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Observation of *CP* Violation in B^0 Decays

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We present an updated measurement of time-dependent *CP*-violating asymmetries in neutral B decays by the *BABAR* detector at the PEP-II asymmetric B Factory at SLAC. The new result uses an additional sample of $\Upsilon(4S)$ decays collected in 2001, bringing the total sample to 32 million $B\overline{B}$ pairs. In this sample, we find events in which one neutral B meson is fully reconstructed in a final state containing charmonium and the flavor of the other neutral B meson is determined from its decay products. The amplitude of the *CP*-violating asymmetry, which in the Standard Model is proportional to sin2β, is derived from the decay time distributions in such events. The result $\sin2\beta = 0.59 \pm 0.14$ (stat) ± 0.05 (syst) establishes *CP* violation in the B meson system at the 4.1σ level. We also determine the direct *CP* term $|\lambda| = 0.93 \pm 0.09(\text{stat}) \pm 0.03(\text{sys})$.

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CP violation has been a central concern of particle physics since its discovery in 1964 [1] in the decays of K^0_L mesons. An elegant explanation of this effect was proposed by Kobayashi and Maskawa, as a *CP*-violating phase in the three-generation CKM quark-mixing matrix [2]. In this picture measurements of *CP*-violating asymmetries in the time distributions of charmonium-containing $b \rightarrow c\overline{c}s$ decays of B^0 and $\overline{B}^0$ mesons provide a direct test of the Standard Model of electroweak interactions [3], uncontaminated by corrections from strong interactions that obscure the theoretical interpretation of the observed *CP* violation in K^0_L decays.

Measurements of the *CP* violating asymmetry parameter sin2β have recently been reported by the *BABAR* [4] and BELLE [5] collaborations, from data taken in 1999 and 2000 at the PEP-II and KEK-B asymmetric-energy e^+e^- colliders respectively, with a better precision than the previous experiments [6]. While the average of all such measurements is suggestive, no single experiment has determined whether or not *CP* symmetry is violated in B decays. In this letter we report a new measurement of sin2β enhanced by 9 million $B\overline{B}$ pairs collected in 2001, additional decay modes, and improvements in data reconstruction and analysis. The *BABAR* detector and the experimental method are described in Ref. [4, 7], so the discussion here is limited to items and issues pertinent to the current analysis.

The complete data set (32 million $B\overline{B}$ pairs) has been used to fully reconstruct a sample B_{CP} of neutral B mesons decaying to $J/\psi K^0_S$, $\psi(2S)K^0_S$, $J/\psi K^0_L$, $\chi_{c1}K^0_S$, and to the $J/\psi K^{*0}, K^{*0} \rightarrow K^0_S\pi^0$ final states. (The last two modes have been added since Ref. [4]). There are several other significant changes in the analysis. Improvements in track and K^0_S reconstruction efficiency in 2001 data produced an approximate 30% increase for a given luminosity in the yields; better alignment of the tracking systems in 2001 data and improvements in the tag vertex reconstruction algorithm increased the sensitivity of the measurement by an additional 10% ;optimizing the $J/\psi K^0_L$ selection has increased the purity of this sample. The final B_{CP} sample contains about 640 signal events, and with all the improvements the statistical power of the analysis is almost doubled with respect to that of Ref. [4].

We examine each of the events in the B_{CP} sample for evidence that the other neutral B meson decayed as a B^0 or a $\overline{B}^0$ (flavor tag). The decay-time distribution for events with a B^0 or a $\overline{B}^0$ tag can be expressed in terms of a complex parameter λ that depends on both $B^0\overline{B}^0$ mixing and on the amplitudes describing $\overline{B}^0$ and B^0 decay to a common final state f [8]. The distribution $\mathrm{f}_+(\mathrm{f}_-)$ of the decay rate when the tagging meson is a $B^0(\overline{B}^0)$ is given by

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

where $\Delta t = t_{CP} - t_{\rm tag}$ is the time between the two B decays, τ_{B^0} is the B^0 lifetime and Δm_{B^0} is the mass difference determined from $B^0\overline{B}^0$ mixing [9]. The first oscillatory term in Eq. 1 is due to interference between direct decay and decay after mixing. A difference between the B^0 and $\overline{B}^0$ distributions or a Δt asymmetry for either flavor tag is evidence for *CP* violation.

