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# Experimental Status of $b \to s(d)\gamma$ Decays

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**Abstract**

Radiative penguin decays provide an indirect probe for physics beyond the Standard Model and contribute to the determination of the CKM matrix elements. Copious quantities of $B$ mesons produced at the $B$–Factories permit precision measurements of radiative penguin decays. We review the experimental status of the radiative penguin processes $b \to s(d)\gamma$.

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# 1 Introduction

Radiative penguin decays are flavor–changing neutral current (FCNC) transitions that are forbidden in the Standard Model (SM) at the tree level, but occur at the loop level. We will focus on the transition with a photon in the final state which happens through penguin loops. Additional contributions to the electromagnetic penguin loops could arise from New Physics effects such as new gauge bosons, charged Higgs bosons or supersymmetric (SUSY) particles. These interfere with the SM processes. Depending on the sign of the interference term enhanced or depleted branching fractions ($\mathcal{B}$'s) result. Moreover, due to the presence of new weak phases; *CP* asymmetries that are small in the SM may be enhanced. This would make it possible to observe indirectly New Physics from the study of the radiative penguin decays.

In addition, these decays are relevant to the determination of the CKM matrix elements. The measurement of the photon energy spectrum, largely insensitive to New Physics, can be used to improve the extraction of the CKM elements $V_{cb}$ and $V_{ub}$ from inclusive semileptonic $B$ decays. Also, a direct estimate of the ratio of the CKM parameters $|V_{td}/V_{ts}|$ can be obtained from the ratio of the branching fractions for the processes $b \to d\gamma$ and $b \to s\gamma$.

In the following sections, the $b \to s\gamma$ followed by the $b \to d\gamma$ process will be reviewed.

# 2 $b \to s\gamma$ final states

The SM $b \to s\gamma$ branching fraction is predicted to be $\mathcal{B}(b \to s\gamma) = (3.73 \pm 0.3) \times 10^{-4}$ [1] at the next–to–leading order (NLO). The present theoretical uncertainty of $\sim 10\%$ is dominated by the mass ratio of the $c$–quark and $b$–quark and the choice of the renormalization scale. New Physics contributions with e.g. charged Higgs exchanges or chargino–squark loops are at the same level as the SM ones. In the Hamiltonian they could appear as new operators or new contributions to the coefficients of the SM operators.

*CP* asymmetries provide another test of the SM. While small in the SM ($\leq 1\%$) [2] they can reach 10–50% in models beyond the SM [3].

For the exclusive decay rate $B \to K^*\gamma$ two recent NLO calculations predict SM branching fractions of $\mathcal{B}(B \to K^*\gamma) = (7.1^{+2.5}_{-2.3}) \times 10^{-5}$ [4] and $\mathcal{B}(B \to K^*\gamma) = (7.9^{+3.5}_{-3.0}) \times 10^{-5}$ [5]. The errors are still dominated by the uncertainties in the form factors.

Differently from the branching fraction and *CP* asymmetry, the photon energy spectrum in $b \to s\gamma$ is not very sensitive to New Physics processes. Moments of the photon energy spectrum can be used to measure the Heavy Quark Effective Theory (HQET) parameters which determine the $b$–quark pole mass ($\overline{\Lambda}$) and the kinetic energy ($\lambda_1$) [6]. These parameters are needed to obtain a precision value of $|V_{cb}|$ from the $b \to c\ell\nu$ inclusive rate.

Moreover, the photon spectrum can be used for the determination of $V_{ub}$ from $B \to X_u\ell\nu$. To lowest order in $\Lambda_{QCD}/M_B$, the $B \to X_s\gamma$ photon energy spectrum, where $X_s$ refers to inclusive strange hadronic states, is given by a convolution of the parton level $b \to s\gamma$ photon energy spectrum with the light–cone shape function of the $B$ meson, which describes all $b$ to light–quark transitions. At the same order in $\Lambda_{QCD}/M_B$, the $B \to X_u\ell\nu$ lepton energy spectrum is given by a convolution of the parton level $b \to u\ell\nu$ lepton energy spectrum with the same shape function [7]. Corrections enter at next order in $\Lambda_{QCD}/M_B$, and these are currently the subject of active investigation [8].

