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Direct CP Violation In Radiative B Decays

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Abstract. We discuss the role of the radiative B decays $B \rightarrow X_{s/d}\gamma$ in our search for new physics focusing on the issue of direct CP violation. We discuss in some detail a SM prediction for the CP asymmetries in inclusive $b \rightarrow s/d$ transitions, namely $|\Delta\mathcal{B}(B \rightarrow X_s\gamma) + \Delta\mathcal{B}(B \rightarrow X_d\gamma)| \sim 1 \cdot 10^{-9}$. Any measured value in significant deviation of this estimate would indicate new sources of CP violation beyond the CKM phase.

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INRODUCTION

It is well-known that radiative B decays like $B \rightarrow X_{s/d}\gamma$ play an important role in our search of new physics. These processes test the SM directly on the quantum level and, thus, are particularly sensitive to new physics (for a recent review see [1]). While the direct production of new (supersymmetric) particles is reserved for the planned hadronic machines such as the LHC at CERN, the indirect search of the B factories already implies significant restrictions for the parameter space of supersymmetric models and will thus lead to important clues for the direct search of supersymmetric particles. It is even possible that these rare processes lead to the first evidence of new physics by a significant deviation from the SM prediction, for example in the observables concerning direct CP violation, although it will then be difficult to identify in this way the new structures in detail. But also in the long run, after new physics has already been discovered, these decays will play an important role in analyzing in greater detail the underlying new dynamics.

One of the main difficulties in examining the observables in B physics is the influence of the strong interaction. As is well known, for matrix elements dominated by long-distance strong interactions there is no adequate quantitative solution available in quantum field theory. The resulting hadronic uncertainties restrict the opportunities in B physics significantly. If new physics does not show up in B physics through large deviations as recent experimental data indicates the focus on theoretically clean variables like inclusive radiative B decays is mandatory.

Within inclusive decays like $B \rightarrow X_{s/d}\gamma$ the long-distance strong interactions are less important and well under control due to the heavy mass expansion. The decay $B \rightarrow X_s\gamma$ was first observed by the CLEO collaboration [2]; these measurements have been refined [3, 4] and confirmed by other experiments [5, 6] (see also [7]). The present world average using the present data from BELLE, CLEO and ALEPH is

$$\mathcal{B}(B \rightarrow X_s\gamma) = (3.22 \pm 0.40) \times 10^{-4}. \quad (1)$$

The theoretical prediction of the Standard Model (SM) up to next-to-leading logarithmic (NLL) precision for the total decay rate of the $B \rightarrow X_s\gamma$ mode [8] is well in agreement with the experimental data. The theoretical NLL prediction for the $B \rightarrow X_s\gamma$ branching ratio [12] leads to

$$\mathcal{B}(B \rightarrow X_s\gamma) = (3.32 \pm 0.14 \pm 0.26) \times 10^{-4}, \quad (2)$$

where the first error represents the uncertainty regarding the scale dependences, while the second error is the uncertainty due to the input parameters. In the second error the uncertainty due to the parameter m_c/m_b is dominant.

This inclusive mode already allows for theoretically clean and rather strong constraints on the parameter space of various extensions of the SM [9, 10, 11]. While many phenomenological analyses of the inclusive $B \rightarrow X_{s/d}\gamma$ decays in supersymmetry are restricted to the assumption of minimal flavour violation including only CKM induced flavour change, a model-independent analysis also has to consider the generic new supersymmetric sources of flavour change due to the mixing in the squark mass matrix. In [11] new model-independent bounds on supersymmetric flavour-violating parameters were derived from $B \rightarrow X_s\gamma$. The importance of interference effects for the bounds on the parameters in the squark mass matrices within the unconstrained MSSM is explicitly demonstrated. In former analyses no correlations between the different sources of flavour violation were taken into account [10]. The new bounds are in general one order of magnitude weaker than the original bounds on the single off-diagonal element, which was derived in previous work [10] by neglecting any kind of interference effects.

