RADIATIVE B DECAYS AT B-FACTORIES

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Abstract

Recent results on radiative B meson decays from Belle and BaBar are reviewed. Belle has reported the first observation of the $b \to d\gamma$ process and put a constraint on $|V_{td}/V_{ts}|$. Thanks to the latest experimental and theoretical developments on inclusive measurements of the $b \to s\gamma$ process, the experimental error of the $b \to s\gamma$ branching fraction has been significantly reduced and is still in a very good agreement with the Standard Model predictions. Search results on CP violation in $b \to s\gamma$ and on exotic radiative decays are also reviewed.

1 Introduction

Radiative B meson decay is prohibited at the tree level in the Standard Model (SM) and thus proceeds through a penguin loop diagram at the lowest order. In the loop diagram, new particles beyond the SM can contribute and may modify the decay amplitude. The $b \to s\gamma$ process has been extensively studied and has been putting stringent constraints on new physics scenarios. A similar process, $b \to d\gamma$, which is further suppressed with respect to $b \to s\gamma$ due to the Cabibbo-Kobayashi-Maskawa (CKM) matrix element factor $|V_{td}/V_{ts}|^2$, is also sensitive to new physics in a complimentary way. A new physics effect may be enhanced with respect to the SM even though such an effect is very small in the $b \to s\gamma$ transition.

The two B-factory experiments, the Belle experiment at the KEKB storage ring at KEK and the BaBar experiment at the PEP-II storage ring at SLAC, have accumulated unprecedented amount of B meson decay events, which allow us to study the $b \to s\gamma$ process in great detail and to search for the $b \to d\gamma$ transition or other exotic radiative decay modes. Belle has collected an integrated luminosity of 560 fb^{-1} at or near the $\Upsilon(4S)$ resonance, of which up to a dataset of 357 fb^{-1} that contain 386×10^6 $B\overline{B}$ events has been analyzed; BaBar has collected 322 fb^{-1} of which up to a 211 fb^{-1} dataset with 232×10^6 $B\overline{B}$ has been analyzed.

In order to search for new physics effects beyond the SM, presence of precise and reliable SM theoretical predictions is essential. To measure the quark-level $b \to s\gamma$ transition, the $B \to X_s\gamma$ process where X_s is an inclusive hadronic state with an s-quark is an ideal mode for which QCD corrections have been thoroughly calculated to the next-to-leading order. Measurements of the photon energy spectrum, which is modified from a delta function to a broad spectrum by QCD effects, can be directly compared with theoretical predictions. From such a comparison, one can extract universal theoretical parameters for other applications such as $b \to u\ell^-\overline{\nu}$ to extract the CKM matrix element $|V_{ub}|$.

When an inclusive measurement is not possible, it is still worthwhile measuring an exclusive channel. For example, an inclusive measurement of the $b \to d\gamma$ process is expected to be extremely difficult due to the large $b \to s\gamma$ background. Therefore, despite the large theoretical uncertainty in the SM prediction, only the exclusive decay channels have been searched for so far.

A photon in the final state is also an unmistakable signature of new physics for the decay modes that are prohibited or heavily suppressed in the SM with expected branching fractions well below the sensitivity of the B-factories.

2 Observation of the $b \to d\gamma$ process

The $b \to d\gamma$ process has three major roles. First, it is sensitive to the magnitude of the CKM element V_{td} or to the ratio $|V_{td}/V_{ts}|$ within the framework of the SM. Secondly, it is sensitive to new physics assuming the value of $|V_{td}|$ from a fit to the CKM unitarity triangle. Thirdly, a large direct CP violation is expected in the decay, and will provide a rich field to study if the mode is established.

The three decay modes $B^- \to \rho^-\gamma$, $\overline{B}^0 \to \rho^0\gamma$ and $\overline{B}^0 \to \omega\gamma$ are presumably the easiest exclusive channels to search for the $b \to d\gamma$ transition. The predicted branching fractions are about 1×10^{-6}, which is about the smallest branching fraction that Belle and BaBar are sensitive with the current datasets.

