Radiative Penguin decays

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A review of recent experimental results on radiative Penguin decays, and their interpretation within the Standard Model.

1 Introduction

Penguin decays are flavour-changing neutral current (FCNC) processes, described primarily by second order weak interactions, where the decay occurs through the emission and reabsorption of W bosons.

In this review I will focus on the recent experimental results on the transition $b \rightarrow s$ coming from radiative penguin decay measurements by the B-factory experiments, BaBar, BELLE and CLEO. The penguin transition has a dominant role in these decays, and a significant role in rare hadronic B decays, where it complicates the extraction of information about the CKM unitarity triangle because of interference with spectator diagrams [1]. Measurements of the radiative decays can be used to constrain calculations of the penguin contributions to the rare hadronic decays.

The measurement of the gamma energy spectrum in the process $b \rightarrow sy$ has recently been used by CLEO to improve the extraction of the CKM elements $V_{cb}$ and $V_{ub}$ from inclusive semileptonic $b$ decays [2]. Details of these moments analyses can be found in [3].

I will also discuss the FCNC transition $b \rightarrow d$, which we expect to find experimental evidence for in the near future. Measurements of this transition are sensitive to the CKM element $V_{ub}$.

For completeness, I note that the FCNC transition $s \rightarrow d$ has a role in the interpretation of $\epsilon'/\epsilon$ in the neutral Kaon system. The Standard Model calculation of $\epsilon'/\epsilon$ has large uncertainties which depend on the interference between penguin contributions [4]. I also note, that the FCNC transition $c \rightarrow u$ is heavily suppressed by CKM factors, and because the $b$ quark is much lighter than the $t$ quark.

2 Measurements of $B \rightarrow K^+\gamma$

The exclusive decay $B \rightarrow K^+\gamma$ was first observed by CLEO in 1992 [5]. BaBar [6] and BELLE [7] have now collected large samples of these decays with clean signals on low backgrounds (Figure 2). The measured branching fractions and world average are summarised in Table 1. A recent theoretical prediction for this branching fraction is $(7.1 \pm 2.5) \times 10^{-5}$ [8], which is larger than the experimental result, but with a 30% uncertainty due to the $B \rightarrow K^*$ form factor.

![Figure 1. Penguin diagram for the $b \rightarrow s(d)$ transition](image)

![Figure 2. BELLE results on exclusive $B \rightarrow K^+\gamma$](image)

|                  | $B^0 \rightarrow K^{*0}\gamma/10^{-5}$ | $B^+ \rightarrow K^{*-}\gamma/10^{-5}$ |
|------------------|----------------------------------------|----------------------------------------|
| BABAR 20 fb$^{-1}$ | 4.23 ± 0.40 ± 0.22                     | 3.83 ± 0.62 ± 0.22                     |
| BELLE 60 fb$^{-1}$ | 3.91 ± 0.23 ± 0.35                     | 4.21 ± 0.35 ± 0.31                     |
| CLEO 9 fb$^{-1}$  | 4.55 ± 0.70 ± 0.34                     | 3.76 ± 0.86 ± 0.28                     |
| Average           | 4.17 ± 0.20 ± 0.18                     | 3.98 ± 0.28 ± 0.16                     |

Table 1. $B \rightarrow K^+\gamma$ branching fraction measurements

There appears to be little prospect of reducing the theoretical uncertainty, so the experimental interest is mostly in the measurement of the CP asymmetry. This is expected to be $\approx 1\%$ in the Standard Model, but could be as large as $10\%$ if
there are new physics contributions \[9\]. Note that the measurements of CP asymmetries in the gluonic penguin decay 
\(B \to \phi K_s\) are not very consistent with \(B \to \psi K_s\). Any new physics introduced to explain this discrepancy is likely to also appear in radiative penguin decays. Table 2 summarizes the measurements of the CP asymmetry in \(B \to K^* \gamma\). These are consistent with zero and statistics limited. With more data it should be possible to reach the accuracy of 1%.

|          | \(-0.044 \pm 0.067 \pm 0.012\) | \(-0.022 \pm 0.048 \pm 0.017\) | \(+0.08 \pm 0.13 \pm 0.03\) | \(-0.027 \pm 0.034 \pm 0.015\) |
|----------|-------------------------------|-------------------------------|-----------------------------|-------------------------------|
| BABAR    |                               |                               |                             |                               |
| BELLE    |                               |                               |                             |                               |
| CLEO     |                               |                               |                             |                               |
| Combined |                               |                               |                             |                               |

Table 2. CP asymmetry measurements in \(B \to K^* \gamma\)

There are also predictions of a few % for the isospin asymmetry in \(B \to K^* \gamma\) \[10\]. The experimental situation can be seen from Table 1, but note that this Table assumes equal production of \(B^+\) and \(B^0\) at the \(\Upsilon(4S)\). This assumption introduces an additional uncertainty into the isospin asymmetry measurement.

