Probing New Physics From CP Violation in Radiative B Decays

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AS-ITP-98-05

Abstract

When new CP-violating interactions are dominated by flavor changing neutral particle exchanges, that may occur in many extensions of the standard model. We examine a type 3 two Higgs doublet model and find that direct CP asymmetries can be as large as about 25%. Time-dependent and time-integrated mixing-induced CP asymmetries up to 85 and 40%, respectively, are possible without conflict with other constraints. It mainly requires an enhanced chromo-magnetic dipole \( b \to s g \) decay to be close to the present experimental bound.

PACS numbers: 11.30.Er 12.60.Fr 13.25.Hw 13.40.Hq

The CP-averaged radiative exclusive decay \( B \to K^* + \gamma \) [1] and inclusive decay \( B \to X_s + \gamma \) [2] represent the first observation of electromagnetic penguins. The CP-averaged branching ratios are consistent at the 2\( \sigma \) level with those [3] expected from a loop involving a top quark and \( W^\pm \) boson in the standard model (SM). Within the present uncertainties from both experimental measurements and theoretical calculations, it is difficult, only from the CP-averaged branching ratios, to distinguish the differences between the uncertainties and new physics effects. However, it does not mean that contributions to the amplitudes from new physics are less important than the one from the SM. This is because, if there exist new interactions involving new CP-violating sources, the magnitude of the amplitude \( A^{NEW}_{EMP} \) from new CP-violating interactions can become comparable with or even larger than the one \( A^{SM}_{EMP} \) from the SM even when radiative decay rate measurements are roughly that expected from the SM. This happens when the contributions to the radiative decay rate from the interference term \( 2Re(A^{SM}_{EMP}A^{NEW*}_{EMP}) \) almost cancel with the one \( |A^{NEW}_{EMP}|^2 \), i.e., \( |A^{NEW}_{EMP}|^2 \simeq -2Re(A^{SM}_{EMP}A^{NEW*}_{EMP}) \). This shows that as long as the relative phase between the two amplitudes ranges from about \((2\pi/3)\) to \((4\pi/3)\), \( |A^{NEW}_{EMP}| \) will become larger than \( |A^{SM}_{EMP}| \). In this case, it will be alternatively interesting
to investigate CP asymmetries in radiative B decays to probe possible new physics effects. In ref. [5], we have shown how this case occurred in a type 3 two Higgs doublet model (2HDM) that was motivated from exploring new CP-violating sources [6]. The model can lead to a sizable direct CP asymmetry in the radiative inclusive decay $b \to s\gamma$ due to new CP-violating sources in the charged Higgs sector. Other models (such as supersymmetric models) with possible large direct CP violation were also discussed in ref.[7]. In this note we will show that by simply adding a fourth generation of quarks and leptons in the type-3 2HDM, direct CP asymmetries in radiative inclusive decays can be larger than 25%. The time-dependent and time-integrated mixing-induced CP asymmetries in the type-3 2HDM, direct CP asymmetries in radiative inclusive decays can be as large as 100% and 50% respectively due to additional than 25%. The time-dependent and time-integrated mixing-induced CP asymmetries in radiative exclusive decays can be as large as 100% and 50% respectively due to additional new CP-violating sources via flavor changing neutral particle exchanges (FCNEs). The important new contributions arise from the penguin loop in which $W \pm$ is replaced by the neutral scalar bosons $H^0_k$ and the top quark is replaced by the fourth beauty $b'$-quark with charge $(-1/3)$. One of the new interesting observations is that CP asymmetry due to the interference between penguin amplitudes via charged and neutral scalar exchanges (i.e., purely new physics) can become dominant and larger than the one from the interference of standard and scalar exchanges. The main reason for such large CP asymmetry is due to significant chromo-magnetic dipole contributions. In this case, an enhanced $b \to s\gamma$ decay will have a branching ratio of order $(6 - 11)\%$. The values at this level appear to be favorable in understanding the large branching ratio of $B \to \eta'K$ decays reported recently by the CLEO Collaboration[4].

