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Recent investigations of direct CP violation in B-meson decays at Belle

Chia-Ling Hsu[*†]
The University of Sydney
E-mail: chia-ling.hsu@sydney.edu.au

We present the summary of recent studies of $B^0 \to \eta\eta$, $B^0 \to \pi^0\pi^0$, $B^+ \to K^+K^-\pi^+$, and $B^0 \to K^0_S K^+\pi^-$ charmless B decays using a data sample of 772 million $B\bar{B}$ pairs collected at the Belle detector running at the $\Upsilon(4S)$ resonance at the KEKB asymmetric-energy e^+e^- collider.

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[*]Speaker.
[†]On Behalf of the Belle Collaboration

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1. Evidence of the decay $B^0 \to \eta\eta$

The $B^0 \to \eta\eta$ decay is dominated by the $b \to u$ Cabibbo- and color-suppressed tree diagram and the $b \to d$ penguin diagram. The branching fraction of this decay is expected to be $(0.3 - 3.1) \times 10^{-6}$ [2].This decay plays an important role in improving the flavor SU(3) calculations of $|S_{ccs} - S_f|$, where the final state f is $\eta' K$ or ϕK, the *CP*-violating parameter $S_f \sim \sin 2\phi_1$ is measured in the time-dependent analysis [3], and the *CP*-violating parameter $S_{c\bar{c}s}$ is measured in the Cabibbo-Kobayashi-Maskawa(CKM)-favored $b \to c\bar{c}s$ decays. The bound on $\sin 2\phi_1$ can be improved by the precise measurement of the branching fraction of $B^0 \to \eta\eta$ [4]. This mode has been studied previously by Belle and BABAR [5, 6]. The best upper limit on this branching fraction is set to be $\mathscr{B}(B^0 \to \eta\eta) < 1.0 \times 10^{-6}$ at 90% confidence level (CL) by BaBar [6].

The $\eta_{3\pi}$ candidates are reconstructed by two oppositely charged pions and a π^0 candidate. The B^0 candidates are identified using two kinematic variables in the center-of-mass frame: the beam constrained mass $M_{\rm bc} \equiv \sqrt{E^2_{\rm beam} - p^2_B}$ and the energy difference $\Delta E \equiv E_B - E_{\rm beam}$, where $E_{\rm beam}$ is the beam energy, and E_B and p_B are the reconstructed energy and momentum of B^0 candidates. The dominant background is from the continuum process $e^+e^- \to q\bar{q}$ $(q = u,d,s,c)$, which is suppressed with a neural network. We transform the neural network output $C_{\rm NN}$ to $C'_{\rm NN} = \ln\left(\frac{C_{\rm NN} - C^{\rm min}_{\rm NN}}{C^{\rm max}_{\rm NN} - C_{\rm NN}}\right)$, where $C^{\rm min}_{\rm NN}$ is -0.8 and $C^{\rm max}_{\rm NN}$ is the maximum variables of the neural network outputs.

The branching fraction of $B^0 \to \eta\eta$ is obtained by a simultaneous fit to the $\eta_{\gamma\gamma}\eta_{\gamma\gamma}$, $\eta_{\gamma\gamma}\eta_{3\pi}$ and $\eta_{3\pi}\eta_{3\pi}$ decay channels. We perform a three dimensional extended unbinned maximum likelihood fit to the variables $M_{\rm bc}$, ΔE and $C'_{\rm NN}$.

The measured branching fraction [7] is $\mathscr{B}(B^0 \to \eta\eta) = (7.6^{+2.7+1.4}_{-2.3-1.6}) \times 10^{-7}$, where the first uncertainty is statistical and the second is systematic. The significance of the result is 3.3σ above zero, and provides the first evidence of this decay.

2. Measurements of branching fraction and *CP* asymmetry on $B^0 \to \pi^0\pi^0$

The CKM angle ϕ_2 can be determined by measuring the time-dependent *CP* violation in $B \to \pi\pi$ decays. Possible penguin contributions can give rise to direct *CP* violation and potentially modify the asymmetry by introducing $\Delta\phi_2$ in the mixing-induced *CP* violation parameter, $S_{CP} = \sqrt{1 - \mathscr{A}^2_{CP}}\sin[2(\phi_2 - \Delta\phi_2)]$. An isospin analysis of the $B \to \pi\pi$ systems is needed to extract $\Delta\phi_2$ information [8].

