TIME-DEPENDENT CP VIOLATION AND MIXING AT B FACTORIES*

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(Received May 15, 2012)

In the last decade, two B-factory experiments, BaBar and Belle performed a large number of measurements related to time-dependent CP violation and B–$\overline{B}^0$ mixing. Achievements of those measurements are reviewed and possible room for New Physics is discussed.

DOI:10.5506/APhysPolB.43.1553
PACS numbers: 11.30.Er, 14.65.Fy, 12.15.Ff

1. Introduction

In the Standard Model (SM) of elementary particle physics, CP violation in the quark sector is described by the Kobayashi–Maskawa (KM) theory [1]. In the KM scheme, a quark-mixing matrix has an irreducible complex phase that gives rise to CP-violating asymmetries. The quark-mixing matrix is written as [2]

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}, \quad (1)$$

where V_{ub} and V_{td} have CP-violating complex phases. Due to the unitarity condition of this matrix, the following relation is expected to hold

$$V_{td}V_{tb}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^* = 0\,. \quad (2)$$

The CP-violating phenomena in B meson decays are related to the angles ϕ_1, ϕ_2 and ϕ_3 defined as shown in Fig. 1. Here, the phase of V_{td} plays a fundamental role to cause CP violation by the interference with V_{cb} and V_{ub} resulting in determination of the CP-violating angles, ϕ_1 and ϕ_2 [3],

* Presented at the Cracow Epiphany Conference on Present and Future of B Physics, Cracow, Poland, January 9–11, 2012.

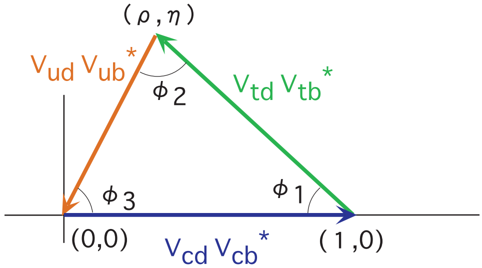

Fig. 1. The unitarity triangle. The CP violation parameters are defined as the angles ϕ_1, ϕ_2 and ϕ_3.

respectively. The angle ϕ_3 is determined by the direct CP asymmetries in $B \to DK^{(*)}$ decays and mentioned in detail elsewhere [4]. Since V_{td} takes part through B^0–$\overline{B}^0$ mixing, a measurement of time evolution of a B meson pair is required to see CP violation phenomena. In addition, since a B meson is so heavy that many decay modes are available, the branching fraction to the modes usable for CP violation is limited. Thus, huge ($\mathcal{O}(10^8)$) amount of B mesons is necessary.

In order to satisfy these requirements, two asymmetric-energy e^+e^- collider B-factory machines, KEKB and PEP-II were built at KEK and SLAC, respectively. Both achieved a peak luminosity of more than 10^{34} cm^{-2}s^{-1} and the KEKB integrated luminosity reached 1000 fb^{-1} while PEP-II realized 550 fb^{-1}. Thanks to efficient operation of these machines, the recorded number of B meson pairs has been found to be 772 M $B\overline{B}$ at Belle and 470 M $B\overline{B}$ at BaBar. In this report, we discuss experimental tests of Kobayashi–Maskawa theory and search for New Physics through time-dependent measurements in the B meson system using these rich statistics data samples.

2. Time-dependent measurements of B meson system

By a measurement of time evolution of B meson pairs, we can get constraints for CP-violating angles, ϕ_1 and ϕ_2, as well as the B^0–$\overline{B}^0$ mixing parameter Δm_d. In the decay chain $\Upsilon(4S) \to B^0\overline{B}^0 \to f_{\rm CP} f_{\rm tag}$, where one of the B mesons decays at time $t_{\rm CP}$ to a CP eigenstate $f_{\rm CP}$ and the other decays at time $t_{\rm tag}$ to a final state $f_{\rm tag}$ that distinguishes between B^0 and $\overline{B}^0$, the decay rate has a time dependence on the $\Upsilon(4S)$ rest frame [5] given by

