PROCEEDINGS OF SCIENCE

# Measurements of CKM angles

**Kenkichi Miyabayashi***
*Department of Physics, Nara Women's University*
*E-mail:* miyabaya@hepl.phys.nara-wu.ac.jp

Measurements of Cabbibo-Kobayashi-Maskawa (CKM) *CP* violating angles as of 2009 are reviewed. The most precise *CP* violation parameter is the angle $\phi_1(\beta) = (21.1 \pm 0.9)^\circ$. The angle $\phi_2(\alpha)$ is obtained to be $(89.0 + 4.4/-4.2)^\circ$ and uncertainty of the angle $\phi_3(\gamma)$ is still $\approx 20^\circ$. The prospect to hunt New Physics beyond Kobayashi-Maskawa theory via *CP* violation measurement is also discussed.

*12th International Conference on B-Physics at Hadron Machines - BEAUTY 2009*
*September 07 - 11 2009*
*Heidelberg, Germany*

*Speaker.

 http://pos.sissa.it/

PoS(BEAUTY 2009)001

## 1. Introduction

During the first decade of the 21st century, two $B$-factory experiments, BaBar and Belle have carried out many $CP$ violation measurements to perform comprehensive test of Kobayashi-Maskawa (KM) theory [1]. As a result, 2008 Nobel Prize in Physics was given to Profs. Kobayashi and Maskawa, that is great pleasure for the experimentalists who contributed to the $B$-factory experiments. In this report, experimental constraints of three $CP$ violating angles, $\phi_1$, $\phi_2$ and $\phi_3$ (or $\beta$, $\alpha$ and $\gamma$) are reviewed. The possibility to hunt New Physics beyond the Standard Model (SM) is also discussed.

## 2. Time-dependent $CP$ violation and $B$-factory experiments

In $B$ meson system, the complex phase in the coupling $V_{td}$ which contributes to $B^0-\overline{B}^0$ mixing cause the $CP$ violation phenomena in many cases, when the neutral $B$ meson decays into a $CP$ eigenstate $f_{CP}$ [2]. Therefore we have to measure the $CP$ asymmetry as a function of the proper time difference between the two $B$ meson decays produced by $\Upsilon(4S)$. Thus time-dependent $CP$ asymmetry is defined as

$$A_{CP}(\Delta t)=\frac{\Gamma(\overline{B}^0(\Delta t)\to f_{CP})-\Gamma(B^0(\Delta t)\to f_{CP})}{\Gamma(\overline{B}^0(\Delta t)\to f_{CP})+\Gamma(B^0(\Delta t)\to f_{CP})}=\mathscr{S}_{CP}\sin(\Delta m\Delta t)+\mathscr{A}_{CP}\cos(\Delta m\Delta t), \quad (2.1)$$

where $\Delta m$ is the mass difference between two mass eigenstates of neutral $B$ meson. The two $CP$ violation parameters, $\mathscr{S}_{CP}$ and $\mathscr{A}_{CP}$ are mixing-induced and direct $CP$ violation parameters, respectively[1].

In order to realize measurements of the time-dependent $CP$ violation, two $B$-factory experiments, Belle at KEK and BaBar at SLAC were built to collect huge number of $B$ meson pairs produced by KEKB and PEP-II energy-asymmetric $e^+e^-$ accelerators, respectively. So far, Belle has accumulated 780 M $B\overline{B}$ pairs while BaBar has 470 M $B\overline{B}$ data sample at $\Upsilon(4S)$. These numbers show remarkable success of the $B$-factories.

## 3. Measurements of $\sin 2\phi_1$

The $b\to c\bar{c}s$ mediated $B$ meson decays such as $B^0\to J/\psi K^0$ is the most suitable process to measure the $CP$ violation angle $\phi_1$ via mixing-induced $CP$ violation because of the absence of complex phase in their decay amplitude, thus the direct relation, $\mathscr{S}_{CP}=-\xi_{CP}\sin 2\phi_1$ holds, where $\xi_{CP}$ is the $CP$ eigenvalue of the final state. Belle presented $\sin 2\phi_1=0.642\pm0.031\pm0.017$ [3] with 535 M $B\overline{B}$ sample and BaBar obtained $\sin 2\phi_1=0.687\pm0.028\pm0.012$ [4] from 465 M $B\overline{B}$ data, where the first error is statistical and second error is systematic. Both are consistent each other considering their errors and $\sin 2\phi_1$ has become a firm reference of the SM.

