\[ B \rightarrow X_s \gamma \] at \ BABAR

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Abstract. We present a measurement of the branching fraction and photon energy spectrum for the decay \( B \rightarrow X_s \gamma \) using data from the BaBar experiment. The data sample corresponds to an integrated luminosity of 210 fb\(^{-1}\), from which approximately 680 000 \( B \bar{B} \) events are tagged by a fully reconstructed hadronic decay of one of the \( B \) mesons. In the decay of the second \( B \) meson an isolated high energy photon is identified. The full reconstruction of one of the \( B \) mesons results in improved background suppression and allows for an inclusive measurement of the photon energy spectrum in the \( B \) rest frame. We measure \( \mathcal{B}(B \rightarrow X_s \gamma) = (3.66 \pm 0.85_{\text{stat}} \pm 0.59_{\text{syst}}) \times 10^{-4} \) for photon energies \( E_\gamma \) above 1.9 GeV. From the measured spectrum we calculate the first and second moments for different minimum photon energies which can be used to extract the heavy quark parameters \( m_b \) and \( \mu_2^\pi \).

1. Introduction
In the Standard Model (SM), the rare radiative penguin decay \( b \rightarrow s \gamma \) proceeds via a flavor changing neutral current. The decay is sensitive to new physics through non-SM heavy particles entering at the loop level [1]. Recent next-to-next-to-leading-order calculations predict branching fractions in the range \( \mathcal{B}(B \rightarrow X_s \gamma) = (3.0 - 3.5) \times 10^{-4} \) for \( E_\gamma > 1.6 \) GeV with uncertainties varying from 7\% to 14\% [2, 3, 4]. Here \( E_\gamma \) is the energy of the signal photon in the rest frame of the \( B \) meson, and the cutoff is chosen to avoid non-perturbative effects at lower energies. The current world average measured branching fraction is \( \mathcal{B}(B \rightarrow X_s \gamma) = (3.55 \pm 0.26) \times 10^{-4} \) \( (E_\gamma > 1.6 \text{GeV}) \) [5, 6]. The moments of the photon energy spectrum are sensitive to the Heavy Quark Expansion parameters \( m_b \) and \( \mu_2^\pi \) [7, 8, 9], related to the mass and momentum of the quark within the \( B \) meson. Improved measurements of these parameters can be used to reduce the uncertainty in the CKM matrix elements \( |V_{cb}| \) and \( |V_{ub}| \) [5, 6].

2. Measurement of \( \mathcal{B}(B \rightarrow X_s \gamma) \)
The measurements presented here are based on a sample of 232 million \( B \bar{B} \) pairs collected on the \( \Upsilon(4S) \) resonance by the BaBar detector at the PEP-II asymmetric-energy \( e^+e^- \) storage ring operating at SLAC. This analysis uses \( \Upsilon(4S) \rightarrow B \bar{B} \) events in which one of the \( B \) mesons (called the tag \( B \)) decays to hadrons and is fully reconstructed. The efficiency for reconstructing a tag \( B \) is approximately 0.3\% in this analysis. The remaining particles in the event originate from the second \( B \) meson (the signal \( B \)). This approach allows for the determination of the momentum, charge, and flavor of the \( B \) mesons, and thus the photon spectrum can be measured in the rest frame of the signal \( B \). The method allows separate measurements for charged and neutral \( B \) mesons and enables the measurement of the direct \( CP \) asymmetry \( A_{CP} \).
2.1. Event selection and fit of signal rates

After reconstruction of the tag $B$ the remaining particles in the event are regarded as coming from the signal $B$. From among these particles we require an isolated photon candidate with energy $E_\gamma > 1.3$ GeV in the $B$ frame. Candidates consistent with stemming from $\pi^0$, $\eta$ or $\rho$ decays are vetoed. To reject continuum (non-$B$) background we combine event shape variables in a Fisher discriminant. Remaining non-$B$ background and $B\bar{B}$ events in which the tag $B$ is misreconstructed are subtracted by means of a fit to the beam-energy-substituted mass $m_{ES} = \sqrt{s/4 - \vec{p}_B^2}$, where $s$ is the total energy squared in the center of mass (c.m.) frame, and $E_B$ and $\vec{p}_B$ are the the c.m. energy and momentum of the tag $B$ candidate. For this, we divide the event sample into 14 distinct intervals of photon energy, each 100 MeV wide, spanning the range 1.3 to 2.7 GeV. In each interval, we extract the number of $B$ events with a binned maximum likelihood fit to the $m_{ES}$ distribution using a Crystal Ball (CB) function for the signal component and an Argus function for the background. Because of the limited data sample we carry out a simultaneous fit of the mass distributions for all of the photon-energy intervals. We allow the shape parameters of the CB and Argus function to vary with photon energy according to polynomials with orders as low as possible in order to achieve an adequate modeling of the data. Examples of the mass distributions and results of the simultaneous fit are shown in Fig. 1.

