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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 $\Upsilon(4S) \to B\overline{B}$ decays collected by the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC. The amplitude of the *CP* asymmetry, $\sin2\beta$ 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 $\sin2\beta = 0.722 \pm 0.040(\text{stat}) \pm 0.023(\text{syst})$ 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 $\sin2\beta$ [4]. The angle β is $\arg\left[-V_{\rm cd}V_{\rm cb}^*/V_{\rm td}V_{\rm tb}^*\right]$, where V_{ij} are CKM matrix elements.

In this Letter we report on an updated measurement of $\sin2\beta$ in $(227 \pm 2) \times 10^6$ $B\overline{B}$ decays using B^0 decays to the final states $J/\psi K^0_S$, $J/\psi K^0_L$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$, and $J/\psi K^{*0}(K^{*0} \to K^0_S\pi^0)$ [5]. The *BABAR* detector and the measurement technique are described in detail in Refs. [6] and [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 $B_{\rm tag}$ 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 $B_{\rm rec}$ and $B_{\rm tag}$, 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 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 [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

$$A_{CP}(\Delta t) \equiv \frac{\mathrm{f}_+ - \mathrm{f}_-}{\mathrm{f}_+ + \mathrm{f}_-} = -\eta_f\,\sin2\beta\,\sin\left(\Delta m_d\,\Delta t\right), \quad (2)$$

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 $J/\psi K^0_L$. Due to the presence of even (L=0, 2) and odd (L=1) orbital angular momenta in the $B \to J/\psi K^{*0}$ 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 ($B_{\rm flav}$) of B^0 decays to the flavor eigenstates $D^{(*)-}h^+(h^+ = \pi^+, \rho^+$, and $a_1^+)$ and $J/\psi K^{*0}(K^{*0} \to K^+\pi^-)$ for calibrating our flavor tagging and Δt resolution. Validation studies 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 $\eta_c \to K^0_S K^+\pi^-$ channel is used in the $B^0 \to \eta_c K^0_S$ and $B^\pm \to \eta_c K^\pm$ modes ($2.91 < m_{K^0_S K^+\pi^-} < 3.05\,\text{GeV}/c^2$).

The time interval Δt between the two B decays is calculated from the measured separation Δz between the decay vertices of $B_{\rm rec}$ and $B_{\rm tag}$ along the collision (z) axis [7]. We find the z position of the $B_{\rm rec}$ vertex from its charged tracks. The $B_{\rm tag}$ decay vertex is determined by fitting tracks not belonging to the $B_{\rm rec}$ candidate to a common vertex, employing constraints from the beam spot location and the $B_{\rm rec}$ momentum [7]. We accept events with a calculated Δt uncertainty of less than 2.5 ps and $|\Delta t| < 20$ ps. The fraction of events satisfying these requirements is 95%. The r.m.s. 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 $B_{\rm tag}$ to be either a B^0 or $\overline{B}^0$. Primary leptons from semileptonic B decays are selected from identified elec-

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 $B_{\rm flav}$ sample.

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

trons 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 $B_{\rm tag}$. 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 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 $m_{\rm ES} = \sqrt{(E^{\rm cm}_{\rm beam})^2 - (p^{\rm cm}_B)^2}$ (all modes except for $J/\psi K^0_L$) or the difference ΔE between the candidate center-of-mass energy and $E^{\rm cm}_{\rm beam}$ ($J/\psi K^0_L$ channel) are used to determine the composition of our final sample (Fig. 1). Here, $E^{\rm cm}_{\rm beam}$ and $p^{\rm cm}_B$ are the beam energy and B momentum in the center-of-mass frame. Events with $m_{\rm ES} > 5.2\,{\rm GeV}/c^2$ ($\Delta E < 80\,{\rm MeV}$) 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 $\eta_c K^0_S$ and $J/\psi K^0_L$ we use simulated events to estimate the fractions of events that peak in the $m_{\rm ES}$ signal region due to cross-feed from other decay modes (peaking background). For the $\eta_c K^0_S$ mode the cross-feed fraction is determined from a fit to the $M_{KK\pi}$ and $m_{\rm ES}$ distributions in data. For the $J/\psi K^0_L$ decay mode, 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 sin2β 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 non-prompt components convolved with a resolution function [7] distinct from that of the signal.

