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 $K\pi\gamma\gamma$ 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 $\mathcal{B}(B^0 \rightarrow K_1^*(1430)^0 \gamma) = [1.3 \pm 0.5\text{(stat)} \pm 0.1\text{(syst)}] \times 10^{-5}$. We measure the branching fraction $\mathcal{B}(B^+ \rightarrow K^0\pi^+\pi^-\gamma) = [2.4 \pm 0.5\text{(stat)} \pm 0.4\text{(syst)}] \times 10^{-5}$, 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.

Since the first measurement of the inclusive branching fraction for $B \rightarrow X_\gamma\gamma$ by the CLEO Collaboration in 1995 [1], the flavor changing neutral current process $b \rightarrow s\gamma\gamma$ 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 $X_\gamma$ state is reconstructed from one kaon and multiple pions, has been the most powerful tool to identify $b \rightarrow s\gamma\gamma$ 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 $B \rightarrow K_1^*(1430)\gamma$ [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 ($\gamma$) 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 MeV/c$^2$ (32 MeV/c$^2$) of the nominal $\pi^0, \eta$ mass (this condition is referred to as the $\pi^0/\eta$ 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 GeV/c$^2$. For the $K^+\pi^-$ final state, the range $M_{K_X} < 1.2$ 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 $\pm 5$ 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 

$$M_{bc} = \sqrt{(E_{\text{beam}})^2 - (|p_{K_X} + p_{\gamma}|/c)^2}$$

and $\Delta E \equiv E_{K_X} + E_{\gamma} - E_{\text{beam}}$, where $E_{\text{beam}}$ is the beam energy, and $p_{K_X}, E_{K_X}, p_{\gamma}, E_{\gamma}$ 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 $|p_{\gamma}| = (E_{\text{beam}} - E_{K_X})/c$ 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-Wolfam 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 $L = L_{\text{sig}}/(L_{\text{sig}} + L_{\text{bg}})$, where the likelihood $L_{\text{sig}}$ ($L_{\text{bg}}$) 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 $S/N + N$ 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 $\Delta E$ 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 $\Delta E$ 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 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 $\Delta E$ data sideband. The distribution for the signal component is modeled by a Gaussian determined from signal MC calibrated by $B^- \rightarrow D^0 \pi^- \gamma$ data. The signal yield is found to be $27 \pm 5$(stat) $\pm 5$(syst) with a statistical significance of $5.0\sigma$. Here the significance is defined as $-2\ln [L(0)/L_{\text{max}}]$, where $L_{\text{max}}$ is the maximum of the likelihood and $L(0)$ is the likelihood for zero signal yield.

The observed signal may be explained as a mixture of three components: $B^0 \rightarrow K^*(1430)^0 \gamma$, $B^0 \rightarrow K^*(1410)^0 \gamma$, 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 ($cos\theta_{hel}$), and $M_{K\pi}$. The expected $cos\theta_{hel}$ distributions are $\sin^2\theta_{hel}, \sin^2\theta_{hel}, \sin\theta_{hel},$ and uniform for these three components, respectively. The PDFs for $cos\theta_{hel}$ and $M_{K\pi}$ are determined from the $\Delta E$ 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 $cos\theta_{hel}$ PDFs for signals are distorted up to 20% due to a nonuniform efficiency. The validity of the method is tested with $B^- \rightarrow D^0 \pi^- \gamma$ data and MC.
The fit results for $M_{K\pi}$ and $\cos\theta_{hel}$ 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, $B^0 \rightarrow K^0_s(1430)^0\gamma$. 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 $B^0 \rightarrow K^0_s(1430)^0\gamma$ 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, $\pi^0/\eta$ veto and best candidate selection (2.0%), and uncertainty of the subdecay branching fractions (2.4%). Assuming an equal production rate for $B^0 B^+$ and $B^- B^0$, this leads to a branching fraction of $B^0 \rightarrow K^0_s(1430)^0\gamma$ 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 $\pi^0$ 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 $57^{+12}_{-11}^{(\text{stat})} \pm 7^{(\text{syst})}/3$ with a 5.9$\sigma$ statistical significance.

