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Measurement of branching fractions and CP and isospin asymmetries for $B \to K^* \gamma$

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The branching fractions of the decays $B^0 \to K^{*0}\gamma$ and $B^+ \to K^{*+}\gamma$ are measured using a sample of $88 \times 10^6 B\overline{B}$ events collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider. We find $\mathcal{B}(B^0 \to K^{*0}\gamma) = [3.92 \pm 0.20(\text{stat}) \pm 0.24(\text{syst})] \times 10^{-5}$, $\mathcal{B}(B^+ \to K^{*+}\gamma) = [3.87 \pm 0.28(\text{stat}) \pm 0.26(\text{syst})] \times 10^{-5}$. Our measurements also constrain the direct *CP* asymmetry to be

$-0.074 < \mathcal{A}(B \to K^*\gamma) < 0.049$ and the isospin asymmetry to be $-0.046 < \Delta_{0-} < 0.146$, both at the 90% confidence level.

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Within the standard model (SM), the decays $B \to K^*\gamma$ proceed dominantly through one-loop $b \to s\gamma$ electromagnetic ''penguin'' transitions [1]. Non-SM virtual particles may be present in these loops, changing the decay rates from the SM predictions. Theoretical calculations of exclusive $B \to K^*\gamma$ decay rates have large uncertainties due to nonperturbative hadronic effects [2–4], limiting their usefulness for probing new physics. Previous measurements [5–7] of the branching fractions are already more precise than SM-based theoretical estimates and are in reasonable agreement with them. Calculations [8,9] of the form factor for $B \to K^*\gamma$ can be tested using improved measurements of these branching fractions.

Much of the theoretical uncertainty in the branching fractions cancels in the ratios defining the isospin asymmetry Δ_{0-} and the CP asymmetry $\mathcal{A}$:

$$\Delta_{0-} = \frac{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\gamma) - \Gamma(B^- \to K^{*-}\gamma)}{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\gamma) + \Gamma(B^- \to K^{*-}\gamma)}, \quad (1)$$

$$\mathcal{A} = \frac{\Gamma(\overline{B} \to \overline{K}^{*}\gamma) - \Gamma(B \to K^{*}\gamma)}{\Gamma(\overline{B} \to \overline{K}^{*}\gamma) + \Gamma(B \to K^{*}\gamma)}, \quad (2)$$

making them stringent tests of the SM. A further advantage of these asymmetries is that some experimental systematic uncertainties cancel in the ratios. The SM predicts a positive value of Δ_{0-} between 5% and 10% [10] and $|\mathcal{A}|$ less than 1% [11]. New physics contributions can modify these values significantly [10,11].

In this paper, we present measurements of the exclusive branching fractions $\mathcal{B}(B^0 \to K^{*0}\gamma)$ and $\mathcal{B}(B^+ \to K^{*+}\gamma)$, the isospin asymmetry (Δ_{0-}), and the CP asymmetries $\mathcal{A}(B^0 \to K^{*0}\gamma)$ and $\mathcal{A}(B^+ \to K^{*+}\gamma)$. K^* refers to the $K^*(892)$ resonance throughout this paper. Inclusion of charge-conjugate decays is implied except in the definitions of $\mathcal{A}$. This analysis uses $(88 \pm 1) \times 10^6 B\overline{B}$ events, from $\Upsilon(4S)$ decays, recorded by the *BABAR* detector [12]. An additional 10 fb^{-1} of data, taken 40 MeV below the $\Upsilon(4S)$ resonance, is used for studying non-B continuum background. After $B \to K^*\gamma$ event reconstruction and background rejection, multidimensional extended maximum likelihood fits are used to extract the final results.

