Measurement of the CP Asymmetry Amplitude $\sin 2\beta$

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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 88 million $\Upsilon(4S) \rightarrow B\overline{B}$ decays collected between 1999 and 2002 with the BABAR detector at the PEP-II asymmetric-energy B Factory at SLAC. We study 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. The amplitude of the CP asymmetry, which in the Standard Model is proportional to $\sin^2 \beta$, is derived from the decay-time distributions in such events. We measure $\sin^2 \beta = 0.741 \pm 0.067 \text{ (stat)} \pm 0.034 \text{ (syst)}$ and $|\lambda| = 0.948 \pm 0.051 \text{ (stat)} \pm 0.030 \text{ (syst)}$. The magnitude of $\lambda$ is consistent with unity, in agreement with the Standard Model expectation of no direct CP violation in these modes.

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The Standard Model of electroweak interactions describes CP violation in weak interactions as a con-
sequence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. In this framework, measurements of CP asymmetries in the proper-time distribution of neutral B decays to charmonium final states provide a direct measurement of \( \sin 2 \beta \), where \( \beta \equiv \arg \left[-V_{cd} V_{ub}^* / V_{td} V_{tb}^* \right] \).

Observations of CP violation in B0 decays were reported last year by the BABAR \( \mathcal{B} \) and Belle \( \mathcal{B} \) collaborations. The PEP-II collider has since delivered an additional 63 fb\(^{-1}\), thereby approximately tripling the data sample near the \( T(4S) \) resonance. In this Letter we report a more precise measurement of \( \sin 2 \beta \) using the full sample of about 88 million \( B\bar{B} \) decays. The BABAR detector and the measurement technique are described in detail in Refs. \( \mathcal{B} \) and \( \mathcal{B} \), respectively. Changes in the analysis with respect to the published result \( \mathcal{B} \) include processing of all data with a uniform event reconstruction, a new flavor-tagging algorithm, and the addition of the decay mode \( B^0 \rightarrow \eta \bar{K}_S^0 \).

We reconstruct a sample of neutral B mesons (\( B_{CP} \)) decaying to the final states \( J/\psi K^0_s, \psi(2S)K^0_s, \chi_{c1} K_S^0, \eta c K_S^0, J/\psi K^{\ast 0} (K^{\ast 0} \rightarrow K^0 \pi^0) \), and \( J/\psi K^0_L \). The \( J/\psi \) and \( \psi(2S) \) mesons are reconstructed through their decays to \( e^+e^- \) and \( \mu^+\mu^- \); the \( \psi(2S) \) is also reconstructed through its decay to \( J/\psi \pi^+\pi^- \). We reconstruct \( \chi_{c1} \) mesons in the decay mode \( J/\psi \gamma \) and \( \eta \) mesons in the \( K^0_S \pi^+\pi^- \) and \( K^+ K^- \pi^0 \) final states. The \( K^0_S \) is reconstructed in its decay to \( \pi^+\pi^- \) (and to \( \pi^0 \pi^0 \) for the \( J/\psi K^{\ast 0} \) mode). We examine each event in the \( B_{CP} \) sample for evidence that the recoiling B meson decayed as a \( B^0 \) or \( B^0 \) (flavor tag).

The proper-time distribution of B meson decays to a CP eigenstate with a \( B^0 \) or \( B^0 \) tag can be expressed in terms of a complex parameter \( \lambda \) that depends on both the \( B^0 \), \( B^0 \) oscillation amplitude and the amplitudes describing \( B^0 \) and \( B^0 \) decays to this final state. The decay rate \( f_+ (f_-) \) when the tagging meson is a \( B^0 (\bar{B}^0) \) is given by

\[
f_\pm (\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[ 1 \pm \frac{2 \Im \lambda}{1 + |\lambda|^2} \sin (\Delta m d \Delta t) \right. \\
\left. + \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \cos (\Delta m d \Delta t) \right],
\]

where \( \Delta t = t_{\text{rec}} - t_{\text{tag}} \) is the difference between the proper decay times of the reconstructed B meson (\( t_{\text{rec}} \)) and the tagging B meson (\( t_{\text{tag}} \)), \( \tau_{B^0} \) is the \( B^0 \) lifetime, and \( \Delta m d \) is the \( B^0 \), \( B^0 \) oscillation frequency. The sine term in Eq. (1) is due to the interference between direct decay and decay after flavor change, and the cosine term is due to the interference between two or more decay amplitudes with different weak and strong phases. CP violation can be observed as a difference between the \( \Delta t \) distributions of \( B^0 \) and \( \bar{B}^0 \)-tagged events or as an asymmetry with respect to \( \Delta t = 0 \) for either flavor tag.

