Measurements of Electroweak Penguin Processes $b \to d, s\gamma$ and $b \to s\ell^+\ell^-$ at Belle

M. Iwasaki
(for the Belle collaboration)

Dept. of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0011 JAPAN

We report the measurements of electroweak penguin processes $b \to d, s\gamma$ and $b \to s\ell^+\ell^-$ at the Belle experiment. The analyses are based on 152 million $B\bar{B}$ events collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB $e^+e^-$ asymmetric-energy collider. The $b \to d\gamma$ transition is studied through exclusive decays: $B^0 \to \rho^0\gamma$, $B^0 \to \omega\gamma$ and $B^+ \to \rho^+\gamma$. We apply fully inclusive and semi-inclusive reconstruction to $b \to s\gamma$ and $b \to s\ell^+\ell^-$ processes, respectively. The results on the exclusive $b \to d\gamma$ and semi-inclusive $b \to s\ell^+\ell^-$ measurements are preliminary.

1 Introduction

In the Standard Model (SM), flavor-changing neutral current (FCNC) process is forbidden at tree level. Such a process can occur at higher order via electroweak penguin and box diagrams. The FCNC process is therefore sensitive to the effects of non-SM physics that may enter these loops.

In this report, we show the measurements of FCNC processes $b \to d, s\gamma$ and $b \to s\ell^+\ell^-$. The $b \to d\gamma$ process is studied through exclusive decays: $B^0 \to \rho^0\gamma$, $B^0 \to \omega\gamma$ and $B^+ \to \rho^+\gamma$. We apply fully inclusive and semi-inclusive reconstruction to $b \to s\gamma$ and $b \to s\ell^+\ell^-$ processes, respectively. These measurements are based on a sample of $152 \times 10^6$ $\Upsilon(4S) \to B\bar{B}$ decays collected with the Belle detector at the KEKB $e^+e^-$ asymmetric-energy collider.

2 Exclusive $b \to d\gamma$

The $b \to d\gamma$ process is suppressed with respect to $b \to s\gamma$ by the Cabibbo-Kobayashi-Maskawa (CKM) factor $|V_{td}/V_{ts}|^2 \sim 0.04$ with a large uncertainty due to lack of precise knowledge on $V_{td}$. 
In this analysis, we use the exclusive reconstruction of the decays, $B^+ \to \rho^+\gamma$, $B^0 \to \rho^0\gamma$, and $B^0 \to \omega\gamma^*$. We also reconstruct $B^+ \to K^{*+}\gamma$ and $B^0 \to K^{*0}\gamma$ for control samples. The following decay chains are used to reconstruct the intermediate states: $\rho^+ \to \pi^+\pi^0$, $\rho^0 \to \pi^+\pi^-$, $\omega \to \pi^+\pi^-\pi^0$, $K^{*+} \to K^+\pi^0$, $K^{*0} \to K^+\pi^-$, and $\pi^0 \to \gamma\gamma$. In each event, we select the photon with the largest energy in the range 1.8 GeV < $E_\gamma$ < 3.4 GeV, in the $e^+e^-$ center-of-mass frame (CM). To suppress backgrounds from $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ decays, we veto the event if the reconstructed mass of the primary photon and any other photon of 30 (200) MeV or more is within $\pm 18$ ($\pm 32$) MeV/$c^2$ of the $\pi^0$ ($\eta$) mass. $B$ candidates are formed by combining a $\rho$ or $\omega$ candidate and the primary photon using two variables: the beam-energy constrained mass $M_{bc} = \sqrt{(E_{\text{beam}}/c^2)^2 - |p_B^*/c|^2}$ and the energy difference $\Delta E = E_B^* - E_{\text{beam}}^*$, where $p_B^*$ and $E_B^*$ are the measured CM momentum and energy, respectively, of the $B$ candidate, and $E_{\text{beam}}^*$ is the CM beam energy. The photon energy is replaced by $E_{\text{beam}}^* - E_{p/\omega}^*$ if the momentum $p_B^*$ is calculated. We define the signal region as $-0.1$ GeV < $\Delta E$ < 0.08 GeV and 5.273 GeV/$c^2$ < $M_{bc}$ < 5.285 GeV/$c^2$.