Recently, quark mass effects within the decay $B \rightarrow X_s\gamma$ were further analysed [13], in particular the definitions of the quark masses m_c and m_b . The charm quark enters in specific NLL matrix elements (see Fig. 1) where the charm quark mass is dominantly off-shell. Therefore, the authors of [13] argue that the running charm mass should be chosen instead of the pole mass. The latter choice was used in all previous analyses [14, 8, 15, 16, 12].

$$m_c^{\text{pole}}/m_b^{\text{pole}} \quad \Rightarrow \quad m_c^{\overline{\text{MS}}}(\mu)/m_b^{\text{pole}}, \quad \mu \in [m_c, m_b]. \quad (3)$$

Since these matrix elements start at NLL order only and, thus, the renormalization scheme for m_c and m_b is an NNLL issue, one should regard this choice as an educated guess of the NNLL corrections. The new choice is guided by the experience gained from many higher-order calculations in perturbation theory. Numerically, the shift from $m_c^{\text{pole}}/m_b^{\text{pole}} = 0.29 \pm 0.02$ to $m_c^{\overline{\text{MS}}}(\mu)/m_b^{\text{pole}} = 0.22 \pm 0.04$ is rather important and leads to a +11% shift of the central value of the $B \rightarrow X_s\gamma$ branching ratio. With their new

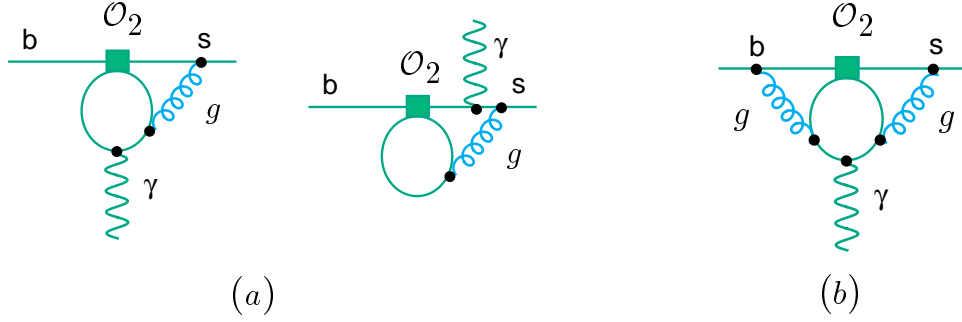


FIGURE 1. a) Typical diagrams contributing to the matrix element of the operator O_2 at the NLL level. b) Typical diagram contributing to the NLL anomalous dimension matrix.

choice of the charm mass their theoretical prediction for the branching ratio is [13]

$$\mathcal{B}(B \rightarrow X_s \gamma) = (3.73 \pm 0.30) \times 10^{-4}, \quad (4)$$

which induces a small difference between the theoretical and the experimental value.

However, because the choice of the renormalization scheme for m_c and m_b is a NNLL effect, their important observation should be reinterpreted into a larger error bar in $m_c^{\overline{\text{MS}}}(\mu)/m_b^{\text{pole}}$ which includes also the value of m_c^{pole} . A more conservative choice would then be $m_c^{\overline{\text{MS}}}(\mu)/m_b^{\text{pole}} = 0.22 \pm 0.07$ which deletes the significance of the perceived discrepancy.

DIRECT CP ASYMMETRY

The CP violation in the B system will yield an important independent test of the SM description of CP violation (see [17]). In particular, detailed measurements of CP asymmetries in rare B decays will be possible in the near future. Theoretical predictions for the *normalized CP asymmetries* of the inclusive channels (see [18, 19, 20]) within the SM lead to

$$\alpha_{CP}(B \rightarrow X_{s/d} \gamma) = \frac{\Gamma(\bar{B} \rightarrow X_{s/d} \gamma) - \Gamma(B \rightarrow X_{\bar{s}/\bar{d}} \gamma)}{\Gamma(\bar{B} \rightarrow X_{s/d} \gamma) + \Gamma(B \rightarrow X_{\bar{s}/\bar{d}} \gamma)} \quad (5)$$

$$\alpha_{CP}(B \rightarrow X_s \gamma) \approx 0.6\%, \quad \alpha_{CP}(B \rightarrow B_d \gamma) \approx -16\% \quad (6)$$

when the best-fit values for the CKM parameters [21] are used. An analysis for the leptonic counterparts is presented in [22]. The normalized CP asymmetries may also be calculated for exclusive decays; however, these results are model-dependent. An example of such a calculation may be found in [23].

CLEO has already presented a measurement of the CP asymmetry in inclusive $b \rightarrow s \gamma$ decays, yielding [24]

$$\alpha_{CP}(B \rightarrow X_s \gamma) = (-0.079 \pm 0.108 \pm 0.022) \times (1.0 \pm 0.030), \quad (7)$$

which indicates that very large effects are already excluded.

