0.82 \sin(\lambda - \beta)) \times 10^{-5}$ MeV for $W_R-W_L$ mixing tree diagram (Fig.3(h)), where $\lambda$ is the $W_L-W_R$ mixing phase and we used the magnitudes of the angles $\theta_{12}, \theta_{13}$ and $\theta_{23}$ in Eq.(22) and $\zeta_\gamma = 0.03$ for the $W_L-W_R$ mixing angle [17]. By examining the above respective magnitude from the eight diagrams in comparison with the average value of the two data, $\epsilon'/\epsilon = (1.5 \pm 0.8) \times 10^{-3}$ [19], imaginary parts of the contributions from the $W_L-W_R$ and $W_R-W_L$ mixing tree diagrams prove to be too large, so that we have to constrain the
phases, \( \alpha, \beta \), and \( \lambda \) as \( \lambda = \alpha \) and \( \alpha - \beta = \pi \), where the latter constraint is obtained in combination with the one that \( \Delta m^{LR}_K(c, c) \) in Eq.(14) should be negative to reproduce the experimental value of \( \Delta m_K \), as seen in Eq.(24). If we use these two constraints and \( \sin \delta = 0.0345(\cos \delta \cong -1.0) \) in Eq.(22) and sum up all of the amplitudes from the eight diagrams, we obtain the following magnitudes for the real and imaginary parts of \( A_0 \) and \( A_2 \),

\[
\begin{align*}
\text{Re}A_0 &= 59.6 - 0.029 \cos \gamma - 0.027 \sin \gamma, \\
\text{Im}A_0 &= 0.0009 + 0.0049 \cos \gamma + 1.00 \sin \gamma, \\
\text{Re}A_2 &= 1.16, \\
\text{Im}A_2 &= 0.
\end{align*}
\] (26)

In order to reproduce the sign and the order of magnitude of \( \varepsilon'/\varepsilon, \gamma = \pi \) is required for the phase \( \gamma \), as can be seen from \( \text{Im}A_0 \) in Eq.(26), and we get by substituting Eq.(26) into Eq.(25) as

\[
\varepsilon' \simeq e^{i\pi/4} \times 0.93 \times 10^{-6},
\] (27)

where we used \( \delta_0 - \delta_2 \simeq \pi/4 \) [19]. If we use the experimental value of \( \varepsilon, \varepsilon \simeq e^{i\pi/4} \times 2.28 \times 10^{-3} \), we eventually obtain

\[
\varepsilon'/\varepsilon \simeq 0.41 \times 10^{-3}.
\] (28)

This value is consistent with the measured value from Fermilab [24], and is compatible with the average value of the data from the two groups, \( \varepsilon'/\varepsilon = (1.5 \pm 0.8) \times 10^{-3} \) [19].

Next, we study the electric dipole moment of neutron in our model. The dipole moment arises from the one loop \( W_L - W_R \) mixing diagrams for the moments of \( u \)- and \( d \)-quarks in the \( SU(2)_L \times SU(2)_R \times U(1) \) model [25]. We neglect here the contributions from Higgs loop and exchange diagrams in order to see the order of magnitude of the dipole moment. The diagrams
contributing to the moments of \( u \) and \( d \) quarks \((d_u \text{ and } d_d)\) are those depicted in Figs.4(a) and (b), respectively.

\( d_u \) and \( d_d \) are expressed as follows [25],

\[
d_u = \frac{4\sqrt{2}eG_F\zeta_g}{32\pi^2} \sum_{j=d,s} m_j \text{Im}(e^{i\lambda V^L_{wj}V^{R*}_{uj}}) \\
\times \left\{ I_1(r_j, s_u) + \frac{1}{3} I_2(r_j, s_u) - \beta \left[ I_1(r_j\beta, s_u\beta) + \frac{1}{3} I_2(r_j\beta, s_u\beta) \right] \right\},
\]

(29)

\[
d_d = \frac{4\sqrt{2}eG_F\zeta_g}{32\pi^2} \sum_{j=u,c} m_j \text{Im}(e^{i\lambda V^L_{jd}V^{R*}_{jd}}) \\
\times \left\{ I_1(r_j, s_d) + \frac{2}{3} I_2(r_j, s_d) - \beta \left[ I_1(r_j\beta, s_d\beta) + \frac{2}{3} I_2(r_j\beta, s_d\beta) \right] \right\},
\]

