Direct CP Violation in Charmless B Decays

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We report the updated results of direct CP violation measurements from Belle and BaBar for the following modes: $B \to h^+h^-/h^\pm\pi^0$, $B \to \eta^{(\prime)}h^\pm$ and $B \to K^\pm\pi^\pm\pi^\mp$, where h stands for a charged kaon or pion. The data used in these studies are up to 386 million $B\bar{B}$ pairs for Belle and 232 million $B\bar{B}$ pairs for BaBar. The current significant measurements include: $\mathcal{A}_{CP}(B \to K^+\pi^-) = -0.108 \pm 0.016$, $\mathcal{A}_{CP}(B \to \rho^0(770)K^+) = 0.31^{+0.11}_{-0.10}$, and $\mathcal{A}_{CP}(B \to \eta K^+) = -0.33 \pm 0.12$ [1].

1. Introduction

In the Standard Model (SM) CP violation arises via the interference of at least two diagrams with comparable amplitudes but different CP conserving and violating phases. Mixing induced CP violation in the B sector has been established in $b \to c\bar{c}s$ transitions [1, 2]. In the SM, direct CP violation is expected to be sizable in the B meson system [3]. Charmless B decays provide a rich sample to understand B decay dynamics and to search for CP violation. The first experimental evidence for direct CP violation was shown by Belle for the decay mode $B^0 \to \pi^+\pi^-$ [4]. This result suggests large interference between tree and penguin diagrams and the existence of final state interactions [5].

The three-body charmless hadronic B mesons decays can provide new possibilities for CP violation searches. In spite of measuring the difference between B and $\bar{B}$ decay rates, one can also measure the difference in relative phase between two quasi-two-body amplitudes, which are often dominated in three-body B decays. This can be achieved via amplitude (Dalitz) analysis. As currently direct CP violation has been observed only in decays of neutral K mesons [6] and recently in neutral B meson decays [7]. Large direct CP violation is expected in charged B decays to some quasi-two-body charmless hadronic modes [8].

The partial rate CP violating asymmetry is defined as:

$$\mathcal{A}_{CP} = \frac{N(\overline{B} \to \overline{f}) - N(B \to f)}{N(\overline{B} \to \overline{f}) + N(B \to f)}, \quad (1)$$

where $N(\overline{B} \to \overline{f})$ is the yield for the $\overline{B}$ decays and $N(B \to f)$ denotes that of the charge-conjugate mode.

We report the updated direct CP violating measurements from both Belle and BaBar. The data used in these study are up to 386 milion $B\bar{B}$ pairs collected at Belle [11] detector and 274 milion $B\bar{B}$ pairs at BaBar. The Belle detector is located at the KEKB e^+e^- asymmetric-energy (3.5 on 8 GeV) collider [10] and BaBar detector [12] is at the SLAC PEP-II asymmetric-energy (3.1 on 9 GeV) e^+e^- storage ring [13]. Both of them are operating at the $\Upsilon(4S)$ resonance.

[1] http://www.slac.stanford.edu/xorg/hfag

2. Event Reconstruction

Charged tracks are required to have momenta transverse to the beam greater than 0.1 GeV/c and to be consistent with originating from the interaction point (IP). For particle identification of charged tracks, a combined likelihood of information from dE/dx of drift chamber, time-of-flight and aerogel Cherenkov counter is used by Belle while an associated Cherenkov-angle from the ring image counter (DIRC) is used by BaBar. For some of the modes described below, charged tracks that are positively identified as electrons or protons are excluded. Candidate π^0 mesons are selected by requiring the two-photon invariant mass to be in the $2.5 \sim 3.5\sigma$ mass window. The momentum vector of each photon is then readjusted to constrain the mass of the photon pair to the nominal π^0 mass. Candidate η mesons are reconstructed by combining a π^0 with at least 250 MeV/c laboratory momentum with a pair of oppositely charged tracks that originate from the interaction point (IP). For Belle, the following requirements are made on the invariant mass of the η candidates: 516 MeV/c^2 $< M_{\gamma\gamma} <$ 569 MeV/c^2 for $\eta \to \gamma\gamma$ and 539 MeV/c^2 $< M_{3\pi} <$ 556 MeV/c^2 for $\eta \to 3\pi$'s. As to BaBar, the following cuts are applied: 490 MeV/c^2 $< M_{\gamma\gamma} <$ 600 MeV/c^2 for $\eta_{\gamma\gamma}$ and 520 MeV/c^2 $< M_{3\pi} <$ 570 MeV/c^2 for $\eta_{3\pi}$. After the selection of each candidate, the η mass constraint is implemented by readjusting the momentum vectors of the daughter particles. The η' mesons are reconstructed via two decay chains: $\eta\pi\pi$ (with $\eta \to \gamma\gamma$) and $\eta' \to \rho\gamma$. In addition, we require the following. All photons are required to have an energy of at least 50 MeV, photons from η' in $\eta' \to \rho\gamma$ of at least 100 MeV. The transverse momenta of $\pi^\pm$ for ρ^0 candidates have to be greater than 200 MeV/c. K^0_S candidates are reconstructed from pairs of oppositely-charged tracks with an invariant mass ($M_{\pi\pi}$) between 480 and 516 MeV/c^2. Each candidate must have a displaced vertex with a flight direction consistent with that of a K_S^0 originating from the IP.

