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Measurement of sin2β with *BABAR*

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We present updated results on time-dependent *CP*-violating asymmetries in neutral B decays to several *CP* eigenstates containing charmonium. In the Standard Model, the amplitude of these asymmetries is proportional to sin2β. We measure sin2β = 0.741 ± 0.067 (stat) ± 0.034 (syst) from a data sample of about 88 million $\Upsilon(4S) \rightarrow B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC. We have also measured *CP*-violating asymmetries in open charm, and penguin modes sensitive to sin2β, which provide important consistency tests of the Standard Model.

1. INTRODUCTION

In the Standard Model of electroweak interactions, *CP* violation arises as a consequence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. Observations of *CP* violation in B^0 decays to charmonium were reported last year by the *BABAR* [1] and Belle [2] collaborations. The PEP-II collider at SLAC has since delivered an additional 63 fb^{-1}, thereby approximately tripling the *BABAR* data sample near the Υ(4S) resonance. Here we report a more precise measurement [3], as well as updated and new results from non-charmonium B^0 decays, using a sample of about 88 million $B\overline{B}$ decays. Changes in the analysis with respect to the previously published result [1] include the processing of all data with a uniform event reconstruction, a new flavor-tagging algorithm, and the addition of the decay mode $B^0 \rightarrow \eta_c K^0_S$. The *BABAR* detector and the measurement technique are described in detail in Refs. [4] and [5].

We reconstruct a sample of neutral B mesons (B_{CP}) decaying to *CP* eigenstates and examine each event for evidence that the recoiling B meson decayed as a B^0 or $\overline{B}^0$ (flavor tag). The proper-time distribution for such events can be expressed in terms of a complex parameter λ that depends on both the B^0-$\overline{B}^0$ oscillation amplitude and the amplitudes describing $\overline{B}^0$ and B^0 decays to the *CP* final state. The decay rate $\mathrm{f}_+(\mathrm{f}_-)$, when the tagging meson is a $B^0(\overline{B}^0)$, is given by

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

where $\Delta t = t_{\rm rec} - t_{\rm tag}$ is the difference between the proper decay times of the reconstructed B meson ($B_{\rm rec}$) and the tagging B meson ($B_{\rm tag}$), τ_{B^0} is the B^0 lifetime, and Δm_d is the B^0-$\overline{B}^0$ oscillation frequency.

In the Standard Model, $\lambda = \eta_f e^{-2i\beta}$ for charmonium modes (e.g. $B^0 \rightarrow J/\psi K^0_S$), where η_f is the *CP* eigenvalue of the final state f, and $\beta \equiv \arg\left[-V_{\rm cd}V^*_{\rm cb}/V_{\rm td}V^*_{\rm tb}\right]$. The time-dependent *CP*-violating asymmetry then becomes

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

2. TAGGING AND VERTEXING

A measurement of A_{CP} requires a determination of the experimental Δt resolution and the fraction w of events in which the tag assignment is incorrect. This mistag fraction reduces the observed *CP* asymmetry by a factor $1 - 2w$. Mistag fractions and Δt resolution functions are determined from a sample of neutral B mesons that

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Table 1
Tagging efficiency, mistag fraction and quality factor for each category (measured from data).

Category	ε (%)	w (%)	Q (%)
`Lepton`	9.1 ± 0.2	3.3 ± 0.6	7.9 ± 0.3
`Kaon I`	16.7 ± 0.2	10.0 ± 0.7	10.7 ± 0.4
`Kaon II`	19.8 ± 0.3	20.9 ± 0.8	6.7 ± 0.4
`Inclusive`	20.0 ± 0.3	31.5 ± 0.9	2.7 ± 0.3
All	65.6 ± 0.5		28.1 ± 0.7

decay to flavor eigenstates ($B_{\rm flav}$) consisting of the channels $D^{(*)-}h^+ (h^+ = \pi^+, \rho^+$, and $a_1^+)$ [1] and $J/\psi K^{*0} (K^{*0} \to K^+\pi^-)$.

