Measurement of Branching Fractions and Mass Spectra of $B \to K\pi\pi\gamma$

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We present a measurement of the partial branching fractions and mass spectra of the exclusive radiative penguin processes $B \to K\pi\pi\gamma$ in the range $m_{K\pi\pi} < 1.8$ GeV/c^2. We reconstruct four final states: $K^+\pi^-\pi^+\gamma$, $K^+\pi^-\pi^0\gamma$, $K_S^0\pi^-\pi^+\gamma$, and $K_S^0\pi^+\pi^0\gamma$, where $K_S^0 \to \pi^+\pi^-$. Using 232×10^6 $e^+e^- \to B\bar{B}$ events recorded by the *BABAR* experiment at the SLAC PEP-II asymmetric-energy storage ring, we measure the branching fractions $\mathcal{B}(B^+ \to K^+\pi^-\pi^+\gamma) = [2.95 \pm 0.13(\text{stat}) \pm 0.20(\text{syst})] \times 10^{-5}$, $\mathcal{B}(B^0 \to K^+\pi^-\pi^0\gamma) = [4.07 \pm 0.22(\text{stat}) \pm 0.31(\text{syst})] \times 10^{-5}$, $\mathcal{B}(B^0 \to K^0\pi^+\pi^-\gamma) = [1.85 \pm 0.21(\text{stat}) \pm 0.12(\text{syst})] \times 10^{-5}$, and $\mathcal{B}(B^+ \to K^0\pi^+\pi^0\gamma) = [4.56 \pm 0.42(\text{stat}) \pm 0.31(\text{syst})] \times 10^{-5}$.

In the standard model (SM) the radiative penguin decay $B \to X_s\gamma$, where X_s is a hadronic system with unit strangeness, proceeds via weak-interaction loop diagrams. New physics, beyond the SM, may also contribute to the loop amplitude and lead to differences from the SM. This possibility has been pursued in inclusive measurements, which are theoretically clean but experimentally challenging, and in exclusive measurements, such as $B \to K\pi\gamma$. We report measurements of the branching fractions (BF) and mass spectra for the decays $B \to K\pi\pi\gamma$ in four channels. SM predictions of the rates and resonance structure of these decays have large uncertainties [1]. The $K^+\pi^+\pi^-\gamma$ and $K^0\pi^+\pi^-\gamma$ decay channels have previously been observed [2]. Throughout this Letter, stated decays include charge conjugate modes.

The decays $B \to K\pi^+\pi^0\gamma$, which have not previously been observed, are of particular interest because these three-body hadronic states permit the measurement, given sufficient statistics, of the photon polarization [3]. The polarization measurement depends on the interference between processes such as $(K\pi^+)\pi^0\gamma$ and $(K\pi^0)\pi^+\gamma$, where () indicates resonant substructure. This measurement may be compared with the SM prediction of nearly complete left-handed polarization.

We use a sample of $(232 \pm 1.5) \times 10^6$ $B\bar{B}$ pairs in a 210.9 fb^{-1} data set collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider. For background studies, we also use a 21.7 fb^{-1} sample collected below the $B\bar{B}$ threshold. The measurement procedure was designed using simulated signal and background events, data in sideband kinematic regions, and reconstructed $B \to D\pi^+$, $D \to K\pi\pi$ decays. Only after we established the selection and fit procedures did we examine signal candidates in the data sample.

A description of the detector exists elsewhere [4]. For this measurement, the most important detector elements are the five-layer silicon microstrip tracking detector (SVT) and the 40-layer drift chamber (DCH), situated in a 1.5 T solenoidal magnetic field, which measure charged particle momenta, the CsI(Tl) electromagnetic calorimeter (EMC), which measures the energies and directions of the photons, and the detector of internally reflected Cherenkov light (DIRC). The DIRC response and energy loss (dE/dx) measured in the SVT and DCH are used to identify charged kaons and pions.

We reconstruct the photon candidate in the $K\pi\pi\gamma$ decay from an EMC shower not associated with a charged track. The photon must be in the fiducial region of the EMC, have a shower-profile consistent with a single photon, and be well separated from other showers. To remove photons from π^0 (η) decays, we combine the candidate with other photons having energies of at least 50(250) MeV/c^2 and reject it if the invariant mass of any combination is within 25(40) MeV/c^2 of the π^0 (η) mass.