In the Standard Model for charmonium-containing $b \rightarrow c\overline{c}s$ decays $\lambda = \eta_f e^{-2i\beta}$, where η_f is the *CP* eigenvalue of the state f and $\beta = \arg\left[\,-V_{\rm cd}V^*_{\rm cb}/V_{\rm td}V^*_{\rm tb}\,\right]$ is an angle of the Unitarity Triangle of the three-generation CKM matrix [2]. Thus, the time-dependent *CP*-violating asymmetry is

$$\begin{aligned} A_{CP}(\Delta t) &\equiv \frac{\mathrm{f}_+(\Delta t) - \mathrm{f}_-(\Delta t)}{\mathrm{f}_+(\Delta t) + \mathrm{f}_-(\Delta t)} \\ &= -\eta_f \sin2\beta \sin\left(\Delta m_{B^0}\,\Delta t\right), \end{aligned} \quad (2)$$

where $\eta_f = -1$ for $J/\psi K^0_S$, $\psi(2S)K^0_S$ and $\chi_{c1}K^0_S$ 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 $J/\psi K^{*0}(K^{*0} \rightarrow K^0_S\pi^0)$ system, there can be *CP*-even and *CP*-odd contributions to the decay rate. By ignoring the angular information in the decay, the measured *CP* asymmetry in $J/\psi K^{*0}$ is reduced by a dilution factor $D_\perp = 1 - 2R_\perp$, where $R_\perp$ is the fraction of L=1 component. We have measured $R_\perp = (16 \pm 3.5)\%$ [10] which, after acceptence corrections, leads to an effective $\eta_f = 0.65 \pm 0.07$.

The hadronic event selection, lepton and charged kaon identification, J/ψ and $\psi(2S)$ reconstruction relevant

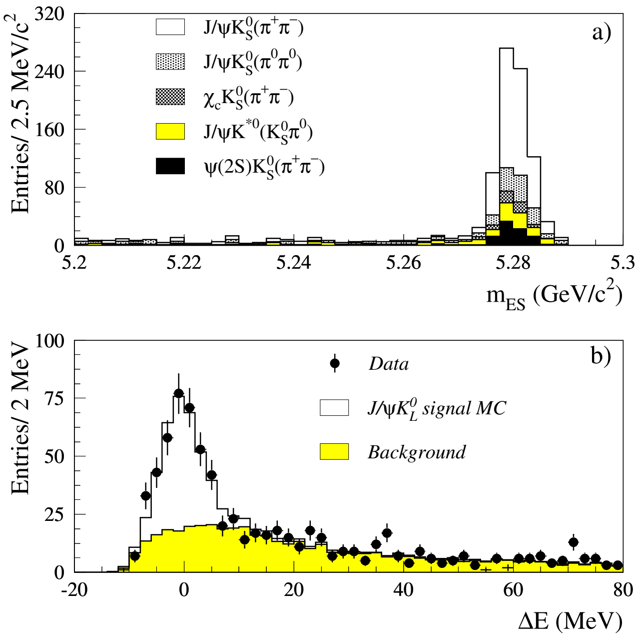

FIG. 1: a) Distribution of $m_{\rm ES}$ for B_{CP} candidates having a K^0_S in the final state; b) distribution of ΔE for $J/\psi\, K^0_L$ candidates.

to this analysis has been described in Ref. [4] as have the selection criteria for the channels $J/\psi\, K^0_S$ ($K^0_S \to \pi^+\pi^-, \pi^0\pi^0$), $\psi(2S)K^0_S$ ($K^0_S \to \pi^+\pi^-$), and $J/\psi\, K^0_L$. These same requirements are applied to the new data sample with the exception of the transverse missing momentum requirement in $J/\psi\, K^0_L$ selection, which is better optimized for the time-dependent asymmetry study.