The $M_{K\pi}$ distribution is shown in Fig. 2(b), where the distribution for $q\bar{q}$ is obtained from the $\Delta E$ sideband and is normalized using the fit result. We observe no signal excess above 1.8 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

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<th>Mode</th>
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<td>$K^+\pi^-\gamma$</td>
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<td>$\cdots$</td>
<td>$5.0^c$</td>
<td>$18 \pm 2$</td>
<td>$0.46^{+0.37}_{-0.12}$</td>
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<td>$19$</td>
<td>$\cdots$</td>
<td>$0.58 \pm 0.12$</td>
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<td>$13$</td>
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<tr>
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<td>$\cdots$</td>
<td>$19 \pm 1$</td>
<td>$\cdots$</td>
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<td>$7.5 \pm 0.7$</td>
<td>$2.4 \pm 0.5^{+0.4}_{-0.2}$</td>
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<td>$3.7$</td>
<td>$5.0 \pm 0.5$</td>
<td>$2.0^{+0.5}<em>{-0.4}^{+0.2}</em>{-0.2}$</td>
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<td>$K^+\rho^-\gamma$</td>
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<td>$43$</td>
<td>$\cdots$</td>
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<td>$K^+\pi^-\pi^+\gamma$ (NR)b</td>
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<td>$\cdots$</td>
<td>$5.0$</td>
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$^a$1.25 GeV/$c^2 < M_{K\pi} < 1.6$ GeV/$c^2$.

$^b$3.2 GeV/$c^2 < M_{K\pi} < 4.6$ GeV/$c^2$.

$^c$MC fit result.

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FIG. 2. (a) $M_{bc}$, (b) $M_{K^*}$, (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). $M_{bc} > 5.27$ 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 $\Delta E$ 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 $|M_{K\pi} - M_{K_1^{*0}}| < 75$ MeV/c$^2$ ($K^*$ mass cut). Likewise for the $K\rho\gamma$ PDF, a mixture of $B^+ \rightarrow K_1(1270)^+ \gamma + K^*(1400)^+\gamma$ 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 $|M_{K\pi} - M_{K_1^{*0}}| < 250$ MeV/c$^2$ and $|M_{K\pi} - M_{K_2^{*0}}| > 125$ MeV/c$^2$ ($\rho\gamma$ 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.

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 $K^{*0}\rho^0\gamma$ final state by applying the $\rho$ mass cut and $|M_{K\pi} - M_{K_1(1270)}| < 100$ 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 $|M_{K\pi} - M_{K_1(1400)}| < 200$ 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 $B^0 \rightarrow K_2^{*0}\gamma$, $B^0 \rightarrow K^*(1410)^0\gamma$, and nonresonant 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 ± 8)% of the total $B \rightarrow X_{s,\gamma}$ decay is accounted for by the $B \rightarrow K^*\gamma$, $B \rightarrow K_2^{*0}(1430)\gamma$, and $B \rightarrow K^*\pi\gamma$ final states.

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| 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 $B^+ \rightarrow K^{*0}\pi^+\gamma$ ($K^*\rho^0\gamma$) is assumed to be half (twice) that of $B^+ \rightarrow K^{*0}\pi^+\gamma$ ($K^*\rho^0\gamma$). |
|-----------------|-------------------|-----------------|
| Mode            | $B \times 10^{-5}$ | Ref.            |
| $B \rightarrow K^*\gamma$ | 4.2 ± 0.4         | [3,17]          |
| $B \rightarrow K_1(1430)^0\gamma$ (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] |


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[8] The charge conjugated modes are implicitly included.
[12] We expect $3 \pm 1 \, B^0 \to D^0 \pi^0$ background which may account for the excess around $M_{K\pi} = 1.85 \text{ GeV}/c^2$.
[16] We consider $K_1(1270), K_1(1400), K^*(1410), K^*_1(1430), K_1(1650)$, and $K^*(1680)$.