Measurements of the CKM angle $\phi_1/\beta$ at the $B$ Factories

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Abstract

In this proceeding, we report the recent measurements of the CKM angle $\phi_1/\beta$ using large data samples collected by the Belle and BaBar experiments. The experiments have collected more than 1 billion $B\bar{B}$ pairs of data sample at the $\Upsilon(4S)$ resonance using the facilities of the asymmetric-energy $e^+e^-$ colliders KEKB and PEP-II.

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1 Introduction

In the standard model (SM), CP violation in $B^0$ meson decays originates from an irreducible complex phase in the $3 \times 3$ Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [1]. The unitarity condition of the CKM matrix gives rise to a relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, which can be represented by a triangle in the complex plane, known as the Unitarity Triangle (UT). The main objective of the $B$-factories is to test the SM picture of the origin of CP violation by measuring the angles (denoted by $\phi_1$, $\phi_2$ and $\phi_3$) and sides of the UT using different $B$ decays. In this paper, we report the recent measurements concerning the angle $\phi_1 (\equiv \pi - \text{arg}(V_{tb}^*V_{td}/V_{cb}^*V_{cd}))$.

2 Experimental Apparatus

The measurements discussed in this paper have been obtained by the Belle and BaBar experiments, located at the KEKB and PEP-II asymmetry-energy $e^+e^-$ $B$ factories. The accelerators operate at the $\Upsilon(4S)$ resonance, which is produced with a Lorentz boost of 0.43 at KEKB (3.5 on 8.0 GeV) [2] and 0.56 at PEP-II (3.1 on 9.0 GeV) [3]. The KEKB accelerator of the $B$ factory in Japan achieved the current world record with a peak luminosity of $2.1 \times 10^{34}$ cm$^{-2}$s$^{-1}$. Both the experiments have already stopped data taking. BaBar stopped operation in April 2008 and collected more than 430 fb$^{-1}$ of data at $\Upsilon(4S)$ resonance. Belle stopped operation in June 2010 and collected more than 710 fb$^{-1}$ of data. After a decade of successful operation, the $B$ factories have a data sample of nearly $1200 \times 10^6 B\overline{B}$ pairs. The Belle and BaBar detectors are described in detail elsewhere [4, 5].

3 Measurements of $\phi_1/\beta$

Measurements of time-dependent CP asymmetries in $B^0$ meson decays that proceed via the dominant CKM favored $b \to c\bar{c}d$ tree amplitude, such as $B^0 \to J/\psi K^0$, have provided a precise measurement of the angle $\phi_1$, thus providing a crucial test of the mechanism of CP violation in the SM. For such decays the interference between the tree amplitude and the amplitude from $B^0 - \overline{B}$ mixing is dominated by the single phase $\phi_1$. Other decay modes, which allow the measurements of $\phi_1$ are $b \to c\bar{c}d$ transitions like $B^0 \to J/\psi\pi^0$, $B^0 \to D^{(*)}+D^{(*)}$, $B^0 \to D^+D^-$. These modes are dominated by tree diagram, but loop may contribute. We can also measure $\phi_1$ from pure penguin decays like $\phi K^0_S$, $f_0 K^0_S$, $K^+K^-K^0$, $K^0\pi^0_\Sigma$, $\eta' K^0_S$ and $\omega K^0_S$. In these decays sensitivity to new physics (NP) increases.

The $\sin 2\phi_1$ measurement from the $B$ factories is one of the main constraints in the global fit by CKM fitter Collaboration. Recently CKM fitter reported a tension

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*BaBar uses an alternative notation $\beta$, $\alpha$ and $\gamma$ corresponding to $\phi_1$, $\phi_2$ and $\phi_3$. 

\( \sim 2.8\sigma \) between the measurement of \( B(B \to \tau\nu) \) and the value predicted from other observables excluding this measurement. So further measurements of \( \sin 2\phi_1 \) will help to clarify this tension.