Supersymmetric predictions for the CP asymmetries in $B \rightarrow X_{s/d}\gamma$ depend strongly on what is assumed for the supersymmetry-breaking sector and are, thus, a rather model-dependent issue. The minimal supergravity model cannot account for large CP asymmetries beyond 2% because of the constraints coming from the electron and neutron electric dipole moments [25]. However, more general models allow for larger asymmetries, of the order of 10% or even larger [26, 19]. Recent studies of the $B \rightarrow X_d\gamma$ rate asymmetry in specific models led to asymmetries between -40% and $+40\%$ [28] or -45% and $+21\%$ [27]. In general, CP asymmetries may lead to clean evidence for new physics by a significant deviation from the SM prediction.

In [29] it was explicitly derived, that a bound on the *combined* asymmetries within the decays $b \rightarrow s\gamma$ and $b \rightarrow d\gamma$, as well as their leptonic counterparts is possible which is more suitable for the experimental settings. It provides a stringent test, if the CKM matrix is indeed the only source of CP violation. Using U-spin, which is the $SU(2)$ subgroup of flavour $SU(3)$ relating the s and the d quark and which is already a well-known tool in the context of nonleptonic decays [30, 31], one derives relations between the CP asymmetries of the exclusive channels $B^- \rightarrow K^{*-}\gamma$ and $B^- \rightarrow \rho^-\gamma$ and of the inclusive channels $B \rightarrow X_s\gamma$ and $B \rightarrow X_d\gamma$. One should make use of the U-spin symmetry only with respect to the strong interactions. Moreover, within *exclusive* final states, the vector mesons like the U-spin doublet (K^{*-}, ρ^-) are favoured as final states because these have masses much larger than the (current-quark) masses of any of the light quarks. Thus one expects, for the ground-state vector mesons, the U-spin symmetry to be quite accurate in spite of the nondegeneracy of m_d and m_s . Defining the rate asymmetries (not the *normalized* CP asymmetries) by

$$\Delta\Gamma(B^- \rightarrow V^-\gamma) = \Gamma(B^- \rightarrow V^-\gamma) - \Gamma(B^+ \rightarrow V^+\gamma) \quad (8)$$

one arrives at the following relation [29]:

$$\Delta\Gamma(B^- \rightarrow K^{*-}\gamma) + \Delta\Gamma(B^- \rightarrow \rho^-\gamma) = b_{exc}\Delta_{exc} \quad (9)$$

where the right-hand side is written as a product of a relative U-spin breaking b_{exc} and a typical size Δ_{exc} of the CP violating rate difference. In order to give an estimate of the right-hand side, one can use the model result from [23] for Δ_{exc} ,

$$\Delta_{exc} = 2.5 \times 10^{-7} \Gamma_B. \quad (10)$$

The relative breaking b_{exc} of U-spin can be estimated, e.g. from spectroscopy. This leads us to

$$|b_{exc}| = \frac{M_{K^*} - m_\rho}{\frac{1}{2}(M_{K^*} + m_\rho)} = 14\%. \quad (11)$$

Certainly, other estimates are also possible, such as a comparison of f_ρ and f_{K^*} . In this case one finds a very small U-spin breaking. Using the more conservative value for b_{exc} , which is also compatible with sum rule calculations of form factors (see [32]), one arrives at the standard-model prediction for the difference of branching ratios

$$|\Delta\mathcal{B}(B^- \rightarrow K^{*-}\gamma) + \Delta\mathcal{B}(B^- \rightarrow \rho^-\gamma)| \sim 4 \times 10^{-8} \quad (12)$$

Note that the right-hand side is model-dependent.

Quite recently, the U-spin breaking effects were also estimated in the QCD factorization approach [33]. Within this approach, it was shown that the U-spin breaking effect essentially scales with the differences of the two form factors, $(F_{K^*} - F_\rho)$. Using the formfactors from the QCD sum rule calculation in [34] and maximizing the CP asymmetries by a specific choice of the CKM angle γ , the authors of [33] obtain

$$\Delta\mathcal{B}(B^- \rightarrow K^{*-}\gamma) + \Delta\mathcal{B}(B^- \rightarrow \rho^-\gamma) \sim -3 \times 10^{-7}, \quad (13)$$

while for the separate asymmetries they obtain:

$$\Delta\mathcal{B}(B \rightarrow K^*\gamma) = -7 \times 10^{-7}, \quad \Delta\mathcal{B}(B \rightarrow \rho\gamma) = 4 \times 10^{-7}. \quad (14)$$

This calculation explicitly shows the limitations of the relation (9) as a SM test.

