Measurements of the CKM angle $\phi_1/\beta$ from Belle and BaBar

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We report recent measurements of the CKM angle $\phi_1/\beta$ using large data samples collected by the Belle and BaBar experiments at the $e^+e^-$ asymmetric-energy colliders.

I. INTRODUCTION

In the Standard Model (SM), the irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix gives rise to CP violation [1]. Measurements of the time-dependent CP-asymmetry amplitudes in final states accessible by both $B^0$ and $\bar{B}^0$ decays probe $\sin 2\phi_1$, where $\phi_1 = \beta = \arg[V_{ub}V_{cb}^*]/{|V_{ub}V_{cb}|}$ is one of the unitary triangle angles. The phase difference $2\phi_1$ between decays with and without $B^0 - \bar{B}^0$ mixing arises from box diagrams which mainly occur through a virtual top quark. An exclusive measurement of $\sin 2\phi_1$ is possible when no-non-trivial relative weak phases appears in the decay mechanism.

In this article we report measurements obtained by the Belle and BaBar experiments at the asymmetric-energy $e^+e^-$ B factories KEKB [2] and PEP-II [3]. Both accelerators operate at the $\Upsilon(4S)$ resonance, which is produced with a Lorentz boost of 0.43 at KEKB and 0.56 at PEP-II. At the time of writing Belle and BaBar collected more than 790 fb$^{-1}$ and 550 fb$^{-1}$ respectively, which corresponds to a total of approximately 1.4 billion $B\overline{B}$ events.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF) and an electromagnetic calorimeter (ECL) comprised of CsI (Ti) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside the coil is instrumented to detect $K_L^0$ mesons and to identify muons (KLM). A detailed description of the Belle detector can be found elsewhere [4].

The momenta of charged particles are measured by the BaBar detector with a tracking system consisting of a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) surrounded by a 1.5 T solenoidal magnet. An electromagnetic calorimeter (EMC) comprising 6580 CsI(Tl) crystals is used to measure photon energies and positions. Charged hadrons are identified with a detector of internally reflected Cherenkov light (DIRC) and ionization measurements in the tracking detectors. The BaBar detector is described in detail elsewhere [5].

II. ANALYSIS TECHNIQUE

To measure time-dependent CP asymmetries we typically fully reconstruct a neutral $B$ meson decaying into a CP eigenstate. From the remaining particles in the event, the vertex of the other $B$ meson, $B_{\text{tag}}$, is reconstructed and its flavor is identified (tagging). When assuming CP conservation in $B^0\overline{B}^0$ mixing and $\Delta\Gamma/\Gamma = 0$, the time-dependent decay rate of the neutral $B$ meson to the CP eigenstate is given by:

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

where $q = +1(-1)$ when the other $B$ meson in the event decay is a $B^0$ ($\overline{B}^0$), $\Delta t = t_{\text{CP}} - t_{\text{tag}}$ is the proper time difference between the two decays. $\tau_{B^0}$ is the neutral $B$ lifetime, $\Delta m_d$ the mass difference between the two $B^0$ mass eigenstates and $S$ and $A$ are the CP-violating parameters

$$S = \frac{2Im(\lambda)}{|\lambda|^2 + 1}, \quad A = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1},$$

where $\lambda$ is a complex parameter depending on the $B^0 - \overline{B}^0$ mixing as well as on the decay amplitudes for both $B^0$ and $\overline{B}^0$ to the CP eigenstate. Note that in the BaBar convention $A = -C$.

When only one diagram contributes to the decay process and no other weak or strong phases appear in the process, the SM predicts $A = 0$ and $S = -\eta\sin 2\phi_1$ where $\eta$ is the CP eigenvalue of the final state. A non-zero value for $A$ would indicate a direct-CP violation. Any large measured deviation with respect to the prediction can be a sign of New Physics. However when other diagrams with different weak phases appear in the interaction, the experimental result of $S$ will not necessarily be equal to $\sin 2\phi_1$. The decays presented in this paper are expected to only have a small deviation from $\sin 2\phi_1$ in the SM.

