

Title	Radiative B meson decays into K pi gamma and K pi pi gamma final states
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Radiative B Meson Decays into $K\pi\gamma$ and $K\pi\pi\gamma$ Final States

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We report observations of radiative B meson decays into the $K^+ \pi^- \gamma$ and $K^+ \pi^- \pi^+ \gamma$ final states. In the $B^0 \rightarrow K^+ \pi^- \gamma$ channel, we present evidence for decays via an intermediate tensor meson state with a branching fraction of $\mathcal{B}(B^0 \rightarrow K_2^*(1430)^0 \gamma) = [1.3 \pm 0.5(\text{stat}) \pm 0.1(\text{syst})] \times 10^{-5}$. We measure the branching fraction $\mathcal{B}(B^+ \rightarrow K^+ \pi^- \pi^+ \gamma) = [2.4 \pm 0.5(\text{stat}) \pm_{0.2}^{+0.4}(\text{syst})] \times 10^{-5}$, in which the $B^+ \rightarrow K^{*0} \pi^+ \gamma$ and $B^+ \rightarrow K^+ \rho^0 \gamma$ channels dominate. The analysis is based on a data set of 29.4 fb^{-1} recorded by the Belle experiment at the KEKB collider.

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Since the first measurement of the inclusive branching fraction for $B \rightarrow X_s \gamma$ by the CLEO Collaboration in 1995 [1], the flavor changing neutral current process $b \rightarrow s \gamma$ has been used as a sensitive probe to search for physics beyond the standard model (SM). In experiments at the $Y(4S)$, a pseudoreconstruction technique, in which the X_s state is reconstructed from one kaon and multiple pions, has been the most powerful tool to identify $b \rightarrow s \gamma$ events. In order to measure more precisely the inclusive rate, a detailed knowledge of the exclusive final states is required. In addition to the already established $B \rightarrow K^* \gamma$ decay [2], there are several known resonances that can contribute to the final state. CLEO has reported evidence for $B \rightarrow K_2^*(1430) \gamma$ [3]. Some theoretical predictions for the branching fractions of the exclusive decays can be found in Ref. [4]. Exclusive decays, such as $B \rightarrow K_1(1400) \gamma$, can also be used to measure the photon helicity, which may differ from the SM prediction in some new physics models [5].

In this Letter, we report on a search for resonant structures K_X above the K^* mass in radiative B meson decays. The analysis is based on a data sample of

29.4 fb^{-1} ($31.9 \times 10^6 B \bar{B}$ events) recorded by the Belle detector [6] at KEKB [7]. KEKB is an asymmetric energy $e^+ e^-$ collider (3.5 GeV on 8 GeV) operated at the $Y(4S)$ resonance. The Belle detector has a three-layer silicon vertex detector, 50-layer central drift chamber (CDC), an array of aerogel Cherenkov counters (ACC), time-of-flight (TOF) scintillation counters, and an electromagnetic calorimeter of CsI(Tl) crystals (ECL).

We select events that contain a high energy photon (γ) with an energy between 1.8 and 3.4 GeV in the $Y(4S)$ center-of-mass (CM) frame and within the acceptance of the barrel ECL ($33^\circ < \theta_\gamma < 128^\circ$). In order to reduce the background from $\pi^0, \eta \rightarrow \gamma \gamma$ decays, we combine the photon candidate with all other photon clusters in the event and reject the candidate if the invariant mass of any pair is within $18 \text{ MeV}/c^2$ ($32 \text{ MeV}/c^2$) of the nominal π^0 (η) mass (this condition is referred to as the π^0/η veto).

We search for K_X resonances decaying into two-body ($K^+ \pi^-$) and three-body ($K^+ \pi^- \pi^+$) final states [8] in the invariant mass (M_{K_X}) range up to $2.4 \text{ GeV}/c^2$. For the $K^+ \pi^-$ final state, the range $M_{K_X} < 1.2 \text{ GeV}/c^2$ is

excluded to remove K^* contributions. Charged tracks are required to have CM momenta greater than 200 MeV/ c , and to have impact parameters within ± 5 cm of the interaction point along the positron beam axis and within 0.5 cm in the transverse plane. To identify kaon and pion candidates, we use a likelihood ratio that is calculated by combining information from the ACC, TOF, and dE/dx (CDC) systems. We apply a tight selection with an efficiency (pion misidentification rate) of 83% (8%) for charged kaon candidates and a loose selection with an efficiency (kaon misidentification rate) of 97% (28%) for charged pion candidates.