For the decay $B^0 \to \chi_{c1} K^0_S$, the mode $\chi_{c1} \to J/\psi\ \gamma$ is reconstructed with mass-constrained J/ψ candidates selected as in other charmonium channels [4]. Photons must have an energy greater than 150 MeV and not be associated to any reconstructed π^0. The resulting $J/\psi\gamma$ mass was required to be within 35 MeV/c^2 of the χ_{c1} mass [9].

For the decay $B^0 \to J/\psi K^{*0}$ the $K^{*0} \to K^0_S\pi^0$ candidate is formed by combining $\pi^0 \to \gamma\gamma$ candidate satisfying $106 \le m_{\gamma\gamma} \le 153\,{\rm MeV}/c^2$ with a K^0_S candidate. The cosine of the angle between the K^0_S momentum vector in the K^{*0} rest frame and the K^{*0} momentum defined in the B rest frame is required to be less than 0.95. We require $792 \le m_{K^0_S\pi^0} \le 992\,{\rm MeV}/c^2$.

B_{CP} candidates are selected by requiring that the difference ΔE between their energy and the beam energy in the center-of-mass frame be less than 3σ from zero. For K^0_S modes, the beam-energy substituted mass $m_{\rm ES} = \sqrt{(E^{\rm cm}_{\rm beam})^2 - (p^{\rm cm}_B)^2}$ must be greater than $5.2\,{\rm GeV}/c^2$. The resolution for ΔE is about 10 MeV, except for the $K^0_S \to \pi^0\pi^0$ mode (33 MeV), the $J/\psi\, K^{*0}$ (20 MeV) and the $J/\psi\, K^0_L$ (3 MeV after B mass constraint). For the purpose of determining numbers of events and purities a signal region $m_{\rm ES} > 5.27\,{\rm GeV}/c^2$ is used for all modes except $J/\psi\, K^0_L$ and $J/\psi\, K^{*0}$.

Fig. 1 shows the resulting $m_{\rm ES}$ distributions for B_{CP} candidates containing a K^0_S, and ΔE for the candidates containing a K^0_L. The B_{CP} sample is composed of 1230 events in the signal region, with an estimated background of 200 events, predominantly in the $J/\psi\, K^0_L$ channel. For that channel, the composition, effective η_f, and ΔE distributions of the individual background sources are taken either from a Monte Carlo simulation (for B decays to J/ψ) or from the $m_{\ell^+\ell^-}$ sidebands in data.

A measurement of A_{CP} requires determination of the experimental Δt resolution and the fraction of events in which the tag assignment is incorrect. A mistag fraction w reduces the observed asymmetry by a factor $(1-2w)$. A sample of B decays $B_{\rm flav}$ [11] used in the determination of the mistag fractions and Δt resolution functions consists of the channels $D^{(*)-}h^+(h^+ = \pi^+, \rho^+, a_1^+)$ and $J/\psi\, K^{*0}$ ($K^{*0} \to K^+\pi^-$). A control sample of charged B mesons decaying to the final states $J/\psi\, K^{(*)+}$, $\psi(2S)K^+$, $\chi_{c1}K^+$ and $\overline{D}^{(*)0}\pi^+$ is used for validation studies.

For flavor tagging, we exploit information from the other B decay in the event. Each event is assigned to one of four hierarchical, mutually exclusive tagging categories or excluded from further analysis. The `Lepton` and `Kaon` catagories contain events with high momentum leptons from semileptonic B decays or with kaons whose charge is correlated with the flavor of the decaying b quark (*e.g.*, a positive lepton yields a B^0 tag). The `NT1` and `NT2` catagories are based on a neural network algorithm whose tagging power arises primarily from soft pions from D^* decays and from recovering unidentified primary leptons [4].

