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Study of Charmless Hadronic B Decays and Rare D Decays at Belle

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We present the summary of recent studies of $B^+ \to K^+K^-\pi^+$ and $B^0 \to \pi^0\pi^0$ charmless B decays, $D^+ \to \pi^+\pi^0$ rare D decay and the first search for D^0 to *invisible final states* using a full data sample ($\sim 1\ \text{ab}^{-1}$) of the Belle experiment at the KEKB asymmetric-energy $e^+ e^-$ collider.

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1. Introduction

Rare B and D meson decays provide a powerful probe to search for physics beyond the standard model (SM). Observation of any significant deviation from the SM will be clear evidence for new physics (NP) beyond the SM. Here we present direct CP asymmetry $\left(\mathscr{A}_{CP} = \frac{|\overline{A}_{\overline{B}\to\overline{f}}/A_{B\to f}|^2-1}{|\overline{A}_{\overline{B}\to\overline{f}}/A_{B\to f}|^2+1}\right.$, where $A_{B\to f}$ and $\overline{A}_{\overline{B}\to\overline{f}}$ are instantaneous decay amplitudes$\left.\right)$ and branching fraction ($\mathscr{B}$) measurements of $B^+ \to K^+K^-\pi^+$ and $B^0 \to \pi^0\pi^0$ charmless hadronic B decays; a search for CP violation in $D^+ \to \pi^+\pi^0$ rare D decay; and the first search for D^0 to *invisible final states* at the Belle experiment. The results are based on the full data sample collected by the Belle detector at KEKB.

2. Measurement of Branching Fraction and Direct CP Asymmetry in $B^+ \to K^+K^-\pi^+$ Decay

The decays of $B^+ \to K^+K^-\pi^+$ are dominated by the Cabibbo-suppressed $b \to u$ tree and $b \to d$ loop transitions. Interference between tree and loop processes with similar amplitudes can cause large CP asymmetries. *BABAR* measured the $\mathscr{B}$ of $B^+ \to K^+K^-\pi^+$ decay as $[5.0 \pm 0.5(stat) \pm 0.5(syst)] \times 10^{-6}$ and $\mathscr{A}_{CP}$ which is consistent with zero [1]. *BABAR* also reported a broad peaking structure near 1.5 GeV/c^2 in the K^+K^- invariant mass distribution. Later, LHCb observed a nonzero inclusive CP asymmetry of $-0.123 \pm 0.017(stat) \pm 0.012(syst) \pm 0.007$ (where the third uncertainty is due to CP asymmetry of the $B^+ \to J/\psi K^\pm$) and a large unquantified local CP asymmetry in the same K^+K^- invariant mass ($M_{K^+K^-}$) region [2, 3]. This analysis aims to quantify the $\mathscr{B}$ and CP asymmetry as a function of $M_{K^+K^-}$ using a data sample that contains 772×10^6 $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector.

Two standard kinematic variables are used to identify B meson candidates: the beam-energy-constrained mass, $M_{bc} = \sqrt{E^2_{beam}/c^4 - |p_B/c|^2}$ 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 reference frame. The primary background is continuum $e^+e^- \to q\bar{q}(q = u,d,s,c)$ events. To eliminate this type of events from signal, a neural network [4] is employed by combining variables based on the event topology. A requirement on the neural network output $\mathscr{C}_{NN} <$ 0.88 suppresses 99% of the continuum events while keeping 48% of the signal. The charm veto is applied to reject charm B decays having the same final-state particles. There are a few charmless B decays contributing to the M_{bc} signal region with corresponding ΔE peak due to K-π misidentification: $B^+ \to K^+K^-K^+$, $B^+ \to K^+\pi^-\pi^+$ and their intermediate resonant modes. Events which remain after removing peaking backgrounds are referred to as 'rare combinatorial' background.