(30)

where \( r_j \equiv (m_j/M_L)^2, \ s_u \equiv (m_u/M_L)^2, \ s_d \equiv (m_d/M_L)^2, \ \beta \equiv (M_R/M_L)^2, \ \zeta_g \) and \( \lambda \) are \( W_L - W_R \) mixing angle and phase, respectively, and

\[
I_1(r, s) \simeq \frac{2}{(1-r)^2} \left( 1 - \frac{11}{4} r + \frac{1}{4} r^2 - \frac{3r^2 \ln r}{2(1-r)} \right),
\]

\[
I_2(r, s) \simeq \frac{2}{(1-r)^2} \left( 1 + \frac{1}{4} r + \frac{1}{4} r^2 + \frac{3r \ln r}{2(1-r)} \right).
\]

(31)

When we use \( m_d = 10\text{MeV}, \ m_s = 200\text{MeV}, \ m_u = 5\text{MeV}, \ m_c = 1.5\text{GeV}, \ \zeta_g = 0.03, \ M_R = 750\text{GeV} \) and \( V^L \) in Eq.(1) and \( V^R \) in Eq.(23), we obtain the following values,

\[
d_u \simeq -10.5 \sin(\alpha - \lambda) \times 10^{-25} \text{e} \cdot \text{cm},
\]

(32)

\[
d_d \simeq \{-20.3 \sin(\alpha - \lambda) + 44.7 \sin(\lambda - \alpha + \gamma - \delta) + 117.4 \sin(\lambda - \alpha + \gamma)\} \\
\times 10^{-25} \text{e} \cdot \text{cm}.
\]

(33)

We take the \( SU(6) \) wave function to calculate the neutron electric dipole moment to obtain

\[
d_n = \frac{1}{3}(4d_d - d_u) \simeq (96.9 \sin \gamma - 2.06 \cos \gamma) \times 10^{-25} \text{e} \cdot \text{cm},
\]

(34)
where we used the phase relation $\lambda = \alpha$, obtained for $\varepsilon'/\varepsilon$, and $\sin \delta = 0.0345(\cos \delta \cong -1.0)$. If we adopt another relation $\gamma = \pi$, also obtained for $\varepsilon'/\varepsilon$, we get

$$d_n \simeq 2.1 \times 10^{-25} \text{ e} \cdot \text{cm}. \quad (35)$$

This value is larger by a factor 2 than the measured upper limit, $|d_n| < 1.1 \times 10^{-25} \text{ e} \cdot \text{cm} \ [19]$, though it is comparable with the limit.

If we relax the relation $\gamma = \pi$ to $\gamma = \pi + x$ with a small $x = (0.010, 0.012, 0.014, 0.016)$, both the theoretical values of $\varepsilon'/\varepsilon$ and $d_n$ simultaneously vary as

$$\varepsilon'/\varepsilon = (1.4, 1.6, 1.8, 2.0) \times 10^{-3}, \quad (36)$$

$$d_n = (1.1, 0.90, 0.70, 0.50) \times 10^{-25} \text{ e} \cdot \text{cm}. \quad (37)$$

This shows that there is a phase value of $\gamma$ around $\gamma \simeq \pi + 0.012$ which satisfies both the experimental value of $\varepsilon'/\varepsilon$ and the upper limit of $d_n$. Therefore, our model agrees with the present experimental situation of $\varepsilon'/\varepsilon$ and $d_n$.

Finally, we discuss CP violation in the nonleptonic decays of $B_d$ and $B_s$ mesons into CP-eigenstates. Integrated CP asymmetry into the CP-eigenstates is defined by [26]

$$C_f = \frac{\Gamma(B^0 \to f) - \Gamma(\bar{B}^0 \to f)}{\Gamma(B^0 \to f) + \Gamma(\bar{B}^0 \to f)} = -\frac{x}{1 + x^2} \sin \varphi_f, \quad (38)$$

$$\varphi_f = C \cdot P(f)(\arg M_{12}^* + 2 \arg A), \quad (39)$$

where $\Gamma(B^0 \to f)$ is the time-integrated decay rate of time-evolved $B^0(t = 0)$ into the final hadronic state $(f)$, $\bar{f}$ the CP-conjugated state of $f$, $x$ the mixing parameter given by $x = \Delta m_B/\Gamma_B$, CP-parity of state $f$, $M_{12}$ the off-diagonal element of mass matrix of the neutral $B^0 - \bar{B}^0$ system and $A$ is the weak amplitude of $\bar{B}^0 \to f$ decay.