We reconstruct B meson candidates from a photon and a K_X system by forming two independent kinematic variables: the beam constrained mass $M_{bc} \equiv \sqrt{(E_{\text{beam}}^*/c^2)^2 - (|\vec{p}_{K_X}^* + \vec{p}_\gamma^*|/c)^2}$ and $\Delta E \equiv E_{K_X}^* + E_\gamma^* - E_{\text{beam}}^*$, where E_{beam}^* is the beam energy, and \vec{p}_γ^* , E_γ^* , $\vec{p}_{K_X}^*$, $E_{K_X}^*$ are the momenta and energies of the photon and the K_X system, respectively, calculated in the CM frame. In order to improve the M_{bc} resolution, the photon momentum is rescaled so that $|\vec{p}_\gamma^*| = (E_{\text{beam}}^* - E_{K_X}^*)/c$ is satisfied.

The largest source of background originates from continuum $q\bar{q}$ ($q = u, d, s, c$) production. To suppress this background, we use a Fisher discriminant [9] formed from six modified Fox-Wolfram moments [10] and the cosine of the B meson flight direction ($\cos\theta_B^*$). The moments are calculated in the rest frame of the B candidate to avoid a correlation with M_{bc} [11]. Signal and background events are classified according to a likelihood ratio $LR = \mathcal{L}_{\text{sig}}/(\mathcal{L}_{\text{sig}} + \mathcal{L}_{\text{bg}})$, where the likelihood \mathcal{L}_{sig} (\mathcal{L}_{bg}) is the product of the probability density functions (PDF) of the Fisher discriminant and $\cos\theta_B^*$ for signal (background). The PDFs for the Fisher discriminant are determined from Monte Carlo (MC) simulations. For $\cos\theta_B^*$, we assume a $1 - \cos^2\theta_B^*$ behavior for signal events and a flat distribution for continuum background. The selection criteria on the likelihood ratio are chosen so that $S/\sqrt{S+N}$ is maximized, where S and N are (MC) signal and background yields, respectively. The optimized criteria retain 68% of the $B^0 \rightarrow K^+\pi^-\gamma$ signal and 42% of the $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ signal.

The B decay signal is separated from background, first by applying a requirement on ΔE and then by fitting the M_{bc} spectrum. If we find multiple candidates with $|\Delta E| < 0.5$ GeV and $M_{bc} > 5.2$ GeV/ c^2 in the same event, we take the candidate which gives the highest confidence level when we fit the K_X decay vertex (best candidate selection). We then select candidates with -100 MeV $< \Delta E < 75$ MeV, which removes 19% and 3% of signal on the lower and higher sides, respectively. We define a ΔE sideband to be 100 MeV $< \Delta E < 500$ MeV at $M_{bc} > 5.2$ GeV/ c^2 , in which we expect negligible signal contribution.

In the $B^0 \rightarrow K^+\pi^-\gamma$ analysis, we obtain the $M_{K\pi}$ distribution shown in Fig. 1(a). We observe an excess