We reconstruct $B^0 \to K^{*0}\gamma$ in the $K^{*0} \to K^+\pi^-$, $K^0_S\pi^0$ modes and $B^+ \to K^{*+}\gamma$ in the $K^{*+} \to K^+\pi^0$, $K^0_S\pi^+$ modes as described in detail in Refs. [6,12]. Reconstructed tracks are identified as final state $\pi^\pm$ and $K^\pm$ mesons by measuring the angle of the Cherenkov cone and energy loss along the track (dE/dx). The K^0_S candidates are composed from pairs of oppositely charged tracks with an invariant mass that is within 3.3σ of the nominal K^0_S mass and with a vertex that is at least 0.3 cm away from the primary event vertex. The π^0-candidate momentum vector is determined by a mass-constrained fit to pairs of photons, reconstructed from energy deposits in the calorimeter that are not matched to tracks. The K and π candidates are combined to form K^* candidates, which are required to have invariant mass in the range $800 < M_{K\pi} < 1000$ MeV/c^2. The primary-photon candidates are required to have high center-of-mass (CM) energy, between 1.5 and 3.5 GeV, and to satisfy additional requirements designed to suppress the large π^0 and η background as described in Ref. [6].

The B-meson candidates are reconstructed by combining the K^* and high-energy photon candidates. We define in the CM frame (denoted by asterisks) $\Delta E^* \equiv E^*_B - E^*_{\rm beam}$, where $E^*_{\rm beam}$ is the beam energy, known to high precision, and $E^*_B = E^*_\gamma + E^*_{K^*}$ is the energy of the B-meson candidate. We also define the beam-energy-substituted mass $m_{\rm ES} \equiv \sqrt{E^{*2}_{\rm beam} - p^{\prime *2}_B}$, where $p^{\prime *}_B$ is the momentum of the B candidate modified by scaling the photon energy to make $E^*_\gamma + E^*_{K^*} - E^*_{\rm beam} = 0$. This procedure reduces the tail in the signal $m_{\rm ES}$ distribution, which results from the asymmetric calorimeter response. For signal decays, this ''rescaled'' $m_{\rm ES}$ peaks near 5.279 GeV/c^2 with a resolution of ≈ 3 MeV/c^2 and ΔE^* peaks near 0 MeV with a resolution of ≈ 50 MeV. We consider only candidates with $m_{\rm ES} > 5.20$ GeV/c^2 and $|\Delta E^*| < 0.3$ GeV.

Background events arise predominantly from random combinations of particles in $q\overline{q}$ production ($q = u, d, s, c$), with the high-energy photon originating from initial-state radiation or from π^0 and η decays. We suppress this jetlike background in favor of the spherical signal events, using several event-shape variables as in Ref. [6]. To maximize separation between signal and background, these variables are combined in neural networks that are separately optimized for each decay mode. Each network is trained using Monte Carlo (MC) events and is validated on statistically independent MC samples. Cuts are made on the neural-network output to suppress continuum background. The $m_{\rm ES}$ and ΔE^* distributions of data are shown in Fig. 1 for all four K^* decay modes.

The remaining background includes that from $B\overline{B}$ events, which is dominated by $B \to X_s\gamma$ decays, where

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§Deceased.