We use multivariate algorithms to identify signatures of B decays that indicate the flavor of $B_{\rm tag}$. Based on the output of a multi-level neural network, we assign each event to one of four hierarchical, mutually exclusive tagging categories. The `Lepton` category contains events with an identified lepton. Events with kaon and soft pion candidates (but not identified leptons) are assigned to the `Kaon I` or `Kaon II` category. All other events are assigned to the `Inclusive` category or excluded from further analysis based on the estimated mistag probability. The tagging efficiencies ε_i for the four tagging categories are measured from data and are summarized in Table 1. The figure of merit for tagging is the effective tagging efficiency $Q \equiv \sum_i \varepsilon_i (1-2w_i)^2$. This algorithm improves Q by about 7% (relative) over the algorithm used in Ref. [5].

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. We employ constraints from the beam spot location and the $B_{\rm rec}$ momentum to improve vertex reconstruction efficiency and resolution. The fraction of events satisfying the vertex quality requirements is 95%. The r.m.s. Δt resolution for practically all accepted events is 1.1 ps.

3. CHARMONIUM MODES

3.1. Event sample

We reconstruct B^0 decays to the following final states containing charmonium: $\eta_f = -1$ modes $J/\psi K_S^0$, $\psi(2S) K_S^0$, $\chi_{c1} K_S^0$, $\eta_c K_S^0$; $\eta_f = +1$ mode $J/\psi K_L^0$; and $J/\psi K^{*0} (K^{*0} \to K_S^0 \pi^0)$. This last mode, $J/\psi K^{*0}$, is not a pure *CP* eigenstate, but is a combination of even (L=0, 2) and odd (L=1) orbital angular momenta final states. In this analysis we do not separate the angular components, so the measured *CP* asymmetry is reduced by a factor $1 - 2R_\perp$, where $R_\perp$ is the fraction of the L=1 component. We have measured $R_\perp = (16.0 \pm 3.5)\%$ [6], which gives an effective $\eta_f = 0.65 \pm 0.07$ for the $J/\psi K^{*0}$ mode after acceptance corrections.

The event selection criteria for the B_{CP} sample are described in Ref. [3]. The selection includes two main discriminating variables constructed from the measured energy and momentum of the final state: the difference ΔE between the decay energy and the beam energy in the center-of-mass frame, and the beam-energy substituted mass $m_{\rm ES} = \sqrt{(E_{\rm beam}^{\rm cm})^2 - (p_B^{\rm cm})^2}$. Since it is not well measured, we determine the K_L^0 momentum in the $J/\psi K_L^0$ mode by applying one of the kinematic constraints (effectively $m_{\rm ES}$), leaving only one (ΔE) of the two discriminating variables for the selection of this mode. Figure 1 shows the $m_{\rm ES}$ distribution for modes containing a K_S^0 or K^{*0} and the ΔE distribution for the $J/\psi K_L^0$ candidates.

To determine numbers of events and purities, a signal region $5.270\ (5.273) < m_{\rm ES} < 5.290\ (5.288)\,{\rm GeV}/c^2$ is used for modes containing K_S^0 (K^{*0}). In the $J/\psi K_L^0$ mode, the ΔE resolution the signal region is defined by $|\Delta E| < 10\,{\rm MeV}$. The signal region contains 2641 events that satisfy the tagging and vertexing requirements. In Table 2 we list the number of events and the signal purity for the tagged B_{CP} candidates.

3.2. Measurement of sin2β

We determine sin2β with a simultaneous unbinned maximum likelihood fit to the Δt distributions of the tagged B_{CP} and $B_{\rm flav}$ samples. In

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[1] Charge conjugation is implied throughout this paper, unless explicitly stated.

this fit, the Δt distributions of the B_{CP} sample are described by Eq. 1 with $|\lambda| = 1$, i.e. with the assumption of no direct CP violation. The Δt distributions 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 and flavor oscillation are reduced by the same factor, $1 - 2w$, due to flavor mistags.