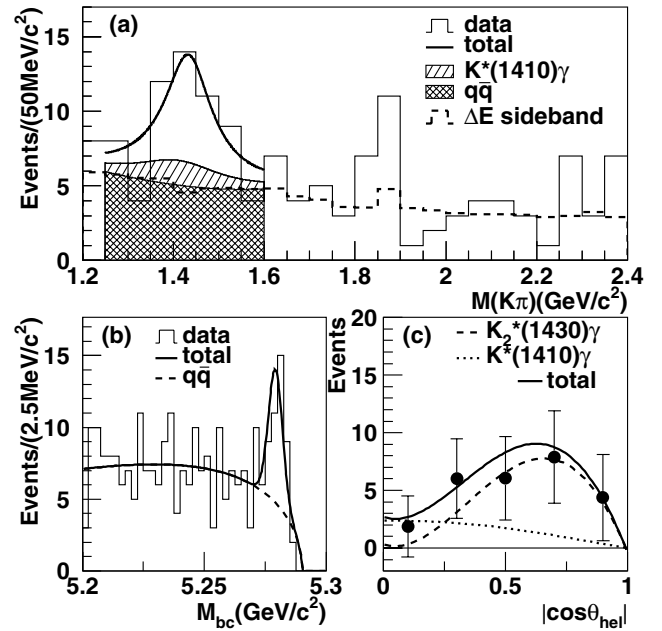


FIG. 1. (a) $M_{K\pi}$, (b) M_{bc} , and (c) $|\cos\theta_{\text{hel}}|$ distributions for $B^0 \rightarrow K^+\pi^-\gamma$ candidates. The unbinned ML fit results are shown in (a) and (c). The $q\bar{q}$ backgrounds are subtracted in (c). $M_{bc} > 5.27$ GeV/ c^2 is applied in (a) and (c), and 1.25 GeV/ $c^2 < M_{K\pi} < 1.6$ GeV/ c^2 is applied in (b) and (c). In (a), ΔE sideband data are scaled to the unbinned ML fit result and overlaid.

around $M_{K\pi} = 1.4$ GeV/ c^2 [12]. The M_{bc} distribution with 1.25 GeV/ $c^2 < M_{K\pi} < 1.6$ GeV/ c^2 is shown in Fig. 1(b). We fit the M_{bc} distribution to extract the signal yield. The distribution for the $q\bar{q}$ background is modeled by an ARGUS function [13] in which the shape is determined from the ΔE data sideband. The distribution for the signal component is modeled by a Gaussian determined from signal MC calibrated by $B^- \rightarrow D^0\pi^-$ data. The signal yield is found to be $27^{+8}_{-7}(\text{stat})^{+3}_{-3}(\text{syst})$ with a statistical significance of 5.0σ . Here the significance is defined as $\sqrt{-2 \ln[\mathcal{L}(0)/\mathcal{L}_{\text{max}}]}$, where \mathcal{L}_{max} is the maximum of the likelihood and $\mathcal{L}(0)$ is the likelihood for zero signal yield.

The observed signal may be explained as a mixture of three components: $B^0 \rightarrow K_2^*(1430)^0\gamma$, $B^0 \rightarrow K^*(1410)^0\gamma$, and nonresonant (NR) $B^0 \rightarrow K^+\pi^-\gamma$. In order to separate these components, we apply an unbinned maximum likelihood (ML) fit to M_{bc} , the cosine of the decay helicity angle ($\cos\theta_{\text{hel}}$), and $M_{K\pi}$. The expected $\cos\theta_{\text{hel}}$ distributions are $\sin^2 2\theta_{\text{hel}}$, $\sin^2\theta_{\text{hel}}$, and uniform for these three components, respectively. The PDFs for $\cos\theta_{\text{hel}}$ and $M_{K\pi}$ are determined from the ΔE sideband data for $q\bar{q}$ background, from the corresponding MC samples for resonant components, and from an inclusive $b \rightarrow s\gamma$ MC sample [11] for the nonresonant component. The $\cos\theta_{\text{hel}}$ PDFs for signals are distorted up to 20% due to a nonuniform efficiency. The validity of the method is tested with $B^- \rightarrow D^0\pi^-$ data and MC.

The fit results for $M_{K\pi}$ and $\cos\theta_{\text{hel}}$ are overlaid in Figs. 1(a) and 1(c), and summarized in Table I. We find evidence for radiative decays via an intermediate tensor state, $B^0 \rightarrow K_2^*(1430)^0\gamma$. The $K^*(1410)^0\gamma$ and nonresonant components are not significant, so we set upper limits. The 90% confidence level upper limit N is calculated from the relation $\int_0^N \mathcal{L}(n)dn = 0.9 \int_0^\infty \mathcal{L}(n)dn$, where $\mathcal{L}(n)$ is the maximum likelihood with the signal yield fixed at n .

We estimate the systematic error due to the fitting procedure as follows. For the signal shapes in the M_{bc} and $M_{K\pi}$ distributions, we vary the mean and width parameters in the fit within their experimental errors. We also test the validity of the background PDFs by replacing them with those obtained from a $q\bar{q}$ MC sample. We assign the largest deviation in these tests as the systematic error of the signal yield.

