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Search for direct CP violation in charmless two-body B decays

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Abstract. We review the status of direct CP violation search in flavor specific B decays with K/π or η/η' in the final state. Results from BaBar, Belle and CLEO will be presented with the averages obtained assuming that experimental errors are not correlated. No evidence of direct CP violation is seen although there are 2σ deviations from 0 for $A_{CP}(K^+\pi^-)$ and $A_{CP}(\eta\pi^+)$.

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Recently observations of mixing induced CP violation have been reported by both the Belle and BaBar experiments [1,2]. The CP violating parameter $\sin(2\phi_1)$, or $\sin(2\beta)$, is precisely measured and the world average value, 0.734 ± 0.055, indicates a large CP violation in the B sector. The most straightforward evidence for CP violation is to measure the difference of the time-integrated decay rate between CP conjugate decays into flavor specific final states. Theoretically the CP violating asymmetry arises with at least two decay amplitudes with comparable strength but containing different CP conserving and CP violating phases. This partial rare asymmetry A_{CP} can be expressed as,

$$A_{CP} = \frac{N(\bar{B} \to \bar{f}) - N(B \to f)}{N(\bar{B} \to \bar{f}) + N(B \to f)} = \frac{\sum_{i,j} a_i a_j \sin(\delta_i - \delta_j)\sin(\theta_i - \theta_j)}{\sum_{i,j} a_i a_j \cos(\delta_i - \delta_j)\cos(\theta_i - \theta_j)}, \quad (1)$$

where δ_i and θ_i are the CP conserving phases and CP violating phase for the amplitude a_i, respectively.

In the standard model, CP asymmetry could be sizeable in charmless hadronic B decays where penguin and $b \to u$ tree amplitudes may be comparable. However, hadronic uncertainties and rescatterings need to be considered in describing hadronic B decays, which makes it difficult to predict A_{CP}. Moreover, new physics may contribute to the penguin loop and result in an unexpected CP asymmetry. Therefore, measuring the decay branching fractions (BF) and CP violating asymmetry from charmless B decays helps to understand B decay dynamics and to probe new physics. In this article, we review the experimental results of CP asymmetry for B decays into hh or $\eta^{(\prime)}h$, where h is π or K. Theoretical predictions from various approaches will be discussed.

Besides the pioneering work of charmless B decays from the CLEO collaboration, both the Belle and BaBar experiments have accumulated more data and provided measurements with better precision. These three experiments all take data at e^+e^- colliders where the CLEO detector is located at the e^+e^- center of mass and Belle and BaBar operate in asymmetric collisions to facilitate the time dependent CP analysis. Results presented in this paper correspond to a data set at $\Upsilon(4S)$ resonance. A relatively small amount of off-resonance data was used to understand the $q\bar{q}$ continuum background, here $q = u, d, s$ or c. A detailed description on these three detectors can be found somewhere else [3,4,5].

B signals are identified using the beam constrained mass (beam energy substituted mass) , $M_{bc} = \sqrt{E^2_{\rm beam} - P^2_B}$, and the energy difference, $\Delta E = E_B - E_{\rm beam}$, where $E_{\rm beam}$ is half of the total e^+e^- energy, and P_B and E_B are the momentum and energy of the B candidate in the $\Upsilon(4S)$ rest frame. Charged K and π mesons are distinguished using the information of the particle identification (PID) devices. In Belle, $K-\pi$ separation is achieved by making a cut on a likelihood ratio, $\mathcal{L}_K/(\mathcal{L}_\pi + \mathcal{L}_K)$, where $\mathcal{L}_K/\mathcal{L}_\pi$ is the likelihood of kaon/pion formed from the PID information. In BaBar and CLEO, the PID probability density function (PDF) is implemented in the likelihood to simultaneously extract B yields with kaon or pion in the final state.

