SLAC-PUB-9031
BABAR-PROC-01/68
hep-ex/0110064
October, 2001

Observation of CP violation in the B^0 system

Christos Touramanis
Department of Physics
Oliver Lodge Laboratory, University of Liverpool
L69 7ZE, Liverpool, U.K.
(for the *BABAR* Collaboration)

Abstract

The *BABAR* detector, operating at energies near the $\Upsilon(4S)$ resonance at the PEP-II asymmetric B Factory at SLAC, has collected a sample of 32 million $B\overline{B}$ pairs by May 2001. A study of time-dependent CP-violating asymmetries in events where one neutral B meson is fully reconstructed in a final state containing charmonium has resulted in the measurement $\sin 2\beta = 0.59 \pm 0.14$ (stat) $\pm$ 0.05 (syst), which establishes CP violation in the B^0 meson system at the 4σ level. B lifetime and mixing measurements from a sub-sample of 23 million $B\overline{B}$ pairs are also presented.

Invited talk presented at the
International Europhysics Conference on HEP
(HEP2001)
12–18 July 2001, Budapest, Hungary

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Work supported by the U.K. Particle Physics and Astronomy Research Council, Advanced Research Fellowship GR/L04177 and by Department of Energy contract DE-AC03-76SF00515.

1 Introduction

Since its discovery in 1964 in the decays of K^0_L mesons [1] *CP* violation has been the subject of many experiments and the motivation for many theoretical developments in particle physics. The three-generation Standard Model accommodates *CP* violation through the presence of a non-zero imaginary phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [2]. The result presented here establishes for the first time the existence of *CP* violation outside the neutral Kaon system.

The primary goal of the *BABAR* experiment at PEP-II is to perform stringent tests of the Standard Model by over-constraining the Unitarity Triangle through *CP* violation measurements (angles α, β and γ) and the determination of its sides ($|V_{ub}|$, $|V_{cb}|$ in semileptonic B decays and $|V_{td}|$ in $B^0\overline{B}^0$ mixing).

2 PEP-II

The PEP-II B Factory [3] is an e^+e^- colliding beam storage ring complex at SLAC designed to produce a luminosity of 3x$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at a center-of-mass energy of 10.58 GeV ($\Upsilon(4S)$ resonance). At the $\Upsilon(4S)$ resonance B mesons can only be produced as B^+B^- or coherent $B^0\overline{B}^0$ pairs. The time evolution of a coherent $B^0\overline{B}^0$ pair is coupled in such a way that the *CP* or flavor of one B at decay time t_1 can be described as a function of the other B flavor at its decay time t_2 and the signed time difference $\Delta t = t_1 - t_2$. The machine has asymmetric energy beams (9.0 GeV electrons on 3.1 GeV positrons), corresponding to a center-of-mass boost of $\beta\gamma$=0.56. An average separation of $\beta\gamma c\tau \approx$250 μm between the two B meson decay vertices allows the measurement of time-dependent decay rate asymmetries. PEP-II has exceeded its design luminosity by 30% while *BABAR*, with a logging efficiency of >95%, has been accumulating data at daily rates up to 260 pb^{-1}.

3 *BABAR*

A detailed description of the detector and its performance can be found in [3]. The volume within the 1.5T *BABAR* superconducting solenoid contains a five layer silicon strip vertex detector (SVT), a central drift chamber with a helium-based gas mixture (DCH), a quartz-bar Cherenkov radiation detector (DIRC) and a CsI(Tl) crystal electromagnetic calorimeter (EMC). Two layers of cylindrical resistive plate counters (RPCs) are located between the barrel calorimeter and the magnet cryostat. The instrumented flux return (IFR) outside the cryostat is composed of 18 layers of radially increasing thickness steel, instrumented with 19 layers of planar RPCs in the barrel and 18 in the endcaps which provide muon and neutral hadron identification.

The SVT has a typical single hit resolution of 15 μm in z and 97% efficiency, while fully reconstructed single B decay vertex resolution in z is 50 μm. Charged particle tracking using the SVT and DCH achieves a resolution of $(\sigma(p_T/p_T))^2 = (0.0015\,p_T)^2 + (0.0045)^2$, where p_T is the transverse momentum in GeV/c. Photons are reconstructed in the EMC, yielding mass resolutions of 6.9 MeV/c^2 for $\pi^0 \to \gamma\gamma$ and 10 MeV/c^2 for $K^0_S \to \pi^0\,\pi^0$.

