Measurements of branching fraction and final-state asymmetry of the $\bar{B}^0(B^0) \rightarrow K^0_S K^\mp \pi^\pm$ decay at Belle

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Abstract

We report the measurement of the branching fraction and final-state asymmetry for the $B^0(B^0) \rightarrow K^0_S K^{\pm} \pi^{\mp}$ decays. The analysis is based on a data sample of 711 fb$^{-1}$ collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. We obtain a branching fraction of $(3.60 \pm 0.33 \pm 0.15) \times 10^{-6}$ and a final-state asymmetry of $(-8.5 \pm 8.9 \pm 0.2)\%$, where the first uncertainties are statistical and the second are systematic. Hints of peaking structures are observed in the differential branching fraction plotted as functions of Dalitz variables.

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Three-body charmless hadronic $B$ decays are suppressed in the standard model (SM) and are also sensitive to localized CP violation in the phase space $[1, 2]$. The $B^0(B^0) \rightarrow K_S^0 K^\pm \pi^\mp$ [3] decays with even number of kaons have a smaller decay rate compared to the cases with odd number of kaons. These proceed via the $b \rightarrow u$ tree-level, the $b \rightarrow u$ $W$-exchange, and the $b \rightarrow d$ penguin process with a virtual loop, which provides an opportunity to search for physics beyond the SM since new heavy particles may cause deviations from SM predictions.

Previous measurements by the BaBar [4, 5] and LHCb [6–8] experiments find hints of structures at the low $K^−\pi^+$ and $K^-K_S^0$ regions that have highly asymmetric helicity angular distributions. However, the yield is not enough to draw firm conclusions with a full Dalitz analysis. Similar studies on $B^+ \rightarrow K^+K^-\pi^+$ were performed by Belle [9], BaBar [10], and LHCb [11, 12], in which strong evidence of localized CP violation was found in the low $M_{K^+K^-}$ region.

By using the full data set of Belle, we expect to measure the branching fraction and final-state asymmetry of $B^0(B^0) \rightarrow K_S^0 K^\pm \pi^\mp$ decays more precisely. Using charges of final-state particles, the latter is defined as

$$A = \frac{N(K_S^0 K^- \pi^+)}{N(K_S^0 K^+ \pi^-)} - \frac{N(K_S^0 K^+ \pi^-)}{N(K_S^0 K^- \pi^+)}$$  \ (1)

where $N$ denotes the measured signal yield of the corresponding $B$ final states. $A$ is distinct from the direct CP asymmetry; rather it is an asymmetry between the decay final states of $K^0K^−\pi^+$ and $K^0K^+\pi^-$ where $K^0(K^0)$ leads to $K_S^0$. We measure $A$ as the measurement of direct CP asymmetry based on flavor tagging won’t be so precise. Only about 30% of events can be effectively flavor-tagged, which would be further affected by $B^0$-$\bar{B}^0$ mixing. In addition, we use the “Plot [13]” method to obtain the background-subtracted yields for the Dalitz variables $M_{K^-\pi^+}$, $M_{\pi^+K_S^0}$, and $M_{K^-K_S^0}$, and hence determine their differential branching fractions. The total branching fraction is extracted by integrating the differential branching fraction.

Our measurements are obtained from a data sample of 711 fb$^{-1}$, corresponding to $772 \times 10^6$ $B\bar{B}$ pairs, collected with the Belle detector [14] operating at the KEKB asymmetric-energy $e^+e^-$ collider [15]. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF) and an electromagnetic calorimeter comprised of CsI(Tl) crystals, all located inside a superconducting solenoid that provides a 1.5 T magnetic field. An iron flux-return yoke located outside the solenoid is instrumented to detect $K^0_L$ mesons and muons. The detector is described in detail elsewhere [14].

This analysis uses the data sets with two different inner-detector configurations. About 140 fb$^{-1}$ were collected with a beam-pipe of radius 2.0 cm and with 3 layers of SVD, while the rest of the data set was recorded with a beam-pipe of radius 1.5 cm and 4 layers of SVD [16]. Large samples Monte Carlo (MC) events for signal and backgrounds are generated with EvtGen [17] and subsequently simulated with GEANT3 [18] with the configurations of the Belle detector. These samples are used to obtain expected distributions of various physical quantities for signal and backgrounds, to optimize selection criteria as well as to determine the signal detection efficiency.