The dominant background for the charmless $B-$to-two-pseudoscalar decays comes from the $q\bar{q}$ continuum. Several event shape variables are chosen to distinguish spherical $B\overline{B}$ events from jet-like continuum events. Belle combines extended Fox-Wolfram moments,including $S_\perp$ for the $\eta'h$ mode, to form a Fisher discriminant [6]. Then this discriminant and the cosine of the B decay angle, with respect to the z axis, are combined to form a likelihood ratio. The continuum background is reduced by applying a cut on this likelihood ratio. Then a ΔE fit

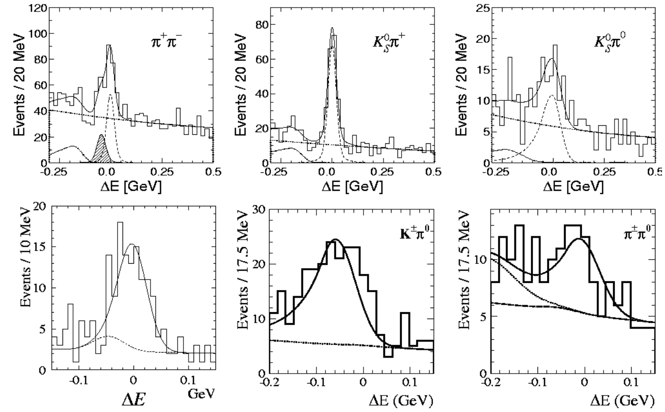

Fig. 1. ΔE distributions of $\pi^+\pi^-$, $K^0\pi^+$, $K_S^0\pi^0$, $K^+\pi^-$, $K^+\pi^0$ and $\pi^+\pi^0$ modes. The *top* three are Belle data and the *bottom* three are BaBar results. The *superimposed curves* correspond to their fit projections

and a two dimensional $M_{bc} - \Delta E$ fit is performed to extract $B \to hh$ and $B \to \eta^{(\prime)} h$ signals, respectively. BaBar and CLEO build the fisher discriminants using two Legendre polynominals and calorimeter nine cones, respectively. Both experiments then include the discriminant, along with $M_{bc}, \Delta E$ and PID PDFs in the maximum likelihood fit to extract B signal yields.

Figure 1 shows the ΔE distributions of $K\pi$ and $\pi\pi$ events from Belle and BaBar data. References [7,8,9] show the BF measurements from Belle, BaBar and CLEO experiments with 78 fb^{-1}, 81 fb^{-1} and 15 fb^{-1} of data, respectively. Except for $B^0 \to \pi^0\pi^0$, all $K\pi$ and $\pi\pi$ decays are measured, assuming $B^0\bar{B}^0$ and B^+B^- are equally produced, with results consistent between each experiment. No $B \to KK$ decays are observed yet. Since the $K\pi$ branching fractions are a factor of two to four larger than that of $\pi\pi$, it is clear that the penguin contribution is large. It is of interest to check the isospin invariance and compare the ratio of branching fractions with theoretical expectations. These ratios of branching fractions (R) are computed using the averages of experimental results, assuming that the experimental errors are uncorrelated.

The averaged BFs in units of 10^{-6} are $18.2 \pm 0.8, 12.8 \pm 1.1, 20.6 \pm 1.4$ and 11.5 ± 1.7 for $K^+\pi^-, K^+\pi^0, K^0\pi^+$ and $K^0\pi^0$ modes, respectively. At first we compute the $K\pi$ BF ratio of the charged pion to neutral pion,

$$[\mathcal{B}(K^+\pi^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(K^0\pi^+)]/2[\mathcal{B}(K^0\pi^0) + \frac{\tau_0}{\tau_+}\mathcal{B}(K^+\pi^0)],$$

where $\tau_0 = (1.539 \pm 0.014)$ ps and $\tau_+ = (1.656 \pm 0.014)$ ps are the B_0 and B_+ lifetimes, respectively. The number obtained for this ratio is 0.80 ± 0.08. According to the sum rules [10], this ratio is close to one, which disagrees with the experimental measurement by 2.5 σ and may suggest that isospin symmetry is not valid. The same study is also applied to the $\pi\pi$ mode using the BF averages $\mathcal{B}(\pi^+\pi^-) = (4.6 \pm 0.4) \times 10^{-6}$ and $\mathcal{B}(\pi^+\pi^0) = (5.3 \pm 0.8) \times 10^{-6}$. The $\pi\pi$ BF ratio $(\tau_+/\tau_0\mathcal{B}(\pi^+\pi^-)/2\mathcal{B}(\pi^+\pi^0))$ is found to be 0.47 ± 0.08, indicating the large isospin asymmetry in the $\pi\pi$ system. Other ratios of branching fractions can be used to constrain the third unitarity triangle $\phi_3(\gamma)$ [11,12]. For instance, $\mathcal{B}(\pi^+\pi^-)/\mathcal{B}(K^+\pi^-) = 0.25 \pm 0.02$. may suggest that γ is greater than 90^0 [13,12]. Two other BF ratios involving neutral pions are, $R_c = 2\Gamma(K^+\pi^0)/\Gamma(K^0\pi^+) = 1.24 \pm 0.14$ and $R_n = \Gamma(K^+\pi^-)/2\Gamma(K^0\pi^0) = 0.79 \pm 0.12$. QCDF indicates that $R_c \sim R_n$, which disagrees with the experimental result by 2.4σ. Although this $R_c - R_n$ discrepancy needs to be confirmed with more data, it has to be understood before using the BF ratios to constrain ϕ_3. Some authors have suggested that the larger $B^0 \to K^0\pi^0$ branching fraction could indicate a large rescattering phase [14].

