$b \rightarrow s\gamma$ decays in the Left-Right Symmetric Model

C. S. Kim* and Yeong Gyun Kim†

Dept. of Physics, Yonsei University, Seoul 120-749, Korea

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Abstract

We consider $b \rightarrow s\gamma$ decays in the Left-Right Symmetric Model. Values of observables sensitive to chiral structure such as the $\Lambda$ polarization in the $\Lambda_b \rightarrow \Lambda\gamma$ decays and the mixing-induced CP asymmetries in the $B_{d,s} \rightarrow M^0\gamma$ decays can deviate in the LRSM significantly from the SM values. The combined analysis of $P_\Lambda$ and $A_{CP}$ as well as $BR(b \rightarrow s\gamma)$ can be used to determine the model parameters.
I. INTRODUCTION

The Left-Right Symmetric Model (LRSM) [1] based upon the electroweak gauge group $SU(2)_L \times SU(2)_R \times U(1)$ represents well-known extensions of the Standard Model (SM), and can lead to interesting new physics effects in the $B$ system [2,3]. Due to the extended gauge structure there are both new neutral and charged gauge bosons, $Z_R$ and $W_R$, as well as a right-handed gauge coupling, $g_R$. The symmetry $SU(2)_L \times SU(2)_R \times U(1)$ can be broken to $SU(2)_L \times U(1)$ by means of vacuum expectation values of doublet or triplet fields. As for $SU(2)_L \times U(1)$ symmetry breaking, we assume that it takes place when the scalar field $\Phi$ acquires the complex vacuum expectation value

$$<\Phi> = \begin{pmatrix} k_1 & 0 \\ 0 & k_2 e^{i\alpha} \end{pmatrix}. \quad (1)$$

After symmetry breaking the charged $W_R$ mixes with $W_L$ of the SM to form the mass eigenstates $W^+_i$, with eigenvalues $M^+_i$, and this mixing is described by two parameters; a real mixing angle $\zeta$ and a phase $\alpha$,

$$\begin{pmatrix} W^+_1 \\ W^+_2 \end{pmatrix} = \begin{pmatrix} \cos \zeta & e^{-i\alpha} \sin \zeta \\ -\sin \zeta & e^{-i\alpha} \cos \zeta \end{pmatrix} \begin{pmatrix} W^+_L \\ W^+_R \end{pmatrix}. \quad (2)$$

The mixing angle $\zeta$ is small and can be expressed as

$$\zeta = \frac{2r}{1+r^2} \frac{M^2_1}{M^2_2}, \quad (r \equiv k_2/k_1). \quad (3)$$

In this model the charged current interactions of the right-handed quarks are governed by a right-handed CKM matrix, $V_R$, which, in principle, need not be related to its left-handed counterpart $V_L$. Here we examine the possibility of using the rare decays $b \to s\gamma$ as a new tool in exploring the parameter space of the LRSM. We assume manifest left-right symmetry, that is $|V_R| = |V_L|$ and $\kappa \equiv g_R/g_L = 1$.

The effective Hamiltonian of $b \to s\gamma$ decay in the LRSM, after ignoring $m_s$, is given by

$$H_{\text{eff}}(b \to s\gamma) = -\frac{4G_F}{\sqrt{2}} V^*_{tb}V_{ts} [C_{7L}O_{7L} + C_{7R}O_{7R}], \quad (4)$$

where

$$O_{7L} = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu}, \quad O_{7R} = \frac{e}{16\pi^2} m_b \bar{s}_R \sigma^{\mu\nu} b_L F_{\mu\nu}. \quad (5)$$
The magnetic moment operator coefficients are given by

\[ C_{7L}(m_b) = C_{7L}^{SM}(m_b) + \frac{m_t}{m_b} V_{tb}^* V_{L} \exp[i \alpha \left[ \eta^{16/23} \tilde{F}(x_t) + \frac{8}{3} (\eta^{14/23} - \eta^{16/23}) \tilde{G}(x_t) \right] ] \]

\[ + \frac{2r(1 + r^2)}{(1 - r^2)^2} \frac{m_t}{m_b} V_{tb}^* V_{L} \exp[i \alpha \left[ \eta^{16/23} \tilde{F}(y_t) + \frac{8}{3} (\eta^{14/23} - \eta^{16/23}) \tilde{G}(y_t) \right] ] , \]  