The remaining background events where the photon candidate is e.g. from a $\pi^0$ or $\eta$ decay, are subtracted using a Monte Carlo (MC) model. The measured numbers of $B$ events are shown in Fig. 1 (c) as a function of photon energy. The points are from data; the solid histogram is from a $B\bar{B}$ MC sample excluding the signal decay $B \rightarrow X\gamma$. The MC prediction has been scaled by fitting to the data region between 1.3 $E_\gamma$ 1.9 GeV, taking into account the small contribution from $B \rightarrow X\gamma$ decays in that region. For $E_\gamma > 1.9$ GeV, we observe 119 $\pm$ 22 $B \rightarrow X\gamma$ signal events over a $B\bar{B}$ background of 145 $\pm$ 9 events. The total number of $B$ mesons is needed as normalisation for the partial branching fraction measurement and is determined from an $m_{ES}$ fit to the tag sample without photon selection.

2.2. Systematic Uncertainties

The systematic uncertainties related with this measurement can be broken down into four main categories: modeling of the $B\bar{B}$ background, $m_{ES}$ fit parameterization, detector response and dependence on the $B \rightarrow X_\ell\gamma$ signal model. In addition there is a small uncertainty that stems from the subtraction of the $B \rightarrow X_\ell\gamma$ contribution.
From the measured spectrum we obtain corrections. The inner error bars shown are statistical only; the outer error bars are the quadratic sum of the statistical and systematic uncertainties. 

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Figure 2. (a) The partial branching fractions with statistical and total error. (b) First and (c) second moments of the photon energy spectrum as a function of $E_{\text{cut}}$. For comparison, the results from [10] (Semi) and [11] (Fully) are shown as well.

### Table 1. Results for $B(B \to X_s \gamma)$ and moments of the photon spectrum with statistical and systematic errors for different values of $E_{\text{cut}}$.

| $E_{\text{cut}}$ (GeV) | $B(B \to X_s \gamma)$ ($10^{-4}$) | $\langle E_{\gamma} \rangle$ (GeV) | $\langle (E_{\gamma} - \langle E_{\gamma} \rangle)^2 \rangle$ (GeV$^2$) |
|-----------------------|---------------------------------|-------------------------------|----------------------------------|
| 1.9                   | 3.66 ± 0.85 ± 0.59              | 2.289 ± 0.058 ± 0.026          | 0.0334 ± 0.0124 ± 0.0065         |
| 2.0                   | 3.39 ± 0.64 ± 0.47              | 2.315 ± 0.036 ± 0.020          | 0.0265 ± 0.0057 ± 0.0024         |
| 2.1                   | 2.78 ± 0.48 ± 0.34              | 2.371 ± 0.025 ± 0.011          | 0.0142 ± 0.0037 ± 0.0013         |
| 2.2                   | 2.48 ± 0.38 ± 0.26              | 2.398 ± 0.016 ± 0.006          | 0.0092 ± 0.0015 ± 0.0010         |
| 2.3                   | 2.07 ± 0.30 ± 0.19              | 2.427 ± 0.010 ± 0.007          | 0.0059 ± 0.0007 ± 0.0003         |

3. Results

The partial branching fractions for $E_{\gamma}$ between 1.9 and 2.6 GeV are shown in Figure 2 after all corrections. The inner error bars shown are statistical only; the outer error bars are the quadratic sum of the statistical and systematic uncertainties. From the measured spectrum we obtain $B(B \to X_s \gamma) = (3.66 ± 0.85_{\text{stat}} ± 0.59_{\text{syst}}) \times 10^{-4}$ for a minimum photon energy $E_{\text{cut}} = 1.9$ GeV. Extrapolating this value down to 1.6 GeV using an extrapolation factor of 0.936 ± 0.010 [6] yields $B(B \to X_s \gamma) = (3.91 ± 0.91_{\text{stat}} ± 0.64_{\text{syst}}) \times 10^{-4}$. The results for the branching fraction $B(B \to X_s \gamma)$ and the moments of the photon energy spectrum for different values of $E_{\text{cut}}$ are given in Table 1. We find good agreement with previous determinations [10, 11, 12, 13]. The full reconstruction method provides an almost background free measurement above photon energies of 2.2 GeV. While statistics limited at present, the full reconstruction approach is expected to provide a clean measurement of the decay $B \to X_s \gamma$ with a larger data sample, in particular as this will also lead to a reduction in the main systematic uncertainties.

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