B meson candidates are identified using two kinematic variables: the energy difference $\Delta E = E_B - E_{\rm beam}$, and the beam constrained mass $M_{\rm bc} = \sqrt{E_{\rm beam}^2 - P_B^2}$, $E_{\rm beam}$ is the run-dependent beam energy in the $\Upsilon(4S)$ rest frame and is determined from $B \to D^{(*)}\pi$ events, and P_B and E_B are the momentum and energy of the B candidate in the $\Upsilon(4S)$ rest frame. The resolutions on $M_{\rm bc}$ and ΔE are about 3 MeV/c^2 and 20–30 MeV, respectively. Events with $M_{\rm bc} > 5.2$ GeV/c^2 and $|\Delta E| < 0.3$ GeV are selected for the analysis.

3. Background reduction

The dominant background comes from the $e^+e^- \to q\bar{q}$ continuum, where $q = u, d, s$ or c. To distinguish signal from the jet-like continuum background, event shape variables and B flavor tagging information are employed. We combine information of correlated shape variables into a Fisher discriminant [14] and compute the likelihood as a product of probabilities of this discriminant and $\cos\theta_B$, where θ_B is the angle between the B flight direction and the beam direction in the $\Upsilon(4S)$ rest frame. A likelihood ratio, $\mathcal{LR} = \mathcal{L}_s/(\mathcal{L}_s + \mathcal{L}_{q\bar{q}})$, is formed from signal ($\mathcal{L}_s$) and background ($\mathcal{L}_{q\bar{q}}$) likelihoods, obtained using events from the signal Monte Carlo (MC) and from data with $M_{\rm bc} < 5.26$ GeV/c^2, respectively. Additional background discrimination is provided by B flavor tagging. An event that contains a lepton (high quality tagging) is more likely to be a $B\overline{B}$ event so a looser $\mathcal{LR}$ requirement can be applied. We divide the data into six sub-samples based on the quality of flavor tagging [15]. Continuum suppression is achieved by applying a mode dependent requirement on $\mathcal{LR}$ for events in each sub-sample according to $N_s^{\rm exp}/\sqrt{N_s^{\rm exp} + N_{q\bar{q}}^{\rm exp}}$, where $N_s^{\rm exp}$ is the expected signal from MC and $N_{q\bar{q}}^{\rm exp}$ denotes the number of background events estimated from data.

4. Signal Extraction

4.1. Maximum-likelihood Method

The signal yields and partial rate asymmetries are obtained using an extended unbinned maximum-likelihood (ML) fit with input variables $M_{\rm bc}$ and ΔE. The likelihood is defined as:

$$\mathcal{L} \;=\; \mathrm{e}^{-\sum_{\rm j}\mathrm{N_j}} \times \prod_{\rm i}(\sum_{\rm j}\mathrm{N_j}\mathcal{P}_{\rm j}) \quad \text{and} \tag{2}$$

$$\mathcal{P}_j \;=\; \frac{1}{2}[1 - q_i \cdot \mathcal{A}_{\mathcal{CP}|}]\mathcal{P}_|(\mathcal{M}_{\rm bc\rangle}, \cdot\mathcal{E}_\rangle), \tag{3}$$

where i is the identifier of the i-th event, $P(M_{\rm bc}, \Delta E)$ is the two-dimensional probability density function (PDF) in $M_{\rm bc}$ and ΔE, q indicates the B meson flavor, $B^+(q = +1)$ or $B^-(q = -1)$, N_j is the number of events for the category j, which corresponds to either signal, $q\bar{q}$ continuum, a reflection due to K-π misidentification, or background from other charmless B decays. For the neutral B mode, $\mathcal{P}_j$ in the equation above is simply $P_j(M_{{\rm bc}i}, \Delta E_i)$ and there is no reflection component.