The number of tagged events and the signal purity, determined from fits to the $m_{\rm ES}$ (all K^0_S modes except K^{*0}) or ΔE (K^0_L mode) distributions in data or from MC simulation (K^{*0} mode) are shown in Table I. The efficiencies and dilutions for the four tagging categories are measured from data and summarized in Table II.

The uncertainty in the Δt measurement is dominated by the measurement of the position $z_{\rm tag}$ of the tagging vertex. The tagging vertex is determined by fitting the tracks not belonging to the B_{CP} (or $B_{\rm flav}$) candidate to a common vertex. The method employed is identical to our previous analysis except for the addition of a constraint from knowledge of the beam spot location and beam direction. This is incorporated through the addition to the tagging vertex of a pseudotrack, computed from the B_{CP} ($B_{\rm flav}$) vertex and three-momentum, the beamspot (with a vertical size of 10 μm) and the average $\Upsilon(4S)$ momentum. The average resolution achieved by this algorithm for $\Delta z = z_{CP} - z_{\rm tag}$ is 180 μm and its efficiency increases from 86% [4] to 97%. The time interval Δt between the two B decays is then determined from the Δz measurement, including an event-by-event correction for the direction of the B with respect to the

TABLE I: Number of tagged events, signal purity and result of fitting for CP asymmetries in the full CP sample and in various subsamples, as well as in the $B_{\rm flav}$ and charged B control samples. Errors are statistical only.

Sample	$N_{\rm tag}$	Purity (%)	sin2β
$J/\psi K^0_S$,$\psi(2S)K^0_S$,$\chi_{c1}K^0_S$	480	96	0.56 ± 0.15
$J/\psi K^0_L$	271	51	0.70 ± 0.34
$J/\psi K^{*0}, K^{*0} \to K^0_S\pi^0$	50	74	0.82 ± 1.00
Full CP sample	801	80	0.59 ± 0.14
$J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$ only			
$J/\psi K^0_S$ ($K^0_S \to \pi^+\pi^-$)	316	98	0.45 ± 0.18
$J/\psi K^0_S$ ($K^0_S \to \pi^0\pi^0$)	64	94	0.70 ± 0.50
$\psi(2S)K^0_S$ ($K^0_S \to \pi^+\pi^-$)	67	98	0.47 ± 0.42
$\chi_{c1}K^0_S$	33	97	2.59 ± 0.67
`Lepton` tags	74	100	0.54 ± 0.29
`Kaon` tags	271	98	0.59 ± 0.20
`NT1` tags	46	97	0.67 ± 0.45
`NT2` tags	89	95	0.10 ± 0.74
B^0 tags	234	98	0.50 ± 0.22
$\overline{B}^0$ tags	246	97	0.61 ± 0.22
$B_{\rm flav}$ sample	7591	86	0.02 ± 0.04
Charged B sample	6814	86	0.03 ± 0.04

TABLE II: Average mistag fractions w_i and mistag differences $\Delta w_i = w_i(B^0) - w_i(\overline{B}^0)$ extracted for each tagging category i from the maximum-likelihood fit to the time distribution for the fully-reconstructed B^0 sample ($B_{\rm flav}$+B_{CP}). The figure of merit for tagging is the effective tagging efficiency $Q_i = \varepsilon_i(1-2w_i)^2$, where ε_i is the fraction of events with a reconstructed tag vertex that are assigned to the i^{th} category. Uncertainties are statistical only. The statistical error on sin2β is proportional to $1/\sqrt{Q}$, where $Q = \sum Q_i$.