There are 34 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 (8), parameters for the signal Δt resolution (8), and parameters for background time dependence (6), Δt resolution (3), and mistag fractions (8). We fix $\tau_{B^0} = 1.542\,\rm ps$ and $\Delta m_d = 0.489\,\rm ps^{-1}$ [7]. The fit to the B_{CP} and $B_{\rm flav}$ samples yields

$$\sin 2\beta = 0.741 \pm 0.067\ (\rm stat) \pm 0.034\ (\rm syst).$$

Figure 2 shows the Δt distributions and the raw asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$ versus Δt for the $\eta_f = -1$ and $\eta_f = +1$, overlaid with the projection of the likelihood fit result.

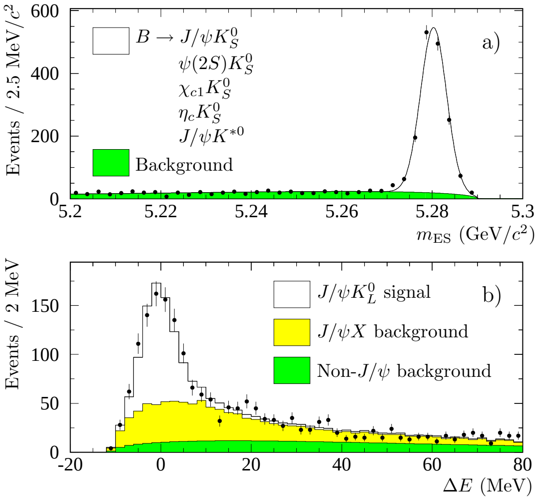

Figure 1. Distributions for B_{CP} candidates satisfying the tagging and vertexing requirements: a) all final states except $J/\psi\, K^0_L$, and b) $J/\psi\, K^0_L$.

Table 2
Number of events in the signal region after tagging and vertexing requirements, signal purity, and results of the CP asymmetry fits.

Sample	$N_{\rm tag}$	$P(\%)$	sin2β
$(J/\psi\,, \psi(2S), \chi_{c1}, \eta_c)K^0_S$	1506	94	0.76 ± 0.07
$J/\psi\, K^0_L$ $(\eta_f = +1)$	988	55	0.72 ± 0.16
$J/\psi\, K^{*0}(K^{*0} \to K^0_S\pi^0)$	147	81	0.22 ± 0.52
Full CP sample	2641	78	0.74 ± 0.07
$(J/\psi\,, \psi(2S), \chi_{c1}, \eta_c)K^0_S$ only $(\eta_f = -1)$			
$J/\psi\,(K^0_S \to \pi^+\pi^-)$	974	97	0.82 ± 0.08
$J/\psi\,(K^0_S \to \pi^0\pi^0)$	170	89	0.39 ± 0.24
$\psi(2S)$ $(K^0_S \to \pi^+\pi^-)$	150	97	0.69 ± 0.24
$\chi_{c1}K^0_S$	80	95	1.01 ± 0.40
$\eta_c K^0_S$	132	73	0.59 ± 0.32
`Lepton` category	220	98	0.79 ± 0.11
`Kaon I` category	400	93	0.78 ± 0.12
`Kaon II` category	444	93	0.73 ± 0.17
`Inclusive` category	442	92	0.45 ± 0.28
B^0 tags	740	94	0.76 ± 0.10
$\overline{B}^0$ tags	766	93	0.75 ± 0.10
$B_{\rm flav}$ sample	25375	85	0.02 ± 0.02
B^+ sample	22160	89	0.02 ± 0.02

The dominant sources of systematic error are the uncertainties in the background content, the assumed parameterization of the Δt resolution function, and possible differences between the $B_{\rm flav}$ and B_{CP} mistag fractions. Most systematic errors are determined with data and will continue to decrease with additional statistics.