In the Standard Model, \( \lambda = \eta f e^{-2i\beta} \) for charmonium-containing \( b \rightarrow c\pi s \) decays, where \( \eta f \) is the CP eigenvalue of the final state \( f \). Thus, the time-dependent CP asymmetry is

\[
A_{\text{CP}} (\Delta t) = \frac{f_+ (\Delta t) - f_- (\Delta t)}{f_+ (\Delta t) + f_- (\Delta t)} = -\eta f \sin 2 \beta \sin (\Delta m d \Delta t),
\]

with \( \eta f = -1 \) for \( J/\psi K^0_s, \psi(2S)K_s^0, \chi_{c1} K^0_s, \) and \( \eta \eta c K^0_s \), and \( +1 \) for \( J/\psi K^0 \). Due to the presence of even (\( L = 0 \)) and odd (\( L = 1 \)) orbital angular momenta in the \( B \rightarrow J/\psi K^{\ast 0} \) 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 \( J/\psi K^{\ast 0} \) is reduced by a factor 1 \( - 2 R_L \), where \( R_L \) is the fraction of the \( L = 1 \) component. We have measured \( R_L = (16.0 \pm 3.5)\% \), which gives \( \eta f = 0.65 \pm 0.07 \) after acceptance corrections in the \( J/\psi K^{\ast 0} \) mode.

The event selection, lepton and \( K^\pm \) identification, and \( J/\psi \) and \( \psi(2S) \) reconstruction used in this analysis are similar to those described in Ref. \( \mathcal{B} \), as are the selection criteria for the channels \( J/\psi K^0_s, \psi(2S)K^0_s, \chi_{c1} K_s^0, J/\psi K^{\ast 0}, \) and \( J/\psi K^0_s \). The \( B^0 \rightarrow \eta \bar{K}_S^0 \) sample selection is described in Ref. \( \mathcal{B} \). In brief, the \( K^\pm \) candidates must satisfy kaon identification criteria and the \( K^0_S \) mode. We select candidates in the \( B^0 \rightarrow J/\psi K^0_s, \psi(2S)K^0_s, \chi_{c1} K^0_s, J/\psi K^{\ast 0}, \) and \( J/\psi K^0_s \) channels, and the \( J/\psi K^0_s \) sample selection is described in Ref. \( \mathcal{B} \). In brief, the \( K^\pm \) candidates must satisfy kaon identification criteria and the \( K^0_S \) mode. The \( J/\psi K^0_s \) sample selection is described in Ref. \( \mathcal{B} \). In brief, the \( K^\pm \) candidates must satisfy kaon identification criteria and the \( K^0_S \) mode. The \( J/\psi K^0_s \) sample selection is described in Ref. \( \mathcal{B} \).
with respect to the thrust axis of the event. We determine the decay vertices of \( B \) from its charged tracks. The \( B \) vertices are assigned to one of four hierarchical, mutually exclusive tagging categories: \( \text{Lepton} \), \( \text{Ko}n \), \( \text{Ko}n \text{I} \), and \( \text{In}clusive \). Each event is assigned to one of these tagging categories based on the estimated mistag probability. The tagging efficiencies are determined from fits to the time interval \( \Delta t \) between the two decay vertices of \( B \). The tagging and vertexing requirements are described in Eq. 4 with |\( \lambda \) | = 1. The \( \Delta t \) distributions of the \( B \) sample evolve according to the known flavor oscillation in

\[
J/\psi K^{*0}(K^{*0} \rightarrow K^+\pi^-). \quad \text{Validation studies are performed with a control sample of } \ B^+ \text{ mesons decaying to the final states } J/\psi K^{(*)+}, \ \psi(2S)K^+, \ \chi_{c1}K^+, \ \eta_2K^+, \ \text{and } T^+K^{*0}_L. \]

We use multivariate algorithms to identify signatures of \( B \) decays that determine the flavor of \( B \). Primary leptons from semileptonic \( B \) decays are selected from identified electrons and muons as well as isolated energetic tracks. We use the charges of identified kaon candidates to 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 \( B \). A neural network, which combines the outputs of these physics-based algorithms, takes into account correlations between different sources of flavor information and provides an estimate of the mistag probability for each event.