There are two major background sources from $B$ decays: $B \to K^*\gamma$, and $B \to \rho/\omega\pi^0$. To suppress $B \to K^*\gamma$, we calculate $M_{K\pi}$, where a kaon mass is assigned to one of the pion candidates, and reject the candidate if $M_{K\pi} < 0.96$ (0.92) GeV/$c^2$ for the $\rho^0\gamma$ ($\rho^+\gamma$) mode. To reject $B \to \rho/\omega\pi^0$, we apply a helicity angle cut $|\cos \theta_{\text{hel}}| > 0.8$ (0.6) for $\rho^0\gamma$ and $\omega\gamma$ ($\rho^+\gamma$) modes. Here, $\theta_{\text{hel}}$ is the angle between $\pi^+$ and $B$ momentum vectors in the $\rho$ rest frame, or between the normal to the $\omega$ decay plane and the $B$ momentum vector in the $\omega$ rest frame.

The background from continuum $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) events is rejected using the event topology information. We use a Fisher discriminant constructed from 16 modified Fox-Wolfram moments and the scalar sum of the transverse momenta. We also use the decay vertex of the candidate $B$ meson as well as the origin of the remaining tracks in the event. The difference between these two vertices along the $z$-axis discriminates continuum events that has a common decay vertex and signal events whose decay vertices are displaced in the laboratory frame.

To obtain the signal yield, we perform an unbinned maximum likelihood fit to $M_{bc}$ and $\Delta E$ to the events in $|\Delta E| < 0.3$ GeV and $M_{bc} > 5.2$ GeV/$c^2$. We perform a simultaneous fit to three signal modes ($B \to (\rho, \omega)\gamma$) plus two $B \to K^*\gamma$ modes, assuming the isospin relations $B(B \to (\rho, \omega)\gamma) \equiv B(B^+ \to \rho^+\gamma) = 2\frac{f_{\rho\rho}}{f_{\rho\rho}}B(B^0 \to \rho^0\gamma) = 2\frac{f_{\rho\rho}}{f_{\rho\rho}}B(B^0 \to \omega\gamma)$ and $B(B^+ \to K^{*+}\gamma) = \frac{f_{\rho\omega}}{f_{\rho\omega}}B(B^0 \to K^{*0}\gamma)$, where we use $f_{\rho\rho} = 1.083 \pm 0.017$. Here, floated parameters are the branching fractions for $B \to (\rho, \omega)\gamma$ and $B \to K^*\gamma$, five background normalizations and five background $\Delta E$ slopes.

Preliminary results of the simultaneous fit are shown in Fig. 1 and given in Table 1. We find the simultaneous fit gives a significance of 3.5, where significance is defined as $\sqrt{-2 \ln(L_0/L_{\text{max}})}$, $L_{\text{max}}$ is the maximum likelihood in the $M_{bc}$ fit, and $L_0$ is the likelihood of the best fit here the signal yield is constrained to be zero.

*Throughout the article charge-conjugate states are implicitly included.

| Mode       | efficiency | signal yield (±stat±syst) | significance | branching fraction (±stat±syst) |
|------------|------------|----------------------------|--------------|---------------------------------|
| $B^+ \to \rho^+\gamma$ | (5.6 ± 0.4)% | (15.5 ± 1.6 ± 1.5) | 2.5 | (1.8 ± 0.9 ± 0.1) × 10^{-6} |
| $B^0 \to \rho^0\gamma$ | (5.0 ± 0.3)% | (3.6 ± 0.6 ± 0.7) | 1.2 | (0.5 ± 0.4 ± 0.2) × 10^{-6} |
| $B^0 \to \omega\gamma$ | (4.7 ± 0.5)% | (8.9 ± 1.8 ± 1.2) | 2.3 | (1.3 ± 0.7 ± 0.2) × 10^{-6} |
| $B \to (\rho, \omega)\gamma$ | --- | --- | 3.5 | (1.8 ± 0.6 ± 0.5 ± 0.1) × 10^{-6} |

Table 1: Results of the efficiency, signal yield, significance, and branching fraction from simultaneous and individual fits. These numbers are preliminary.
Figure 1: Projections of the simultaneous fit results to $M_{bc}$ and $\Delta E$ of the individual modes to the signal region, for $B^0 \to \omega \gamma$ (a and b), $B^+ \to \rho^+ \gamma$ (c and d), and $B^0 \to \rho^0 \gamma$ (e and f). Lines represent the total fit result (black), signal (red), $K^* \gamma$ (blue) and continuum (green) components. $B \to (\rho/\omega)\pi^0$ components are invisibly small.