## 2.1 The Exclusive Process $B \to K^*\gamma$

The exclusive $B \to K^*\gamma$ modes have been studied by *BABAR* [9], Belle [10] and CLEO [14], where Belle used the highest statistics sample. Utilizing kinematic constraints resulting from a full $B$ reconstruction in the $B$ rest frame provides a substantial reduction of the $q\overline{q}$ (continuum) background. The Belle *beam–constrained* [1] mass distribution is shown in Figure 2.1 for all the $K^*$ decay channels.

The measured branching fractions from all the experiments and the corresponding average are summarized in Table 1.

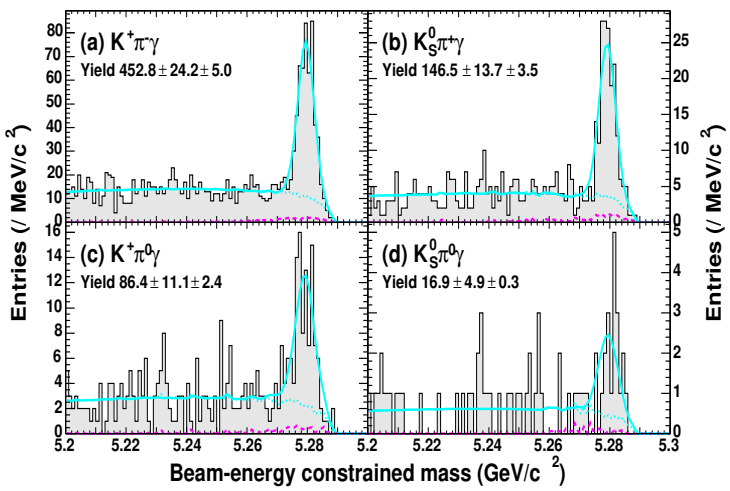


Figure 1: Belle [10] *beam–constrained* mass distribution for the exclusive $B \to K^*\gamma$ for the four $K^*$ final states.

Due to the large theoretical errors of 35–40%, the average branching fraction measurement is still consistent with the NLO SM predictions.

The direct *CP* asymmetry is defined, at the quark level, as:

$$A_{CP} = \frac{\Gamma(b \to s\gamma) - \Gamma(\overline{b} \to \overline{s}\gamma)}{\Gamma(b \to s\gamma) + \Gamma(\overline{b} \to \overline{s}\gamma)}.$$

Table 1 summarizes the measurements of the direct *CP* asymmetry in $B \to K^*\gamma$. These are consistent with zero and are statistics limited.

Isospin asymmetry, $\Delta_{0+}$, is calculated by Belle using the world average value $\tau_{B^+}/\tau_{B^0} = 1.083 \pm 0.017$ [11]. The result is: $\Delta_{0+} = +0.003 \pm 0.045 \pm 0.018$, where the first error is statistical and

[1] Results for exclusive $B$ decays are typically presented using the following kinematic variables. If $(E_B^*, \vec{p}_B^*)$ is the four–momentum of a reconstructed $B$ candidate in the overall CM ($\Upsilon(4S)$) frame, we define

$$\Delta E^* \equiv E_B^* - E_{\rm beam}^* \ ,$$

$$m_{\rm ES} \ (\text{or } M_{bc}) \equiv \sqrt{{E_{\rm beam}^*}^2 - p_B^{*2}} \ .$$

The latter is called the *energy–substituted* (*BABAR*) or *beam–constrained* (Belle, CLEO) mass. Signal events peak at $\Delta E^*$ near 0 GeV and $m_{\rm ES}$ ($M_{bc}$) near $B$ meson mass; whereas continuum background lacks peaks.

the second systematic. It is consistent with no asymmetry, having assumed equal production of charged and neutral $B$'s at the $\Upsilon(4S)$ mass peak. The isospin asymmetry can be used to set limits on Wilson coefficients [12].

