International Journal of Modern Physics A

Improved measurement of *CP*-violation in $B \to (c\bar{c})K^{(*)0}$ decays

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Received (Day Month Year)
Revised (Day Month Year)

We present results on time-dependent *CP* asymmetries in neutral B decays. The amplitude of the *CP* asymmetry, sin2β in the Standard Model, is derived from decay-time distributions from events in which one neutral B meson is fully reconstructed in a final state containing a charmonium meson and the other B meson is determined to be either a B^0 or $\overline{B}^0$ from its decay products. Using data collected by the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC, we measure $\sin 2\beta = 0.722 \pm 0.040(\mathrm{stat}) \pm 0.023(\mathrm{syst})$ and $\cos 2\beta = 2.72^{+0.50}_{-0.79}(\mathrm{stat}) \pm 0.27(\mathrm{syst})$, determining the sign of cos2β to be positive at 86% CL.

Keywords: *CP* violation,*B* decays

1. Introduction

Charge-parity (*CP*) violation in the B meson system has been established by the *BABAR*[1] and Belle[2] collaborations. The Standard Model of electroweak interactions describes *CP* violation as a consequence of an irreducible phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix[3]. In this framework, measurements of *CP* asymmetries in the proper-time distribution of neutral B decays to *CP* eigenstates containing a charmonium and K^0 meson provide a direct measurement of sin2β [4]. The angle β is $\arg\left[-V_{\mathrm{cd}}V^*_{\mathrm{cb}}/V_{\mathrm{td}}V^*_{\mathrm{tb}}\right]$, where V_{ij} are CKM matrix elements.

The proper-time distribution of B meson decays to a *CP* eigenstate f can be expressed in terms of a complex parameter λ[5], which depends on both the B^0-$\overline{B}^0$ oscillation amplitude and the decay amplitudes for $\overline{B}^0 \to f$ and $B^0 \to f$. The decay rate $\mathrm{f}_+(\mathrm{f}_-)$ when the other B meson B_{tag} decays as a B^0 ($\overline{B}^0$) is given by

$$\mathrm{f}_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 \pm \frac{2\mathcal{I}m\lambda}{1+|\lambda|^2}\sin\left(\Delta m_d \Delta t\right) \mp \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos\left(\Delta m_d \Delta t\right)\right], \quad (1)$$

for a B from a $\Upsilon(4S) \to B^0\overline{B}^0$ decay, where Δt is the difference between the proper decay times of the reconstructed B meson B_{rec} and B_{tag}, τ_{B^0} is the B^0 lifetime, and Δm_d is the B^0-$\overline{B}^0$ oscillation frequency. The decay width difference $\Delta\Gamma$ between the B^0 mass eigenstates is assumed to be zero. The sine term in Eq. 1 is due to the interference between direct decay and decay after a net B^0-$\overline{B}^0$ oscillation. A non-zero cosine term arises from the interference between decay amplitudes with different weak and strong phases (direct *CP* violation) or from *CP* violation in B^0-$\overline{B}^0$ mixing.

In the Standard Model, *CP* violation in mixing is negligible, as is direct *CP* violation for $b \to c\overline{c}s$ decays that contain a charmonium meson[5]. With these assumptions $\lambda = \eta_f e^{-2i\beta}$, where η_f is the *CP* eigenvalue of final state f. Thus, the time-dependent *CP* asymmetry is

$$A_{CP}(\Delta t) \equiv \frac{\mathrm{f}_+ - \mathrm{f}_-}{\mathrm{f}_+ + \mathrm{f}_-} = -\eta_f \,\sin 2\beta\, \sin(\Delta m_d\, \Delta t), \tag{2}$$

with $\eta_f = -1$ for $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$, and $+1$ for $J/\psi K^0_L$.

The parameter $\cos 2\beta$ appears as a factor in the interference between the CP-odd and the two CP-even amplitudes in the time- and angle-dependent distribution describing the decay $B \to J/\psi K^{*0}$ ($K^{*0} \to K^0_S\pi^0$, $J/\psi \to \ell p \ell^-$) [6,7,8,9]. The sign of $\cos 2\beta$, however, can not be determined using only $B \to J/\psi K^*$ decays due to a two-fold ambiguity in the relative strong phases among the three $B \to J/\psi K^*$ decay amplitudes. We use the known dependence on $K\pi$ invariant mass of the relative phase between the S-wave and P-wave $K\pi$ $I = 1/2$ scattering amplitudes in the vicinity of the $K^*(892)$ to resolve the two-fold ambiguity in the relative strong phases among the three amplitudes for $B \to J/\psi K^*$.

