Experimental Status of the CKM Angle β

James F. Hirschauer (from the BABAR Collaboration)

Fermi National Accelerator Laboratory, Batavia, IL, 60510, USA

Abstract. We summarize measurements of the CKM angle β at the B-factories emphasizing a comparison of β measured in the $B^0 \to c\bar{c}K^{(*)0}$ decay channels and $\beta_{\rm eff}$ measured in $b \to q\bar{q}s$ decay channels, such as $B^0 \to \omega K^0_S$, $B^0 \to \eta' K^0$, $B^0 \to \pi^0 K^0_S$, and $B^0 \to K^0_S K^0_S K^0_S$.

INTRODUCTION

Measurements of time-dependent CP asymmetries in $B^0 \to (c\bar{c})K^{(*)0}$ decays, which are dominated by color-suppressed $b \to c\bar{c}s$ tree amplitudes, have provided crucial tests of the mechanism of CP violation in the Standard Model (SM). These amplitudes contain the leading b-quark couplings, given by the Cabibbo-Kobayashi-Maskawa [1] (CKM) flavor mixing matrix, for kinematically allowed transitions.

Decays to charmless final states such as ϕK^0, $\pi^0 K^0$, $\eta' K^0$, and ωK^0 are CKM-suppressed $b \to q\bar{q}s$ ($q = d, s$) processes dominated by a single loop (penguin) amplitude. This amplitude has the same weak phase $\beta = \arg\left(-V_{cd}V^*_{cb}/V_{td}V^*_{tb}\right)$ of the CKM mixing matrix as that measured in the $b \to c\bar{c}s$ transition, but is sensitive to the possible presence of new heavy particles in the loop [2].

The B-factories [3] are asymmetric-energy e^+e^- storage rings constructed at SLAC National Laboratory, USA, and KEK, Japan, to measure the parameters of the CKM matrix. There the BABAR and Belle detectors recorded 425 and 771 fb^{-1} of data at an energy corresponding to the mass of the $\Upsilon(4S)$, which has a branching fraction for decay to $B\bar{B}$ that is essentially unity.

The CKM phase β is accessible experimentally through interference between the direct decay of the B meson to a CP eigenstate and $B^0\bar{B}^0$ mixing followed by decay to the same final state. This interference is observable through the time evolution of the decay. At the B-factories, we reconstruct one B^0 from $\Upsilon(4S) \to B^0\bar{B}^0$, which decays to the CP eigenstate $(c\bar{c})K^{(*)0}$, ωK^0_S, $\eta' K^0$, $\pi^0 K^0_S$, or $K^0_S K^0_S K^0_S$ (B_{CP}). From the remaining particles in the event we also reconstruct the decay vertex of the other B meson ($B_{\rm tag}$) and identify its flavor. The difference $\Delta t \equiv t_{CP} - t_{\rm tag}$ of the proper decay times t_{CP} and $t_{\rm tag}$ is obtained from the measured distance between the decay vertices of the B_{CP} and $B_{\rm tag}$ and the boost ($\beta\gamma = 0.56$) of the $\Upsilon(4S)$ system. In the $\pi^0 K^0_S$ and $K^0_S K^0_S K^0_S$ analyses we compute Δt and its uncertainty with a geometric fit to the $\Upsilon(4S) \to B^0\bar{B}^0$ system taking into account the reconstructed K^0_S trajectory, the knowledge of the average e^+e^- interaction point and the average B meson lifetime (for BABAR). The distribution of Δt

CP1182, *Intersections of Particle and Nuclear Physics, Proceedings of the 10th International Conference,* edited by M. L. Marshak

is given by

$$F(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} 1 \mp \Delta w \pm (1-2w)\left[-\eta_f S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)\right],$$

where η_f is the *CP* eigenvalue of final state f, the upper (lower) sign denotes a decay accompanied by a B^0 ($\bar{B}^0$) tag, τ is the mean B^0 lifetime, Δm_d is the mixing frequency, w is the mistag rate, and $\Delta w \equiv w(B^0) - w(\bar{B}^0)$ is the difference in mistag rates for B^0 and $\bar{B}^0$ tag-side decays. The tagged flavor and mistag parameters w and Δw are determined with neural network based algorithms.

