Recent measurements of branching fractions and $CP$ asymmetries of charmless hadronic $B$ meson decays at Belle

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Hadronic $B$ decays without a charm quark constitute a powerful probe to search for physics beyond the standard model as well as to provide constraints on $CP$ violation parameters. We report final measurements from Belle of the branching fractions and $CP$ asymmetries for the decays $B^0 \rightarrow \pi^0\pi^0$ and $B^\pm \rightarrow K^\pm K^- \pi^\mp$. The $B^0 \rightarrow \pi^0\pi^0$ measurements enable us to improve constraints on the angle $\phi_2$ of the CKM unitarity triangle. For $B^\pm \rightarrow K^\pm K^- \pi^\mp$ we measure $CP$ asymmetry as a function of the invariant mass of the $K^\pm K^-$ system, where we find a strong evidence for large $CP$ violation and a large increase in yield at low mass region. This result challenges conventional theoretical approaches as it requires a large enhancement in both tree and loop level diagrams in the same small region of phase-space.

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1. Introduction

Charless decays of $B$ mesons to hadronic final states are suppressed in the standard model (SM), hence they constitute a powerful probe to search for new physics as well as to provide constraints on $CP$ violation parameters. Any significant deviation from SM expectations of the branching fraction or $CP$ asymmetry will be a hint towards new physics. In this paper, we present measurements of branching fractions and $CP$ asymmetries for the charmless hadronic $B$ decays $B^\pm \rightarrow K^+K^-\pi^\pm$ and $B^0 \rightarrow \pi^0\pi^0$ based on the full $\Upsilon(4S)$ data collected with the Belle detector at the KEKB asymmetric energy $e^+e^-$ collider [1].

2. $B^\pm \rightarrow K^+K^-\pi^\pm$ decay

$B$ meson decays to three-body charmless hadronic final states of $K^+K^-\pi^+$ [2] are dominated by the Cabbibo-suppressed $b \rightarrow u$ tree and $b \rightarrow d$ loop transitions. Large $CP$ asymmetries can occur in these decays, due to interference between SM tree and loop level diagrams with similar amplitudes. An unidentified structure has been measured by BaBar [3] and LHCb [4, 5] in the low $K^+K^-$ invariant mass spectrum of the $B^+ \rightarrow K^+K^-\pi^+$ decay. Also, LHCb reported a non-zero inclusive $CP$ asymmetry of $-0.123 \pm 0.017 \pm 0.012 \pm 0.007$ (where, the first uncertainty is statistical, the second is the systematic, and the third is due to the $CP$ asymmetry of the $B^+ \rightarrow J/\psi K^+$ reference mode) and a large unquantified local $CP$ asymmetry in the same mass region. These results suggest that final-state interactions can be a contributing factor to $CP$ violation [6, 7]. With this study, we attempt to quantify the $CP$ asymmetry and branching fraction as a function of the $K^+K^-$ invariant mass based on a data sample collected at the $\Upsilon(4S)$ resonance by the Belle detector comprising of $772 \times 10^6 B\bar{B}$, which corresponds to an integrated luminosity of 711 fb$^{-1}$, and an additional 89.4 fb$^{-1}$ of off-resonance sample recorded at a center-of-mass energy around 60 MeV below the $\Upsilon(4S)$ resonance.

We combine two oppositely-charged kaons with a charged pion to reconstruct $B^+ \rightarrow K^+K^-\pi^+$. Charged kaons and pions are identified based on a likelihood ratio obtained by combining information from the aerogel Cherenkov counters, time-of-flight counters, and central drift chamber, $L_{K/\pi} = \frac{L_K}{\sqrt{(L_K)^2 + (L_\pi)^2}}$, where $L_K$ and $L_\pi$ are the likelihoods for the kaon and pion hypothesis, respectively. Tracks with $L_{K/\pi} > 0.6$ are chosen as kaons and those with $L_{K/\pi} < 0.4$ as pions. Signal $B$ events are identified with two kinematic variables: the beam-energy constrained mass, $M_{bc} = \sqrt{E_{beam}^2/c^4 - |p_B/c|^2}$ and the energy difference, $\Delta E = E_B - E_{beam}$, where $E_{beam}$ is the beam energy and $E_B$ and $p_B$ are the energy and momentum of the $B$ candidate in the center-of-mass frame, respectively. The fit region is defined as $M_{bc} > 5.24$ GeV/c$^2$ and $-0.3 < \Delta E < 0.3$ GeV, while the signal-enhanced region is defined as $5.27 < M_{bc} < 5.29$ GeV/c$^2$ and $-0.05 < \Delta E < 0.05$ GeV. When multiple $B$ candidates are present in an event, we choose the candidate with the best fit quality from the $B$ vertex fit. This is done for 19% of events and the selection efficiency is 92%.

