Improved Measurement of CP Asymmetries in $B^0 \to (c\bar{c})K^{0(*)}$ Decays

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We present results on time-dependent *CP* asymmetries in neutral *B* decays to several *CP* eigenstates. The measurements use a data sample of about 227×10^6 $\Upsilon(4S) \rightarrow B\overline{B}$ decays collected by the *BABAR* detector at the PEP-II asymmetric-energy *B* Factory at SLAC. The amplitude of the *CP*asymmetry, $\sin 2\beta$ 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. We measure $\sin 2\beta = 0.722 \pm 0.040(\mathrm{stat}) \pm 0.023(\mathrm{syst})$ in agreement with the standard model expectation.

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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 $\sin 2\beta$ [4]. The angle β is $\arg[-V_{\mathrm{cd}}V_{\mathrm{cb}}^*/V_{\mathrm{td}}V_{\mathrm{tb}}^*]$, where V_{ij} are CKM matrix elements.

In this Letter we report on an updated measurement of $\sin 2\beta$ in $(227 \pm 2) \times 10^6$ $B\overline{B}$ decays using B^0 decays to the final states $J/\psi K_S^0$, $J/\psi K_L^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, $\eta_c K_S^0$, and $J/\psi K^{*0}$ ($K^{*0} \to K_S^0\pi^0$) [5]. The *BABAR* detector and the measurement technique are described in detail in Refs. [6,7], respectively. Changes in the analysis with respect to the previously published result include 140×10^6 more $B\overline{B}$ events, an improved event reconstruction applied to all of the data, a new flavor-tagging algorithm, and fewer assumptions about the CP properties of background events.

The proper-time distribution of B meson decays to a CP eigenstate f can be expressed in terms of a complex parameter λ [8], 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

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

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 is due to the interference between direct decay and decay after a net B^0-$\overline{B}^0$oscillation. A nonzero 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 $b \to c\bar{c}s$ decays that contain a charmonium meson [8]. 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

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

with $\eta_f = -1$ for $J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, and $\eta_c K_S^0$, and $+1$ for $J/\psi K_L^0$. Because of the presence of even ($L = 0, 2$) and odd ($L = 1$) orbital angular momenta in the $J/\psi K^{*0}$ final state, there can be CP-even and CP-odd contributions to the decay rate. When the angular information in the decay is ignored, the measured CP asymmetry in $J/\psi K^{*0}$ is reduced by a factor $|1 - 2R_\perp|$, where $R_\perp$ is the fraction of the $L = 1$ contribution. We have measured $R_\perp = 0.230 \pm 0.015 \pm 0.004$ [9], which gives an effective $\eta_f = 0.51 \pm 0.04$, after acceptance corrections.

In addition to the CP modes described above, we utilize a large sample (B_{flav}) of B^0 decays to the flavor eigenstates $D^{(*)-}h^+$, ($h^+ = \pi^+$, ρ^+, and a_1^+) and $J/\psi K^{*0}$ ($K^{*0} \to K^+\pi^-$) for calibrating our flavor tagging and Δt resolution. Studies to measure apparent CP violation from unphysical sources are performed with a control sample of B^+ mesons decaying to the final states $J/\psi K^{(*)+}$, $\psi(2S)K^+$, $\chi_{c1}K^+$, and $\eta_c K^+$. The event selection and candidate reconstruction are unchanged from those described in Refs. [1,7,10], except that only the $\eta_c \to K_S^0 K^+\pi^-$ channel is used in the $B^0 \to \eta_c K_S^0$ and $B^\pm \to \eta_c K^\pm$ modes ($2.91 < m_{K_S^0 K^+\pi^-} < 3.05\ \mathrm{GeV}/c^2$).

