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Measurement of the $B \to X_s \gamma$ branching fraction and photon energy spectrum using the recoil method

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I. INTRODUCTION

We present measurements of the branching fraction and photon-energy spectrum of the decay $B \to X_s \gamma$ using data from the BABAR experiment. The data sample corresponds to an integrated luminosity of 210 fb$^{-1}$, from which approximately 680,000 $BB$ 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. We measure $\mathcal{B}(B \to X_s \gamma) = (3.66 \pm 0.85_{\text{stat}} \pm 0.60_{\text{syst}}) \times 10^{-4}$ for photon energies $E_\gamma$ above 1.9 GeV in the $B$ rest frame. From the measured spectrum we calculate the first and second moments for different minimum photon energies, which are used to extract the heavy-quark parameters $m_b$ and $\mu_+^2$. In addition, measurements of the direct $CP$ asymmetry and isospin asymmetry are presented.

II. EVENT SELECTION

Using 1114 exclusive hadronic decay channels [15], which represent about 5% of the total decay width of the $B^0$ and $B^+$ mesons, we identify events in which one of the two $B$ mesons is fully reconstructed. The kinematic consistency of the tag $B$ candidates is checked with two variables, the beam-energy-substituted mass $m_{ES} = \sqrt{s/4 - p_B^2}$, and the energy difference $\Delta E = E_B - \sqrt{s}/2$, where $s$ is the total energy squared in the center-of-mass (c.m.) frame, and $E_B$ and $p_B$ are the c.m. energy and momentum of the tag $B$ candidate. We require $|\Delta E| \leq 60$ MeV, a window of approximately $\pm 3\sigma$.

Those particles in the event that are not reconstructed as part of the tag $B$ are regarded as coming from the signal $B$. Among these particles we require an isolated photon candidate with energy $E_\gamma > 1.3$ GeV in the $B$ frame. To ensure a well reconstructed photon, we require the electromagnetic shower to lie within the calorimeter acceptance and to satisfy isolation and shower shape requirements.
The background events consist of nonsignal $B$ decays and continuum background from $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ and $c\bar{c}$ events. The continuum events are suppressed by using a Fisher discriminant that combines 12 variables related to the different event decay topologies of $BB$ and continuum events. These include event-shape variables such as the thrust, as well as information on the energy flow relative to the direction of the candidate signal photon.

To discriminate against photons from $\pi^0$ and $\eta$ decays, we combine the signal candidate photon with any other photon in the event associated with the signal $B$. The event is vetoed if the pair’s invariant mass is consistent with a $\pi^0$ or $\eta$. Furthermore, the event is rejected if the candidate photon combined with a $\rho^\pm \rightarrow \pi^\pm \pi^0$ decay assuming that the second photon from the $\pi^0$ decay is lost.

### III. FIT OF SIGNAL RATES

The distribution of $m_{ES}$ for the selected events has a peak around the mass of the $B$ meson, corresponding to correctly reconstructed $BB$ events, and a broad background component that stems from non-$BB$ and misreconstructed $BB$ events. The peak is modeled with a crystal ball (CB) function [16]. This contains two parameters that correspond to the mean and width of the Gaussian core and two additional parameters that describe a power-law tail extended to masses below the core region. The nonpeak background term is described with an ARGUS function [17].

Applying the selection criteria outlined above yields approximately 7700 events. We divide the event sample into 14 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 peak events with a binned maximum likelihood fit to the $m_{ES}$ distribution.

The limited size of the data sample means that it is not possible to fit all of the parameters related to the shape of the CB and ARGUS functions individually in separate intervals of photon energy. One expects, however, a smooth variation of the shapes as a function of $E_\gamma$. To impose this smoothness, a simultaneous fit of the $m_{ES}$ distributions for all of the photon-energy intervals is carried out. The variation of the shape parameters with photon energy is described by polynomials, whose orders are the lowest possible that allow an adequate modeling of the data. Examples of the $m_{ES}$ distributions and results of the simultaneous fit are shown in Fig. 1. The global $\chi^2$ is 330 for the charged $B$ sample and 357 for the neutral sample, both for 387 degrees of freedom.

