Measurement of $B \rightarrow K^{*-}(892)\gamma$ Branching Fractions and CP and Isospin Asymmetries

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</tbody>
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Measurement of $B \rightarrow K^*(892)$ γ Branching Fractions and CP and Isospin Asymmetries

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We present an analysis of the decays $B^0 \to K^0(892)\gamma$ and $B^+ \to K^{*+}(892)\gamma$ using a sample of about $383 \times 10^6 B\bar{B}$ events collected with the BABAR detector at the PEP-II asymmetric energy $B$ factory. We measure the branching fractions $\mathcal{B}(B^0 \to K^0\gamma) = (4.47 \pm 0.10 \pm 0.16) \times 10^{-5}$ and $\mathcal{B}(B^+ \to K^{*+}\gamma) = (4.22 \pm 0.14 \pm 0.16) \times 10^{-3}$. We constrain the direct CP asymmetry to be
the assumed signal branching fraction is 4

are the rates for signal and background, respectively, and

The dominant source of background is continuum events

maximum statistical sensitivity of

requirements described below have been optimized for the

supercede the previous

and a GEANT4 [16] detector simulation. These results

use of events simulated using Monte Carlo (MC) methods

mal supersymmetric model parameter space [12].

In this Letter, we report measurements of

In the standard model (SM), the decays

B → K* γ decays are reconstructed in the following K*

modes: K*0 → K+ π−, K*0 → Ks π0, K*+ → K+ π0, and

K*+ → Kπ+ π−. For each signal decay mode, the selection

requirements described below have been optimized for the

maximum statistical sensitivity of S/ √ S + B, where S and

and B are the rates for signal and background, respectively, and

the assumed signal branching fraction is 4.0 × 10−5 [3].

The dominant source of background is continuum events

[e+ e− → q ¯ q(γ), with q = u, d, s, c] that contain a high-

energy photon from a π0 or η decay or from an initial-state

radiation process. Backgrounds coming from BB events

are mostly from higher-multiplicity b → sγ decays, where

one or more particles have not been reconstructed, and

from decays of one B → K* γ mode that enter the signal

selection of another mode by misreconstructing the K*

meson.

Photon candidates are identified as localized energy

deposits in the calorimeter (EMC) that are not associated

with any charged track. The signal photon candidate is

required to have a c.m. energy between 1.5 and 3.5 GeV,

to be well isolated and to have a shower shape consistent

with an individual photon [17]. In order to veto photons

from π0 and η decays, we form photon pairs composed of

the signal photon candidate and all other photon candidates

in the event. We then reject signal photon candidates con-

sistent with coming from a π0 or η decay based on a

likelihood ratio that uses the energy of the partner photon,

and the invariant mass of the pair.

Charged particles, except those used to form Ks candidates,

are selected from well-reconstructed tracks that have

at least 12 hits in the drift chamber (DCH), and are required

to be consistent with coming from the e+ e− interaction

region. They are identified as K or π mesons by the

Cherenkov angle measured in the Cherenkov photon de-

tector (DIRC) as well as by energy loss of the track

(dE/dx) in the silicon vertex tracker and DCH. The Ks candidates

are reconstructed from two oppositely charged

tracks that come from a common vertex. In the K*0 → Ks π0

(K*+ → Kπ+ π0) mode, we require the invariant mass of the pair to be

0.49 < mπ− < 0.52 GeV/c2 (0.48 < mπ− < 0.52 GeV/c2) and the reconstructed decay length of the Ks to be at least 9.3(10) times its uncertainty.

We form π0 candidates by combining two photons (ex-

cluding the signal photon candidate) in the event, each of

which has an energy greater than 30 MeV in the laboratory

frame. We require the invariant mass of the pair to be

0.112 < mγγ < 0.15 GeV/c2 and 0.114 < mγγ <

0.15 GeV/c2 for the K*0 → Ks π0 and K*+ → K+ π0

modes, respectively. In order to refine the π0 three-

momentum vector, we perform a mass-constrained fit of the

two photons.

We combine the reconstructed K and π mesons to form

K* candidates. We require the invariant mass of the pair to satisfy

0.78 < mK+ π− < 1.1 GeV/c2, 0.82 < mK+ π0 <

1.0 GeV/c2, 0.79 < mK+ ρ0 < 1.0 GeV/c2, and

0.79 < mKs π− < 1.0 GeV/c2. The charged track pairs of the

K*0 → K+ π− mode are required to originate from a com-

mon vertex.