We begin with a model independent description on CP asymmetries in radiative B decays. Writing the amplitude for the processes $B \to X_q\gamma$ ($q = s, d$) as $A_{X_q\gamma} =< X_q\gamma|O^{L,R}_q|B > \tilde{C}^{L,R}_q + < X_q\gamma|O^{R}_q|B > \tilde{C}^{R}_q$ with $O^{L,R}_q = -(G_F m_b/4\sqrt{2}\pi^2)\epsilon|\sigma^{\mu\nu}|P_{L,R}bF_{\mu\nu}$ with $P_{L,R} = (1 \pm \gamma_5)/2$, the coefficients $\tilde{C}^{L,R}_q$ can be expressed by the following form

$$\tilde{C}^{L,R}_q = v_t^qC^{L,R}_{qq} + iv_t^qC^{L,R}_{qg}f_{g\gamma}$$

$$+ i \left( v_c^qC^{L,R}_{qc}f_{c\gamma} + v_u^qC^{L,R}_{qu}f_{u\gamma} \right) \quad (1)$$

For the charge conjugate processes $\bar{B} \to \bar{X}_q\gamma$, one has

$$\tilde{C}^{L,R}_{\bar{q}} = v_t^{\bar{q}}C^{L,R}_{\bar{q}q} + iv_t^{\bar{q}}C^{L,R}_{\bar{q}g}f_{g\gamma}$$

$$+ i \left( v_c^{\bar{q}}C^{L,R}_{q\bar{c}}f_{c\gamma} + v_u^{\bar{q}}C^{L,R}_{q\bar{u}}f_{u\gamma} \right) \quad (2)$$

where $v_i^q = V_{iq}V_{ib} (i=t,c,u)$ with $V_{ij}$ being the CKM matrix elements. $C^{L,R}_{qq}$ and $C^{L,R}_{qf}$ ($f=c,u$) are Wilson coefficient functions for gluon emission and four quark operators. $f_{g\gamma}$, $f_{c\gamma}$, and $f_{u\gamma}$ represent virtual corrections to the matrix element due to final state interactions or rescatterings[8, 9].

To see how the CP asymmetry observable $A^{CP}_{X_q\gamma}$ is sensitive to new physics, we may decompose $C^{L,R}_{q\gamma}$ ($v = \gamma, g$) and $C^{L,R}_{qf}$ ($f = u, c$) into two parts: $C^{L,R}_{q\gamma} = \tilde{C}^{L,R}_{q\gamma} + C^{L,R}_{q\gamma}/v_t^q$ and $C^{L,R}_{qf} = \tilde{C}^{L,R}_{qf} + C^{L,R}_{qf}/v_t^q$. Where $\tilde{C}^{L,R}_{ij}$ denote the contributions from the SM and $C^{L,R}_{ij}$ represent the contributions from possible new physics. In the SM, one has $C^{L,R}_{q\gamma} = ...$
\[ \sum_f [\tilde{C}_{qq}^{LR}(f) v_f^q / v_f^t] (t, c, u) \] with \( \tilde{C}_{qq}^{LR}(f) \) are Wilson coefficient functions corresponding to a loop-quark \( f \). As the photon in the SM is predominantly left-handed and \( m_u, m_c \ll m_t \), to a good approximation, we will ignore the contributions from coefficient functions \( \tilde{C}_{qq}^{R} \) and \( \tilde{C}_{qq}^{L}(f) \) with \( f = c, u \). It is also expected that new physics effects at the tree level are small in comparison with the one in the SM, namely, \( |\tilde{C}_{qf}^{L}| \ll |\tilde{C}_{qf}^{L}| \) and \( |\tilde{C}_{qf}^{R}| \ll 1 \) with \( f = c, u \). With these considerations, CP asymmetry \( A_{Xq\gamma}^{CP} \) is given by

\[
A_{Xq\gamma}^{CP} = \frac{\Gamma - \tilde{\Gamma}}{\Gamma + \tilde{\Gamma}} \approx \frac{2}{|\tilde{C}_{q\gamma}^{L}|^2 + |\tilde{C}_{q\gamma}^{R}|^2} \\
\cdot \left[ f_{g\gamma} \left( \tilde{C}_{qq}^{L}(t) Im(\tilde{C}_{q\gamma}^{L} / v_t^q) - \tilde{C}_{qq}^{L}(t) Im(\tilde{C}_{q\gamma}^{L} / v_t^q) \right) \right. \\
+ \left( \tilde{C}_{qq}^{L}(t) Im(\tilde{C}_{q\gamma}^{L} v_t^q) + \tilde{C}_{qq}^{L}(t) Im(\tilde{C}_{q\gamma}^{L} v_t^q) \right) / |v_t^q|^2 \\
+ f_{g\gamma} \left( Im(\tilde{C}_{q\gamma}^{L} \tilde{C}_{q\gamma}^{L}) + Im(\tilde{C}_{q\gamma}^{L} \tilde{C}_{q\gamma}^{L}) \right) / |v_t^q|^2 \\
- \tilde{C}_{q\gamma}^{L}(t) \left( \tilde{C}_{qq}^{L} f_{c\gamma} Im(v_t^q / v_t^q) + \tilde{C}_{qq}^{L} f_{c\gamma} Im(v_t^q / v_t^q) \right) \right] \\
(3)
\]

where the last term is the pure new physics effects and the third term represents pure new physics effects. The first two terms arise from the interference between the SM and new CP-violating interactions. Here the first term is related to the chromo-magnetic dipole operator and the second term to the four quark operators. For simplicity, we will not consider contributions from gluon bremstrahlung processes as they do not affect our main conclusions.