Leptons and hadrons are identified using a combination of measurements from all the *BABAR* components, including energy loss dE/dx in the DCH and in the SVT. Electron identification is mainly based on deposited energy and shower characteristics in the EMC, while muons are identified in the IFR and confirmed by their minimum ionizing signal in the EMC. Excellent kaon identification in the barrel region is provided by the DIRC, which achieves a $K-\pi$ separation of $>3.4\sigma$ in the range 0.25–3.0 GeV/c.

4 Mixing and CP violation with dilepton events

The mass difference Δm_d between the two mass eigenstates of the neutral B system (sensitive to $|V_{td}|$) is measured by comparing the rate of neutral B meson pairs decaying with the same b quark flavor to the rate of decays with the opposite flavor sign. At the $\Upsilon(4S)$ this time dependent asymmetry gives direct access to Δm_d:

$$A_{\Delta m_d}(\Delta t) = \frac{N(B^0\overline{B}^0)(\Delta t) - (N(B^0B^0)(\Delta t) + N(\overline{B}^0\overline{B}^0)(\Delta t))}{N(B^0\overline{B}^0)(\Delta t) + (N(B^0B^0)(\Delta t) + N(\overline{B}^0\overline{B}^0)(\Delta t))} = \cos(\Delta m_d \cdot \Delta t) \qquad (1)$$

where Δt is the difference between the two neutral B decay times. The simplest way to determine the b quark flavor of the decaying neutral B is to use primary leptons as tagging particles. $A_{\Delta m_d}(\Delta t)$ can be constructed directly from the rates of "like-sign" $(l^+,l^+)+(l^-,l^-)$ and "unlike-sign" (l^+,l^-) events. A sample of 100,000 dilepton events has been selected from 23 million $B\overline{B}$ pairs (charged and neutral). Cascade decays background $(b \to c \to l)$ is suppressed by a neural network using kinematic information of the events. The charged B content of the sample is extracted from the data together with Δm_d. In the *boost approximation* used in this measurement the decay time difference is calculated as: $\Delta t = \Delta z/c < \beta\gamma >$, where the small flight path of the B mesons perpendicular to the z axis is ignored. The Δz resolution is extracted from simulation and has been validated by comparisons to real data control samples (e.g. J/ψ decays). The time dependent asymmetry is shown in Fig. 1. The preliminary result is:

$$\Delta m_d = 0.499 \pm 0.010(\text{stat.}) \pm 0.012(\text{syst.})\hbar\,\text{ps}^{-1} \qquad (2)$$

CP and T violation in $B^0\overline{B}^0$ mixing can be probed in the same way as in $K^0\overline{K}^0$ mixing [4]. Its magnitude is given by the parameter ε:

$$A_T(|\Delta t|) = \frac{Nb(l^+,l^+) - Nb(l^-,l^-)}{Nb(l^+,l^+) + Nb(l^-,l^-)} \approx \frac{4Re(\varepsilon)}{1+|\varepsilon|^2} \qquad (3)$$

Using our dilepton sample we obtain the preliminary result:

$$\frac{4Re(\varepsilon)}{1+|\varepsilon|^2} = (1.2 \pm 2.9(\text{stat.}) \pm 3.6(\text{syst.})) \times 10^{-3} \qquad (4)$$

which is the most precise measurement of this quantity to date. The A_T distribution is also shown in Fig. 1.

5 Time-dependent measurements with exclusively reconstructed B events

High purity B event samples are obtained when the hadronic decay of one B meson is fully reconstructed. In such events the kinematics and decay vertex, as well as the flavor or CP content of the exclusively reconstructed B are fully determined. The events where in addition the decay vertex of the other B meson can be determined are used for lifetime measurements. The $B^0\overline{B}^0$ events where both the decay vertex and flavor (at decay time) of the other B can be determined are used for mixing or CP violation measurements.

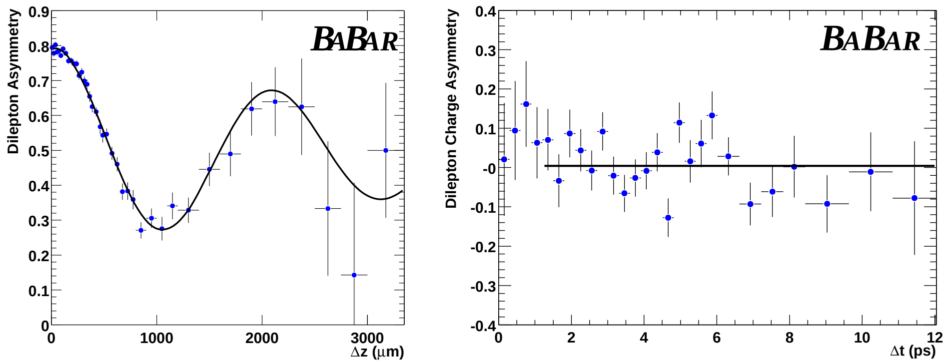

Figure 1: Left: The time dependent asymmetry between unmixed and mixed dilepton events. Right: The asymmetry A_T. The fit results are superimposed on both asymmetry plots.