The K* and high-energy photon candidates are com-

bined to form B candidates. We define in the c.m. frame

(the asterisk denotes a c.m. quantity) ΔE ≡ E_B^* − E_B^beam^, where

E_B^* is the energy of the B meson candidate and E_B^beam^ is the beam energy. The beam-energy-substituted mass is

defined as

where p_B^* is the moment-
tum of the $B$ candidate. In addition, we consider the helicity angle $\theta_H$ of the $K^*$, defined as the angle between the momenta one of the daughters of the $K^*$ meson and the $B$ candidate in the $K^*$ rest frame. The distribution of $\cos\theta_H$ is $\sin^2\theta$ for signal events. Signal events have $\Delta E$ close to zero with a Gaussian resolution of approximately 50 MeV, and an $m_{ES}$ distribution centered at the mass of the $B$ meson with a Gaussian resolution of approximately 3 MeV/$c^2$. We only consider candidates in the ranges $-0.3 < \Delta E < 0.3$ GeV, $m_{ES} > 5.22$ GeV/$c^2$, and $|\cos\theta_H| < 0.75$. To eliminate badly reconstructed events, we apply a loose selection criterion to the vertex separation (and its uncertainty) along the beam axis between the $B$ meson candidate and the rest of the event (ROE). The ROE is defined as all charged tracks and neutral energy deposits in the calorimeter that are not used to reconstruct the $B$ candidate.

In order to reject continuum background, we combine 13 variables into a neural network. One class of these variables exploits the topological differences between isotropically distributed signal events and jetlike continuum events by considering correlations between the $B$ meson candidate and the ROE. The other class exploits the fact that $B$ meson decays tend to not conserve flavor, while continuum events tend to be flavor-conserving. The discriminating variables are described in Ref. [18]. Each signal mode has a separately trained neural network, whose output peaks at a value of one for signal-like events and zero for background-like events. A selection is made upon the output.

After applying all the selection criteria, there are, on average, $\sim1.1B^0/B^+$ candidates per event in simulated signal events. In events with multiple candidates, we select the candidate with the reconstructed $K^*$ mass closest to the nominal $K^*$ mass [19].

We perform an unbinned extended maximum likelihood fit to extract the signal yield, constructing a separate fit for each mode. Since the correlations among the three observables $(m_{ES}, \Delta E, \cos\theta_H)$ are small, we use uncorrelated probability distribution functions (PDFs) each representing the observables to construct the likelihood function. The likelihood function is

$$L = \exp\left(-\sum_{i=1}^{M} n_i \prod_{j=1}^{N} \sum_{l=1}^{L} P_j(x_j; \alpha_l)\right)$$