A two-dimensional unbinned maximum-likelihood (ML) fit to M_{bc} and ΔE distributions in bins of $M_{K^+K^-}$ is performed to determine the signal yield and $\mathscr{A}_{CP}$. The measured inclusive branching fraction and direct CP asymmetry are [5]

$$\mathscr{B}(B^+ \to K^+K^-\pi^+) = (5.38 \pm 0.40 \pm 0.35) \times 10^{-6} \text{ and } \mathscr{A}_{CP} = -0.170 \pm 0.073 \pm 0.017 .$$

Figure 1 shows quantified differential $\mathscr{B}$ and $\mathscr{A}_{CP}$ as a function of $M_{K^+K^-}$. A strong evidence of large CP asymmetry with 4.8 σ significance is found in the region where $M_{K^+K^-}$ is smaller than 1.1 GeV/c^2, consistent with the *BABAR* and LHCb meausurements.

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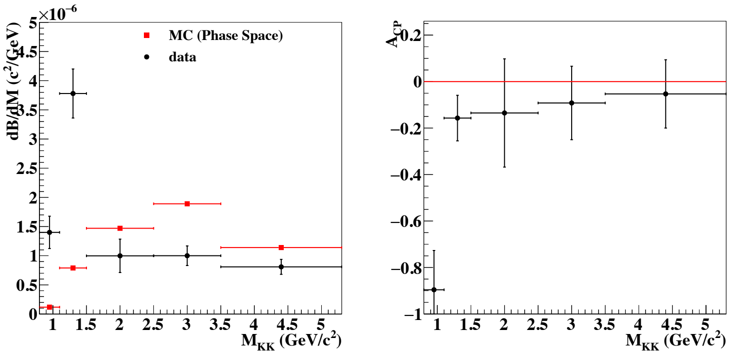

Figure 1: Measured differential $\mathscr{B}$ (left), and direct CP (right) as a function of $M_{K^+K^-}$. Each point is obtained from a two-dimensional fit with systematic uncertainty included. Red squares with error bars on the left figure indicate the expected signal distributions in a three-body phase-space MC sample. Note that the phase-space hypothesis is rescaled to the total observed $B^+ \to K^+K^-\pi^+$ signal yield.

3. Measurement of Branching Fraction and Direct CP Asymmetry in $B^0 \to \pi^0\pi^0$ Decay

The CKM angle ϕ_2 can be determined by measuring the time-dependent CP violation in $B^0 \to \pi^+\pi^-$ decay. Possible penguin contributions can give rise to direct CP violation, $\mathscr{A}_{CP} \neq 0$, and potentially modify the asymmetry by introducing $\Delta\phi_2$ term in the mixing-induced CP violation parameter, $S_{CP} = \sqrt{1-A_{CP}^2}\,\sin[2(\phi_2 - \Delta\phi_2)]$. To extract $\Delta\phi_2$ information, an isospin analysis of the entire $B \to \pi\pi$ system is needed [6]. The branching fraction and $\mathscr{A}_{CP}$ for $B^0 \to \pi^0\pi^0$ are the least well determined among the $B \to \pi\pi$ decays. *BABAR* (with 467 million $B\overline{B}$ events) and Belle (with 275 million $B\overline{B}$ events) report the $\mathscr{B}$ of 1.8×10^{-6} and 2.3×10^{-6}, respectively [7, 8]. On the other hand, the theoretical prediction is below 1×10^{-6} [9, 10]. This analysis measures $\mathscr{B}$ and $\mathscr{A}_{CP}$ in $B^0 \to \pi^0\pi^0$ based on the full Belle data sample that contains 752 million $B\overline{B}$ pairs.

