Observation of CP Violation in the $B^0$ Meson System


(BABAR Collaboration)

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We present an updated measurement of time-dependent $CP$-violating asymmetries in neutral $B$ decays with the BABAR detector at the PEP-II asymmetric $B$ Factory at SLAC. This result uses an additional sample of $Y(4S)$ decays collected in 2001, bringing the data available to $32 \times 10^6 B\bar{B}$ pairs. We select 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 $\sin2\beta$, is derived from the decay time distributions in such events. The result $\sin2\beta = 0.59 \pm 0.14$(stat) $\pm 0.05$(syst) establishes $CP$
CP violation has been a central concern of particle physics since its discovery in 1964 in the decays of $K_S^0$ mesons [1]. To date, this phenomenon has not been observed in any other system. An elegant explanation of this effect was proposed by Kobayashi and Maskawa, as a CP-violating phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [2]. In this picture, measurements of CP-violating asymmetries in the time distributions of $B^0$ decays to charmonium final states provide a direct test of the standard model of electroweak interactions, free from strong interaction corrections [3].

Measurements of the CP-violating asymmetry parameter $\sin 2\beta$ have recently been reported by the BABAR [4] and Belle [5] Collaborations, from data taken in 1999–2000 at the PEP-II and KEKB asymmetric-energy $e^+ e^-$ colliders, respectively, with better precision than previous experiments [6]. In this Letter we report a new measurement of $\sin 2\beta$, enhanced by $9 \times 10^6 B\bar{B}$ pairs collected in 2001, additional decay modes, and improvements in data reconstruction and analysis. The BABAR detector and the experimental method are described in Refs. [4,7], so the discussion here is limited to items and issues pertinent to the current analysis.

$$f_\pm (\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}(1 + |\lambda|^2)^{1/2}} \left[ 1 + \frac{|\lambda|^2}{2} \right]$$

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

In the standard model $\lambda = \eta_f e^{-2i\beta}$ for charmonium-containing $b \to c\bar{c}s$ decays, $\eta_f$ is the CP eigenvalue of the state $f$ and $\beta = \arg[-V_{c d} V_{c b}^*/V_{c d} V_{c b}]$ is an angle of the unitarity triangle of the three-generation CKM matrix [2]. Thus, the time-dependent CP-violating asymmetry is

$$A_{\text{CP}}(\Delta t) = \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)} = -\eta_f \sin 2\beta \sin(\Delta m_{B^0} \Delta t),$$

where $\eta_f = -1$ for $J/\psi K^0_{S}$, $\psi(2S)K^0_{S}$, and $\chi_{c1}K^0_{S}$ and $+1$ for $J/\psi K^0_L$. Because of the presence of even $(L = 0,2)$ and odd $(L = 1)$ orbital angular momenta in the $J/\psi K^{*0}$ ($K^{*0} \to K^0 \pi^0$) system, there are 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 dilution factor $D = 1 - 2R_{\Delta l}$, where $R_{\Delta l}$ is the fraction of the $L = 1$ component. We have measured $R_{\Delta l} = (16 \pm 3.5\%)$ [10], which, after acceptance corrections, leads to an effective $\eta_f = 0.65 \pm 0.07$ for the $J/\psi K^{*0}$ mode.

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

For the decay $B^0 \to J/\psi K^{*0}$, the $K^{*0} \to K^0 \pi^0$ candidate is formed by combining a $\pi^0 \to \gamma \gamma$ candidate satisfying $106 \leq m_{\gamma\gamma} \leq 153$ 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 $796 \leq m_{K^0_S \pi^0} \leq 996$ MeV/$c^2$. 

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The complete data set ($32 \times 10^6 B\bar{B}$ pairs) has been used to fully reconstruct a sample $B_{CP}$ of neutral $B$ mesons decaying to the $J/\psi K^0_{S}$, $\psi(2S)K^0_{S}$, $J/\psi K^0_L$, $\chi_{c1}K^0_{S}$, and $J/\psi K^{*0}$ ($K^{*0} \to K^0 \pi^0$) 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 produce an approximately 30% increase in the yields for a given luminosity. Better alignment of the tracking systems in 2001 data and improvements in the tagging vertex reconstruction algorithm increase the sensitivity of the measurement by an additional 10%. Optimization of the $J/\psi K^0_L$ selection increases 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 $\bar{B}^0$ (flavor tag). The decay-time distributions for events with a $B^0$ or a $\bar{B}^0$ tag can be expressed in terms of a complex parameter $\lambda$ that depends on $J/\psi K^{*0}$ mixing and on the amplitudes describing $B^0$ and $\bar{B}^0$ decay to a common final state $f$ [8]. The distribution $f_+(f_-)$ of the decay rate when the tagging meson is a $B^0$ ($\bar{B}^0$) is given by