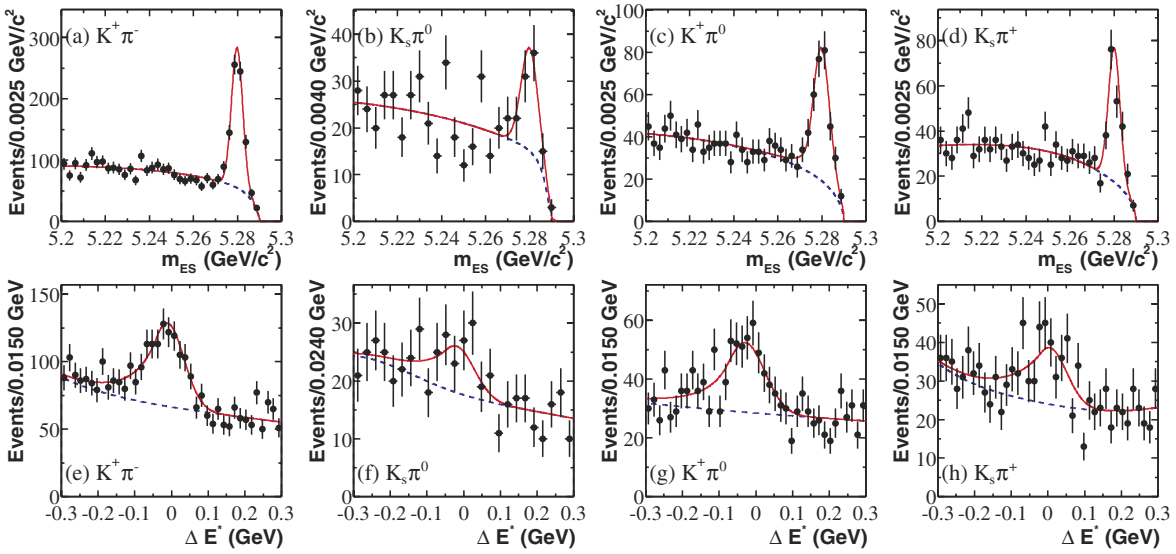

FIG. 1 (color online). $m_{\rm ES}$ and ΔE^*distributions for the $B \to K^* \gamma$ candidates. The points are data, and the solid and dashed curves show the projections of the complete fit and the background component alone, respectively. The fits used to extract the signal yields are described in the text.

X_s represents hadronic final states other than K^*. If one or more particles escape detection, X_s may be incorrectly reconstructed as K^*, leading to a value of $m_{\rm ES}$ near the B-meson mass, but with ΔE^* distinctly negative.

For each decay mode, the signal yield and asymmetry $\mathcal{A}$ (except for the $K_s\pi^0$ mode) are simultaneously extracted using an extended unbinned maximum likelihood fit,

$$\mathcal{L} = \exp\left(-\sum_{i=1}^{3} n_i\right)\left[\prod_{j=1}^{N}\sum_{i=1}^{3} N_i \mathcal{P}(\vec{x}_j;\vec{\alpha}_i)\right],$$

to the two-dimensional distribution of $m_{\rm ES}$ and ΔE^* with three hypotheses (index i): signal, continuum background, and B background. The probability density function (PDF) $\mathcal{P}(\vec{x}_j;\vec{\alpha}_i)$ for each of the three hypotheses is the product of individual PDFs of the fit variables $\vec{x}_j = (m_{\rm ES}, \Delta E^*)$. $\vec{\alpha}_i$ are the shape parameters for the PDFs described below. In the three self-flavor-tagged modes ($K^+\pi^-$, $K^+\pi^0$, and $K_s\pi^+$), $N_i = \frac{1}{2}(1 - \mathcal{F}\mathcal{A}_i)n_i$, where n_i and $\mathcal{A}_i$ stand for the total yield and CP asymmetry of signal, continuum background, and B background, while in the $K_s\pi^0$ decay mode, $N_i = n_i$. The bottom-quark flavor $\mathcal{F}$ is defined as -1 for b quarks and $+1$ for $\bar{b}$ quarks. In the $K^+\pi^-$ mode, mistagging is possible if both the pion and kaon are misidentified, but this probability is negligibly small. We assume that the CP asymmetry of the B background and that of the continuum background are the same.

To reduce systematic errors, most of the fit parameters for the signal and for the continuum background are determined by a fit to data. For continuum background, the ΔE^* distribution is modeled by a first-order polynomial function with the exception of $K_s\pi^+$, where a second-order polynomial is used. The $m_{\rm ES}$ distribution for continuum background is modeled with an ARGUS function [13]. In the $K^+\pi^0$ decay mode, the continuum background shape is simultaneously fit to the off-resonance data to obtain a stabler fit. For the B background, the Gaussian distribution

