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CP VIOLATION AT B-FACTORIES

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Abstract

Recent results on CP violation from the *BaBar* and *BELLE* experiments at asymmetric e^+e^- B-Factories are summarized. The results of two groups on the time dependent CP asymmetry in $b \to sc\bar{c}$ are in good agreement. The similar measurements for penguin dominated B meson decays may indicate a contribution from physics beyond Standard Model. The first meaningful measurements of ϕ_2 and ϕ_3 angles of the CKM unitarity triangle are presented.

Introduction

Nature of CP violation is important for understanding of the origin of the matter in the Universe. Numerous experimental studies aim to constrain the parameters of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1] as a unique source of CP violation in the Standard Model (SM). The key to test the SM is to do many overconstrained measurements, *i.e.*, compare them by putting constraints on three angles of the unitary triangle (UT). These angles can be extracted from the measured time-dependent CP asymmetry in different neutral B decay channels. Independent measurements of ϕ_1, ϕ_2 and ϕ_3 allow us to verify the unitarity relation, and perform a search for New Physics (NP) comparing magnitudes of the same angle measured with modes dominated by either tree or penguin amplitudes [1].

1 B-Factories

Last few years most of the CP violation measurements in B meson decays are coming from e^+e^- asymmetric colliders (B-Factories). Due to multibunch operation, efficient suppression of the electron cloud beam instability and day-by-day tremendous efforts in understanding of the machine, two B-Factories, PEP-II at SLAC (USA) and KEKB at KEK (Japan) achieved luminosities of about $10^{34} cm^{-2} s^{-1}$. Detectors, *BaBar* [2] and *Belle* [3], operating at PEP-II and KEKB by summer 2004 recorded integrated luminosity $244 fb^{-1}$ and $287 fb^{-1}$, respectively.

2 Measurement of the time dependent CP asymmetry

At the B-Factories $B\bar{B}$ pairs are produced in $\Upsilon(4S)$ decays almost at rest in the center-of-mass frame. Due to the different energy of colliding e^+e^- beams the B mesons are boosted with a parameter $\beta\gamma = 0.56(0.43)$ for *BaBar* (*Belle*) enabling a measurement of the time-dependent CP asymmetry in B^0 decays [1].

This CP asymmetry is obtained by measuring the proper time difference Δt between a fully reconstructed B^0 meson (B_{cp}) decaying into a given final state f, and the partially reconstructed recoil B^0 meson (B_{tag}). The asymmetry in the decay rate is

$$a_{f_{CP}} = \frac{\Gamma[\bar{B}^0(t) \to f] - \Gamma[B^0(t) \to f]}{\Gamma[\bar{B}^0(t) \to f] + \Gamma[B^0(t) \to f]} = S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t), \quad (1)$$

where Δm_d is the B^0–$\bar{B}^0$ mixing frequency. The parameters C and S describe the magnitude of CP violation in the decay and in the interference between decay and mixing (mixing-induced), respectively. We expect $C = 0$ in the case of a single dominant decay amplitude, because direct CP violation requires at

Mode	*BaBar*	*Belle*
$J\psi K_S(K_S \to \pi^+\pi^-)$	0.82 ± 0.08	0.67 ± 0.08
All with $\eta_f = -1$	0.76 ± 0.07	0.73 ± 0.06
$J\psi K_L$	0.72 ± 0.16	0.80 ± 0.13
All charmonium modes	$0.74 \pm 0.07 \pm 0.03$	$0.73 \pm 0.06 \pm 0.03$

Table 1: The CP asymmetry ($\sin 2\phi_1$) from different charmonium modes.

least two comparable amplitudes with different CP violating phases, while S is linked to the CKM phases, e.g. S=$sin2\phi_1$ for $B^0 \to J/\psi K_S$.

3 CKM phase $\phi_1(\beta)$

3.1 $b \to c\bar{c}s$ modes

The first observation of CP violation in the B^0 system was announced in 2001 by *BaBar* and *Belle* [4]. New and most precise measurements of ϕ_1 were reported in [5, 6]. The data sample of 88 (152) millions $B\bar{B}$ pairs has been used by *BaBar* (*Belle*) to fully reconstruct the B^0 mesons decaying into CP eigenstates such as $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$ (CP-odd) and $J/\psi K_L$ (CP-even) as well as $J/\psi K^*$ final state. The obtained results are listed in Table 1, where two experiments are in good agreement. The average of the two experiments [7] $\sin 2\phi_1 = 0.739 \pm 0.049$ is consistent with SM predictions.

