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Radiative $B$ Meson Decays into $K\pi\gamma$ and $K\pi\pi\pi$ Final States


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Since the first measurement of the inclusive branching fraction for $B \to X_s \gamma$ by the CLEO Collaboration in 1995 [1], the flavor changing neutral current process $b \to s \gamma$ 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 $b \to s \gamma$ 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 $B \to K^+ \gamma$ decay [2], there are several known resonances that can contribute to the final state. CLEO has reported evidence for $B \to K^*_s(1430) \gamma$ [3]. Some theoretical predictions for the branching fractions of the exclusive decays can be found in Ref. [4]. Exclusive decays, such as $B \to K_s(1400) \gamma$, 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 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 $\pi^0 \eta \to \gamma \gamma \gamma$ 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
We reconstruct \( B \) meson candidates from a photon and a \( K_X \) system by forming two independent kinematic variables: the beam constrained mass \( M_{bc} \) and the \( K_X \) mass:\n\[ M_{bc} = \sqrt{(E_{\text{beam}}/c)^2 - (|\vec{p}_{K_X} + \vec{p}_\gamma|/c)^2} = \Delta E + E_{\gamma} - E_{\text{beam}}, \]
where \( E_{\text{beam}} \) is the beam energy, \( \vec{p}_{K_X} \) and \( \vec{p}_\gamma \) 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 \(|\vec{p}_\gamma| = (E_{\text{beam}} - E_{K_X})/c\) 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 \( L_R = L_{\text{sig}}/(L_{\text{sig}} + L_{\text{bg}}) \), 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 \( S/(S + N) \) is maximized, where \( S \) and \( N \) are (MC) signal and background yields, respectively. The optimized criteria retain 68% of the \( B^0 \to K^+ \pi^- \gamma \) signal and 42% of the \( B^+ \to K^+ \pi^- \pi^+ \gamma \) 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 \( B^0 \to K^+ \pi^- \gamma \) 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 a Gaussian function [13] in which the shape is determined from the \( M_{bc} \) data sideband. The distribution for the signal component is modeled by a Gaussian determined from signal MC calibrated by \( B^- \to D^0 \pi^- \) data. The signal yield is found to be \( 27_{-8}^{+12}(\text{stat.})_{-5}^{+5}(\text{syst.}) \) with a statistical significance of 5.0\(\sigma\). Here the significance is defined as \( \sqrt{2 \ln (L(0)/L_{\text{max}})} \), 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: \( B^0 \to K^+_s(1430)^0 \gamma, B^0 \to K^+(1410)^0 \gamma, \) and nonresonant (NR) \( B^0 \to K^+ \pi^- \gamma \). 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 \( \sin^2 \theta_{\text{hel}} \) and \( \sin^2 \theta_{\text{hel}} \), and uniform for these three components, respectively. The PDFs for \( \cos \theta_{\text{hel}} \) and \( M_{K\pi} \) are determined from the \( \Delta E \) sideband data for \( q\bar{q} \) background, from the corresponding MC samples for resonant components, and from an inclusive \( b \to s\gamma \) 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 \( B^- \to D^0 \pi^- \) data and MC.
The fit results for $M_{K\pi}$ and $\cos\theta_{\text{bel}}$ 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, $B_c^0 \rightarrow K_2^{*}(1430)^0 \gamma$. 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 $\int_0^N L(n)dn = 0.9 \int_0^\infty L(n)dn$, where $L(n)$ 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, $\pi^0/\gamma$ veto and best candidate selection (2.0%), and uncertainty of the subdecay branching fractions (2.4%). Assuming an equal production rate for $B^0B^0$ 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 $K^{*}(1410)^0 \gamma$ 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 $57^{+12}_{-11}(\text{stat})^{+2}_{-3}(\text{syst})$ 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 $\Delta E$ 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 structure. 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 $M_{K\pi\gamma}$ 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

| Mode | Signal yield | UL (yield) | Significance | Efficiency(%) | $B \times 10^{-5}$ | UL $(\times 10^{-5})$
<table>
<thead>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+\pi^-\gamma^a$</td>
<td>$27^{+8}<em>{-7}^{+1}</em>{-3}$</td>
<td>$\cdots$</td>
<td>$5.0^c$</td>
<td>$18 \pm 2$</td>
<td>$0.46^{+0.13}_{-0.05}$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$K_2^{*}(1430)^0 \gamma</td>
<td>$21^{+8}<em>{-7}^{+1}</em>{-3}$</td>
<td>$\cdots$</td>
<td>$3.2$</td>
<td>$5.0 \pm 0.3$</td>
<td>$1.3 \pm 0.5 \pm 0.1$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$K^*(1410)^0 \gamma</td>
<td>$7.7^{+7.1}<em>{-5.7}^{+0.5}</em>{-1.3}$</td>
<td>$19$</td>
<td>$0.58 \pm 0.12$</td>
<td>$\cdots$</td>
<td>$13$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$K^+\pi^-\gamma$ (NR)$^b$</td>
<td>$0.0^{+4.6}_{-0.0} \pm 0.0$</td>
<td>$15$</td>
<td>$19 \pm 1$</td>
<td>$\cdots$</td>
<td>$0.26$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$K^+\pi^-\pi^+\gamma^b$</td>
<td>$57^{+12}<em>{-11}^{+6}</em>{-2}$</td>
<td>$\cdots$</td>
<td>$5.9^c$</td>
<td>$7.5 \pm 0.7$</td>
<td>$2.4 \pm 0.5^{+0.4}_{-0.2}$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$K^{*0}\pi^+\gamma^b$</td>
<td>$33^{+10}_{-11}^{+2}$</td>
<td>$\cdots$</td>
<td>$3.7$</td>
<td>$5.0 \pm 0.5$</td>
<td>$2.0^{+0.7}_{-0.2}$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$K^+\rho^0\gamma</td>
<td>43$</td>
<td>$\cdots$</td>
<td>$2.2$</td>
<td>$7.4 \pm 0.7$</td>
<td>$1.0 \pm 0.5^{+0.2}_{-0.3}$</td>
<td>$2.0$</td>
</tr>
<tr>
<td>$K^+\pi^-\pi^+\gamma$ (NR)$^b$</td>
<td>$0^{+13}_{-10}^{+2}$</td>
<td>$20$</td>
<td>$7.6 \pm 0.7$</td>
<td>$\cdots$</td>
<td>$0.92$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$K_1(1270)^+\gamma</td>
<td>40 \pm 2.4 \pm 0.3</td>
<td>10</td>
<td>$0.40 \pm 0.08$</td>
<td>$\cdots$</td>
<td>$9.9$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$K_1(1400)^+\gamma</td>
<td>26 \pm 6 \pm 0</td>
<td>36</td>
<td>$2.6 \pm 0.3$</td>
<td>$\cdots$</td>
<td>$5.0$</td>
<td>$\cdots$</td>
</tr>
</tbody>
</table>

