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Direct CP violation and charmless B decays at Belle

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We report measurements of branching fractions and direct CP violating asymmetries for B meson decays to pseudoscalar-pseudoscalar final states based on a data sample of 772 million $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. The difference of CP asymmetry between the decays $B^\pm \to K^\pm\pi^0$ and $B^0 \to K^\pm\pi^\mp$ is measured to be $\Delta A_{K\pi} = 0.112 \pm 0.028$ with a significance of 4.0σ, which is sensitive to new physics in the electro-magnetic penguin loop, The obtained partial width ratios of $B \to K\pi$, variables that probe new physics also in the electro-magnetic penguin loop, are $R_c = 1.05 \pm 0.03 \pm 0.05$ and $R_n = 1.04 \pm 0.05 \pm 0.06$. Furthermore, we see the evidences of direct CP violation for both $B^\pm \to \eta K^\pm$ and $B^\pm \to \eta\pi^\pm$; the corresponding asymmetries are $A_{CP}(B^\pm \to \eta K^\pm) = -0.38 \pm 0.11 \pm 0.01$ and $A_{CP}(B^\pm \to \eta\pi^\pm) = -0.19 \pm 0.06 \pm 0.01$ with significances of 3.8σ and 3.0σ, respectively. We also observe the decay $B^0 \to \eta K^0$ for the first time and the the branching fraction is measured to be $\mathscr{B}(B^0 \to \eta K^0) = (1.27^{+0.33}_{-0.29} \pm 0.08) \times 10^{-6}$ with a significance of 5.4σ.

XXIst International Europhysics Conference on High Energy Physics
21-27 July 2011
Grenoble, Rhône Alpes France

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PoS(EPS-HEP2011)140

Charmless B decays provide a rich ground to understand the mechanism of B meson decays and a good place to search for new physics. Although theoretical calculations on the branching fractions under various approaches suffer from large hadronic uncertainties, new physics or underlying mechanism can still be revealed using the direct CP violating asymmetries (A_{CP}) and ratios of branching fractions, where many theoretical uncertainties cancel out. The observable A_{CP} is defined as $A_{CP} \equiv \frac{\Gamma(B^-(\overline{B}^0)\to hh^{-(0)})-\Gamma(B^+(B^0)\to hh^{+(0)})}{\Gamma(B^-(\overline{B}^0)\to hh^{-(0)})+\Gamma(B^+(B^0)\to hh^{+(0)})}$ and $\Gamma(B \to hh)$ is the partial decay width. In this article we report the branching fractions and direct CP violating asymmetries of B decays to hh ($h = K, \pi, \text{or } \eta$) decays using the final Belle dataset. The data sample corresponds to (772 $\pm$ 11) $\times 10^6$ $B\overline{B}$ pairs collected with the Belle detector at the KEKB e^+e^- asymmetric-energy (3.5 GeV on 8 GeV) collider [1] operating at the $\Upsilon(4S)$ resonance. The whole data sample was reprocessed with a better tracking software and we do have better understandings of the Belle detector. The production rates of B^+B^- and $B^0\overline{B}^0$ pairs are assumed to be equal in $\Upsilon(4S)$ decay.

The event selection and B candidate reconstruction are similar to those documented in our previous publications [2, 3]. Charged kaons and pions are identified using the Belle particle identification devices [4]. Candidate K^0 and π^0 mesons are selected by $K^0_S \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$, respectively. Two η decay channels are used: $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$. Candidate B mesons are identified by the "beam-energy-constrained" mass, $M_{\rm bc} \equiv \sqrt{E^{*2}_{\rm beam}/c^4 - p^{*2}_B/c^2}$, and the energy difference, $\Delta E \equiv E^*_B - E^*_{\rm beam}$, where $E^*_{\rm beam}$ is the run-dependent beam energy, and E^*_B and p^*_B are the reconstructed energy and momentum of the B candidates in the center-of-mass (CM) frame, respectively. For the decays with π^0 or η in the final state, the correlation between $M_{\rm bc}$ and ΔE is relatively large, due to the photon shower leakage in the calorimeter. To reduce the $M_{\rm bc}$-ΔE correlation for this case, $M_{\rm bc}$ is calculated by first shifting the magnitude of $\pi^0(\eta)$ momentum but retaining its direction such that ΔE equals to 0. The correlation of the two variables for the typical $K^\pm\pi^0$ mode is reduced from $+18\%$ to -4%.