4.2. Dalitz Analysis

As to the three-body direct CP violation study, an unbinned maximum likelihood fit method is also used. For the study performed by Belle, the distribution of background events is parametrized by an empirical function with 11 parameters [18]. As found in the previous paper by Belle [18], the three-body $B^+ \to K\pi\pi^+$ amplitude is well-described by a coherent sum of $K^*(892)^0\pi^+$, $K_0^*(1430)^0\pi^+$, $\rho(770)^0K^+$, $f_0(980)K^+$, $f_X(1300)K^+$ and χ_cK^+ quasi-two-body channels and a non-resonant amplitude. In order to describe an excess of signal events at $M(\pi\pi) \simeq 1.3$ GeV/c^2 a $f_X(1300)K^+$ channel was introduced. The best fit is achieved assuming $f_X(1300)$ is a scalar state; the mass and width determined from the fit (see below) are consistent with those for $f_0(1370)$ [22]. Each quasi-two-body amplitude includes a Breit-Wigner function, a B decay form-factor parametrized in a single-pole approximation, a Blatt-Weisskopf factor [20] for the intermediate resonance decay, and a function that describes angular correlations between final state particles. This is multiplied by a factor of $ae^{i\delta}$ that describes the relative magnitude and phase of the contribution. The non-resonant amplitude is parametrized by an empirical function $\mathcal{A}_{\rm nr}(K\pi\pi^+) = a_1^{\rm nr}e^{-\alpha s_{13}}e^{i\delta_1^{\rm nr}} + a_2^{\rm nr}e^{-\alpha s_{23}}e^{i\delta_2^{\rm nr}}$, where α, $a_i^{\rm nr}$ and $\delta_i^{\rm nr}$ are fit parameters, $s_{13} \equiv M^2(K^+\pi^-)$, and $s_{23} \equiv M^2(\pi\pi)$. In the analysis performed by Belle, a modified model that changing the parameterization of the $f_0(980)$ line-shape from a Breit-Wigner function to a Flatté parameterization [21] and adding two more channels: $\omega(782)K^+$ and $f_2(1270)K^+$ is used. For CP violation studies the amplitude for each quasi-two-body channel is modified from $ae^{i\delta}$ to $ae^{i\delta}(1{\pm}be^{i\varphi})$, where the plus (minus) sign corresponds to the B^+ (B^-) decay. With such a parameterization the charge asymmetry, $\mathcal{A_{CP}}$, for a particular quasi-two-body $B{\to}f$ channel is given by

$$A_{CP}(f) = \frac{N^- - N^+}{N^- + N^+} = -\frac{2b\cos\varphi}{1+b^2}. \tag{4}$$

It is worth noting that in this parametrization zero relative phase between B^- and B^+ amplitudes is assumed.

5. DCPV measurements

5.1. Two-body B decays

The first evidence of direct CP violation in two-body B decays in $B^0 \to \pi^+\pi^-$ was claimed by Belle [4]. However, this is not confirmed by the BaBar experiment [24]. There are both tree diagram and penguin diagram contributing to $B \to K^+\pi^-$. Therefore, large CP violation is expected in this decay channel. In the summer of 2005, both Belle and BaBar reported their updated measurements for the $K^+\pi^-$, $K^+\pi^0$ and $\pi^+\pi^0$ modes [25]. In spite of the results from B factories, CDF also report their measurements on the $K^+\pi^-$ mode and is included in the world average shown in table I. Note that the deviation between $A_{CP}(B^0 \to K^+\pi^-)$ and $A_{CP}(B^+ \to K^+\pi^0)$ is of 3.1σ for Belle only and the world average is now about 3.8σ.

Table I Summary table of $A_{CP}(B \to hh)$.