The $B^0 \to \pi^0\pi^0$ candidates from the subsequent decay of π^0 mesons to two photons. The dominant background arises from the continuum process. To suppress this, a Fisher discriminant (T_c) from event shape variables. The signal yield and $\mathscr{A}_{CP}$ are extracted using an unbinned extended maximum likelihood fit to $M_{\rm bc}$, ΔE, and T_c. We obtain a signal yield of 217 ± 32 events in the dataset. The branching fraction and $\mathscr{A}_{CP}$ determined to be $\mathscr{B}(B^0 \to \pi^0\pi^0) = (1.31 \pm 0.19 \pm 0.19) \times 10^{-6}$ and $A_{CP} = +0.14 \pm 0.36 \pm 0.10$, where the quoted uncertainties are statistical and systematic, respectively. The measured branching fraction is consistent with the *BABAR* measurement [9] and supersedes the previous Belle one [10].

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These results are combined with Belle's earlier measurements of $B \to \pi\pi$ [11, 12, 13] to exclude the *CP*-violating parameter ϕ_2 from the range $15.5^\circ < \phi_2 < 75.0^\circ$ at 95% confidence level [13].

3. Measurements of branching fraction and *CP* asymmetry on $B^+ \to K^+K^-\pi^+$

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 [14]. In recent years, unidentified structure has been measured by BaBar [15] and LHCb [16] in the K^+K^- low-invariant-mass spectrum of the $B^+ \to K^+K^-\pi^+$ decay. The LHCb studies revealed a non-zero inclusive *CP* asymmetry of $-0.123 \pm 0.017 \pm 0.012 \pm 0.007$ and a large unquantified local *CP* asymmetry in the same mass region. These results suggest that final-state interactions may be a contributing factor to *CP* violation [17, 18].

The dominant background is from continuum $e^+e^- \to q\bar{q}$ $(q = u,d,s,c)$ processes. A neural network is employed by combining variables based on the event topology in order to suppress the continuum background. Veto criteria are introduced to suppress the background contributions from B decays via the dominant $b \to c$ transition. There are a few modes of B decays via $b \to q$ $(q = u,d,s)$ processes that contribute in the $M_{\rm bc}$ signal region with a corresponding ΔE peak background. These peaking backgrounds are due to $K-\pi$ misidentification, including $B^+ \to K^+K^-K^+$, $B^+ \to K^+\pi^-\pi^+$, and their intermediate resonant modes.

To investigate the localized *CP* asymmetry in the low $M_{K^+K^-}$ region, the signal yield and $\mathcal{A}_{CP}$ are extracted by performing a two-dimensional extended unbinned maximum likelihood fit in $M_{\rm bc}$ and ΔE in the bins of $M_{K^+K^-}$. The inclusive branching fraction is obtained by integrating the differential branching fraction over the entire mass range. The resulting branching fraction and direct *CP* asymmetry are [19] $\mathcal{B}(B^+ \to K^+K^-\pi^+) = (5.38 \pm 0.40 \pm 0.35) \times 10^{-6}$ and $\mathcal{A}_{CP} = -0.170 \pm 0.073 \pm 0.017$, where the quoted uncertainties are statistical and systematic, respectively.

An excess and a large $\mathcal{A}_{CP}$ are seen in $M_{K^+K^-} < 1.5$ GeV/c^2, confirming the observations by BaBar and LHCb. A strong evidence of large *CP* asymmetry of $-0.90 \pm 0.17 \pm 0.03$ with 4.8σ significance is found in the region of $M_{K^+K^-} < 1.1$ GeV/c^2.

4. Measurements of branching fraction and *CP* asymmetry on $B^0 \to K^0_S K^+\pi^-$

The decays with even number of kaons proceed via the $b \to u$ tree-level, the $b \to u$ W-exchange, and the $b \to d$ 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 [20] and LHCb [21] experiments find hints of structures at the low $K^-\pi^+$ and $K^-K^0_S$ 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 $B^+ \to K^+K^-\pi^+$ were performed by Belle [19], BaBar [15], and LHCb [16], in which strong evidence of localized *CP* violation was found in the low $M_{K^+K^-}$ region.

Veto criteria are introduced to suppress the background contributions from B decays via the dominant $b \to c$ transition. There are a few modes that contribute in the $M_{\rm bc}$ signal region with a

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corresponding ΔE peak background. These peaking backgrounds are due to $K-\pi$ misidentification, including $B^0 \to K^-K^+K^0_S$, $B^0 \to \pi^-\pi^+K^0_S$, and their intermediate resonant modes.

The signal yield and $\mathscr{A}_{CP}$ are extracted using an unbinned extended maximum likelihood fit to $M_{\rm bc}$, ΔE, and $C'_{\rm NN}$. The resulting branching fraction and direct CP asymmetry are [22] $\mathscr{B}(B^+ \to K^+K^-\pi^+) = (3.60 \pm 0.33 \pm 0.15) \times 10^{-6}$ and $\mathscr{A}_{CP} = (-8.5 \pm 8.9 \pm 0.2)\%$, where the quoted uncertainties are statistical and systematic, respectively.

Hints of peaking structures are seen 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 low $M_{K^-\pi^+}$ and $M_{\pi^+K^0_S}$ spectrums.

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