The measurements of $\sin 2\phi_1$ reported in this paper can be grouped according to their quark transitions:

- $b \to c\bar{u}d$ transitions : $B^0 \to D^{(*)0}h^0$;
- $b \to c\bar{e}s$ transitions : $B^0 \to J/\psi K^0_S$, $B^0 \to J/\psi K^0_L$, $B^0 \to J/\psi K^{*0}$, $B^0 \to \psi(2S)K^0_S$, $B^0 \to \eta_c K^0_S$ and $B^0 \to \chi_{c1} K^0_S$. 

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- $b \to c\bar{s}d$ transitions: $B^0 \to J/\psi \pi^0$ and $B^0 \to D^{*+}D^{-}$.

The decays are grouped from top to bottom with decreasing tree amplitude or increasing sensitivity to New Physics. Finally we will also give an overview of recent measurements of $\cos 2\phi_1$ provided by $B^0 \to D^{(*)}_L h^0$ and $B^0 \to D^+D^-K_S^0$ decays.

III. $B^0 \to D^{(*)}_L h^0$ ($h^0 = \pi^0, \eta, \omega$)

The decay $B^0 \to D^{(*)}_L h^0(h^0 = \pi^0, \eta, \omega)$ is governed by a color-suppressed $b \to c\bar{s}d$ tree diagram. When the neutral $D$ meson decays to a $CP$ eigenstate Eq. 1 holds. The next-to-leading order diagram is a doubly Cabibbo and color-suppressed tree diagram with the same quark transitions as the main diagram. Therefore the SM corrections on $\sin 2\phi_1$ are expected to be only at the percent level [6]. However, $R$-parity-violating super-symmetric processes could enter at the tree level and lead to a deviation from the SM prediction.

BaBar reported a measurement of $\sin 2\phi_1$ [7] by reconstructing the following decay modes $D^{*0}_L \to D^0\pi^0$ and $D^0 \to K^+K^-, D^0 \to K_S^0\pi^0$ and $D^0 \to K_S^0\omega$. The analysis is performed on 383 $\times 10^6 B\bar{B}$ pairs of which 340 $\pm 32$ signal events are reconstructed. The measured $CP$-violating parameters,

$$\sin 2\phi_1 = 0.56 \pm 0.23 \text{(stat)} \pm 0.05 \text{(syst)},$$

$$A = 0.23 \pm 0.16 \text{(stat)} \pm 0.04 \text{(syst)},$$

are consistent with the SM expectations.

IV. $B^0 \to c\bar{s}K^0$ TRANSITIONS

The $b \to c\bar{s}K^0$ transitions are referred to as the golden modes due to their relatively large branching fractions $O(10^{-4} - 10^{-5})$, low experimental background levels and high reconstruction efficiencies. Typically a signal purity of more than 95% is obtained for $B^0 \to J/\psi(t^+t^-)K_S^0(\pi^+\pi^-)$ decays. Furthermore the theoretical uncertainties are small [8]. These modes are dominated by a color-suppressed $b \to c\bar{s}d$ tree diagram and the dominant penguin diagram has the same weak phase. The highest order term with a different weak phase is a Cabibbo-suppressed penguin contribution. Therefore the prediction $\mathcal{S} = -\sin 2\phi_1$ and $A = 0$ is valid to a good accuracy. Recent theoretical calculations suggest that the correction on $\mathcal{S}$ is of the order of $10^{-3} - 10^{-4}$ [9]. Because of the high experimental precision and the low theoretical uncertainty these modes serve as a benchmark in the SM, which means that any other measurement of $\sin 2\phi_1$ that has a significant deviation, beyond the usual small SM corrections, indicates evidence for New Physics.