The selection criteria for the final-state charged particles in the $\bar{B}^0(B^0) \rightarrow K_S^0 K^\pm \pi^\mp$ reconstruction are based on information obtained from the tracking systems (SVD and
mesons and $K^0_S$ sample in which the branching fractions are much larger than the measured or expected exclusion limits. They are mainly due to the two-body decays $J/\psi \rightarrow K^-\pi^+$ and $J/\psi \rightarrow \mu^+\mu^-$. These decays can be identified by peaks at the nominal decay, and the identification is enhanced by using a neural network (NN) which combines seven kinematic variables of the reconstructed $B$ meson. The $B$ candidates are required to have $M_{bc} > 5.255$ GeV/$c^2$ and $|\Delta E| < 0.15$ GeV, and the signal region is defined as $5.272$ GeV/$c^2 < M_{bc} < 5.288$ GeV/$c^2$ and $|\Delta E| < 0.05$ GeV. We require a vertex fit for $B^0(B^0) \rightarrow K^+K^-\pi^+\pi^-$ candidates with $\chi^2 < 100$. We find that $9\%$ of events have more than one $B$ candidates. In those cases, we choose the one with the smallest $\chi^2$ value. Our best $B$ selection method chooses the correct candidate in $99\%$ of cases.

The dominant background arises from the continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u,d,s,c$) process. To suppress this, we construct a Fisher discriminant from 17 modified Fox-Wolfram moments. To further improve the distinguishing power, we combine the output of the Fisher discriminant with four more variables in a NN. These are: the cosine of the angle between the reconstructed $B$ flight direction and the beam direction in the CM frame, the offset between the vertex of the reconstructed $B$ and that of the rest of the tracks' vertex along the $z$ axis, the cosine of the angle between the thrust axis of the reconstructed $B$ and that of the rest of the event in the CM frame, and a $B$ meson flavor tagging quality variable. The NN is trained with signal and continuum MC samples. The NN output ($C_{NN}$) ranges from $-1$ to $1$, and it is required to be greater than $0.7$. This removes $93\%$ of continuum background while $82\%$ of the signal is retained. We transform $C_{NN}$ to $C'_{NN} \equiv \log(C_{NN}/C_{NN}^\text{min})$, where $C_{NN}^\text{min}$ is $0.7$ and $C_{NN}^\text{max}$ is the maximum value of $C_{NN}$.

Background events from $B$ decays mediated via the $b \rightarrow c$ transition (generic $B$ decays) exhibit peaking structures in the signal region. They are mainly due to the two-body decays of $D$ mesons and $J/\psi$, e.g., $D^0 \rightarrow K^-\pi^+$, $D^- \rightarrow K^-K^0_S$, $D^+_s \rightarrow K^-K^0_S$, $J/\psi \rightarrow e^+e^-$, and $J/\psi \rightarrow \mu^+\mu^-$. These decays can be identified by peaks at the nominal $D$ and $J/\psi$ mass in the distributions of the invariant masses of two of the final-state particles ($M_{K^-\pi^+}$, $M_{\pi^+K^0_S}$, $M_{K^-K^0_S}$, and the cases with changing the masses hypothesis of charged kaon or pion). We exclude the events within $4\sigma$ of the peaking structures to suppress the contributions from $D$ mesons and $J/\psi$.

The rare $B$ background coming from $b \rightarrow u,d,s$ transitions is studied with a large MC sample in which the branching fractions are much larger than the measured or expected value. Two modes are found to have peaks near the $\Delta E$ signal region: $B^0 \rightarrow K^-K^+K^0_S$ and $B^0 \rightarrow \pi^-\pi^+K^0_S$, including their intermediate resonant modes. Rest of the rare $B$ events...
have a relatively flat $\Delta E$ distribution.

The signal yield and $A$ are extracted from a three-dimensional extended unbinned maximum likelihood fit, with the likelihood defined as

$$L = \frac{e^{-\sum_j N_j}}{N!} \prod_{i=1}^{N} \left( \sum_j N_j P_j^i \right),$$

where,

$$P_j^i = \frac{1}{2} (1 - q^i \cdot A_j) \times \left( M_{bc}^i \Delta E^i, C_{NN}^i \right),$$

$N$ is the total number of candidate events, $N_j$ is the number of events in category $j$, $i$ denotes event index, $q^i$ is the charge of $K^\pm$ in the $i$-th event, $A_j$ is the value of final-state asymmetry of the $j$-th category, $P_j$ represents the value of the corresponding three-dimensional probability density function (PDF), and $M_{bc}^i, \Delta E^i,$ and $C_{NN}^i$ are the $M_{bc}, \Delta E,$ and $C_{NN}$ value of the $i$-th event, respectively.

