SNSN-323-63
February 10, 2011

$b \to s\gamma$ and $b \to d\gamma$ (B factories)

Wenfeng Wang

University of Notre Dame Du Lac, South Bend, IN 46556, USA

The photon spectrum in $B \to X_{s,d}\gamma$ decay, where $X_s(d)$ is any strange (non-strange) hadronic state, is studied using data samples of $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ decays collected by the *BABAR* and Belle experiments. Here I present the latest measurements of the branching fraction and spectral moments from $B \to X_s\gamma$ decays by Belle and the direct CP asymmetry $A_{CP}(B \to X_{s+d}\gamma)$ measured at *BABAR*. The determination of $|V_{td}/V_{ts}|^2$ is also presented.

PRESENTED AT

6th International Workshop on the CKM Unitarity
Triangle(CKM2010),

1 Introduction

The electromagnetic radiative process $b \to q\gamma$ ($q = s, d$) proceeds at leading order via the loop diagram in the Standard Model (SM). Here the SM predication of the inclusive rate $\Gamma(B \to X_s\gamma)$ can be equated with the precisely calculable partonic rate $\Gamma(b \to s\gamma)$ at the level of a few percent [1] (heavy quark duality). An extraordinary theoretical effort has led to a precision SM prediction for the branching fraction at the next-to-next-to-leading order (four-loop), $\mathrm{BR}(B \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ ($E_\gamma >$ 1.6 GeV) [2], where E_γ is the photon energy measured in the rest frame of the B meson. The possibility for new heavy particles to enter into the loop at leading order could cause significant deviations from the SM prediction. A recent review can be seen in [3].

New physics can also significantly enhance the direct CP asymmetry for $b \to s\gamma$ and $b \to d\gamma$ decay [4] without changing the branching fraction. We define

$$A_{CP} = \frac{\Gamma(b \to s\gamma + b \to d\gamma) - \Gamma(\bar{b} \to \bar{s}\gamma + \bar{b} \to \bar{d}\gamma)}{\Gamma(b \to s\gamma + b \to d\gamma) + \Gamma(\bar{b} \to \bar{d}\gamma + \bar{b} \to \bar{d}\gamma)} \tag{1}$$

which is $\sim 10^{-6}$ in the SM, with nearly exact cancellation of opposite asymmetries for $b \to s\gamma$ and $b \to d\gamma$. Thus any non-zero measurements of this joint asymmetry is an indication of new physics.

The shape of the photon energy spectrum, which is insensitive to non-SM physics [5], can be used to determine the Heavy Quark Expansion (HQE)parameters, m_b and μ_π^2, related to the mass and momentum of the b quark within the B meson. These parameters can be used to reduce the error in the extraction of the CKM matrix elements V_{cb} and V_{ub} from the inclusive semi-leptonic B-meson decays, $B \to X_c\ell\nu$ and $B \to X_u\ell\nu$ ($\ell = e$ or μ) [6] .

The inclusive rate for $b \to d\gamma$ is suppressed compared to $b \to s\gamma$ by a factor $|V_{td}/V_{ts}|^2$ in the SM. This ratio can also be obtained from the B_d and B_s mixing frequencies [7]. New physics effects would enter in different ways in mixing and radiative decays. Measurements of $|V_{td}/V_{ts}|$ using the exclusive modes $B \to (\rho, \omega)\gamma$ and $B \to K^*\gamma$ [8, 9] are now well-established, with theoretical uncertainties of 7% [10]. A measurement of inclusive $b \to d\gamma$ relative to $b \to s\gamma$ would determine $|V_{td}/V_{ts}|$ with reduced theoretical uncertainties. We parametrize the inclusive ratio (following [11]) by:

$$\frac{\mathrm{BR}(b \to d\gamma)}{\mathrm{BR}(b \to s\gamma)} = \zeta^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 (1 + \Delta R) \tag{2}$$

where ζ accounts for any remaining SU(3) breaking and ΔR accounts for weak annihilation in B^+ decays.

B factories, *BABAR* [12] and Belle [13], already accumulated more than one billion of $B\overline{B}$ events, which allows *BABAR* and Belle collaborations to perform precision measurements on $b \to s\gamma$ and $b \to d\gamma$ processes [14]. Here I summarize the latest experimental achievements on the above inclusive processes.