5.1 Exclusive B reconstruction

B^0 mesons are fully reconstructed in hadronic modes of (a) definite flavor: $B^0 \to D^{(*)-}\pi^+$, $D^{(*)-}\rho^+$, $D^{(*)-}a_1^+$, $J/\psi\, K^{*0}(K^{*0} \to K^+\pi^-)$ and (b) known CP content: $B^0 \to J/\psi\, K^0_S$, $\psi(2S)K^0_S$, $J/\psi\, K^0_L$, $\chi_{c1}K^0_S$, $J/\psi\, K^{*0}(K^{*0} \to K^0_S\pi^0)$. In the following the two samples are referred to as $B_{\rm flav}$ and B_{CP} respectively. $B^\pm$ mesons are reconstructed in the hadronic modes $B^- \to D^0\pi^-$, $D^{*0}\pi^-$, $J/\psi\, K^-$, $\psi(2S)K^-$ (throughout this paper conjugate modes are implied).

The selections have been optimized for signal significance, using on-peak, off-peak and simulated data. Charged particle identification, mass (or mass difference) and vertex constraints are used wherever applicable. The signal for each decay mode is identified in the two-dimensional distribution of the kinematical variables ΔE and $m_{\rm ES}$: $\Delta E = E^*_{\rm rec} - E^*_b$ is the difference between the B candidate energy and the beam energy and $m_{\rm ES} = \sqrt{E^{*2}_b - \boldsymbol{p}^{*2}_{\rm rec}}$ is the mass of a particle with a reconstructed momentum $\boldsymbol{p}^*_{\rm rec} = \sum_i \boldsymbol{p}^*_i$ assumed to have the beam energy, as is the case for a true B meson. In events with several B candidates only the one with the smallest ΔE is considered. The ΔE and $m_{\rm ES}$ variables have minimal correlation. The resolution in $m_{\rm ES}$ is $\approx 3\,{\rm MeV}/c^2$, dominated by the beam energy spread. The resolution in ΔE is mode dependent and varies in the range of 12–40 MeV. For each mode a rectangular signal region is defined by the three standard deviation bands in $m_{\rm ES}$ ($5.27 < m_{\rm ES} < 5.29\,{\rm GeV}/c^2$) and ΔE (mode dependent interval). The composition of each sample is determined by fitting the $m_{\rm ES}$ distribution for candidates within the signal region in ΔE to the sum of a single Gaussian representing the signal and a background function introduced by the ARGUS collaboration [5].

5.2 Δt calculation and resolution

Since no stable charged particle emerges from the $\Upsilon(4S)$ decay point, the production point of the B mesons and thus their individual decay times cannot be determined. However the decay time difference Δt between the two is sufficient for the description of a coherent B meson pair (decay length difference technique).

The difference of the proper decay times of the B mesons $\Delta t = t_1 - t_2$ is determined from the separation along the boost direction $\Delta z = z_1 - z_2$, including an event-by-event correction for the direction of the B with respect to the z direction in the $\Upsilon(4S)$ frame. z_1 is determined from the charged tracks that constitute the exclusively reconstructed B_1 candidate. The other B vertex is determined by fitting the tracks not belonging to the B_1 candidate to a common vertex. Tracks from photon conversions are removed. Pairs of tracks compatible with the decay of a long lived K^0 or Λ are replaced by the parent neutral pseudotrack. To reduce the bias in the forward z direction from charm decay products, the track with the largest contribution to the vertex χ^2, if above 6, is removed and the fit is iterated until no track fulfills this condition. Knowledge of the beam spot location and beam direction is incorporated in the B_2 vertex determination through the addition of a pseudotrack to its vertex, computed from the B_1 vertex and three-momentum, the beam spot (with a vertical size of $10\,\mu$m) and the $\Upsilon(4S)$ momentum. The Δz reconstruction efficiency is 97%. For 99% of the reconstructed vertices the r.m.s. Δz resolution measured in data is $180\,\mu$m, dominated by the z_2 vertex. An event is accepted if it has converged fits for the two B vertices, an error of less than $400\,\mu$m on Δz, and a measured $|\Delta t| < 20$ ps.