(6)

\[ C_{7R}(m_b) = \frac{m_t}{m_b} \left( \frac{V_{ts}^* V_{L}}{V_{ts}} \right)^* e^{-i \alpha} \left[ \eta^{16/23} \tilde{F}(x_t) + \frac{8}{3} (\eta^{14/23} - \eta^{16/23}) \tilde{G}(x_t) \right] \]

\[ + \frac{2r(1 + r^2)}{(1 - r^2)^2} \frac{m_t}{m_b} \left( \frac{V_{tb}^* V_{L}}{V_{tb}} \right)^* e^{-i \alpha} \left[ \eta^{16/23} \tilde{F}(y_t) + \frac{8}{3} (\eta^{14/23} - \eta^{16/23}) \tilde{G}(y_t) \right] , \]  

(7)

where

\[ C_{7L}^{SM}(m_b) = \eta^{16/23} F(x_t) + \frac{8}{3} (\eta^{14/23} - \eta^{16/23}) G(x_t) + \sum h_i \eta^{p_i} , \]  

(8)

with \( \eta = \alpha_s(M_1)/\alpha_s(m_b) \), \( x_t = (m_t/M_1)^2 \) and \( y_t = (m_t/M_H)^2 \), where \( M_H \) is the mass of the charged physical scalars. The various functions of \( x_t, y_t, \) and the coefficients \( h_i, \) and powers \( p_i \) can be founded in the Ref. [3].

II. OBSERVABLES SENSITIVE TO CHIRAL STRUCTURE

A. Branching fraction of inclusive decay \( \mathcal{BR}(b \to s\gamma) \)

The decay rate for inclusive \( b \to s\gamma \) decay is given by

\[ \Gamma(b \to s\gamma) = \frac{C_{F} \cdot m_b^5}{32 \pi^3} |\alpha_{em}| V_{ts}^* V_{tb}^2 \left[ |C_{7L}(m_b)|^2 + |C_{7R}(m_b)|^2 \right] . \]  

(9)

It is common practice to normalize this radiative partial width to the semileptonic rate

\[ \Gamma(b \to c e \bar{\nu}) = \frac{C_{F} \cdot m_b^5}{192 \pi^3} |V_{cb}| f \left( \frac{m_c}{m_b} \right) \left[ 1 - \frac{2}{3\pi} \alpha_s(m_b) g \left( \frac{m_c}{m_b} \right) \right] , \]  

(10)

where \( f(x) = 1 - 8x^2 - 24x^4 \ln x + 8x^6 - x^8 \) represents a phase space factor, and the function \( g(x) \) encodes next-to-leading order strong interaction effects [4]. In terms of the ratio \( R \),

\[ R \equiv \frac{\Gamma(b \to s\gamma)}{\Gamma(b \to c e \bar{\nu})} = \frac{6 |V_{ts}^* V_{tb}^2| |\alpha_{em}| |C_{7L}(m_b)|^2 + |C_{7R}(m_b)|^2}{\pi |V_{cb}|^2 f \left( \frac{m_c}{m_b} \right) \left[ 1 - \frac{2}{3\pi} \alpha_s(m_b) g \left( \frac{m_c}{m_b} \right) \right] } , \]  

(11)

the \( b \to s\gamma \) branching fraction is obtained by

\[ \mathcal{BR}(b \to s\gamma) = \mathcal{BR}(b \to c e \bar{\nu}) \times R \simeq \mathcal{BR}(B \to X \ell \nu)_{exp} \times R \sim (0.105) \times R. \]  

(12)
In Eqs. (8,9), we neglected the $1/m_b^2$ corrections. For $\mathcal{BR}(b \to s\gamma)$, we also use the present experimental value [5] of the branching fraction for $B \to X_s\gamma$ decay,

$$\mathcal{BR}(B \to X_s\gamma) = (3.15 \pm 0.35_{\text{stat}} \pm 0.32_{\text{syst}} \pm 0.26_{\text{model}}) \times 10^{-4}. \quad (13)$$