2 Direct CP asymmetry in $B \to X_{s,d}\gamma$

The result presented* is based on a data sample of $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ collisions collected with the BABAR detector at the PEP-II asymmetric-energy e^+e^- collider. The on-resonance integrated luminosity is 347 fb^{-1} and 36 fb^{-1} of off-resonance data, taken 40 MeV below the $\Upsilon(4S)$ resonance energy, are used to estimate the continuum background ($q\overline{q} : q = udsc, \tau^+\tau^-$).

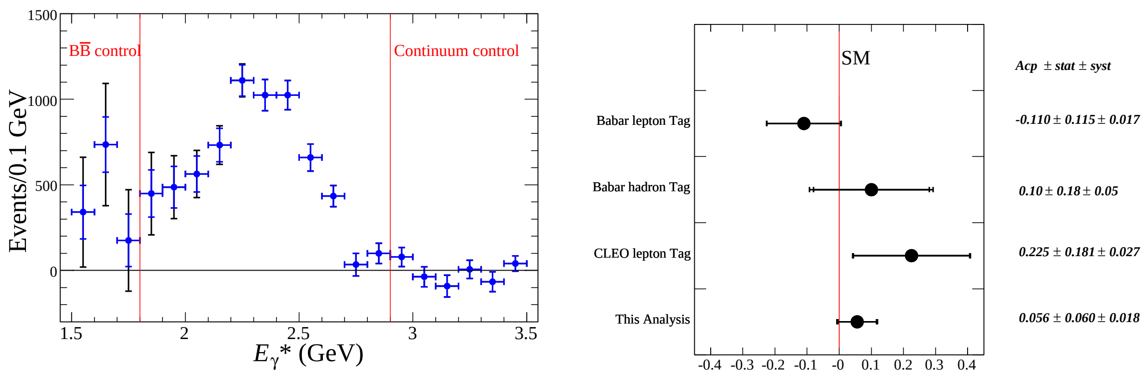

Figure 1: Left: The photon spectrum in $347 fb^{-1}$ of data after background subtraction. The inner error bars are statistical only, while the outer include both statistical and systematic errors in quadrature; Right: Measurements of A_{CP} ($B \to X_{s+d}\gamma$), with statistical and systematic errors. The three published results, top to bottom, are from references [15].

The analysis begins by requiring a high-energy photon, characteristic of $B \to X_s\gamma$ decays, while photons from π^0 and η are vetoed. The background from continuum events is significantly suppressed by charged lepton tagging and by exploiting the more jet-like topology of the $q\overline{q}$ or $\tau^+\tau^-$ events compared to the isotropic $B\overline{B}$ decays. The remaining continuum backgrounds are estimated with off-resonance data. The non signal $B\overline{B}$ background arises predominantly from π^0,η decay but also from decays of other light mesons, mis-reconstructed electrons and hadrons, which are estimated using Monte Carlo simulation and corrected the data and MC difference using appropriate control samples. Figure 1 shows the observed photo spectrum after subtracting off-resonance data and the corrected $B\overline{B}$ backgrounds. Two prior

*The branching fraction of $B \to X_s\gamma$ and its spectra shape from same analysis will be present in near future.

selected control regions, $B\overline{B}$ control ($1.53 < E_\gamma^* < 1.8\,\mathrm{GeV}$) and Continuum control ($2.9 < E_\gamma^* < 3.5\,\mathrm{GeV}$), are used to validate the background estimation. In the $B\overline{B}$ control region we find $1252 \pm 272(stat.) \pm 841(syst.)$ events, dominated by $B\overline{B}$ background with a small signal contribution component (200-400 events depending on models); the continuum region yields s $-100 \pm 138(stat.)$ events, consistent with zero which showing good estimation of off-resonance subtraction.

The direct CP asymmetry, A_{CP} $(B \to X_{s+d}\gamma)$ is measured by dividing the signal sample into B and $\overline{B}$ decays according to the charge of the lepton tag to measure $A_{CP}^{\text{meas}}(B \to X_{s+d}\gamma) = \frac{N^+ - N^-}{N^+ + N^-}$, where $N^{+(-)}$ are the positively (negatively) tagged signal yields. The asymmetry must be corrected for the dilution due to the mistag fraction ω, $A_{CP}(B \to X_{s+d}\gamma) = \frac{1}{1-2\omega} A_{CP}^{\text{meas}}(B \to X_{s+d}\gamma)$. the missing fraction ω is found to be 0.131 ± 0.007, from $B^0 - \overline{B}^0$ oscillation, the fraction of events with wrong-sign leptons from the B decay chain and the similar fraction due to misidentification of hadrons as leptons.

