Mixing-Induced *CP* Asymmetries in Radiative *B* Decays in and beyond the Standard Model

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In the standard model (SM) the photon in radiative $\overline{B}^0$ and $\overline{B}_s$ decays is predominantly left handed. Thus, mixing-induced *CP* asymmetries in $b \to s\gamma$ and $b \to d\gamma$ are suppressed by m_s/m_b and m_d/m_b, respectively, and are very small. In many extensions of the SM, such as the left-right symmetric model (LRSM), the amplitude of right-handed photons grows proportional to the virtual heavy fermion mass, which can lead to large asymmetries. In the LRSM, asymmetries larger than 50% are possible even when radiative decay rate measurements agree with SM predictions. [S0031-9007(97)03554-0]

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B meson decays may exhibit *CP* violation effects in a variety of manners [1]. In the standard model (SM), B^0 decays to *CP* eigenstates such as $J/\psi K_S$ involve large time-dependent rate asymmetries between B^0 and $\overline{B}^0$, which are given in terms of pure Cabibbo-Kobayashi-Maskawa (CKM) phases. On the other hand, certain asymmetries, such as in $B_s \to J/\psi\phi$, are expected to be extremely small in the SM, and are therefore very sensitive to sources of *CP* violation beyond the SM. This example represents a class of decay processes, in which large measurable effects of new physics in *CP* asymmetries originate in additional sizable contributions to $B_q - \overline{B}_q$ $(q = d, s)$ mixing [2]. Much smaller effects, which are harder to measure and have considerable theoretical uncertainties, can occur as new contributions to neutral *B* decay amplitudes [3]. Similarly, theoretical calculations of *CP* violation in charged *B* decays entail sizable uncertainties due to final state interaction phases and, therefore, as a rule, cannot be used as unambiguous signals of new physics.

In the present Letter we demonstrate a new way in which large *CP* asymmetries in neutral *B* decays can be introduced by new physics in processes where the SM predicts very small *CP* violation. We consider radiative B^0 and B_s decays, $B^0, B_s \to M^0\gamma$, where M^0 is any hadronic self-conjugate state $M^0 = \rho^0, \omega, \phi, K^{*0}$ (where $K^{*0} \to K_S\pi^0$), etc. As in $B^0 \to J/\psi K_S$ and $B_s \to J/\psi\phi$, the asymmetries in $B \to M^0\gamma$ are due to the interference between mixing and decay. The final states are not pure *CP* eigenstates. Rather, in the SM, they consist to a very good approximation of equal admixtures of states with positive and negative *CP* eigenvalues. Thus, due to an almost complete cancellation between contributions from positive and negative *CP* eigenstates, the asymmetries in $b \to q\gamma$ are very small. They are given by m_q/m_b, where the quark masses are current masses. This situation can be significantly modified in certain models beyond the SM by new terms in the decay amplitude. This rather special mechanism is to be contrasted with the more common new physics effect, in which large *CP* violation is due to additional contributions to $B_q - \overline{B}_q$ mixing.

While our focus will be on *mixing-induced CP* violation, we recall for completeness that *direct CP* violation in radiative *B* decays, occurring also in charged *B* decays, was already studied in the past for both the exclusive [4–6] and inclusive [7] cases. These effects depend on rescattering phases. Since final states in interesting *exclusive* decays involve a hadron and a photon, electromagnetic (soft) final state phases are small and can be neglected. The remaining strong phases, originating in the absorptive part of the penguin amplitude, can be calculated perturbatively. The calculation, which includes bound state effects, involves a fair amount of model dependence. The resulting asymmetries in the SM are at a level of 1% and 10% for processes such as $B \to K^*\gamma$ and $B \to \rho\gamma$, respectively [4]. Asymmetries in *inclusive* $b \to s\gamma$ and $b \to d\gamma$ were calculated in the SM and were found to be at most at this level and probably smaller [7]. Inclusive asymmetries were also calculated in models beyond the SM. In a two-Higgs-doublet model containing flavor-changing neutral Higgs exchange, the asymmetry in $b \to s\gamma$ can reach at most a level of 10% [8]. This would provide some evidence for new physics, albeit an uncertainty in calculating final state interaction effects. However, in the left-right symmetric model (LRSM) the asymmetries were found to be at most only slightly larger than in the SM [9], which would be insufficient to signal new physics.

As we will show below, mixing-induced *CP* asymmetries in exclusive radiative B^0 and B_s decays, from $b \to s\gamma$ and $b \to d\gamma$, are very small in the SM and can be 50% and larger in the LRSM, for instance. Such asymmetries would be clear evidence for physics beyond the SM. The general nature of our argument, which does not depend on assumptions about final state interactions, will be explained first.

