SLAC-PUB-12847
arXiv:0710.0466[hep-ex]
October 2007

Measurement of β in B decays to charm and charmonium in *BABAR*

Marco Bomben, on behalf of the *BABAR* Collaboration
Università degli Studi & I.N.F.N. - Trieste, Via Alfonso Valerio 2, 34100 Trieste - Italy
E-mail: `Marco.Bomben@ts.infn.it`

Abstract. In this article we will review recent *BABAR* measurements of Unitarity Triangle angle β in B meson decays to *charm* and *charmonium*.

1. Introduction

Measurements of time-dependent *CP* asymmetries in B^0 meson decays, through the interference between decays with and without B^0-$\overline{B}^0$ mixing, have provided stringent tests on the mechanism of *CP* violation in the standard model (SM). The time-dependent *CP* asymmetry amplitude equals to $\sin 2\beta$ in the SM if the B meson decays to a final states that can be accessed to by both B^0 and $\overline{B}^0$. The angle $\beta = \arg(V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$ is a phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. The phase difference, 2β, between decays with and without B^0-$\overline{B}^0$ mixing, arises through the box diagrams in B^0-$\overline{B}^0$ mixing, which are dominated by the diagrams with virtual top quark.

In this paper we present a review of recent measurements of β at *BABAR* experiment at the asymmetric-energy e^+e^- B Factory PEP-II; neutral B meson decays to *charm* and *charmonium* studies are reported, including precision measurements using $B^0 \rightarrow (c\overline{c})K^0$ decays, tree decays with penguin pollutions, $B^0 \rightarrow D^{(*)\pm}D^{\mp}$, and new decay modes $B^0 \rightarrow D^{(*)0}h^0$ ($h^0 = \pi^0$, $\eta^{(\prime)}$, ω).

2. Time-Dependent *CP* Asymmetry

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, $B_{\rm tag}$, is reconstructed and its flavor is identified (tagged). The proper decay time difference $\Delta t = t_{CP} - t_{\rm tag}$, between the signal B (t_{CP}) and $B_{\rm tag}$ ($t_{\rm tag}$) is determined from the measured distance between the two B decay vertices projected onto the boost axis and the boost ($\beta\gamma = 0.56$ at PEP-II) of the center-of-mass (c.m.) system. The Δt distribution is given by:

$$\begin{aligned} F_{\pm}(\Delta t) &= \frac{\Gamma e^{-\Gamma|\Delta t|}}{4}[1 \mp \Delta w \pm && (1)\\ &\quad (1-2w)(\eta_f \mathcal{S}\sin(\Delta m\Delta t) - \mathcal{C}\cos(\Delta m \Delta t))]\,, && (2)\end{aligned}$$

where the upper (lower) sign is for events with $B_{\rm tag}$ being identified as a B^0 ($\overline{B}^0$), η_f is the *CP* eigenvalue of the final state, Δm is the B^0-$\overline{B}^0$ mixing frequency, Γ is the mean decay rate

Contributed to International Europhysics Conference On High Energy Physics (EPS-HEP2007),
7/19/2007-7/25/2007, Manchester, England

Work supported by US Department of Energy contract DE-AC02-76SF00515

of the neutral B meson, the mistag parameter w is the probability of incorrectly identifying the flavor of $B_{\rm tag}$, and Δw is the difference of w for B^0 and $\overline{B}^0$. In the SM, the parameters $\mathcal{S} = {\rm Im}\lambda/(1+|\lambda|)$ and $\mathcal{C} = (1-|\lambda|)/(1+|\lambda|)$, where $\lambda = \frac{q}{p}\frac{\overline{\mathcal{A}}_f}{\mathcal{A}_f}$, and $\mathcal{A}_f$ ($\overline{\mathcal{A}}_f$) is the amplitude of B^0 ($\overline{B}^0$) decaying to the CP final state f. In the SM, if only one diagram contributes to the decay process, $\mathcal{S} = -\sin 2\beta$ and $\mathcal{C} = 0$. A non-zero value of $\mathcal{C}$ would indicate direct CP violation.

Because there can be other diagrams with a different weak phase, the experimental result of $\mathcal{S}$ does not necessarily equal to $-\sin 2\beta$. To separate the measured value from the standard model $\sin 2\beta$, we denote the measured one $\sin 2\beta_{\rm eff}$.

3. $B^0 \to (c\overline{c})K^0$

The $B^0 \to (c\overline{c})K^0$ modes are called "golden modes" because of relatively large ($\mathcal{O}(10^{-4}$–$10^{-5})$) branching fractions, low experimental backgrounds and high reconstruction efficiencies, and small theoretical uncertainties [2].