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 $BB$ MC sample that excludes the signal decay $B \rightarrow X\gamma$. Because of the large background at low energy the signal region is defined as $E_\gamma > 1.9$ GeV. This choice was optimized in MC studies. 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 $BB$ background of 145 $\pm$ 9 events.

For $1.3 < E_\gamma < 1.9$ GeV a comparison of the data and background gives a $\chi^2$ of 9.7 for 5 degrees of freedom. The probability to observe a value at least this great is 8.4%. Our estimate of the systematic uncertainty in the background (described below) is in fact smaller than the observed data-background difference; therefore we regard this difference primarily as a statistical fluctuation.

To determine the partial branching fractions, we require the total number of $BB$ events in the sample after selection of the tag $B$ candidates. In a procedure analogous to that described for the $m_{ES}$ fits in bins of $E_\gamma$, we divide the data into four intervals of estimated tag $B$ candidate purity and perform a simultaneous fit of the $m_{ES}$ distributions. We obtain approximately 680 000 $BB$ events corresponding to an efficiency of 0.3%.

![FIG. 1 (color online). Fits to the distribution of the beam-energy-substituted mass $m_{ES}$ for two $E_\gamma$ regions. The dashed curve shows the CB term and the dotted curve is the ARGUS term, corresponding to $B$ and non-$B$ events, respectively; the solid curve is their sum. (a) $1.6 \text{ GeV} < E_\gamma < 1.7 \text{ GeV}$ for the charged $B$ sample. (b) $2.3 \text{ GeV} < E_\gamma < 2.4 \text{ GeV}$ for the neutral $B$ sample. (c) The measured numbers of $B$ events as a function of photon energy. The points are from data; the histogram is from a $BB$ MC sample which excludes the signal decay $B \rightarrow X\gamma$.](image-url)
IV. DETERMINING THE PHOTON SPECTRUM

The differential decay rate \((1/\Gamma_B)(d\Gamma/dE_\gamma)\) is measured in bins of the \((B\text{-frame})\) photon energy for \(E_\gamma > 1.9\text{ GeV}\) up to the kinematic limit at 2.6 GeV. It is estimated for the \(i\)th bin as

\[
\frac{1}{\Gamma_B \ dE_\gamma} \frac{d\Gamma_i}{dE_\gamma} = \frac{N_i - b_i}{\epsilon_i N_B},
\]

where \(N_i\) is the number of \(B\) events in the bin, \(b_i\) is the number of \(B\) mesons from decays other than \(B \rightarrow X_\gamma\), \(N_B\) is the total number of \(B\) mesons in the sample, and \(\epsilon_i\) is the efficiency, which corrects for both acceptance and bin-to-bin resolution effects. The values \(b_i\) are determined by means of a simultaneous fit to the \(m_{ES}\) distributions as described previously, using a sample of MC data consisting of \(B\bar{B}\) events excluding the signal decay \(B \rightarrow X_\gamma\). As the differential decay rate is normalized using the total width of the \(B\) meson, \(\Gamma_B\), the integral of (1) over all photon energies yields the branching fraction. To evaluate the selection efficiency \(\epsilon_i\), we model the signal photon-energy spectrum using the kinetic scheme \([18]\) with \(m_B = 4.60\text{ GeV}\) and \(\mu^2 = 0.4\text{ GeV}^2\). The value of \(\epsilon_i\) is determined from

\[
\epsilon_i = \frac{N_{\text{found},i}/N_{\text{sim}}}{N_{\text{true},i}/N_{\text{gen}}} C_{\text{tag}},
\]

where \(N_{\text{found},i}\) is the number of events found in a MC sample of \(B \rightarrow X_\gamma\) with detector simulation and \(N_{\text{sim}}\) is the number of events in the simulated sample. These quantities are found using the same fit procedure as applied to the real data for \(N_i\) and \(N_B\). In the denominator of (2), \(N_{\text{true},i}\) is the true number of events with photon energies in bin \(i\) and \(N_{\text{gen}}\) is the total number of events generated. These values are determined using the event generator for \(B \rightarrow X_\gamma\) decays only, without detector simulation. The factor \(C_{\text{tag}}\) estimated using the MC model, corrects for the small dependence of the probability to find a tag \(B\) on the presence of a \(B \rightarrow X_\gamma\) final state. The efficiency increases roughly linearly with photon energy, and is approximately 30% (65%) for \(E_\gamma = 1.9\text{ GeV}\) (2.6 GeV).