We select $K^\pm$ and $\pi^\pm$ candidates from charged tracks consistent with a kaon or pion mass hypothesis in the DIRC and in the dE/dx in the SVT and DCH. We reconstruct K_S^0 candidates from pairs of oppositely charged tracks and determine the decay vertex with a fit. We require that the invariant mass falls within 11 MeV/c^2 of the K_S^0 mass, that the distance between the B decay vertex and the K_S^0 vertex exceeds 5 times the uncertainty on the distance, and that the angle between the K_S^0 trajectory and its momentum is less than 100 mrad. We reconstruct π^0 candidates from pairs of EMC showers each with energy >50 MeV. We require the invariant mass to be within 16 MeV/c^2 of the π^0 mass and that the energy of each pair in the $\Upsilon(4S)$ center of mass (c.m.) frame exceeds 450 MeV; this last selection is about 83% efficient.

The dominant source of background is continuum production of light quark-antiquark pairs, in which a high-energy photon typically is produced either by initial state radiation, or from the decay of a π^0 or η in which one photon is not detected. To reject these backgrounds, we construct a Fisher discriminant [5] from the polar angle of the B candidate in the c.m. frame, the angle between the thrust axis of the B and the thrust axis of the remaining charged and neutral particles, and the ratio of the second to zeroth angular moments of the remaining charged and neutral particles around the thrust axis of the B. We optimize the coefficients independently in each channel to discriminate between simulated signal and continuum.

We perform a geometric fit to the reconstructed B candidate, with production vertex constrained to the nominal beam spot, rejecting the candidate if the final state is inconsistent with decay from a single vertex. We define $\Delta E^* \equiv E_B^* - E_{\text{beam}}^*$ and $m_{\text{ES}} \equiv \sqrt{E_{\text{beam}}^{*2} - \mathbf{p}_B^{*2}}$, where E_B^* and $\mathbf{p}_B^*$ are the c.m. energy and momentum of the B candidate, and E_{beam}^* is the c.m. energy of each beam. We require $m_{\text{ES}} > 5.2$ GeV/c^2 and $|\Delta E^*| < 0.15$ GeV.

We also require that the invariant mass of the $K\pi\pi$ system, $m_{K\pi\pi}$, fall below 1.8 GeV/c^2; this eliminates much of a rising continuum background with very little expected signal loss. It also removes $K\pi\pi$ combinations from D decays, in $B \to D\pi^0$ and $B \to D\eta$ where the π^0 or η are misreconstructed as a photon. In an event in which we reconstruct multiple candidates in one channel that pass the selection requirements (occurring in 11%–27% of selected signal events, depending on the channel), we keep the candidate with the largest vertex probability (with the best π^0 mass in the $K_S^0\pi^+\pi^0\gamma$ channel, with the π^0 mass as a tie breaker in the $K^+\pi^-\pi^0\gamma$ channel) and reject the others. Candidates reconstructed in different channels are allowed in the same event. The dependence of the efficiency of our selection requirements on intermediate resonance and on $m_{K\pi\pi}$ has been checked and found to be small; systematic uncertainties are discussed later.

The dominant backgrounds from $B\bar{B}$ events after the selection criteria have been applied are $b \to s\gamma$ processes. We categorize these backgrounds: (i) "cross feed" from misreconstructed $K\pi\pi\gamma$ decays, such as by choosing incorrectly a particle from the other B, (ii) $B \to K\pi\gamma$ decays that combine with a track from the other B to form a $K\pi\pi\gamma$ candidate, and (iii) backgrounds from all other $b \to s\gamma$ decays. A cross feed candidate may be reconstructed in the same decay channel in which it is produced, or in a different channel, and can also be produced in a $B \to K\pi\gamma$ decay that is not used in this analysis (such as $B^+ \to K^+\pi^0\pi^0\gamma$). We model our signal as well as cross feed backgrounds with simulated $B \to K_X\gamma$ decays, where K_X is any of the five lowest-lying $J > 0$ kaon resonances above the $K^*(892)$. We study backgrounds from $K\pi\gamma$ using simulated $B \to K^*(892)\gamma$ and $B \to K_2^*(1430)\gamma$ decays. We study backgrounds from other $b \to s\gamma$ decays using an inclusive simulation according to the model of Kagan and Neubert [6] with $m_b = 4.8$ GeV/c^2, tuned to match multiplicity distributions measured in inclusive $b \to s\gamma$ decays [7]. The largest final background contributions from $b \to s\gamma$ processes are cross feed backgrounds, for which we obtain yields ranging from 55% to 95% of the signal yields.