**B. $\Lambda$ Polarization in $\Lambda_b \to \Lambda\gamma$ decay**

One way to access the chiral structure is to consider the decay of baryons. From the experimental side the decay $\Lambda_b \to \Lambda\gamma$ is a good candidate, since the subsequent $\Lambda$ decay $\Lambda \to p\pi$ is self analyzing [6]. The expected branching ratio is of order $10^{-5}$ and should be measurable at future hadronic $B$ factories, HERA-B, BTeV and LHC-B. The chiral structure can be studied by measuring the polarization of $\Lambda$, via the angular distribution,

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta} = \frac{1}{2}(1 + P_\Lambda \cos\theta), \quad (14)$$

where

$$P_\Lambda = \frac{|C_{7L}(m_b)|^2 - |C_{7R}(m_b)|^2}{|C_{7L}(m_b)|^2 + |C_{7R}(m_b)|^2}, \quad (15)$$

and $\theta$ is the angle between the direction of the momentum of $\Lambda$ in the rest frame of $\Lambda_b$ and the direction of the $\Lambda$ polarization in the $\Lambda$ rest frame.

**C. Mixing-induced CP Asymmetry in $B_{d,s} \to M^0\gamma$ decays**

Next, we consider the mixing-induced CP asymmetry for $B_{d,s} \to M^0\gamma$ decays [7]. Here $M^0$ is any hadronic self-conjugate state, with CP eigenvalue $\xi = \pm 1$. The decay amplitudes are denoted by

\begin{align*}
A(\bar{B}_{d,s} \to M^0\gamma_L) &= A \cos \psi e^{i\phi_L}, \\
A(\bar{B}_{d,s} \to M^0\gamma_R) &= A \sin \psi e^{i\phi_R}, \\
A(B_{d,s} \to M^0\gamma_R) &= \xi A \cos \psi e^{-i\phi_L}, \\
A(B_{d,s} \to M^0\gamma_L) &= \xi A \sin \psi e^{-i\phi_R}. \quad (16)
\end{align*}
Here the parameter $\psi$ gives the relative amount of left-polarized photons compared to right-polarized photons in $B_{d,s}$ decays, and $\phi_{L,R}$ are CP-odd weak phases. Using the time-dependent rates $\Gamma(t)$ and $\Gamma(t)$ for $B_{d,s} \to M^0\gamma$ and $B_{d,s} \to M^0\gamma$ respectively, one finds a time-dependent CP asymmetry

$$A(t) = \frac{\Gamma(t) - \Gamma(t)}{\Gamma(t) + \Gamma(t)} = \xi A_{CP} \sin(\Delta m t),$$

where

$$A_{CP} \equiv \sin(2\psi) \sin(\phi_M - \phi_L - \phi_R),$$

and $\Delta m$ and $\phi_M$ are the mass difference and phase in the $B_{d,s} - \bar{B}_{d,s}$ mixing amplitude.

In terms of $C_{7L(R)}$, the $\psi$ and $\phi_{L(R)}$ are given by

$$\sin(2\psi) = \frac{2|C_{7L}(m_b)| C_{7R}(m_b)}{|C_{7L}(m_b)|^2 + |C_{7R}(m_b)|^2},$$

$$\phi_L = \sin^{-1}\left(\frac{\text{Im}(C_{7L}(m_b))}{|C_{7L}(m_b)|}\right), \quad \phi_R = \sin^{-1}\left(\frac{\text{Im}(C_{7R}(m_b))}{|C_{7R}(m_b)|}\right).$$