$$\text{Im} \lambda \sin(\Delta m_{B^0} \Delta t) \pm \frac{1 - |\lambda|^2}{2} \cos(\Delta m_{B^0} \Delta t)$$

where $D = 1 - 2R_{\Delta l}$, with $R_{\Delta l}$ the fraction of the $L = 1$ component. We have measured $R_{\Delta l} = (-16 \pm 3.5\%)$ [10], which, after acceptance corrections, leads to an effective $\eta_f = 0.65 \pm 0.07$ for the $J/\psi K^{*0}$ mode.
$B_{CP}$ candidates are selected by requiring that the difference $\Delta E$ between their energy and the beam energy in the center-of-mass frame be less than $3\sigma$ from zero. For modes involving $K_{S}^{0}$, the beam-energy substituted mass $m_{ES} = \sqrt{(E_{\text{beam}})^2 - (p_B^{\text{w}})^2}$ must be greater than 5.2 GeV/$c^2$. The resolution for $\Delta E$ is about 10 MeV, except for the $K_{S}^{0} \rightarrow \pi^{0}\pi^{0}$ mode (33 MeV), the $J/\psi K^{*0}$ mode (20 MeV), and the $J/\psi K_{L}^{0}$ mode (3.5 MeV after $B$ mass constraint). For the purpose of determining numbers of events and purities, a signal region $m_{ES} \geq 5.27$ GeV/$c^2$ is used for all modes except $J/\psi K_{L}^{0}$ and $J/\psi K^{*0}$.

Figure 1 shows the resulting $m_{ES}$ distributions for $B_{CP}$ candidates containing a $K_{S}^{0}$ and the $\Delta E$ distribution for the candidates containing a $K_{L}^{0}$. The $B_{CP}$ sample contains 1230 events in the signal region (before tag and vertex requirements), with an estimated background of 200 events, predominantly in the $J/\psi K_{L}^{0}$ channel. For that channel, the composition, effective $\eta_{t}$, and $\Delta E$ distributions of the individual background sources are taken either from a Monte Carlo simulation (for $B$ decays to $J/\psi$) or from the $m_{c\ell\bar{\ell}}$ sidebands in data.

A measurement of $A_{CP}$ requires a determination of the experimental $\Delta t$ resolution and the fraction of events in which the tag assignment is incorrect. A mistag fraction $w$ reduces the observed asymmetry by a factor of $(1 - 2w)$. A sample of self-tagging $B$ decays $B_{t\text{av}}$ used in the determination of the mistag fractions and $\Delta t$ resolution functions consists of the channels $D^{(*)-}h^{+}$ ($h^{+} = \pi^{+}, \rho^{+}, a_{1}^{+}$) and $J/\psi K^{*0}$ ($K^{*0} \rightarrow K^{+}\pi^{-}$) [11]. A control sample of charged $B$ mesons decaying to the final states $J/\psi K^{(*)+}$, $\psi(2S)K^{+}$, $\chi_{c1}K^{+}$, and $D^{(*)0}\pi^{+}$ 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 categories 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 or kaon yields a $B^{0}$ tag). The NT1 and NT2 categories are based on a neural network algorithm whose tagging power arises primarily from soft pions from $D^{(*)}$ decays and from recovering unidentified isolated primary leptons [4].

The numbers of tagged events are shown in Table I as are the signal purities. Purities are determined from fits to the $m_{ES}$ (all $K_{S}^{0}$ modes except $K^{*0}$) or $\Delta E (K_{L}^{0}$ mode) distributions in data or from Monte Carlo simulation ($K^{*0}$ mode). The efficiencies and mistag fractions for the four tagging categories are measured from data and summarized in Table II.

The time interval $\Delta t$ between the two $B$ decays is then determined from the separation along the boost direction $\Delta z = z_{CP} - z_{tag}$, including an event-by-event correction for the direction of the $B$ with respect to the $z$ direction in the Y(4S) frame. $z_{CP}$ is determined from the charged tracks that constitute the $B_{CP}$ candidate. The tagging vertex is determined by fitting the tracks not belonging to the $B_{CP}$ (or $B_{t\text{av}}$) 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 constraint is incorporated through the addition of a pseudotrack to the tagging vertex, computed from the $B_{CP}$ ($B_{t\text{av}}$) vertex and three-momentum, the beam spot (with a vertical size of 10 $\mu$m), and the Y(4S) momentum. The $\Delta z$ reconstruction efficiency is 97%. For 99% of the reconstructed vertices the rms $\Delta z$ resolution measured in data is 180 $\mu$m, dominated by the $z_{tag}$ vertex. An accepted candidate must have a converged fit for the $B_{CP}$ and $B_{tag}$ vertices, an error of less than 400 $\mu$m on $\Delta z$, and a measured $|\Delta t| < 20$ ps. After tag and vertexing requirements about 640 signal events remain.