We estimate other sources of background candidates from B decays other than $b \to s\gamma$ processes by simulating generic B decays. We pay special attention to B decays with $K\pi\pi\pi^0$ and $K\pi\pi\eta$ final states; if the π^0 or η decays asymmetrically and we do not detect the lower-energy photon, the kinematic properties of the resulting B candidate may resemble a signal candidate. We study these decays using high-statistics simulated samples and look for signal candidates that are reconstructed from a single $B \to K\pi\pi\pi^0$ or $B \to K\pi\pi\eta$ decay. We expect to reconstruct fewer than two such candidates per channel.

We perform a maximum likelihood fit to the joint $m_{ES} - \Delta E^*$ distribution of our selected candidates. We fit all four channels simultaneously to account for cross feed back-

grounds between channels. The likelihood function contains terms for correctly reconstructed signal candidates, cross feed background candidates between all 16 combinations of the production and reconstruction channels, backgrounds from $B \to K\pi\gamma$ and from other $b \to s\gamma$ decays, and backgrounds from continuum events. We have determined from simulations that the dominant continuum background component adequately accounts for combinatoric backgrounds from other $B\bar{B}$ decays, which do not show strong peaks in m_{ES} and ΔE^*.

The likelihood function for a candidate reconstructed in decay channel i with kinematic variables $y \equiv (m_{ES}, \Delta E^*)$ is given by

$$\mathcal{L}^i(y) = N_{B\bar{B}}[\mathcal{B}^i \epsilon_s^i f_s^i(y) + \sum_j \mathcal{B}^j \epsilon_x^{ji} f_x^{ji}(y)] + n_c^i f_c^i(y)$$
$$+ n_b^i f_b^i(y),$$

where $N_{B\bar{B}}$ is the number of $B\bar{B}$ pairs in our data set; $\mathcal{B}^i$ is the branching fraction for decay channel i; ϵ_s^i and f_s^i are the efficiency and probability density function (PDF) for correctly reconstructed signal candidates in decay channel i; ϵ_x^{ji} and f_x^{ji} are the efficiency and PDF for cross feed background candidates produced in channel j and reconstructed in channel i; n_c^i and f_c^i are the yield and PDF for backgrounds from continuum and generic $B\bar{B}$ decay events in channel i; and n_b^i and f_b^i are the yield and PDF for backgrounds from other $b \to s\gamma$ processes in channel i. We further parametrize the likelihood function by the four data-taking runs during which data were collected, accounting for slight changes in experimental conditions.

The branching fractions $\mathcal{B}^i$, yields n_c^i, and shape parameters of f_c^i are varied in the fit; other efficiencies, yields, and PDF shapes are fixed from simulation studies. We parametrize f_s^i as the product of Crystal Ball functions [8] of m_{ES} and of ΔE^*, f_x^i as the product of a Crystal Ball function of m_{ES} and a linear function of ΔE^*, and f_c^i as the product of an Argus function [9] of m_{ES} and an exponential function of ΔE^*. We use a binned parametrization for f_b^i. As the signal and cross feed terms are both scaled by the parameters $\mathcal{B}^i$, the cross feed background yields vary with the signal branching fractions, and we measure the branching fractions from yields of both signal and cross feed candidates.

TABLE I. Results of the fit for $B \to K\pi\pi\gamma$, for $m_{K\pi\pi} <$ 1.8 GeV/c^2. The first error is statistical, the second systematic. The yields do not include the channel cross feeds, which are included in the fit to obtain the branching fractions.

Channel	Yield	Branching fraction (10^{-5})
$K^+\pi^-\pi^+\gamma$	899 ± 38	$2.95 \pm 0.13 \pm 0.19$
$K^+\pi^-\pi^0\gamma$	572 ± 31	$4.07 \pm 0.22 \pm 0.31$
$K^0\pi^+\pi^-\gamma$	176 ± 20	$1.85 \pm 0.21 \pm 0.12$
$K^0\pi^+\pi^0\gamma$	164 ± 15	$4.56 \pm 0.42 \pm 0.30$

Table I shows the fit results. Projections in m_{ES}, along with the fit results, are displayed in Fig. 1. The fit probability (P value) is evaluated with a likelihood ratio statistic [10], assuming Poisson-distributed bin contents, to be 10%. The distribution of the test statistic under the null hypothesis is evaluated by simulation.