2. sin2β Results

Using a data sample of about 227×10^6 $\Upsilon(4S) \to B\overline{B}$ decays, we determine $\sin 2\beta$ with a simultaneous maximum likelihood fit to the Δt distributions of the tagged B_{CP} events and a sample of B decays to flavor eigenstates ($B_{\rm flav}$ sample). The Δt distributions of the B_{CP} sample are modeled by Eq. 1 with $|\lambda| = 1$. Those of the $B_{\rm flav}$ sample evolve according to the known frequency for flavor oscillation in B^0 mesons. The observed amplitudes for the *CP* asymmetry in the B_{CP} sample and for flavor oscillation in the $B_{\rm flav}$ sample are assumed to be reduced by the same factor $1-2w$ due to flavor mistags, where w is the fraction of events where the flavor of $B_{\rm tag}$ is determined incorrectly. The Δt distributions for the signal are convolved with a common resolution function and backgrounds are incorporated with an empirical description of their Δt spectra, containing prompt and non-prompt components convolved with a resolution function distinct from that of the signal.

The fit to the B_{CP} and $B_{\rm flav}$ samples yields

$$\sin 2\beta = 0.722 \pm 0.040(\mathrm{stat}) \pm 0.023(\mathrm{syst}). \tag{3}$$

Figure 1 shows the Δt distributions and asymmetries in yields between B^0 tags and $\overline{B}^0$ tags for the $\eta_f = -1$ and $\eta_f = +1$ samples as a function of Δt, overlaid with the projection of the likelihood fit result.

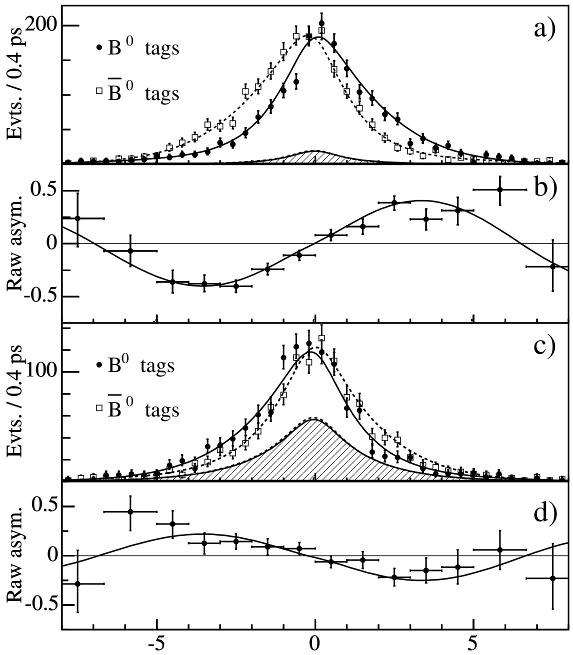

Fig. 1. a) Number of $\eta_f = -1$ candidates ($J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$) in the signal region with a B^0 tag and with a $\overline{B}^0$ tag, and b) the raw asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$, as functions of Δt. Figs. c) and d) are the corresponding plots for the $\eta_f = +1$ mode $J/\psi K^0_L$. All plots exclude `Other`-tagged events. The solid (dashed) curves represent the fit projections in Δt for B^0 ($\overline{B}^0$) tags. The shaded regions represent the estimated background contributions.

3. $\cos 2\beta$ results

We determine $\cos 2\beta$ using a data sample of about 88×10^6 $\Upsilon(4S) \to B\overline{B}$ decays. First, the angular decay parameters (three decay amplitudes and two relative phases, as defined in Ref[10]) must be determined. We find

$$\begin{aligned}
\delta_\parallel - \delta_0 &= (2.73 \pm 0.10 \pm 0.05)\,\mathrm{rad}, \\
\delta_\perp - \delta_0 &= (0.18 \pm 0.07 \pm 0.05)\,\mathrm{rad}, \\
|A_0|^2 &= 0.566 \pm 0.012 \pm 0.005, \\
|A_\parallel|^2 &= 0.204 \pm 0.015 \pm 0.005, \\
|A_\perp|^2 &= 0.230 \pm 0.015 \pm 0.004,
\end{aligned} \tag{4}$$

where the strong phases are determined to within a two-fold ambiguity: $(\delta_\parallel - \delta_0) \to -(\delta_\parallel - \delta_0)$ and $(\delta_\perp - \delta_0) \to \pi - (\delta_\perp - \delta_0)$

As shown in Fig. 2, we observe a significant contribution to $B \to J/\psi K\pi$ beyond just a $B \to J/\psi K^*(892)$ contribution. Thus, we reanalyze our data in the region close to the K^* resonance including an additional S-wave contribution in order