where $N$ is the number of events, $M = 3$ is the number of hypotheses (signal, continuum, and $B\bar{B}$), and $n_i$ is the yield of a particular hypothesis. $P_j$ is the product of one-dimensional PDFs over the three dimensions $x$, and $\alpha$ represents the fit parameters. All types of $B\bar{B}$ background are included in the $B\bar{B}$ component, which is suppressed by the use of $\cos\theta_H$. The signal $m_{ES}$ distribution for the $K^{*0} \rightarrow K_S\pi^0$ and $K^{*+} \rightarrow K^+\pi^0$ modes is described by a Crystal Ball function [20], which has two tail parameters that are fixed to values obtained from MC simulation. For the $K^{*0} \rightarrow K^+\pi^-$ and $K^{*+} \rightarrow K_S\pi^+$ modes, the signal $m_{ES}$ distribution is parametrized as a piecewise function $f(x) = \exp\left[-(x - \mu)^2/\sigma_L^2 + \alpha_{L,R}(x - \mu)^2\right]$, defined to the left (L) and right (R) of $\mu$, which is the peak position of the distribution. Here, $\sigma_{L,R}$ and $\alpha_{L,R}$ are the widths and measures of the tails, respectively, to the left and right of the peak. We constrain $\sigma_L = \sigma_R$, which is fixed, and float $\alpha_{L,R}$ to values obtained from MC simulation. This same function also describes the signal $\Delta E$ distribution for each mode, but with different values for the parameters. In addition, we allow $\sigma_L$ and $\sigma_R$ to float independently. The $\cos\theta_H$ distribution for the signal component is modeled by a second-order polynomial, with all of its parameters floating in the fit. For the continuum hypothesis, the $m_{ES}$ PDF is parametrized by an ARGUS function [21], with its shape parameter floating in the fit. The continuum $\Delta E$ and $\cos\theta_H$ shapes are modeled by a first- or second-order polynomial with its parameters floating in the fit. Various functional
TABLE I. The signal reconstruction efficiency $\epsilon$, the fitted signal yield $N_S$, branching fraction, $B$, and $CP$ asymmetry, $A$, for each decay mode. Errors are statistical and systematic, with the exception of $\epsilon$ and $N_S$, which have only systematic and statistical errors, respectively.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\epsilon$ (%)</th>
<th>$N_S$</th>
<th>$B \times 10^{-5}$</th>
<th>Combined $B \times 10^{-5}$</th>
<th>$A$</th>
<th>Combined $A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+\pi^-$</td>
<td>21.8 ± 0.8</td>
<td>2400.0 ± 55.4</td>
<td>4.45 ± 0.10 ± 0.17</td>
<td>4.47 ± 0.10 ± 0.16</td>
<td>-0.016 ± 0.022 ± 0.007</td>
<td>-0.003 ± 0.017 ± 0.007</td>
</tr>
<tr>
<td>$K_\pi^0$</td>
<td>13.0 ± 0.9</td>
<td>256.0 ± 20.6</td>
<td>4.66 ± 0.37 ± 0.35</td>
<td>4.22 ± 0.14 ± 0.16</td>
<td>+0.040 ± 0.039 ± 0.007</td>
<td>-0.006 ± 0.041 ± 0.007</td>
</tr>
<tr>
<td>$K^+\pi^0$</td>
<td>15.3 ± 0.8</td>
<td>872.7 ± 37.6</td>
<td>4.38 ± 0.19 ± 0.26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^+\pi^+$</td>
<td>20.1 ± 0.7</td>
<td>759.1 ± 33.8</td>
<td>4.13 ± 0.18 ± 0.16</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

forms are used to describe the $B\bar{B}$ background, all parameters of which are taken from MC simulation and held fixed. All of the component yields are floating.

Figure 1 and Table I show the results of the likelihood fit to data. The branching fractions have been obtained using $B(Y(4S) \rightarrow B^0\bar{B}^0) = 0.484 ± 0.006$, $B(Y(4S) \rightarrow B^+\bar{B}^-) = 0.516 ± 0.006$ [19]. Also shown are the combined branching fractions, which have been calculated taking into account correlated systematic errors.

The $CP$ asymmetry $A$ is measured in three modes: $K^{*0} \rightarrow K^+\pi^-$, $K^{*+} \rightarrow K^+\pi^+$, and $K^+ \rightarrow K_S\pi^+$. In each of these modes, the final state of the signal $B$ meson is determined by its final state daughters. The fit is accomplished by performing a simultaneous fit to the two flavor subsamples ($K^+$ and $K^0$) in each mode. All shape parameters are assumed to be flavor independent and the $A$ of each component is floated in the fit. Table I gives the individual and combined $A$ results.

Table II lists the sources of systematic uncertainty for the branching fractions for all four modes. The “fit model” systematic incorporates uncertainties due to imperfect knowledge of the normalization and shape of the inclusive $B \rightarrow X_{s}\gamma$ spectra, and the choice of fixed parameters. The “signal PDF bias” systematic uncertainty characterizes any bias resulting from correlations among the three observables, or incorrect modeling of the signal PDFs. The remaining sources of error on the signal efficiency are studied using control samples in the data. From all of these studies, we derive signal efficiency correction factors and associated uncertainties. The total corrections are 0.953, 0.897, 0.919, and 0.936 for the $K^{*0} \rightarrow K^+\pi^-$, $K^{*0} \rightarrow K_S\pi^0$, $K^{*+} \rightarrow K^+\pi^0$, and $K^+ \rightarrow K_S\pi^+$ modes, respectively. The systematic error on $A$ comes entirely from the hadronic interaction of the final state mesons with the detector material. This can cause asymmetries in tracking efficiency, which is studied using existing hadronic interaction data, and in particle identification, which is studied using a $D^{*+} \rightarrow D^0\pi^+(D^0 \rightarrow K^-\pi^+) B$ control sample. The $D^*$ control sample gives a shift of $-0.33\%$ for $K^0$ and $+0.03\%$ for $K^+$, while the hadronic data give a shift of $-0.38\%$ for $K_S$ and $+0.02\%$ for $K^-$. The systematic errors for the isospin asymmetry are calculated from the branching fractions, taking into account correlated systematic errors.