The phase of $B_{d,s} - \bar{B}_{d,s}$ mixing can be also affected by new LRSM contributions [8], and is given by $\phi_M = \phi_{SM}^M + \delta_M$ where

$$\delta_M = \tan^{-1}\left(\frac{h \sin \sigma}{1 + h \cos \sigma}\right).$$

Here $h = |M_{12}^{LR}|/|M_{12}^{SM}|$ measures the relative size of the left-right contribution to the non-diagonal element $M_{12}$ and can be written as

$$h = F(M_2) \left(\frac{1.6 \text{ TeV}}{M_2}\right)^2 + \left(\frac{12 \text{ TeV}}{M_H}\right)^2,$$

where $F(M_2)$ is a complicated function of the $M_2$. The phase $\sigma$ can be expressed as

$$e^{i\sigma} = -\frac{V_{td}^{L*} V_{tb}^{L}}{V_{td}^{R*} V_{tb}^{R}}, \quad e^{i\sigma} = -\frac{V_{ts}^{L} V_{tb}^{R}}{V_{ts}^{R*} V_{tb}^{L*}},$$

for $B_d$ and $B_s$ systems, respectively. And $\phi_{SM}^M = 2\beta$ and $\phi_{SM}^M = 0$ for $B_d$ and $B_s$ systems, respectively (where $-\beta$ is the phase of $V_{td}$ in the standard convention).
III. COMBINED ANALYSIS

In this Section, we perform the combined analysis of three observables, $\mathcal{BR}(b \to s\gamma)$, $P_{\Lambda}$ and $A_{CP}$. Fig. 1 is the contour plot for $\mathcal{BR}(b \to s\gamma)$ and $P_{\Lambda}$ on the $(|C_{7L}(m_{b})|, |C_{7R}(m_{b})|)$ plane. Two solid curves indicate the 1σ range of the measured values of inclusive $\mathcal{BR}(b \to s\gamma)$. Three dashed lines correspond to three different values of $P_{\Lambda}$, as indicated in the figure. From the measurements of $\mathcal{BR}(b \to s\gamma)$ and $P_{\Lambda}$, one can determine the magnitudes $|C_{7L}(m_{b})|$ and $|C_{7R}(m_{b})|$ separately. And the measurement of $A_{CP}$ would give some informations on the phases of $C_{7L}(m_{b})$ and $C_{7R}(m_{b})$.

A. Simple Case

First, we consider a simple case. We assume $V_{L} = V_{R}$ and ignore the contributions from $W_{2}^{\pm}$ and charged physical scalars. Then only two new physics parameters, $\zeta$ and $\alpha$, remain. To illustrate the usefulness of $P_{\Lambda}$ measurements, let’s consider $\alpha = 0$ case. Fig. 2(a) shows the dependence of inclusive $\mathcal{BR}(b \to s\gamma)$ on the mixing angle $\zeta$ in this case. Two horizontal dashed lines indicate the 1σ range of the present measured values of inclusive $\mathcal{BR}(b \to s\gamma)$. It is clear from the figure that the SM result is essentially obtained when $\zeta = 0$, and also that a conspiratorial solution occurs when $\zeta \sim -0.01$. These two cases are indistinguishable, and even independent of any further improvements in the measurement of the inclusive $\mathcal{BR}(b \to s\gamma)$. However, if $P_{\Lambda}$ in $\Lambda_{b} \to \Lambda\gamma$ decays is measured in addition, these two solutions are definitely distinguishable as indicated in Fig. 2(b), which shows the dependence of $P_{\Lambda}$ on the mixing angle $\zeta$. The $\zeta \sim 0$ case corresponds to $P_{\Lambda} \sim +1$, and the $\zeta \sim -0.01$ case corresponds to $P_{\Lambda} \sim -1$.

When we vary the phase $\alpha$ between 0 and $\pi$ radian, $P_{\Lambda}$ can have all the possible values from +1 to −1, while satisfying the inclusive $\mathcal{BR}(b \to s\gamma)$ constraints. Figs. 3(a) and 3(b) show the dependence of $P_{\Lambda}$ on $\zeta$ and $\alpha$ respectively, where we impose the present experimental $\mathcal{BR}(B \to X_{s}\gamma)$ constraints. The larger magnitudes of $\zeta$ gives larger deviations of $P_{\Lambda}$ from the SM expectation, $P_{\Lambda}(SM) = +1$. Because the measurements of $\mathcal{BR}(b \to s\gamma)$ and $P_{\Lambda}$ determine only the magnitudes of $C_{7L}(m_{b})$ and $C_{7R}(m_{b})$, the $\zeta$ can be determined up to the sign ambiguity.