The issue is much more attractive in the *inclusive* modes. Due to the $1/m_b$ expansion for the inclusive process, the leading contribution is the free b -quark decay. In particular, there is no sensitivity to the spectator quark and thus one arrives at the following relation for the CP rate asymmetries [29]:

$$\Delta\Gamma(B \rightarrow X_s\gamma) + \Delta\Gamma(B \rightarrow X_d\gamma) = b_{inc}\Delta_{inc}. \quad (15)$$

In this framework one relies on parton-hadron duality; so one can actually compute the breaking of U-spin by keeping a nonvanishing strange quark mass. The typical size of b_{inc} can be roughly estimated to be of the order of $|b_{inc}| \sim m_s^2/m_b^2 \sim 5 \times 10^{-4}$; $|\Delta_{inc}|$ is again the average of the moduli of the two CP rate asymmetries. These have been calculated (for vanishing strange quark mass), e.g. in [18] and thus one arrives at

$$|\Delta\mathcal{B}(B \rightarrow X_s\gamma) + \Delta\mathcal{B}(B \rightarrow X_d\gamma)| \sim 1 \times 10^{-9}. \quad (16)$$

Any measured value in significant deviation of (16) would be an indication of new sources of CP violation. Although only an estimate is given here, it should again be stressed that in the inclusive mode the right-hand side in (16) can be computed in a model-independent way with the help of the heavy mass expansion.

Going beyond leading order in the $1/m_b$ expansion the first subleading corrections are of order $1/m_b^2$ only. The $1/m_b^2$ corrections are induced by the imaginary part of the forward scattering amplitude $T(q)$:

$$T(q) = i \int d^4x \langle B | T O_7^+(x) O_7(0) | B \rangle \exp(iqx) \quad . \quad (17)$$

where only the magnetic operator O_7 is taken into account. Using the operator product expansion for $T O_7^+(x) O_7(0)$ and heavy quark effective theory methods, the decay width $\Gamma(B \rightarrow X_s\gamma)$ reads [38, 39] (modulo higher terms in the $1/m_b$ expansion):

$$\begin{aligned} \Gamma_{B \rightarrow X_s\gamma}^{(O_7, O_7)} &= \frac{\alpha G_F^2 m_b^5}{32\pi^4} |V_{tb}V_{ts}|^2 C_7^2(m_b) \left(1 + \frac{\delta^{NP}}{m_b^2}\right) \quad , \\ \delta^{NP} &= \frac{1}{2}\lambda_1 - \frac{9}{2}\lambda_2 \quad , \end{aligned} \quad (18)$$

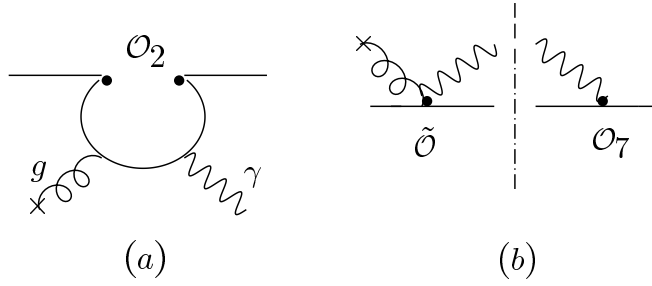


FIGURE 2. a) Feynman diagram from which the operator \tilde{O} arises. b) Relevant cut-diagram for the (O_2, O_7) -interference.

where λ_1 and λ_2 are the parameters for kinetic energy and the chromomagnetic energy. Using $\lambda_1 = -0.5 \text{ GeV}^2$ and $\lambda_2 = 0.12 \text{ GeV}^2$, one gets $\delta^{NP} \simeq -4\%$. Thus, the contributions are small and cancel in the sum of the rate asymmetries - in the limit of U-spin symmetry. The U-spin breaking effects in this contribution also induce an overall factor m_s^2/m_b^2 in addition - as one can read off from the explicit results for the $B \rightarrow X_s l^+ l^-$ case [35].