We combine the branching fractions and the ratio of the $B^+$ and $B^0$ lifetime $\tau_+ / \tau_0 = 1.071 ± 0.009$ [19] to obtain the isospin asymmetry $\Delta_0^+ / \Delta_0^- = 0.066 ± 0.021 ± 0.022$, which corresponds to $0.017 < \Delta_0^- / \Delta_0^+ < 0.116$ at the 90% confidence interval. We also measure $\Delta A(B^+ \rightarrow K^{*+}\gamma) = 0.018 ± 0.028 ± 0.007$. The total combined $CP$ asymmetry is $A = -0.003 ± 0.017 ± 0.007$, with a 90% confidence interval of $-0.033 < A < 0.028$.

Figure 2 shows the relativistic $P$-wave Breit-Wigner line shape fit to the $K\pi$ invariant mass distribution of data events weighted using the sPlot technique [22] to project out the signal component. For the $K^{*0} \rightarrow K_S\pi^0$ and $K^{*+} \rightarrow K^+\pi^0$ modes, we convolve the Breit-Wigner line shape with a Gaussian with a width of 10 MeV (determined

<table>
<thead>
<tr>
<th>TABLE II. Systematic errors (in %) of the branching fractions.</th>
<th>$K^+\pi^-$</th>
<th>$K_S\pi^0$</th>
<th>$K^+\pi^0$</th>
<th>$K_S\pi^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(Y(4S) \rightarrow B^0\bar{B}^0) / B(Y(4S) \rightarrow B^+\bar{B}^-)$</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>$B\bar{B}$ sample size</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>1.2</td>
<td>\cdots</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Particle identification</td>
<td>0.6</td>
<td>\cdots</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Photon selection</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>$\pi^0$ reconstruction</td>
<td>\cdots</td>
<td>3.0</td>
<td>3.0</td>
<td>\cdots</td>
</tr>
<tr>
<td>$\pi^0$ and $\eta$ veto</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$K_S$ reconstruction</td>
<td>\cdots</td>
<td>0.7</td>
<td>\cdots</td>
<td>0.7</td>
</tr>
<tr>
<td>Neural net efficiency</td>
<td>1.5</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Fit model</td>
<td>0.8</td>
<td>5.6</td>
<td>3.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Signal PDF bias</td>
<td>0.9</td>
<td>2.2</td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Sum in quadrature</td>
<td>3.9</td>
<td>7.5</td>
<td>5.7</td>
<td>4.1</td>
</tr>
</tbody>
</table>
from MC simulation) to account for detector resolution. For the $K^{*0} \rightarrow K^+ \pi^-$ and $K^{*+} \rightarrow K^0 \pi^+$ modes, the detector resolution is negligible. The results are consistent with the signal events containing only $P$-wave $K^*$ mesons and no other $K\pi$ resonances. We estimate the contribution from the $K^*(1430)$ to the invariant mass regions $m_{K^+\pi^-}$, $m_{K^0\pi^0}$, and $m_{K^+\pi^0}$ defined above by using the measured values of the branching fractions of $B^0 \rightarrow K^{*0}(1430)\gamma$ and $B^+ \rightarrow K^{*+}(1430)\gamma$ [23]. We find that the contribution is $\sim 1$ event or less.

We conclude that, using a sample that is almost 5 times larger than previously used, we have made considerably more precise measurements of the $B \rightarrow K^*\gamma$ decay processes than Refs. [2–4]. The measured isospin and $CP$ asymmetries and branching fractions are consistent with SM expectations. By tightly constraining these observables, we have set limits on supersymmetric and other new physics processes, which can interfere with SM processes.

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[1] $K^*$ refers to the $K^*(892)$ resonance throughout this Letter.
[10] Charge conjugate modes are implied throughout, except for the $CP$ asymmetry.