| | $\mathcal{B}(B^0 \to K^{*0}\gamma) \times 10^{-5}$ | $\mathcal{B}(B^+ \to K^{*+}\gamma) \times 10^{-5}$ | $A_{CP}$ |
|---|---|---|---|
| *BABAR* [9] (21 fb$^{-1}$) | $4.23 \pm 0.40 \pm 0.22$ | $3.83 \pm 0.62 \pm 0.22$ | $-0.044 \pm 0.076 \pm 0.012$ |
| Belle [10] (78 fb$^{-1}$) | $4.09 \pm 0.21 \pm 0.19$ | $4.40 \pm 0.33 \pm 0.24$ | $-0.001 \pm 0.044 \pm 0.008$ |
| CLEO [14] (9 fb$^{-1}$) | $4.55\,^{+0.72}_{-0.68} \pm 0.34$ | $3.76\,^{+0.89}_{-0.83} \pm 0.28$ | $+0.08 \pm 0.13 \pm 0.03$ |
| Average | $4.18 \pm 0.23$ | $4.14 \pm 0.33$ | $-0.005 \pm 0.037$ |

Table 1: $B \to K^*\gamma$ branching fraction and direct $CP$ asymmetry measurements.

In addition to the already established $B \to K^*\gamma$ decay, there are several known resonances that can contribute to the $X_s$ final state. Current measurements of higher than $K^*(892)$ mass systems are from Belle [13] and CLEO [14]. Note that the decay $B \to \phi K\gamma$ was observed recently by Belle [15] for the first time. Theoretical predictions cover a wide range; results so far are consistent with those from a relativistic form factor model as in Ref. [16].

### 2.2 Inclusive $b \to s\gamma$

Two experimental approaches have been used to measure the inclusive rate for the $b \to s\gamma$ process. The "fully inclusive" method measures the high energy photon spectrum without identifying the hadronic system $X_s$. Continuum backgrounds are suppressed with event shape information, and then subtracted using off–resonance data. $B$ decay backgrounds are subtracted using a generic Monte Carlo prediction, which is cross–checked with a $b \to s\pi^0$ analysis.

*BABAR* [17] has presented a preliminary result from a fully inclusive analysis in which the "other" $B$ is leptonically tagged to almost completely suppress the continuum background. CLEO [18] has published a measurement combining several techniques to reduce the background [2].

A "semi–inclusive" method, which measures a sum of exclusive $B \to X_s\gamma$ decays, has been used by both *BABAR* [20] and Belle [21]. The hadronic $X_s$ system is reconstructed by *BABAR* (Belle) in 12 (16) final states with a mass range up to 2.40 (2.05) GeV. This includes about 50 % of all $b \to s\gamma$ final states. Continuum and $B$ decay backgrounds are subtracted by a fit to the beam–constrained $B$ mass in the same way as in an exclusive analysis.

Figure 2 summarizes the measurements of the $b \to s\gamma$ branching fraction. The theoretical error is quoted as the extrapolation of the inclusive rate from the measured energy range to the full photon spectrum. CLEO has a lower threshold (2.0 GeV) than *BABAR* (2.1 GeV) and Belle (2.25 GeV). Presently, errors are slightly larger than the theoretical uncertainty. Computing a world average is complicated by the correlated systematic and theoretical errors. The fully inclusive method has a dominant systematic error from the $B$ decay background subtraction. The semi–inclusive method has a dominant systematic error from the efficiency for reconstructing the final states, including a correction for missing final states that are not considered. The average branching fraction reported, $\mathcal{B} = (3.40 \pm 0.39) \times 10^{-4}$, is computed assuming the systematic errors uncorrelated, for simplicity. A first attempt to consider the correlations among the errors can be found in [22].

[2] CLEO has recently published a search for baryons in $b \to s\gamma$ events [19], setting upper limits on corrections to the $\mathcal{B}$ and the photon energy spectrum, which are less than half of the combined quoted statistical and systematical errors in Ref. [18].

The present $\mathcal{B}(B \to X_s\gamma)$ measurements already provide a significant constraint on the SUSY parameter space. For example limits on new physics contributions to $B \to X_s\gamma$ have been calculated using the minimal supergravity model (SUGRA) [23] and charged Higgs bosons [1].