With all the selection criteria applied, the signal MC sample contains 98% of the correctly-reconstructed signal $B$ events (‘true’ signal) and 2% self-crossfeed (scf) events. In the fit, the ratio of scf to true signal events is fixed. The signal yield ($N_{sig}$) is the combined yield of the two PDFs. In addition to the signal part, five more categories are included in the fit: continuum background, generic $B$ background, $B^0 \rightarrow K^- K^+ K_S^0, B^0 \rightarrow \pi^- \pi^+ K_S^0,$ and the rest of the rare $B$ background. The true signal PDF is described by a product of a sum of two Gaussian functions in $M_{bc}$, a sum of three Gaussian functions in $\Delta E$, and an asymmetric Gaussian function in $C_{NN}$. These signal PDF shapes are calibrated including possible data-MC differences obtained from study of the control mode: $B^0 \rightarrow D^- \pi^+$ with $D^- \rightarrow K_S^0 \pi^-$. The continuum background PDF PDF is described by a product of an ARGUS function [25] in $M_{bc}$, a second-order polynomial in $\Delta E$, and a combination of a Gaussian and an asymmetric Gaussian function in $C_{NN}$. The shape parameters of the continuum background PDF are free in the data fit, except for the ARGUS end-point which is fixed to 5.2892 GeV/$c^2$. For the others (scf, generic $B$, $B^0 \rightarrow K^- K^+ K_S^0, B^0 \rightarrow \pi^- \pi^+ K_S^0,$ and rare $B$), their PDFs are described by a smoothed histogram in $\Delta E$ and $M_{bc}$, and an asymmetric Gaussian function in $C_{NN}$ whose shape is based on MC. The yield of each category is floated. Except for the signal, $A$ is fixed to zero for the other categories.

The projections of the fit are shown in Fig. We obtain a signal yield of $490_{-45}^{+46}$ with a statistical significance of 13 standard deviations, and an $A$ of $(8.5 \pm 8.9)\%$. The significance is defined as $\sqrt{\text{2ln}(L_0/L_{\text{max}})}$, where $L_0$ and $L_{\text{max}}$ are the likelihood values obtained by the fit with and without the signal yield fixed to zero, respectively.

The branching fraction is calculated using

$$B = \frac{N_{\text{sig}}}{\epsilon \times \eta \times N_{B\bar{B}}},$$

where $N_{\text{sig}}, N_{B\bar{B}}, \epsilon,$ and $\eta$ are the fitted signal yield, the number of $B\bar{B}$ pairs ($= 772 \times 10^6$), the reconstruction efficiency of signal, and the efficiency calibration factor, respectively. The last quantity contains calibrations due to various systematic effects: $\eta = \eta_K \times \eta_\pi \times \eta_{NN} \times \eta_{\text{fit}},$ where $\eta_K(= 0.9948 \pm 0.0083)$ and $\eta_\pi(= 0.9512 \pm 0.0079)$ are the corrections due to the $K^\pm$ and $\pi^\pm$ identification with requirement on $L_K$ and $L_\pi,$ and are obtained by the control sample study of $D^{\ast+} \rightarrow D^0 \pi^+$ with $D^0 \rightarrow K^+ \pi^-$, $\eta_{NN}(= 0.9897 \pm 0.0208)$ is due to the requirement on $C_{NN}$ and is obtained by the $B^0 \rightarrow D^- \pi^+$ with $D^- \rightarrow K_S^0 \pi^-$ control sample.
study, and $\eta_{\text{fit}} (= 1.022 \pm 0.004)$ is due to fit bias and is obtained by ensemble test on the fitter. The reconstruction efficiency for the signal ($\epsilon$) is $(26.7 \pm 0.03)\%$ with all the selection criteria applied.

Figure 2 shows the background-subtracted Dalitz plot obtained with the $sPlot$ method. There seem to be some structures around the region of 2 GeV/$c^2$ < $M_{bc}$ < 5.288 GeV/$c^2$ and 0 < $C_{\text{NN}}'$ < 5. (b) $M_{bc}$ in $|\Delta E| < 0.05$ GeV and 0 < $C_{\text{NN}}'$ < 5. (c) $C_{\text{NN}}'$ in $|\Delta E| < 0.05$ GeV and and 5.272 GeV/$c^2$ < $M_{bc}$ < 5.288 GeV/$c^2$.