The *BABAR* collaboration studied $J/\psi K^0_S$ and $J/\psi K^0_L$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$ and $J/\psi K^{*0}(K^0_S\pi^0)$ decay modes to measure sin2β, reconstructing approximately 6900 CP-odd signal events and 3700 CP-even signal events from 383×10^6 $B\overline{B}$ pairs. The result was $\sin 2\beta_{\rm eff} = +0.714 \pm 0.032 \pm 0.018$ and $\mathcal{C} = +0.049 \pm 0.022 \pm 0.017$ [3].

Because of the high experimental precision and low theoretical uncertainty, the result from these modes serves as a benchmark in the SM; any other measurements of $\sin 2\beta$ that have a significant deviation from it, beyond the usually small SM corrections, would indicate evidence for new physics.

4. $B^0 \to D^{(*)\pm}D^{\mp}$

The decay $B^0 \to D^{(*)\pm}D^{\mp}$ is dominated by a color-allowed Cabibbo-suppressed $b \to c\overline{c}d$ tree diagram. The penguin diagram in the SM has a different weak phase and is expected to contribute few percent correction [4] to CP asymmetry. A large deviation in $\sin 2\beta_{\rm eff}$ from that in $B^0 \to (c\overline{c})K^0$ would indicate possible new physics contribution to the loop in the penguin diagram.

The final state D^+D^- is a CP eigenstate so $\mathcal{S} = -\sin 2\beta$ and $\mathcal{C} = 0$ in the SM when neglecting the penguin contribution. The final state $D^{*\pm}D^{\mp}$ is not a CP eigenstate. The decay amplitudes can have a strong phase difference δ, i.e., $\mathcal{A}(B^0 \to D^{*+}D^-)/\mathcal{A}(B^0 \to D^{*-}D^+) = Re^{i\delta}$. As a result, the $\mathcal{S}$ and $\mathcal{C}$ parameters, (+ for $D^{*+}D^-$ and − for $D^{*-}D^+$) are $\mathcal{S}_\pm = 2R\sin(2\beta_{\rm eff} \pm \delta)/(1+R^2)$, and $\mathcal{C}_\pm = \pm(R^2-1)/(R^2+1)$, assuming there is no direct CP violation.

The *BABAR* collaboration measured CP parameters $\mathcal{S}$ and $\mathcal{C}$ in $B^0 \to D^+D^-$ using 384×10^6 $B\overline{B}$ pairs. The results were: $\mathcal{S} = -0.54 \pm 0.34 \pm 0.06$ and $\mathcal{C} = 0.11 \pm 0.22 \pm 0.07$ [5], which is consistent with the SM with small penguin contributions. Figure 1 shows the Δt distributions for B^0-tagged and $\overline{B}^0$-tagged events separately. For the result from Belle, the plots show clear difference between the yields of B^0-tagged and $\overline{B}^0$-tagged events. The consistency of these two results are quite low ($\chi^2/{\rm dof} = 12/2$, or C.L.=0.003, corresponding to 3σ).

Belle collaboration recently reports evidence for a large direct CP violation in D^+D^- channel using a data sample of 535×10^6 $B\overline{B}$ pairs. They measure $\mathcal{S} = -1.13 \pm 0.37 \pm 0.09$ and $\mathcal{C} = -0.91 \pm 0.23 \pm 0.06$ [6]. The CP conservation, $\mathcal{S} = \mathcal{C} = 0$, is excluded at 4.1σ level and $\mathcal{C} = 0$ is excluded at 3.2σ. The *BABAR* and Belle results are marginally compatible: the χ^2 probability is at 0.3% Confidende Level (C.L.).

BABAR also reports an updated measurement of $B^0 \to D^{*\pm}D^{\mp}$ [5]. The result is $\mathcal{C}_{D^{*+}D^-} = 0.18 \pm 0.15 \pm 0.04$, $\mathcal{S}_{D^{*+}D^-} = -0.79 \pm 0.21 \pm 0.06$, $\mathcal{C}_{D^{*-}D^+} = 0.23 \pm 0.15 \pm 0.04$, and

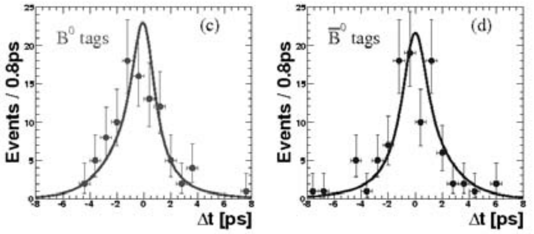

Figure 1. Δt distributions of $B^0 \to D^+D^-$. Left plot is for B^0-tagged events and right one for $\overline{B}^0$-tagged events. The points represent the data; the superimposed is the result of the fit to the data.