Both BaBar [10] and Belle [11] studied $CP$ violation in these decays. Belle reconstructed around 7500 signal events in the $B^0 \to J/\psi K_S^0$ channel and 6500 signal events in the $B^0 \to J/\psi K_S^0$ channel using $535 \times 10^6 B\bar{B}$ pairs. BaBar reconstructed additional modes such as $J/\psi K^*\pi^0$, $\psi(2S)K_S^0$, $\eta K^0_S$ and $\chi_c K^0_S$. Using a data sample of $383 \times 10^6 B\bar{B}$ pairs BaBar reconstructed approximately 6900 $CP$-odd signal events and 3700 $CP$-even signal events.

The results of the time-dependent $CP$ analysis are shown in Table I including the BaBar result using only the $J/\psi K^0$ modes, to provide a direct comparison with Belle. The measurements of the two experiments agree well within the statistical uncertainties.

Belle recently reported also a measurement of the $CP$-violation parameters in the $B^0 \to \psi(2S)K_S^0$ channel [12]. Using a sample of $657 \times 10^6 B\bar{B}$ pairs $1284 \pm 38$ signal events are reconstructed. The measured $CP$-violating parameters are included in Table I.

Table I: $CP$-violating parameters measured by Belle and BaBar with the golden modes, the errors are statistical only.

|        | $\sin 2\phi_1$       | $\mathcal{A}$       |
|--------|-----------------------|----------------------|
| BaBar  | $J/\psi K^0$          | $0.697 \pm 0.035$    | $-0.035 \pm 0.025$ |
| BaBar  | all $c\bar{s}s$       | $0.714 \pm 0.032$    | $-0.049 \pm 0.022$ |
| Belle  | $J/\psi K^0$          | $0.642 \pm 0.031$    | $0.018 \pm 0.021$  |
| Belle  | $\psi(2S)K_S^0$       | $0.72 \pm 0.09$      | $0.04 \pm 0.07$    |

\[ \sin(2\beta) = \sin(2\phi_1) \]

Figure 1: Comparison between the Belle and BaBar measurements of $\sin 2\phi_1$ with $b \to c\bar{s}d$ decays. The bottom line shows the world average.

Figure 1 summarizes the results of $\sin 2\phi_1$ for $b \to c\bar{s}d$ decays from Belle and BaBar. A world average is calculated by the Heavy Flavor Averaging Group (HFAG) [13],

$$\sin 2\phi_1 = 0.680 \pm 0.025,$$

which reduces the total uncertainty on $\sin 2\phi_1$ to 3.7%.
BaBar also analyzed the $CP$-odd fraction of $b \to c\bar{s}s$ decays containing two vector particles. The $CP$ eigenstate of these decays can be $+1$ or $-1$ depending on the total angular momentum. To disentangle the $CP$-odd fraction a three-dimensional angular analysis is performed on $232 \times 10^6 B\bar{B}$ events [14]. The extracted $CP$-odd fractions are shown in Table II. The result of $B \to J/\psi K^*$ is within two standard deviations consistent with $CP$-odd fraction measured at the Belle using $277 \times 10^6 B\bar{B}$ pairs. The $CP$-odd fraction for the neutral $B$ decay reads $0.195 \pm 0.012$ (stat) $\pm 0.008$ (syst) and for the charged $B$ decays $0.180 \pm 0.014$ (stat) $\pm 0.010$ (syst) [15].

TABLE II: $CP$-odd fractions of three vector-vector $b \to c\bar{c}s$ decay modes, measured by BaBar. The first error mentioned is statistical, the second is systematic.

| Decay          | $CP$-odd fraction       |
|----------------|-------------------------|
| $B \to J/\psi K^*$ | $0.233 \pm 0.010 \pm 0.005$ |
| $B \to \psi(2S) K^*$ | $0.30 \pm 0.06 \pm 0.02$ |
| $B \to \chi_c K^*$   | $0.03 \pm 0.04 \pm 0.02$ |

V. $B^0 \to J/\psi \pi^0$

The $B^0 \to J/\psi \pi^0$ decay takes place through a $b \to c\bar{s}d$ transition. The dominant tree diagram is Cabibbo suppressed but contrary to the golden modes, the dominant penguin diagram is of the same order as the tree diagram and has a different weak phase. Therefore, even within the SM, the deviation in $\sin 2\phi_1$ could be substantial.