Category	ε (%)	w (%)	Δw (%)	Q (%)
`Lepton`	10.9 ± 0.3	8.9 ± 1.3	0.9 ± 2.2	7.4 ± 0.5
`Kaon`	35.8 ± 0.5	17.6 ± 1.0	-1.9 ± 1.9	15.0 ± 0.9
`NT1`	7.8 ± 0.3	22.0 ± 2.1	5.6 ± 3.2	2.5 ± 0.4
`NT2`	13.8 ± 0.3	35.1 ± 1.9	-5.9 ± 2.7	1.2 ± 0.3
All	68.4 ± 0.7			26.1 ± 1.2

z direction in the $\Upsilon(4S)$ frame. An accepted candidate must have a converged fit for the B_{CP} and $B_{\rm tag}$ vertices, an error of less than $400\,\mu$m on Δz , and a measured $|\Delta t| < 20$ ps.

The sin2β measurement is made with an unbinned maximum likelihood fit to the Δt distribution of the combined B_{CP} and $B_{\rm flav}$ tagged samples. The Δt distribution of the former is given by Eq. 1, with $|\lambda| = 1$. The $B_{\rm flav}$ sample evolves according to the known rate for flavor oscillations in neutral B mesons. The amplitudes for B_{CP} asymmetries and for $B_{\rm flav}$ flavor oscillations are reduced by the same factor $(1-2w)$ due to mistags. Both distributions are convoluted with a common Δt resolution function and corrected for backgrounds, incorporated with different assumptions about their Δt evolution and convoluted with a separate resolution function. Events are assigned signal and background probabilities based on the $m_{\rm ES}$ (all modes except $J/\psi K^0_L$) or ΔE ($J/\psi K^0_L$) distributions.

The representation of the Δt resolution function is the same as in [4] with small changes: all offsets are modeled to be proportional to $\sigma_{\Delta t}$ since this quantity is correlated with the weight that the daughters of long-lived charm particles have in the tagging vertex reconstruction. Separate resolution functions have been used for the data collected in year 1999 and 2000 and those collected in year 2001 due to the significant improvement in the silicon vertex detector (SVT) alignment. The scale factor for the tail component is fixed to the Monte Carlo value since it is strongly correlated with the other resolution function parameters.

A total of 45 parameters are varied in the fit, including sin2β (1), the average mistag fraction w and the difference Δw between B^0 and $\overline{B}^0$ mistags for each tagging category (8), parameters for the signal Δt resolution (16), and parameters for background time dependence (9), Δt resolution (3) and mistag fractions (8). The determination of the mistag fractions and signal Δt resolution function is dominated by the high-statistics $B_{\rm flav}$ sample, while background parameters are governed by events with $m_{\rm ES} < 5.27\,{\rm GeV}/c^2$. As a result, the largest correlation between sin2β and any linear combination of the other free parameters is only 0.127. We fix $\tau_{B^0} = 1.548$ ps and $\Delta m_{B^0} = 0.472\,\hbar\,{\rm ps}^{-1}$ [9].

Fig. 2 shows the Δt distributions and the CP asymmetries A_{CP} as a function of Δt overlaid with the likelihood fit result for the $\eta_f = -1$ and $\eta_f = +1$ samples. The combined fit to the CP decay modes and the flavor decay modes yields

$$\sin 2\beta = 0.59 \pm 0.14\ ({\rm stat}) \pm 0.05\ ({\rm syst}).$$

Repeating the fit with all parameters fixed to their determined values except sin2β, we find a total contribution of ± 0.02 to the error on sin2β due to the combined statistical uncertainties in mistag rates, Δt resolution and background parameters. The dominant sources of systematic error are the assumed parameterization of the Δt resolution function (0.03), due in part to residual uncertainties in SVT alignment, possible differences in the mistag fractions between the $B_{\rm CP}$ and $B_{\rm flav}$ samples (0.03) and uncertainties in the level, composition, and CP asymmetry of the background in the selected CP events (0.02). The systematic errors from uncertainties in Δm_{B^0} and τ_{B^0} and from the parameterization of the background in the selected $B_{\rm flav}$ sample are small; an increase of $0.02\,\hbar\,{\rm ps}^{-1}$ in the value for Δm_{B^0} decreases sin2β by 0.015.