The interference of the vector-vector final state $J/\psi K^*$ and vector-scalar $J/\psi K_0^*(1430)$ can be used to measure the sign and magnitude of $\cos 2\phi_1$. Knowledge of the $\cos 2\phi_1$ sign partially resolves the four-fold ambiguity in the ϕ_1 angle. The simultaneous time-dependent and angular analysis of *BaBar* in $J/\psi K_S \pi^0$ decay favors a positive sign for $\cos 2\phi_1$ [8]:

$$\cos 2\phi_1 = +2.72^{+0.50}_{-0.79}(stat) \pm 0.27(syst).$$

3.2 CP Violation in the Penguin dominated modes

In the SM, decays to the charmless final states with odd strange mesons like $B^0 \to \phi K_S$ are dominated by the $b \to s\bar{s}s$ gluonic penguin diagrams. We expect $C = 0$ in the SM because there is only one dominant decay mechanism. Since ϕK_S decays proceed through a CP odd final state, we expect $S = \sin 2\phi_1$.

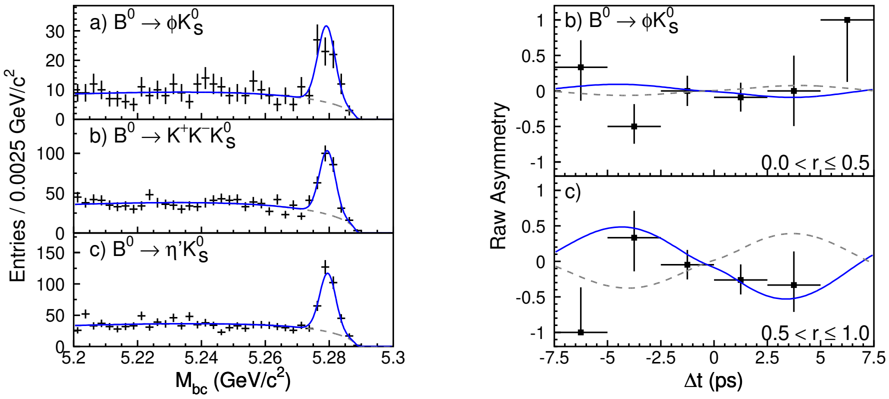

Figure 1: *The beam-energy constrained mass distributions for three penguin dominated modes: $\phi K_S, K^+K^-K_S, \eta' K_S$ (left) and the raw asymmetry for ϕK_S decay (right) mode measured by Belle.*

Other contributions in the SM which can deviate the measured asymmetry from $\sin 2\phi_1$ are rather small [9]. Figure 1 shows the beam-energy constrained mass distributions for three modes: $\phi K_S, K^+K^-K_S$, $\eta' K_S$, obtained by *Belle*. The CP violation result indicates a deviation from the value obtained with charmonium modes of about 3.5σ:

$$S_{\phi K^0} = -0.96 \pm 0.50(stat)^{+0.09}_{-0.11}(syst)$$

Figure 1 shows the raw asymmetry for such a mode with the SM expectation overlaid. On the other hand, the *BaBar* result [10]

$$S_{\phi K^0} = +0.47 \pm 0.34(stat)^{+0.08}_{-0.06}(syst),$$

is consistent with $\sin 2\phi_1$.

A more statistically accurate CP violation study can be made using all decays to KKK_S. This sample is a few times larger than in ϕK_S decay. The CP content of the three-body final state can be determined from isospin symmetry assumptions and measured branching fractions of KKK_S and KK_SK_S decays, as suggested by *Belle* [11]. One then observes [12] that the CP-even state is strongly dominating the decay channel ($f_{even} = 0.98 \pm 0.15 \pm 0.04$). It is fortunate because it increases the experimental sensitivity to CP violation. Two results reported in [13, 14]

$$
\begin{aligned}
-S_{KKK_S} &= +0.51 \pm 0.26(stat) \pm 0.05(syst)^{+0.18}_{-0.00}(CP_{+}cont.)\ (Belle) \\
-S_{KKK_S} &= +0.57 \pm 0.26(stat) \pm 0.04(syst)^{+0.17}_{-0.00}(CP_{+}cont.)\ (BaBar)
\end{aligned}
$$

are in a good agreement with the SM expectation.

HFAG-group summarized the measured CP asymmetry relevant to $\sin 2\phi_1$ for the charmonium and penguin dominated modes [7]. The 2.4σ difference in average between the two types of decays is not enough to state whether it is a NP effect. Much more data are necessary for a conclusive result.