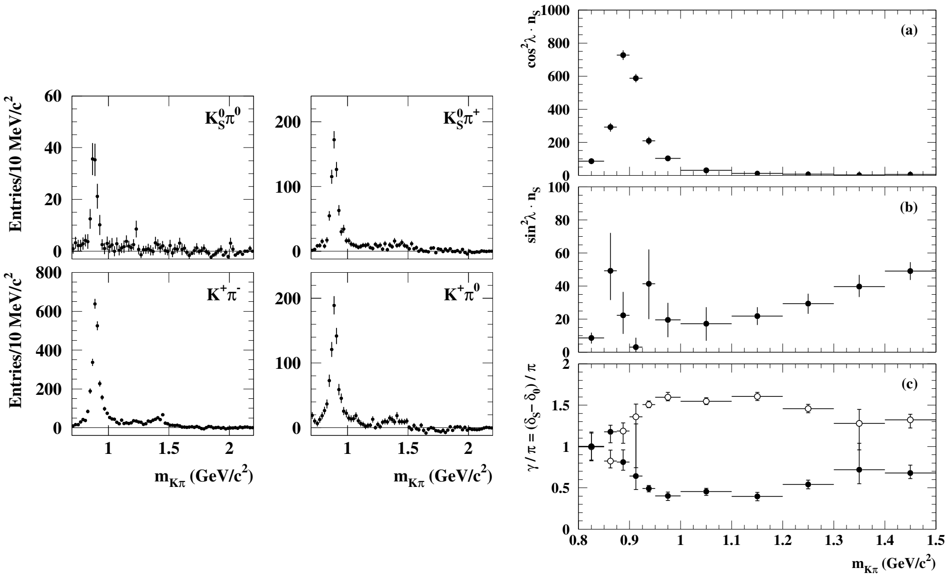

Fig. 2. Left, the background-subtracted $K\pi$ invariant mass distributions for $J/\psi\, K\pi$ candidates in data, for (clockwise from top-left) $B^0 \to J/\psi\, K^{*0}(K^0_S\pi^0)$, $B^+ \to J/\psi\, K^{*0}(K^0_S\pi^+)$, $B^0 \to J/\psi\, K^{*0}(K^+\pi^-)$, and $B^+ \to J/\psi\, K^{*0}(K^+\pi^0)$. Right, (a) The P-wave intensity times number of events; i.e., $n_P \cos^2\lambda$; (b) the S-wave intensity times number of events; i.e., $n_S \sin^2\lambda$. These are the numbers of events that would be observed in each interval for the amplitude under consideration, if it were the only amplitude. The fraction of S-wave intensity integrated over the range $0.8 < m_{K\pi} < 1.0\,\mathrm{GeV}/c^2$ is found to be $(7.3 \pm 1.8)\%$. (c) The evolution of γ/π with $m_{K\pi}$, for the two sets of strong phases.

to resolve the strong phase ambiguity. The dominant P-wave has the canonical Breit-Wigner form with a phase δ_P that increases rapidly with $K\pi$ invariant mass $m_{K\pi}$, while the S-wave phase δ_S increases slowly with $m_{K\pi}$[12]. Accordingly, $\delta_S - \delta_P$, where δ_P is assumed to be common to the three $B \to J/\psi\, K\pi$ P-wave amplitudes, is expected to decrease rapidly as $m_{K\pi}$ increases from below to above the K^* resonance. As shown in Figure 2, find that one solution for $\delta_S - \delta_P$ yields this expected behaviour while the other has precisely the opposite behavior. Thus the strong phase ambiguity is resolved

$$\begin{aligned} \delta_{\parallel} - \delta_0 &= (-2.73 \pm 0.10 \pm 0.05)\,\mathrm{rad}, \\ \delta_{\perp} - \delta_0 &= (+2.96 \pm 0.07 \pm 0.05)\,\mathrm{rad}, \end{aligned} \tag{5}$$

Finally, we measure $\cos 2\beta$ using *CP* channel $B^0 \to J/\psi\, K^{*0}(K^0_S\pi^0)$. We determine

$$\cos 2\beta = +2.72^{+0.50}_{-0.79}(\mathrm{stat}) \pm 0.27(\mathrm{syst}). \tag{6}$$

We determine the significance of the sign of cos2β using simulated experiments., where the generated values for sin2β and cos2β are +0.731 and +0.68, respectively. An unbinned likelihood fit is performed to this distribution, using the sum of two Gaussian functions. The relative proportion of these experiments that measure $\cos 2\beta$ to be $+2.72$ and -2.72 are used to discriminate between the $\cos 2\beta = \pm\sqrt{1-\sin^2 2\beta_0} = \pm 0.68$ hypotheses. We find that $\cos 2\beta$ is positive at the 86% confidence level.

4. Conclusion

We have presented new results on the measurement of sin2β and cos2β using B^0 decays to final states containing a charmonium meson and a K^0 or K^{*0}. We find

$$\begin{aligned} \sin 2\beta &= 0.722 \pm 0.040(\mathrm{stat}) \pm 0.023(\mathrm{syst}), \\ \cos 2\beta &= +2.72^{+0.50}_{-0.79}(\mathrm{stat}) \pm 0.27(\mathrm{syst}). \end{aligned} \tag{7}$$

consistent with the range implied by other measurements and theoretical estimates of the magnitudes of CKM matrix elements in the context of the Standard Model[11].

Acknowledgments

The author's work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48. The collaboration is grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality.

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