Table 1 summarizes the A_{CP} results as well as the averages, where only 9.1 fb^{-1} of data was used in the CLEO analysis. The $\pi^+\pi^-$ measurements were obtained in the time-dependent CP analysis [15,16] and the average was provided by the heavy flavor averaging group [17]. Although no conclusive evidence of direct CP violation is seen, both the $K^+\pi^-$ and $\pi^+\pi^-$ channels have hints of CP asymmetry with around 2-2.6 σ significances. If their central values persist, we will probably observe direct CP violation in the B meson system with 400 fb^{-1} of data by combining Belle and BaBar results. More data are needed for the other four modes to reduce the errors. It is interesting to notice that in the $K^+\pi^-$ mode, that provides the largest statistics in the $B \to K\pi$ decays, the central values of all three experiments are on the negative side. Different theoretical approaches on factorizations provide different predictions on $A_{CP}(K^+\pi^-)$. For instance, QCD improved factorization (QCDF) predicts a small but positive A_{CP} ($(5 \pm 9)\%$), while perturbative QCD suggests that it should be negative ($(-12.9 \sim -21.9)\%$) [20]. As for the $\pi^+\pi^-$ mode, QCDF gives a small negative asymmetry ($(-6 \pm 12)\%$) but PQCD indicates that A_{CP} on $\pi^+\pi^-$ could be large ($(16 \sim 30)\%$). Therefore, precise measurements in the future can test which theoretical approach is favored.

It has been suggested that combining the ratio of branching fractions and A_{CP} on the $K\pi$ modes one can extract or constrain ϕ_3/γ [18]. Based on 1σ average of $\Gamma(B^0 \to K^+\pi^-)/\Gamma(B^+ \to K^0\pi^+)$ and $A_{CP}(K^+\pi^-)$, PQCD method is able to extract the ϕ_3 allowed range, $51^0 \leq \phi_3 \leq 90^0$, by obtaining the ratio of tree to penguin amplitudes and their strong phase difference [20]. A similar study was performed by Gronau and Rosner [19]. After eliminating the strong phase difference in the $K^+\pi^-$ mode, a lower bound $\phi_3 > 50^0$ was provided. Furthermore, the decay rate and A_{CP} with π^0 in the final state also give the information on ϕ_3. An upper 1σ bound $\phi_3 < 80^0$ is obtained using the four $K\pi$ decay branching fractions and $A_{CP}(K^+\pi^0)$. In the future, more precise measurements will be provided by the B factories. If the discrepancies in the $K\pi$ isospin symmetry remains, one needs to consider physics beyond the standard model and the $R - A_{CP}$ method to extract ϕ_3 should be modified.

In the $B \to \eta' h$ decays, two sub decay channels are considered to reconstruct η and η' mesons: $\eta \to \gamma\gamma, \eta \to \pi^+\pi^-\pi^0$ and $\eta' \to \eta\pi^+\pi^-, \eta' \to \rho\gamma$. Their branching fractions are given in [21,22,23]. In the $\eta' h$ modes, only the

Table 1. Summary of CP violating asymmetry for $B \to K\pi/\pi\pi$ and $B \to \eta^{(\prime)} K/\pi$ decays. The data sample used in the Belle $\eta' K^+$ measurement is 43 fb^{-1}