The large B_{CP} sample allows a number of consistency checks, including separation of the data by decay mode, tagging category, and $B_{\rm tag}$ flavor. The results of fits to these subsamples are found to be statistically consistent. Fits to the control samples of non-CP decay modes (the $B_{\rm flav}$ sample and B^+ mesons decaying to the final states $J/\psi\, K^{(*)+}$, $\psi(2S)K^+$, $\chi_{c1}K^+$, $\eta_c K^+$, and $\overline{D}^{(*)0}\pi^+$) indicate no statistically significant asymmetry, as expected. The results of these checks are given in Table 2.

This measurement of sin2β improves upon the precision of each of the previous measurements [1,2] by a factor of two. The measured value is in good agreement with the expectation implied by the measurements and theoretical esti-

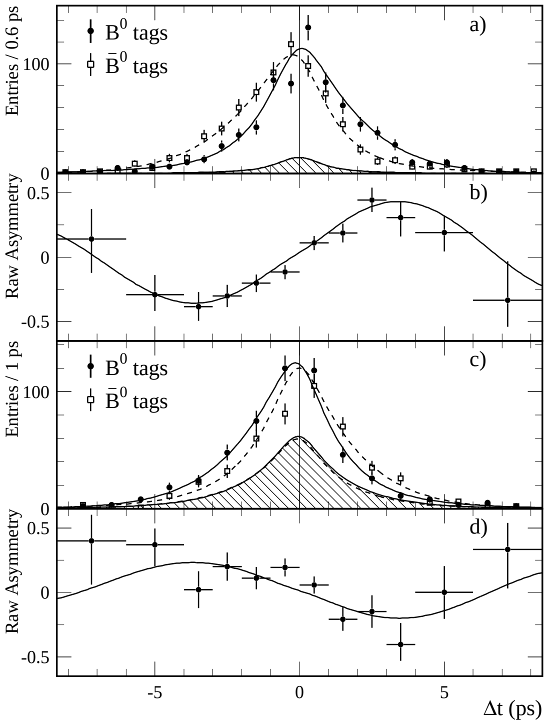

Figure 2. Number of tagged events, raw asymmetry, and fit projections as functions of Δt for $\eta_f = -1$ (a & b) and $\eta_f = +1$ (c & d) candidates. The shaded regions represent the background contributions.

mates of the magnitudes of CKM matrix elements in the context of the Standard Model, and provides a precise and model-independent constraint on the position of the apex of the Unitarity Triangle.

3.3. Direct *CP* violation

We also measure the parameter $|\lambda|$ in Eq. 1 from a fit to the $\eta_f = -1$ sample, which has high purity and requires minimal assumptions on the effect of backgrounds. This parameter is sensitive to the difference in the number of B^0- and $\overline{B}^0$-tagged events. In order to account for differences in reconstruction and tagging efficiencies for B^0 and $\overline{B}^0$ mesons, we incorporate five additional free parameters in this fit. We obtain $|\lambda| = 0.948 \pm 0.051$ (stat) $\pm$ 0.030 (syst). We simultaneously fit the coefficient of the sine term in Eq. 1 and find it to be 0.759 ± 0.074 (stat). These results are consistent with the no direct *CP* violation hypothesis ($|\lambda| = 1$) and with our $\sin 2\beta$ measurement.

4. OPEN CHARM MODE

Within the context of the Standard Model, the open charm decay $B^0 \to D^{*+}D^{*-}$ is expected to have a time-dependent *CP*-violating asymmetry [8]. Up to corrections due to theoretically uncertain penguin diagram contributions [9], the Cabibbo-suppressed tree diagram produces an asymmetry sensitive to $\sin 2\beta$. Factorization models predict that the penguin-induced correction is small [10], so comparisons with the *CP* asymmetry in charmonium modes provides a valuable test of these models and a consistency check on the Standard Model.

The selection of $B^0 \to D^{*+}D^{*-}$ candidates is described in Ref [11] and results in a sample of 102 tagged events with a purity of 82%. The $B^0 \to D^{*+}D^{*-}$ mode consists of three partial wave contributions with two different *CP* parities: even (*S*- and *D*-waves) and odd (*P*-wave). Since *CP*-even and odd components can be separated by a one-dimensional angular analysis in the transversity basis [12], we parameterize the tagged B^0 decay rate in terms of the transversity angle and fit for the complex *CP*-even (odd) parameters $\lambda_+(\lambda_\perp)$, and $R_\perp$ the fraction of signal events with *CP*-odd parity.