The event selection efficiency for $B^0 \rightarrow K_2^*(1430)^0\gamma$ is $(5.0 \pm 0.3)\%$ including the subdecay branching fractions. The error includes contributions from photon detection (2.8%), tracking (2.3% per track), kaon identification (0.6%), pion identification (0.5%), event selection including likelihood ratio, π^0/η veto and best candidate selection (2.0%), and uncertainty of the subdecay branching fractions (2.4%). Assuming an equal production rate for $B^0\bar{B}^0$ and B^+B^- , this leads to a branching fraction of $B^0 \rightarrow K_2^*(1430)^0\gamma$ of $[1.3 \pm 0.5(\text{stat}) \pm 0.1(\text{syst})] \times 10^{-5}$.

The result agrees with the predictions based on a relativistic form factor calculation [4]. Our result is also consistent with the CLEO measurement [3] when we neglect the nonresonant component and assume as they did that the $K^*(1410)\gamma$ component is negligible.

In the $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ analysis, we find additional background sources from a MC study. Cross feed from

$B \rightarrow K^*\gamma$ to $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ becomes negligible after removing positively identified $B \rightarrow K\pi\gamma$ events. The size of the cross feed from other $b \rightarrow s\gamma$ decays, especially from those with a π^0 in the final state, is estimated by using the inclusive $b \rightarrow s\gamma$ MC sample. The contribution from the $b \rightarrow c$ background is estimated by using a corresponding MC sample.

To extract the signal yield, we fit the M_{bc} distribution shown in Fig. 2(a). In addition to a Gaussian and an ARGUS function to describe the signal and $q\bar{q}$ background components obtained using the same method as in the $B \rightarrow K\pi\gamma$ analysis, smoothed MC histograms for the $b \rightarrow s\gamma$ cross feed and other B meson decays are used to model the M_{bc} shape, where the normalizations are fixed assuming the luminosity and the measured $b \rightarrow s\gamma$ branching fraction [11,15]. We find the signal yield of $57_{-11}^{+12}(\text{stat})_{-2}^{+6}(\text{syst})$ with a 5.9σ statistical significance.

The $M_{K\pi}$ distribution is shown in Fig. 2(b), where the distribution for $q\bar{q}$ is obtained from the ΔE sideband and is normalized using the fit result. We observe no signal excess above $1.8 \text{ GeV}/c^2$. The $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ signal may be explained as a sum of decays through kaonic resonances such as $B^+ \rightarrow K_1(1400)^+\gamma$ and $B^+ \rightarrow K^*(1680)^+\gamma$. The current statistics and the existence of a large number of resonances prevent us from decomposing the resonant substructure. However, it is still possible to measure the $K^*\pi\gamma$ and $K\rho\gamma$ components separately, as most of the resonances have sizable decay rates through the $K^*\pi$ and $K\rho$ channels.

To find the composition of the signal, we perform an unbinned ML fit to M_{bc} , $M_{K\pi}$, and $M_{\pi\pi}$ with three signal components ($K^*\pi\gamma$, $K\rho\gamma$, and nonresonant $K\pi\pi\gamma$) and a $q\bar{q}$ background component. In addition, the components from $b \rightarrow s\gamma$ cross feed and from other B meson decays

TABLE I. Measured signal yields, statistical significances, reconstruction efficiencies, branching fractions (\mathcal{B}), and 90% confidence level upper limits (UL) including systematic errors. The first and second errors are statistical and systematic, respectively. Efficiencies include the subdecay branching fractions [14]. Efficiencies for $K^+\pi^-\gamma$ and $K^+\pi^-\pi^+\gamma$ are based on a mixture of the measured subcomponents.