![Figure 1](image1)

**FIG. 1**: Projections of the fit results of $\bar{B}^0(B^0) \rightarrow K_S^0 K^{\mp+}$ decay on $\Delta E$, $M_{bc}$, and $C_{\text{NN}}'$. (a) $\Delta E$ in 5.272 GeV/$c^2$ < $M_{bc}$ < 5.288 GeV/$c^2$ and 0 < $C_{\text{NN}}'$ < 5. (b) $M_{bc}$ in $|\Delta E| < 0.05$ GeV and 0 < $C_{\text{NN}}'$ < 5. (c) $C_{\text{NN}}'$ in $|\Delta E| < 0.05$ GeV and 5.272 GeV/$c^2$ < $M_{bc}$ < 5.288 GeV/$c^2$.

Sources of various systematic uncertainties on the branching fraction calculation are shown in Table I. The uncertainty due to the total number of $B\bar{B}$ pairs is 1.4%. The uncertainty due to the charged-track reconstruction efficiency is estimated to be 0.35% per track by using the partially reconstructed $D^{\mp+} \rightarrow D^0 \pi^+$ with $D^0 \rightarrow \pi^+\pi^-K_S^0$ events. The uncertainty due to the $K^{\pm}$ and $\pi^{\pm}$ identification are obtained by the control sample study of $D^{\mp+} \rightarrow D^0 \pi^+$ with $D^0 \rightarrow K^+\pi^-$. The uncertainty due to the $K_S^0 \rightarrow \pi^+\pi^-$ branching fraction is based on the world average value $(69.2 \pm 0.05)\%$ [24]. The uncertainty due to $K_S^0$ identification is estimated to be 1.6% based on a control sample of $D^{\mp+} \rightarrow D^0 \pi^+$ with $D^0 \rightarrow K_S^0\pi^0$. The uncertainty due to continuum suppression with the requirement on $C_{\text{NN}}$ and is obtained by the $B^0 \rightarrow D^-\pi^+$ with $D^- \rightarrow K_S^0\pi^-$ control sample study. The

![Image 2](image2)

![Image 3](image3)
uncertainty of the reconstruction efficiency is estimated due to limited MC statistics. The uncertainty due to the fixed signal and background PDF shapes is estimated by the deviation of fitted signal yield with varying the conditions of those PDFs in different cases. For all the smoothed histograms, we vary the binning conditions of those histograms. For the other PDFs with fixed parameterization, the fixed parameters are randomized by using Gaussian random number to repeat data fits with various parameter sets, and the uncertainty of the yield distribution is quoted. The uncertainty due to fit bias is obtained by ensemble test on the fitter.

Sources of various systematic uncertainties on $\mathcal{A}$ are listed in Table III. The uncertainty due to $K^\pm$ and $\pi^\pm$ detection bias are obtained by control sample studies of $D^+ \to \phi\pi^+$ and $D_s^+ \to \phi\pi^+$ [26], and $D^+ \to K^0_S\pi^+$ [27], respectively. The uncertainty due to the fixed signal and background PDF shapes is using the same way as the one for the uncertainty on branching fraction. It is also estimated by the deviation of fitted $\mathcal{A}$ with varying the conditions of those PDFs in different cases.

In conclusion, we have performed a measurement of branching fraction and $\mathcal{A}$ of the
eff. Yield 31
0.292 122 0.237 152 13 (GeV/
M 1.1 2.5 1.1 π 3.5 K
2.5 0.289 47.5 ± 20.5 ± 2.0 3.2 ± 1.4 ± 0.1 9.4 ± 14.3 ± 0.4 38.1 ± 14.7 ± 1.6 1.3 ± 1.9 ± 0.1 5.2 ± 2.0 ± 0.2
π

FIG. 4: Differential branching fraction as functions of the $M_{K^-\pi^+}$, $M_{K^-K^0_S}$, and $M_{\pi+K^0_S}$ for the two reconstructed $B$ final states: $K^0_S K^-\pi^+$ (red error bar) and $K^0_S K^+\pi^-$ (blue error bar).