The dominant background arises from $e^+e^- \to q\overline{q}$ $(q = u, d, s, c)$ continuum events. We use topological event variables to distinguish spherically distributed $B\overline{B}$ events from the jet-like continuum background. First we combined a set of modified Fox-Wolfram moments [5] into a Fisher discriminant. A signal/background likelihood is formed using this discriminant and other uncorrelated variables such as the cosine of the polar angle of the B flight direction and the decay flight length difference (ΔZ) between the signal and accompanying Bs. A loose continuum suppression $R > 0.2$ is applied, where $R = L_{\rm sig}/(L_{\rm sig} + L_{q\overline{q}})$ and $L_{\rm sig}$ ($L_{q\overline{q}}$) is the signal (continuum) likelihood. The variable R is then transformed into R', defined as $R' = \ln(\frac{R-0.2}{1.0-R})$ for the signal extraction.

The signal yields are extracted by performing extended unbinned maximum likelihood fits to the ($M_{\rm bc}$, ΔE, $\mathscr{R}'$) distributions of the selected candidate events. The likelihood function for each mode is defined as

$$\mathscr{L} = e^{-\sum_j N_j} \times \prod_i (\sum_j N_j \mathscr{P}^i_j) \quad \text{and}$$

$$\mathscr{P}^i_j = \frac{1}{2}[1 - q^i \cdot A_{CP\,j}] P_j(M^i_{\rm bc}, \Delta E^i, R'^i), \tag{1}$$

where i denotes the i-th event and N_j is the number of events for the category j, which corresponds to either signal, continuum, the feed-across due to K-π misidentification, or the background from other charmless B decays. $P_j(M_{\rm bc}, \Delta E, R'^i)$ is the probability density function (PDF) in $M_{\rm bc}$, ΔE

and R'^i. Here q is the flavor of B-meson candidates, which is $+1$ for $B^+(B^0)$ and -1 for $B^-(\overline{B}^0)$. For the CP eigen modes, $\mathscr{P}^i_j$ in Eq. 1 is simply $P_j(M^i_{\rm bc}, \Delta E^i, R'^i)$.

Table 1: Extracted signal yields, product of efficiencies and sub-decay branching ratios ($\mathscr{B}_s$), calculated branching fractions, significance of CP asymmetries, and CP asymmetries for individual modes. The branching fraction and A_{CP} errors are statistical and systematic, respectively.

Mode	Yield	Eff.$\times\mathscr{B}_s$(%)	$\mathscr{B}(10^{-6})$	$\mathscr{S}$	A_{CP}
$K^\pm\pi^\mp$	7525 ± 127	48.82	$20.00\pm0.34\pm0.63$	4.4	$-0.069\pm0.014\pm0.007$
$\pi^+\pi^-$	2111 ± 89	54.79	$5.04\pm0.21\pm0.18$	–	–
$K^\pm\pi^0$	3731 ± 92	38.30	$12.62\pm0.31\pm0.56$	1.9	$+0.043\pm0.024\pm0.002$
$\pi^\pm\pi^0$	1846 ± 82	40.80	$5.86\pm0.26\pm0.38$	0.6	$-0.025\pm0.043\pm0.007$
$K^0K^\pm$	134 ± 23	15.64	$1.11\pm0.19\pm0.05$	0.1	$+0.017\pm0.168\pm0.002$
$K^0\pi^\pm$	3229 ± 71	17.46	$23.97\pm0.53\pm0.69$	0.7	$-0.014\pm0.021\pm0.006$
$K^0\overline{K}^0$	103 ± 15	10.61	$1.26\pm0.19\pm0.06$	–	–
$K^0\pi^0$	960 ± 46	12.87	$9.66\pm0.46\pm0.49$	–	–
$\eta K^\pm$			$2.04^{+0.22}_{-0.21}\pm0.10$	3.8	$-0.38\pm0.11\pm0.01$
$\eta(\gamma\gamma)$	$192.6^{+26.6}_{-25.3}$	13.25	$1.95^{+0.26}_{-0.25}\pm0.09$	2.9	$-0.36\pm0.13\pm0.01$
$\eta(3\pi)$	$80.2^{+14.9}_{-13.9}$	4.94	$2.29^{+0.43}_{-0.40}\pm0.15$	2.4	$-0.42\pm0.18\pm0.01$
$\eta\pi^\pm$			$3.97^{+0.27}_{-0.26}\pm0.21$	3.0	$-0.19\pm0.06\pm0.01$
$\eta(\gamma\gamma)$	$466.6^{+36.1}_{-35.0}$	15.34	$4.11^{+0.32}_{-0.31}\pm0.19$	1.8	$-0.14\pm0.08\pm0.01$
$\eta(3\pi)$	$138.6^{+18.5}_{-17.5}$	5.44	$3.63\pm0.49\pm0.25$	2.5	$-0.31^{+0.13}_{-0.12}\pm0.01$
ηK^0			$1.32^{+0.33}_{-0.29}\pm0.07$	–	–
$\eta(\gamma\gamma)$	$39.8^{+12.7}_{-11.5}$	4.15	$1.23^{+0.39}_{-0.36}\pm0.06$	–	–
$\eta(3\pi)$	$16.2^{+6.4}_{-5.4}$	1.48	$1.48^{+0.59}_{-0.49}\pm0.10$	–	–