3 Inclusive $b \to s \gamma$

We recently measured the $b \to s \gamma$ branching fraction using a fully-inclusive approach. The detailed descriptions are written in Ref.\textsuperscript{7}. In this analysis, to extract the signal $b \to s \gamma$ spectrum, we collect all high-energy photons, vetoing those originating from $\pi^0$ and $\eta$ decays to two photons. The contribution from continuum events is subtracted using the off-resonance sample. The remaining backgrounds from $B \bar{B}$ events are subtracted using Monte-Carlo (MC) distributions scaled by data control samples. After subtracting the backgrounds, we correct the photon spectrum for the signal selection efficiency function obtained from signal MC, applying the correction determined by data control samples.

The efficiency-corrected spectrum is shown as a function of CM photon energy in Figure 2. The two error bars for each point show the statistical and the total error, including the systematic error which is correlated among the points. As expected, the spectrum above the 3 GeV endpoint for decays of $B$ mesons from the $\Upsilon(4S)$ is consistent with zero. Integrating this spectrum from 1.8 to 2.8 GeV, we obtain a partial branching fraction of $\mathcal{B}(b \to s \gamma) = (3.59 \pm 0.32^{+0.30}_{-0.31}^{+0.11}_{-0.07}) \times 10^{-4}$, where the errors are statistical, systematic and theoretical, respectively. This result is in good agreement with the latest theoretical calculations\textsuperscript{8,9}. We have also measured the moments of the distribution and obtain $\langle E_{\gamma} \rangle = 2.289 \pm 0.026 \pm 0.034$ GeV and $\langle E_{\gamma}^2 \rangle - \langle E_{\gamma} \rangle^2 = 0.0311 \pm 0.0073 \pm 0.0063$ GeV$^2$ for $E_{\gamma} > 1.8$ GeV, where the errors are statistical and systematic.
4 Semi-inclusive $b \rightarrow s\ell^+\ell^-$

We study the inclusive $B \rightarrow X_s\ell^+\ell^-$ process, where $\ell$ is an electron or a muon and $X_s$ is a hadronic system containing an $s$-quark. The $s$-quark hadronic system is reconstructed with a semi-inclusive reconstruction approach: reconstruct with one $K^\pm$ or $K^0_s$ and up to four pions (at most one pion can be neutral). Compared to a fully inclusive approach, this method has the advantage of having the strong kinematical discrimination by using the beam-energy constrained mass $M_{bc}$ and the energy difference $\Delta E$.

In addition to the discrimination, further background suppression to reduce the large combinatorial backgrounds is necessary. The main contribution to the combinatorial background is from semileptonic decays in $B\bar{B}$ events. In these events, $B \rightarrow X_s\ell^+\ell^-$ candidates are reconstructed with the decay products from both $B\bar{B}$ mesons. Such a background event has a significant amount of missing energy due to the neutrinos from the semileptonic decays. Another contribution to the combinatorial background is from continuum events, which are effectively suppressed with event-shape variables.

There are two background sources that can peak in $M_{bc}$ and $\Delta E$. The first is from $B \rightarrow J/\psi X$ and $B \rightarrow \psi(2S)X$ decays with $J/\psi(\psi(2S)) \rightarrow \ell^+\ell^-$. This peaking background is efficiently removed with cuts on the dilepton mass $m(\ell^+\ell^-)$. The resulting veto sample provides a large control sample of decays with a signature identical to that of the signal. The second is from $B \rightarrow K^\pm(K^0_s)n\pi$ ($n > 1$) decays with misidentification of two charged pions as leptons. We estimate these peaking background contaminations, then subtract them from the signal yield.