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ 1 \; + \; q \left[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t) \right] \right\} . \quad (3)$$

Here $\mathcal{S}$ and $\mathcal{A}$ are CP-violation parameters, τ_{B^0} is the B^0 lifetime, Δm_d is the mass difference between the two neutral B mass eigenstates, $\Delta t = t_{\rm CP} - t_{\rm tag}$, and the b-flavor charge $q = +1$ (-1) when the tagging B meson is a B^0 $\left(\overline{B}^0\right)$. By selecting the neutral B decays into $f_{\rm CP}$ via the amplitudes containing no complex phase, the CP violation is caused by the interference between decay and V_{td} in mixing to give ϕ_1 determination, while the CP asymmetry is related to ϕ_2 in the case of $b \to u$ transition induced decays.

Instead of the B decays into $f_{\rm CP}$, collecting the events in which one neutral B meson decays into the flavor-specific final state enables us to determine the B^0–$\overline{B}^0$ mixing parameter Δm_d, by measuring opposite–same flavor asymmetry as a function of Δt. In this section, experimental determinations of these quantities are reviewed.

2.1. Measurements of sin$2\phi_1$

For the $b \to c\bar{c}s$ transition induced decay of the neutral B meson such as $B^0 \to (c\bar{c})K^0$, the SM predicts $\mathcal{S} = -\xi_f \sin 2\phi_1$ and $\mathcal{A} = 0$ with very small theoretical uncertainty [5], where $\xi_f = +1$ (-1) corresponds to CP-even (-odd) final states and ϕ_1 is one of the three interior angles of the most symmetric KM unitarity triangle, defined as $\phi_1 \equiv \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$ [3]. Therefore, the BaBar and Belle collaborations have published increasingly more precise determinations of $\sin 2\phi_1$ [6,7]. The latest measurements were reported with 465×10^6 $B\overline{B}$ and 535×10^6 $B\overline{B}$ by BaBar [8] and Belle [9], respectively.

More recently, thanks to the successful operation of the KEKB accelerator, Belle accumulated 772 M $B\overline{B}$ on the $\Upsilon(4S)$ resonance by the end of its operation. Out of those, 620 M $B\overline{B}$ collected by the newer detector configuration with a 1.5 cm radius beampipe, a 4-layer silicon vertex detector and a small-cell inner drift chamber have been reprocessed with an improved charged track reconstruction algorithm and a finely returned CsI crystal hit threshold of shower reconstruction in the electromagnetic calorimeter. Using this large statistics data, Belle has recently performed its final measurement of $\sin 2\phi_1$ [10]. The B decays to the CP-odd eigenstates, $f_{\rm CP} = J/\psi K_{\rm S}^0, \psi(2S)K_{\rm S}^0$ and $\chi_{c1}K_{\rm S}^0$, and the CP-even eigenstate, $f_{\rm CP} = J/\psi K_L^0$ are reconstructed. As shown in Fig. 2, the $B^0 \to f_{\rm CP}$ decay signal other than $J/\psi K_L^0$ is identified by two kinematic variables calculated in the $\Upsilon(4S)$ rest frame (cms): the energy difference $\Delta E \equiv E_B^* - E_{\rm beam}^*$ and the beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{(E_{\rm beam}^*)^2 - (p_B^*)^2}$, where $E_{\rm beam}^*$ is the beam energy in cms of the $\Upsilon(4S)$ resonance, and E_B^* and p_B^* are the cms energy and momentum of the reconstructed B candidate, respectively.