Mode	Signal yield	UL (yield)	Significance	Efficiency(%)	$\mathcal{B} (\times 10^{-5})$	UL ($\times 10^{-5}$)
$K^+\pi^-\gamma^a$	$27_{-7}^{+8}{}_{-3}^{+1}$	...	5.0^c	18 ± 2	$0.46_{-0.12}^{+0.13}{}_{-0.07}^{+0.05}$	...
$K_2^*(1430)^0\gamma$	$21_{-7}^{+8}{}_{-1}^{+0}$	...	3.2	5.0 ± 0.3	$1.3 \pm 0.5 \pm 0.1$	...
$K^*(1410)^0\gamma$	$7.7_{-5.7}^{+7.1}{}_{-1.3}^{+0.5}$	19	...	0.58 ± 0.12	...	13
$K^+\pi^-\gamma$ (NR) ^a	$0.0_{-0.0}^{+4.6} \pm 0.0$	15	...	19 ± 1	...	0.26
$K^+\pi^-\pi^+\gamma^b$	$57_{-11}^{+12}{}_{-2}^{+6}$	...	5.9^c	7.5 ± 0.7	$2.4 \pm 0.5_{-0.2}^{+0.4}$	...
$K^{*0}\pi^+\gamma^b$	$33_{-10}^{+11} \pm 2$	...	3.7	5.0 ± 0.5	$2.0_{-0.6}^{+0.7} \pm 0.2$	...
$K^+\rho^0\gamma^b$	$24 \pm 12_{-4}^{+4}$	43	2.2	7.4 ± 0.7	$1.0 \pm 0.5_{-0.3}^{+0.2}$	2.0
$K^+\pi^-\pi^+\gamma$ (NR) ^b	$0_{-0}^{+11} \pm 0$	20	...	7.6 ± 0.7	...	0.92
$K_1(1270)^+\gamma$	$4.0 \pm 2.4 \pm 0.6$	10	...	0.40 ± 0.08	...	9.9
$K_1(1400)^+\gamma$	$26 \pm 6_{-0}^{+2}$	36	...	2.6 ± 0.3	...	5.0

^a $1.25 \text{ GeV}/c^2 < M_{K\pi} < 1.6 \text{ GeV}/c^2$.

^b $M_{K\pi\pi} < 2.4 \text{ GeV}/c^2$.

^c M_{bc} fit result.

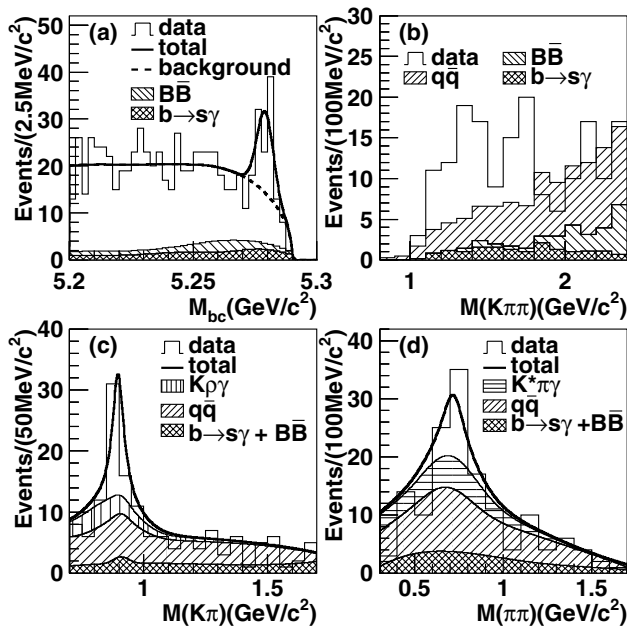


FIG. 2. (a) M_{bc} , (b) M_{K_X} , (c) $M_{K\pi}$, and (d) $M_{\pi\pi}$ distributions. The fit result of the M_{bc} distribution is shown in (a), while the result of the unbinned ML fit is shown in (c) and (d). $M_{bc} > 5.27 \text{ GeV}/c^2$ is applied in (b), (c) and (d).

are included in the fit with fixed normalizations. The $M_{K\pi}$ and $M_{\pi\pi}$ shapes for the $q\bar{q}$ background are determined from the ΔE sideband data, and those for the other components are determined from the corresponding MC samples.

In order to model the signal PDF for the $K^*\pi\gamma$ component, we use a mixture of $B^+ \rightarrow K_1(1400)^+\gamma \rightarrow K^{*0}\pi^+\gamma$ and $B^+ \rightarrow K^*(1680)^+\gamma \rightarrow K^{*0}\pi^+\gamma$ MC. The $K_1(1400)\gamma$ fraction of the mixture is determined to be 0.74 ± 0.14 by examining a background-subtracted $M_{K\pi\pi}$ distribution for candidates with $|M_{K\pi} - M_{K^*}| < 75 \text{ MeV}/c^2$ (K^* mass cut). Likewise for the $K\rho\gamma$ PDF, a mixture of $B^+ \rightarrow K_1(1270)^+\gamma \rightarrow K^+\rho^0\gamma$ and $B^+ \rightarrow K^*(1680)^+\gamma \rightarrow K^+\rho^0\gamma$ MC is used, where the $K_1(1270)\gamma$ fraction is determined to be 0.68 ± 0.17 according to a background-subtracted $M_{K\pi\pi}$ distribution for candidates with $|M_{\pi\pi} - M_\rho| < 250 \text{ MeV}/c^2$ and $|M_{K\pi} - M_{K^*}| > 125 \text{ MeV}/c^2$ (ρ mass cut).