3 Measurements of \(b \to s \gamma\)

Two approaches have been used to measure the inclusive rate. The “fully inclusive” method measures the high energy photon spectrum without identifying the specific \(B \to X_s \gamma\) decay modes. 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.

CLEO \[13\] has published a measurement of the photon energy spectrum down to a threshold \(E^*_\gamma > 2.0\)GeV, where \(E^*_\gamma\) is measured in the \(\Upsilon(4S)\) rest frame (Figure 3). BaBar \[14\] has presented a preliminary result from a fully inclusive analysis in which they use lepton tags from the other \(B\) to almost completely suppress the continuum background (Figure 4). Note that the lepton tags do not help suppress B decay backgrounds.

![Figure 3. CLEO measurement of inclusive \(b \to s \gamma\)](image)

The inclusive rate for \(b \to s \gamma\) can be quite accurately predicted to be \((3.60 \pm 0.30) \times 10^{-4}\) \[11\]. The experimental measurements of this inclusive rate provide an important constraint on new physics contributions to penguin diagrams \[12\].

![Figure 4. Preliminary BaBar result for lepton-tagged inclusive \(b \to s \gamma\). Full circles are data, open triangles background (mostly from \(b \to c\) decays).](image)

A “semi-inclusive” method, which measures a sum of exclusive \(B \to X_s \gamma\) decays, has been used by both BaBar \[15\] and BELLE \[16\]. 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. Results can be shown in terms of the recoil mass \(M(X^*_s)\) (see Figure 5), or equivalently in terms of the gamma energy, \(E_\gamma\), measured in the \(B\) rest frame.

Figure 6 summarizes the measurements of the \(b \to s \gamma\) branching fraction. 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. This is common to the BaBar and CLEO measurements. 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. Again this is common to the BaBar and BELLE measurements. Note that Figure 5 shows that this efficiency systematic depends on the theoretical modeling of the spectral shape.

The theoretical error is quoted as the extrapolation of the inclusive rate from the measured energy range to the full photon spectrum [17]. CLEO has a lower threshold (2.0GeV), than BaBar (2.1GeV) and BELLE (2.25GeV). Thus the small 7% theoretical error can only be applied to the CLEO result. In taking a world average I have assumed a “typical” extrapolation error of 10%. Together with a conservative treatment of the correlated experimental systems, I obtain:

\[ BF(b \rightarrow s \gamma) = (3.47 \pm 0.23 \pm 0.32 \pm 0.35) \times 10^{-4} \]

For the convenience of theorists setting constraints on new physics I also give the 90% C.L. limits:

\[ 2.8 \times 10^{-4} < BF(b \rightarrow s \gamma) < 4.2 \times 10^{-4} \]

It is also interesting to look for inclusive CP asymmetries. CLEO has published a measurement of the asymmetry in the sum of \( b \rightarrow s \gamma \) and \( b \rightarrow d \gamma \) from their fully inclusive analysis [13]. \( A_{CP}(b \rightarrow (s+d)\gamma) = -0.079 \pm 0.108 \pm 0.022 \). This asymmetry is exactly zero in the Standard Model, and in many extensions, so it is more interesting to measure the asymmetry in \( b \rightarrow s \gamma \) alone. This can be done using the semi-inclusive method.

4 \( B \rightarrow \rho\gamma \) and \( V_{td} \)

The measurement of the Cabibbo suppressed transition \( b \rightarrow d \gamma \) is difficult because the signal is \( \approx 20\times \) smaller, and the continuum background is \( \approx 3\times \) larger. It is also important to remove \( b \rightarrow s \gamma \) events which are a serious background.

\[ BF(\rho \rightarrow \omega \gamma) < 3 \times 10^{-6} \]

\[ BF(\rho^+ \rightarrow \pi^+ \gamma) < 3 \times 10^{-6} \]

\[ BF(\rho^- \rightarrow \pi^- \gamma) < 3 \times 10^{-6} \]