The processes $b \to q\gamma$ $(q = d, s)$ can be described by the dipole type effective Lagrangian [10]

$$H_{\rm eff} = -\sqrt{8}\, G_F \, \frac{e m_b}{16\pi^2} \, F_{\mu\nu} \left[\frac{1}{2} \, F_L^q \bar{q} \sigma^{\mu\nu} (1 + \gamma_5) b + \frac{1}{2} \, F_R^q \bar{q} \sigma^{\mu\nu} (1 - \gamma_5) b \right]. \tag{1}$$

F_L^q and F_R^q are the amplitudes for the emission of *left* and *right* polarized photons in b (i.e., $\overline{B}$-meson) decay. In the SM, $F_R^q / F_L^q \approx m_q / m_b$, where the masses are current masses. It can be easily understood why the photons emitted from these b decays are predominantly left handed. The term proportional to F_L^q has the helicity structure $b_R \to q_L \gamma_L$, while the F_R^q term describes $b_L \to q_R \gamma_R$. In the SM penguin diagram with W exchange, only the left-handed components of the external fermions couple to the W; therefore helicity flip must occur on an external leg. Helicity flip on the b-quark leg is proportional to m_b and contributes to F_L^q, while helicity flip on the q-quark leg is proportional to m_q and contributes to F_R^q. This argument holds to all orders in strong interactions since QCD preserves quark helicities.

CP asymmetries in radiative neutral B decays, which follow from the interference of mixing and decay [1], require that both B and $\overline{B}$ decay to a common state. That is, both should decay to states with the same photon helicity. (States with different helicities do not interfere quantum mechanically, since *in principle* the photon helicity can be measured.) Thus, the asymmetry in $b \to q\gamma$ vanishes in the limit $F_R^q / F_L^q = 0$. In the SM these mixing-induced asymmetries are therefore expected to be quite small, at most of the order of a few percent in $b \to s\gamma$ and even smaller in $b \to d\gamma$.

Larger *CP* asymmetries can occur in extensions of the SM in which the amplitudes of radiative b decays can receive additional contributions from penguin diagrams with a heavy *right-handed* internal fermion *f*. If a left-to-right helicity flip occurs on the internal fermion line, then the amplitude for producing right-handed photons will have an additional enhancement of m_f / m_b with respect to the SM. There are a number of models with this property, which are potential candidates for large time-dependent *CP* asymmetries in radiative B^0 and B_s decays. A few examples are the $SU(2)_L \times SU(2)_R \times U(1)$ left-right symmetric model [11] to be studied below, $SU(2) \times U(1)$ models with exotic fermions (mirror or vector-doublet quarks) [12], and nonminimal supersymmetric models [13]; these will be investigated elsewhere [14].

Let us consider in some detail the time dependence of a generic exclusive decay process, $B_q(t) \to M^0 \gamma$, for a state which is identified ("tagged") as a B_q (rather than a $\overline{B}_q$) at time $t = 0$. M^0 is any hadronic self-conjugate state, with *CP* eigenvalue $\xi = \pm 1$. We denote

$$\begin{aligned} A(\overline{B} \to M^0 \gamma_L) &= A \cos\psi e^{i\phi_L}, \\ A(\overline{B} \to M^0 \gamma_R) &= A \sin\psi e^{i\phi_R}, \\ A(B \to M^0 \gamma_R) &= \xi A \cos\psi e^{-i\phi_L}, \\ A(B \to M^0 \gamma_L) &= \xi A \sin\psi e^{-i\phi_R}. \end{aligned} \tag{2}$$

For simplicity, we have suppressed the index describing the flavor q of the neutral B meson and the flavor of q' in the underlying $b \to q'\gamma$ decay. ψ gives the relative amount of left- and right-polarized photons in $\overline{B}_q$ decays, $\phi_{L,R}$ are *CP*-odd weak phases, while electromagnetic final state phases are absorbed in the amplitude A (which controls the overall rate) and can be neglected.