So far, only CLEO [24] has measured the direct *CP* asymmetry, using a technique which does not suppress the background coming from $b \to d\gamma$ decays (which is expected to have a large *CP* asymmetry). Thus, the measured direct *CP* asymmetry is $0.965\times\mathcal{A}_{CP}(B \to X_s\gamma)+0.02\times\mathcal{A}_{CP}(B \to X_d\gamma) = (-0.079\pm0.108\pm0.022)\times(1.0\pm0.03)$. The first error is statistical, while the second and third errors represent additive and multiplicative systematic uncertainties, respectively. The theoretical expected $\mathcal{B}(B \to X_d\gamma)$ is used. Results are consistent with no asymmetry.

*BABAR* [20] and CLEO [18] have published a measurement of the photon energy spectrum down to a threshold $E^*_\gamma > 2.1$ and 2.0 GeV, respectively, where $E^*_\gamma$ is measured in the $B$ [3] and in the laboratory rest frame, respectively (see Figure 3).

From the measured spectrum *BABAR* and CLEO have extracted the first moment in the $B$ rest frame, $\langle E_\gamma\rangle$, finding $\langle E_\gamma\rangle = 2.35 \pm 0.04 \pm 0.04$ GeV and $\langle E_\gamma\rangle = 2.346 \pm 0.032 \pm 0.011$ GeV, respectively. Using expressions in the $\overline{MS}$ renormalization scheme, to order $1/M_B^3$ and order $\alpha_s^2\beta_0$ [6], *BABAR* and CLEO obtain $\overline{\Lambda} = 0.37\pm0.09\pm0.07\pm0.10$ GeV and $\overline{\Lambda} = 0.35\pm0.08\pm0.10$ GeV from the first moment. The errors are statistical, systematic (combined in the CLEO measurement) and theoretical, respectively.

Moreover, CLEO has used their measured $B \to X_s\gamma$ photon energy spectrum to determine the light–cone shape function. Using this information, CLEO extracts $|V_{ub}| = (4.08 \pm 0.34 \pm 0.44 \pm 0.16 \pm 0.24) \times 10^{-3}$ [25], where the first two uncertainties are experimental and the last two from theory.

## 3 $b \to d\gamma$ final states

Both inclusive and exclusive $b \to d\gamma$ decays, which are suppressed by $\mid V_{td}/V_{ts} \mid^2 \sim 1/20$ with respect to corresponding $b \to s\gamma$ modes, have not been seen yet. An NLO calculation, which includes long–distance effects of $u$–quarks in the penguin loop, predicts a range of $6.0 \times 10^{-6} \leq \mathcal{B}(B \to X_d\gamma) \leq 2.6 \times 10^{-5}$ [26] for the inclusive branching fraction. The uncertainty is dominated by imprecisely known CKM parameters.

A branching fraction measurement of $B \to X_d\gamma$ provides a determination of $\mid V_{td}/V_{ts} \mid$ with small theoretical uncertainties. A determination of $\mid V_{td}/V_{ts} \mid$ in the exclusive modes $B \to \rho(\omega)\gamma$ bears enhanced model uncertainties, since form factors are not precisely known.

The *CP* asymmetry predicted in the SM for the inclusive process is foreseen between $\sim 7$ % and $\sim 35$ % [26].

Studies of the $b \to d\gamma$ decays for now focus primarily on searching for the exclusive process $B \to \rho/\omega\gamma$. The corresponding branching fraction is predicted to be $\mathcal{B}(B \to \rho\gamma) = (1.6^{+0.8}_{-0.5}) \times 10^{-5}$ [4], while the *CP* asymmetry is of the order of 10% [4].

From the experimental point of view, the $B \to \rho(\omega)\gamma$ is more difficult than $B \to K^*\gamma$ because the backgrounds are bigger since this mode is CKM suppressed and $u\overline{u}, d\overline{d}$ continuum processes are enhanced compared to $s\overline{s}$ continuum processes.

[3] Note that in case of a semi–inclusive analysis results can be shown in terms of the mass of the hadronic system $X_s$ or, equivalently, in terms of the photon energy, $E_\gamma$, because $E_\gamma = \frac{M_B^2 - M_{X_s}^2}{2M_B}$ in the $B$ rest frame.