$\mathcal{S}_{D^{*-}D^+} = -0.44 \pm 0.22 \pm 0.06$. Using a slightly different parametrization [7], the *BABAR* indicated that which indicates that $\sin 2\beta_{\rm eff} \neq 0$ it is non-zero at approximately 4σ level.

5. $B^0 \to D^{(*)0}h^0$ ($h^0 = \pi^0$, $\eta^{(\prime)}$, ω)

The decay $B^0 \to D^{(*)0}h^0$ ($h^0 = \pi^0$, $\eta^{(\prime)}$, ω) is dominated by a color-suppressed $b \to \overline{u}d$ tree diagram. The final state is a *CP* eigenstate if the neutral D meson also decays to a *CP* eigenstate, and therefore Eq. 1 applies. This mode is free of penguin diagrams. The next diagram is also a color-suppressed tree diagram, $b \to u\overline{c}d$, which is doubly Cabibbo suppressed. The SM correction on $\sin 2\beta_{\rm eff}$ is believed to be a few percent [8]. There could be "new physics" contributions thanks to some R-parity-violating supersymmetry models [8], entering at tree level.

BABAR recently reported a measurement of $\sin 2\beta_{\rm eff}$ using $D^{(*)0}\pi^0$ with $D^0 \to K^+K^-$, $K^0_S\omega$, and $D^{(*)0}\eta$ with $D^0 \to K^+K^-$, and $D^0\omega$ with $D^0 \to K^+K^-$, $K^0_S\omega$, $K^0_S\pi^0$. The D^{*0} is reconstructed from $D^{*0} \to D^0\pi^0$, when applicable. *BABAR* uses 383×10^6 $B\overline{B}$ pairs and obtains $\sin 2\beta_{\rm eff} = 0.56 \pm 0.23 \pm 0.05$ and $\mathcal{C} = -0.23 \pm 0.16 \pm 0.04$ [9]. This result is 2.3σ away from *CP* conservation.

6. Conclusion

The measurement of $\sin 2\beta$ is a rich program at the B Factory PEP-II. A total of more than 380 million $\Upsilon(4S) \to B\overline{B}$ pairs have been analyzed at the *BABAR* experiment; the result has achieved a precision of 4% in $\sin 2\beta$ measurement,$\sin 2\beta = 0.678 \pm 0.026$, using $B^0 \to (c\overline{c})K^0$ decays.

Belle observes evidence for large direct *CP* asymmetry in $B^0 \to D^+D^-$ channel. However, it is not confirmed by *BABAR*, whose result is in agreement with Standard Model expectation $C_f = 0$. More data are needed to resolve this discrepancy. The *BABAR* collaboration presented a measurement on $B^0 \to D^{*+}D^-$ too, observing evidence of *CP* violation at 4 standard deviations; the results for these analysis are perfectly consistent with the Stadard Model expectations.

The *BABAR* collaboration reported the first-time measurement of S_f and C_f in $B^0 \to D^{(*)0}h^0$ ($h^0 = \pi^0$, $\eta^{(\prime)}$, ω) channels, when reconstructing D^0 meson in *CP* eigenstates; the results are consistent with the Standard Model expectations of $S_f = -\sin 2\beta$ and $C_f = 0$.

[1] Cabibbo N 1963 *Phys. Rev. Lett.* **10** 531 ; Kobayashi M and Maskawa T 1973 *Prog. Theoret. Phys.* **49** 652
[2] Ciuchini M, Pierini M and Silvestrini L 2005 *Phys. Rev. Lett.* **95** 221804 ; Li H and Mishima S 2006 *Preprint* hep-ph/0610120
[3] Aubert B *et al.* (*BABAR* Collaboration) 2007 submitted to *Phys. Rev. Lett., Preprint* hep-ex/0703021
[4] Xing Z z 2000 *Phys. Rev. D* **61** 014010
[5] Aubert B *et al.* (*BABAR* Collaboration) 2007 *Phys. Rev. Lett.* **99** 071801
[6] Fratina S *et al.* (Belle Collaboration) 2007 submitted to *Phys. Rev. Lett. Preprint* arXiv:hep-ex/0702031
[7] Aubert B *et al.* (*BABAR* Collaboration) 2007 *Phys. Rev. Lett.* **91** 201802
[8] Grossman Y and Worah M P 1997 *Phys. Lett. B* **395** 241
[9] Aubert B *et al.* (*BABAR* Collaboration) 2007 submitted to *Phys. Rev. Lett. Preprint* arXiv:hep-ex/0703019