The time interval Δt between the two B decays is calculated from the measured separation Δz between the decay vertices of B_{rec} and B_{tag} along the collision (z) axis [7]. We find the z position of the B_{rec} vertex from its charged tracks. The B_{tag} decay vertex is determined by fitting tracks not belonging to the B_{rec} candidate to a common vertex, employing constraints from the beam spot location and the B_{rec} momentum [7]. We accept events with a calculated Δt uncertainty of less than 2.5 ps and

TABLE I. Efficiencies ϵ_i, average mistag fractions w_i, mistag fraction differences $\Delta w_i \equiv w_i(B^0) - w_i(\overline{B}^0)$, and Q extracted for each tagging category i from the B_{flav} data.

Category	ε (%)	w (%)	Δw (%)	Q (%)
Lepton	8.6 ± 0.1	3.2 ± 0.4	-0.2 ± 0.8	7.5 ± 0.2
Kaon I	10.9 ± 0.1	4.6 ± 0.5	-0.7 ± 0.9	9.0 ± 0.2
Kaon II	17.1 ± 0.1	15.6 ± 0.5	-0.7 ± 0.8	8.1 ± 0.2
Kaon-Pion	13.7 ± 0.1	23.7 ± 0.6	-0.4 ± 1.0	3.8 ± 0.2
Pion	14.5 ± 0.1	33.0 ± 0.6	5.1 ± 1.0	1.7 ± 0.1
Other	10.0 ± 0.1	41.1 ± 0.8	2.4 ± 1.2	0.3 ± 0.1
All	74.9 ± 0.2			30.5 ± 0.4

$|\Delta t| < 20$ ps. The fraction of events satisfying these requirements is 95%. The rms Δt resolution is 1.1 ps for the 99.7% of these events that exclude outliers.

We use multivariate algorithms to identify signatures of B decays that determine ("tag") the flavor at decay of the B_{tag} to be either a B^0 or $\overline{B}^0$. Primary leptons from semileptonic B decays are selected from identified electrons and muons as well as isolated energetic tracks. The charges of identified kaon candidates define a kaon tag. Soft pions from D^{*+} decays are selected on the basis of their momentum and direction with respect to the thrust axis of B_{tag}. These algorithms are combined to account for correlations among different sources of flavor information and to provide an estimate of the mistag probability for each event. These algorithms have been improved relative to Ref. [1] with the addition of information from low-momentum (secondary) electrons, $\Lambda \to p\pi$ decays, and additional correlations among identified kaon candidates.

Each event is assigned to one of six tagging categories if the estimated mistag probability is less than 45%. The Lepton category contains events with an identified lepton; the remaining events are divided into the Kaon I, Kaon II, Kaon-Pion, Pion, or Other categories based on the estimated mistag probability. This new definition of tagging categories improves the overall performance of the tagging algorithm, while largely preserving the separation of events with differing sources of tagging information. For each category (i), the tagging efficiency ε_i and fraction w_i of events having the wrong tag assignment are measured from data (Table I). The effective tagging efficiency $Q \equiv \sum_i \varepsilon_i (1-2w_i)^2$ improves by about 5% (relative) over the algorithm used in Ref. [1]. In addition, the correlations among the mistag parameters and those of the Δt resolution function are reduced.

The beam-energy substituted mass $m_{\text{ES}} = \sqrt{(E_{\text{beam}}^{\text{cm}})^2 - (p_B^{\text{cm}})^2}$ (all modes except for $J/\psi K_L^0$) or the difference ΔE between the candidate center-of-mass energy and $E_{\text{beam}}^{\text{cm}}$ ($J/\psi K_L^0$ channel) are used to determine the composition of our final sample (Fig. 1). Here, $E_{\text{beam}}^{\text{cm}}$ and p_B^{cm} are the beam energy and B momentum in the center-of-mass frame. Events with $m_{\text{ES}} > 5.2\ \text{GeV}/c^2$ ($\Delta E <$ 80 MeV) are used so that the properties of the background contributions can be measured. The more restricted signal region (Table II) contains 7730 CP candidate events that satisfy the tagging and vertexing requirements.