Mode	CLEO (9.1 fb^{-1})	Belle (78 fb^{-1})	BaBar (81 fb^{-1})	Avg.
$B^0 \to K^+\pi^-$	$-0.04 \pm 0.16 \pm 0.02$	$-0.07 \pm 0.06 \pm 0.01$	$-0.10 \pm 0.05 \pm 0.02$	-0.08 ± 0.04
$B^0 \to \pi^+\pi^-$		$0.77 \pm 0.27 \pm 0.08$	$0.30 \pm 0.25 \pm 0.4$	0.49 ± 0.19
$B^+ \to K^+\pi^0$	$-0.29 \pm 0.23 \pm 0.02$	$0.23 \pm 0.11^{+0.01}_{-0.04}$	$-0.09 \pm 0.09 \pm 0.01$	0.00 ± 0.07
$B^+ \to \pi^+\pi^0$		$-0.14 \pm 0.24^{+0.05}_{-0.04}$	$-0.03^{+0.18}_{-0.17} \pm 0.02$	-0.07 ± 0.14
$B^+ \to K^0\pi^+$	$0.18 \pm 0.24 \pm 0.02$	$0.07^{+0.09+0.01}_{-0.08-0.03}$	$-0.05 \pm 0.08 \pm 0.01$	0.02 ± 0.06
$B^0 \to K^0\pi^0$			$0.03 \pm 0.36 \pm 0.09$	0.03 ± 0.37
$B^+ \to \eta' K^+$	$0.03 \pm 0.12 \pm 0.02$	$-0.01 \pm 0.07 \pm 0.02$	$0.04 \pm 0.05 \pm 0.01$	0.02 ± 0.04
$B^+ \to \eta\pi^+$			$-0.51^{+0.20}_{-0.18} \pm 0.01$	$-0.51^{+0.20}_{-0.18}$
$B^+ \to \eta K^+$			$-0.32^{+0.22}_{-0.18} \pm 0.01$	$-0.32^{+0.22}_{-0.18}$

$\eta' K$ decays have been observed with large branching fractions ($(6 \to 8) \times 10^{-6}$). On the contrary in the ηh decays, both $\mathcal{B}(\eta K)$ and $\mathcal{B}(\eta\pi)$ were measured with roughly the same rate, while $\mathcal{B}(\eta K^*)$ was obtained with five to six times larger branching fractions. The experimental results confirmed the early theoretical prediction [24] that interference between two penguin diagrams and the known η/η' mixing angle enhance $B \to \eta' K$ but reduce $B \to \eta K$. The situation is reversed for the $\eta/\eta' K^*$ due to a parity flip for the vector K^*. It is still a challenge to explain the large $\eta' K$ branching fraction. Precise measurements on all $\eta^{(\prime)} K^{(*)}$ modes help understand the details of interference and test a possible singlet contribution.

It's also interesting to check the isospin symmetry for the $\eta' K$ channel, which is most precisely measured. Using the averages $\mathcal{B}(B^+ \to \eta' K^+) = (78 \pm 5) \times 10^{-6}$ and $\mathcal{B}(B^0 \to \eta' K^0) = (61 \pm 6) \times 10^{-6}$, we obtain

$$\frac{\tau_0}{\tau_+} \mathcal{B}(\eta' K^+)/\mathcal{B}(\eta' K^0) = 1.19 \pm 0.13, \tag{2}$$

which is 1.5σ away from 1. Investigations of charge asymmetry on $\eta' K^+$ were made (see Table 1) and no evidence of direct CP violation was observed, consistent with the theoretical expectation based on the penguin dominant amplitude. A search for A_{CP} on $B^+ \to \eta K^+/\eta\pi^+$ was reported by the BaBar collaboration [22]: $A_{CP}(\eta\pi^+) = -0.51^{+0.20}_{-0.18} \pm 0.01$ and $A_{CP}(\eta K^+) = -0.32^{+0.22}_{-0.18} \pm 0.01$. Although there is only 2.6σ deviation on $\eta\pi^+$ charge asymmetry, the large negative central value agrees with theoretical predictions with various factorization approaches [25]. These theoretical calculations in general agree that the charge asymmetry could be 20% or larger in the $\eta K, \eta\pi$ and $\eta'\pi$ modes. BaBar result disfavors a large positive $A_{CP}(\eta\pi)$. If there are indeed large charge asymmetries in the $B \to \eta K$ and $B \to \eta\pi$ decays, direct CP violation would be observed with 400 fb^{-1} by both Belle and BaBar.

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