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

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

$^c$ $M_{bc}$ fit result.
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 $B^+ \to K^+_1(1420)^0\gamma \to K^{*0}\pi^+\gamma$ and $B^+ \to K^+(1680)^+\gamma \to K^{*0}\pi^+\gamma$ MC. The $K^+_1(1420)$ fraction of the mixture is determined to be $0.74 \pm 0.14$ by examining a background-subtracted $M_{K\pi\pi}$ distribution for candidates with $|M_{K\pi} - M_{K^+}| < 75$ MeV/$c^2$ ($K^*$ mass cut). Likewise for the $K\rho\gamma$ PDF, a mixture of $B^+ \to K^+_1(1420)^0\gamma \to K^{*0}\rho^+\gamma$ and $B^+ \to K^+(1680)^+\gamma \to K^{*0}\rho^+\gamma$ MC is used, where the $K^+_1(1420)$ fraction is determined to be $0.68 \pm 0.17$ according to a background-subtracted $M_{K\pi\pi}$ distribution for candidates with $|M_{\pi\pi} - M_{\rho}| < 250$ MeV/$c^2$ and $|M_{K\pi} - M_{K^+}| > 125$ MeV/$c^2$ ($\rho^0$ 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 $B^+ \to K^+\pi^+\pi^+\gamma$ branching fraction is dominated by $B^+ \to K^{*0}\pi^+\gamma$ and $B^+ \to K^{*0}\rho^+\gamma$; the statistical significance for the sum of the two is calculated to be $6.2\sigma$, and the nonresonant component is consistent with zero.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$B \times 10^{-5}$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to K^+\gamma$</td>
<td>$4.2 \pm 0.4$</td>
<td>[3,17]</td>
</tr>
<tr>
<td>$B^+ \to K^+_1(1420)\gamma$ (excluding $K^+\pi\gamma$, $K\rho\gamma$)</td>
<td>$0.9 \pm 0.3$</td>
<td></td>
</tr>
<tr>
<td>$B^+ \to K^+\pi\gamma$</td>
<td>$3.1 \pm 1.0$</td>
<td></td>
</tr>
<tr>
<td>$B^+ \to K\rho\gamma$</td>
<td>$3.0 \pm 1.6$</td>
<td></td>
</tr>
<tr>
<td>Sum of exclusive modes</td>
<td>$11.2 \pm 2.1$</td>
<td></td>
</tr>
<tr>
<td>$B^+ \to X_s\gamma$ (inclusive)</td>
<td>$32.2 \pm 4.0$</td>
<td>[11,15]</td>
</tr>
</tbody>
</table>

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

We also search for resonant decays by applying further kinematical requirements. We search for $B^+ \to K^+_1(1270)^+\gamma$ in the $K^+\rho^0\gamma$ 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 $2.0 \pm 0.6$ events. To find $B^+ \to K^+_1(1420)^+\gamma$ in the $K^{*0}\pi^+\gamma$ final state, we apply the $K^*$ mass cut and $|M_{K\pi} - M_{K^+_1(1420)}| < 200$ 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 $B^0 \to K^{*+}(1430)^0\gamma$, $B^0 \to K^+(1410)^0\gamma$, and nonresonant components, and find that only the first one is significant. For $B^+ \to K^+\pi^+\pi^+\gamma$, we observe the decay mode and measure the branching fraction. The branching fractions for $B^+ \to K^+\pi^+\pi^+\gamma$ 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 $B \to X_s\gamma$ decay is accounted for by the $B \to K^+\gamma$, $B \to K^{*+}(1430)^0\gamma$, and $B \to K^+\pi\gamma$ final states.

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Republic of Slovenia; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

*On leave from Nova Gorica Polytechnic, Slovenia.


[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 $K_1(1270)$, $K_1(1400)$, $K^*(1410)$, $K_2^*(1430)$, $K_1(1650)$, and $K^*(1680)$.