For all modes except $\eta_c K_S^0$ and $J/\psi K_L^0$ we use simulated events to estimate the fractions of events that peak in the m_{ES} signal region due to cross-feed from other decay modes (peaking background). For the $\eta_c K_S^0$ mode the cross-feed fraction is determined from a fit to the $M_{KK\pi}$ and m_{ES} distributions in data. For the $J/\psi K_L^0$ decay mode,

TABLE II. Number of events N_{tag} in the signal region after tagging and vertexing requirements, signal purity P including the contribution from peaking background, and results of fitting for CP asymmetries in the B_{CP} sample and various subsamples. In addition, results on the B_{flav} and charged B control samples test that no artificial CP asymmetry is found where we expect no CP violation ($\sin 2\beta = 0$). Errors are statistical only. The signal region is $5.27 < m_{\text{ES}} <$ 5.29 GeV/c^2 ($|\Delta E| < 10$ MeV for $J/\psi K_L^0$).

Sample	N_{tag}	P (%)	$\sin 2\beta$
Full CP sample	7730	76	0.722 ± 0.040
$J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, $\eta_c K_S^0$	4370	90	0.75 ± 0.04
$J/\psi K_L^0$	2788	56	0.57 ± 0.09
$J/\psi K^{*0}$ ($K^{*0} \to K_S^0 \pi^0$)	572	68	0.96 ± 0.32
1999–2002 data	3032	77	0.74 ± 0.06
2003–2004 data	4698	77	0.71 ± 0.05
$J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, $\eta_c K_S^0$ only ($\eta_f = -1$)			
$J/\psi K_S^0$ ($K_S^0 \to \pi^+\pi^-$)	2751	96	0.79 ± 0.05
$J/\psi K_S^0$ ($K_S^0 \to \pi^0\pi^0$)	653	88	0.65 ± 0.12
$\psi(2S)K_S^0$ ($K_S^0 \to \pi^+\pi^-$)	485	82	0.88 ± 0.14
$\chi_{c1}K_S^0$	194	81	0.69 ± 0.23
$\eta_c K_S^0$	287	64	0.17 ± 0.25
Lepton category	490	96	0.75 ± 0.08
Kaon I category	648	93	0.75 ± 0.08
Kaon II category	1021	89	0.77 ± 0.09
Kaon-Pion category	769	90	0.77 ± 0.15
Pion category	835	87	0.96 ± 0.22
Other category	607	88	0.23 ± 0.51
B_{flav} sample	75 878	85	0.021 ± 0.013
B^+ sample	18 294	88	0.003 ± 0.020

the composition, effective η_f, and ΔE distribution of the individual background sources are determined either from simulation (for $B \to J/\psi X$) or from the $m_{\ell^+\ell^-}$ sidebands in data (for fake $J/\psi \to \ell^+\ell^-$).

We determine $\sin 2\beta$ with a simultaneous maximum likelihood fit to the Δt distributions of the tagged B_{CP} and $B_{\rm flav}$ samples. 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. The Δt distributions for the signal are convolved with a common resolution function, modeled by the sum of three Gaussians [7]. Backgrounds are incorporated with an empirical description of their Δt spectra, containing prompt and nonprompt components convolved with a resolution function [7] distinct from that of the signal.

There are 65 free parameters in the fit: $\sin 2\beta$ (1), the average mistag fractions w and the differences Δw between B^0 and $\overline{B}^0$ mistag fractions for each tagging category (12), parameters for the signal Δt resolution (7), parameters for CP background time dependence (8), and the difference between B^0 and $\overline{B}^0$ reconstruction and tagging efficiencies (7), for $B_{\rm flav}$ background, time dependence (3), Δt resolution (3), and mistag fractions (24). For the CP modes (except for $J/\psi K_L^0$), the apparent CP asymmetry of the nonpeaking background in each tagging category is allowed to float. This asymmetry is parameterized so that it does not depend on the value of $\sin 2\beta$.

We fix $\tau_{B^0} = 1.536$ ps, $\Delta m_d = 0.502$ ps^{-1} [11], $|\lambda| = 1$, and $\Delta\Gamma = 0$. The determination of the mistag fractions and Δt resolution function parameters for the signal is dominated by the high-statistics $B_{\rm flav}$ sample. Background parameters are determined mainly from events with $m_{\rm ES} < 5.27$ GeV/c^2.