We perform an extended, unbinned maximum likelihood fit to the $M_{bc}$ distribution in the region $M_{bc} > 5.2$ GeV/$c^2$ to extract the signal yield as well as the shape and yield of the combinatorial background. We fit the $M_{bc}$ distributions for the selected $B \rightarrow X_se^+e^-$ and $B \rightarrow Xs\mu^+\mu^-$ candidates separately, and $B \rightarrow X_s\ell^+\ell^- (\ell = e, \mu)$. The obtained results are shown in Figures 3(a)-(c). Figure 3(d) shows the distribution for $B \rightarrow X_s\mu^+\mu^-$ candidates. There is no peaking component as expected. Using a sample of $152 \times 10^6 B\bar{B}$ decays, we observe a signal of $72.3 \pm 13.8(stat) \pm 4.6(syst)$ events.

Figures 4(a)-(c) show the distributions of hadronic mass $M_{xs}$, lepton pair mass $M_{\ell\ell}$, and $q^2 \equiv M_{\ell\ell}^2$ for electron and muon channels combined, obtained by performing the nominal likelihood fit in separate $M_{xs}$, $M_{\ell\ell}$, and $q^2$ regions.
Figure 3: Distributions of $M_{bc}$ for selected (a) $B \rightarrow X_s e^+ e^-$, (b) $B \rightarrow X_s \mu^+ \mu^-$, (c) $B \rightarrow X_s \ell^+ \ell^-$, ($\ell = e, \mu$), and (d) $B \rightarrow X_s e^\pm \mu^\mp$ candidates. The red lines represent the result of the fits, and the green and blue lines represent the peaking and combinatorial background components under the signal peaks, respectively.

Figure 4: Distributions of number of signal events as a function of (a) hadronic mass $M_{xs}$ (b) lepton pair mass $M_{ll}$, and (c) $q^2 \equiv M_{ll}^2$ for electron and muon channels combined for data (points) and Monte Carlo signal (histogram). The vertical error bars represent statistical errors only.
The preliminary results of the measured branching fractions for \( M(\ell^+\ell^-) > 0.2 \text{ GeV}/c^2 \) are

\[
\mathcal{B}(B \to X_s e^+e^-) = \left(4.45 \pm 1.32^{+0.84}_{-0.79}\right) \times 10^{-6},
\]
\[
\mathcal{B}(B \to X_s \mu^+\mu^-) = \left(4.30 \pm 1.06^{+0.74}_{-0.70}\right) \times 10^{-6}, \text{ and}
\]
\[
\mathcal{B}(B \to X_s \ell^+\ell^-) = \left(4.39 \pm 0.84^{+0.78}_{-0.73}\right) \times 10^{-6},
\]

where the first error is statistical and the second error is systematic. The combined \( B \to X_s \ell^+\ell^- \) branching fraction is the weighted average of the branching fractions for the electron and muon channels, where we assume the individual branching fractions to be equal for \( M(\ell^+\ell^-) > 0.2 \text{ GeV}/c^2 \).

5 Summary

We have studied the electroweak penguin processes \( b \to d,s \gamma \) and \( b \to s\ell^+\ell^- \) based on a sample of \( 152 \times 10^6 \Upsilon(4S) \to \overline{B}B \) decays at the Belle experiment. The \( b \to d \gamma \) transition is studied through exclusive decays: \( B^0 \to \rho^0 \gamma \), \( B^0 \to \omega \gamma \) and \( B^+ \to \rho^+ \gamma \). We apply fully inclusive and semi-inclusive reconstruction to \( b \to s \gamma \) and \( b \to s\ell^+\ell^- \) processes, respectively.

We present the first evidence for the \( b \to d \gamma \) process using a simultaneous fit to the \( B \to \rho \gamma \) and \( B^0 \to \omega \gamma \) modes. The preliminary result is consistent with the SM predictions \(^{10,11}\). We measure the branching fraction and photon energy spectrum of inclusive \( b \to s \gamma \) process in the energy range \( 1.8 \text{ GeV} \leq E_\gamma^* \leq 2.8 \text{ GeV} \). For the first time 95% or more of the spectrum is measured, allowing the theoretical uncertainties to be reduced to a very low level. We measure the branching fraction for the \( B \to X_s \ell^+\ell^- \), where \( \ell = e \) or \( \mu \) and \( X_s \) hadronic system is semi-inclusively reconstructed. The preliminary measurement is consistent with the recent prediction by Ali et al. \(^{12}\).

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