Recently Belle [1)] has reported the first observation of the $b \to d\gamma$ process in a combined fit to these three exclusive modes. The analysis uses a standard technique to reconstruct the B meson candidate using the beam-energy constrained mass $M_{\rm bc} = \sqrt{E_{\rm beam}^2 - p_B^2}$ and the energy difference $\Delta E = E_B - E_{\rm beam}$. There are many background sources: the largest background is due to the continuum $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) production where photon is from copious π^0 productions. The continuum background is suppressed by using a likelihood ratio based on event shape variables, the vertex displacement Δz and the B meson direction $\cos\theta_B$, and an output of a flavor-tagging algorithm. The second largest background source is $B \to K^*\gamma$ decays whose final state is similar to the signal; they can be reduced by particle identification, mass of the "K"π system where a kaon mass is assigned to one of the pions. The set of hadronic decay modes $B \to (\rho, \omega)\pi^0$ is another background source which can be suppressed by a π^0/η veto algorithm and the decay helicity angle of ρ and ω. Background from other $b \to s\gamma$ or charmless hadronic decays are smaller. In order to maximize the sensitivity, the selection criteria are chosen to maximize a figure of merit $N_S/\sqrt{N_B}$ where $N_{S(B)}$ is the number of expected signal (sum of all background) events.

The combined fit was performed by assuming the following isospin relation

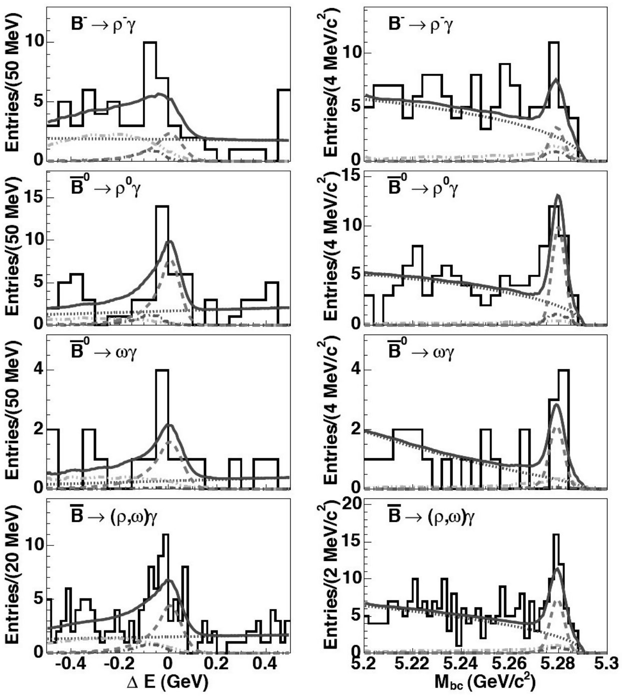

Figure 1: *Individual fit results to the $B^- \to \rho^-\gamma$, $\overline{B}^0 \to \rho^0\gamma$ and $\overline{B}^0 \to \omega\gamma$ modes and simultaneous fit results to the combined $B \to (\rho,\omega)\gamma$ modes by Belle. Curves are the signal (dashed), continuum (dotted), $B \to K^*\gamma$ (dot-dashed), other background (dot-dot-dashed) components and their sum (solid).*

between decay widths,

$$\Gamma(B \to (\rho,\omega)\gamma) \equiv \Gamma(B^- \to \rho^-\gamma) = 2\Gamma(\overline{B}^0 \to \rho^0\gamma) = 2\Gamma(\overline{B}^0 \to \omega\gamma). \qquad (1)$$

Fig. 1 shows the results of individual fits and the combined fit. The resulting branching fractions and the significance of the fits are,

$$\begin{aligned}
\mathcal{B}(B^- \to \rho^-\gamma) &= (0.55\,^{+0.42}_{-0.36}\,^{+0.09}_{-0.08}) \times 10^{-6} \quad (1.6\sigma) \\
\mathcal{B}(\overline{B}^0 \to \rho^0\gamma) &= (1.25\,^{+0.37}_{-0.33}\,^{+0.07}_{-0.06}) \times 10^{-6} \quad (5.2\sigma) \\
\mathcal{B}(\overline{B}^0 \to \omega\gamma) &= (0.56\,^{+0.34}_{-0.27}\,^{+0.05}_{-0.10}) \times 10^{-6} \quad (2.3\sigma) \\
\mathcal{B}(B \to (\rho,\omega)\gamma) &= (1.32\,^{+0.34}_{-0.31}\,^{+0.10}_{-0.09}) \times 10^{-6} \quad (5.1\sigma).
\end{aligned} \qquad (2)$$

A similar analysis performed by BaBar [2)] with 211×10^6 $B\overline{B}$ events has yielded no significant signal, with a branching fraction $\mathcal{B}(B \to (\rho,\omega)\gamma) = (0.6 \pm 0.3 \pm 0.1) \times 10^{-6}$ or an upper limit $\mathcal{B}(B \to (\rho,\omega)\gamma) < 1.2 \times 10^{-6}$ (90% C.L.).