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

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

Fig. 2 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.

In a separate fit with only the $\eta_f = -1$ sample, we obtain $|\lambda| = 0.950 \pm 0.031({\rm stat}) \pm 0.015({\rm syst})$. The correlation between the coefficients multiplying the $\sin(\Delta m_d \Delta t)$ and $\cos(\Delta m_d \Delta t)$ terms in Eq. (1) is -2%.

The sources of systematic error are summarized in Table III. These include the uncertainties in the level and

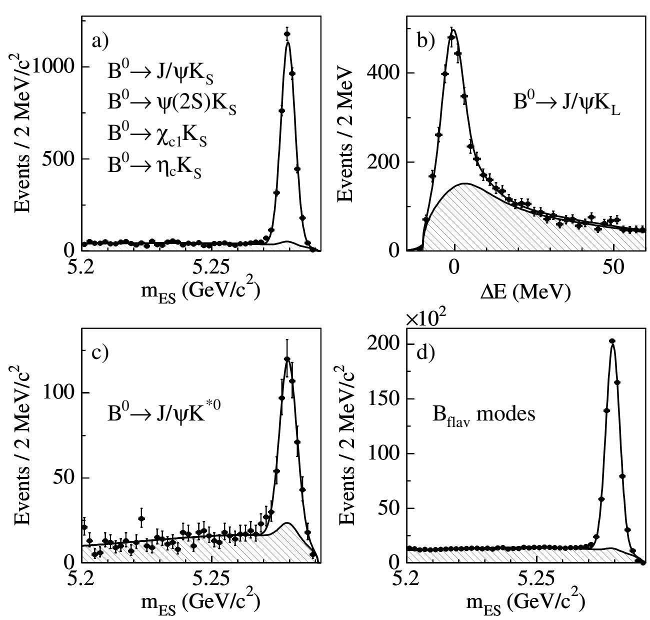

FIG. 1. Distributions for B_{CP} and $B_{\rm flav}$ candidates satisfying the tagging and vertexing requirements: (a) $m_{\rm ES}$ for the final states $J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, and $\eta_c K_S^0$; (b) ΔE for the final state $J/\psi K_L^0$; (c) $m_{\rm ES}$ for $J/\psi K^{*0}$ ($K^{*0} \to K_S^0\pi^0$); and (d) $m_{\rm ES}$ for the $B_{\rm flav}$ sample. In each plot, the shaded region is the estimated background contribution.