In the case of $B_d$ decay, the dominant contribution to $M_{12}$ is the $W_L - W_R$ box diagram with $c$- and $t$- quark exchange as calculated in §2, and this has
the phase $e^{-i(\alpha-\gamma+\delta)}$. In Table I, we list the CP asymmetry of various $B_d$ decay modes by showing the angle $\varphi_f$ for each weak quark subprocess for the case of using phase relations $\gamma = \pi$ and $\beta = \alpha - \pi$ obtained from the study of $\varepsilon'/\varepsilon$ and for the case without the relations. On the fifth column of Table I, we record the predictions of $\varphi_f$ from the Standard Model, where $\alpha, \beta$ and $\gamma$ are three angles of the unitarity triangle, not our phases in $V_R$. From Table I, we can see the remarkable difference between our model and the Standard Model.

For $B_s$ decays, first we estimate the mixing parameter $x_s$ of $B_s - \bar{B_s}$ mixing. The dominant contribution is the diagram in Fig.5. The off-diagonal element $M_{12}$ in the $B_s - \bar{B_s}$ system is given by

$$M_{12} = <B_s|H_{eff}^{LR}(c,t)|\bar{B_s}>$$

$$= \frac{2G_F^2M_s^2\beta_g}{\pi^2} \left[ \left( \frac{m_{B_s}}{m_b + m_s} \right)^2 + \frac{1}{6} \right] \frac{1}{4f_{B_s}^2} B_{B_s} m_{B_s} V_{tb}^{LR} V_{ts}^{LR*} V_{cb}^{LR*}$$

$$\times B(x_c, x_t, \beta_g). \quad (40)$$

If we take $m_{B_s} = 5.37$GeV, $m_s = 0.2$GeV and $f_{B_s}\sqrt{B_{B_s}} = 0.15$GeV in Eq.(40), we get

$$M_{12} \simeq 43.5 e^{-i(\beta-\gamma+\delta)} \times 10^{-10} \text{ MeV}, \quad (41)$$

and the mixing parameter $x_s$ is obtained to be

$$x_s = \tau_{B_s} \Delta m_{B_s} = 2\tau_{B_s} |M_{12}| \simeq 20, \quad (42)$$

where we used $\tau_{B_s} \simeq 1.5 \times 10^{-12}$ s. When we use $f_{B_s}\sqrt{B_{B_s}} = (0.15 \pm 0.05)$GeV, we obtain $x_s = 20 \times (1 \pm 0.78)$. From Eq.(42), we expect that $B_s - \bar{B_s}$ system have a very rapid oscillation as compared with the $B_d - \bar{B_d}$ system. This feature is the same as in the Standard Model. The $x_s$ has recently been measured and obtained to be $x_s > 9 \quad (27)$.

CP asymmetry $C_f$ in Eq.(38) for $B_s$ meson decays into hadronic CP-eigenstates is below 0.05 due to the large oscillation $x_s \sim 20$, and this is
about 1/10 the CP asymmetry in $B_d$ decays. Since the phase of $M_{12}$ for $B_s$ decay is the same as for the $B_d$ decay up to minus sign as can be seen from Eq.(41), which is obtained by use of the relation $\alpha - \beta = \pi$, the structure of the angle $\varphi_f$ of $C_f$ is same between $B_d$ and $B_s$ decays up to the additional $\pi$ in $B_d$ decays, as seen in Table II. This point is remarkably different from the Standard Model. The typical predictions about the CP asymmetry from our model are the following,

$$C_f(B_d \to D^+ D^-) = C_f(B_d \to D_1^0 K_s) = C_f(B_d \to \pi^+ \pi^-) = -C_f(B_d \to D_1^0 \pi^0) \simeq -C_f(B_d \to \psi K_s),$$

$$C_f(B_s \to \psi K_s) = C_f(B_s \to D_1^0 \phi) = C_f(B_s \to \rho^0 K_s) = -C_f(B_s \to D_1^0 K_s) \simeq -C_f(B_s \to D_s^+ D_s^-),$$

for the case of using $\gamma = \pi$. The last equalities $\simeq$ of both Eqs.(43) and (44) come from the contamination of small phase $\delta(\sim 2^\circ)$.