Using the time evolution of a state $B_q(t)$, which oscillates into a mixture of B_q and $\overline{B}_q$ and decays at time t to $M^0\gamma$, we find the time-dependent decay rate

$$\Gamma(t) \equiv \Gamma[B_q(t) \to M^0 \gamma] = e^{-\Gamma t} |A|^2 \times [1 + \xi \sin(2\psi) \sin(\phi_M - \phi_L - \phi_R) \sin(\Delta m t)]. \tag{3}$$

ϕ_M is the phase of $B_q - \overline{B}_q$ mixing, which is model dependent. The corresponding rate $\overline{\Gamma}(t)$ for an initial $\overline{B}_q$ is similar; however, the second term appears with opposite sign. Thus, one finds a *CP* asymmetry

$$\mathcal{A}(t) \equiv \frac{\Gamma(t) - \overline{\Gamma}(t)}{\Gamma(t) + \overline{\Gamma}(t)} = \xi \sin(2\psi) \times \sin(\phi_M - \phi_L - \phi_R) \sin(\Delta m t). \tag{4}$$

Here we have neglected, as usual, the small width difference between the two neutral B meson states and denoted their mass difference by Δm. We have also neglected *direct CP* violation. As explained in the introduction, such asymmetries are expected to be small in the SM, at most of order 1% and 10% in (exclusive) $b \to s\gamma$ and $b \to d\gamma$, respectively. They would show up as an additional small $\cos(\Delta m t)$ term in the asymmetry and would add a correction to the coefficient of the $\sin(\Delta m t)$ term [1]. This correction, which depends on unknown final state interaction phases, causes some uncertainty in this coefficient, but it does not invalidate our conclusions below.

The expression Eq. (4) is similar to the well-known form of an asymmetry obtained for decays to *CP* eigenstates, such as $B^0 \to J/\psi K_S$. The new factor $\sin(2\psi)$ describes helicity suppression, following from the opposite helicities to which B_q and $\overline{B}_q$ prefer to decay. It is the origin of the small asymmetry expected in the SM.

So far, the expression for the asymmetry is general. Now consider the asymmetries for the four cases of B^0 and B_s decays from $b \to s\gamma$ and $b \to d\gamma$. In these cases we find $\phi_M = 2\beta(0)$ for $B^0(B_s)$, and

$$\begin{aligned} &\text{for } b \to s\gamma : \sin(2\psi) \approx \frac{2m_s}{m_b}, \quad \phi_L = \phi_R \approx 0; \\ &\text{for } b \to d\gamma : \sin(2\psi) \approx \frac{2m_d}{m_{le}}, \quad \phi_L = \phi_R \approx \beta, \end{aligned} \tag{5}$$

where $-\beta$ is the phase of V_{td} in the standard convention [1]. We note that in B^0 and B_s decays to nonstrange states the asymmetry vanishes identically, due to a cancellation between the weak phases appearing in $B_q - \overline{B}_q$ mixing and in the decay amplitudes. In decays to strange final states, the asymmetry is proportional to $\sin(2\beta)$. The sign of the asymmetry is determined also by ξ, the CP eigenvalue of the hadron M^0. We list a few examples of asymmetries expected in the SM:

$$\begin{aligned} \mathcal{A}(B^0 \to K^{*0}\gamma) &\approx (2m_s/m_b)\sin(2\beta)\sin(\Delta mt)\,; \\ \mathcal{A}(B^0 \to \rho^0\gamma) &\approx 0\,, \\ \mathcal{A}(B_s \to K^{*0}\gamma) &\approx -(2m_d/m_b)\sin(2\beta)\sin(\Delta mt)\,; \\ \mathcal{A}(B_s \to \phi\gamma) &\approx 0\,, \end{aligned} \tag{6}$$

where K^{*0} is observed through $K^{*0} \to K_S\pi^0$.

Now we turn to the LRSM [11] in order to study the asymmetries in this extension of the SM. We will limit our analysis to the most commonly discussed version based on a discrete $L \leftrightarrow R$ symmetry, in which $g_R = g_L$ and the left and right quark mixing matrices are related to each other either by $V^R = V^L$ or by $V^R = (V^L)^*$. A very strong lower limit on the W_R mass was obtained from the $K_L - K_S$ mass difference [15], $m(W_2) > 1.4$ TeV, and a rather stringent upper bound on $W_L - W_R$ mixing was derived from semileptonic d and s decays [16], $0 \le \zeta \le 3 \times 10^{-3}$, where [17]

$$\begin{pmatrix} W_1^+ \\ W_2^+ \end{pmatrix} = \begin{pmatrix} \cos\zeta & e^{-i\omega}\sin\zeta \\ -\sin\zeta & e^{-i\omega}\cos\zeta \end{pmatrix} \begin{pmatrix} W_L^+ \\ W_R^+ \end{pmatrix}. \tag{7}$$

The limit on ζ assumes a small CP violation phase ω and becomes somewhat weaker for larger phases [18]. If the discrete $L \leftrightarrow R$ symmetry is abandoned, the above constraints on the parameters of the model loosen substantially [18], in which case it can have sizable nonstandard effects in B physics [19]. In the present discussion, we insist on the discreate symmetry.

