CP Violation sensitivity at the Belle II Experiment

Tao Luo*

Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics,
Fudan University, Shanghai, China 200443
**E-mail: luot@fudan.edu.cn*

The sensitivity on the measurements of the angles of the CKM unitarity triangle, i.e. ϕ_1, ϕ_2 and ϕ_3, for Belle II experiment is presented in this letter, the CKM mechanism is expected to be tested at 1% level on Belle II.

Keywords: CP Violation; the angles of the CKM unitarity triangle; the Belle II experiment.

1. Introduction

The weak interactions of quarks are described by the Cabibbo-Kobayashi-Maskawa (CKM)[1,2] matrix, which needs to meet the unitary condition, so it has four degrees of freedom. If we select proper variables, the CKM matrix can be expressed by three rotation angles and one phase (A, λ, ρ, η). The unitary condition of CKM matrix can be converted to six free triangles in the complex plane, and one of the triangles is related to the B meson decays, which is shown in Fig. 1. In this triangle, the side lengths are related to the amount of branching fractions for the corresponding decays, and also the possible $b\bar{b}$ mixing, while the widths of the three angles are related to the amount of the CP Violation (CPV) of difference decay processes. These angles are just what we are interested in for the following parts of this letter. Due to history reasons, these three angles have two sets of names, α, β, γ, and ϕ_1, ϕ_2, ϕ_3. They are corresponding to each other like what are shown in Fig. 1. ϕ_1, ϕ_2, ϕ_3 are used in this letter.

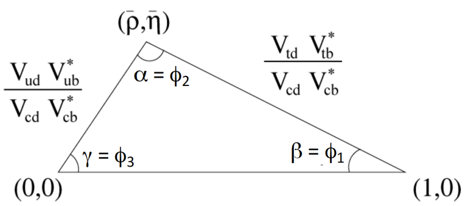

Fig. 1. The B^0 Unitarity Triangle (UT).

The values of ϕ_1[3–6] can be extracted from $b \to c\bar{c}s$ and $q\bar{q}s$ decay channels, such as: $B^0 \to J/\psi K_s^0$, $B^0 \to \phi K_S^0$, and $B^0 \to \eta' K_S^0$; the effective ϕ_2 can be extracted from $B \to u\bar{u}d$ processes, such as $B \to \pi\pi$, $\rho\rho$ and $\rho\pi$; the values of ϕ_3 can be extracted from $B \to c\bar{u}s$ processes, such as the golden mode $B^{\pm} \to DK^{\pm}$. The expected sensitivity of the measurement of these angles from part of these decay modes on Belle II will be introduced one by one in the following parts of this letter.

2. Time dependent measurements

One of the most important tasks on Belle II is to measure the time dependent CP violation of B meson decay, from this measurement, we can extract ϕ_1. This section just displays how to extract ϕ_1 from B^0 decay. With asymmetric energies, e^+ and e^- collide inside Belle II detector at $\Upsilon(4S)$ energy region, which is shown in Fig. 2. One B meson decays to J/ψ and K_S, which is taken as the signal CP side; the

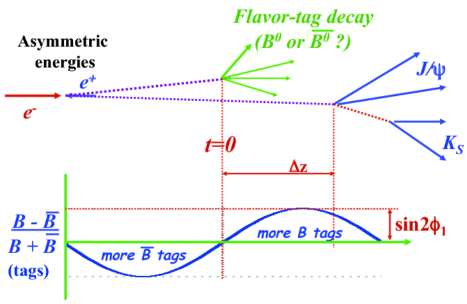

Fig. 2. Asymmetric B-factories at $\Upsilon(4S)$.

other B meson decays to other final states, which is taken as the flavor-tag side; the distance between this two B mesons can be determined by the detector, and then converted into time difference through the equation:

$$\Delta t = \Delta z/\beta\gamma c. \tag{1}$$

The difference of the time-dependent decay rates for the initial B meson, which decays to a CP eigenstate $J/\psi K_S$, can be expressed in Eq.(2); this CP asymmetry is related to S and C, which represent the indirect and direct CPV. By fitting to the B meson time dependent CP asymmetry ($\alpha_{f_{CP}}(\Delta t)$) distribution, we can extract S and ϕ_1 from the data.

$$\alpha_{f_{CP}}(\Delta t) \equiv \frac{\Gamma_{\bar{B}\to f_{CP}}(\Delta t) - \Gamma_{B\to f_{CP}}(\Delta t)}{\Gamma_{\bar{B}\to f_{CP}}(\Delta t) + \Gamma_{B\to f_{CP}}(\Delta t)} = \mathrm{S}\sin(\Delta\mathrm{M}\Delta\mathrm{t}) - \mathrm{C}\cos(\Delta\mathrm{M}\Delta\mathrm{t}), \tag{2}$$

where

$$\mathrm{S} = -\xi_{\mathrm{f}}\sin 2\phi_1, \mathrm{C} \approx 0. \tag{3}$$

3. Belle II Detector on SuperKEKB

KEKB has been upgraded to SuperKEKB, accordingly, the Belle detector has been upgraded to Belle II[7]. Two of the most important upgrades for the accelerator are: the beam size has been reduced to $\frac{1}{20}$ of that used for KEKB, and reaches nano meter level; the beam currents have been doubled. So totally the peaking luminosity of SuperKEKB will achieve 40 time of that for KEKB, reaching up to 8×10^{35}. The Belle II experiment expects to accumulate 50 ab^{-1} data[12] by 2024. There are many upgrades needed for the Belle II detector in order to increase the performance and cope with much more severe background conditions. The main improvement in performance is in two aspects: new tracking detector: Central Drift Chamber and new vertex determination detector; two new charged particle identification detectors[7].