$\mathcal{A}_{CP}$(%)	BaBar	Belle	World Avg.
$K^+\pi^-$	$-13.3 \pm 3.0 \pm .9$	$-11.3 \pm 2.2 \pm .8$	$-10.8 \pm .17$
$K^+\pi^0$	$+6 \pm 6 \pm 1$	$+4 \pm 4 \pm 2$	$+4 \pm 4$
$\pi^+\pi^0$	$-1 \pm 10 \pm 2$	$-2 \pm 8 \pm 1$	$+1 \pm 6$

As to $A_{CP}(B \to \eta h)$, direct CP violation is expected with the interference between penguin processes and CKM suppressed tree process. The A_{CP} results are updated by both Belle and BaBar. A 2.9σ significance of $A_{CP}(B \to \eta K^+)$ is seen by Belle, but only about 1σ seen by BaBar. [26] While in the $B \to \eta' h$ decays, $B \to \eta' K^+$ is penguin dominated while $B \to \eta'\pi^+$ has interference between tree and penguin. But there is no significant direct CP asymmetry seen by either experiments [27]. The summary of results are listed in table II.

5.2. Three-body B decays

The direct CP violation measurements in three-body B decays are performed with dalitz analysis by both Belle and BaBar in 2005 [28]. The table III shows the direct CP asymmetries for each quasi-two body decay channels.

Among these quasi-two-body decay channels, Belle claimed the first evidence of direct CP asymmetry in $B \to \rho^0(770)K^\pm$ with 3.9σ statistical significance. By comparing with null-asymmetry assumed toy MC, they claim the significance would be about 3.7σ. Also, a tensor-pseudoscalar mode $B \to f_2(1270)K^\pm$ was observed by Belle with more than 6σ significance and the charge asymmetry measurement is given. This is not seen by BaBar and only an upper-limit on the branching fraction is given.

Table II Summary table of $A_{CP}(B \to \eta^{(\prime)}h)$.

$\mathcal{A}_{CP}$(%)	BaBar	Belle	World Avg.
$B \to \eta K^+$	$-20. \pm 15. \pm 1.$	$-55. \pm 19. \pm 4.$	$-33. \pm 12.$
$B \to \eta\pi^+$	$-13. \pm 12. \pm 1.$	$-10. \pm 11. \pm 2.$	$-11. \pm 8.$
$B \to \eta\rho^+$	$+2. \pm 18. \pm 2.$	$-17. \pm 33. \pm 2.$	$-3. \pm 16.$
$B \to \eta' K^+$	$+3.3 \pm 2.8 \pm .5$	$+2.9 \pm 2.8 \pm 2.1$	$+3.1 \pm 2.1$
$B \to \eta'\pi^+$	$+14. \pm 16. \pm 1.$	$+15. \pm 38. \pm 6.$	$+14. \pm 15.$

Table III Summary table of A_{CP} in $B \to K^\pm\pi^\pm\pi^\mp$ three-body decays.

A_{CP}(%)	BaBar	Belle	World Avg.
$K^\pm\pi^\pm\pi^\mp$	$-1.3 \pm 3.7 \pm 1.1$	$+4.9 \pm 2.6 \pm 2.0$	$+2.2 \pm 2.9$
$K^*(892)\pi^\pm$	$+7 \pm 8 \pm 7$	$-14.9 \pm 6.4 \pm 2.1$	-8.6 ± 5.6
$K^*(1430)\pi^\pm$	$-6.4 \pm 3.2^{+2.3}_{-2.6}$	$+7.6 \pm 3.8^{+2.8}_{-2.2}$	-0.2 ± 2.9
$\rho(770)K^\pm$	$+32 \pm 13^{+10}_{-8}$	$+30 \pm 11^{+11}_{-5}$	$+31^{+11}_{-10}$
$f_0(980)K^\pm$	$+9 \pm 10^{+10}_{-6}$	$-7.7 \pm 6.5^{+4.6}_{-2.6}$	$-2.6^{+6.8}_{-6.4}$
$f_2(1270)K^\pm$	—	$-59 \pm 22 \pm 4$	-59 ± 22
$\chi_{c0}K^\pm$	—	$-6.5 \pm 20 \pm 2^{+29}_{-14}$	—

6. Conclusions

There are lots of fruitful experimental results since last FPCP meeting and many improvements on the theoretical calculations. We now have observation of direct CP violation in $B \to K^+\pi^-$ mode and its sign and amplitude can be better understood with next to leading order (NLO) calculations [29]. However, the deviation between $A_{CP}(B \to K^+\pi^-)$ and $A_{CP}(B \to K^+\pi^0)$ may need further clarifying theoretically [30].

Other than $B \to K^+\pi^-$, there are some hints or evidence of direct CP asymmetry seen by Belle, but those are not yet confirmed by BaBar. Therefore, more statistics are still needed for both B-factories to clarify the situation.

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