The dominant backgrounds are from $e^+e^- \rightarrow q\bar{q}$ ($q = u,d,s,c$) continuum process. The $B\bar{B}$ events are spherical in shape whereas the particles from continuum events are collimated into two back-to-back jets. We make use of this difference in event topology by using a neural network [8] to combine several shape variables along with other properties of the event that distinguish $q\bar{q}$ from $B\bar{B}$ events. A requirement on the neural network output ($C_{NN} > 0.88$) is applied to suppress
One needs all these observables in order to determine certain asymmetries among the $B \rightarrow \pi \pi$ decays. We find strong evidence for a large CP violation in the signal-enhanced region. Background contributions from $B$ mesons mediated by the dominant $b \rightarrow c$ transition are investigated with an MC sample of such decays. To suppress these backgrounds, candidates for which the invariant mass of the $K^+K^-$ or $K^+\pi^-$ system lies in the range 185–188 MeV/$c^2$ are removed. This selection window corresponds to $\pm 3.75\sigma$ around the nominal $D^0$ mass [9], where $\sigma$ is the mass resolution. Backgrounds from charmless $B$ decays are studied with a large MC sample, where one of the $B$ mesons decays via a process with a known branching fraction. The study reveals that a few modes contribute in the $M_{bc}$ signal region with a corresponding $\Delta E$ peak, denoted collectively as the “rare peaking” background. These peaking backgrounds are due to $K-\pi$ misidentification, which consist of $B^+ \rightarrow K^+K^-K^+$, $B^+ \rightarrow K^+\pi^-\pi^+$, and their intermediate resonant modes. Events that remain after removing the peaking components are called the “rare combinatorial” background.

The signal yield is extracted by performing a two-dimensional unbinned extended maximum likelihood fit in $M_{bc}$ and $\Delta E$ with the likelihood defined as

$$\mathcal{L} = e^{-\Sigma N_i} \prod_i \left[ \sum_j N_j \mathcal{P}_j \right]$$

where $i$ denotes the event index, $N_j$ is the yield for the component $j$, $q_i$ is the charge of $B$ candidates ($q_i = \pm 1$ for $B^\pm$), and $\mathcal{P}_j$ is the probability density function (PDF) corresponding to the component $j$. Figure 1 shows the fit results of first two $M_{K^+K^-}$ bins in the signal-enhanced region. The resulting branching fraction and CP asymmetry are [10]

$$\mathcal{B}(B^+ \rightarrow K^+K^-\pi^+) = (5.38 \pm 0.40 \pm 0.35) \times 10^{-6} \quad (2.2)$$

and

$$A_{CP} = -0.182 \pm 0.071 \pm 0.016, \quad (2.3)$$

where the quoted uncertainties are statistical and systematic, respectively.

To investigate the localized CP asymmetry in the low $M_{K^+K^-}$ region, we determine the signal yield and $A_{CP}$ in bins of $M_{K^+K^-}$. The fitted results are shown in Table 1 and Fig. 2, where an excess of signal yield as well as a large $A_{CP}$ are seen in $M_{K^+K^-} < 1.5$ GeV/$c^2$, confirming the observations by BaBar and LHCb. We find strong evidence for a large CP asymmetry of $-0.90 \pm 0.17 \pm 0.03$ with a significance of 4.8$\sigma$ for $M_{K^+K^-} < 1.1$ GeV/$c^2$.

3. $B^0 \rightarrow \pi^0\pi^0$ decay

One of the proposed techniques to measure $\phi_2$ is to perform an isospin analysis of the entire $B \rightarrow \pi\pi$ system [11]. This requires measurements of $\mathcal{B}$ and $A_{CP}$ for $B^+ \rightarrow \pi^+\pi^0$ and $B^0 \rightarrow \pi^0\pi^0$ decays, along with that of $\mathcal{B}$ and time-dependent CP asymmetry for the $B^0 \rightarrow \pi^+\pi^-$ decay. One needs all these observables in order to determine $\phi_2$ as electroweak tree and loop processes contribute with different phases to $B \rightarrow \pi\pi$ decays. The $\mathcal{B}$ and $A_{CP}$ for $B^0 \rightarrow \pi^0\pi^0$ are the least well determined among the $B \rightarrow \pi\pi$ decays. This decay is also important to probe the disagreement...
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Figure 1: Signal-enhanced projections of the $M_{bc}$--$\Delta E$ fit to data in the first (left) and second (right) $M_{K^+K^-}$ bins. Points with error bars are the data, red solid curves are the fit result, blue solid curves are the sum of the signal and the self cross-feed, cyan dotted curves are the continuum background, brown dash dotted curves are the generic $B$ backgrounds, and green dashed curves are the rare $B$ backgrounds.