$B^0 \to J/\psi K_L^0$ candidates are identified by the value of p_B^* calculated using a two-body decay kinematic assumption. In total, the signal yield of the CP-odd modes is 15560 events and $J/\psi K_L^0$ signal is obtained to be 10040 events. Taking flavor tagging [11] and reconstruction of $f_{\rm CP}$ as well as

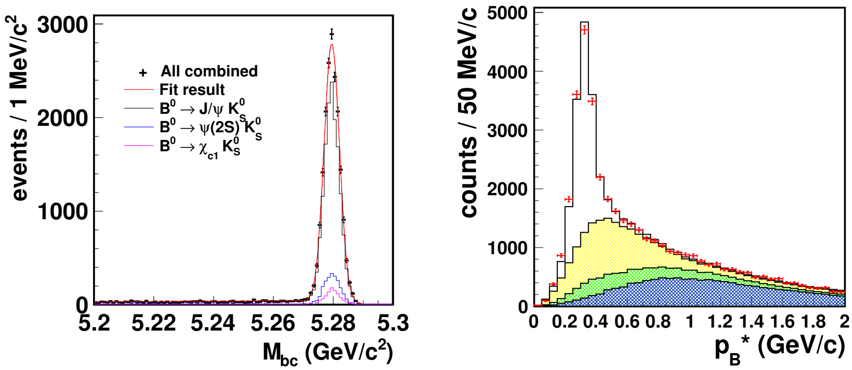

Fig. 2. (color online) $M_{\rm bc}$ distribution within the ΔE signal region for $B^0 \to J/\psi K^0_{\rm S}$ (black), $\psi(2S)K^0_{\rm S}$ (blue) and $\chi_{c1}K^0_{\rm S}$ (magenta), the superimposed curve (red) shows the fit result from all those modes combined (top) and p^*_B distribution $B^0 \to J/\psi K^0_L$ candidates with the results of the fit separately indicated as signal (open histogram), background events with a real J/ψ and a real K^0_L (pale grey/yellow), with a real J/ψ without a real K^0_L (grey/green) and without a real J/ψ (dark grey/blue) (bottom).

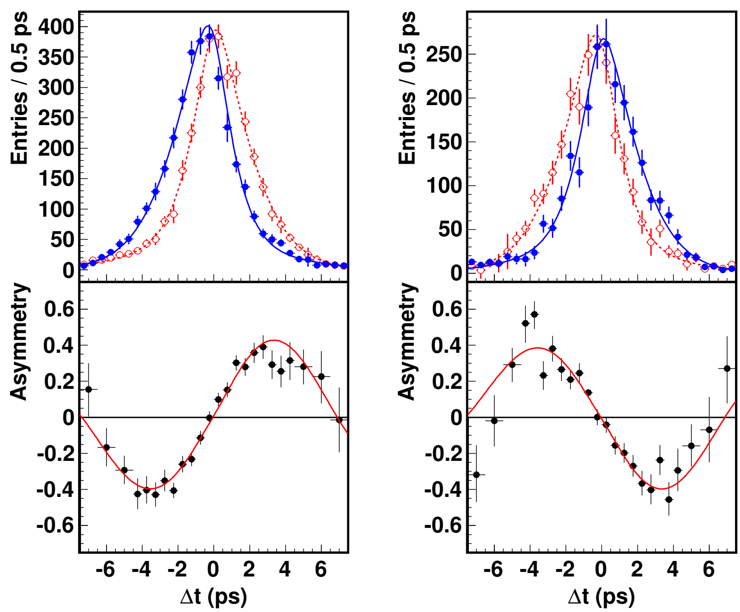

Fig. 3. (color online) The background-subtracted Δt distribution for $q = +1$ (grey/red) and $q = -1$ (black/blue) events and asymmetry for good tag quality events in $(c\bar{c})K^0_{\rm S}$ (left) and $J/\psi K^0_{\rm S}$ (right) cases.

$f_{\rm tag}$ vertices [12] into account, an unbinned maximum likelihood fit is done in the Δt distribution with the formula (3), two CP violation parameters, $\sin 2\phi_1 = -\xi_f \mathcal{S}$ and $\mathcal{A}$ are obtained to be

$$\sin 2\phi_1 = 0.667 \pm 0.023(\text{stat}) \pm 0.012(\text{syst})\,, \quad (4)$$

$$\mathcal{A} = 0.006 \pm 0.016(\text{stat}) \pm 0.012(\text{syst})\,. \quad (5)$$

The background-subtracted Δt distribution for $q = +1$ and $q = -1$ events and asymmetry for good tag quality events are shown in Fig. 3. The world average of $\sin 2\phi_1$ is now 0.68 ± 0.02 that is a firm SM reference.

