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CP violation in Belle/BaBar part-2

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We review CP violation measurements based on a data sample of more than 1 billion $B\bar{B}$ pairs collected with the Belle detector at the KEKB and the BABAR detector at the PEP-II e^+e^- asymmetric-energy collider. Review of unitary triangle parameters ϕ_1 and ϕ_2 measurement and recent new results are described in this part.

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1. Introduction

In the decay sequences $\Upsilon(4S) \to B^0\bar{B}^0 \to f_{CP} f_{\rm tag}$, where one of the B mesons decays at time t_{CP} to a CP eigenstate f_{CP} and the other decays at time $t_{\rm tag}$ to a final state $f_{\rm tag}$ that distinguishes between B^0 and $\bar{B}^0$, the decay rate has a time dependence given by

$$P(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 + q \cdot \left[S_f \sin(\Delta m_d \Delta t) + A_f \cos(\Delta m_d \Delta t)\right]\right]. \tag{1.1}$$

Here, S_f and A_f are parameters that describe mixing-induced and direct CP violation, respectively, τ_{B^0} is the B^0 lifetime, Δm_d is the mass difference between the two B^0 mass eigenstates, $\Delta t = t_{CP} - t_{\rm tag}$, and the b-flavor charge, $q = +1(-1)$ when the tagged B meson is a $B^0(\bar{B}^0)$. At the KEKB and PEP-II asymmetric-energy e^+e^- collider [2, 3], $\Upsilon(4S)$ is produced with a Lorentz boost. Since B^0 and $\bar{B}^0$ mesons are approximately at rest in the $\Upsilon(4S)$ center-of-mass system (CM), the Δt can be determined from the displacement between the f_{CP} and $f_{\rm tag}$ decay vertices along flight direction of $\Upsilon(4S)$, z : $\Delta t \simeq (z_{CP} - z_{\rm tag})/(\beta\gamma c) \equiv \Delta z/(\beta\gamma c)$. Since most of the CP eigenstates are not flavor-specific, q is determined using the information of $f_{\rm tag}$ such as flavor of charged lepton, high momentum kaon and low momentum pion from D_s decay. To collect information of the B decay products, large-solid-angle magnetic spectrometers are installed around interaction point of both accelerators. They consist of number of different type of particle detectors for vertex reconstruction, charged particle tracking and momentum measurement, photon energy measurement and particle identification [4, 5].

2. ϕ_1/β measurement

B^0 decays that proceed via $b \to c\bar{c}K^0$ transition are referred to as "golden modes" since these are clean both experimentally and theoretically due to relatively large branching fractions and small background contamination. A color-suppressed tree diagram is a dominant contribution of these mode and $S_f = -\xi_f \sin 2\phi_1$ is predicted in a good approximation in the Standard Model (SM), where $\xi_f = +1(-1)$ corresponds to CP-even (-odd) final states and ϕ_1 is an angle of the unitary triangle. In the most recent analysis in the BABAR, they reconstruct the decay modes of $B^0 \to J/\psi K^0_S$, $B^0 \to \psi(2S)K^0_S$, $B^0 \to \chi_{c1}K^0_S$, $B^0 \to \eta_c K^0_S$ and $B^0 \to J/\psi K^0_L$ as the sample for simultaneous fit to extract the CP violation parameters from 465 million $B^0\bar{B}^0$ pairs [8]. $B^0 \to J/\psi K^0_S$ and $B^0 \to J/\psi K^0_L$ are reconstructed from 535 million $B^0\bar{B}^0$ sample in the Belle [7]. The $\sin 2\phi_1$ obtained from both experiments are consistent within errors. All of the results together with world average value calculated by Heavy Flavor Averaging Group (HFAG) [6] are listed in Table 1. When comparing this result to other measurements of unitary triangle, difference with V_{ub} that is determined from branching fraction of $B^+ \to \tau^+\nu$ decay is indicated [9]. To identify this difference, we need further accuracy for both parameters. Reconstruction of $b \to c\bar{c}s$ CP eigenstates using 772 million $B\bar{B}$ has done and $\sin 2\phi_1$ will be extracted in near future with full data set accumulated in the Belle.