As can be seen from the following relation

$$\frac{1}{2} \left[ \varphi(B_d \to \psi K_s) + \varphi(B_d \to \pi^+ \pi^-) + \varphi(B_s \to \rho^0 K_s) \right] = \frac{1}{2}(\alpha + \delta) \neq \pi,$$  

the angles of these three modes do not necessarily construct the unitarity triangle in our model. This fact generally holds in the $SU(2)_L \times SU(2)_R \times U(1)$ model in which a new particle ($W_R$) causes the $B_{d(s)}$ decays [28].

4. Discussions and conclusions

Hadronic decays of $B$ mesons caused by the $b$ to $c$ transition originate from the quark subprocesses $b \to c\bar{c}s$, $b \to c\bar{u}d$ and $b \to c\bar{u}s$, in addition to the process $b \to c\bar{c}d$ which was used to constrain the mixing angles of $V^R$ by use of the mode $B^- \to \psi \pi^-$ in §2. As for the process $b \to c\bar{c}s$, the decay rate of
\[ B_d \rightarrow D^*-D_s^+ \] is related to the differential decay rate of \( B_d \rightarrow D^*\ell^+\nu \) at the momentum transfer squared \( q^2 = m_{D_s}^2 \) to the lepton pair by the following equation by using the factorization hypothesis and the heavy quark effective theory \([29, 30]\),

\[
\frac{\Gamma(B_d \rightarrow D^*-D_s^+)}{d\Gamma(B_d \rightarrow D^*\ell^+\nu)/dq^2|_{q^2=m_{D_s}^2}} = 6\pi^2 f_{D_s}^2 |V_{cs}|^2, \tag{46}
\]

where \( f_{D_s} \) is the decay constant of \( D_s \) meson. By using the experimental values \( f_{D_s} = 430 \pm 150_{-130}^{+40} \) MeV \([31]\), \( \text{Br}(B_d \rightarrow D^*-D_s^+) = (1.2 \pm 0.6) \times 10^{-2} \) \([19]\) and \( d\text{Br}(B_d \rightarrow D^*\ell^+\nu)/dq^2|_{q^2=m_{D_s}^2} = (0.47 \pm 0.08) \times 10^{-2} \text{GeV}^{-2} \) \([30]\), we obtain \( |V_{cs}^R| = 0.23 - 0.96 \) from Eq.(46), since \( b \rightarrow c\bar{c}s \) is mediated by \( W_R \) exchange in our model. This value of \( |V_{cs}^R| \) agrees with the one in Eq.(23).

As for the process \( b \rightarrow c\bar{u}d \), decay rate of the relevant mode \( B_d \rightarrow D^*\pi^+ \) and the different decay rate of \( B_d \rightarrow D^*\ell^+\nu \) at \( q^2 = m_{\pi}^2 \) are related by the following equation in the same way as for the above process,

\[
\frac{\Gamma(B_d \rightarrow D^*\pi^+)}{d\Gamma(B_d \rightarrow D^*\ell^+\nu)/dq^2|_{q^2=m_{\pi}^2}} = 6\pi^2 f_{\pi}^2 |V_{ud}|^2. \tag{47}
\]

When we use the experimental values \( \text{Br}(B_d \rightarrow D^*\pi^+) = (2.6 \pm 0.4) \times 10^{-3} \) \([19]\) and \( d\text{Br}(B_d \rightarrow D^*\ell^+\nu)/dq^2|_{q^2=m_{\pi}^2} = (0.25 \pm 0.08) \times 10^{-2} \text{GeV}^{-2} \) \([30]\) and \( f_\pi = 0.132 \text{GeV} \), we obtain \( |V_{ud}^R| = 0.80 - 1.0 \) in our model and this is satisfied by the value \( |V_{ud}^R| = 0.984 \) in Eq.(23).

As for the final process \( b \rightarrow c\bar{u}s \), decay rates of the modes coming from this process like \( B_d \rightarrow D^*K^+ \) have not been measured. In our model the branching ratio of \( B_d \rightarrow D^*K^+ \) is related to the observed ratio of \( \text{Br}(B_d \rightarrow D^*\pi^+) = (2.6 \pm 0.4) \times 10^{-3} \) by the following equation,

\[
\frac{\text{Br}(B_d \rightarrow D^*K^+)}{\text{Br}(B_d \rightarrow D^*\pi^+)} \approx \frac{|V_{us}^R|^2}{|V_{ud}^R|^2}. \tag{48}
\]