The process $b \to s\gamma$ was studied within the left-right symmetric model by several authors [20,21]. In addition to the SM penguin operator with W (and t) exchange, the amplitude contains two penguin-type terms which are potentially large: An amplitude with $W_L - W_R$ mixing and an amplitude involving charged scalar exchange. Both amplitudes contain an enhancement factor m_t/m_b due to helicity flip on the internal t quark line. For illustration purposes, we will adopt the results of Ref. [21] for the first contribution including QCD corrections and will neglect the charged Higgs term assuming that the charged Higgs is sufficiently heavy (e.g., $m_H > 20$ TeV). We consider the case $V^R = V^L$. The terms F_L^q and F_R^q describing the amplitudes for emission of left- and right-handed photons in $b \to q\gamma$ are given approximately by

$$\begin{aligned} F_L &\propto F(x) + \eta_{\mathrm{QCD}} + \zeta\,\frac{m_t}{m_b}\,e^{i\omega}\tilde{F}(x)\,, \\ F_R &\propto \zeta\,\frac{m_t}{m_b}\,e^{-i\omega}\tilde{F}(x)\,, \end{aligned} \tag{8}$$

where $x = (m_t/m_{W_1})^2$, $\eta_{\mathrm{QCD}} = -0.18$, and the functions F and $\tilde{F}$ are defined as [21]

$$\begin{aligned} F(x) &= \frac{x(7 - 5x - 8x^2)}{24(x-1)^3} - \frac{x^2(2-3x)}{4(x-1)^4}\ln x\,, \\ \tilde{F}(x) &= \frac{-20 + 31x - 5x^2}{12(x-1)^2} + \frac{x(2-3x)}{2(x-1)^3}\ln x\,. \end{aligned} \tag{9}$$

Note that the ratio of the left and right helicity amplitudes for $b \to q\gamma$ does not depend on the q quark flavor. The two amplitudes are proportional to a common QCD factor and to equal left and right CKM factors $V_{tb}V_{tq}^*$.

The term $F(x) + \eta_{\mathrm{QCD}}$ in (8) is the SM result, while the terms which involve the small mixing ζ are proportional to m_t/m_b. For the latter ratio we use a pole mass $m_t = 175$ GeV, and $m_b(\mu = m_t) = 3$ GeV, which is obtained from a pole mass of 4.8 GeV. The m_t/m_b enhancement and the factor $\tilde{F}(x)/[F(x) + \eta_{\mathrm{QCD}}] = 2.1$ partially overcome the stringent bound on ζ. Consequently, as pointed out in Ref. [21], the effect of $W_L - W_R$ mixing on the rate of $b \to q\gamma$ may be significant. Using the above values, the ratio of rates in the LRSM and in the SM is given by $\Gamma(\mathrm{LRSM})/\Gamma(\mathrm{SM}) \approx |e^{-i\omega} + z|^2 + z^2$, where $z = 120\zeta$.

The CP asymmetry Eq. (4) results from an interference of F_L and F_R, and depends on the two parameters describing $W_L - W_R$ mixing, the mixing parameter ζ, and the CP violating phase ω. We find the following expressions for the parameters which determine the asymmetry in $B_q \to X_{q'}\gamma$:

$$\begin{aligned} \tan\psi &\approx \frac{z}{|e^{-i\omega} + z|}, \\ \phi_L + \phi_R &\approx \arg(e^{-i\omega} + z) + 2\beta\delta_{q'd}\,, \end{aligned} \tag{10}$$

where $q' = d, s$ denotes the flavor in $b \to q'\gamma$. The phase of $B_q - \overline{B}_q$ mixing is unaffected by new LRSM contributions [2], and is approximately the same as in the SM, $\phi_M = 2\beta$ and $\phi_M = 0$ for B^0 and B_s, respectively.