Assuming the SM, one can extract the ratio of the CKM matrix elements $|V_{td}/V_{ts}|$ from the ratio of the combined $B \to (\rho,\omega)\gamma$ branching fraction to that of $B \to K^*\gamma$ using the following formula [3],

$$\frac{\mathcal{B}(B \to (\rho,\omega)\gamma)}{\mathcal{B}(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{(1 - m^2_{(\rho,\omega)}/m^2_B)^3}{(1 - m^2_{K^*}/m^2_B)^3} \zeta^2 [1 + \Delta R], \tag{3}$$

where $\zeta = 0.85 \pm 0.10$ is a form factor ratio, and $\Delta R = 0.1 \pm 0.1$ is an $SU(3)$ breaking correction factor. This determination of $|V_{td}/V_{ts}|$ is complementary to the one with the $B^0_s - \overline{B}^0_s$ mixing at Tevatron, but it suffers from a large theory error even though a ratio is used to cancel various theoretical uncertainties. The resulting $|V_{td}/V_{ts}|$ by Belle,

$$|V_{td}/V_{ts}| = 0.199\,^{+0.026}_{-0.025}(\text{exp.})\,^{+0.018}_{-0.015}(\text{theo.}) \tag{4}$$

is compatible with the CKM unitarity triangle from other measurements, and therefore the SM has passed another non-trivial test in the $b \to d$ transition. The $b \to d\gamma$ modes will be further studied in future with larger datasets for example to study CP violation.

3 Inclusive $b \to s\gamma$ measurement

One can consider that the $b \to s\gamma$ mode also has three similar major roles. First, the photon can be used as a probe to extract universal parameters to describe B decay properties that are common between $B \to X_s\gamma$ and semileptonic decays $B \to X_c\ell\overline{\nu}$ and $B \to X_u\ell\overline{\nu}$. Secondly, it is sensitive to new physics such as charged Higgs bosons, SUSY particles, left-right symmetric models and so on, assuming the magnitude of the CKM matrix element V_{ts} is derived from the unitarity relation. Thirdly, one can reverse the order to measure $|V_{ts}|$ assuming no new physics effects. Recently the first role is highlighted especially because it has allowed us to significantly reduce the error of $|V_{ub}|$. Here, we focus more on the second role; the third role is usually disregarded since it is almost equivalent to the second role if the final goal is to find a new physics effect.

There are two major experimental techniques to measure the inclusive branching fraction of $B \to X_s\gamma$. The first is a full-inclusive method, in which only the high energy photon is measured without requiring a reconstructed B

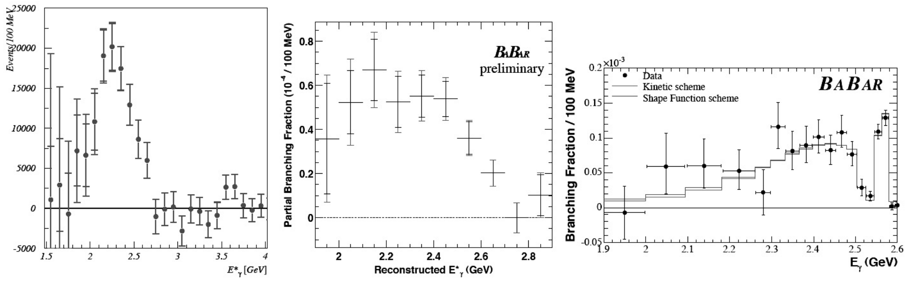

Figure 2: *Measured photon energy spectrum using the full-inclusive method by Belle (left) and BaBar (center), and that using the semi-inclusive method by BaBar (right).*

meson. The second is a semi-inclusive method, in which as many B meson decay final states as possible are exclusively reconstructed using $M_{\rm bc}$ and ΔE and are summed up.