### 4 Analysis Technique

In the \( B \) meson system, the \( CP \) violating asymmetry lies in the time-dependent decay rates of the \( B^0 \) and \( \bar{B}^0 \) decays to a common \( CP \)-eigenstate \( (f_{CP}) \). The asymmetry can be written as:

\[
A_{CP}(t) = \frac{\Gamma[\bar{B}^0(t) \to f_{CP}] - \Gamma[B^0(t) \to f_{CP}]}{\Gamma[B^0(t) \to f_{CP}] + \Gamma[B^0(t) \to f_{CP}]} = S \sin(\Delta m_d t) + A \cos(\Delta m_d t)
\]

where

\[
S = \frac{2 \text{Im} \lambda}{|\lambda|^2 + 1} \quad A = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}.
\]

Here \( \Gamma(B^0(\bar{B}^0) \to f_{CP}) \) is the decay rate of a \( B^0(\bar{B}^0) \) meson decays to \( f_{CP} \) at a proper time \( t \) after the production, \( \Delta m_d \) is the mass difference between the two neutral \( B \) mass eigenstates, \( \lambda \) is a complex parameter depending on the \( B^0 - \bar{B}^0 \) mixing as well as the decay amplitudes of the \( B \) meson decays to the \( CP \) eigenstate. The parameter \( S \) is the measure of mixing-induced \( CP \) violation, whereas \( A \) is the measure of direct \( CP \) violation.

In the \( B \) factories, in order to measure the time-dependent \( CP \) violation parameters, we fully reconstruct one neutral \( B \) meson into a \( CP \) eigenstate. From the remaining particles in the event, the vertex of the other \( B \) meson is reconstructed and its flavor is identified. In the decay chain \( \Upsilon(4S) \to B^0\bar{B}^0 \to f_{CP}f_{\text{tag}} \), where one of the \( B \) mesons decays at time \( t_{CP} \) to a \( CP \) eigenstate \( f_{CP} \), which is our signal mode, and the other decays at time \( t_{\text{tag}} \) to a final state \( f_{\text{tag}} \) that distinguishes between \( B^0 \) and \( \bar{B}^0 \), the decay rate has a time dependence given by

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

Here \( \tau_{B^0} \) is the neutral \( B \) lifetime, \( \Delta t = t_{CP} - t_{\text{tag}} \), and the \( b \)-flavor charge \( q \) equals \( +1 \) (\( -1 \)) when the tagging \( B \) meson is identified as \( B^0 \) (\( \bar{B}^0 \)). Since the \( B^0 \) and \( \bar{B}^0 \) are approximately at rest in the \( \Upsilon(4S) \) center-of-mass system, \( \Delta t \) can be determined from the displacement in \( z \) between the \( f_{CP} \) and \( f_{\text{tag}} \) decay vertices: \( \Delta t \approx \Delta z/\beta c \), where \( c \) is the speed of light. The vertex position of the \( f_{CP} \) decay is reconstructed using charged tracks (for example, lepton tracks from \( J/\psi \) in \( B^0 \to J/\psi K^0_S \) decays) and

\footnote{Note that BaBar uses the convention \( C = -A \).}
that of the $f_{\text{tag}}$ decay from well-reconstructed tracks that are not assigned to $f_{\text{CP}}$ \cite{ref7}. The $\Delta z$ is approximately 200 $\mu$m in Belle and 250 $\mu$m in BaBar. We also consider the effect of detector resolution and mis-identification of the flavor \cite{ref8}. Finally, the $CP$ violation parameters are obtained from an unbinned maximum likelihood fit to the $\Delta t$ distribution.

5 $b \rightarrow c\bar{c}s$ Decay Modes

The $b \rightarrow c\bar{c}s$ decays are known as the golden modes for $CP$ violation measurements. They have clean experimental signatures: many accessible modes with relatively large branching fractions ${\mathcal O}(10^{-4})$, low experimental background levels and high reconstruction efficiencies. These modes are dominated by a color-suppressed $b \rightarrow c\bar{c}s$ tree diagram and the dominant penguin diagram has the same weak phase. The $CP$ violation comes from the $V_{td}$ element in the mixing box diagram, which contains the phase. For $f_{\text{CP}}$ final states resulting from a $b \rightarrow c\bar{c}s$ transition, the SM predicts $S = -\xi_{\text{CP}} \sin 2\phi_1$ and $A = 0$, where $\xi_{\text{CP}}$ is known as the $CP$ eigenvalue and have values $+1(-1)$ for $CP$-even ($CP$-odd) final states. The asymmetry is given as

$$A_{\text{CP}} = \xi_{\text{CP}} \sin(2\phi_1) \sin(\Delta m \Delta t).$$

(3)

We can verify this experimentally by measuring the number of $B^0(\bar{B}^0)$ decays to $CP$ eigenstate. Because of the high experimental precision and low theoretical uncertainty these modes provide a reference point in the SM. A non-zero value of $A$ or any measurement of $\sin 2\phi_1$ that has a significant deviation indicates an evidence for NP.