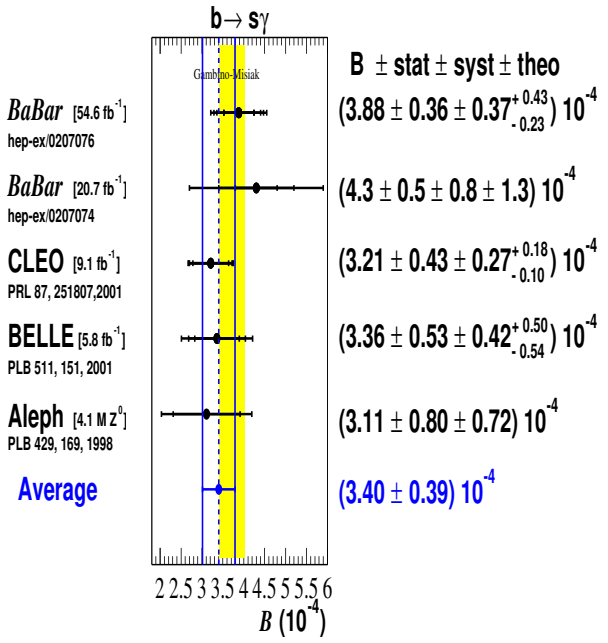


Figure 2: Summary of $b \to s\gamma$ branching fractions. The shaded band shows the theoretical prediction described in Ref. [1].

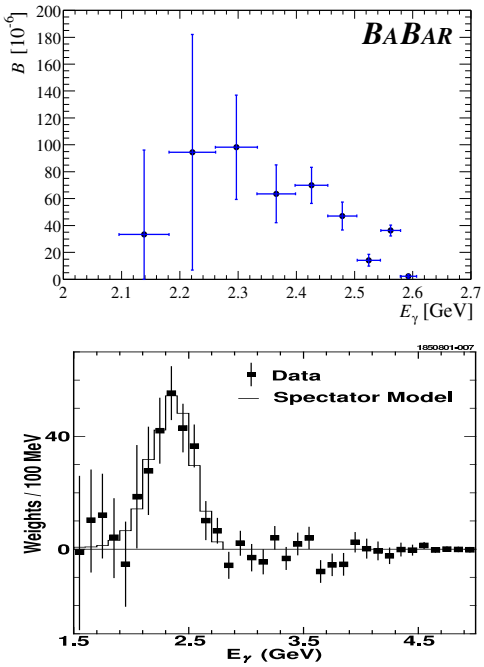


Figure 3: *BABAR* [20] (upper plot) and CLEO [18] (lower plot) photon energy spectrum in $b \to s\gamma$ decays.

The smallest upper limits on the exclusive decays $B \to \rho(\omega)\gamma$ come from *BABAR* [27], which uses a neural network to suppress most of the continuum background. The $B \to K^*\gamma$ events are removed using particle identification to veto kaons, with a $K \to \pi$ fake rate of $\approx$1%. A multi–dimensional likelihood fit is made to the remaining events (see Figure 4) to give 90 % C.L. upper limits of 1.2, 2.1 and $1.0\times10^{-6}$ on $\rho^0\gamma$, $\rho^+\gamma$ and $\omega\gamma$, respectively. Assuming isospin symmetry, this gives a combined limit $\mathcal{B}(B \to \rho\gamma) < 1.9 \times 10^{-6}$ (90 % C.L.). Limits from Belle and CLEO can be found in Refs. [28] and [14], respectively.

Of particular theoretical interest is the ratio $\mathcal{B}(B \to \rho\gamma)$ to $\mathcal{B}(B \to K^*\gamma)$ as most of the theoretical uncertainty cancels and so it can be used to determine the ratio $\mid V_{td}/V_{ts} \mid$.