We can predict as \( \text{Br}(B_d \rightarrow D^*K^+) = (6.1 \pm 1.0) \times 10^{-5} \) by using the magnitudes of \( |V_{us}^R| \) and \( |V_{ud}^R| \) in Eq.(23). This value is about 1/2 of the predicted value \((1.3 \pm 0.2) \times 10^{-4}\) of the Standard Model.
In conclusion, we investigated the purely right-handed $b$ to $c$ and $b$ to $u$ coupling model with full mixing angles and phases in $V^R$ in the framework of $SU(2)_L \times SU(2)_R \times U(1)$ gauge model. The model has turned out to be viable still under the new circumstance that the right-handed $W$ boson mass $M_R > 720$ GeV. It satisfies the experimental values of CP-violating parameter $\varepsilon^'/\varepsilon$ in the neutral kaon system and the upper limit of neutron electric dipole moment. The model would predict a remarkably different pattern of CP asymmetry in $B_d$ and $B_s$ decays into hadronic CP-eigenstates from that in Standard Model. We expect that the asymmetry will be measured to test the model at the $B$- factories under construction.

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References


Figure captions

**Fig.1.** The $W_L - W_R$ box diagram with $c$- and $t$- quark exchanges for calculating $\Delta m_{B_d}$.

**Fig.2.** The box diagrams for calculating $\Delta m_K$ ; (a)$W_L - W_L$ box diagram with two $c$- quark exchanges, (b)$W_L - W_R$ box with two $c$- quark exchanges, and (c)$W_R - W_R$ box with two $t$- quark exchanges.

**Fig.3.** The diagrams for calculating CP-violating parameter $\varepsilon'$ ; (a)$W_L$-exchange tree diagram, (b)$W_R$-exchange tree diagram, (c)$W_L$-loop penguin diagram, (d)$W_R$-loop penguin diagram, (e)$W_L - W_R$ mixing penguin diagram, (f)$W_R - W_L$ mixing penguin diagram, (g)$W_L - W_R$ mixing tree diagram, (h)$W_R - W_L$ mixing tree diagram.

**Fig.4.** The one loop diagrams for calculating (a) $u$- and (b) $d$- quark electric dipole moment.

**Fig.5.** The $W_L - W_R$ box diagram with $c$- and $t$- quark exchanges for calculating $B_s - \bar{B}_s$ mixing.
Table 1: List of the angles $\varphi_f$ in the CP asymmetry $C_f$ for $B_d$ decays into hadronic CP-eigenstates without and with the phase relations $\gamma = \pi$ and $\beta = \alpha - \pi$ for various quark subprocesses in our model and in the Standard Model (fifth column).

<table>
<thead>
<tr>
<th>Subprocess</th>
<th>$B_d$ decay mode</th>
<th>$\varphi_f$</th>
<th>$\varphi_f$ with $\frac{\gamma=\pi,}{\beta=\alpha-\pi}$</th>
<th>$\varphi_f$(S.M.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \to c\bar{c}s$</td>
<td>$B_d \to \psi K_s$</td>
<td>$\alpha - \gamma + \delta$</td>
<td>$\pi + \alpha + \delta$</td>
<td>$2\beta$</td>
</tr>
<tr>
<td>$b \to c\bar{u}d$</td>
<td>$B_d \to D^0 \pi^0$</td>
<td>$\alpha + \gamma - \delta$</td>
<td>$\pi + \alpha - \delta$</td>
<td>$2\beta$</td>
</tr>
<tr>
<td>$b \to c\bar{c}d$</td>
<td>$B_d \to D^+ D^-$</td>
<td>$-(\alpha - \gamma - \delta)$</td>
<td>$-(\pi + \alpha - \delta)$</td>
<td>$-2\beta$</td>
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<td>$-2\beta$</td>
</tr>
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<td>$B_d \to \pi^+ \pi^-$</td>
<td>$-(\alpha - \gamma - \delta)$</td>
<td>$-(\pi + \alpha - \delta)$</td>
<td>$2\alpha$</td>
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<td>$B_d \to \pi^0 K_s$</td>
<td>$\alpha - \gamma - \delta$</td>
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<td>?</td>
</tr>
<tr>
<td>$b \to u\bar{c}s$</td>
<td>$B_d \to D^0 K_s$</td>
<td>$-\alpha - 3\gamma + \delta$</td>
<td>$-(\pi + \alpha + \delta)$</td>
<td>$2\alpha$</td>
</tr>
<tr>
<td>$b \to u\bar{c}d$</td>
<td>$B_d \to D^0 l^0 \pi^0$</td>
<td>$\alpha - 3 \gamma - \delta$</td>
<td>$\pi + \alpha - \delta$</td>
<td>$-2\alpha$</td>
</tr>
<tr>
<td>$b \to s\bar{s}s$</td>
<td>$B_d \to \phi K_s$</td>
<td>$\alpha - \gamma + \delta$</td>
<td>$\pi + \alpha + \delta$</td>
<td>$2\beta$</td>
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<tr>
<td>$b \to s\bar{d}d$</td>
<td>$B_d \to \pi^0 K_s$</td>
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<td>$B_d \to \pi^0 \pi^0$</td>
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<td>$-(\pi + \alpha + \delta)$</td>
<td>$-2\beta$</td>
</tr>
</tbody>
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Table 2: List of the angles $\varphi_f$ in the CP asymmetry $C_f$ for $B_s$ decays into hadronic CP-eigenstates without and with the phase relations $\gamma = \pi$ and $\beta = \alpha - \pi$ for various quark subprocesses in our model and in the Standard Model (fifth column).