2.2. Measurements of CP violation in $B^0 \to D^+D^-$ and $D^{*+}D^{*-}$ decays

In SM, $b \to c\bar{c}d$ transition induced neutral B meson decays also provide a possibility to access the CP violation angle ϕ_1 because leading order diagram of the decay amplitude contain same weak phase as $b \to c\bar{c}s$ case. On the other hand, if the $b \to d$ penguin diagram contribution or other New Physics effect are substantial, a precise measurement of CP violation in $b \to c\bar{c}d$ induced decay may reveal a deviation from the standard $\sin 2\phi_1$ measurement. The tree diagram of $B^0 \to D^+D^-$ and $D^{*+}D^{*-}$ decays is the color favored one among $b \to c\bar{c}d$ amplitudes. These decay modes have been revisited by Belle using its full integrated luminosity accumulated at the $\Upsilon(4S)$ resonance. For $B^0 \to D^+D^-$, we get $\mathcal{S} = -1.06^{+0.21}_{-0.14} \pm 0.08$ and $\mathcal{A} = +0.43 \pm 0.16 \pm 0.08$ [13]. $\mathcal{A}$ has decreased compared to the previous Belle publication with 535 M $B\overline{B}$ pairs [14] within a statistically consistent range. In $B^0 \to D^{*+}D^{*-}$, the CP violation parameters are measured to be $\mathcal{S} = -0.79 \pm 0.13 \pm 0.03$ and $\mathcal{A} = +0.15 \pm 0.08 \pm 0.02$. Especially in this mode, as a result of data reprocessing, the signal yield from 772 M $B\overline{B}$ pairs is 2.2 times larger than the yield with 657 M $B\overline{B}$ sample used in the previous result [15]. It gives us significant improvement, CP violation parameters' errors are down to 60% with respect to the previous publication. In spite of the improvement of this measurement precision, we observed no significant deviation from the SM expectation so far.

2.3. Determination of ϕ_2

In B decays into proper $f_{\rm CP}$ mediated by the $b \to u$ transition, its complex phase interferes with B^0–$\overline{B}^0$ mixing and results in the CP violation that can determine the angle ϕ_2. There would be the $b \to d$ penguin contribution that cause a complexity to extract the angle ϕ_2 from the observed CP violation, however we can solve it by isospin analysis. As the B decay final states to obtain ϕ_2, there are three possibilities; $\pi\pi$, $\rho\rho$ and $\rho\pi$. From the $\pi\pi$ [16, 17], $\rho\rho$ [18, 19] and $\rho\pi$ [18, 19] modes, ϕ_2 is determined to be $(89.0^{+4.4}_{-4.2})^\circ$. In addition, the measurements related to the $a_1\pi$ decay mode have been performed [20, 21] which can determine effective ϕ_2.

2.4. Measurements of Δm_d

By selecting the flavor specific final state of the neutral B meson decay, we can determine the B^0–$\overline{B}^0$ mixing parameter Δm_d by measuring time evolution of opposite–same flavor asymmetry. For this purpose, semileptonic $\overline{B^0} \to D^{*+}\ell^-\bar{\nu}$ decay is the most suitable process because of its relatively high branching fraction and absence of the tag side interference. Based on a 88 M $B\overline{B}$ sample, BaBar took a partial reconstruction approach for the neutral B meson decay to the $D^{*+}\ell^-\bar{\nu}$ final state and the accompanying B meson flavor is identified by a high momentum lepton [22]. Belle applied a full reconstruction method for $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}$ as well as hadronic decays such as $\overline{B}^0 \to D^{(*)+}\pi^-$, $D^{*+}\rho^-$ using a 152 M $B\overline{B}$ sample, and opposite side B flavor is tagged by the same method as the one for other time-dependent CP violation measurements [23]. BaBar and Belle results are approximately 5 times more precise than LEP and Tevatron experiments. Now the world average is obtained to be $\Delta m_d = 0.507 \pm 0.004$ ps^{-1}, 1% precision has been achieved. This gives another reference point to constrain a unitarity triangle, *i.e.* $|V_{td}|$ in the SM framework.