Table 1: Signal yield, efficiency, differential branching fraction, and $A_{CP}$ for individual $M_{KK}$ bins

<table>
<thead>
<tr>
<th>$M_{K^+K^-}$ (GeV/$c^2$)</th>
<th>$N_{sig}$</th>
<th>Eff. (%)</th>
<th>$d\mathcal{B}/dM$ ($\times 10^{-7}$)</th>
<th>$A_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8–1.1</td>
<td>59.8 ± 11.4 ± 2.6</td>
<td>19.7</td>
<td>14.0 ± 2.7 ± 0.8</td>
<td>−0.90 ± 0.17 ± 0.03</td>
</tr>
<tr>
<td>1.1–1.5</td>
<td>212.4 ± 21.3 ± 6.6</td>
<td>19.3</td>
<td>37.8 ± 3.8 ± 1.9</td>
<td>−0.16 ± 0.10 ± 0.01</td>
</tr>
<tr>
<td>1.5–2.5</td>
<td>113.5 ± 26.7 ± 18.0</td>
<td>15.6</td>
<td>10.0 ± 2.3 ± 1.6</td>
<td>−0.15 ± 0.23 ± 0.03</td>
</tr>
<tr>
<td>2.5–3.5</td>
<td>110.1 ± 17.6 ± 4.1</td>
<td>15.1</td>
<td>10.0 ± 1.6 ± 0.5</td>
<td>−0.09 ± 0.16 ± 0.01</td>
</tr>
<tr>
<td>3.5–5.3</td>
<td>172.6 ± 25.7 ± 6.87</td>
<td>16.3</td>
<td>8.1 ± 1.2 ± 0.5</td>
<td>−0.05 ± 0.15 ± 0.00</td>
</tr>
</tbody>
</table>

Figure 2: Measured differential branching fractions (left) and $A_{CP}$ (right) as a function of $M_{K^+K^-}$. Each point is obtained from a two-dimensional fit with systematic uncertainty included. Red squares with error bars in the left plot show the expected signal distribution for a three-body phase space MC sample. Note that the phase space hypothesis is rescaled to the experimentally observed total $B^+ \rightarrow K^+K^-\pi^+$ signal yield.
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between quantum-chromodynamics-based factorization, which predicts $\mathcal{B}$ below $1 \times 10^{-6}$ [12, 13], and previous measurements from Belle and BaBar of $(1.8 - 2.3) \times 10^{-6}$ [14,15]. Our study is based on a data sample recorded at the $\Upsilon'(4S)$ resonance with the Belle detector comprising of $752 \times 10^6$ $B\bar{B}$ pairs, which corresponds to an integrated luminosity of 693 fb$^{-1}$, and an additional 83.35 fb$^{-1}$ recorded 60 MeV below the $\Upsilon(4S)$ resonance.

We reconstruct the signal $B^0$ candidate from a pair of $\pi^0$ candidates, each subsequently decaying to two photons. In addition to photons reconstructed from clusters in the electromagnetic calorimeter (ECL) that do not match any charged track, photons that convert to $e^+e^-$ pairs in the silicon vertex detector (SVD) are recovered and reconstructed as $\pi^0 \rightarrow \gamma e^+e^-$. This provides a 5.3% increase in detection efficiency. These photons must have an energy greater than 50 (100) MeV in the barrel (endcap) region of the ECL. The invariant mass of the two-photon combination must lie in the range $115 < m_{\gamma\gamma} < 152 \text{ MeV}/c^2$, corresponding to $\pm 2.6 \sigma$ around the nominal $\pi^0$ mass [9]. As in the case of $B^+ \rightarrow K^+ K^- \pi^+$, two kinematic variables $\Delta E$ and $M_{bc}$ are used to select the signal candidates. All candidates satisfying $M_{bc} > 5.26 \text{ GeV}/c^2$ and $-0.3 < \Delta E < 0.2 \text{ GeV}$ are retained for further analysis. For 7.2% of the events, there are multiple $B^0$ candidates in which we choose the one that minimizes the deviation of the two $\pi^0$'s reconstructed invariant masses from the world average [9]. This criterion selects the true $B^0$ candidate in 90% of MC events.