The theoretical SM predictions for a near-zero asymmetry do not require the entire spectrum to be measured. To reduce the sensitivity to background, the signal region is restricted to $2.1 < E_\gamma^* < 2.8\,\mathrm{GeV}$. In this selected energy region, the tagged signal yields are $N^+ = 2623 \pm 158(stat.)$ and $N^- = 2397 \pm 151(stat.)$ giving an asymmetry of $A_{CP}^{\text{meas}}(B \to X_{s+d}\gamma) = 0.045 \pm 0.044$. Finally the $A_{CP}^{\text{meas}}(B \to X_{s+d}\gamma)$ is corrected for mistagging and bias to give $A_{CP} = 0.056 \pm 0.060(stat.) \pm 0.018(syst.)$, where the systematic error is mainly from non signal $B\overline{B}$ background and the lepton tagging efficiency. The result is consistent with no observed asymmetry, consistent with SM expectation and previous measurements. A comparison of the result to published measurements is shown in figure 1. The current measurement is the most precise to date.

3 Branching fraction and moments of $b \to s\gamma$

Currently the most precise measurement of the inclusive $B \to X_s\gamma$ branching fractions has been done by Belle [16]. The data consists of a sample of 605 fb^{-1} taken on the $\Upsilon(4S)$ resonance. Another 68 fb^{-1} sample was taken at an energy 60 MeV below the resonance.

The signal spectrum is extracted by collecting all high energy photons, vetoing those originating from π^0 and η decays to two photons. The non $B\overline{B}$ background, mainly $e^+e^- \to q\overline{q}$ $(q = u, d, s, c)$ events, is subtracted using the off-resonance sample. The remaining background from $B\overline{B}$ are subtracted using Monte-Carlo simulated distributions normalized using data control samples.

The analysis proceeds in two different streams, with lepton tag (LT) and without (MAIN). Two samples give similar sensitivity to the signal while being largely statistically independent. After these selection criteria, 41.1×10^5 (24.6×10^4) and

3.5×10^5 (0.9×10^4) photon candidates survive in the MAIN (LT) stream of the on- and off-resonance data samples, respectively.

The photon candidates from $B\overline{B}$ background is divided into six categories:(i) π^0; (ii)η; (iii) other real photons from decays of ω, η' and J/ψ mesons; (iv) mis-identified calorimeter clusters from K_L^0 and $\overline{n}$; (v) electrons misidentified as photons and; (vi) beam background. Each category is checked using appropriate control samples as described in Ref.[17]. Each background yield, scaled by the described procedures, is subtracted from the data spectrum. The photon energy ranges 1.4-1.7 GeV and 2.8-4.0 GeV were chosen a prior as control regions to test the integrity of the background subtraction since in the low energy region the little signal expected is negligible with respect to the uncertainty on the background, and no signal is possible in the high energy region above the kinematic limit. The yield in the high energy region are 1245 ± 4349 and 292 ± 410 candidates in the MAIN and LT stream, respectively, while corresponding yields in the low energy region are -1629 ± 3071 and -745 ± 623, respectively.

To obtain the true spectrum, a three-step unfolding procedure is used to correct the raw spectrum. The procedure does not distinguish between $B \to X_s\gamma$ and $B \to X_d\gamma$. Assuming the shape of the corresponding photon energy spectra are equivalent, the contribution of $B \to X_d\gamma$ is subtracted using the ratio $R_{d/s} = (4.5 \pm 0.3)\%$. Boost corrections, obtained from MC simulation, are used to derive the measurements in the rest frame of the B meson. The two streams, MAIN and LT, are combined taking the correlation into count.

The measured branching fraction in the B-meson rest frame is $BF(B \to X_s\gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$ for the photon energy range from 1.7 GeV to 2.8 GeV. The most accurate measurement is given in the photon energy range 2.0 GeV to 2.8 GeV, $BF(B \to X_s\gamma) = (3.02 \pm 0.10 \pm 0.11) \times 10^{-4}$. Here the errors are statistical and systematic, respectively. The measured branching fractions are in agreement with the latest theoretical calculation. The measured spectral moments can be used to reduce the uncertainty on $|V_{ub}|$ [18, 19].