Figure 2 shows background-subtracted $m_{K\pi\pi}$ mass spectra. Background subtraction is achieved using the results of the fits to calculate event-by-event weights to extract the signal component [11]. We present branching fractions in bins of $m_{K\pi\pi}$, which are largely model independent, instead of extracting $B \to K_X\gamma$ branching fractions for specific K_X resonances. Disentangling the resonance structure requires careful modeling of amplitudes and relative phases of interfering processes, including in the decays of the K_X resonances, not all of which are well measured. A partial wave analysis to extract the resonance structure and measure the photon polarization should be possible with future data sets.

We validate the procedure for extracting branching fractions and $m_{K\pi\pi}$ distributions using fits to simulated samples. We verify that the branching fractions and mass spectra obtained from these toy fits reproduce on average

the simulation inputs. We use the same procedure to extract the $m_{K\pi\pi}$ distributions for continuum and generic $B\bar{B}$ backgrounds and for backgrounds from $b \to s\gamma$ decays; these are consistent with the expected distributions.

Systematic uncertainties arise from various sources, shown in Table II. The largest sources are (i) the $\Upsilon(4S)$ branching fractions to B^+B^- and $B^0\bar{B}^0$ are each assumed to be 0.5. We assign a 2.6% systematic uncertainty to this, based on current information [12]. (ii) The uncertainty on the photon selection efficiency determined from simulated events is estimated to be 2.7%. (iii) From studies of $B \to D\pi^{\pm}$, $D \to K\pi$ events, we assign an uncertainty of 4.2% to the charged kaon identification efficiency. (iv) The uncertainty of the π^0 selection efficiency is estimated at 3.0%. (v) There is considerable uncertainty in the models we use to estimate backgrounds, including cross feed dependence, from $b \to s\gamma$ processes. We estimate the effect of this uncertainty on both the branching fractions and mass spectra by simulating these backgrounds with substantially different models. The largest effect is in the $K_S^0\pi^-\pi^+\gamma$ channel, where the uncertainty is 4.0%. (vi) We measure a shift in the beam energy in $B \to D\pi^{\pm}$ decays, on average 0.6 MeV; we estimate the effect of this on our fits. (vii) We estimate bias in the fit due to uncertain parametrization of the signal and background PDFs. The
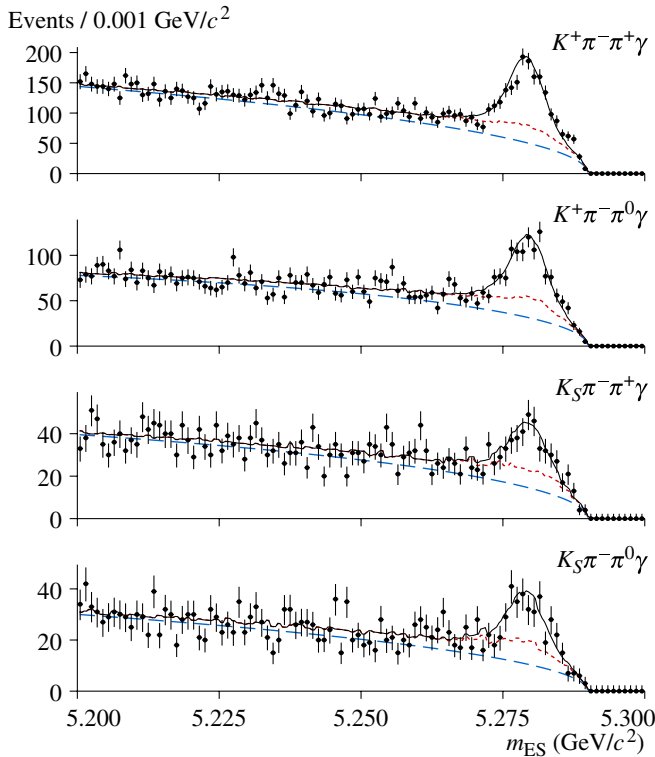
Events / 0.001 GeV/c^2