From a time-integrated fit and corrected for acceptance, we measure $R_\perp = 0.07 \pm 0.06(\text{stat}) \pm 0.03(\text{syst})$. Since the *CP*-odd fraction is small, we fix the *CP*-odd parameters in the time-dependent fit to those measured from the charmonium analysis, assuming the penguin diagram contribution is negligible, i.e. $|\lambda_\perp| = 1$ and $\text{Im}(\lambda_\perp) = -0.741$. With a suitably large statistical sample, one can fit the *CP*-odd and even parameters simultaneously.

Performing a time-dependent fit including both cosine and sine terms in Eq. 1 yields the preliminary result [11]

$$\begin{aligned} \mathrm{Im}(\lambda_+) &= 0.31 \pm 0.43(\mathrm{stat}) \pm 0.13(\mathrm{syst}) \\ |\lambda_+| &= 0.98 \pm 0.25(\mathrm{stat}) \pm 0.09(\mathrm{syst}). \end{aligned}$$

If the penguin contribution can be neglected, then $|\lambda_+| = 1$ and $\mathrm{Im}(\lambda_+) = -\sin 2\beta$. By making this assumption and refitting, we find that the change in the likelihood corresponds to a 2.7 standard deviation from the result of the fit in charmonium ($\sin 2\beta = 0.741$).

5. PENGUIN MODES

Since the tree diagram is Cabibbo-suppressed, the decay $B^0 \to J/\psi\pi^0$ ($\eta_f = +1$) has comparable tree and penguin contributions. The tree diagram has the same weak phase as charmonium modes containing neutral kaons (e.g. $B^0 \to J/\psi K^0_S$); however, a portion of the penguin diagram contributes a different weak phase. We therefore perform a time-dependent *CP*-violating asymmetry fit for the coefficients ($S_{J/\psi\,\pi^0}$ and $C_{J/\psi\,\pi^0}$) of the sine and cosine terms in Eq. 1.

We select 49 tagged events with a purity of 59% and measure the preliminary result [13]

$$\begin{aligned} C_{J/\psi\,\pi^0} &= 0.38 \pm 0.41\ (\mathrm{stat}) \pm 0.09\ (\mathrm{syst}), \\ S_{J/\psi\,\pi^0} &= 0.05 \pm 0.49\ (\mathrm{stat}) \pm 0.16\ (\mathrm{syst}). \end{aligned}$$

In the absence of the penguin contribution, we expect $C_{J/\psi\,\pi^0} = 0$ and $S_{J/\psi\,\pi^0} = -\sin 2\beta$.

The charmless decay $B^0 \to \phi K^0_S$ ($\eta_f = -1$) is dominated by gluonic penguin diagrams and within the Standard Model should have the same weak phase as the charmonium modes. The predicted deviation of the effective sin2β measured in this mode, compared to the Standard Model parameter, is smaller than 4% [14]. A measurement of sin2β in ϕK^0_S therefore probes new physics participating in penguin loops.

From the analysis described in Ref. [15], we find 66 tagged candidates with a purity of 50%. Setting $|\lambda| = 1$ and fitting only the coefficient $S_{\phi K^0_S}$ of the sine term in Eq. 1, we determine $S_{\phi K^0_S} = -0.19^{+0.52}_{-0.50}(\mathrm{stat}) \pm 0.09(\mathrm{syst})$. In the absence of new physics, $S_{\phi K^0_S} = \sin 2\beta$ at the few percent level.

In these first measurements from *BABAR* on the *CP*-violating asymmetry in penguin modes sensitive to sin2β, the statistical precision of the results do not yet provide a meaningful test of the Standard Model; however, high statistics in the future provide a good opportunity to challenge the theory.

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