4 The measurements of time-dependent CP asymmetry related to CKM phase $\phi_2(\alpha)$

The extraction of $\sin 2\phi_2$ from time-dependent asymmetry is complicated by the presence of both tree and gluonic penguin amplitudes in $B \to hh(h = \pi, \rho)$ like decays. Neutral B transitions to the CP eigenstate $\pi^+\pi^-$ can exhibit mixing-induced CP violation through interference between decays with and without B^0–$\bar{B}^0$ mixing, and direct CP violation through interference between the $b \to u$ tree and $b \to d$ penguin decay processes. The significant tree-penguin interference leads to $C_{\pi\pi} \neq 0$ and introduces additional phase which can shift the experimentally measurable parameter $\phi_{2\text{eff}}$ away from the value of ϕ_2. The difference between $\phi_{2\text{eff}}$ and ϕ_2 can be determined from an isospin analysis of the related decays $B^\pm \to \pi^\pm\pi^0$ and $B^0, \bar{B}^0 \to \pi^0\pi^0$ [15]. The observation of the last decay with a relatively large branching fraction [16], [17] demonstrates the essential gluonic penguin contribution in this mode. However, this leads to additional difficulties for ϕ_2 extraction from $B \to \pi^+\pi^-$ decays.

Results on CP violation in the $B^0, \bar{B}^0 \to \pi^+\pi^-$ decay are summarized in Table 2, see Ref. [18, 19]. The *Belle* group rules out the CP-conserving case, $S_{\pi\pi} = C_{\pi\pi} = 0$ at the 5.2σ level. It also finds evidence of direct CP violation with a 3.2σ significance. *BaBar* does not confirm the observation of large CP violation in this decay channel reported by *Belle*. However, two results agree within errors.

The first measurement of the $B^\pm \to \rho^\pm\rho^0$ branching fraction by *Belle* [20] and the upper limit for $B^0 \to \rho^0\rho^0$ [21] by *BaBar* indicate a small penguin contribution to the $B \to \rho\rho$ decay. Higher branching fraction and smaller shift of

Parameter	*BaBar* (123 M BB)	*Belle* (152 M BB)
$S_{\pi\pi}$	$-0.40 \pm 0.22(stat) \pm 0.03(syst)$	$-1.00 \pm 0.21(stat) \pm 0.07(syst)$
$C_{\pi\pi}$	$-0.19 \pm 0.19(stat) \pm 0.05(syst)$	$-0.58 \pm 0.15(stat) \pm 0.07(syst)$
$S_{\rho\rho}$	$-0.19 \pm 0.33(stat) \pm 0.11(syst)$	
$C_{\rho\rho}$	$-0.23 \pm 0.24(stat) \pm 0.14(syst)$	

Table 2: Results on CP violation measurements in $B \to \pi^+\pi^-$ and $B \to \rho^+\rho^-$.

the measured $\phi_{2\text{eff}}$ from ϕ_2 compared to $B^0, \bar{B}^0 \to \pi^+\pi^-$ make $B^0, \bar{B}^0 \to \rho^+\rho^-$ decays more attractive for the extraction of the CKM angle ϕ_2. Measurements of the longitudinal polarization in the $B^+ \to \rho^+\rho^0$ decay [20] provide evidence that the CP-even component dominates in $B \to \rho\rho$ decays.

This fortunate situation for measuring ϕ_2 in the $\rho^+\rho^-$ final state was confirmed by *BaBar* in [22] with an angular analysis. The first attempt to observe the time-dependent CP-violation in $B^0 \to \rho^+\rho^-$ had been done by *BaBar* in a pioneering work [23]. Fig. 2 shows the Δt distribution for the reconstructed $\rho^+\rho^-$ events. The time-dependent CP asymmetry is shown in Figure 2 (c), where the curve represents the fit of the asymmetry. The new *BaBar* result [24] for $B^0, \bar{B}^0 \to \rho^+\rho^-$ decay, obtained with 123 million $B\bar{B}$ is presented in Table 2. Ignoring possible non-resonant contributions, interference, I=1 amplitudes and assuming isospin symmetry, by using the data on $BR(B^0 \to \rho^0\rho^0)$, one can relate the CP parameters $S_{\rho\rho}$ and $C_{\rho\rho}$ to the CKM angle ϕ_2 up to a four-fold ambiguity. Selecting the solution closest to the CKM best fit average [25], this corresponds to

$$\phi_2 = 96^\circ \pm 10^\circ(stat) \pm 4^\circ(syst) \pm 13^\circ(peng),$$

where the last error is the additional contribution from penguins that is bounded at $< 13^\circ$ (68.3% C.L.)