To compare with other results we subtract the \(B \rightarrow X_\gamma\) component from the differential decay rates using the standard model prediction (for the \(CP\) and isospin asymmetries discussed below, however, we do not make this correction). The values \(\mathcal{B}(B \rightarrow X_\gamma)\) and \(\mathcal{B}(B \rightarrow X_\gamma)\) are in the ratio \([V_{td}/V_{ts}]^2\) assuming the same efficiency for the two categories of events. Therefore, the branching ratio is lowered by \((4.0 \pm 0.4)\%\) \([19,20]\).

V. SYSTEMATIC UNCERTAINTIES

There are four main sources of systematic uncertainty, which are summarized in Table I: modeling of the \(B\bar{B}\) background, the \(m_{ES}\) fits, detector response and dependence on the \(B \rightarrow X_\gamma\) signal model. In addition there is an uncertainty from the subtraction of the \(B \rightarrow X_{\gamma\gamma}\) contribution.

After subtraction of the nonpeak background using the \(m_{ES}\) distribution, the remaining background is mainly composed of \(B\bar{B}\) events with the selected photon coming from a \(\pi^0\) or \(\eta\) decay. Photons from \(\pi^0\) account for 55% to 65% depending on \(E_\gamma\) and the charge of the tag \(B\), while the contribution from \(\eta\) mesons varies from 18% to 29%. The remaining backgrounds include fake photons from \(\bar{\nu}\) annihilation, real photons from bremsstrahlung or from \(\omega\) decays, and electromagnetic showers from \(e^\pm\) misidentified as photons. As the MC prediction for the \(B\bar{B}\) background is scaled to the data at low energy, there is no uncertainty stemming from the absolute rate, but rather only from the shape of the distribution as a function of \(E_\gamma\).

The uncertainty from the inclusive \(\pi^0\) and \(\eta\) spectra is investigated by using \(E_\gamma\) dependent correction factors for the \(\pi^0\) and \(\eta\) yields from a large control sample of \(B \rightarrow X_\gamma\) candidate events, obtained using a lepton tag. These correction factors are typically around 5% for \(\pi^0\) yields while they can be up to 30% for \(\eta\) yields. The remaining backgrounds have a roughly linear slope with \(E_\gamma\); this is varied by \(\pm 30\%\). We use the difference obtained with the modi-

<table>
<thead>
<tr>
<th>(E_\gamma) (GeV)</th>
<th>(1/(\Gamma_B)(d\Gamma/dE_\gamma)\times10^{-4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9–2.0</td>
<td>0.28 0.56 0.34 0.26 0.13 0.19 0.03</td>
</tr>
<tr>
<td>2.0–2.1</td>
<td>0.60 0.42 0.24 0.18 0.12 0.08 0.05</td>
</tr>
<tr>
<td>2.1–2.2</td>
<td>0.31 0.29 0.14 0.11 0.06 0.03 0.03</td>
</tr>
<tr>
<td>2.2–2.3</td>
<td>0.40 0.23 0.13 0.07 0.05 0.09 0.03</td>
</tr>
<tr>
<td>2.3–2.4</td>
<td>0.91 0.22 0.13 0.07 0.08 0.05 0.06</td>
</tr>
<tr>
<td>2.4–2.5</td>
<td>0.74 0.17 0.19 0.09 0.05 0.02 0.05</td>
</tr>
<tr>
<td>2.5–2.6</td>
<td>0.43 0.12 0.19 0.09 0.03 0.07 0.04</td>
</tr>
</tbody>
</table>

Beginner: A fit to the data yields the following values for the differential decay rate in bins of photon energy:

- For \(E_\gamma = 1.9\text{ GeV}\), the rate is 0.28\%.
- For \(E_\gamma = 2.0\text{ GeV}\), the rate is 0.60\%.
- For \(E_\gamma = 2.1\text{ GeV}\), the rate is 0.31\%.
- For \(E_\gamma = 2.2\text{ GeV}\), the rate is 0.40\%.
- For \(E_\gamma = 2.3\text{ GeV}\), the rate is 0.91\%.
- For \(E_\gamma = 2.4\text{ GeV}\), the rate is 0.74\%.
- For \(E_\gamma = 2.5\text{ GeV}\), the rate is 0.43\%.