Both Belle [16] and BaBar [17] have updated their $CP$-violating measurements in this decay. Belle performed an analysis on $535 \times 10^6 B\bar{B}$ pairs and obtained 290 events in the signal region, while BaBar used $466 \times 10^6 B\bar{B}$ pairs and obtained 184 signal events. The plots in Figure 2 show the proper time distribution and the raw asymmetry, defined as $(N_+ - N_-)/(N_+ + N_-)$, where $N_+ (N_-)$ is the number of observed neutral $B$ candidates with $q = +1 (-1)$. Within the experimental uncertainties, the results are compatible with the SM prediction. The measured $CP$ parameters are summarized in Table III. The BaBar result shows an evidence of $CP$ violation, obtained with a $4\sigma$ significance.

VI. $B^0 \to D^{*+}D^{*-}$

The measurements of the double charm decay $B^0 \to D^{*+}D^{*-}$ are updated by both experiments [18] and the high statistics signals are shown in the left plots of Figure 3. The Belle analysis is performed on $657 \times 10^6 B\bar{B}$ pairs and has extracted $545 \pm 29$ signal events while the BaBar analysis found $638 \pm 38$ signal events in $383 \times 10^6 B\bar{B}$ pairs. The tree amplitude is CKM-suppressed and the contribution of penguin diagrams in this decay is estimated to be at the percent level [19]. The $CP$ eigenvalue of the

FIG. 3: The measured $M_{bc}$ and $\cos \beta_{tr}$ distributions in the signal region for BaBar (top) and Belle (bottom). The solid lines represent the projections of the fit results, the dotted lines are the background components.
$D^{*+}D^{*-}$ pair is +1 when it decays via a $S$ and $D$ wave or −1 for a $P$ wave. A helicity study is performed to extract the $CP$-odd fraction, $R_{\text{odd}}$, which dilutes the measurement of $S$. The angular analysis is performed in the so-called transversity basis and the Belle and BaBar results are shown in the right plots of Figure 3. The extracted $CP$-odd fraction is $R_{\text{odd}} = 0.143 \pm 0.034 \text{(stat)} \pm 0.008 \text{(syst)}$ for BaBar and $R_{\text{odd}} = 0.116 \pm 0.042 \text{(stat)} \pm 0.004 \text{(syst)}$ for Belle, consistent with previous measurements.

Figure 4 shows the $\Delta t$ distribution and the raw asymmetry for events with a good-quality tag. The fitted $CP$ parameters are consistent with each other and the SM predictions. BaBar found $A = 0.02 \pm 0.11 \text{(stat)} \pm 0.02 \text{(syst)}$ and $\sin 2\phi_1 = 0.66 \pm 0.19 \text{(stat)} \pm 0.04 \text{(syst)}$ while the Belle result is: $A = 0.16 \pm 0.13 \text{(stat)} \pm 0.02 \text{(syst)}$ and $\sin 2\phi_1 = 0.93 \pm 0.24 \text{(stat)} \pm 0.15 \text{(syst)}$.

FIG. 4: Top: the $\Delta t$ distributions of $B^0 \rightarrow D^{*+}D^{*-}$ events in the signal region for $B^0$ ($\bar{B}^0$) tagged candidates. Bottom: the raw asymmetry as a function of $\Delta t$. The lines represent the fit result. The plots on the left show the BaBar result while the plots on the right are the Belle results.