To demonstrate which CP-violating sources may lead to a significant CP asymmetry in the radiative B decays, we first consider the case that only one of new CP-violating interactions plays a dominant role. In this case the third term in the bracket of eq.(3) vanishes since \( \tilde{C}_{q\gamma}^{L,R} \) and \( \tilde{C}_{qq}^{L,R} \) have the same phase. For the decays \( B \to X_s + \gamma \), CP asymmetry from the SM is below 1\%[8]. The second term in the bracket of eq.(3) is suppressed either from the CKM matrix element \( |v_t^q / v_t^q| \ll 1 \) or from phase space factor that was found [9] at the leading-order to be \( f_{c\gamma} \simeq 0.145f_{g\gamma} \simeq 0.16f_{g\gamma} + f_{g\gamma} = 2\alpha_s / 9 \) [10]. In this case, possible significant CP asymmetry in the decays \( B \to X_s + \gamma \) will mainly arise from the first term in the bracket of eq.(3). We further consider the case that \( |\tilde{C}_{q\gamma}^{L,R}|^2 \ll |\tilde{C}_{q\gamma}^{L,R}|^2 \) and will focus on the first term in the bracket of eq.(3). Its maximal value occurs at \( \tilde{C}_{q\gamma}^{L} + Re(\tilde{C}_{q\gamma}^{L} / v_t^q) \simeq 0 \) with \( Im(\tilde{C}_{q\gamma}^{L} / v_t^q) \simeq \pm |\tilde{C}_{q\gamma}^{L}| \) even when radiative decay rate measurements agree with the SM predictions. One then has for this case

\[
A_{Xq\gamma}^{CP} = \frac{\Gamma - \tilde{\Gamma}}{\Gamma + \tilde{\Gamma}} \approx \frac{4\alpha_s}{9} \left( \frac{\tilde{C}_{qq}^{L}(t)}{\tilde{C}_{q\gamma}^{L}(t)} - \frac{Im(\tilde{C}_{qq}^{L} / v_t^q)}{Im(\tilde{C}_{q\gamma}^{L} / v_t^q)} \right) \]
(4)

where \( \tilde{C}_{qq}^{L}(t) \) and \( \tilde{C}_{qq}^{L}(t) \) have been evaluated to the next-to-leading order corrections[3]. In our present considerations, only leading-order corrections[11] are needed. When evaluating with \( \alpha_s(m_h) \simeq 0.214 \) and \( m_t(m_t) = 175\text{GeV} \), we have \( \tilde{C}_{q\gamma}^{L}(t) \simeq -0.31 \) and \( \tilde{C}_{qq}^{L}(t) \simeq -0.15 \).

To apply the above model-independent analyses to extensions of the SM, we first consider the simple type-3 2HDM presented in [5, 6]. The important new contributions to penguin loops arise from new CP-violating sources in the charged Higgs sector. In that case, we
have $\text{Im}(\tilde{C}_{qq}^L/v_t^2) = \text{Im}(\chi_{H+}^{q\nu})C_{qq}^{H+} (v = \gamma, g)$. Here $\chi_{H+}^{q\nu} = \xi_k \xi_k$ with $\xi_k$ being complex couplings [5]. $C_{H+}^{H+}$ and $C_{qq}^{H+}$ are integral functions[5]. For charged Higgs mass ranging from $m_{H+} \simeq 100$ GeV to $m_{H+} \simeq 1$ TeV, we find that the corresponding values of the maximal CP asymmetry range from $a_{\chi_{H+}^{q\nu}}^{C_{H+}^{H+}} \simeq \pm 5\%$ to $a_{\chi_{H+}^{q\nu}}^{C_{qq}^{H+}} \simeq \pm 10\%$. It is of interest to note that the values of the above defined maximal CP asymmetry increase as the charged Higgs mass goes up. This is because the ratio $C_{qq}^{H+}/C_{H+}^{H+}$ increases as the charged Higgs mass becomes larger.