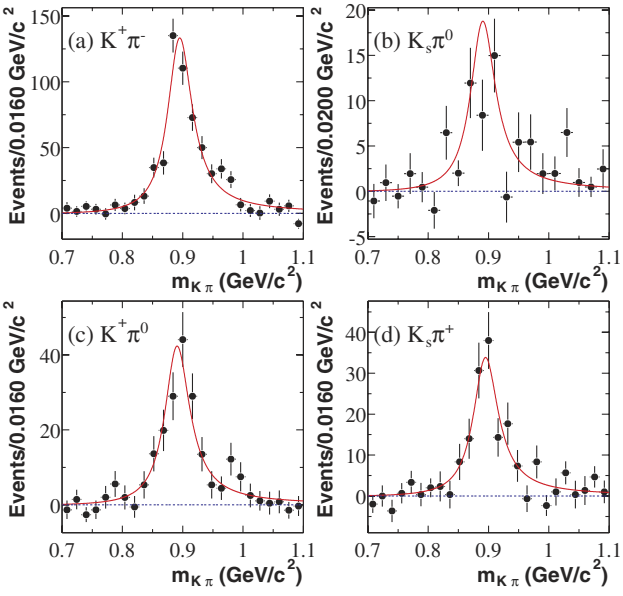

FIG. 2 (color online). $m_{K\pi}$ spectra for the different decay modes for events in the signal region after background subtraction using sidebands in $m_{\rm ES}$ and ΔE^*. The points are data and solid curves represent relativistic p-wave Breit-Wigner line shapes with masses and widths of K^* taken from Ref. [17].

TABLE I. The signal efficiency ϵ, the fitted signal yield N_S, the branching fraction $\mathcal{B}$, and the CP asymmetry $\mathcal{A}$ for each decay mode. The combined branching fractions for $B^0 \to K^{*0}\gamma$ and $B^+ \to K^{*+}\gamma$, and combined CP asymmetry for all three modes studied, are also shown. Errors are statistical and systematic, with the exception of ϵ and N_S, which have only systematic and statistical errors, respectively. The detailed systematic errors are listed in Table II.

Mode	$\epsilon(\%)$	N_S	$\mathcal{B}(\times 10^{-5})$	Combined $\mathcal{B}(\times 10^{-5})$	$\mathcal{A}$	Combined $\mathcal{A}$
$K^+\pi^-$	24.4 ± 1.4	583 ± 30	$3.92 \pm 0.20 \pm 0.23$	$3.92 \pm 0.20 \pm 0.24$	$-0.069 \pm 0.046 \pm 0.011$	$-0.013 \pm 0.036 \pm 0.010$
$K_s\pi^0$	15.3 ± 1.9	62 ± 15	$4.02 \pm 0.99 \pm 0.51$			
$K^+\pi^0$	17.4 ± 1.6	251 ± 23	$4.90 \pm 0.45 \pm 0.46$	$3.87 \pm 0.28 \pm 0.26$	$0.084 \pm 0.075 \pm 0.007$	
$K_s\pi^+$	22.1 ± 1.4	157 ± 16	$3.52 \pm 0.35 \pm 0.22$		$0.061 \pm 0.092 \pm 0.007$	

used for ΔE^* and the Novosibirsk function [14] used for $m_{\rm ES}$ have all shape parameters fixed to values determined from MC. The signal ΔE^* distribution is modeled as a Crystal Ball function [15], which is a Gaussian distribution with a lowside power-law tail that is fixed using MC. The $m_{\rm ES}$ distribution for signal is modeled as a Gaussian function, except for the $K^+\pi^0$ decay mode, where a Crystal Ball function, with tail parameters fixed using MC fits, is used to accommodate a lowside tail due to the π^0 energy lost from the calorimeter. The same lowside tail in the $K_s\pi^0$ decay mode is ignored due to the small number of events in this mode.

Correlations between $m_{\rm ES}$ and ΔE^* distributions could introduce a bias in the signal yields. To study this, randomly selected events from our detailed MC simulation of the signal were mixed with background events generated using the PDF from the fit. In this way, we determined that the $K^+\pi^-$ efficiency must be corrected by multiplying it by 0.98. For the $K^0_S\pi^0$, $K^+\pi^0$, and $K^0_S\pi^+$ modes, the corresponding numbers are 0.91, 0.96, and 0.96. The error in this fit bias due to MC statistics is included as a systematic uncertainty. These MC studies also indicate that correlations between the B background and the continuum background fit yields do not affect the fitted signal yield.

The projections of the maximum likelihood fits on $m_{\rm ES}$ and ΔE^* are shown in Fig. 1 for each decay mode. Figure 2 shows that the background-subtracted $K\pi$ invariant mass distributions agree well with the expected K^* resonance shape. This confirms that the signal is consistent with coming from only true K^* decays.