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<td>$B_s \to D^0 D^-$</td>
<td>$\beta + \gamma - \delta - 2\alpha$</td>
<td>$-(\alpha + \delta)$</td>
<td>$0$</td>
</tr>
<tr>
<td>$b \to c\bar{u}d$</td>
<td>$B_s \to D^0 K_s$</td>
<td>$\beta - \gamma + \delta - 2\alpha$</td>
<td>$-\alpha - \delta$</td>
<td>$0$</td>
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<tr>
<td>$b \to c\bar{c}d$</td>
<td>$B_s \to \psi K_s$</td>
<td>$-\beta + \gamma + \delta - 2\alpha$</td>
<td>$\alpha - \delta$</td>
<td>$0$</td>
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<tr>
<td>$b \to c\bar{u}s$</td>
<td>$B_s \to D^0 \phi$</td>
<td>$-\beta + \gamma + \delta - 2\alpha$</td>
<td>$\alpha - \delta$</td>
<td>$0$</td>
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<tr>
<td>$b \to u\bar{u}d$</td>
<td>$B_s \to \phi K_s$</td>
<td>$-\beta + \gamma + \delta - 2\alpha$</td>
<td>$\alpha - \delta$</td>
<td>$2\gamma$</td>
</tr>
<tr>
<td>$b \to u\bar{u}s$</td>
<td>$B_s \to K^+ K^-$</td>
<td>$\beta + \gamma + \delta - 2\alpha$</td>
<td>$-\alpha - \delta$</td>
<td>?</td>
</tr>
<tr>
<td>$b \to u\bar{c}s$</td>
<td>$B_s \to D^0 \phi$</td>
<td>$-(\beta + 3 \gamma - \delta - 2\alpha)$</td>
<td>$\alpha + \delta$</td>
<td>$2\gamma$</td>
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<tr>
<td>$b \to u\bar{c}d$</td>
<td>$B_s \to D^0 K_s$</td>
<td>$\beta + 3 \gamma + \delta - 2\alpha$</td>
<td>$-(\alpha - \delta)$</td>
<td>$-2\gamma$</td>
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<tr>
<td>$b \to s\bar{s}s$</td>
<td>$B_s \to \eta \eta$</td>
<td>$\beta + \gamma - \delta - 2\alpha$</td>
<td>$-(\alpha + \delta)$</td>
<td>$0$</td>
</tr>
<tr>
<td>$b \to s\bar{d}d$</td>
<td>$B_s \to K_s K_s$</td>
<td>$\beta + \gamma - \delta - 2\alpha$</td>
<td>$-(\alpha + \delta)$</td>
<td>$0$</td>
</tr>
<tr>
<td>$b \to d\bar{s}s$</td>
<td>$B_s \to \phi K_s$</td>
<td>$-\beta + \gamma - \delta - 2\alpha$</td>
<td>$\alpha + \delta$</td>
<td>$2\beta$</td>
</tr>
<tr>
<td>$b \to d\bar{d}d$</td>
<td>$B_s \to \pi^0 K_s$</td>
<td>$-(\beta + \gamma - \delta - 2\alpha)$</td>
<td>$\alpha + \delta$</td>
<td>$2\beta$</td>
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