In the SM, we expect $C = 0$ and $-\eta S = \sin 2\beta$ to an accuracy of $10^{-3} - 10^{-4}$ for $B^0 \to (c\bar{c})K^{(*)0}$ decays [4]. The same expectations hold for the penguin decays, assuming penguin dominance of the $b \to s$ transition and neglecting other CKM-suppressed amplitudes with different weak phases. However, these CKM-suppressed amplitudes and the color-suppressed tree diagram introduce additional weak phases whose contributions may not be negligible [5, 6, 7, 8]. As a consequence, the measured S_f ($\sin 2\beta_{\rm eff}$) may differ from $\sin 2\beta$ even within the SM. This deviation $\Delta S_f = S_f - \sin 2\beta$ is estimated in several theoretical approaches: QCD factorization (QCDF) [5, 9], QCDF with modeled rescattering [10], soft collinear effective theory [11], and SU(3) symmetry [6, 8, 13]. The estimates are channel dependent. Estimates of ΔS from QCDF are in the ranges $(0.0, 0.2)$, $(-0.03, 0.03)$, and $(0.01, 0.12)$ for ωK^0_S, $\eta' K^0$, and $\pi^0 K^0_S$, respectively [9, 11, 12]; SU(3) symmetry provides bounds of $(-0.05, 0.09)$ for $\eta' K^0$ and $(-0.06, 0.12)$ for $\pi^0 K^0_S$ [13]. Predictions that use isospin symmetry to relate several amplitudes, including the $I = \frac{3}{2}$ $B \to K\pi$ amplitude, give an expected value for $S_{\pi^0 K^0_S}$ near 1.0 instead of $\sin 2\beta$ [14].

In these proceedings, we summarize measurements of time-dependent *CP* parameters in the aforementioned $b \to c\bar{c}s$ and $b \to q\bar{q}s$ B^0 decays. Detailed descriptions of each analysis are given in Refs. [17, 18, 19, 20].

ANALYSIS TECHNIQUE

After applying loose selection criteria to reduce the dominant continuum $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) background, we perform an unbinned maximum likelihood (ML) fit to the data to separate signal from background and obtain the *CP*-violation parameters for each decay channel. As input to the ML fit, we use two kinematic variables and a Fisher or likelihood combination of event-shape variables. As kinematic variables we use two nearly uncorrelated variables: the energy difference between the B candidate and half of the known beam energy and the beam-energy-substituted mass, which is the invariant mass of the reconstructed B candidate computed with the constraint that the energy difference is zero.

At the B-factories, we can only reconstruct the direction of K^0_L mesons. Because of this partial reconstruction in analyses with a K^0_L, we constrain the mass of the B meson to the nominal value [21] during the determination of the B decay vertex. This constraint causes the kinematic variables to be completely correlated, so *BABAR* uses only the energy difference and Belle uses only the center-of-mass B momentum in the ML fit.

TABLE 1. Measurements of *CP* parameters from *BABAR* and Belle. The first errors are statistical and the second are systematic.

Mode	*BABAR* $-\eta_f S_f$	*BABAR* C_f	Belle $-\eta_f S_f$	Belle C_f
$c\bar{c}K^{(*)0}$	$0.69 \pm 0.03 \pm 0.01$	$0.03 \pm 0.02 \pm 0.02$	$0.64 \pm 0.03 \pm 0.02$	$0.02 \pm 0.02 \pm 0.01$
ωK^0_S	$0.55^{+0.26}_{-0.29} \pm 0.02$	$-0.52^{+0.22}_{-0.20} \pm 0.03$	$0.11 \pm 0.46 \pm 0.07$	$0.09 \pm 0.29 \pm 0.06$
$\eta' K^0$	$0.57 \pm 0.08 \pm 0.02$	$-0.08 \pm 0.06 \pm 0.02$	$0.64 \pm 0.10 \pm 0.04$	$0.01 \pm 0.07 \pm 0.05$
$\pi^0 K^0_S$	$0.55 \pm 0.20 \pm 0.03$	$0.13 \pm 0.13 \pm 0.03$	$0.67 \pm 0.31 \pm 0.08$	$-0.14 \pm 0.13 \pm 0.06$
$K^0_S K^0_S K^0_S$	$0.90^{+0.20}_{-0.18}\,^{+0.04}_{-0.03}$	$-0.16 \pm 0.17 \pm 0.03$	$0.30 \pm 0.32 \pm 0.08$	$-0.31 \pm 0.20 \pm 0.07$

RESULTS

The fit results are shown in Table 1. All S_f results are consistent with SM expectations. In particular, the world averages of S_f in $c\bar{c}K^{(*)0}$ and the theoretically clean $\eta' K^0$ channel differ by less than 1σ. All C_f results are consistent with zero direct *CP*-violation.