The b-flavor of the other B meson, B^0_{tag}, is used to extract the $\mathscr{A}_{CP}$ and the effect of $B\overline{B}$ mixing is corrected. To distinguish signal from background, two kinematic variables, M_{bc} and ΔE, are deployed. Event shape variables are combined in the Fisher discriminant (T_c) to suppress continuum background. The signal yield and $\mathscr{A}_{CP}$ are obtained using an unbinned extended maximum-likelihood fit to M_{bc}, ΔE and T_c. The fit projection plots of ΔE, M_{bc}, and T_c are shown in Figure 2. The fit yields 217 ± 32 signal candidates. The $\mathscr{B}$ and $\mathscr{A}_{CP}$ are determined as

$$\mathscr{B}(B^0 \to \pi^0\pi^0) = (1.31 \pm 0.19 \pm 0.19) \times 10^{-6} \text{ and } \mathscr{A}_{CP} = -0.14 \pm 0.36 \pm 0.10\,.$$

The signal significance, including the systematic uncertainty, is 6.4 standard deviations. The measured $\mathscr{B}$ is consistent with the *BABAR* measurement and supersedes the previous Belle one [8].

All Belle $B \to \pi\pi$ measurements [11, 12, 13] are combined to exclude ϕ_2 from $15.5^\circ < \phi_2 < 75.0^\circ$ at 95% confidence level [11].

4. Search for CP violation in $D^+ \to \pi^+\pi^0$

In contrast to strange and bottom sectors, the SM predictions of CP asymmetry in the charm sector are much smaller. The singly Cabibbo-suppressed $D^+ \to \pi^+\pi^0$ decay is an excellent can-

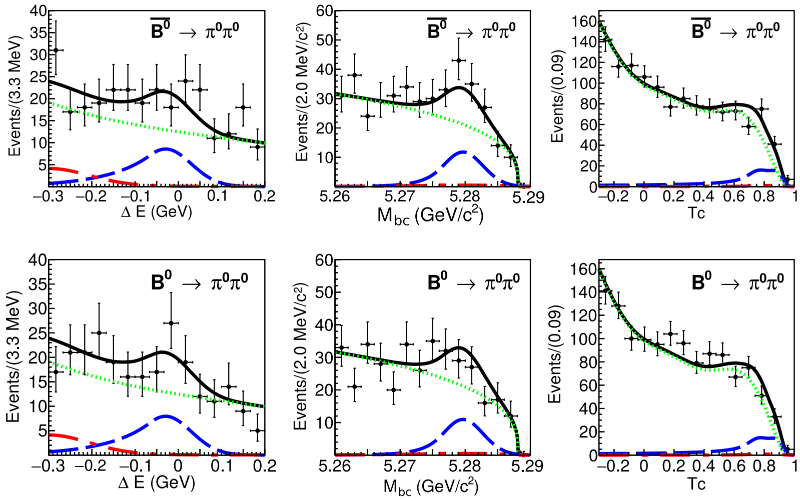

Figure 2: Projections of the fit results onto ΔE (left), M_{bc} (middle), and T_c (right) in the signal-enhanced region: $5.275\ GeV/c^2 < M_{bc} < 5.285\ GeV/c^2$, $-0.15\ GeV < \Delta E < 0.05\ GeV$, and $T_c > 0.7$. Data are points with error bars; the full fit results are shown by the solid black curves. Contributions from signal, continuum $q\bar{q}$, combined $\rho\ \pi$, and other rare B 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) b-flavor charge (q) of B^0_{tag}.

didate to search for CP violation in the charm system. In addition to a search for CP violation in $D^+ \to \pi^+\pi^0$, Grossman, Kagan and Zupan suggest verifying a sum rule relating individual asymmetries of the three isospin-related $D \to \pi\pi$ decays [14] to probe potential NP. The CP asymmetry of $D^+ \to \pi^+\pi^0$ decay measured by CLEO ($\mathscr{A}_{CP}(D^+ \to \pi^+\pi^0) = (2.9 \pm 2.9 \pm 0.3)\%$) has high statistical uncertainty and therefore limits the precision with which the sum rule can be tested [15].

