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Belle studies of CP violation in $B \to \pi\pi$ decays

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Abstract. A measurement of CP violating asymmetries in $B^0 \to \pi^+\pi^-$ decays in a data sample of 78 fb^{-1} is presented. The data are taken on $\Upsilon(4S)$ resonance with the Belle detector in the KEKB asymmetry e^+e^- collider. A time-dependent analysis is performed for 740 reconstructed $B^0 \to \pi^+\pi^-$ candidates and the CP violation parameters are obtained to be $A_{\pi\pi} = +0.77 \pm 0.27 \pm 0.08$ and $S_{\pi\pi} = -1.23 \pm 0.41^{+0.08}_{-0.07}$. The result rules out the CP-conservation hypothesis ($A_{\pi\pi} = 0$, $S_{\pi\pi} = 0$) at 3.4σ.

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1 Introduction

One of the goals of the B-factory experiment is the precise determination of the unitarity triangle. In particular, non-zero angles of the triangle are the direct manifestation of the CP violation in B meson decays and the measurement of the angles is the primary purpose of the experiment. One of the angles was already measured as $\sin 2\phi_1$ with a precision of less than 10% by Belle [1] and BaBar [2] experiments and the CP violation in B meson decays was established. However, for the test of the Standard Model, the measurements of the other angles are essential. The determination of the angle ϕ_2 is the next target of the experiment.

The angle ϕ_2 can be measured by studying the decay $B^0 \to \pi^+\pi^-$ [3]. The decay occurs via the interplay of the $B^0 - \overline{B^0}$ mixing and the tree and penguin decays as shown in Fig. 1. The time evolution of the decay is expressed as

$$P_{\pi\pi}(\Delta t) = \frac{e^{-|\Delta t/\tau_B|}}{4\tau_B} \times(1 + q \cdot \{S_{\pi\pi}\sin(\Delta m_d \Delta t) + A_{\pi\pi}\cos(\Delta m_d \Delta t)\}) \quad (1)$$

where Δt is the decay time difference between B^0 and $\overline{B^0}$ mesons and τ_B is the life time of a B^0 meson. Δm_d is the mass difference between two B^0 mass eigenstates. q is $+1$ for the tag-side B_0 decay while -1 for $\overline{B_0}$ decay. $S_{\pi\pi}$ and $A_{\pi\pi}$ are the CP violating parameters to be measured. If the contribution by the penguin diagram is negligible, $S_{\pi\pi} = \sin 2\phi_2$ and $A_{\pi\pi} = 0$. However, the contribution is expected to be significant and ϕ_2 determined from $S_{\pi\pi}$ measurement can be shifted by θ due to the strong phase difference between tree and penguin diagrams. The value of θ can be determined by the isospin analysis [4].

In this talk, the measurement of $S_{\pi\pi}$ and $A_{\pi\pi}$ in $B^0 \to \pi^+\pi^-$ decays at the Belle experiment is discussed. Also reported is the status of the isospin analysis.

2 CP asymmetry in $B^0 \to \pi^+\pi^-$

The analysis is performed using a data sample with an integrated luminosity of 78 fb^{-1} corresponding to about 85 million $B\overline{B}$ pairs. The data are taken with the Belle detector [5] in the KEKB asymmetric e^+e^- collider [6]. The detail of the analysis procedure is described in [7].

B^0 mesons are reconstructed from two oppositely charged pions. The pions are selected by requiring the particle identification likelihood to be consistent with pions. The likelihood is calculated using the hit information in aerogel Cerenkov counters and the dE/dx measured in a central drift chamber. Candidate B^0 mesons are selected using two variables, the beam constrained mass (M_{bc}) and the energy difference (ΔE), defined in the center-of-mass frame of the B^0 meson. M_{bc}, which is the invariant mass of a reconstructed π^+ and π^- pair calculated taking the energy to be the beam energy, is required to be in the range $5.271 < M_{bc} < 5.287$ GeV/c^2. ΔE is the difference between the energy of the B candidate and the beam energy and is required to satisfy $|\Delta E| < 0.057$ GeV.