FIG. 1 (color online).   Distributions of m_{ES} (points). Projected m_{ES} distributions from the fit are shown as cumulative curves: continuum and generic $B\bar{B}$ component (dashed line), $b \to s\gamma$ component (dotted line, includes cross feed), and signal (solid line). The small oscillation in the dotted and solid curves is due to the use of binned distributions to model the $b \to s\gamma$ component.
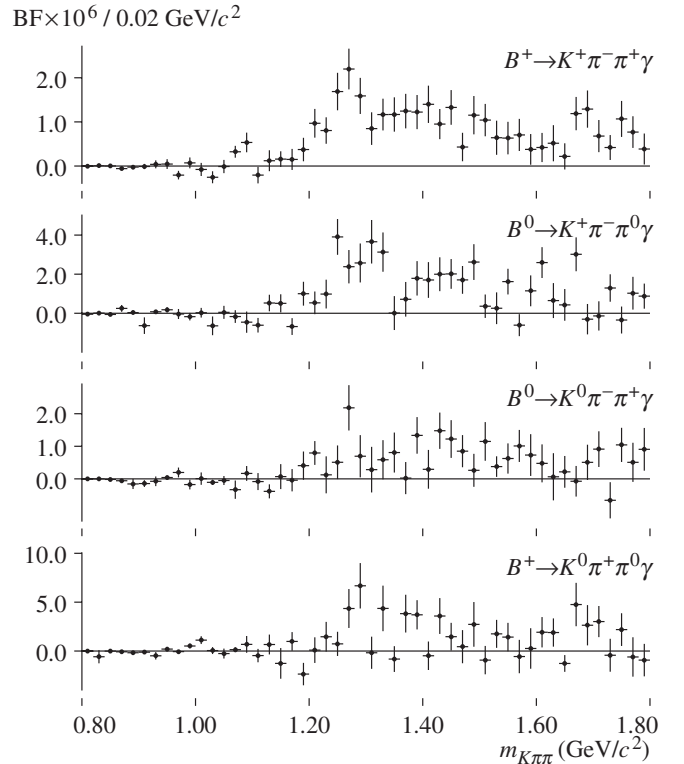
BF$\times 10^6$ / 0.02 GeV/c^2

FIG. 2.   Background-subtracted $m_{K\pi\pi}$ spectra. The branching fraction in each bin is computed from the weighted event yield. Error bars show statistical uncertainties; the systematic uncertainties due to $b \to s\gamma$ model assumptions are small.

PHYSICAL REVIEW LETTERS

TABLE II. Estimated systematic uncertainties in the branching fractions, in percent, by source and decay channel.

Source	$K^+\pi^-\pi^+$	$K^+\pi^-\pi^0$	$K^0_S\pi^-\pi^+$	$K^0_S\pi^+\pi^0$
$B\bar{B}$ count	1.1	1.1	1.1	1.1
$\Upsilon(4S)$ BF	2.6	2.6	2.6	2.6
Efficiencies:				
Photon selection	2.7	2.7	2.7	2.7
π^0 and η veto	1.0	1.0	1.0	1.0
Tracking	1.4	1.1	1.1	0.8
Kaon selection	4.2	4.2	1.6	1.6
$\pi^\pm$ selection	1.4	1.0	1.4	1.0
π^0 selection		3.0		3.0
Fisher cut	1.0	1.0	1.0	1.0
Vertex probability	0.7	0.7	0.7	0.7
MC statistics	0.5	0.7	0.8	1.1
Backgrounds:				
$b\to s\gamma$ model	1.4	1.0	4.0	1.3
$B\to K\pi\pi\pi^0/\eta$	0.2	0.1	0.0	0.6
Beam energy shift	1.0	0.5	1.6	0.6
PDF shape	0.1	2.9	0.9	0.2
Fit bias	1.6	1.3	1.3	3.5
Total	6.7	7.6	6.7	6.8

largest effect is in the $K^0_S\pi^+\pi^0\gamma$ channel, where the uncertainty is 3.5%.

We have measured branching fractions for $B\to K\pi\pi\gamma$ in four decay channels for $m_{K\pi\pi} < 1.8$ GeV/c^2. The $K\pi^+\pi^-$ channels are consistent with the previous measurement [2]. We present first observations of decays in the $K\pi^+\pi^0\gamma$ channels that are important to measuring the photon polarization. The branching fractions are relatively large in the context of $B\to X_s\gamma$ decays, providing encouragement that a polarization measurement may be possible with future data sets. Mass spectra for the $K\pi\pi$ system are also presented. We observe an enhancement near 1.3 GeV/c^2 and substantial branching fractions at higher masses. Untangling the resonant contributions presents a challenge for the polarization measurement.

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