These rates are consistent with the standard model prediction, within uncertainties.
MEASUREMENT OF THE \( B \to X_\gamma \gamma \) …

fied MC compared to the standard MC simulation as a
systematic uncertainty.

To assess the uncertainty related to the parametrization
chosen for the \( m_{ES} \) fit, additional coefficients are intro-
duced that allow linear or higher-order dependence of the
CB and ARGUS function shape parameters on the photon
energy. The maximum variation in the fitted rates is taken
as the systematic uncertainty. A similar set of variations for
the dependence of the shape parameters on the \( B \) meson
purity is carried out for the \( m_{ES} \) fits used to determine
the total number of \( B \) mesons in the data sample. To allow for
a small peaking component in the distribution of \( m_{ES} \) from
\( B^\pm \) decays reconstructed as \( B^0 \) (\( \bar{B}^0 \)) decays and
vice versa, we remove these events from the MC sample and
take the difference in the result as a systematic uncertainty.

The uncertainties related to the detector modeling and
event reconstruction are estimated by comparing MC
simulations of track and photon efficiencies as well as
particle identification efficiencies with data control
samples. From these comparisons we estimate correspond-
ing systematic errors, which are in all cases small com-
pared to other uncertainties.

To assess the uncertainty in the efficiency due to the
assumed shape of the \( E_\gamma \) spectrum, we vary \( m_b \) and \( \mu^2_{\tau} \)
in the kinetic scheme by \( \pm 0.1 \) GeV and \( \pm 0.1 \) GeV\(^2\), respecti-
vately. These variations are large compared to the uncer-
tainties in the world average [10] in order to cover
alternative Ansätze for the heavy quark distribution func-
tion [21,22]. They also account for uncertainties related to
the small rate of \( B \to X_\gamma \) decays expected below 1.9 GeV.

VI. RESULTS

The partial branching fractions \((1/\Gamma_B)(d\Gamma/dE_\gamma)\)
are shown in Fig. 2 after all corrections. The inner error bars
show the statistical uncertainties. The outer error bars show
the quadratic sum of the statistical and systematic terms.

By integrating the spectrum, we obtain \( \mathcal{B}(B \to X_\gamma \gamma) =
(3.66 \pm 0.85^{+0.60}_{-0.60} \times 10^{-4}) \) for the di-

erential decay rate and for the moments of the photon-
energy spectrum for various minimum photon energies \( E_{cut} \)
are given in Table I. The branching fraction for larger values
of \( E_{cut} \) and the correlations between the measure-
ments are given in Ref. [23]. Our results are in good
agreement with those presented in Refs. [1–4].

We also measure the isospin asymmetry \( \Delta_{0^-} \),

\[
\Delta_{0^-} = \frac{\Gamma(B^0 \to X_{s,d}\gamma) - \Gamma(B^- \to X_{s,d}\gamma)}{\Gamma(B^0 \to X_{s,d}\gamma) + \Gamma(B^- \to X_{s,d}\gamma)}, \tag{3}
\]

where inclusion of charge conjugate modes is implied. It
has been argued that enhanced power corrections to the
\( B \to X_\gamma \gamma \) rate could also lead to values of \( \Delta_{0^-} \) as large as
+10% [24]. Therefore, experimental measurements of
\( \Delta_{0^-} \) can help determine the size of these effects and hence
reduce the theoretical uncertainty on the total rate. To
obtain decay rates from the branching fractions we use
the \( B \) meson lifetimes: \( \tau(B^0) = 1.530 \pm 0.008 \text{ ps} \) and
\( \tau(B^+) = 1.638 \pm 0.011 \text{ ps} \) [25]. For photon energies
greater than 2.2 GeV, we obtain \( \Delta_{0^-} = -0.06 \pm 0.15^{+0.07}_{-0.07} \text{ stat} \).