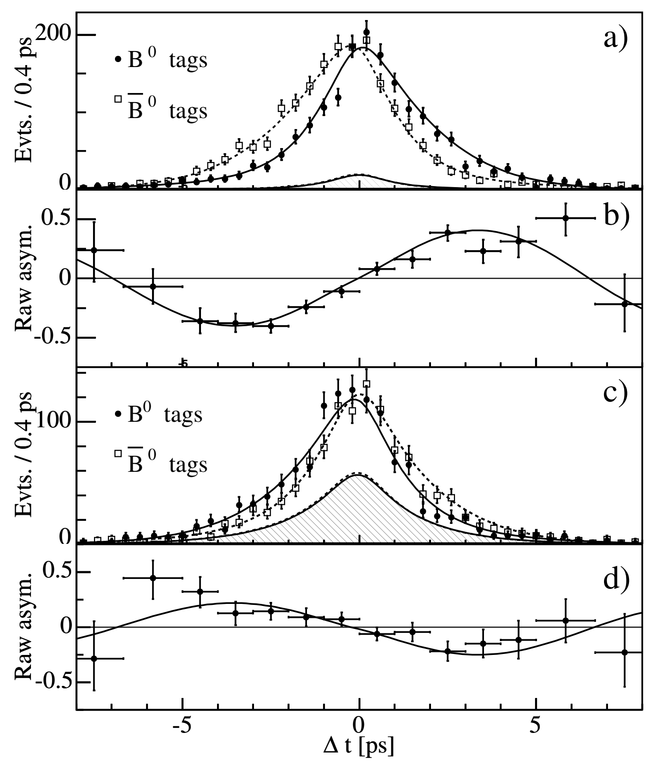

FIG. 2. (a) Number of $\eta_f = -1$ candidates ($J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, and $\eta_c K_S^0$) in the signal region with a B^0 tag N_{B^0} and with a $\overline{B}^0$ tag $N_{\overline{B}^0}$, and (b) the raw asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$, as functions of Δt. (c) and (d) are the corresponding plots for the $\eta_f = +1$ mode $J/\psi K_L^0$. 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.

TABLE III. Sources of systematic error on $\sin 2\beta$ and $|\lambda|$.

Source	σ ($\sin 2\beta$)	σ ($|\lambda|$)
CP backgrounds	0.012	0.002
Δt resolution function	0.011	0.003
$J/\psi K_L^0$ backgrounds	0.011	not applicable
Mistag fraction differences	0.007	0.001
Beam spot	0.007	0.001
Δm_d, τ_B, $\Delta\Gamma/\Gamma$, $|\lambda|$	0.005	0.001
Tag-side interference	0.001	0.014
MC statistics	0.003	0.003
Total systematic error	0.023	0.015

CP asymmetry of the peaking background, the assumed parameterization of the Δt resolution function, possible differences between the B_{flav} and B_{CP} mistag fractions, knowledge of the event-by-event beam spot position, and the possible interference between the suppressed $\bar{b} \to \bar{u}c\bar{d}$ amplitude with the favored $b \to c\bar{u}d$ amplitude for some tagside B decays [12]. In addition, we include the variation due to the assumed values of $|\lambda|$ and $\Delta\Gamma$. We assign the change in the measured $\sin 2\beta$ when we float $|\lambda|$ and when we set $\Delta\Gamma/\Gamma = \pm 0.02$, the latter being considerably larger than recent standard model estimates [13]. The total systematic error on $\sin 2\beta$ ($|\lambda|$) is 0.023 (0.015).

The large B_{CP} sample allows a number of consistency checks, including separation of the data by decay mode and tagging category, as shown in Table II. Considering statistical errors only, the probability of finding a worse agreement in measured $\sin 2\beta$ values across decay modes is 7% and between tagging categories is 86%. The results of fits to the control samples of non-CP decay modes indicate no statistically significant asymmetry.

This measurement of $\sin 2\beta$ supersedes our previous result [1] and is 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 [14]. The theoretical uncertainty on the interpretation of the measurement of $\sin 2\beta$ in these modes is approximately 0.01 [8]. As the current measurement is statistics limited, future measurements will add further model-independent constraints on the position of the apex of the unitarity triangle [14].

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[1] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **89**, 201802 (2002).
[2] BELLE Collaboration, K. Abe *et al.*, Phys. Rev. D **66**, 071102 (2002).
[3] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
[4] A. B. Carter and A. I. Sanda, Phys. Rev. D **23**, 1567 (1981); I. I. Bigi and A. I. Sanda, Nucl. Phys. **B193**, 85 (1981).
[5] Charge-conjugate reactions are included implicitly unless otherwise specified.
[6] *BABAR* Collaboration, B. Aubert *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 1 (2002).
[7] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **66**, 032003 (2002).
[8] See, for example, Review of Particle Properties, edited by S. Eidelman *et al.*,, [and , Phys. Lett. B **592**, 136 (2004)].
[9] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **71**, 032005 (2005).
[10] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **70**, 011101 (2004).
[11] Particle Data Group, S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004).
[12] O. Long, M. Baak, R. N. Cahn, and D. Kirkby, Phys. Rev. D **68**, 034010 (2003).
[13] A. S. Dighe *et al.*, Nucl. Phys. **B624**, 377 (2002); M. Ciuchini *et al.* J. High Energy Phys. 08 (2003), 031.
[14] See, for example, F. J. Gilman, K. Kleinknecht, and B. Renk, in Ref. [8], p. 130.