Belle recently reported new measurements with its full data sample ($772 \times 10^6 B\bar{B}$ pairs) using the modes $B^0 \rightarrow J/\psi K^0$, $B^0 \rightarrow \psi' K^0_S$ and $B^0 \rightarrow \chi_{c1} K^0_S$. The $J/\psi$ candidates are reconstructed from their decays to $e^+e^-$ and $\mu^+\mu^-$, with the $K^0_S$ reconstructed from $\pi^+\pi^-$. The $\psi'$ candidates are reconstructed from $e^+e^-$, $\mu^+\mu^-$ as well as $J/\psi \pi^+\pi^-$ decays. The $\chi_{c1}$ is reconstructed from its decays to $J/\psi \gamma$. Belle reported nearly 15600 $CP$-odd signal events with a purity of 96% and nearly 10000 $CP$-even signal events with a purity of 63%. Belle observed $CP$ violation in all charmonium modes and the results are summarized in Table 1.

Figure 1 shows the background-subtracted $\Delta t$ distributions for good-tagged events only (all charmonium modes are combined). We define the raw asymmetry in each $\Delta t$ bin as $(N_+ - N_-)/(N_+ + N_-)$, where $N_+$ ($N_-$) is the number of observed candidates with $q = +1$ ($-1$). The systematic uncertainties are significantly improved compared to the previous Belle measurements \cite{ref9,ref10} due to a better model for the resolution function (decay mode independent). Combining all charmonium modes, Belle reported the world’s most precise measurements:

$$\sin 2\phi_1 = 0.668 \pm 0.023(\text{stat}) \pm 0.013(\text{syst}),$$
$$A = 0.007 \pm 0.016(\text{stat}) \pm 0.013(\text{syst}).$$

(4)
BaBar reconstructed the decay modes $B^0 \to J/\psi K^0$, $B^0 \to \psi' K^0_S$, $B^0 \to \chi_{c1} K^0_S$, $B^0 \to \eta_c K^0$ and $B^0 \to J/\psi K^{*0}$. Using a data sample of $465 \times 10^6 B\bar{B}$ pairs, BaBar reported nearly 8400 $CP$-odd signal events with a purity of 93% and nearly 5800 $CP$-even signal events with a purity of 56%. Combing all charmonium modes BaBar measured $\sin 2\phi_1 = 0.687 \pm 0.028 \pm 0.012$ and $C = 0.024 \pm 0.020 \pm 0.016$ \cite{11}.

Combining the measurements from Belle and BaBar, the new world average calculated by the Heavy Flavor Averaging Group (HFAG) is \cite{12}

$$\sin 2\phi_1 (b \to c\bar{c}s) = 0.678 \pm 0.020,$$
$$A(b \to c\bar{c}s) = -0.013 \pm 0.017. \tag{5}$$

Figure 2 summarizes the results of $\sin 2\phi_1$ for $b \to c\bar{c}s$ decays from Belle and BaBar. The measurements of the two experiments agree very well within the statistical uncertainties. The experimental uncertainty on $\sin 2\phi_1$ is reduced to 3% and thus serves as a firm reference point for the SM. The value of $A$ is consistent with zero. The new results will definitely provide a better constraint on the allowed region in the CKM fitter. The measurement of $\sin 2\phi_1$ leaves a two-fold ambiguity in the value of $\phi_1$. Both Belle and BaBar measured the sign of $\cos 2\beta$ to be positive at 98.3% and 86%
confidence levels, respectively. This favors the smaller value of $\phi_1$ solution. The new measurements give the value \[ \phi_1(\beta) = (21.4 \pm 0.8)^\circ, \] which is the most precise measurement with $< 1^\circ$ error.

Figure 2: The left plot shows the comparison between the Belle and BaBar measurements of $\sin 2\phi_1$ with $b \to c\bar{c}s$ decays and constraints on $\phi_1$ on the $(\rho, \eta)$ plane is shown in the right plot. The hatched area is excluded corresponding to the negative $\cos(2\phi_1)$ solution.