Recently, indirect determination of $\sin 2\phi_1$ using $V_{ub}$, $\Delta m_d$ and $\varepsilon_K$ is found to be slightly higher than the direct measurement. $\mathscr{B}(B^+\to\tau^+\nu_\tau)$ is also higher than that obtained from the CKM global fit. Because of such a tension, Belle plans to revisit soon $\sin 2\phi_1$ measurement with its full $\Upsilon(4S)$ integrated luminosity corresponding to 780 M $B\overline{B}$.

[1]In some cases, $\mathscr{C}_{CP}=-\mathscr{A}_{CP}$ is used to represent the direct $CP$ violation.

## 4. $\phi_2$ measurement

The interference between $b \to u$ mediated decays into proper $f_{CP}$ and $B^0 - \overline{B}^0$ mixing results in the $CP$ violation that can determine the angle $\phi_2$. There would be the $b \to d$ penguin contribution that cause a complexity to extract the angle $\phi_2$ from the observed $CP$ violation, however we can solve it by isospin analysis. As the $B$ decay final states to obtain $\phi_2$, there are three possibilities; $\pi\pi$, $\rho\rho$ and $\rho\pi$. From $\pi\pi$ [5] [6], $\rho\rho$ [7] [8] and $\rho\pi$ [7] [8] modes, $\phi_2$ is determined to be $(89.0^{+4.4}_{-4.2})^\circ$. In addition, BaBar collaboration performed measurements related to $a_1\pi$ decay mode [11] which can determine effective $\phi_2$.

## 5. $\phi_3$ measurement

The angle $\phi_3$ is determined by the $CP$ violation phenomena caused by the interference between $b \to c$ and $b \to u$ transitions. It takes place in the charged $B$ meson decays into a neutral $D$ meson and a charged Kaon, when the neutral $D$ meson decays into the final state where both $D^0$ and $\overline{D}^0$ can decay. Logically the most straight-forward approach is GLW method [12] to utilize the neutral $D$ meson decays into $CP$ eigenstates. The errors of $CP$ asymmetries of these decay modes are obtained to be $\sim 0.1$ [13] [14]. ADS method [15] suggests to use suppressed $D$ decay modes to obtain enhanced $CP$ asymmetry. Its sensitivity is still limited by statistics of the suppressed decay mode signal yield. [16] [17].

The measurement that can give the most stringent constraint on $\phi_3$ is the Dalitz analysis technique to use the neutral $D$ meson decay into $K^0_S\pi^+\pi^-$ [18]. BaBar includes $D \to K^0_S K^+K^-$ and tried $D \to \pi^+\pi^-\pi^0$ mode [19]. While Belle recently added not only $D^* \to D\pi^0$ but also $D^* \to D\gamma$ [20] because these also can be used when $D \to K^0_S\pi^+\pi^-$ occurs. Currently Dalitz model uncertainty is $9^\circ$ (Belle) or $5^\circ$ (BaBar), it can be reduced down to $2^\circ$ by an improved analysis technique using coherent $D\overline{D}$ production data at CLEO-c [21]. Among three $CP$ violation angles, constraint of $\phi_3$ has still the least precision of $\sim 20^\circ$.

## 6. *CP* violation in penguin modes

The constraints on KM unitarity triangle have been obtained by the $B$ decays mediated by the tree diagrams where the SM predominantly contributes. On the other hand, 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. Especially in SM, $b \to s$ penguin mediated $B$ decays such as $B^0 \to \phi K^0$, $B^0 \to \eta' K0$, $B^0 \to K^0_S K^0_S K^0_S$ and so on are theoretically clean 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 $B^0 \to J/\psi K^0$.