We now consider another interesting case in which new CP-violating interactions are dominated by flavor changing neutral particle exchanges (FCNEs). This case may occur in many extensions of the SM. As a simple example, we further consider the type-3 2HDM by adding a fourth generation of quarks and leptons with heavy neutrinos. It has been pointed out by Cheng and Sher[12] and others and reemphasized by Hall and Weinberg [13] that FCNE may be suppressed by an approximate flavor symmetry. The scalar interactions concerned in our present considerations are given in the physics basis by

$$L_S = (\sqrt{2} G_F)^{1/2} \sum_{k=1}^{3} H^0_k [S^{(k)}_{bL} b_L^* b_R^* + S^{(k)}_{bL} b_L^* b_R^*] + \sum_{q=s,d} (S^{(k)}_{qg} q^*_L b_R^* + S^{(k)}_{qg} q^*_L b_R^*) + h.c]$$

(5)

with $S^{(k)}_{ij}$ being parameterized by the averaged masses $S^{(k)}_{ij} = \sqrt{m_i m_j} \eta_{ij}^{(k)}$, $\eta_{ij}^{(k)}$ are complex coupling constants. Where $H^0_k = (h, H, A)$ are the three physical neutral scalars. $H^0_2 \equiv H^0$ plays the role of the Higgs boson in the SM. We will neglect the fourth $t'$ quark effects by assuming small mixings $|\nu_{t'}^2| \ll |\nu_t^2|$. It is then not difficult to find that $\text{Im}(\tilde{C}_{qq}^L/v_t^2) = \text{Im}(\chi_{H}^{q\nu})C_{qq}^{H^0} (v = \gamma, g)$ with $\chi_{H}^{q\nu} = \sqrt{(m_q/4m_h)} \eta_{q\nu}^{(h)} \eta_{q\nu}^{(h)}$, $C_{H}^{H^0} = \eta^{16/23}[-\frac{1}{3} E(y^0) + \frac{5}{3} E(y^0)(\eta^{-2/23} - 1)]$ and $C_{qq}^{H^0} = \eta^{14/23} E(y^0)$ (here $y^0 = m_0^2/m_i^2$ and $\eta = \alpha_s(m_W)/\alpha_s(m_h) \simeq 0.56$). Of particular interest, the ratio $C_{H}^{H^0}/C_{H}^{H^0} \simeq \pm 5.3$. This leads to a parameter-independent maximal CP asymmetry $a_{\chi_{H}^{q\nu}}^{C_{H}^{H^0}} \simeq \pm 55\%$ and an enhanced branching ratio for chromo-magnetic dipole decay $b \rightarrow sg$ at the level $B(b \rightarrow sg) \simeq 22\%$.

When going back to the general case, we find that for $B \rightarrow X_{s\gamma}$ processes when $m_{H^0} \simeq m_{\nu} \simeq 200$ GeV, $\text{Im}(\chi_{H}^{q\nu}) \simeq 0$, $\text{Re}(\chi_{H}^{q\nu}) \simeq 4.5$, $\text{Im}(\chi_{H}^{q\nu}/v_t^2) \simeq \pm 7.0$ and $\text{Re}(\chi_{H}^{q\nu}/v_t^2) \simeq -0.09$, the resulting direct CP asymmetry is $A_{X_{s\gamma}}^{\text{CP}} \simeq \pm 27\%$. Here $\pm 54\%$ arise from the pure CP-violating scalar interactions and $\pm 27\%$ from the interference of standard and neutral scalar exchanges. Note that these two contributions have an opposite sign. The resulting branching ratio of the chromo-magnetic dipole decay $b \rightarrow sg$ is found to be $B(b \rightarrow sg) \simeq 7\%$. This value is very close to a preliminary experimental bound 6.8% (Ref. 14) much larger than the SM predictions $B(b \rightarrow sg) \simeq 0.2\%$. This limit is increased to 9.0% at 90% C.L. if one uses more recent charmed baryon and chamonium yields presented in Refs. 15 and 16 and makes use of the relative $\Lambda_b$ and $\Lambda_c$ yields given in Ref. 17. Since there may exist large uncertainties when extracting the upper bound[18], we shall use the current bounds only as a reference.