Here we present the measurement of $\mathscr{A}_{CP}$ for the $D^+ \to \pi^+\pi^0$ decay based on 921 fb^{-1} of Belle data. A sample of D^+ mesons tagged by $D^{*+} \to D^+\pi^0$ decays (*tagged* sample) and another not tagged by D^{*+} decays (*untagged* sample) are considered for the $\mathscr{A}_{CP}$ measurement. The decay $D^+ \to K^0_S\pi^+$ is used as a normalization channel ($\mathscr{A}^{K\pi}_{CP} = (0.363 \pm 0.094 \pm 0.067)\%$ [16]) to correct the pion detection efficiency asymmetry, $A^{\pi^\pm}_{\varepsilon}$, and the forward-backward asymmetry, A_{FB}, originating due to interference between the amplitudes mediated by a virtual photon, Z^0 boson, and higher order effects in $e^+e^- \to c\bar{c}$.

The raw asymmetry is related to $A^{\pi\pi}_{raw} = \frac{N(D^+\to\pi^+\pi^0)-N(D^-\to\pi^-\pi^0)}{N(D^+\to\pi^+\pi^0)+N(D^-\to\pi^-\pi^0)} = A^{\pi\pi}_{CP} + A_{FB} + A^{\pi^\pm}_{\varepsilon}$, where $N(D^+ \to \pi^+\pi^0)$ and $N(D^- \to \pi^-\pi^0)$ are the yields for the signal and its CP-conjugate process, respectively. A simultaneous fit to the invariant mass (M_D) is employed to determine the raw asymmetries. For the tagged sample, the raw asymmetries are obtained as $\mathscr{A}^{\pi\pi}_{raw}$=$(+0.52 \pm 1.92)\%$ (signal) and $\mathscr{A}^{K\pi}_{raw}$=$(0.29 \pm 0.44)\%$ (normalization mode); the corresponding results for untagged sample are $\mathscr{A}^{\pi\pi}_{raw}$=$(+3.77 \pm 1.60)\%$ and $\mathscr{A}^{K\pi}_{raw}$=$(0.25 \pm 0.17)\%$.

The difference in the raw asymmetries is represented as $\Delta\mathscr{A}_{raw} \equiv \mathscr{A}^{\pi\pi}_{raw} - \mathscr{A}^{K\pi}_{raw} = \mathscr{A}^{\pi\pi}_{CP} - \mathscr{A}^{K\pi}_{CP}$, and is calculated for both tagged and untagged sample : $\Delta\mathscr{A}_{raw}(tagged) = (+0.81 \pm 1.97 \pm 0.19)\%$ and $\Delta\mathscr{A}_{raw}(untagged) = (+4.02 \pm 1.61 \pm 0.32)\%$. A combination of the two [17] results in

$\Delta A_{raw} = (+2.67 \pm 1.24 \pm 0.20)\%$. Finally, we obtain

$$\mathscr{A}_{CP}(D^+ \to \pi^+\pi^0) = (+2.31 \pm 1.24 \pm 0.23)\% ,$$

which is consistent with zero, as expected in the Standard Model [18]. The precision is improved by more than a factor of two over the measurement performed by CLEO.

5. Search for $D^0 \to$ invisible final states

The estimated $\mathscr{B}$ of helicity-suppressed $D^0 \to \nu\bar{\nu}$ decay is 1.1×10^{-30} [19], which is impossible to be reached by current collider experiments. The $\mathscr{B}$ of D^0 to invisible final states may be enhanced up to $\mathscr{O}(10^{-15})$ with several dark matter candidates in the non-SM mechanism [20, 21].