The advantage of the full-inclusive method is the high and almost uniform efficiency as a function of the photon energy E_γ, while the disadvantages are the lack of good variables to reduce the huge amount of background and the limited resolution of the photon energy in the B meson rest frame since the initial B meson direction is unknown. The largest background is the continuum background which is reliably subtracted using the off-resonance data taken below the $\Upsilon(4S)$ resonance. However, the amount of the off-resonance data is typically only 10% of the on-resonance data taken at the $\Upsilon(4S)$ and hence determines the size of the statistical error. The second largest background is due to copious high energy π^0 from B decays, which is subtracted using Monte Carlo (MC) simulation that is based on a measured $B \to \pi^0$ spectrum in the data. Since the spectrum goes down and background increases rapidly towards a lower E_γ, one has to apply a minimum photon energy cut and extrapolate the spectrum below the cut assuming a theoretical model. Both Belle [4)] and BaBar [5)] have performed full-inclusive analyses based on 140 fb^{-1} (15 fb^{-1}) and 81.5 fb^{-1} (9.6 fb^{-1}) on-resonance (off-resonance) datasets, respectively. Belle requires the minimum photon energy to be 1.8 GeV while BaBar's case it is 1.9 GeV. The measured E_γ spectra are shown in Fig. 2.

The advantage of the semi-inclusive method is the background reduction power and the high resolution of the photon energy which is derived from the invariant mass of the X_s final state, while the disadvantage is the large uncertainty due to many missing final states that cannot be reconstructed especially for the lower E_γ range. In the BaBar's analysis [6] using a 81.5 fb^{-1} dataset, the X_s state is either a kaon (K^+ or K^0_S) plus 1 to 4 pions (of which up to two can be neutral), a kaon plus η plus up to two pions, or three kaons plus up to one pion, with the mass below 2.8 GeV. This corresponds to the minimum photon energy of 1.9 GeV. The E_γ spectrum is also shown in Fig. 2. Belle [7] has also reported a similar analysis with 6 fb^{-1} with a smaller number of final states and lower maximum X_s mass.

One of the techniques to make use of the measured E_γ spectrum is to calculate the moments of the spectrum as functions of the E_γ cut. The first and second moments correspond to the mean and the width of the spectrum. Several theoretical schemes are available for the theoretical description of the E_γ spectrum based on operator production expansion (OPE). The moments can be directly compared with predictions and can be used to extract universal OPE parameters. In a kinetic scheme [8], the parameters are the b quark mass m_b and the Fermi momentum squared μ_π^2. It has been shown that these parameters extracted from the fit to the existing $B \to X_s\gamma$ measurements are in very good agreement with the ones from a fit to the $B \to X_c\ell\overline{\nu}$ mode, and a combined fit to the two modes give a very accurate determination of them. Thus obtained parameters are

$$\begin{aligned} m_b &= 4.590 \pm 0.025(\text{exp}) \pm 0.030(\text{OPE})\ \text{GeV}, \\ \mu_\pi^2 &= 0.401 \pm 0.019(\text{exp}) \pm 0.035(\text{OPE})\ \text{GeV}^2. \end{aligned} \tag{5}$$

These parameters are useful to reduce the experimental error of the $B \to X_s\gamma$ branching fraction, as well as to significantly reduce the error of $|V_{ub}|$ from $B \to X_u\ell\overline{\nu}$ measurements. The model dependence of the E_γ extrapolation, which use to be one of the largest systematic error, is now reduced to be about 1%. It also allows us to extrapolate the measurements to any given E_γ cut with which an average can be calculated in a consistent way as shown in Fig. 3. The thus calculated world average with $E_\gamma > 1.6$ GeV [9] is

$$\mathcal{B}(B \to X_s\gamma;\, E_\gamma > 1.6\ \text{GeV}) = (355 \pm 24\,^{+9}_{-10} \pm 3) \times 10^{-6}, \tag{6}$$

which is very consistent with SM expectations, e.g. [10], $(357 \pm 30) \times 10^{-6}$.

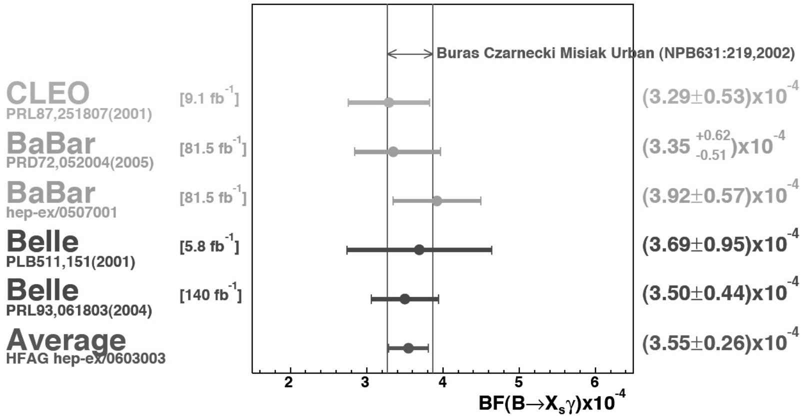

Figure 3: *Rescaled $B \to X_s\gamma$ branching fractions to $E_\gamma > 1.6$ GeV and their average using the OPE parameters in Eq. 5.*