Table 1 summarizes the fit results. Significant signals are observed for all the decay modes. The branching fraction for each mode is calculated by dividing the efficiency-corrected signal yield by the number of $B\overline{B}$ pairs. The new measurements are consistent with our previous results [2, 3] but are more precise. Besides more data and better reconstrcution software, the improvement is mainly achieved by performing $M_{\rm bc}-\Delta E-R'$ three-dimensional fits instead of $M_{\rm bc}-\Delta E$ two-dimensional fits with severe continuum suppression. The decay $B^0\to\eta K^0$ is observed for the first time with a significance of 5.4σ including systematics. Figure 1 shows the ΔE and $M_{\rm bc}$ projections of the fit for the $B\to K\pi,\pi\pi$ and KK decays. The ratios of branching fractions for the $K\pi$ and $\pi\pi$ modes, shown in Table 2, are computed by properly removing the common systematic uncertainites. The first two raws of Table 2 are equentially R_c and R_n, that are consistent with the Standard Model predictions plus several theoretical approaches [6, 7, 8, 9]. Note that the uncertainties of these two ratios are close to the theory errors.

Clear CP asymmetry is observed only in the $B^0\to K^\pm\pi^\mp$ decay with the central value $A_{CP}(B^0\to K^\pm\pi^\mp)=-0.069\pm0.014\pm0.07$, which is 1.6σ away from our previous measurement [10] with $535\times10^6 B\overline{B}$ pairs. The change is mainly due to the statistical fluctuation since the CP asymmetry in the latest dataset is closer to 0. The central value of the corresponding A_{CP} for $B^\pm\to K^\pm\pi^0$ is positive, though with large error, consistent with the previous result [10]. We confirm that there is

Table 2: Partial width ratios of $B \to K\pi$ and $\pi\pi$ decays. The first and second errors are statistical and systematic, respectively.

Modes	Ratios
$2\Gamma(K^+\pi^0)/\Gamma(K^0\pi^+)$	$1.05 \pm 0.03 \pm 0.05$
$\Gamma(K^+\pi^-)/2\Gamma(K^0\pi^0)$	$1.04 \pm 0.05 \pm 0.06$
$\Gamma(K^+\pi^-)/\Gamma(K^0\pi^+)$	$0.90 \pm 0.03 \pm 0.03$
$\Gamma(\pi^+\pi^-)/\Gamma(K^+\pi^-)$	$0.25 \pm 0.01 \pm 0.01$
$\Gamma(\pi^+\pi^-)/2\Gamma(\pi^+\pi^0)$	$0.46 \pm 0.03 \pm 0.03$
$\Gamma(\pi^+\pi^0)/\Gamma(K^0\pi^0)$	$0.56 \pm 0.04 \pm 0.03$
$2\Gamma(\pi^+\pi^0)/\Gamma(K^0\pi^+)$	$0.49 \pm 0.02 \pm 0.03$