There are also nonperturbative corrections which scale with $1/m_c^2$ [36], which are induced by the interference of the magnetic O_7 and the four-quark operator O_2 . This effect is generated by the diagram in Fig. 2a (and by the one, not shown, where the gluon and the photon are interchanged); g is a soft gluon interacting with the charm quarks in the loop. Up to a characteristic Lorentz structure, this loop is given by the integral

$$\int_0^1 dx \int_0^{1-x} dy \frac{xy}{m_c^2 - k_g^2 x(1-x) - 2xyk_g k_\gamma} . \quad (19)$$

As the gluon is soft, i.e. $k_g^2, k_g k_\gamma \approx \Lambda^{QCD} m_b/2 \ll m_c^2$, the integral can be expanded in k_g . The (formally) leading operator, denoted by \tilde{O} , is

$$\tilde{O} = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* C_2 \frac{e Q_c}{48\pi^2 m_c^2} \bar{s} \gamma_\mu (1 - \gamma_5) g_s G_{\nu\lambda} b \varepsilon^{\mu\nu\rho\sigma} \partial^\lambda F_{\rho\sigma} . \quad (20)$$

Then working out the cut diagram shown in Fig. 2b, one obtains the nonperturbative contribution $\Gamma_{B \rightarrow X_s \gamma}^{(\tilde{O}, O_7)}$ to the decay width, which is due to the (O_2, O_7) interference. Normalizing this contribution by the LL partonic width, one obtains

$$\frac{\Gamma_{B \rightarrow X_s \gamma}^{(\tilde{O}, O_7)}}{\Gamma_{b \rightarrow s \gamma}^{LL}} = -\frac{1}{9} \frac{C_2 \lambda_2}{C_7 m_c^2} \simeq +0.03 . \quad (21)$$

This result corresponds to the leading term in an expansion in the parameter $t = k_g k_\gamma / 2m_c^2$. The expansion parameter is approximately $m_b \Lambda_{QCD} / 2m_c^2 \approx 0.3$ (rather than Λ_{QCD}^2 / m_c^2) and it is not a priori clear whether formally higher order terms in the m_c expansion are numerically suppressed. However, the explicit expansion of the complete vertex function, corresponding to Fig. 2a, shows that higher order terms are indeed suppressed, because the corresponding coefficients are small (see i.e. [37]).

Moreover, the operator \tilde{O} does not contain any information on the strange mass, thus, also in these contributions one finds the same overall suppression factor from the U-spin breaking.

The corresponding long-distance contributions from up-quark loops are CKM suppressed in the $B \rightarrow X_s \gamma$ case, but this does not hold in the $B \rightarrow X_d \gamma$ case. Naively, one could expect that the corresponding contributions from up-quark loops scale with $1/m_u^2$. However, following the approach of [37], one easily shows that the general vertex function cannot be expanded in the parameter t in that case. However, the expansion in inverse powers of t is reasonable. The leading term in this expansion scales like $t^{-1} \sim m_u^2/k_g k_\gamma$ and therefore cancels the factor $1/m_u^2$ in the prefactor (see the analogous $1/m_c^2$ factor in (20)) and one gets a suppression factor $(\Lambda_{QCD}^2/m_u^2) \cdot (m_u^2/k_g k_\gamma)$ [37]. Thus, although the expansion in inverse powers in t induces nonlocal operators, one explicitly finds that the leading term scales with Λ_{QCD}/m_b ¹.

This argument improves the discussion in [29] where the argument was given that vector dominance calculations in [40] show that the long-distance contributions from the up-quark loops to the decay rates are found to be rather small. However, that argument in [29] does not allow any statement about the effects of the U-spin breaking in contrast to the one given here.

Summing up, the analysis shows that the known nonperturbative contributions to (16) are under control and small and that this prediction provides a clean SM test, if generic new CP phases are present or not. Any significant deviation from the estimate (16) would be a strong hint to non-CKM contributions to CP violation.

Finally, we emphasize that an analogous prediction for the leptonic inclusive $B \rightarrow X_{s/d} \gamma$ modes is also possible taking into account some specific cuts on the invariant dilepton spectrum.

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¹ Also in the exclusive case an explicit analysis within the QCD factorization approach leads to this suppression factor [33].

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