There are 65 free parameters in the fit: sin2β (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 tag-

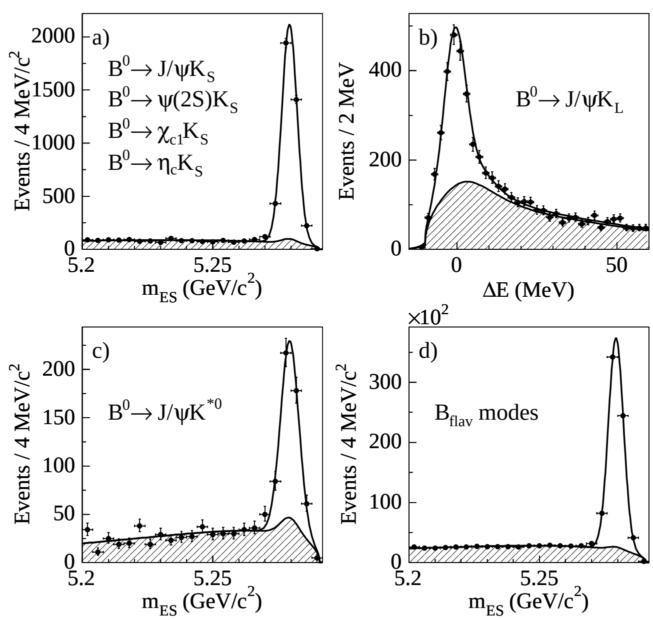

FIG. 1: Distributions for B_{CP} and $B_{\rm flav}$ candidates satisfying the tagging and vertexing requirements: a) $m_{\rm ES}$ for the final states $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$, b) ΔE for the final state $J/\psi K^0_L$, c) $m_{\rm ES}$ for $J/\psi K^{*0}(K^{*0}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

TABLE II: Number of events $N_{\rm tag}$ 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 $B_{\rm flav}$ and charged B control samples test that no artificial CP asymetry is found where we expect no CP violation ($\sin2\beta = 0$). Errors are statistical only. The signal region is $5.27 < m_{\rm ES} < 5.29\,{\rm GeV}/c^2$ ($|\Delta E| < 10\,{\rm MeV}$ for $J/\psi\,K^0_L$).

Sample	$N_{\rm tag}$	$P(\%)$	$\sin2\beta$
Full CP sample	7730	76	0.722 ± 0.040
$J/\psi\,K^0_S$,$\psi(2S)K^0_S$,$\chi_{c1}K^0_S$,$\eta_c K^0_S$	4370	90	0.75 ± 0.04
$J/\psi\,K^0_L$	2788	56	0.57 ± 0.09
$J/\psi\,K^{*0}(K^{*0}\to K^0_S\pi^0)$	572	68	0.96 ± 0.32
1999-2002 data	3032	77	0.74 ± 0.06
2003-2004 data	4698	77	0.71 ± 0.05
$J/\psi\,K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$ only ($\eta_f = -1$)			
$J/\psi\,K^0_S$ ($K^0_S\to\pi^+\pi^-$)	2751	96	0.79 ± 0.05
$J/\psi\,K^0_S$ ($K^0_S\to\pi^0\pi^0$)	653	88	0.65 ± 0.12
$\psi(2S)K^0_S$ ($K^0_S\to\pi^+\pi^-$)	485	82	0.88 ± 0.14
$\chi_{c1}K^0_S$	194	81	0.69 ± 0.23
$\eta_c K^0_S$	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
$B_{\rm flav}$ sample	72878	85	0.021 ± 0.013
B^+ sample	18294	88	0.003 ± 0.020