### TABLE I: Signal yields, efficiency, and differential branching fraction in each $M_{K^-\pi^+}$, $M_{K^-K^0_S}$, and $M_{\pi+K^0_S}$ bin.

| $K^0_S K^+\pi^+$ yield | $K^0_S K^+\pi^-$ yield | $K^0_S K^+\pi^-$ yield |
|-------------------------|-------------------------|-------------------------|
| $M_{K^-\pi^+}$          | $M_{K^-K^0_S}$          | $M_{\pi+K^0_S}$         |
| 0~1.1                   | 0.301 69.2 ± 18.0 ± 3.0 4.1 ± 1.1 ± 0.2 | 40.3 ± 12.7 ± 1.7 28.9 ± 12.8 ± 1.2 4.5 ± 1.5 ± 0.2 3.4 ± 1.5 ± 0.1 |
| 1.1~1.5                 | 0.306 71.3 ± 17.8 ± 3.1 11.4 ± 2.8 ± 0.5 | 31.4 ± 12.3 ± 1.4 39.9 ± 12.9 ± 1.7 10.0 ± 3.9 ± 0.4 12.8 ± 4.1 ± 0.5 |
| 1.5~2.5                 | 0.289 47.5 ± 20.5 ± 2.0 3.2 ± 1.4 ± 0.1 | 9.4 ± 14.3 ± 0.4 38.1 ± 14.7 ± 1.6 1.3 ± 1.9 ± 0.1 5.2 ± 2.0 ± 0.2 |
| 2.5~3.5                 | 0.262 149.7 ± 21.7 ± 6.4 11.2 ± 1.6 ± 0.5 | 56.5 ± 14.6 ± 2.4 93.2 ± 16.1 ± 4.0 8.4 ± 2.2 ± 0.4 13.9 ± 2.4 ± 0.6 |
| >3.5                    | 0.237 152.7 ± 22.0 ± 6.6 7.4 ± 1.1 ± 0.3 | 79.9 ± 15.5 ± 3.4 72.8 ± 15.5 ± 3.1 7.8 ± 1.5 ± 0.3 7.1 ± 1.5 ± 0.3 |

$\bar{B}^0(B^0) \to K^0_S K^-\pi^+\pi^-$ decay based on a data sample of 711 fb$^{-1}$ collected by Belle. We obtain a branching fraction of $(3.60 \pm 0.33 \pm 0.15) \times 10^{-6}$ and an $A$ of $(−8.5 \pm 8.9 \pm 0.2)\%$, where their first uncertainty is statistical and the second is systematic. The measured $A$ is consistent with null asymmetry. Hints of peaking structures are seen around a region of 2 GeV$^2$/c$^4 > M_{K^-K^0_S}^2$ and 7 GeV$^2$/c$^4 < M_{\pi+K^0_S}^2 < 23$ GeV$^2$/c$^4$ in the Dalitz plot. A cross-check is done by the differential branching fraction with projecting on each Dalitz variable, and hints of peaking resonances are seen at around 1.2 GeV/c$^2$ of $M_{K^-K^0_S}$ and around 4.2 GeV/c$^2$ of $M_{\pi+K^0_S}$ when compared to the phase space MC. No obvious $K^*$ structure is seen at both the low $M_{K^-\pi^+}$ and $M_{\pi+K^0_S}$ spectrum, which is also consistent with the BaBar and LHCb results [3, 7, 8]. No localized final-state asymmetry is observed. In the near
TABLE II: Summary of systematic uncertainties on the branching fraction.

| Source | in % |
|--------|------|
| $N_{B\bar{B}}$ | 1.4 |
| Tracking | 0.7 |
| $K^\pm$ identification | 0.8 |
| $\pi^\pm$ identification | 0.8 |
| $\mathcal{B}(K_S^0 \to \pi^+\pi^-)$ | 0.1 |
| $K_S^0 \to \pi^+\pi^-$ identification | 1.6 |
| Continuum suppression with NN | 2.1 |
| Reconstruction efficiency (MC statistics) | 0.1 |
| Signal PDF | 2.7 |
| Background PDF | 0.4 |
| Fit bias | 0.4 |
| **Total** | **4.3** |

TABLE III: Summary of systematic uncertainties on $A$.

| Source | in % |
|--------|------|
| Detector bias | 0.6 |
| Signal PDF | 2.7 |
| Background PDF | 0.9 |
| **Total** | **2.9** |

future, the experiments with large data sets such as Belle II and LHCb can provide more detailed analysis employing a full Dalitz analysis to search for the intermediate resonances and localized final-state asymmetry.

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