3. ϕ_2/α measurements

Considering the asymmetry as same as Eq. 1.1 in $b \to u\bar{u}d$ tree diagram, one of the angle of the unitary triangle ϕ_2 is measured in a number of CP-eigenstates with a time-dependent decay

Table 1: Results of $\sin 2\phi_1$ from $b \to c\bar{c}K^0$ decay modes.

Decay mode	$\sin 2\phi_1$	
Belle 535 $\times 10^6 B\bar{B}$		
$B^0 \to J/\psi K_S^0$	0.643 ± 0.038	
$B^0 \to J/\psi K_L^0$	0.641 ± 0.057	
$B^0 \to J/\psi K^0$	$0.642 \pm 0.031 \pm 0.017$	
BABAR 465 $\times 10^6 B\bar{B}$		
$B^0 \to J/\psi K_S^0$	0.657 ± 0.036	
$B^0 \to J/\psi K_L^0$	0.694 ± 0.061	
$B^0 \to J/\psi K^0$	$0.666 \pm 0.031 \pm 0.013$	
All charmonium combined		0.673 ± 0.023

Table 2: Results from $B^0 \to \pi^+\pi^-$ and $B^0 \to \rho^+\rho^-$ decay modes.

decay mode	Experiment	Data sample ($\times 10^6 B\bar{B}$)	S_f	A
$\pi^+\pi^-$	Belle	657	$-0.61 \pm 0.10 \pm 0.04$	$-0.55 \pm 0.08 \pm 0.05$
	BABAR	465	$-0.68 \pm 0.10 \pm 0.03$	$-0.25 \pm 0.08 \pm 0.02$
$\rho^+\rho^-$	Belle	535	$0.19 \pm 0.30 \pm 0.07$	$-0.16 \pm 0.21 \pm 0.07$
	BABAR	387	$-0.17 \pm 0.20^{+0.05}_{-0.06}$	$0.01 \pm 0.15 \pm 0.06$

rate measurement. However, a gluonic penguin contamination is considerable so that the mixing induced term S_f in Eq. 1.1 is described as $S_f = -\xi_f(1-A^2)\sin 2\phi_2^{\rm eff}$, where $\phi_2^{\rm eff}$ is an effective ϕ_2 that is defined as difference of the ϕ_2 and its phase shift $\Delta\phi_2$. To solve this puzzle, there are two approaches. The isospin relations in two-body decay system [10] are used in one method. Using the relation with measured *CP* violation parameters and branching fractions, phase shift is determined with four-fold ambiguity. In the $B^0 \to \pi^+\pi^-$ decay mode, both of the Belle and BABAR obtain significantly large S_f and A_f as shown in Table 2 [11, 12]. The Belle and BABAR set exclude region for ϕ_2 as $8^\circ < \phi_2 < 81^\circ$ (95.4% CL) and $23^\circ < \phi_2 < 67^\circ$ (90% CL), respectively. For measurement in $B^0 \to \rho^+\rho^-$ mode, angular analysis is needed to determine the polarization ratio since $B^0 \to \rho\rho$ is the decay from a pseudoscholar to two vector mesons. From the angular analysis, longitudinally polarized state is dominant (94.1% Belle and 99.2% BABAR) and the *CP* violation parameters are obtained as listed in Table 2 [13, 14]. Recently, the BABAR updates a branching fraction of $B^0 \to \rho^+\rho^0$ using 465 million $B\bar{B}$ sample and it effectively contributes to reduce an ambiguity of the ϕ_2 determination using $SU(2)$ isospin relation: $\phi_2 = 92.4^{+6.0}_{-6.5}$ and $-1.8^\circ < \Delta\phi_2 < 6.7^\circ$ (68% CL). Another technique to determine the ϕ_2 and $\Delta\phi_2$ is a time-dependent Dalitz plot analysis for $B^0 \to \pi^+\pi^-\pi^0$. In this method, interferences among three $B \to \rho\pi$ states are modeled so that $\Delta\phi_2$ is determined if the Dalitz plot density is properly determined. [15, 16]. The Belle and BABAR preform a study for signal yield of 971 ± 41 and 2067 ± 86 and set interval as $68^\circ < \phi_2 < 95^\circ$ and $\phi_2 = (87^{+45}_{-13})^\circ$ at 68.3% CL, respectively [17, 18]. Considering all the results above, a world average of the ϕ_2 is calculated by HFAG [6] as $\phi_2 = (89.0^{+4.4}_{-4.2})^\circ$ at 68% CL.