The large sample of reconstructed events 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 shown in Table I for the high-purity K^0_S events. The probability of

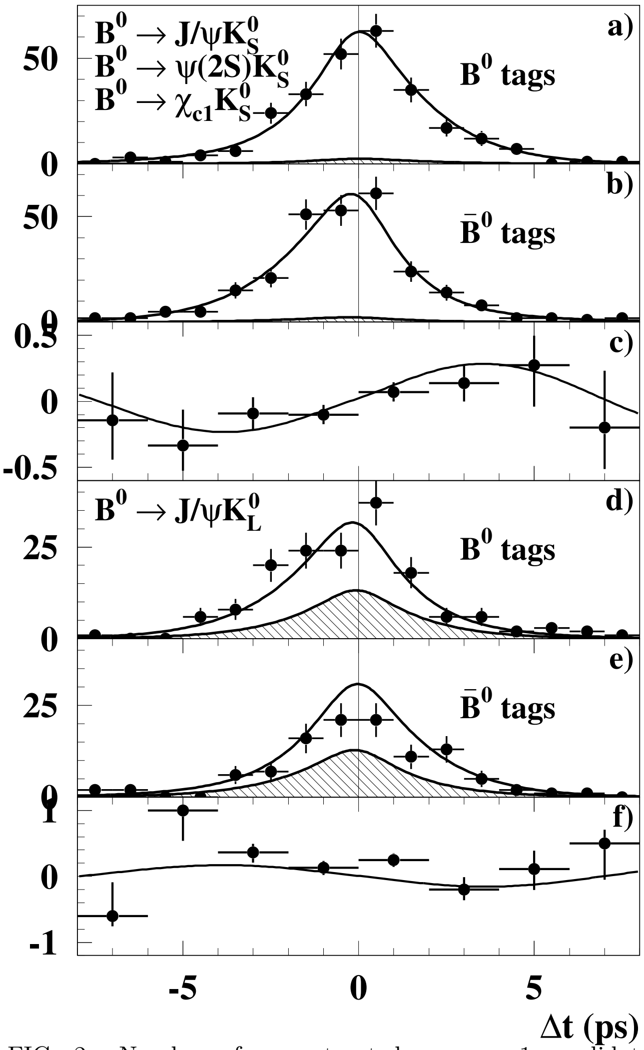

FIG. 2: Number of reconstructed $\eta_f = -1$ candidates ($J/\psi K^0_S$, $\psi(2S)K^0_S$, and $\chi_{c1}K^0_S$) a) with a B^0 tag N_{B^0} and b) with a $\overline{B}^0$ tag $N_{\overline{B}^0}$ and c) the asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$ as function of Δt. The solid curves represent the result of the combined fit to all selected CP events. The figures d)–f) contain the corresponding information for the $J/\psi K^0_L$ mode. The probability of obtaining a lower likelihood, evaluated using a Monte Carlo technique, is 27% .

finding a worse agreement among different modes is estimated to be 8%. Table I also shows results of fits with the samples of non-*CP* decay modes, where no statistically significant asymmetry is found. Performing the current analysis on the previously published data sample and with the same modes yields a value of sin2β =0.32±0.18, consistent with the published value [4]. Using the same decay modes in the year 2001 data, the analysis yields sin2β =0.83±0.23, which is consistent with the 1999-2000 data at the 1.8σ level.

If $|\lambda|$ is allowed to float in the fit to the $\eta_f = -1$ sample, the value obtained is

$$|\lambda| = 0.93 \pm 0.09(\mathrm{stat}) \pm 0.03(\mathrm{sys}).$$

The systematic error in this measurement is dominated by the statistical uncertainty in the relative tagging efficiency between B^0 and $\overline{B}^0$ mesons.

This measurement of sin2β establishes *CP* violation in B decays at 4.1σ level. The probability of obtaining a value of sin2β = 0.59 or higher when the true value is 0 is less than 3.2×10^{-5}. This direct measurement is in agreement with the range implied by measurements and theoretical estimates of the magnitudes of CKM matrix elements [12].

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