Next, we consider $A_{CP}$ in the radiative $B_{d,s}$ decays, $B_{d,s} \to M^{0} + \gamma$, e.g., $B_{d} \to K^{*} + \gamma$
and $B_s \to \phi + \gamma$. The dependences of $A_{CP}$ on the $\zeta$ and $\alpha$ is shown in Figs. 4(a) and 4(b), respectively, for $B_d \to M^0\gamma$ decay. And in Figs. 4(c) and 4(d) we show the dependence of $A_{CP}$ on the $\zeta$ and $\alpha$ for $B_s \to M^0\gamma$ decay. Here we impose the present experimental inclusive $BR(B \to X_s\gamma)$ constraints [3]. For numerical value of $\beta$, we use the central value of the recent CDF measurement [9] of $\sin 2\beta$ from $B_d \to J/\psi + K_s$,

$$\sin 2\beta = 0.79^{+0.41}_{-0.44}. \quad (24)$$

It is clear from the figures that $A_{CP}$ can have rather large values between $-20\%$ and $90\%$ for $B_d \to M^0\gamma$ decay, and up to $\pm 60\%$ for $B_s \to M^0\gamma$ decay, while the SM expectation values $A_{CP}(SM)$ are almost zero. We can see that different sign of $\zeta$ with same magnitude correspond to different values of $A_{CP}$. Therefore, the sign ambiguity of $\zeta$ determined from $P_\Lambda$ measurements can be resolved by measuring $A_{CP}$. Moreover, $P_\Lambda$ and $A_{CP}$ have definite correlations, as shown in Figs. 5(a) and (b) for $B_d \to M^0\gamma$ and for $B_s \to M^0\gamma$, respectively. Any deviations from these correlations would indicate the failure of the manifest left-right symmetric scenario which we assume in this subsection.

**B. General Case**

Now we consider more general case. We assume that the elements of $V_R$ have arbitrary phase. We also consider the contributions from $W^\pm_2$ and charged physical scalars. In this case, $C_{7L}(m_b)$ depends on the parameters; $r, \omega_1, M_2$ and $M_H$. And $C_{7R}(m_b)$ depends on $r, \omega_2, M_2$ and $M_H$. The parameters $\omega_1$ and $\omega_2$ are defined as

$$e^{i\omega_1} \equiv \frac{V^\ast_{Rtb}}{V^\ast_{Ltb}} e^{i\alpha}, \quad e^{i\omega_2} \equiv \frac{V^\ast_{Rts}}{V^\ast_{Lts}} e^{i\alpha}. \quad (25)$$

For further numerical calculations, we fix $M_2 = 1.6$ TeV and $M_H = 12$ TeV.

While the magnitude of $C_{7L}(m_b)$ depends on the $r$ and $\omega_1$, the magnitude of $C_{7R}(m_b)$ only on the $r$ but not on the $\omega_2$. Therefore, $P_\Lambda$ depends on the $r$ and $\omega_1$ but not on the $\omega_2$. The dependences of $P_\Lambda$ on the $r$ and $\omega_1$ are shown in Figs. 6(a) and 6(b), respectively. For large $r$, the value of $P_\Lambda$ can be largely deviated from the SM value due to the large contributions from charged physical scalars even though $\zeta$ is small. From the measurement of $P_\Lambda$ we can determine the values of $r$ and $\omega_1$ (up to discrete ambiguity) for given values of $M_2$ and $M_H$.  

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In $B_d \to M^0 \gamma$ decays, $A_{CP}$ has additional dependences on another new phase $\omega_3$ and also on phase $\beta$ through $\phi_M$, the phase of $B_d - \bar{B}_d$ mixing. The phase $\omega_3$ is defined by

$$e^{i\omega_3} \equiv \frac{V^*_{td}R}{V^*_{td}L}e^{i\alpha}. \quad (26)$$

The dependence of $A_{CP}$ on $\omega_2$ appear only through $\phi_R$ in this case. And the phase of $B_d - \bar{B}_d$ mixing, $\phi_M$ would be determined independently from the measurement of $A_{J/\Psi K_s}$, i.e. the mixing induced CP asymmetry in the $B_d \to J/\Psi + K_s$ decays. \[9\]