6 $b \to c\bar{c}d$ Decay Modes

The $B^0 \to J/\psi\pi^0$ decay takes place through a $b \to c\bar{c}d$ transition. The dominant tree diagram is Cabibbo-suppressed. However, there is a penguin diagram of the same order that has a different weak phase. So, small deviation in $\sin 2\phi_1$ from golden modes is expected in the SM. The BaBar result provides an evidence of $CP$ violation at 4$\sigma$ level [13], while the value for Belle result is 2.4$\sigma$ [14]. The decay $B^0 \to D^+D^-$ also goes through the $b \to c\bar{d}d$ transition. This mode requires an angular analysis to separate $CP$-even and $CP$-odd events. Belle reports a statistical significance of 3.2$\sigma$ for direct $CP$ violation in the $B^0 \to D^+D^-$ mode [15].

7 $b \to sq\bar{q}$ Decay Modes

An alternative way to measure the angle $\phi_1$ is to measure the time-dependent $CP$ asymmetries in charmless hadronic final states. These are $b \to s$ penguin dominated decays. Any non-SM particles, like Higgs or SUSY particles can enter the loop. So, these are sensitive to NP. The value of $S$ is expected to be $\sin 2\phi_1$ for a pure penguin amplitude, but can be different if there is an extra $CP$ phase from NP. As a
consequence, an effective $\sin 2\phi_1$ value is measured. Significant deviation from $\sin 2\phi_1$ in golden modes would indicate NP. The deviations have been estimated in several theoretical models and are expected to be positive. These estimates are mode and model dependent.

Belle and BaBar have recently performed time-dependent Dalitz analyses in the $B^0 \to K^+ K^- K^0_S$ \cite{16} final state using $657 \times 10^6 B\bar{B}$ \cite{17} and $465 \times 10^6 B\bar{B}$ pairs, respectively. This gives directly the value of $\phi_1$ (we do not need to worry about the two-fold ambiguity here). The results are consistent with the SM expectation from $b \to c\bar{c}s$ decays. The $\sin 2\phi_1^{\text{eff}}$ in various $b \to s$ penguin modes is summarized in Fig. 3. The results are consistent between Belle and BaBar and also consistent with the SM expectation within the statistical uncertainties. It is fair to say that we need more data to see a sensitivity comparable with theoretical uncertainties.

![Diagram of sin(2β eff) = sin(2φ_1 eff) for various models and experiments.](image)

Figure 3: The summary of effective $\sin 2\phi_1$ measurements in $b \to s$ penguin decay modes.

8 Conclusion

In this review, we have presented the recent measurements of the CKM angle $\phi_1/\beta$ by Belle and BaBar. Thanks to the excellent performance of the two $B$ factories, which collected large data sample at the $\Upsilon(4S)$ resonance; the angle $\phi_1$ has been measured with $< 1^\circ$ precision. The $CP$ violating parameters in $b \to c\bar{c}s$ decays are the most precise measurements and provides a reference point for new physics searches. The time-dependent $CP$ asymmetry in penguin dominated decays is consistent with standard model expectations within the uncertainties of the measurement.
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References

[1] N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).

[2] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A 499, 1 (2003), and other papers included in this volume.

[3] PEP-II Conceptual Design Report, SLAC-PUB-0418 (1993).

[4] A. Abashian et al., Nucl. Instrum. Methods Phys. Res., Sect. A 479, 117 (2002).

[5] B. Aubert et al., Nucl. Instrum. Methods Phys. Res., Sect. A 479, 1 (2002).

[6] 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).

[7] H. Tajima et al., Nucl. Instrum. Methods Phys. Res., Sect. A 533, 370 (2004).

[8] H. Kakuno et al., Nucl. Instrum. Methods Phys. Res., Sect. A 533, 516 (2004).

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

[10] H. Sahoo et al. (Belle Collaboration), Phys. Rev. D 77, 091103 (2008).

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

[12] Heavy Flavor Averaging Group, winter 2011 update. Check their webpage for updated results: http://www.slac.stanford.edu/xorg/hfag/.

[13] B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. 101, 021801 (2008).

[14] S. E. Lee et al. (Belle Collaboration), Phys. Rev. D 77, 071101 (2008).

[15] S. Fratina et al. (Belle Collaboration), Phys. Rev. Lett. 98, 221802 (2007).

[16] Y. Nakahama et al. (Belle Collaboration), Phys. Rev. D 82, 073011 (2010).

[17] B. Aubert et al. (BaBar Collaboration), arXiv:0808.0700.