Table I shows signal efficiencies, yields from the fits, and branching fractions ($\mathcal{B}$) calculated using our recent measurement [16] of the production ratio of charged and neutral B events, $R^{+/0} \equiv \Gamma(e^+e^- \to B^+B^-)/\Gamma(e^+e^- \to B^0\bar{B}^0) = 1.006 \pm 0.048$ at $\sqrt{s} = M_{\Upsilon(4S)}$.

Combined values of $\mathcal{B}(B^0 \to K^{*0}\gamma)$ and $\mathcal{B}(B^+ \to K^{*+}\gamma)$, which are also shown in Table I, are calculated taking into account correlated systematic errors between modes. We further combined these measurements, using the lifetime ratio $\tau_{B^+}/\tau_{B^0} = 1.083 \pm 0.017$ [17] and our measurement of $R^{+/0}$, to find the isospin asymmetry, $\Delta_{0-} = 0.050 \pm 0.045(\text{stat}) \pm 0.028(\text{syst}) \pm 0.024(R^{+/0})$, which corresponds to an allowed region of $-0.046 < \Delta_{0-} < 0.146$ at the 90% confidence level. We also present a combined $\mathcal{A}$ measurement in Table I, which corresponds to an allowed region of $-0.074 < \mathcal{A}(B \to K^*\gamma) < 0.049$ at the 90% confidence level.

The systematic error on the branching fraction for each mode is shown in Table II. Most of the uncertainties are determined as in our previous analysis [6], so we provide details only for the new procedures used. The neural-network inputs are generally independent of the fully reconstructed $B \to K^*\gamma$ candidate, so we determine their efficiencies and systematic uncertainties with high-purity control samples with reconstructed $B^- \to D^0\pi^-$ and $B^0 \to D^-\pi^+$. The ''PDF parametrization'' error comes from MC studies of our fitting procedure, in which we estimate the uncertainty incurred by fixing parameters in the continuum and B background models. This includes uncertainty in the inclusive branching fraction and spectral shape of $B \to X_s\gamma$.

The systematic uncertainties in the measurement of $\mathcal{A}$ are also shown in Table II. The first three contributions arise from potential particle-antiparticle asymmetries in

TABLE II. Fractional systematic uncertainties on the branching fractions $\mathcal{B}$ and absolute systematic uncertainties on CP asymmetry $\mathcal{A}$.

Description	Systematic errors on $\mathcal{B}(\%)$ $K^+\pi^-$	$K^0_s\pi^0$	$K^+\pi^0$	$K^0_s\pi^+$
Number of B events	1.1	1.1	1.1	1.1
$R^{+/0}$	2.4	2.4	2.4	2.4
Tracking efficiency	1.6		0.8	0.8
Charged particle identification	1.0		1.0	1.0
Photon efficiency	2.5	7.6	7.6	2.5
Photon isolation cut	2.0	2.0	2.0	2.0
π^0, η veto	1.0	1.0	1.0	1.0
K_s efficiency		3.0		3.0
Neural network	3.0	3.5	2.7	2.8
PDF parametrization	2.2	7.3	2.7	1.4
MC statistics/fit bias	0.9	3.2	2.4	1.6
Total	5.8	12.3	9.4	6.3
	Systematic errors on $\mathcal{A}$ (%)			
Tracking efficiency	0.35		0.25	0.25
Charged particle identification	1.00		0.55	0.53
Nuclear interaction asymmetry	0.20		0.35	0.15
B-background asymmetry	0.25		0.25	0.25
Total	1.1		0.7	0.7

the detector response, including differences in interaction cross sections for K^+ and K^- and for π^+ and π^- (estimated with a method similar to that used in Ref. [18]). The uncertainty due to a possible asymmetry in the B background, which is dominated by $B \to X_s\gamma$, is estimated by varying the background according to the uncertainty in our recent measurement of $\mathcal{A}(B \to X_s\gamma)$ [19].

We conclude that both the isospin and CP asymmetries in $B \to K^*\gamma$ decay processes are consistent with SM predictions. The branching fractions measured are also consistent with SM-based calculations and are more precise than those predictions. These measurements are consistent with previous results [5–7].

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