4. ϕ_1 determination from $b \to c\bar{c}s$ decay channels

As mentioned in previous section, $B^0 \to J/\psi K^0$ is the golden mode for extracting ϕ_1 for two reasons[3,4]: 1. The expected theoretical uncertainty is small; 2. The experimental signature is clean. This process happens mainly through the tree diagram process, but there is also penguin pollution. One good thing is that the theoretical estimates on penguin pollution have been significantly improved. Table 1 shows the current status of this angle determination from Belle. For S measurement, it is statistical uncertainty dominated. Table 2 shows the expected uncertainties on Belle II at 50 ab^{-1} data, which will give results with precision better than 1% comparing to the current 5 %. The results will become systematic uncertainty dominated by then.

Table 1. Current status of ϕ_1 determination from Belle[8].

PRL108 171802	-	Value	stat. (10^{-3})	syst. (10^{-3})
$J/\psi K^0$	S	+0.67	29	13
	$\mathcal{A} \equiv -$C	-0.015	21	$^{+45}_{-23}$
$c\bar{c}s$	S	+0.667	23	12
	$\mathcal{A} \equiv -$C	-0.006	16	12

Table 2. Belle2 expected uncertainties on ϕ_1 determination @ 50 ab^{-1}. Case1: irreducible syst. same as Belle; Case2: irreducible syst. (vertexing)reduced by a factor 2 due to the new Pixel Vertex detector and improved tracking and alignment algorithms[12]

Expected errors (10^{-3})	-	stat.	syst. reducible	syst.(case 1)	syst.(case 2)
$J/\psi K^0$	S	3.5	1.2	8.2	4.4
	$\mathcal{A} \equiv -$C	2.5	0.7	$^{+43}_{-22}$	$^{+42}_{-11}$
$c\bar{c}s$	S	2.7	2.6	7.0	3.6
	$\mathcal{A} \equiv -$C	1.9	1.4	10.6	8.7

5. ϕ_2 determination on Belle II

The values of ϕ_2 angle are determined mainly through $b \to u\bar{u}d$ processes, such as $B \to \pi\pi$, $\rho\rho$, and $\rho\pi$. Because of the existence of non-negligible strong phase, we can not extract ϕ_2 directly but determine the effective ϕ_2 like Eq. 4. C is no longer equal to 0, which means that there will be direct CP violation.

$$\mathrm{S} = \sin(2\phi_2^{\mathrm{eff}}), \phi_2^{\mathrm{eff}} = \phi_2 + \Delta\phi_2; \mathrm{C} \neq 0 \tag{4}$$

As an example, Table. 3 shows the expected sensitivity of ϕ_2 determination from $B \to \pi\pi$ channels at 50 ab^{-1} Belle II data from the isospin analysis of MC simulation. Belle II will make big contributions on the research of these channels, especially on the branch fraction measurements.

Table 3. Branching fractions and CP asymmetry parameters entering in the isospin analysis of the $B \to \pi\pi$ system: Belle measurements at 0.8 ab^{-1} together with the expected Belle II sensitivity at 50 ab^{-1}.[12]

	Value	0.8 ab^{-1}	50 ab^{-1}
$\mathcal{B}_{\pi^+\pi^-}$ [10^{-6}]	5.04	$\pm 0.21 \pm 0.18$ [10]	$\pm 0.03 \pm 0.08$
$\mathcal{B}_{\pi'\pi'}$ [10^{-6}]	1.31	$\pm 0.19 \pm 0.18$ [9]	$\pm 0.04 \pm 0.04$
$\mathcal{B}_{\pi^+\pi'}$ [10^{-6}]	5.86	$\pm 0.26 \pm 0.38$ [10]	$\pm 0.03 \pm 0.09$
$\mathrm{C}_{\pi^+\pi^-}$	-0.33	$\pm 0.06 \pm 0.03$ [11]	$\pm 0.01 \pm 0.03$
$\mathrm{S}_{\pi^+\pi^-}$	-0.64	$\pm 0.08 \pm 0.03$ [11]	$\pm 0.01 \pm 0.01$
$\mathrm{C}_{\pi^0\pi^0}$	-0.14	$\pm 0.36 \pm 0.12$ [9]	$\pm 0.03 \pm 0.01$
$\mathrm{S}_{\pi^0\pi^0}$	-	-	$\pm 0.29 \pm 0.03$

6. Summary

Belle has been a successful B factory, especially for the research on CPV. Major upgrades of KEKB and Belle have been made to build SuperKEKB and Belle II. CKM mechanism will be tested at 1% level[12] on Belle II. Some flavor variables are still to be measured precisely, therefore a lot of room for discoveries at Belle II are expected!

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