4 $b \to d\gamma$

Here we present the first significant observation of the $b \to d\gamma$ transition in the hadronic mass range $M(X_d) > 1.0\,\mathrm{GeV}/c^2$, used in the determination of $|V_{td}/V_{ts}|$ via the ratio of inclusive widths.Inclusive $B \to X_s\gamma$ and $B \to X_d\gamma$ rates are extrapolated from the measurements of the partial decay rates of seven exclusive final states in the hadronic mass ranges $0.5 < M(X_d) < 1.0\,\mathrm{GeV}/c^2$ and $1.0 < M(X_d) < 2.0\,\mathrm{GeV}/c^2$. Here the X_d includes $\pi^+\pi^-$, $\pi^+\pi^-\ \pi^0$, $\pi^+\pi^-\ \pi^+$, $\pi^+\pi^-\ \pi^+\pi^-$, $\pi^+\pi^-\ \pi^+\ \pi^0$ and $\pi^+\eta$; while the X_s includes $K^+\ \pi^-$, $K^+\ \pi^0$, $K^+\ \pi^+\pi^-$, $K^+\ \pi^-\ \pi^0$ $K^+\ \pi^-\ \pi^+\pi^-$, $K^+\ \pi^-\ \pi^+\ \pi^0$ and $K^+\eta$. We combine these measurements and make a model-dependent

Table 1: Signal yields (N_S), efficiencies (ϵ). partial branching fractions (BF) and inclusive branching fractions ($\mathcal{B}$) for the measured decay modes. The first error is statistical the the second systematic (including error from extrapolation to missing decay modes, for the inclusive $\mathcal{B}$).

	$M(X_s)0.4-1.0$	$M(X_d)0.4-1.0$	$M(X_s)1.0-2.0$	$M(X_d)1.0-2.0$ (GeV/c^2)
N_S	804 ± 33	35 ± 9	990 ± 42	56 ± 14
ϵ	4.5%	3.1%	1.6%	1.9%
$BF(\times 10^{-6})$	$18.9 \pm 0.8 \pm 0.8$	$1.2 \pm 0.3 \pm 0.1$	$65.7 \pm 2.8 \pm 5.9$	$3.2 \pm 0.8 \pm 0.5$
$\mathcal{B}(\times 10^{-6})$	$38.3 \pm 1.6 \pm 1.5$	$1.3 \pm 0.3 \pm 0.1$	$192 \pm 80 \pm 45$	$7.9 \pm 2.0 \pm 3.3$
$\frac{\mathcal{B}(b\to d\gamma)}{\mathcal{B}(b\to s\gamma)}$	$0.0033 \pm 0.009 \pm 0.003$		-	

extrapolation to higher hadronic mass to obtain an inclusive branching fraction ($\mathcal{B}$) for $b \to (s,d)\gamma$. These measurements use a sample of 471×10^6 $B\overline{B}$ pairs collected by the *BABAR* experiment.

The signal yields in the data for the combination of all seven decay modes are determined from two-dimensional extended maximum likelihood fits to the ΔE^* and $m_{\rm ES}$ distributions after all event selections, where $\Delta E^* = E^*_B - E^*_{\rm beam}$, E^*_B is the energy of the B meson candidate and $E^*_{\rm beam}$ is the beam energy, and $m_{\rm ES} = \sqrt{E^{*2}_{\rm beam} - \vec{p}^{\,*2}_B}$, $\vec{p}^{\,*}_B$ is the momentum of the B candidate. Table 1 gives the signal yields, efficiencies and partial branching fractions.

To obtain inclusive $\mathcal{B}(b \to s\gamma)$ and $\mathcal{B}(b \to d\gamma)$ we need to correct the partial $\mathcal{B}$ values in Table 1 for the fractions of missing final states. After correcting for the 50% of missing decay modes with neutral kaons, the low mass $B \to X_s\gamma$ measurement is found to be consistent with previous measurements of the rate for $B \to K^*\gamma$ [14]. For the low mass $B \to X_d\gamma$ region, we correct for the small amount of non-reconstructed ω final states ($\omega \to \pi^0\gamma$ and others), and find a partial branching fraction consistent with previous measurements of BR($B \to (\rho,\omega)\gamma$) [14]. We assume that non-resonant decays do not contribute in this region.

In the high mass region, the missing fractions depend on the fragmentation of the hadronic system and are expected to be different for X_d and X_s. We explore the uncertainty in the correction for missing modes by considering several alternative models. The resulting missing fractions vary by up to 50% relative to the nominal model. We therefore independently vary final states with ≥ 5 stable hadrons, or with $\geq 2\pi^0$ or η mesons, by $\pm 50\%$.

