Radiative B meson decays into K pi gamma and K pi pi gamma final states

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


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28University of Kansas, Lawrence, Kansas
29University of Siena, Siena
30University of Tokyo, Tokyo
31University of Tsukuba, Ibaraki
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33University of Vienna, Vienna
34University of Washington, Seattle
35Yonsei University, Seoul
36YORK University, Toronto
37Yukawa Institute for Theoretical Physics, Kyoto
We observe radiative $B$ meson decays into the $K^+\pi^-\gamma$ and $K^+\pi^-\pi^+\gamma$ final states. In the $B^0 \to K^+\pi^-\gamma$ channel, we provide evidence for decays via an intermediate tensor meson state with a branching fraction of $(1.3 \pm 0.5 \text{(stat)} \pm 0.1 \text{(syst)}) \times 10^{-5}$. We measure the branching fraction $B(B^+ \to K^+\pi^-\pi^+\gamma) = [2.4 \pm 0.5 \text{(stat)} \pm 0.4 \text{(syst)}] \times 10^{-5}$, in which the $B^+ \to K^0\pi^+\gamma$ and $B^+ \to K^+\rho^0\gamma$ 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 $B \to X_s\gamma$ 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 $B \to K^{*0}(1430)\gamma$ [3]. Some theoretical predictions for the branching fractions of the exclusive decays can be found in Ref. [4]. Exclusive decays, such as $B \to K^{*0}(1400)\gamma$, 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 × 10$^6$ $B\overline{B}$ 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 $\pi^0, \eta \to \gamma\gamma$ 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$^2$ 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 \( K^\ast \) contributions. Charged tracks are required to have CM momenta greater than 200 MeV/c, and to have impact parameters within \( \pm 5 \text{ cm} \) 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 \( M_{bc} = \sqrt{(E_{\text{beam}} c^2)^2 - ((\vec{p}_{K_X} + \vec{p}_{\gamma})/c)^2} \) and \( \Delta E = E_{K_X} + E_{\gamma} - E_{\text{beam}} \), where \( E_{\text{beam}} \) is the beam energy, and \( \vec{p}_{\gamma}, \vec{p}_{K_X}, E_{K_X}, E_{\gamma} \) 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 \( |\vec{p}_{\gamma}| = (E_{\text{beam}} - E_{K_X})/c \) 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 \((\cos \theta_B^d)\). 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 \( \cos \theta_B^d \) for signal (background). The PDFs for the Fisher discriminant are determined from Monte Carlo (MC) simulations. For \( \cos \theta_B^d \), we assume a \( 1 - \cos^2 \theta_B^d \) 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 \( B^0 \rightarrow K^\ast + \pi^- \gamma \) 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 \( |\Delta E| < 0.5 \text{ GeV} \) and \( M_{bc} > 5.2 \text{ GeV}/c^2 \) 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 \( -100 \text{ MeV} < \Delta E < 75 \text{ MeV} \), which removes 19% and 3% of signal on the lower and higher sides, respectively. We define a \( \Delta E \) sideband to be \( 100 \text{ MeV} < \Delta E < 500 \text{ MeV} \) at \( M_{bc} > 5.2 \text{ GeV}/c^2 \), 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 \( M_{K\pi} = 1.4 \text{ GeV}/c^2 \) [12]. The \( M_{bc} \) distribution with \( 1.25 \text{ GeV}/c^2 < M_{K\pi} < 1.6 \text{ GeV}/c^2 \) 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 \( B^- \rightarrow D^0 \pi^- \pi^+ \) data. The signal yield is found to be \( 27 \pm 1.3 \text{ (stat)} \pm 1.2 \text{ (syst)} \) with a statistical significance of 5.0 \sigma. Here the significance is defined as \( \sqrt{2\ln(\mathcal{L}_0/\mathcal{L}_{\text{max}})} \), where \( \mathcal{L}_{\text{max}} \) 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: \( B^0 \rightarrow K^\ast(1430)^0 \gamma, B^0 \rightarrow K^\ast(1410)^0 \gamma, \) 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 \( \sin^2 \theta_{hel}, \sin \theta_{hel}, \) 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 \( B^- \rightarrow D^0 \pi^- \pi^+ \) data and MC.