Figures 2(c) and 2(d) show the distributions and fit results for $M_{K\pi}$ and $M_{\pi\pi}$. The selection efficiency is estimated from a MC sample with the mixture of resonances used for the PDF determination. We also consider other well-established resonances [16] which give slightly different efficiencies, and assign the difference in the result as a systematic error. The signal yields, the efficiencies, and the branching fractions are listed in Table I. The total $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ branching fraction is dominated by $B^+ \rightarrow K^{*0}\pi^+\gamma$ and $B^+ \rightarrow K^+\rho^0\gamma$; the statistical significance for the sum of the two is calculated to be 6.2σ , and the nonresonant component is consistent with zero.

TABLE II. Exclusive and inclusive branching fractions for the $b \rightarrow s\gamma$ process. Equal branching fractions are assumed for neutral and charged B decays. Using isospin, the branching fraction of $B^+ \rightarrow K^{*+}\pi^0\gamma$ ($K^0\rho^+\gamma$) is assumed to be half (twice) that of $B^+ \rightarrow K^{*0}\pi^+\gamma$ ($K^+\rho^0\gamma$).

Mode	$\mathcal{B} (\times 10^{-5})$	Ref.
$B \rightarrow K^*\gamma$	4.2 ± 0.4	[3,17]
$B \rightarrow K_2^*(1430)\gamma$ (excluding $K^*\pi\gamma, K\rho\gamma$)	0.9 ± 0.3	
$B \rightarrow K^*\pi\gamma$	3.1 ± 1.0	
$B \rightarrow K\rho\gamma$	3.0 ± 1.6	
Sum of exclusive modes	11.2 ± 2.1	
$B \rightarrow X_s\gamma$ (inclusive)	32.2 ± 4.0	[11,15]

We find evidence for the decay $B^+ \rightarrow K^{*0}\pi^+\gamma$ with a 3.7σ significance, while the $B^+ \rightarrow K^+\rho^0\gamma$ channel alone yields only 2.2σ . Systematic errors are evaluated using the same procedures as in the $B \rightarrow K\pi\gamma$ analysis.

We also search for resonant decays by applying further kinematical requirements. We search for $B^+ \rightarrow K_1(1270)^+\gamma$ in the $K^+\rho^0\gamma$ final state by applying the ρ mass cut and $|M_{K_X} - M_{K_1(1270)}| < 100 \text{ MeV}/c^2$. We find six candidates with a background expectation of 2.0 ± 0.6 events. To find $B^+ \rightarrow K_1(1400)^+\gamma$ in the $K^{*0}\pi^+\gamma$ final state, we apply the K^* mass cut and $|M_{K_X} - M_{K_1(1400)}| < 200 \text{ MeV}/c^2$. We obtain a sizable signal; however, we provide only upper limits due to a lack of ability to distinguish these resonances. The results are also listed in Table I.

In conclusion, we have studied radiative B decays with the $K^+\pi^-\gamma$ and $K^+\pi^-\pi^+\gamma$ final states. For $K^+\pi^-\gamma$, we consider $B^0 \rightarrow K_2^*(1430)^0\gamma$, $B^0 \rightarrow K^*(1410)^0\gamma$, and non-resonant components, and find that only the first one is significant. For $B^+ \rightarrow K^+\pi^-\pi^+\gamma$, we observe the decay mode and measure the branching fraction. The branching fractions for $B \rightarrow K^*\pi\gamma$ and $K\rho\gamma$ are consistent with the sum of predicted rates of resonant decays [4]. As listed in Table II, we find $(35 \pm 8)\%$ of the total $B \rightarrow X_s\gamma$ decay is accounted for by the $B \rightarrow K^*\gamma$, $B \rightarrow K_2^*(1430)\gamma$, and $B \rightarrow K\pi\pi\gamma$ final states.

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