The sin2$\beta$ measurement is made with a simultaneous unbinned maximum likelihood fit to the $\Delta t$ distributions of the $B_{CP}$ and $B_{t\text{av}}$ tagged samples. The $\Delta t$ distribution of the former is given by Eq. (1), with $|\lambda| = 1$. The $B_{t\text{av}}$ sample evolves according to the known rate for flavor oscillations in neutral $B$ mesons [9]. The amplitudes for $B_{CP}$ asymmetries and for $B_{t\text{av}}$ flavor oscillations are reduced by the same factor $(1 - 2w)$ due to wrong tags. Both distributions are convolved with a common $\Delta t$ resolution function and backgrounds are accounted for by adding terms to the likelihood, incorporated with different assumptions about their $\Delta t$ evolution and convolved with a separate resolution function. Events are assigned signal and background probabilities based on the $m_{ES}$ (all modes except $J/\psi K_{L}^{0}$) or $\Delta E (J/\psi K_{L}^{0}$) distributions.

![FIG. 1. (a) Distribution of $m_{ES}$ for $B_{CP}$ candidates having a $K_{S}^{0}$ in the final state; (b) distribution of $\Delta E$ for $J/\psi K_{L}^{0}$ candidates.](image-url)
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 $B_{\text{flav}}$ and charged $B$ control samples. Errors are statistical only.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$N_{\text{tag}}$</th>
<th>Purity (%)</th>
<th>$\sin 2 \beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi K^0_s$, $\psi(2S)K^0_s$, $\chi_{c1}K^0_s$</td>
<td>480</td>
<td>96</td>
<td>$0.56 \pm 0.15$</td>
</tr>
<tr>
<td>$J/\psi K^0_s$ ($\eta_f = +1$)</td>
<td>273</td>
<td>51</td>
<td>$0.70 \pm 0.34$</td>
</tr>
<tr>
<td>$J/\psi K^{*0}$, $K^{-}\rightarrow K^0\pi^0$</td>
<td>50</td>
<td>74</td>
<td>$0.82 \pm 1.00$</td>
</tr>
<tr>
<td>Full CP sample</td>
<td>803</td>
<td>80</td>
<td>$0.59 \pm 0.14$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$J/\psi K^0_s$, $\psi(2S)K^0_s$, $\chi_{c1}K^0_s$ only ($\eta_f = -1$)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi K^0_s$ ($K^0_s \rightarrow \pi^+\pi^-$)</td>
<td>316</td>
<td>98</td>
<td>$0.45 \pm 0.18$</td>
</tr>
<tr>
<td>$J/\psi K^0_s$ ($K^0_s \rightarrow \pi^0\pi^0$)</td>
<td>64</td>
<td>94</td>
<td>$0.70 \pm 0.50$</td>
</tr>
<tr>
<td>$\psi(2S)K^0_s$ ($K^0_s \rightarrow \pi^+\pi^-$)</td>
<td>67</td>
<td>98</td>
<td>$0.47 \pm 0.42$</td>
</tr>
<tr>
<td>$\chi_{c1}K^0_s$</td>
<td>33</td>
<td>97</td>
<td>$2.59 \pm 0.55$</td>
</tr>
<tr>
<td>Lepton tags</td>
<td>74</td>
<td>100</td>
<td>$0.54 \pm 0.29$</td>
</tr>
<tr>
<td>Kaon tags</td>
<td>271</td>
<td>98</td>
<td>$0.59 \pm 0.20$</td>
</tr>
<tr>
<td>NT1 tags</td>
<td>46</td>
<td>97</td>
<td>$0.67 \pm 0.45$</td>
</tr>
<tr>
<td>NT2 tags</td>
<td>89</td>
<td>95</td>
<td>$0.10 \pm 0.74$</td>
</tr>
<tr>
<td>$B^0$ tags</td>
<td>234</td>
<td>98</td>
<td>$0.50 \pm 0.22$</td>
</tr>
<tr>
<td>$\bar{B}^0$ tags</td>
<td>246</td>
<td>97</td>
<td>$0.61 \pm 0.22$</td>
</tr>
<tr>
<td>$B_{\text{flav}}$ non-CP sample</td>
<td>7591</td>
<td>86</td>
<td>$0.02 \pm 0.04$</td>
</tr>
<tr>
<td>Charged $B$ non-CP sample</td>
<td>6814</td>
<td>86</td>
<td>$0.03 \pm 0.04$</td>
</tr>
</tbody>
</table>