![Figure 1](image-url)
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, $B^0 \rightarrow K^*_2(1430)^0\gamma$. 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, $\pi^0/\gamma$ 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 $57^{+12}_{-11}(\text{stat})^{+4}_{-2}(\text{syst})$ with a 5.9$r$ 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 $M_{\pi\pi}$ 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>
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<tr>
<th>Mode</th>
<th>Signal yield</th>
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<th>Significance</th>
<th>Efficiency(%)</th>
<th>$B \times 10^{-5}$</th>
<th>UL $\times 10^{-5}$</th>
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<tr>
<td>$K^+\pi^-\gamma^0$</td>
<td>$27^{+8}<em>{-7} \pm 3^{+1}</em>{-1}$</td>
<td>⋯</td>
<td>5.0$^c$</td>
<td>18 $\pm$ 2</td>
<td>$0.46^{+0.13}<em>{-0.05}$ $^{+0.05}</em>{-0.07}$</td>
<td>⋯</td>
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<tr>
<td>$K^*_2(1430)^0\gamma$</td>
<td>$21^{+5}<em>{-4} \pm 0.2^{+0.3}</em>{-0.1}$</td>
<td>⋯</td>
<td>3.2</td>
<td>$5.0 \pm 0.3$</td>
<td>$1.3 \pm 0.5 \pm 0.1$</td>
<td>⋯</td>
</tr>
<tr>
<td>$K^*(1410)^0\gamma$</td>
<td>$7.7^{+7.1}<em>{-5.7} \pm 0.5^{+0.5}</em>{-0.3}$</td>
<td>19</td>
<td>⋯</td>
<td>$0.58 \pm 0.12$</td>
<td>⋯</td>
<td>13</td>
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<tr>
<td>$K^+\pi^-\gamma$ (NR)$^b$</td>
<td>$0^{+4.6}_{-4.6} \pm 0$</td>
<td>15</td>
<td>⋯</td>
<td>$19 \pm 1$</td>
<td>⋯</td>
<td>0.26</td>
</tr>
<tr>
<td>$K^+\pi^-\pi^+\gamma^b$</td>
<td>$57^{+12}<em>{-11} \pm 2^{+0.2}</em>{-0.1}$</td>
<td>⋯</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>⋯</td>
</tr>
<tr>
<td>$K^0\pi^+\gamma_b$</td>
<td>$33^{+10}_{-11} \pm 2$</td>
<td>⋯</td>
<td>3.7</td>
<td>$5.0 \pm 0.5$</td>
<td>$2.0^{+0.7}_{-0.2} \pm 0.2$</td>
<td>⋯</td>
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<tr>
<td>$K^+\rho^0\gamma_b$</td>
<td>$24^{+12}_{-10} \pm 4$</td>
<td>43</td>
<td>⋯</td>
<td>$7.4 \pm 0.7$</td>
<td>$1.0 \pm 0.5^{+0.2}_{-0.3}$</td>
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<td>$K^+\pi^-\pi^+\gamma$ (NR)$^b$</td>
<td>$0^{+1.0}_{-1.0} \pm 0$</td>
<td>20</td>
<td>⋯</td>
<td>$7.6 \pm 0.7$</td>
<td>⋯</td>
<td>0.92</td>
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<tr>
<td>$K_1(1270)^+\gamma$</td>
<td>$4.0^{+2.4}_{-2.0} \pm 0.6$</td>
<td>10</td>
<td>⋯</td>
<td>$0.40 \pm 0.08$</td>
<td>⋯</td>
<td>9.9</td>
</tr>
<tr>
<td>$K_1(1400)^+\gamma$</td>
<td>$26 \pm 2^{+1}_{-1}$</td>
<td>36</td>
<td>⋯</td>
<td>$2.6 \pm 0.3$</td>
<td>⋯</td>
<td>5.0</td>
</tr>
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$^a1.25$ GeV/$c^2 < M_{K\pi} < 1.6$ GeV/$c^2$.

$^bM_{K\pi\pi} < 2.4$ GeV/$c^2$.

$^cM_{bc}$ 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 $B^+ \to K_1(1400)^+ \gamma \to K^{*0}\pi^+\gamma$ and $B^+ \to K^*(1680)^+\gamma \to K^{*0}\pi^+\gamma$ 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 $|M_{K\pi} - M_{K_1}| < 75$ MeV/c$^2$ ($K^*$ mass cut). Likewise for the $K\rho\gamma$ PDF, a mixture of $B^+ \to K_1(1270)^+\gamma + K^{*0}\rho^0\gamma$ and $B^+ \to K^*(1680)^+\gamma \to K^{*0}\rho^0\gamma$ 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 $|M_{K\pi} - M_{K_1}| < 250$ MeV/c$^2$ and $|M_{K\pi} - M_{K_1}| > 125$ 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 $B^+ \to K^{*0}\rho^0\gamma$; 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 $B^+ \to K^{*0}\pi^+\gamma$ with a 3.7σ significance, while the $B^+ \to K^{+}\rho^0\gamma$ channel alone yields only 2.2σ. 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 $K^{*0}\rho^0\gamma$ 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 $B^+ \to K_1(1400)^+\gamma$ 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 $B^0 \to K^*_2(1430)^0\gamma$, $B^0 \to K^{*+}(1410)^0\gamma$, and nonresonant components, and find that only the first one is significant. For $B^+ \to K^{+}\pi^+\gamma$, we observe the decay mode and measure the branching fraction. The branching fractions for $B \to K^{*+}\gamma$ 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 $B \to X_{s}\gamma$ decay is accounted for by the $B \to K^{*+}\gamma$, $B \to K_2^*(1430)^0\gamma$, and $B \to K^{*+}\pi^+\gamma$ final states.

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

<table>
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<th>Mode</th>
<th>$\mathcal{B}(\times 10^{-5})$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to K^+\gamma$</td>
<td>4.2 ± 0.4</td>
<td>[3,17]</td>
</tr>
<tr>
<td>$B \to K_1(1430)^+\gamma$ (excluding $K^+\pi^+\gamma$, $K\rho\gamma$)</td>
<td>0.9 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>$B \to K^*\pi^+\gamma$</td>
<td>3.1 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>$B \to K\rho\gamma$</td>
<td>3.0 ± 1.6</td>
<td></td>
</tr>
<tr>
<td>Sum of exclusive modes</td>
<td>11.2 ± 2.1</td>
<td></td>
</tr>
<tr>
<td>$B \to X_{s}\gamma$ (inclusive)</td>
<td>32.2 ± 4.0</td>
<td>[11,15]</td>
</tr>
</tbody>
</table>
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 $3 \pm 1$ $B^0 \rightarrow D^0 \pi^0$ background which may account for the excess around $M_{K\pi} = 1.85$ GeV/$c^2$.


[16] We consider $K_1(1270)$, $K_1(1400)$, $K^*(1410)$, $K^*_2(1430)$, $K^*_1(1650)$, and $K^{*(0)}(1680)$.