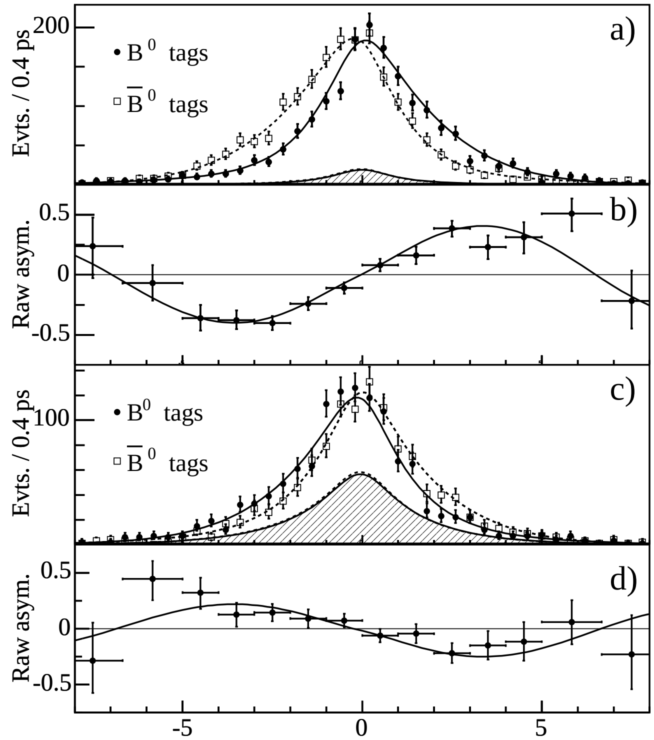

FIG. 2: a) Number of $\eta_f = -1$ candidates ($J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$) in the signal region with a B^0 tag N_{B^0} and with a $\overline{B}^0$ tag $N_{\overline{B}^0}$, and b) the raw asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$, as functions of Δt. 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.

ging efficiencies (7); for $B_{\rm flav}$ background, time dependence (3), Δt resolution (3), and mistag fractions (24). For the CP modes (except for $J/\psi\,K^0_L$), the apparent CP asymmetry of the non-peaking background in each tagging category is allowed to float. This asymmetry is parameterized so that it does not depend on the value of $\sin2\beta$.

We fix $\tau_{B^0} = 1.536\,{\rm ps}$, $\Delta m_d = 0.502\,{\rm ps}^{-1}$ [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 $m_{\rm ES} < 5.27\,{\rm GeV}/c^2$.

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

$$\sin2\beta = 0.722 \pm 0.040({\rm stat}) \pm 0.023({\rm syst}).$$

Figure 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 high purity $\eta_f = -1$ sample, we obtain $|\lambda| = 0.950 \pm 0.031({\rm stat}) \pm 0.013({\rm syst})$. 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 CP asymmetry of the peaking background, the assumed parameterization of the Δt resolution function, possible differences between the $B_{\rm flav}$ 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 tag-side 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 $\sin2\beta$ 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 $\sin2\beta$ ($|\lambda|$) is 0.023 (0.013).

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 $\sin2\beta$ 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

TABLE III: Sources of systematic error on sin2β and $|\lambda|$.

Source	$\sigma(\sin 2\beta)$	$\sigma(\lvert\lambda\rvert)$
CP backgrounds	0.012	0.002
Δt resolution function	0.011	0.003
$J/\psi K^0_L$ backgrounds	0.011	N/A
Mistag fraction differences	0.007	0.001
Beam spot	0.007	0.001
Δm_d, τ_B, $\Delta\Gamma/\Gamma$, $\lvert\lambda\rvert$	0.005	0.001
Tag-side interference	0.003	0.012
MC statistics	0.003	0.003
Total systematic error	0.023	0.013

indicate no statistically significant asymmetry.

This measurement of sin2β 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 sin2β 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]. We are 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. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from CONACyT (Mexico), A. P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

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