As described in Ref. [29], the ratio can be written as:

$$\frac{\mathcal{B}(B \to \rho\gamma)}{\mathcal{B}(B \to K^*\gamma)} = S_\rho |\frac{V_{td}}{V_{ts}}|^2 \left(\frac{1 - m_\rho^2/M_B^2}{1 - m_{K^*}^2/M_B^2}\right)^3 \zeta^2[1 + \Delta R]$$

where $S_\rho$ is 1/2 (1) for $\rho^0$ ($\rho^\pm$) mesons, $\zeta$ is the ratio of the HQET form factors, $\Delta R$ accounts for possible weak annihilation and long distance contributions which appear mainly in $B^+ \to \rho^+\gamma$. Eventually these can be checked by comparing $\rho^+\gamma$ and $\rho^0\gamma$. Using the above equation the constraint on the CKM elements $\mid V_{td}/V_{ts} \mid$ is shown in the $\rho/\eta$ plane in Figure 5. It is not as tight as the constraint from $B_s/B_d$ mixing. However, New Physics may appear in different ways in penguin and mixing diagrams, so it is important to measure it in both processes.

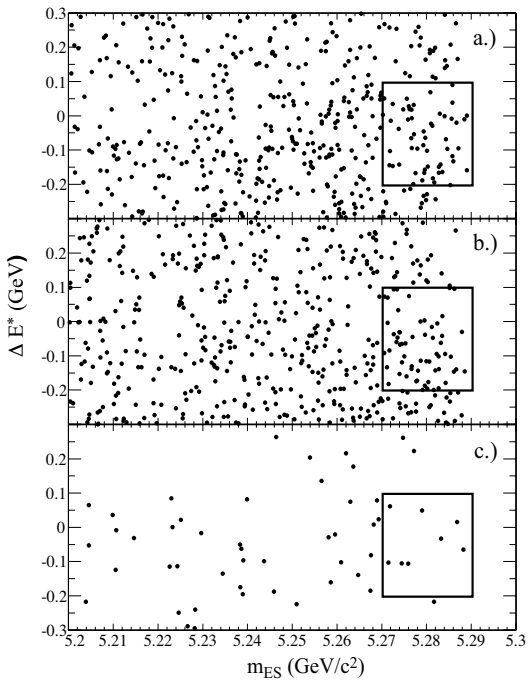


Figure 4: *BABAR* [27] $\Delta E^*$ versus the $m_{\rm ES}$ multi–dimensional likelihood fit regions for the (a) $B \to \rho^0\gamma$ (b) $B \to \rho^+\gamma$ (c) $B \to \omega\gamma$ candidates.

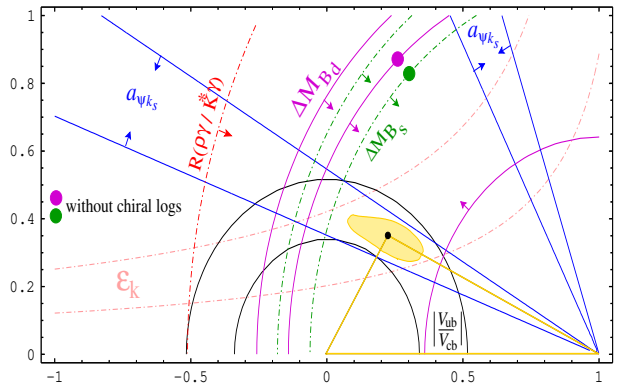


Figure 5: Constraint on CKM unitarity triangle obtained in Ref. [29] from the upper limit on $B \to \rho\gamma$ [27].

## 4 Conclusions and Outlook

A review of recent experimental results of radiative penguin decays $b \to s(d)\gamma$ is presented. The $b \to s\gamma$ process in the exclusive and exclusive final states is well established and more statistics can be used to improve the limits (or indirectly find evidence) of New Physics and to improve the measurement of the photon energy spectrum, toward a better determination of the CKM matrix elements.

There is not yet evidence of $b \to d\gamma$ decays but *BABAR* and Belle expect to collect $\approx 500$ fb$^{-1}$ by 2005. This should be sufficient to observe $B \to \rho\gamma$. It may also be feasible to measure the inclusive $b \to d\gamma$ rate. For the measurement of $|V_{td}/V_{ts}|$, the ratio of $b \to d\gamma$ to $b \to s\gamma$ has much smaller theoretical uncertainties than the ratio of the exclusive decays.

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