The direct \( CP \) asymmetry \( A_{CP} \),

\[
A_{CP} = \frac{\mathcal{B}(B \to X_{s,d}\gamma) - \mathcal{B}(B \to X_{s,d}\gamma)}{\mathcal{B}(B \to X_{s,d}\gamma) + \mathcal{B}(B \to X_{s,d}\gamma)} \frac{1}{1 - 2\omega}, \tag{4}
\]
is measured by splitting the tag sample into \( B \) and \( \bar{B} \)
mesons. The dilution factor \( \frac{1}{1 - 2\omega} \) accounts for the mistag
fraction \( \omega \), here simply the time integrated \( B^0 \) mixing
probability of \( \chi_d = 0.188 \pm 0.003 \) [25] multiplied by the
fraction of \( B^0 \) events in the total data sample. \( A_{CP} \) can be
significantly enhanced by new physics [19] while in the
SM it is predicted to be around \( 10^{-4} \) [26,27]. We obtain a
value of \( A_{CP} = 0.10 \pm 0.18^{+0.05}_{-0.05} \text{ stat} \) for photon ener-
gies above 2.2 GeV.

For both \( \Delta_{0^-} \) and \( A_{CP} \), a photon-energy cutoff of
2.2 GeV is chosen because it facilitates comparison with
previous results and minimizes the total uncertainty. Our
results are in good agreement with previous measurements
[3,4,28–30].

Finally, we use heavy-quark expansions in the kinetic
scheme [18] and our measurements of the \( E_\gamma \) moments to
determine the parameters \( m_b \) and \( \mu^2_{\tau} \). We include
the theoretical uncertainties quoted in Ref. [18] in the overall
covariance matrix used in the fit. To minimize the theo-
retical uncertainty we only use moments with \( E_{cut} \leq
2.0 \text{ GeV} \) and obtain \( m_b = 4.46^{+0.21}_{-0.23} \text{ GeV} \) and
\( \mu^2_{\tau} = 0.64^{+0.39}_{-0.38} \text{ GeV}^2 \) with a correlation of \( \rho = -0.94 \).

VII. CONCLUSIONS

We have measured the \( B \to X_\gamma \gamma \) branching fraction and
moments of the photon-energy spectrum above several

FIG. 2. The partial branching fractions \((1/\Gamma_B)(d\Gamma/dE_\gamma)\) with statistical (inner) and total (outer) uncertainties.
minimum photon energies. We find $B(B \to X_s \gamma) = (3.66 \pm 0.85_{\text{stat}} \pm 0.60_{\text{syst}} \times 10^{-4}$ for photon energies $E_{\gamma}$ above 1.9 GeV. Dividing by an extrapolation factor of 0.936 $\pm$ 0.010 [10] we obtain $B(B \to X_s \gamma) = (3.91 \pm 0.91_{\text{stat}} \pm 0.64_{\text{syst}} \times 10^{-4}$ for $E_{\gamma} > 1.6$ GeV. The moments of the spectrum can be used to improve the knowledge of the heavy-quark parameters $m_b$ and $\mu^2_{b\gamma}$; we obtain $m_b = 4.46_{-0.23}^{+0.21}$ GeV and $\mu^2_{b\gamma} = 0.64_{-0.38}^{+0.39}$ GeV$^2$ in the kinetic scheme. In addition we measured the isospin asymmetry $A_{0^-} = -0.06 \pm 0.15_{\text{stat}} \pm 0.07_{\text{syst}}$ and direct CP asymmetry $A_{CP} = 0.10 \pm 0.18_{\text{stat}} \pm 0.05_{\text{syst}}$ for photon energies above 2.2 GeV. The full reconstruction (recoil) method provides an almost background free measurement above photon energies of 2.2 GeV. Although statistics are limited at present, this approach is expected to provide a competitive measurement of the decay $B \to X_s \gamma$ with the larger data sample that is being accumulated at the $B$-factories, in particular, as the main systematic uncertainties will also be reduced with a larger data sample.

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