One of the major background sources are the continuum events ($e^+e^- \to q\overline{q}$). To reduce the contamination, two parameters are used. One is the Fischer discriminant consisting of 6 modified Fox-Wolfram moments [8], and the other is the angle of the flight direction of candidate B meson with respect to z axis defined in the center-of-mass frame. Likelihood functions are defined for the signal (L_{sig}) and background (L_{bg}) with these parameters. The function shape for the signal is determined from a Monte Carlo simulation, while the background shape is from the sideband data in $5.20 < M_{bc} < 5.26$ GeV/c^2 and $-0.3 < \Delta E < 0.5$ GeV. A ratio of likelihoods ($LR = L_{sig}/(L_{sig} + L_{bg})$) is calculated for each event and the event selection is done applying the cut in LR. The cut value is changed according to the flavor tagging condition.

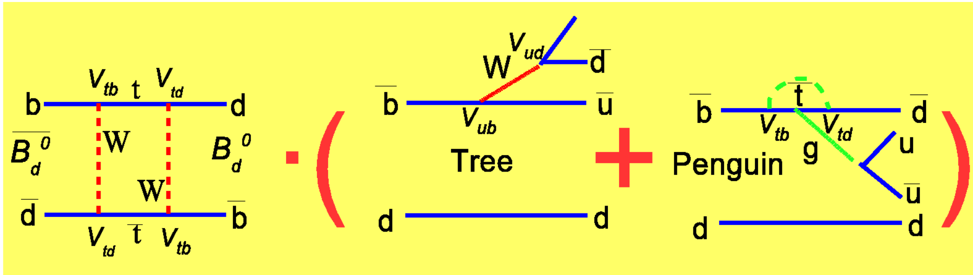

Fig. 1. Diagrams contributed to $B^0 \to \pi^+\pi^-$ decay

The flavor tagging and the vertex reconstruction are done using the same algorithm as that used for the $\sin 2\phi_1$ measurement [1]. The flavor tagging is performed by looking at the charge of inclusive leptons and hadrons in the tag-side B meson decay and gives the flavor of the B meson (q) and the probability of wrong tag (w). The vertex reconstruction is tested by measuring the lifetime of the B^0 in the selected $B^0 \to \pi^+\pi^-$ sample and the lifetime is obtained to be $1.42^{+0.14}_{-0.12}$ ps which is consistent with the PDG value.

The CP violation parameters, $S_{\pi\pi}$ and $A_{\pi\pi}$, are determined by the unbinned maximum likelihood fit. A probability density function (PDF) is defined as

$$PDF = (1 - f_{ol}) \int_{-\infty}^{+\infty} \{(f_{\pi\pi} P_{\pi\pi}(\Delta t', w; A_{\pi\pi}, S_{\pi\pi}) + f_{K\pi} P_{K\pi}(\Delta t', w)) \cdot R_{sig}(\Delta t - \Delta t') + f_{q\bar{q}} P_{q\bar{q}}(\Delta t) \cdot R_{q\bar{q}}(\Delta t - \Delta t')\} d\Delta t' + f_{ol} P_{ol}(\Delta t) \quad (2)$$

where $P_{\pi\pi}$ is the theoretical time evolution in 1 in which q is replaced with the diluted flavor tag $q(1-2w)$. $P_{K\pi}$ is a PDF for the contaminating $B \to K\pi$ decays in which no CP violation is assumed. These two functions are convolved with a signal resolution function R_{sig} whose parameters are the same as those used for the $\sin 2\phi_1$ measurement. $P_{q\bar{q}}$ is a PDF for continuum events which is composed of a lifetime component and a $\delta(\Delta t)$ function component. The fractions of two components and the lifetime are determined from a fit to the sideband data. The function is convolved with a background resolution function $R_{q\bar{q}}$ whose parameters are determined using the sideband data. A small number of events which make tails in large $|\Delta t|$ regions (outliers) are described by an outlier function P_{ol}.

$f_{\pi\pi}$ is a fraction of signal as a function of ΔE and M_{bc} while $f_{K\pi}$, $f_{q\bar{q}}$, and f_{ol} are the background fraction functions for $B \to K\pi$, continuum and outlier components, respectively. The fractions are calculated event-by-event from M_{bc} and ΔE of the event using these functions. The parameters in the functions are obtained using the sideband and signal Monte Carlo data.