4. Direct CP violation in $B^+ \to J/\psi K^+$

The decay of $B^+ \to J/\psi K^+$ is mainly induced with $b \to c$ tree diagram. There are contribution from other transitions so that slight shift on the CP asymmetry:

$$A_{CP} \equiv \frac{B(B^- \to J/\psi K^-) - B(B^+ \to J/\psi K^+)}{B(B^- \to J/\psi K^-) + B(B^+ \to J/\psi K^+)} \tag{4.1}$$

is expected (∼0.3%) in the SM. On the other hand, when considering contribution of new physiscs in $b \to s$ penguin diagram, the asymmetry is enhanced due to extra CP phase, for example $A_{CP} = O(1\%)$ and $O(10\%)$ for the models with extra $U(1)'$ gauge boson and extra coupling to charged Higgs, respectively. Current world average of A_{CP} in PDG is $(+0.9 \pm 0.8)\%$. Recently, precise measurement using 41315 ± 205 reconstructed signal from 772 million $B\bar{B}$ sample are performed in Belle. There are systematic bias on observed A_{CP} due to the detector acceptance and interaction rate difference between K^+ and K^-. It is estimated using control sample decay modes: $D_s^+ \to \phi(\to K^+K^-)\pi^+$ and $D^0 \to K^-\pi^+$. After applying the correction, A_{CP} is obtained to be $(-0.76 \pm 0.50 \pm 0.22)\%$ [19].

5. $b \to sq\bar{q}$ time-dependent CP violation

In the decay modes that induced by $b \to s$ transition, there are loop appears in first order of flavor changing neutral current processes. Contribution of new physics to the loop is expected in several models and such effect is appeared as extra CP phase.

In $b \to sq\bar{q}$ transition, $S_f = -\xi_f \sin 2\phi_1$ is expected in Eq. 1.1 if no extra CP phase contribute to the loop. Comparison of $\sin 2\phi_1$ measured from this process ($\equiv \sin 2\phi_1^{\rm eff}$) to that obtained from $b \to c\bar{c}s$ process is a good probe to search for new physics. Belle recently publish updated result of $\sin 2\phi_1^{\rm eff}$ measurement using the modes which decay into $B^0 \to K^+K^-K_S^0$ final states [23]. Since there are large interferences among K^+K^- resonances, large systematic error is unavoidable in quasi-2-body analysis of the $\sin 2\phi_1^{\rm eff}$ measurement in $B^0 \to f^0K^0$ and $B^0 \to \phi K^0$ decays. To solve this, a time-dependent measurement is performed with Dalitz plot of three-body final states by considering the interference of each resonance. Measured $\sin 2\phi_1^{\rm eff}$ are listed in Table 3 together with other decay modes by $b \to sq\bar{q}$ process. More statistic is needed to find out significant deviation between $sin2\phi_1$ and $\sin 2\phi_1^{\rm eff}$.