The dominant background is from $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) continuum process. To suppress this, we develop a Fisher discriminant ($T_c$) out of 16 modified Fox-Wolfram moments [16] combined with the cosine of the polar angle of the $B$ candidate with respect to the $z$-axis and the cosine of the angle between the thrust axis of the $B$ candidate and rest of event in the center-of-mass frame. All candidates with $T_c$ values below $-0.3$ are discarded, removing 72% of the continuum background while retaining 98% of signal events. Background events that arise from $b \rightarrow c$ transitions are mostly due to out-of-time ECL events originating from $e^+e^-$ interactions, which leave large energy deposits in the ECL. This leads to a “pileup” event resembling a hadronic event with high energy back-to-back photons in the center-of-mass frame, and thus passes the first-level trigger. When combined with random photons from the hadronic interaction, they appear as two $\pi^0$'s with a large invariant mass. These events peak near the nominal $B$ mass [9] in $M_{bc}$. Since the events are recorded in coincidence with hadronic interactions, they also mimic $B$-like events in the continuum suppression variable $T_c$. A criterion on the trigger time of the ECL crystals, which selects ECL interactions in-time with the rest of the event, is employed to suppress this background removing 99% of pileup at the cost of only 1% of signal. The dominant background from the rare $B$ decays ($b \rightarrow u, d, s$ transitions) is due to $B^+ \rightarrow \rho^+ \pi^0$, where the charged pion from the subsequent $\rho^+ \rightarrow \pi^+ \pi^0$ decay is lost. This background peaks at similar values of $M_{bc}$ and $T_c$ as signal, but has $\Delta E$ shifted to negative values due to energy loss from the missing $\pi^+$.

The flavor of the reconstructed $B$ candidate is determined via a tagging procedure described in Ref. [17]. The tagging information is given by two parameters: the $b$-flavor charge $q [+1 (-1)$ tagging a $B^0(\bar{B}^0)]$ and purity $r$. For the signal extraction, separate PDFs are constructed for the SVD1 (S1) and SVD2 (S2) data sets. We divide the data into seven bins, each for positive and negative tagged $r$-values, for both S1 and S2. The signal yield and $A_{CP}$ are extracted by performing a three-dimensional simultaneous unbinned extended maximum likelihood fit to the subsequent 28 data sets with $M_{bc}$, $\Delta E$ and $T_c$. Figure 3 shows the signal-enhanced projections of the fits to data in the three variables. We obtain a signal yield of $217 \pm 32$ events. The results are [18]...
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\[ \mathcal{B}(B^0 \to \pi^0 \pi^0) = (1.31 \pm 0.19 \pm 0.18) \times 10^{-6} \]  

(3.1)

and

\[ A_{CP} = +0.14 \pm 0.36 \pm 0.12, \]  

(3.2)

where the quoted uncertainties are statistical and systematic, respectively.

Combining our results for \( \mathcal{B} \) and \( A_{CP} \) for \( B^0 \to \pi^0 \pi^0 \) with Belle’s previous measurements of \( \mathcal{B} \) and time-dependent CP asymmetry for \( B^0 \to \pi^+ \pi^- \) [19] and \( \mathcal{B} \) and \( A_{CP} \) for \( B^+ \to \pi^+ \pi^0 \) [20] allows us to employ the isospin analysis of Ref. [11] to constrain \( \phi_2 \). The result of the fit is shown in Fig. 4. Our results exclude \( 15.5^\circ < \phi_2 < 75.0^\circ \) at 95% confidence level.

\[ \text{Figure 3: Projections of the fit results onto (left) } \Delta E, \text{ (middle) } M_{bc}, \text{ and (right) } T_c. \text{ Data are points with error bars; the full fit results are shown by the solid black curves. Contributions from signal, continuum } q\bar{q}, \text{ combined } \rho \pi, \text{ and other rare } B \text{ decays are shown by the dashed blue, dotted green, and dash-dotted red curves, respectively. The top (bottom) row panels are for events with positive (negative) } q \text{ tags.} \]

\[ \text{Figure 4: Scan of the confidence level for } \phi_2 \text{ using only data from } B \to \pi \pi \text{ measurements of the Belle experiment. The dashed red curve shows the previous constraint from Belle data [19], while the solid blue curve includes our new results. The straight black dashed line is the 95% confidence level and the green dot dashed line shows 68% confidence level.} \]
4. Conclusion

We have reported the recent measurements from Belle of the branching fractions and CP asymmetries for $B^\pm \to K^+K^-\pi^\pm$ and $B^0 \to \pi^0\pi^0$ decays using a data sample collected with the Belle detector. For the decay $B^\pm \to K^+K^-\pi^\pm$, we confirm the observations by BaBar and LHCb, and find strong evidence for a large CP asymmetry at the low $M_{K^+K^-}$ region. Measurements of $\mathcal{B}$ and $\mathcal{A}_{CP}$ in $B^0 \to \pi^0\pi^0$ enable improved constraints on the angle $\phi_2$ of the CKM unitarity triangle. Although the result is closer to theory predictions than the earlier Belle [14] and BaBar [15] measurements, it is still larger than expectations. The upcoming Belle II experiment [21], with its projected 50 times increased luminosity, will enable precision measurements of $\mathcal{B}$ and $\mathcal{A}_{CP}$ of $B^0 \to \pi^0\pi^0$ and other $B \to \pi\pi$ decays to strongly constrain $\phi_2$.

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References

[2] Throughout this paper, the inclusion of the charge-conjugate decay modes is implied unless otherwise stated.
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