The best limits on the exclusive decays \( B \rightarrow \rho(\omega)\gamma \) come from BaBar [19], which uses a neural network to suppress most of the continuum background. The \( B \rightarrow K^{*}\gamma \) events are removed using particle identification to veto kaons, with a \( K \rightarrow \pi \) fake rate of \( \approx 1\% \). A multi-dimensional likelihood fit is made to the remaining events (Figure 7), to give 90% C.L. upper limits of 1.2, 2.1 and 1.0\times 10^{-6} on \( \rho^0\gamma \), \( \rho^+\gamma \) and \( \omega\gamma \) respectively. Assuming isospin symmetry, this gives a combined limit \( BF(B \rightarrow \rho\gamma) < 1.9 \times 10^{-6} \) (90% C.L.).
The ratio of $B \to \rho \gamma$ to $B \to K^{*} \gamma$ can be described by [20]:

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

where $\zeta = 0.76 \pm 0.10$ is an SU(3) breaking factor in the ratio of form factors. $\Delta R = 0.0 \pm 0.2$ accounts for possible weak annihilation and long distance contributions which appear mainly in $B^{+} \to \rho^{0} \gamma$. Eventually these can be checked by comparing $\rho^{+} \gamma$ and $\rho^{0} \gamma$. Using the above equation gives $|V_{td}/V_{ts}| < 0.34$. This constraint on the CKM element $V_{td}$ is shown in the $\rho/\eta$ plane in Figure 8. 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 $V_{td}$ in both processes.

![Figure 8](image)

**Figure 8.** Constraint on CKM unitarity triangle obtained from upper limit on $B \to \rho \gamma$

BaBar and BELLE each 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 using the semi-inclusive method. For the extraction 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 [21].

5 Measurements of $b \to s \ell^{+} \ell^{-}$

These FCNC decays are described by a combination of radiative and electroweak penguins, and a box diagram (Figure 9). This makes them more sensitive to new physics contributions than $b \to s \gamma$. There is particular interest in an eventual measurement of the forward-backward lepton asymmetry as a function of the dilepton mass, $\hat{s} = m_{\ell}^2/m_{B}^2$ [22].

![Figure 9](image)

**Figure 9.** Diagrams contributing to $b \to s \ell^{+} \ell^{-}$

The exclusive decays $B \to K^{+} \ell^{-}$, $B \to K^{*\mu^{+}\mu^{-}}$ and $B \to K^{0} e^{+} e^{-}$, are predicted to have branching fractions of $(0.35 \pm 0.12), (1.19 \pm 0.39)$ and $(1.58 \pm 0.49) \times 10^{-6}$ respectively [23]. The difference between the $K^{*}$ decays is due to a pole at low $\hat{s}$ from the radiative penguin diagram.

The decay $B \to K^{*} \ell^{+} \ell^{-}$ was first observed by BELLE [24], and has now been confirmed by BaBar [25], who also see evidence for $B \to K^{*+} \ell^{-}$ (Figure 10).

![Figure 10](image)

**Figure 10.** BaBar measurement of $B \to K^{*} \ell^{+} \ell^{-}$ and preliminary evidence for $B \to K^{*} \ell^{+} \ell^{-}$ using $800 fb^{-1}$ of data

### Table 3. Summary of measurement of $B \to K^{*} \ell^{+} \ell^{-}$

|       | $B \to K^{*} \ell^{+} \ell^{-}/10^{-6}$ | $B \to K^{*} \ell^{+} \ell^{-}/10^{-6}$ |
|-------|---------------------------------------|---------------------------------------|
| **BABAR** | $0.78^{+0.32}_{-0.20} \pm 0.15$               | $1.26^{+0.23}_{-0.44} \pm 0.17$       |
| **BELLE** | $0.58^{+0.18}_{-0.13} \pm 0.06$               | $1.0^{+0.5}_{-0.4} \pm 0.2$           |
| **Average** | $0.66^{+0.19}_{-0.13} \pm 0.06$               | $1.10^{+0.35}_{-0.13}$                |

The inclusive rate is predicted to be $4.2 \pm 0.7(6.9 \pm 1.0) \times 10^{-6}$ for $s\mu^{+}\mu^{-}(se^{+}e^{-})$. BELLE has measured this inclusive rate [26] using a semi-inclusive sum of final states (Figure 11). With the requirements $m_{ll} > 0.2$GeV and $M(X_{s}) < 2.1$GeV, they measure

$$
BF(b \to s \ell^{+} \ell^{-}) = 6.1 \pm 1.4(stat.)^{+1.4}_{-1.1}(syst.) \times 10^{-6}
$$
which is somewhat larger than the $s\mu^+\mu^-$ prediction.

These results already provide interesting new constraints on extensions of the Standard Model. With larger data samples at the B-factories, and eventually at the LHC, it will be possible to make precise tests of the theoretical predictions for these decays.

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