Combining the two mass regions, taking into account a partial cancellation of the missing fraction errors in the ratio of $b \to d\gamma$ to $b \to s\gamma$, we find $\mathcal{B}(b \to d\gamma)/\mathcal{B}(b \to s\gamma) = 0.040 \pm 0.009(stat.) \pm 0.010(syst.)$ in the mass range $M(X) < 2.0\,{\rm GeV}/c^2$. For the unmeasured region $M(X) > 2.0$ GeV/c^2 the differences between $b \to s\gamma$ and $b \to d\gamma$ are small and almost completely cancel in the ratio.

Conversion of the ratio of inclusive branching fractions to the ratio $|V_{td}/V_{ts}|$ is done according to [11], which requires $\overline{\rho}$ and $\overline{\eta}$ as input. However, since these are partially determined from previous measurements of $|V_{td}/V_{ts}|$, we instead re-express $\overline{\rho}$ and $\overline{\eta}$ in terms of the independent CKM angle β. This procedure yields a value of $|V_{td}/V_{ts}| = 0.199 \pm 0.022(stat.) \pm 0.024(syst.) \pm 0.002(th.)$ competitive with more model-dependent determinations from the measurement of the exclusive modes $B \to (\rho, \omega)\gamma$ and $B \to K^*\gamma$ [8, 9].

5 Summary

Here I summarized the experiment progresses on the inclusive $b \to s\gamma$ and $b \to d\gamma$ after the last CKM workshop. Belle measured the inclusive branching fraction in the B-meson rest frame, $BF(B \to X_s\gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$, for the photon energy range from 1.7 GeV to 2.8 GeV. *BABAR* presents the most precise direct CP asymmetry measurement to date, its preliminary result is consistent with SM prediction. *BABAR*also measured the ratio of $b \to d\gamma$ over $b \to s\gamma$ using seven exclusive modes, providing the independent determination of $|V_{td}/V_{ts}|$.

ACKNOWLEDGEMENTS

I am grateful to the wonderful works from *BABAR* and Belle collaborations. Thanks also to the organizers of the CKM2010 for all efforts in making this venue successful.

References

[1] I. I. Y. Bigi *et al.*, Phys. Lett. B **293** 430 (1992).

[2] M. Misiak *et al.*, Phys. Rev. Lett. **98** 022002 (2007).

[3] T. Hurth *et al.*, Ann.Rev.Nucl.Part.Sci.60:645,2010.

[4] T. Hurth *et al.*, Nucl. Phys. **B704** 56 (2005).

[5] A.L. Kagan, M. Neubert, Eur. Phys. J. C7 (1999) 5-27.

[6] C.W. Bauer *et al*, Phys. Rev. **D70** 094017 (2004); B.O. Lange *et al.*,Phys. Rev. **D72** 073006 (2005); C.W. Bauer *et al.*, Phys. Rev. **D67** 054012 (2003); P. Gambino *et al.*, JHEP, **10** 058 (2007).

[7] A. Abulencia *et al.*, [CDF Collaboration], Phys. Rev. Lett. **97**, 242003 (2006).

[8] D. Mohapatra *et al.* [Belle Collaboration], Phys. Rev Lett. **96**, 221601 (2006).

[9] B. Aubert *et al.* [*BABAR* Collaboration], Phys. Rev Lett. **98**, 151802 (2007).

[10] P. Ball, G. Jones and R. Zwicky, Phys. Rev. D **75**, 054004 (2007).

[11] A. Ali, H. Asatrian & C. Greub, Phys. Lett. B **429**, 87 (1998). K. Nakamura *et al.*, Particle Data Group, J. Phys. G **37** 075021 (2010).

[12] B. Aubert *et al.*, [*BABAR* Collaboration], Nucl. Instrum. Methods A **479**, 1 (2002).

[13] S. KuroKawa *et al.*, Bell Collaboration, Nucl. Instrum. Methods A **479**, 117 (2002).

[14] K. Nakamura *et al.* (Particle Data Group). J. Phys. G **37**, 075021 (2010).

[15] B. Aubert *et al.*,Phys. Rev. Lett. **97** 171803 (2006); B. Aubert *et al.*,Phys. Rev. **D77** 051103 (2008); T. E. Coan *et al.*,Phys. Rev. Lett. **86** 5661 (2001).

[16] A. Limosani *et al.* (Belle Collaboration). Phys. Rev. Lett. bf 103 241801 (2009);

[17] P. Koppenburg *et al.* Phys. Rev. Lett. 93, 061803 (2004).

[18] F. U. Bernlochner *et al.*, arXiv:1102.0210.

[19] Heavy Flavor Averaging Group, E. Barberio *et al.*, arXiv:0704.3575 (hep-ex) (2007).