3. Tension with $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ and room for New Physics

The KM scheme has been tested, however there is a noticeable tension reaching a 2.8σ level between the global fit without $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ and experimental measurements of it, where a $\sin 2\phi_1$ measurement gives a stringent constraint on the former. Of course, New Physics (NP) could be present in $B^+ \to \tau^+\nu_\tau$ process, thus we need an update of this measurement. However, in this section, other possible room to accommodate NP is to be discussed. As explained in Sec. 2.1, the time-dependent CP violation is the result of interference between decay and mixing of the neutral B meson system. Here, if NP is substantial and has a different phase from the SM in $b \to c\bar{c}s$ decay amplitudes, it should cause direct CP violation in $B^\pm \to J/\psi K^\pm$. Including Belle latest measurement [24], no direct CP violation has been observed so far, $(1 \pm 7) \times 10^{-3}$ in PDG2011. Therefore, NP room is unlikely in $b \to c\bar{c}s$ decays, but there is room in B^0–$\overline{B}^0$ mixing.

4. Search for New Physics in $b \to s$ penguin modes

The B decays caused by the penguin diagrams are expected to be good at probing the New Physics effects beyond the SM, because of their one loop nature. In SM, $b \to s$ penguin mediated B decays such as $B^0 \to \phi K^0$, $B^0 \to \eta' K0$, $B^0 \to K^0_{\rm S} K^0_{\rm S} K^0_{\rm S}$ are expected to have effective $\sin 2\phi_1$ ($\sin 2\phi_1^{\rm eff}$) which is same as the $\sin 2\phi_1$ obtained by $b \to c\bar{c}s$ induced B decay such as $B^0 \to J/\psi K^0$.

Recently, because $\phi \to K^+K^-$, $f_0 \to K^+K^-$ and non-resonant contributions overlap (as do $\rho^0 \to \pi^+\pi^-$ and $f_0 \to \pi^+\pi^-$), time-dependent Dalitz analyses have been performed in three-body decays such as $B^0 \to (K^+K^-)K^0_{\rm S}$ and $B^0 \to (\pi^+\pi^-)K^0_{\rm S}$ to resolve those overlapping contributions at the amplitude level. A statistical error is still dominant in the precision of $\sin 2\phi_1^{\rm eff}$ of $b \to s$ mediated B decays, typically $0.1 \sim 0.2$ [25]. Thus in order to obtain sensitivity in $\sin 2\phi_1^{\rm eff}$ of $\mathcal{O}(10^{-2})$, we need an integrated luminosity of $\mathcal{O}(10{\rm ab}^{-1})$. This fact requires a Super B-factory as well as LHCb experiment results.

5. Summary

$\sin 2\phi_1$ is now determined to be 0.68 ± 0.02 in world average, it is a firm SM reference point. Another CP violation angle ϕ_2 is constrained to be $89.0^{+4.4} - 4.2^{\circ}$, then the unitarity triangle appears to be a right triangle. Δm_d is precisely measured by B factories, 1% precision has been achieved and it gives another firm reference. Tension around $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ urges an update of measurement, while comparing to $\sin 2\phi_1$, we expect mixing has room for NP. In order to hunt for a NP effect by CP violation measurements in $\mathcal{O}(10^{-2})$ sensitivity, LHCb results and super B-factory experiments are awaited.

Author's participation to Cracow Epiphany Conference 2012 was supported by MEXT KAKENHI, Grant-in-Aid for Scientific Research on Innovative Areas, entitled "Elucidation of New Hadrons with a Variety of Flavors".

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