The parameters ζ and ω are constrained by the agreement between the calculation of the branching ratio for $B \to X_s\gamma$ within the SM [22], $B(B \to X_s\gamma)_{\mathrm{SM}} = (3.28 \pm 0.33) \times 10^{-4}$, and experiment [23], $B(B \to X_s\gamma)_{\mathrm{EXP}} = (2.32 \pm 0.67) \times 10^{-4}$. The constraint is not very stringent due to the present sizable theoretical and experimental uncertainties. Moreover, since the radiative rate measurements do not probe the photon helicity, the CP asymmetries (which do depend on the photon helicity) may be quite large even when the rate agrees precisely with the SM prediction. In this case we have $|e^{-i\omega} + z|^2 + z^2 = 1$, a solution of which is $z = -\cos\omega$. Consequently, $\sin(2\psi) = |\sin(2\omega)|$, $\phi_L + \phi_R = \pm\pi/2 + 2\beta\delta_{q'd}$, where the $+$ and $-$ signs correspond to $0 < \omega < \pi$ and $\pi < \omega < 2\pi$, respectively. The asymmetry is given by $\mathcal{A}(t) = \mp\xi|\sin(2\omega)|\cos(\phi_M - 2\beta\delta_{q'd})\sin(\Delta mt)$. The largest asymmetry is obtained when ζ takes its present experimental upper limit $\zeta = 0.003$, corresponding to $|\sin(2\omega)| = 0.67$. (The limit on ζ is actually somewhat higher for $\omega \neq 0$ [18], and the asymmetry can be correspondingly larger.) In this case we find, instead of the SM predictions Eqs. (6),

$$\begin{aligned} \mathcal{A}(B^0 \to K^{*0}\gamma) &\approx \mp 0.67\cos(2\beta)\sin(\Delta mt)\,, \\ \mathcal{A}(B^0 \to \rho^0\gamma) &\approx \mp 0.67\sin(\Delta mt)\,, \\ \mathcal{A}(B_s \to K^{*0}\gamma) &\approx \mp 0.67\cos(2\beta)\sin(\Delta mt)\,, \\ \mathcal{A}(B_s \to \phi\gamma) &\approx \mp 0.67\sin(\Delta mt)\,. \end{aligned}$$

All four asymmetries can be larger than 50% in the LRSM. ($10° < \beta < 35°$ [1].)

We comment briefly on expected branching ratios for the interesting processes. We focus our attention on processes of the type $B_q \to M^0\gamma$, where M^0 is a single (unstable) meson state. One may also consider three-body decays, such as $B_q \to P^+P^-\gamma$ ($P = \pi, K$); however, this would require separating different angular momentum P^+P^- states which have specific *CP* values. So far, only the exclusive $B \to K^*\gamma$ was measured [24], $B(B \to K^*\gamma) \sim 4.5 \times 10^{-5}$. The corresponding branching ratio of $B^0 \to \rho^0\gamma$ is expected to be lower by a factor $|V_{td}/V_{ts}|^2$ in the SM, which would make it about an order of magnitude smaller. ($0.15 < |V_{td}/V_{ts}| < 0.33$ [1].) One expects $B(B_s \to \phi\gamma) \sim B(B \to K^*\gamma)$ and $B(B_s \to K^*\gamma) \sim B(B^0 \to \rho^0\gamma)$.

Measuring an asymmetry requires tagging and, at an e^+e^- collider operating at the $\Upsilon(4S)$, it also needs time dependence. That is, one must measure the distance of the B decay point away from its production. In this respect, the ρ^0 and ϕ can be easily handled by their prompt and dominant decays to a pair of pions and kaons, respectively. But, due to the K_S finite lifetime, it would be hard to trace a K^{*0} decaying to $K_S\pi^0$ back to its point of production. In addition, the K^{*0} decay, via $K_s\pi^0$, to the final $\pi^+\pi^-\pi^0$ state involves a suppression factor of 1/9, which makes the effective rate of $B^0 \to K^{*0}\gamma$ comparable to that of $B^0 \to \rho^0\gamma$. In hadronic colliders, where $B\overline{B}$ pairs are produced incoherently, no time dependence is required. As we have shown, in models such as the LRSM, the above modes and similar ones may involve large asymmetries of order 10% or even 50%. With branching ratios of a few times 10^{-6}, asymmetries of order 10%–50% should be within the reach of planned sources of B mesons providing $\mathcal{O}(10^8)$ and $\mathcal{O}(10^9)$ B's, respectively. Clearly, improved bounds on the parameters of the model, ζ and ω in the case of LRSM, would be obtained if no asymmetries were found at this level.

In summary, it was pointed out that the *inclusive rate* of radiative B decays is sensitive to certain types of new physics. The photon helicity measured by *mixing-induced CP asymmetries* turns out, on the other hand, to be sensitive to a different type of effect which appears in some extensions of the SM such as the LRSM. Since the SM predicts very small *CP* violation, observing sizable asymmetries, irrespective of their precise values, would be a clear signal of physics beyond the SM.

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