It is known that the $B \to X_s\gamma$ branching fraction is very sensitive to the type-II charged Higgs mass for any value of $\tan\beta$. Previously the limit was as high as 350 GeV, partly because the measured rate was lower than the prediction. Using the latest average, the limit of the type-II charged Higgs mass is about 300 GeV and is still a very stringent constraint. Since the experimental error will certainly decrease further with larger datasets, it is crucial to reduce the theory error which is expected to be achieved soon by inclusion of the next-to-next-to-leading order QCD corrections.

4 More searches for new physics

4.1 CP violation in $b \to s\gamma$

One of the possibility to find a new physics effect is the CP violation in $b \to s\gamma$. In the SM [11)], direct CP violation is expected to be only 0.4%, and, even if one considers SUSY [12)], it will be only up to a few percent due to stringent constraints from the electric dipole moment of the electron. Therefore, it is a clear sign of new physics if a direct CP asymmetry is found to be a few percent, or it could be a very exotic new physics if it is even larger. The current average is $A_{CP}(B \to X_s\gamma) = (0.5 \pm 3.6)\%$, and is consistent with zero.

$B \to K^0_S \pi^0 \gamma$ using the technique that is used to measure the unitarity angle ϕ_1/β. The time dependent asymmetry is parametrized with a sine term and a cosine term, $S \sin \Delta m \Delta t + A \cos \Delta m \Delta t$, where S and A correspond to the time-dependent and direct asymmetries, respectively. The SM left handed coupling suppresses the value of S to be around 0.04 or at most 0.10, and thus any large S would be due to non-SM right handed coupling. The latest results from Belle and BaBar are

$$\begin{array}{ccc} S = -0.21 \pm 0.40 \pm 0.05 & A = +0.40 \pm 0.23 \pm 0.04 & (\text{BaBar } K^{*0}\gamma) \\ S = +0.9 \pm 1.0 \pm 0.2 & A = +1.0 \pm 0.5 \pm 0.3 & (\text{BaBar other } K^0_S\pi^0\gamma) \\ S = +0.08 \pm 0.41 \pm 0.10 & A = +0.12 \pm 0.27 \pm 0.10 & (\text{Belle all } K^0_S\pi^0\gamma) \end{array} \tag{7}$$

where they are separately measured for the $B \to K^{*0}\gamma \to K^0_S\pi^0\gamma$ and other $B \to K^0_S\pi^0\gamma$ by BaBar while they are combined by Belle. The error on S is still very large, and it is still a long way to a precision to be sensitive to a deviation from the SM if it exists.

4.2 Exotic radiative decays

The photon in the final state provides a very clear signature for exotic decays that only proceed through an annihilation or exchange diagram and hence extremely suppressed in the SM. Belle [15] has searched for $B^0 \to \gamma\gamma$ and set an upper limit $\mathcal{B}(B^0 \to \gamma\gamma) < 6.2 \times 10^{-7}$ (90% C.L.), where the SM expectation is about 3×10^{-8}. BaBar [16] has searched for $B^0 \to \phi\gamma$ and $B^0 \to D^{*0}\gamma$ and set upper limits $\mathcal{B}(B^0 \to \phi\gamma) < 8.5 \times 10^{-7}$ and $\mathcal{B}(B^0 \to D^{*0}\gamma) < 2.5 \times 10^{-5}$ (90% C.L.), where the SM expectations are about 4×10^{-12} and 10^{-6}, respectively.

5 Summary

Recent results on radiative B decays by Belle and BaBar are reviewed. All the results are so far in good agreement with the SM, or in other words, no hint of new physics has been found despite the expected sensitivity. The first observation of the $b \to d\gamma$ process in the exclusive modes $B \to \rho\gamma$ and $B \to \omega\gamma$ by Belle opened a new window in the studies of radiative B decays for which large direct CP violation is expected. The error on the $B \to X_s\gamma$ branching fraction has significantly reduced, thanks to the recent progress in the experimental techniques and the theoretical understanding of the E_γ spectrum. CP violation in $b \to s\gamma$ and exotic radiative decay modes have been searched for with no significant results yet. Both Belle and BaBar have accumulated large amount of data to make radiative decays very interesting, and are accumulating more to produce further exciting new results on $b \to s\gamma$ and $b \to d\gamma$.

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