The representation of the $\Delta t$ resolution function is the same as in [4] with small changes: all offsets are modeled to be proportional to $\sigma_{\Delta t}$, which is correlated with the weight that the daughters of long-lived charm particles have in the tag vertex reconstruction. Separate resolution functions have been used for the data collected in 1999–2000 and 2001, due to the significant improvement in the silicon vertex tracker (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 likelihood fit, including $\sin 2 \beta$ (1), the average mistag fraction $w$ and the difference $\Delta w$ between $B^0$ and $\bar{B}^0$ mistags for each tagging category (8), parameters for the signal $\Delta t$ resolution (16), and parameters for background time dependence (9), $\Delta t$ resolution (3), and mistag fractions (8). The determination of the mistag fractions and signal $\Delta t$ resolution function is dominated by the large $B_{\text{flav}}$ sample. Background parameters are governed by events with $m_{ES} < 5.27$ GeV/$c^2$. As a result, the largest correlation between $\sin 2 \beta$ and any linear combination of the other free parameters is only 0.13. We fix $\tau_{B^0} = 1.548$ ps and $\Delta m_{B^0} = 0.472$ ps$^{-1}$ [9]. The value of $\sin 2 \beta$ and the CP asymmetry in the $\Delta t$ distribution were once more hidden, following publication of our result in Ref. [4], until the event selection was optimized and all other aspects of the present analysis were complete.

Figure 2 shows the $\Delta t$ distributions and $A_{CP}$ as a function of $\Delta t$ overlaid with the likelihood fit result for the $\eta_f = -1$ and $\eta_f = +1$ samples. The probability of obtaining a lower likelihood, evaluated with a parametrized simulation of a large number of data-sized experiments, is 27%. The simultaneous fit to all CP decay modes and flavor decay modes yields

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

Repeating the fit with all parameters except $\sin 2 \beta$ fixed to their values at the global maximum likelihood, we
attribute a total contribution in quadrature of 0.02 to the error on $\sin2\beta$ due to the combined statistical uncertainties in mistag fractions, $\Delta t$ resolution, and background parameters. The dominant sources of systematic error are the parametrization of the $\Delta t$ resolution function (0.03), due in part to residual uncertainties in SVT alignment, possible differences in the mistag fractions between the $B_{CP}$ and $B_{flav}$ 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 $\Delta m_{B^0}$ and $\tau_{B^0}$ and from the parametrization of the background in the $B_{flav}$ sample are small; an increase of 0.02 $\hbar$ ps$^{-1}$ in the value for $\Delta m_{B^0}$ decreases $\sin2\beta$ 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 $B_{tag}$ flavor. The results of fits to these subsamples are shown in Table I. The consistency between the six CP modes is satisfactory, the probability of finding a worse agreement being 8%. The observed asymmetry in the number of $B^0$ (160) and $\bar{B}^0$ (113) tags in the $J/\psi K^0_L$ sample has no impact on the $\sin2\beta$ measurement. Table I also shows results of fits to 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 decay modes yields a value of $\sin2\beta = 0.32 \pm 0.18$, consistent with the published value [4]. For only these decay modes, the year 2001 data yield $\sin2\beta = 0.83 \pm 0.23$, consistent with the 1999–2000 results at the 1.8$\sigma$ level; for the $J/\psi K^0_L (K^0_S \rightarrow \pi^+\pi^-)$ channel the consistency is at the 1.4$\sigma$ level.

If $|\lambda|$ is allowed to float in the fit to the $\eta = -1$ sample, which has high purity and requires minimal assumptions on the effect of backgrounds, the value obtained is $|\lambda| = 0.93 \pm 0.09$ (stat) $\pm 0.03$ (syst). The sources of the systematic error in this measurement are the same as in the $\sin2\beta$ analysis. In this fit, the coefficient of the $\sin(\Delta m_{B^0}\Delta t)$ term in Eq. (1) is measured to be $\sin2\beta = 0.56 \pm 0.4$ (stat), in agreement with Table I.

The measurement of $\sin2\beta = 0.59 \pm 0.14$ (stat) $\pm 0.05$ (syst) reported here establishes CP violation in the $B^0$ meson system at the 4.1$\sigma$ level. This significance is computed from the sum in quadrature of the statistical and additive systematic errors. The probability of obtaining this value or higher in the absence of CP violation is less than $3 \times 10^{-5}$. The corresponding probability for the $\eta = -1$ modes alone is $2 \times 10^{-4}$. This direct measurement is consistent with the range implied by measurements and theoretical estimates of the magnitudes of CKM matrix elements [12].

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[11] Throughout this paper, flavor-eigenstate decay modes imply also their charge conjugate.