Figure 2 (right) shows the constraint on ϕ_2 from the $\pi\pi$ and the $\rho\rho$ systems. *BaBar* and *Belle* average branching fractions, polarization in $\rho\rho$ and asymmetry C and S measurements are used to perform the Gronau-London isospin analysis. One can conclude that $\rho\rho$ system provides the most precise constraint on α, where the knowledge of penguin pollution is dominant.

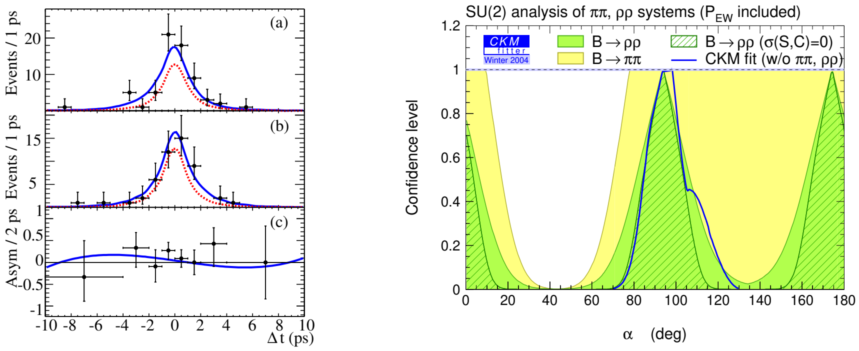

Figure 2: *The Δt distribution for signal enriched (a) B^0 and (b) $\bar{B}^0$ tagged events. The dashed line represents the sum of backgrounds and the solid line is the sum of signal and backgrounds. The time-dependent CP asymmetry is shown in (c), where the curve represents the asymmetry (left). Constraints on ϕ_2 obtained from the $\pi\pi$ and the $\rho\rho$ systems (right).*

5 CKM phase $\phi_3(\gamma)$

Various methods using $B \to DK$ decays have been introduced [26] to measure the unitarity triangle angle ϕ_3 but the statistics accumulated by current experiments is not yet sufficient to reasonably constrain ϕ_3. A novel technique based on the analysis of the three-body D^0 decay [27] has a higher statistical precision compared to branching fraction based methods.

This method is based on two key observations: D^0 and $\bar{D}^0$ mesons can decay to a common final state such as $K_s\pi^+\pi^-$, and the decay $B^+ \to D^{(*)}K^+$ can produce D^0 mesons of both flavors via $\bar{b} \to \bar{c}u\bar{s}$ and $\bar{b} \to \bar{u}c\bar{s}$ transitions, where the relative phase θ_+ between the two interfering amplitudes is the sum, $\delta + \phi_3$, of strong and weak interaction phases. In the charge conjugate mode, the relative phase $\theta_- = \delta - \phi_3$, so both phases can be extracted from the measurements of such B decays and their charge conjugate modes. The phase measurement is based on the analysis of the Dalitz distribution of the D^0 three-body final state. The two amplitudes interfere if D^0 and $\bar{D}^0$ mesons decay into the same final state $K_s\pi^+\pi^-$. Assuming no CP asymmetry in D decays, the amplitude of the $B^{\pm}$ decay is written as

$$M_{\pm} = f(m_{\pm}^2, m_{\mp}^2) + re^{i\phi_3 \pm i\delta} f(m_{\mp}^2, m_{\pm}^2), \tag{2}$$

where m_+^2 and m_-^2 are the squared invariant masses of the $K_s\pi^+$ and $K_s\pi^-$ combinations, respectively, and $f(m_+, m_-)$ is the complex amplitude of the decay $D^0 \to K_s\pi^+\pi^-$. Once the functional form of f is fixed by choosing a model for $D \to K_S\pi^+\pi^-$ decays, the D Dalitz distributions for B^+ and B^- decays can be fitted simultaneously by the above expressions for M_+ and M_-, with r, ϕ_3, and δ as free parameters. Thus the method is directly sensitive to the value of ϕ_3 and does not require additional assumptions on the values of r and δ.

The first measurement of ϕ_3 using this technique was performed by *Belle* based on 140 fb^{-1} [28]. From the combined fit of the $D \to K_S\pi^+\pi^-$ Dalitz plot distributions in the $B \to D^0K$ and $B \to D^{0*}K$ decays, *Belle* obtained the value of $\phi_3 = 81^\circ \pm 19^\circ(stat) \pm 13^\circ(syst) \pm 11^\circ(mod)$. The 95% confidence interval is $35^\circ < \phi_3 < 127^\circ$.