We report the first search for the D^0 decays to invisible final states using 924 fb^{-1} data collected at and near the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances. To identify D^0 decays containing invisible particles, the charm tagger method is used to select an inclusive D^0 sample [22]. The process $e^+e^- \to c\bar{c} \to D^{(*)}_{tag} X_{frag} \overline{D}^{(*)-}_{sig}$ with $\overline{D}^{(*)-}_{sig} \to \overline{D}^{(0)}_{sig}\pi^-_s$ is reconstructed except for $\overline{D}^{(0)}_{sig}$. Here, $D^{(*)}_{tag}$ and X_{frag} denote a charm particle ($D^{(*)0}$, $D^{(*)+}$, $D^{(*)+}_s$ or Λ^+_c) and extra fragmentation particles, respectively. The inclusive D^0 yield is extracted from a one dimensional extended unbinned maximum likelihood fit to the missing mass for the $D^{(*)}_{tag}\, X_{frag}\, \pi^-_s$ system (M_{D^0}). Requiring no remaining final state particles associated with $\overline{D}^0_{sig}$ selects the invisible D^0 decay candidates. A two-dimensional extended unbinned maximum-likelihood fit to the invariant mass distributions of D^0 and the residual energy in the electromagnetic calorimeter E_{ECL} is used to extract the $D^0 \to$ invisible signal yield. Figure 3 shows the projections of the fit. The fitted signal yield is $-6.3^{+22.5}_{-21.0}$, which is consistent with zero. An upper limit on the $\mathscr{B}$ is determined as 9.4×10^{-5} at the 90% confidence level [23].

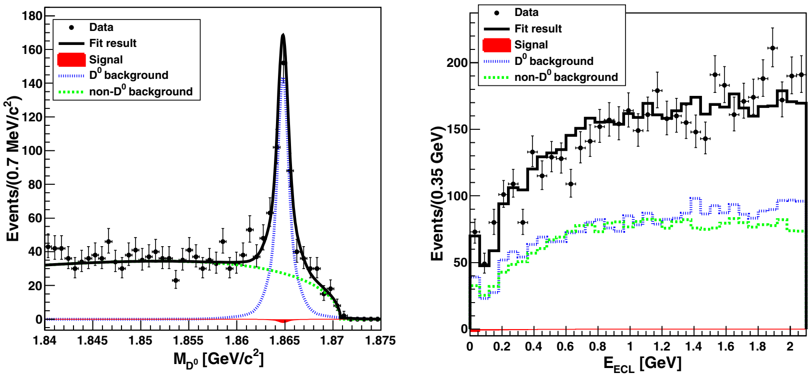

Figure 3: Fit results of D^0 decays to invisible final states. The left plot shows the M_{D^0} distribution for $E_{ECL} < 0.5$ GeV and right plot shows E_{ECL} for $M_{D^0} > 1.86$ GeV/c^2. The points with error bars are data, the blue dotted line is D^0 background, the green dashed line is non-D^0 background, the red filled area is the signal of D^0 decaying to invisible final states and the solid black line is the total fit result.

6. Summary

We have summarized recent studies from Belle on $B^+ \to K^+K^-\pi^+$ and $B^0 \to \pi^0\pi^0$ charmless B decays, $D^+ \to \pi^+\pi^0$ rare D decay and the first search for D^0 to invisible final states using the full Belle data set. The $\mathscr{B}$ and $\mathscr{A}_{CP}$ in $B^+ \to K^+K^-\pi^+$ are quantified as a function of K^+K^- invariant mass. We confirm the large *CP* asymmetry with 4.8 σ significance in the low $M_{K^+K^-}$ region consistent with the *BABAR* and LHCb measurements. An extensive data set from Belle II and LHCb is needed to understand the origin of the low-mass dynamics. Measurements of the $\mathscr{B}$ and $\mathscr{A}_{CP}$ in $B^0 \to \pi^0\pi^0$ have been presented. The results are used to update the ϕ_2 constraint from Belle. A search for *CP* violation in the $D^+ \to \pi^+\pi^0$ decay crucial to test the isospin sum rule has been discussed. The $\mathscr{A}_{CP}$ is consistent with the SM expectation (null asymmetry), and the precision is improved by more than a factor of two over the previous measurement. The first search for D^0 decays into invisible final states has been performed, and no significant signal yield is found.

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