So far, there have been many two-body and quasi-two-body analyses. However, $\phi \to K^+K^-$, $f_0 \to K^+K^-$ and non-resonant contributions overlap (as do $\rho^0 \to \pi^+\pi^-$ and $f_0 \to \pi^+\pi^-$), therefore recently time-dependent Dalitz analyses have been performed in three-body decays such as $B^0 \to (K^+K^-)K^0_S$ and $B^0 \to (\pi^+\pi^-)K^0_S$ to resolve those overlapping contributions in amplitude level. The precision of $\sin 2\phi_1^{\rm eff}$ of $b \to s$ mediated $B$ decays is still statistically limited, typically $0.1 \sim 0.2$ [22]. 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 experiment.



PoS(BEAUTY 2009)001

## 7. Summary

In summary, $\sin 2\phi_1 = 0.67 \pm 0.02$ is gotten to be a firm SM reference. Constraint on $\phi_2$ is obtained to be $(89.0^{+4.4}_{4.2})^\circ$. If the unitarity triangle is a right triangle, it indicates a miracle of nature. The precision of $\phi_3$ is still $\sim 20^\circ$, it is just starting to be constrained. In order to hunt new physics effect via *CP* violation at $b \to s$ mediated *B* decays by achieving $\mathcal{O}(10^{-2})$ sensitivity, we need $\mathcal{O}(10\mathrm{ab}^{-1})$ thus a Super *B*-factory experiment is awaited.

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group and the NII for valuable computing and SINET3 network support. We acknowledge support from MEXT, JSPS and Nagoya's TLPRC (Japan); ARC and DIISR (Australia); NSFC (China); MSMT (Czechia); DST (India); MEST, NRF, NSDC of KISTI (Korea); MNiSW (Poland); MES and RFAAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE (USA). Author's participation to Beauty2009 conference was supported by MEXT KAKENHI, Grant-in-Aid for Scientific Research on Innovative Areas, entitled "Elucidation of New hadrons with a Variety of Flavors".

## References

[1] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[2] A. B. Carter and A. I. Sanda, Phys. Rev. D **23**, 1567 (1981); I. I. Bigi and A. I. Sanda, Nucl. Phys. B **193**, 85 (1981).

[3] K.-F. Chen *et al.* (Belle Collaboration), Phys. Rev. Lett. **98**, 031802 (2007).

[4] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. **D 79**, 072009 (2009).

[5] H. Ishino *et al.* (Belle Collaboration), Phys. Rev. Lett. **98**, 211801 (2007).

[6] B. Aubert *et al.* (BaBar Collaboration), arXiv:0807.4226.

[7] A. Somov *et al.* (Belle Collaboration), Phys. Rev. **D 76**, 011104 (2006).

[8] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. **D 76**, 052007 (2007).

[9] A. Kusaka *et al.* (Belle Collaboration), Phys. Rev. Lett. **98**, 221602 (2007).

[10] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. **D 76**, 012004 (2007).

[11] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. Lett. **98**, 181803 (2007).

[12] Michael Gronau and David London, Phys. Lett. **B 253**, 483 (1991); Michael Gronau and Daniel Wyler, Phys. Lett. **B 265**, 172 (1991).

[13] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. **D 77**, 111102 (2008).

[14] K. Abe *et al.* (Belle Collaboration), Phys. Rev. **D 73**, 051106 (2004).

[15] David Atwood, Isard Dunietz and Amarjit Soni, Phys. Rev. Lett. **78**, 3257 (1997); Phys. Rev. **D 63**, 036005 (2001).

[16] Y. Horii *et al.* (Belle Collaboration), Phys. Rev. **D 78**, 071901 (2008).

[17] "Hadronic $b \to c$ decays related to $\gamma$ at BaBar", talk given at EPS HEP 2009.

[18] Anjan Giri, Yuval Grossman, Abner Soffer and Jure Zupan, Phys. Rev. **D 68**, 054018 (2003); A. S. Bondar, Proceedings of Belle Dalitz Analysis meeting, 24-26 Sep. 2002.



PoS(BEAUTY 2009)001

[19] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. **D 78**, 034023 (2008).

[20] A. Poluektov *et al.* (Belle Collaboration), Phys. Rev. **D 73**, 112009 (2006); atXiv:0803.3375.

[21] R. A. Briere *et al.* (CLEO Collaboration), Phys. Rev. **D 80**, 032002 (2009).

[22] Heavy Flavor Averaging Group, Summary as of 2009 Summer under `http://www.slac.stanford.edu/xorg/hfag/`.