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Note that the following interesting case may occur, i.e., the direct CP asymmetry may become small but mixing-induced CP asymmetries suggested recently by Atwood, Gronau and Soni[19] could be large. The mixing-induced CP asymmetries require both the $B^0$ and $\bar{B}^0$ to be able to decay to a common final state. In the radiative $B$ decays, both should decay to states with the same photon helicity. Let $A^L_R$ and $A^R$ denote the decay amplitudes of $B^0 \rightarrow X^0_{q \gamma L,R}$ and $\bar{B}^0 \rightarrow X^0_{q \gamma L,R}$, respectively. We find that the amplitudes for emission of left- and right-handed photons in $B^0 \rightarrow X^0_q + \gamma$ are approximately $A^L_q \propto v^L_q C_q^L + v^R_q C_q^R$ and $A^R \propto \tilde{X}_q^{H^0} C_q^0 (\tilde{X}_q^{H^0} = \sqrt{(m_q/4m_b)}q^{(k)}_{b'q'} q^{(k)}_{b'q'})$. It is seen that freedom of the parameters $\chi_q^{H^0}$ and $\tilde{X}_q^{H^0}$ allows us to obtain solutions which satisfy $|A^L_q| \sim |A^R|$ with a maximal CP-violating phase. It is easy to obtain a solution: $\text{Im}(\chi_q^{H^0}/v^L_q) \sim \text{Im}(\chi_q^{H^0}/v^L_q) \sim 0$ (i.e., new contributions to direct CP asymmetries will be negligible), $\text{Re}(\chi_q^{H^0}/v^L_q) \sim -2.2$ and $|\chi_q^{H^0}| \sim 9.9$ for $m_{H^+} \sim 200\text{GeV}$ and $m_{H^0} \sim m_b$. Such solutions will lead to maximal time-dependent mixing-induced CP asymmetry $\mathcal{A}_q(t) = (\Gamma(t) - \bar{\Gamma}(t))/(\Gamma(t) + \bar{\Gamma}(t))|_{\text{max}} \sim \pm \sin(\Delta m_{B^0\tau})$ and time-integrated mixing-induced CP asymmetry $\mathcal{A}_q|_{\text{max}} \sim \pm 46\%$. For this case, we find that the branching ratio for the chromo-magnetic dipole decay $b \rightarrow s g$ is $B(b \rightarrow s g) \sim 11\%$. Such a value was found[20] to be interesting in understanding the recent observation[4] of large branching ratios concerning $\eta'$ yields in the charmless $B$ decays. The values at this level were also known to be favorable to lower the theoretical predictions for the semileptonic branching ratio of $B \rightarrow X_c e\bar{\nu}$ decay from $B(B \rightarrow X_c e\bar{\nu}) = 12\%$ to $B(B \rightarrow X_c e\bar{\nu}) = 10.8\%$. When taking $B(b \rightarrow s g) \sim 6\%$, we find that $\mathcal{A}_q(t)|_{\text{max}} \sim \pm 0.87 \sin(\Delta m_{B^0\tau})$ and $\mathcal{A}_q|_{\text{max}} \sim \pm 40\%$. It is noted that the resulting ranges of the parameters are consistent with other constraints. In particular, it does not affect very much the $B_s^0 - \bar{B}_s^0$ mixing. Therefore, mixing-induced CP asymmetries in radiative exclusive $B$ decays are sensitive to new physics that may only lead small contributions to the $B_s^0 - \bar{B}_s^0$ mixing. It implies that to distinguish from new physics phenomena that may have large contributions to the $B_s^0 - \bar{B}_s^0$ mixing, one may use, except by directly measuring this mixing, the method discussed recently by London and Soni[21] by measuring the CP angle $\beta$ via hadronic $b \rightarrow s$ penguin decays and comparing its value to that obtained in $B \rightarrow \psi K_S$.

In conclusion, though CP-averaged branching ratios of radiative $B$ decays are roughly those expected from the SM, its radiative decay amplitudes can still receive larger contributions from new CP-violating interactions beyond the SM. Such phenomena can be probed by the observation of sizable CP asymmetries in radiative $B$ decays and an enhanced chromo-magnetic dipole decay $b \rightarrow s g$. The analyses presented here can easily be applied to many extensions of the SM, such as SU(2) × U(1) with vector-like quarks as well as nonminimal supersymmetric standard models[7, 22], where one should carefully analyze all possible contributions together from various interactions. It is of interest to note that direct CP asymmetries and mixing-induced CP asymmetries in radiative $B$ decays as well as CP asymmetries in hadronic $b \rightarrow s$ penguin decays probe, to a large extent, different new physics effects and may compensate each other.

Acknowledgments: The author would like to thank Lincoln Wolfenstein for reading the manuscript and for useful suggestions. This work was supported in part by the NSF of
China under grant (# 19625514).

References