6. $B^0 \to \phi K_S^0 \gamma$ time-dependent CP violation

In the scheme of the SM, radiative photon from $b \to s\gamma$ process is flavor-specific. $B^0\bar{B}^0$ mixing can occur only through a helicity flip so that CP violation is suppressed by the quark mass ratio: $S_f = -2(m_s/m_b)\sin 2\phi_1 \sim 0$. Among those process, the most sensitive decay mode to measure the CP violation is $B^0 \to K_S^0\pi^0\gamma$ and obtained results in both Belle and BABAR are consistent with expectation from SM [25, 26]. Recently, first measurement in $B^0 \to \phi K_S^0\gamma$ mode is performed in Belle. Branching fraction which has 5.4σ significance $(2.66 \pm 0.60 \pm 0.32)$ has set from 772 million $B\bar{B}$ sample. Using the same reconstructed signal events, CP violation parameters are measured as $S = 0.74^{+0.72+0.10}_{-1.05-0.24}$ and $A = 0.35 \pm 0.58^{+0.23}_{-0.10}$. This result is consistent with the SM expectation and other $b \to s\gamma$ decay modes.

Table 3: Results of $\sin 2\phi_1^{\rm eff}$ from $b \to sq\bar{q}$ decay modes.

Decay mode	Experiment	Data sample ($\times 10^6 B\bar{B}$)	$\sin 2\phi_1^{\rm eff}$
ϕK^0	Belle	657	$0.90^{+0.09}_{-0.19}$
	BABAR	465	$0.26 \pm 0.26 \pm 0.03$
$\eta' K^0$	Belle	535	$0.64 \pm 0.10 \pm 0.04$
	BABAR	467	$0.57 \pm 0.08 \pm 0.02$
$K_S^0 K_S^0 K_S^0$	Belle	535	$0.30 \pm 0.32 \pm 0.08$
	BABAR	465	$0.90^{+0.18}_{-0.20}{}^{+0.03}_{-0.04}$
$\pi^0 K^0$	Belle	657	$0.67 \pm 0.31 \pm 0.08$
	BABAR	467	$0.55 \pm 0.20 \pm 0.03$
$\rho^0 K^0$	Belle	657	$0.64^{+0.19}_{-0.25} \pm 0.09 \pm 0.10$
	BABAR	383	$0.35^{+0.26}_{-0.31} \pm 0.06 \pm 0.03$
ωK^0	Belle	535	$0.11 \pm 0.46 \pm 0.07$
	BABAR	467	$0.55^{+0.26}_{-0.29} \pm 0.02$
$f_0 K^0$	Belle	657	$0.63^{+0.16}_{-0.18}$
	BABAR	*	$0.60^{+0.16}_{-0.19}$
$f_2 K_S^0$	BABAR	383	$0.48 \pm 0.52 \pm 0.06 \pm 0.10$
$f_X K_S^0$	BABAR	383	$0.20 \pm 0.52 \pm 0.07 \pm 0.07$
$\pi^0 \pi^0 K_S^0$	Belle	657	$-0.72 \pm 0.71 \pm 0.08$
	BABAR	227	$-0.43 \pm 0.49 \pm 0.09$
$\phi K_S^0 \pi^0$	BABAR	465	$0.97^{+0.03}_{-0.52}$
$\pi^+ \pi^- K_S^0$ (non-resonant)	BABAR	383	$0.01 \pm 0.31 \pm 0.05 \pm 0.09$
$K^+ K^- K_S^0$	BABAR	535	$0.68 \pm 0.15 \pm 0.03^{+0.21}_{-0.13}$
(excl. ϕK^0)	BABAR	465	$0.86 \pm 0.08 \pm 0.03$
Naive average of all $b \to s$ measurements			0.64 ± 0.04

* $B^0 \to f^0 K^0$ are combination of Dalitz analysis results of two final states: $\pi^+\pi^- K_S^0$ and $K^+K^-K_S^0$. BABAR used 383 and 465 million $B\bar{B}$ for former and latter, respectively.

7. Summary

Using data sample accumulated in b-factories, we have observed large CP violation in B decays. We have measured unitary triangle in good accuracy and results are consistent with SM expectation within the errors: $\phi_1 = (21.1. \pm 0.9)^\circ$ and $\phi_2 = (89.0^{+4.4}_{-4.2})^\circ$. Search for new physics contribution such as extra CP phase in $b \to s$ electroweak penguin is ongoing.Though we have obtained the results with the most precise errors in many decay modes, further study using larger number of data sample is needed to find out the evidence of the new physics.

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