Conclusion

Two B-factories have established CP violation in B^0 decays, its magnitude is in agreement with the CKM interpretation of this phenomenon in the SM. The similar measurements for penguin dominated B meson decays may indicate a contribution from physics beyond SM. The first meaningful measurements of ϕ_2 and ϕ_3 angles of the CKM unitarity triangle were done. More data which will provide definitive results regarding these measurements are coming.

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References

1. For a review of CP violation phenomenology, see D. Kirkby and Y. Nir in S. Eidelman *et al.*, Phys. Rev. Lett. **592**, 1 (2004). We use the (ϕ_1, ϕ_2, ϕ_3) notation for the angles of the Unitarity Triangle.

2. BaBar, B. Aubert *et al.*, Nucl. Instrum. Methods **A479** 1 (2002).

3. Belle, A. Abashian *et al.*, Nucl. Instrum. Methods **A479** 117 (2002).

4. BaBar, B. Aubert *et al.*, Phys. Rev. Lett. **87**, 091801; Belle, K. Abe *et al.*, Phys. Rev. Lett. **87**, 091802 (2001).

5. BaBar, B. Aubert *et al.*, Phys. Rev. Lett. **89**, 201802 (2002).

6. Belle, K. Abe *et al.*, BELLE-CONF-0353, (2003), presented at LP'03, hep-ex/0308036.

7. Havy Flavour Averaging Group: http://www.slac.stanford.edu/xorg/hfag

8. M.Verderi, hep-ex/0406082, Contributed to the Proceedings Recontres de Moriond, EW session, 21-28 March, 2004, La Thuile, Italy.

9. D.London and A.Soni, Phys. Lett. B **407**, 61 (1997); Y.Grossman, Z.Ligeti, Y.Nir and H.Quinn, Phys. Rev. D **68**, 015004 (2003); M.Gronau, Y.Grossman and J.Rosner, Phys. Lett. B **579**, 331 (2004).

10. BaBar, B. Aubert *et al.*, hep-ex/0403026, submitted to PRL.

11. Belle, K. Abe *et al.*, hep-ex/0208030. Contributed to 31st International Conference on High Energy Physics (ICHEP 2002), Amsterdam, The Netherlands, 24-31 Jul 2002.

12. Belle, A.Garmash *et al.*, Phys. Rev. D **69**, 012001 (2004).

13. Belle, K.Abe *et al.*, Phys. Rev. Lett. **91**, 261801 (2003).

14. BaBar, B. Aubert *et al.*, hep-ex/0406005, submitted to PRL.

15. M. Gronau and D. London Phys. Rev. Lett. **65**, 3381 (1990).

16. BaBar, B. Aubert *et al.*, hep-ex/0303028.

17. Belle, K. Abe *et al.*, Phys. Rev. Lett. **91**, 261801 (2003).

18. BaBar, B. Aubert *et al.*, hep-ex/0408089, 32^{nd} International Conference on High-Energy Physics, ICHEP 04, 16-22 August, 2004, Beijing, China.

19. Belle, K. Abe *et al.*, Phys. Rev. Lett. **93**, 021601 (2004).

20. Belle, J. Zhang *et al.*, Phys. Rev. Lett. **91**, 221801 (2003), hep-ex/0306007.

21. BaBar, B. Aubert *et al.*, Phys. Rev. Lett. **91**, 171802 (2003), hep-ex/0307026.

22. BaBar, B. Aubert *et al.*, Phys. Rev. D **69**, 031102 (2004).

23. BaBar, B. Aubert *et al.*, hep-ex/0404029, submitted to PRL.

24. L.Roos, hep-ex/0407051, Contributed to the Proceedings Recontres de Moriond, EW session, 21-28 March, 2004, La Thuile, Italy.

25. A. Höcker *et al.*, Eur. Phys. Jour. **21**, 225 (2001).

26. M. Gronau and D. Wyler, Phys. Lett. **B265**, 172 (1991); I. Dunietz, Phys. Lett. **B270**, 75 (1991); D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. **78**, 3257 (1997).

27. A. Giri, Yu. Grossman, A. Soffer, J. Zupan, Phys. Rev. D **68**, 054018 (2003); This technique was proposed independently in Belle Collaboration, and the analysis of experimental data was under way before the A.Giri *et al.* publication appeared (Proceedings of BINP Special Analysis Meeting on Dalitz Analysis, 24-26 Sep. 2002, unpublished).

28. Belle, A.Poluektov, *et al.*, hep-ex/0406067, submitted to PRD.