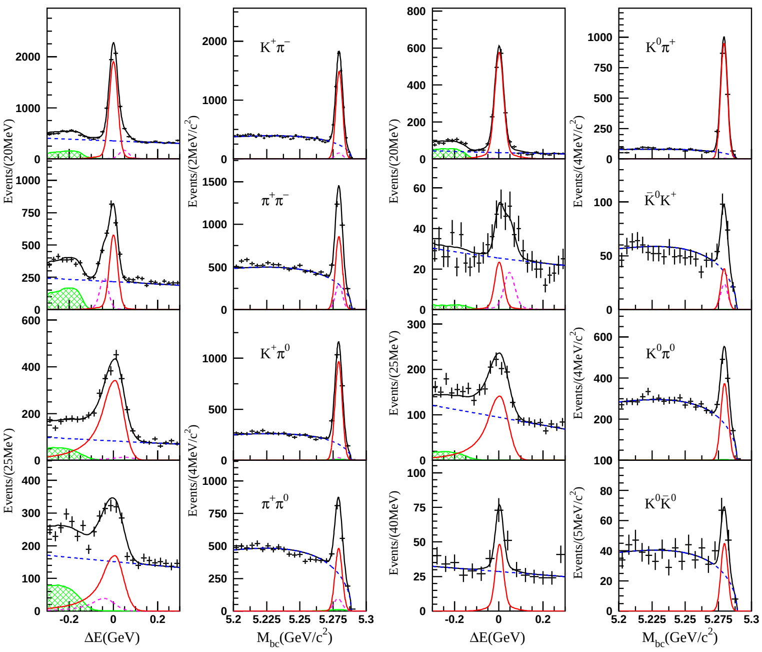

Figure 1: M_{bc} and ΔE distributions for the eight $B \to hh$ ($h = K$ or π) decay modes. Points with error bars are and the curves represent the various components from the fit: signal (dot-dashed), continuum (dashed), charmless B decays (hatched), background from mis-identification (dotted), and sum of all components (solid). The M_{bc} and ΔE projections of the fits are for events in the R' signal enhanced region and and 5.271 GeV/$c^2 < M_{bc}$ (left) and $|\Delta E| < 0.06$ GeV (right). (A looser requirement, -0.14 GeV $< \Delta E < 0.06$ GeV, is used for the modes with a π^0 meson in the final state.)

indeed a large A_{CP} difference between the neutral and charged B decays to $K\pi$. And the difference is measured to be $\Delta A_{K\pi} = +0.112 \pm 0.028$ at 4σ significance. In this study we also find evidences of direct CP asymmetries for the $B^\pm \to \eta K^\pm$ and $B^\pm \to \eta\pi^\pm$. Both asymmetries are negative and large in magnitude, as shown in Fig. 2. These large negative asymmetries agree with some theortical predictions but disagree with the others [11, 12, 13, 14]. All our results serve as a good discriminant for various theoretical approaches.

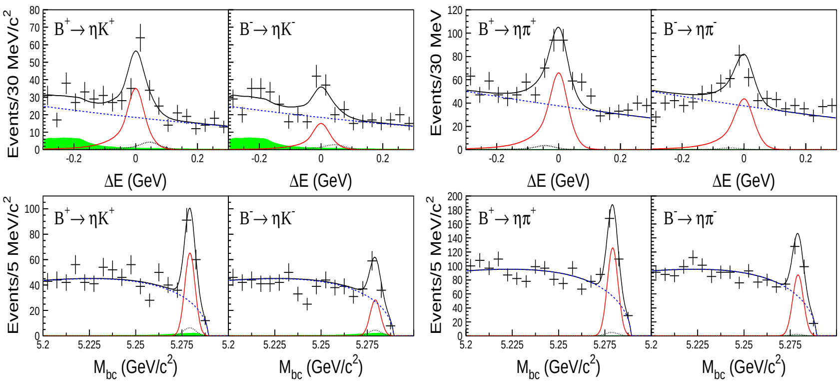

Figure 2: ΔE and M_{bc} projections for $B^+ \to \eta h^+$ and $B^- \to \eta h^-$ candidates with the $\eta \to \gamma\gamma$ and $\eta \to 3\pi$ modes combined. Points with errors represent the data, the full fit functions and signals are shown by solid curves, dashed lines show the continuum contributions, dotted lines for feed-across background from misidentification and filled histograms are the contributions from charmless B decays. The ΔE and M_{bc} projections of the fits are for events that have the other two variables in their signal regions.

In summary we report measurements of the branching fractions and direct CP asymmetries for $B \to hh$ decays using the Belle final data sample. Our results of the branching fractions and their ratios are the most precise. We confirm that the A_{CP} difference between charged and neutral B decays to $K\pi$ is large and see evidence for A_{CP} $B^\pm \to \eta K^\pm$ and $B^\pm \to \eta \pi^\pm$.

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