VII. MEASUREMENT OF $\cos 2\phi_1$

The measurements of $\sin 2\phi_1$ leaves a 4-fold ambiguity in the value of $\phi_1$ which can be partially resolved by measuring $\cos 2\phi_1$. We will show two analyses in this section that measured the sign $\cos 2\phi_1$.

In the first analysis both $B^0$ and $\bar{B}^0$ mesons decay to the final state $D^{*+}D^{*-}K_S^0$. A potential interference effect of the decay proceeding through an intermediate resonance can be measured by dividing the $B$-decay Dalitz plot into regions with $s^+ > (<) s^-$, where $s^\pm \equiv m_4^2(D^{*\pm}K_S^0)$ [20]. Belle performed a measurement on $449 \times 10^6 B\bar{B}$ pairs which corresponds to $131.2_{-14.1}^{+14.8}$ extracted signal events and measured $2J_{23}/J_0 \cos \phi_1 = -0.23^{+0.43}_{-0.41} \text{(stat)} \pm 0.13 \text{(syst)}$ [21], where $J_{23}$ and $J_0$ are the integrals over the half-Dalitz space, $s^+ > s^+$ and the imaginary component, $1m(\bar{a}a^*)$ respectively, where $a(\bar{a})$ are the decay amplitudes of $B^0(\bar{B}^0) \rightarrow D^{*+}D^{*-}K_S^0$. Although the sign of the factor $2J_{23}/J_0$ can be deduced from theory, a model-independent sign of $\cos 2\phi_1$ could not be obtained given the errors. A similar analysis is also performed by BaBar on $230 \times 10^6 B\bar{B}$ pairs and concluded $\cos 2\phi_1 > 0$ with 94% confidence level [22].

A second technique to determine the sign of $\cos 2\phi_1$ utilizes the decay $B^0 \rightarrow (\pi^+\pi^-K_S^0)h^0$, where $h^0 = \eta, \eta', \pi^0$ or $\omega$. This decay can occur with and without $B^0\bar{B}$ mixing and interference effects are visible across the $D^0$ Dalitz plot. Belle performed this analysis on $386 \times 10^6 B\bar{B}$ events [23] and the fit of the full Dalitz plot gives $\sin 2\phi_1 = 0.78 \pm 0.44 \text{(stat)} \pm 0.22 \text{(syst + model)}$ and $\cos 2\phi_1 = 1.87^{+0.40}_{-0.53} \text{(stat)}^{+0.22}_{-0.32} \text{(syst + model)}$, which gives a preferred positive sign of $\cos 2\phi_1$ at 96.8% confidence level. The result from BaBar [24] on $383 \times 10^6 B\bar{B}$ events reads $\sin 2\phi_1 = 0.29 \pm 0.34 \text{(stat)} \pm 0.03 \text{(syst)} \pm 0.05 \text{(model)}$ and $\cos 2\phi_1 = 0.42 \pm 0.49 \text{(stat)} \pm 0.09 \text{(syst)} \pm 0.13 \text{(model)}$ leading to a preferred positive sign for $\cos 2\phi_1$ at 86% confidence level.

VIII. CONCLUSIONS

Various decay modes have been used by Belle and BaBar to measure $\sin 2\phi_1$ using high statistics $B\bar{B}$ samples. The two experiments have also performed measurements of the sign of $\cos 2\phi_1$, which is preferred to be positive. The measurements of the $CP$-violating parameters in the $b \rightarrow c\bar{s}c$ channels are the most precise results available and given the positive sign of $\cos 2\phi_1$, the world average gives $\phi_1 = 21.5^\circ \pm 1.0^\circ$ and $\phi_1 = 201.5^\circ \pm 1.0^\circ$, where the first is in accord with the Standard Model. Finally, the new results of $B$ decays to $D_{CP}^{*+}h^0 (h^0 = \pi^0, \eta, \omega)$, $J/\psi\pi^0$ and $D^{*+}D^{*-}$ are shown. The $CP$ violating parameters are consistent with the Standard Model expectations within the uncertainties of the measurement.

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