By using the outputs of the physics-based algorithms and the estimated mistag probability, each event is assigned to one of four hierarchical, mutually exclusive tagging categories: \( \text{Lepton} \), \( \text{Ko}n \), \( \text{Ko}n \text{I} \), and \( \text{In}clusive \). Each event is assigned to one of these tagging categories based on the estimated mistag probability. The tagging efficiencies are determined from fits to the time interval \( \Delta t \) between the two decay vertices of \( B \). The tagging and vertexing requirements are described in Eq. 4 with |\( \lambda \) | = 1. The \( \Delta t \) distributions of the \( B \) sample evolve according to the known flavor oscillation in

\[
\text{TABLE I: Efficiencies } \epsilon_i, \text{ average mistag fractions } w_i, \text{ mistag fraction differences } \Delta w_i = w_i(B^0) - w_i(B^+), \text{ and } Q \text{ extracted for each tagging category } i \text{ from the } B_{\text{flav}} \text{ and } B_{\text{CP}} \text{ samples.}
\]

| Category   | \( \epsilon (\%) \) | \( w (\%) \) | \( \Delta w (\%) \) | \( Q (\%) \) |
|------------|-----------------|--------------|-----------------|---------|
| Lepton     | 9.1 ± 0.2       | 3.3 ± 0.6    | −1.5 ± 1.1      | 7.9 ± 0.3 |
| Ko1        | 16.7 ± 0.2      | 10.0 ± 0.7   | −1.3 ± 1.1      | 10.7 ± 0.4 |
| Ko2        | 19.8 ± 0.3      | 20.9 ± 0.8   | −4.4 ± 1.2      | 6.7 ± 0.4 |
| Inclusive  | 20.0 ± 0.3      | 31.5 ± 0.9   | −2.4 ± 1.3      | 2.7 ± 0.3 |
| All        | 65.6 ± 0.5      | 28.1 ± 0.7   |                |          |

FIG. 1: Distributions for \( B \) candidates satisfying the tagging and vertexing requirements: a) \( m_{ES} \) for the final states \( J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0, \eta_2K_S^0, \text{ and } J/\psi K^{*0}(K^{*0} \rightarrow K_S^0\pi^0) \), and b) \( \Delta E \) for the final state \( J/\psi K_L^0 \).
The ∆tions are listed in Table I. Background parameters are three Gaussians. Backgrounds are incorporated with a common resolution function, modeled by the sum of high-statistics prompt and non-prompt components convolved with the fitted value of sin²β.

J/ψK termination of the mistag fractions and ∆B in various subsamples, as well as in the B_{flav} and charged B control samples. Errors are statistical only.

Errors are statistical only.

There are 34 free parameters in the fit: sin²β (1), the average mistag fractions w and the differences ∆w between B⁰ and B̄⁰ mistag fractions for each tagging category (8), parameters for the signal ∆t resolution (8), and parameters for background time dependence (6), ∆t resolution (3), and mistag fractions (8). We fix τ_{B⁰} = 1.542 ps and ∆m_{d} = 0.489 ps⁻¹ [3]. The determination of the mistag fractions and ∆t resolution function parameters for the signal is dominated by the high-statistics B_{flav} sample. The measured mistag fractions are listed in Table I. Background parameters are determined from events with m_{ES} < 5.27 GeV/c² (except J/ψK⁰ and J/ψK*⁰). The largest correlation between sin²β and any linear combination of the other free parameters is 0.13. We observe a bias of 0.014 ± 0.005 in the fitted value of sin²β in simulated events. Part of this bias (0.004) is due to a correlation between the mistag fractions and the ∆t resolution not explicitly incorporated in the fit. Therefore we subtract 0.014 from the fitted value of sin²β in data and include 0.010 in the systematic error.

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

\[ \sin^2 \beta = 0.741 \pm 0.067 \text{ (stat)} \pm 0.034 \text{ (syst)} \]

Figure 2 shows the ∆t distributions and asymmetries in yields between B⁰ tags and B̄⁰ tags for the \( \eta_f = -1 \) and \( \eta_f = +1 \) samples as a function of ∆t, overlaid with the projection of the likelihood fit result.