$$A_{J/\Psi K_s} = \sin(\phi_M). \quad (27)$$

Therefore, in addition to $P_\Lambda$, for the $B_d$ system the value of $\omega_2$ can be determined up to discrete ambiguity for given values of $M_2$ and $M_H$ from the measurement of $A_{CP}$. In $B_s \to M^0 \gamma$ decays, $A_{CP}$ has dependence on the $\omega_2$ through $\phi_R$ and also on $\phi_M$. As can be seen from Eq. (18), $A_{CP}$ can have any values between $-\sin(2\Psi)$ and $+\sin(2\Psi)$ depending on the $\omega_2$. The dependences of $\sin(2\Psi)$, the maximum value of $A_{CP}$, on the $r$ and $\omega_1$ are shown in the Figs. 7(a) and 7(b), respectively, for $B_{d,s} \to M^0 \gamma$ decays. It is clear that the values of $A_{CP}$ can be largely deviated from the SM prediction. From the measurement of $A_{CP}$ in addition to $P_\Lambda$, the value of $\omega_2$ can be also determined up to discrete ambiguity for given values of $M_2$ and $M_H$.

To summarize, in this paper we considered the radiative $B$ hadron decay in the Left-Right Symmetric Model (LRSM). Values of observables sensitive to chiral structure such as the $\Lambda$ polarization in the $\Lambda_b \to \Lambda \gamma$ decays and the mixing-induced CP asymmetries in the $B_{d,s} \to M^0 \gamma$ decays can deviate in the LRSM significantly from the SM values. The combined analysis of $P_\Lambda$ and $A_{CP}$ as well as $\mathcal{BR}(b \to s\gamma)$ can be used to determine the model parameters. From the correlations between $P_\Lambda$ and $A_{CP}$, the validity of the manifest left-right symmetry scenario can also be tested.

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FIG. 1. Contour plots for the inclusive $BR(b \to s\gamma)$ and $P_\Lambda$. Two solid curves indicate the $1\sigma$ range of the present measured values of inclusive $BR(B \to X_s\gamma)$. 
(a) Dependence of inclusive \( \text{BR}(b \to s\gamma) \) on mixing angle \( \zeta \). Two horizontal dashed lines indicate the 1\( \sigma \) range of the present measured values of inclusive \( \text{BR}(B \to X_s\gamma) \). (b) Dependence of \( P_A \) on mixing angle \( \zeta \). In both cases we fix \( \alpha = 0 \).
FIG. 3. Dependence of $P_\Lambda$ on (a) $\zeta$, and on (b) $\alpha$. Here we imposed the present inclusive $BR(B \to X_s \gamma)$ constraints.
FIG. 4. Dependence of $A_{CP}$ on $\zeta$, and on $\alpha$ is shown in (a) and (b), respectively, for $B_d \to M^0\gamma$ decay; and in (c) and (d), respectively, for $B_s \to M^0\gamma$ decay. Here we imposed the present inclusive $BR(B \to X_s\gamma)$ constraints.
FIG. 5. Correlations between $A_{CP}$ and $P_{\Lambda}$: (a) and (b) correspond to $B_d \rightarrow M^0\gamma$ and $B_s \rightarrow M^0\gamma$ decays, respectively. Here we imposed the present inclusive $\mathcal{BR}(B \rightarrow X_s\gamma)$ constraints.
FIG. 6. Dependences of $P_{\Lambda}$ on (a) $r$, and on (b) $\omega_1$. Here we imposed the present inclusive $BR(B \to X_s\gamma)$ constraints and fix $M_2 = 1.6$ TeV and $M_H = 12$ TeV.
FIG. 7. Dependences of $\sin(2\Psi)$, the maximum value of $A_{CP}$, on $r$, and on $\omega_1$ are shown in (a) and (b), respectively, for $B_{d,s} \to M^0\gamma$ decay. Here we imposed the present inclusive $\mathcal{BR}(B \to X_s\gamma)$ constraints and fix $M_2 = 1.6$ TeV and $M_H = 12$ TeV.