Decay channels such as $B^0 \to J/\psi K^{*0}$ and $B^0 \to D^{(*)+}D^{(*)-}K^0_S$ are sensitive to $\cos 2\beta$ and can help resolve the $\frac{\pi}{2} - \beta$ trigonometric ambiguity on the value of β. In these channels, *BABAR* determines that $\cos 2\beta > 0$ at 89% and 94% confidence level, respectively [22]. Interference in the $D^{(*)0}$ Dalitz plot (DP) allows *BABAR* and Belle to determine $\cos 2\beta > 0$ at 86% and 98% confidence level in the $D^{(*)0}h^0$ channel [23]. Finally, through interference in the $K^+K^-K^0_S$ DP, *BABAR* determines $\cos 2\beta > 0$ at 4.8σ [24].

CONCLUSIONS

We summarize measurements of mixing-induced *CP*-violation parameters in the $b \to c\bar{c}s$ modes and several $b \to q\bar{q}s$ penguin-dominated B^0 decays at the *B*-factories. Discrepancies between the measurements of $\sin 2\beta$ and $\sin 2\beta_{\rm eff}$ are consistent with expectations from the SM.

ACKNOWLEDGEMENTS

I thank the organizers (and the student helpers) of CIPANP 09 for a well-organized and interesting conference. I also thank my *BABAR* collaborators for their support, especially my thesis advisors, Bill Ford and Jim Smith.

REFERENCES

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

2. Y. Grossman and M. P. Worah, Phys. Lett. B **395**, 241 (1997); D. Atwood and A. Soni, Phys. Lett. B **405**, 150 (1997); M. Ciuchini *et al.*, Phys. Rev. Lett. **79**, 978 (1997).
3. *BABAR* Collaboration, B. Aubert *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 1 (2002); Belle Collaboration, Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 117 (2002).
4. H. Boos, T. Mannel, and J. Reuter, Phys. Rev. D **70**, 036006 (2004). *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **66**, 032003 (2002).
5. M. Beneke and M. Neubert, Nucl. Phys. B **675**, 333 (2003).
6. C.-W. Chiang, M. Gronau, and J. L. Rosner, Phys. Rev. D **68**, 074012 (2003); M. Gronau, J. L. Rosner, and J. Zupan, Phys. Lett. B **596**, 107 (2004).
7. D. London and A. Soni, Phys. Lett. B **407**, 61 (1997).
8. Y. Grossman, Z. Ligeti, Y. Nir, and H. Quinn, Phys. Rev. D **68**, 015004 (2003).
9. M. Beneke, Phys. Lett. B **620**, 143 (2005).
10. H. Y. Cheng, C-K. Chua, and A. Soni, Phys. Rev. D **72**, 014006 (2005), Phys. Rev. D **71**, 014030 (2005); S. Fajfer, T. N. Pham, and A. Prapotnik-Brdnik Phys. Rev. D **72**, 114001 (2005).
11. A. R. Williamson and J. Zupan, Phys. Rev. D **74**, 014003 (2006).
12. H-Y. Cheng, C-K. Chua, and A. Soni, Phys. Rev. D **72**, 014006 (2005).
13. M. Gronau, J. L. Rosner, and J. Zupan, Phys. Rev. D **74**, 093003 (2006).
14. A. J. Buras, R. Fleischer, S. Recksiegel, and F. Schwab, Phys. Rev. Lett. **92**, (2004) 101804; R. Fleischer, S. Jager, D. Pirjol, and J. Zupan, arXiv:0806.2900 [hep-ph]; M. Gronau and J. L. Rosner arXiv:0807.3080 [hep-ph].
15. M. Beneke, Phys. Lett. B **620**, 143 (2005) [arXiv:hep-ph/0505075].
16. G. Buchalla, G. Hiller, Y. Nir and G. Raz, JHEP **0509**, 074 (2005) [arXiv:hep-ph/0503151].
17. *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **79** 072009 (2009).
18. Belle Collaboration, K.F. Chen *et al.*, Phys. Rev. Lett. **98** 031802 (2007).
19. *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **79** 052003 (2009).
20. *BABAR* Collaboration, B. Aubert *et al.*, CKM 2008 Preliminary.
21. Particle Data Group, Y.-M. Yao *et al.*, J. Phys. **G33**, 1 (2006).
22. *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **71** 032005 (2005); Belle Collaboration, R. Itoh *et al.*, Phys. Rev. Lett. **95** 091601 (2005); *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **74** 091101 (2006); Belle Collaboration, J. Dalseno *et al.*, Phys. Rev. D **76** 072004 (2007).
23. *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **99** 231802 (2007); Belle Collaboration, P. Krokovny *et al.*, Phys. Rev. Lett. **97** 081801 (2006).
24. *BABAR* Collaboration, B. Aubert *et al.*, arXiv:0808.0700 [hep-ex].