The dominant sources of systematic error are the uncertainties in the level, composition, and CP asymmetry of the background in the selected CP events (0.023), the assumed parameterization of the ∆t resolution function (0.017), due in part to residual uncertainties in the internal alignment of the vertex detector, and possible differences between the B_{flav} and B_{CP} mistag fractions (0.012). The total systematic error is 0.034. Most sys-

### Table II: Number of events \( N_{\text{tag}} \) in the signal region after tagging and vertexing requirements, signal purity \( P \), and results of fitting for CP asymmetries in the B_{CP} sample and in various subsamples, as well as in the B_{flav} and charged B control samples. Errors are statistical only.

| Sample | \( N_{\text{tag}} \) | \( P(\%) \) | sin²β |
|--------|---------------------|-------------|--------|
| J/ψK⁺⁰ \( \rightarrow \pi^+ \pi^- \) | 1506 | 94 | 0.76 ± 0.07 |
| J/ψK⁺⁰ \( (\eta_f = +1) \) | 988 | 55 | 0.72 ± 0.16 |
| J/ψK⁺⁰ \( (\eta_f \rightarrow K_{\pi}^0 \pi^0) \) | 147 | 81 | 0.22 ± 0.52 |
| Full CP sample | 2641 | 78 | 0.74 ± 0.07 |
| J/ψK⁺⁰ \( (\eta_f \rightarrow K_{\pi}^0 \pi^0) \) \( (\eta_f = -1) \) | 974 | 97 | 0.82 ± 0.08 |
| J/ψK⁺⁰ \( (\eta_f \rightarrow K_{\pi}^0 \pi^0) \) \( (\eta_f = -1) \) | 170 | 89 | 0.39 ± 0.24 |
| \( \psi(2S) K_{\pi}^0 \) \( (K_{\pi}^0 \rightarrow \pi^+ \pi^-) \) | 150 | 97 | 0.69 ± 0.24 |
| \( \chi_{c1} K_{\pi}^0 \) | 80 | 95 | 1.01 ± 0.40 |
| \( \eta f K_{\pi}^0 \) | 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⁺ tags | 740 | 94 | 0.76 ± 0.10 |
| B̄⁻ tags | 766 | 93 | 0.75 ± 0.10 |
| B_{flav} sample | 25375 | 85 | 0.02 ± 0.02 |
| B⁺ sample | 22160 | 89 | 0.02 ± 0.02 |

FIG. 2: a) Number of \( \eta_f = -1 \) candidates \( (J/ψK_{\pi}^0, \psi(2S) K_{\pi}^0, \chi_{c1} K_{\pi}^0, \text{and } \eta f K_{\pi}^0) \) in the signal region with a \( B^0 \) tag \( N_{\text{tag}} \) and with a \( B\bar{\text{t}} \) tag \( N_{\text{tag}} \), and b) the raw asymmetry \( (N_{B^0} - N_{B\bar{\text{t}}})/(N_{B^0} + N_{B\bar{\text{t}}}) \) as functions of ∆t. The solid (dashed) curves represent the fit projection in ∆t for \( B^0 \) (\( B\bar{\text{t}} \)) tags. The shaded regions represent the background contributions. Figures c) and d) contain the corresponding information for the \( \eta_f = +1 \) mode \( J/ψK_{\pi}^0 \).
tematic 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 $B_{tag}$ flavor. The results of fits to these $\eta_f = -1$ subsamples are shown in Table II and found to be statistically consistent. The results of fits to the control samples of non-$CP$ decay modes indicate no statistically significant asymmetry.

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 $\bar{B}^0$-tagged events. In order to account for differences in reconstruction and tagging efficiencies for $B^0$ and $\bar{B}^0$ mesons, we incorporate five additional free parameters in this fit. We obtain $|\lambda| = 0.948 \pm 0.051$ (stat) $\pm 0.030$ (syst). The coefficient of the $\sin(\Delta m_q \Delta t)$ term in Eq. 1 is measured to be $0.759 \pm 0.074$ (stat). The dominant contribution to the systematic error for $|\lambda|$, conservatively estimated to be 0.025, is due to interference between the suppressed $\bar{b} \to \bar{u}cd$ amplitude with the favored $b \to c\bar{u}d$ amplitude for some tag-side $B$ decays. The other sources of systematic error for $|\lambda|$ are the same as in the $\sin2\beta$ measurement.

This measurement of $\sin2\beta$ supersedes our previous result [3] and improves upon the precision of each of the previous measurements [3,4] by a factor of two. While the measured value is consistent with the range implied by the measurements and theoretical estimates of the magnitudes of CKM matrix elements in the context of the Standard Model, it provides a precise and model-independent constraint on the position of the apex of the Unitarity Triangle [12].

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