A likelihood is defined as a product of the PDF for 760 candidate events and the CP violation parameters are determined by maximizing the likelihood. In the fit, $A_{\pi\pi}$ and $S_{\pi\pi}$ are the only free parameters. Figure 2 (a) and (b) show the raw Δt distributions for the high-purity samples tagged as $q = +1$ and -1, respectively. Figure 2(c) shows the distributions after the background subtraction and (d) shows the background-subtracted asymmetry between $q = +1$ and -1 samples. The curves the in figures show the results of the fit. As seen, a large asymmetry is observed.

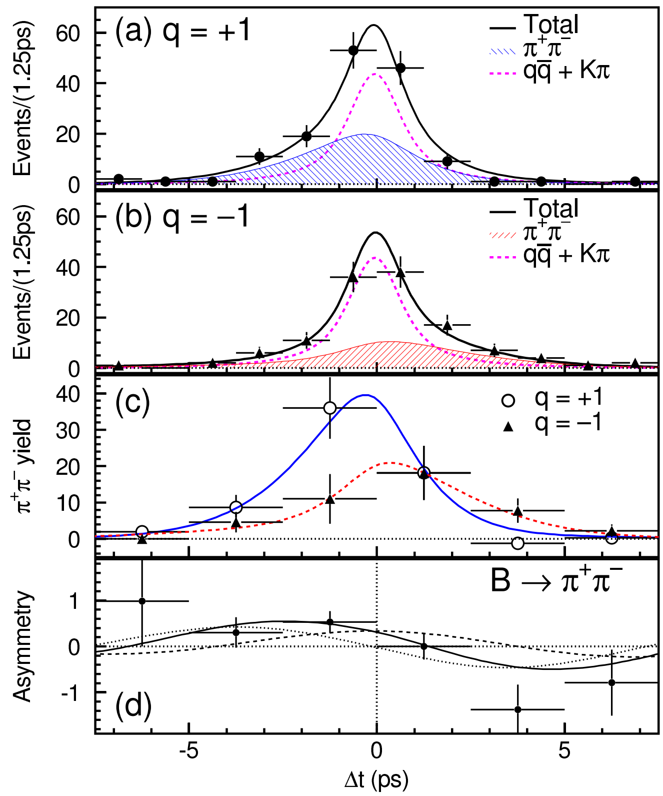

Fig. 2a,b. Unweighted Δt distributions for $q = +1$ and -1 candidates, **c** Δt distributions after background subtraction, and **d** Background-subtracted CP asymmetry between $q = +1$ and -1 samples. The *curves* in the figures are results of the fit

From the fit, CP violation parameters are obtained to be $A_{\pi\pi} = +0.77 \pm 0.27 \pm 0.08$ and $S_{\pi\pi} = -1.23 \pm 0.41^{+0.08}_{-0.07}$. Statistical errors are estimated using pseudo Monte Carlo experiments since the obtained $(A_{\pi\pi}, S_{\pi\pi})$ point is out of the physical limit where the shape of the likelihood function can be distorted. Major sources of the systematic error are uncertainties in the background fractions and vertex reconstruction, however, the size of the systematic errors is small compared to the statistical ones with the current statistics.

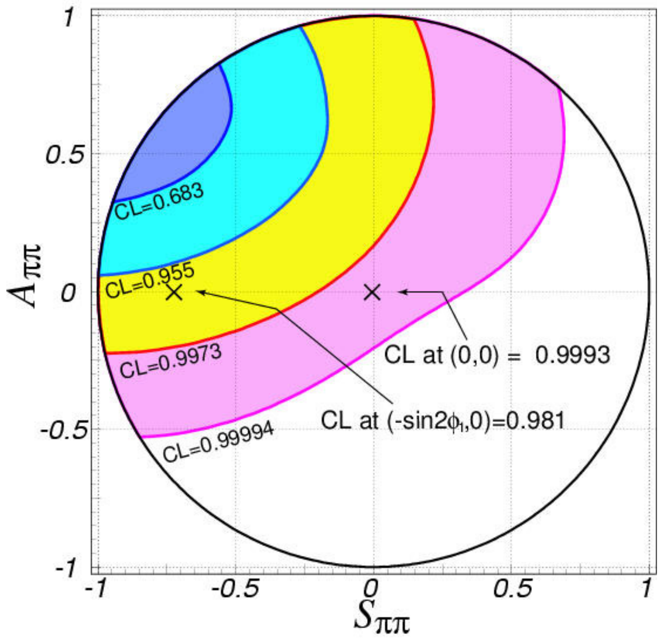

Fig. 3. Confidence regions in the $A_{\pi\pi} - S_{\pi\pi}$ plane

A statistical significance of the obtained result is estimated using the Feldman-Cousins frequentist approach. The confidence interval is calculated from the distributions obtained by pseudo Monte Carlo experiments and the effect of the systematic error is taken by the Gaussian smearing. Figure 3 shows the calculated confidence regions in the $A_{\pi\pi} - S_{\pi\pi}$ plane. As seen, the CP conservation hypothesis ($A_{\pi\pi} = 0.0, S_{\pi\pi} = 0.0$) is ruled out at 3.4σ and the result gives the evidence for the CP violation in $B^0 \to \pi^+\pi^-$ decays. A hypothesis of $A_{\pi\pi} = 0.0$ is also ruled out at (at least) 2.2σ which is the indication of the direct CP violation in the decay.

$A_{\pi\pi}$ and $S_{\pi\pi}$ can be expressed as a function of ϕ_1, ϕ_2 and the penguin-to-tree ratio in $B^0 \to \pi^+\pi^-$ decays [9]. Using the relation with ϕ_1 to be 23.5° (from the average of sin2ϕ_1 measurements by Belle and BaBar) and with the theoretical estimation of the penguin-to-tree ratio in the range 0.15-0.45, a constraint on ϕ_2 is calculated and obtained to be $78° \le \phi_2 \le 152°$ at 95.5% confidence level.

3 Status of isospin analysis

As discussed in the previous section, a penguin contribution to $B^0 \to \pi^+\pi^-$ decay shifts the angle ϕ_2 as measured from the CP asymmetry by θ and θ can be determined using the isospin analysis [4]. For this analysis, precise measurements of the decay amplitudes of $B^0 \to \pi^+\pi^-$, $B^+ \to \pi^+\pi^0$, and $B^0 \to \pi^0\pi^0$ (and their charge conjugates) are necessary. Their branching fractions are measured using the data sample with 78 fb^{-1}. The detail of the measurements is covered in a separate talk [10].

Table 1. Measured branching fractions for $B^0 \to \pi^+\pi^-$, $B^+ \to \pi^+\pi^0$, and $B^0 \to \pi^0\pi^0$ decays

Mode	Br($\times 10^{-6}$)	Significance (σ)
$B^0 \to \pi^+\pi^-$	$4.4 \pm 0.6 \pm 0.3$	8.5
$B^+ \to \pi^+\pi^0$	$5.3 \pm 1.3 \pm 0.5$	4.5
$B^0 \to \pi^0\pi^0$	< 4.4	(90% CL)

Table 1 summarizes the measured branching fractions. The statistics of $B^0 \to \pi^0\pi^0$ candidates is still low and the upper limit is calculated at a 90% confidence level for the mode. Using the measured branching fractions, a constraint on the value of θ is calculated following the formalism by Gronau *et al.* [11] and obtained to be $|\theta| < 68°$ at a 90% confidence level.

4 Summary

The CP asymmetry in $B^0 \to \pi^+\pi^-$ decays is studied in a data sample with an integrated luminosity of 78fb^{-1} collected by the Belle detector in the KEKB asymmetric e^+e^- collider. The CP violation parameters are measured to be $A_{\pi\pi} = +0.77 \pm 0.27 \pm 0.08$ and $S_{\pi\pi} = -1.23 \pm 0.41^{+0.08}_{-0.07}$. The result gives the evidence for the CP violation in $B^0 \to \pi^+\pi^-$ at 3.4σ and also the indication of the direct CP violation at least at 2.2σ.

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