The modelling of the resolution function $\mathcal{R}$ is a crucial element of all time-dependent measurements. In the case of B lifetime measurements, studies both on simulated and real data have shown that adding a zero-mean Gaussian distribution and its convolution with a decay exponential provides the best compromise between different sources of uncertainties. The width of the Gaussian is scaled by the per-event Δt error, derived from the vertex fits. A zero-mean Gaussian distribution with width fixed at 10 ps is used to describe outliers (less than 1% of events with incorrectly reconstructed vertices).

In the mixing and *CP* violation measurements the time resolution is described by the sum of three Gaussian distributions (core, tail and outliers) with different means. In the *CP* fit the means are modeled to be proportional to the per-event Δt error, which is correlated with the weight that the daughters of long-lived charm particles have in the tag vertex reconstruction. The core and tail widths are scaled by the per-event Δt error. The outlier width is fixed to 8 ps.

5.3 Flavor tagging

For flavor tagging we exploit information from the incompletely reconstructed 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.

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 and w_i is the mistag fraction for the same category. The statistical error on $\sin 2\beta$ is proportional to $1/\sqrt{Q}$, where $Q = \sum Q_i$. The efficiencies and mistag fractions for the four tagging categories are measured from data and summarized in Table 1.

5.4 B lifetime and mixing measurements

The results presented here have been obtained from a sample of approximately 23 million $B\overline{B}$ pairs collected by *BABAR* between October 1999 and October 2000. Samples of $\approx$6000 B^0 and $\approx$6300 B^+ signal events have been selected with background contamination of less than 10%. The results of a fit with a Gaussian signal distribution and an ARGUS background function [5] are superimposed on the m_{ES} distribution of the final sample in Fig. 2. The B meson lifetimes are extracted from unbinned maximum likelihood fits to the Δt distributions, also shown in Fig. 2. We obtain:

$$\begin{aligned}\tau_{B^0} &= 1.546 \pm 0.032 \text{ (stat)} \pm 0.022 \text{ (syst) ps}\\ \tau_{B^+} &= 1.673 \pm 0.032 \text{ (stat)} \pm 0.023 \text{ (syst) ps}\\ \tau_{B^+}/\tau_{B^0} &= 1.082 \pm 0.026 \text{ (stat)} \pm 0.012 \text{ (syst)}\end{aligned}$$

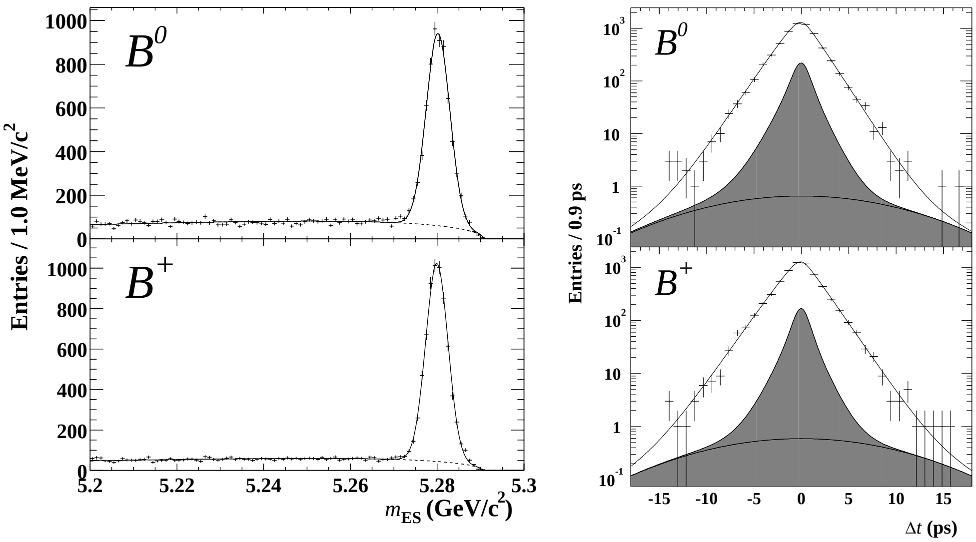

Figure 2: Left: m_{ES} distributions of the selected neutral (top) and charged (bottom) B candidates. Right: Δt distribution for the B^0 (top) and B^+ (bottom) events within 2σ of the B mass in m_{ES} with superimposed fit results. The single-hatched areas are the background components and the cross-hatched areas represent the outlier contributions.

Neutral B meson pairs, produced as $B^0\overline{B}^0$ decay either as $B^0\overline{B}^0$ (unmixed) or B^0 B^0 ($\overline{B}^0$ $\overline{B}^0$) (mixed), allowing to observe $B^0\overline{B}^0$ mixing and measure Δm_d. A sample of $\approx$4500 such events where the flavor of the second B at the time of its decay has been tagged has been obtained. The Δt distributions and the mixing oscillation are shown in Fig. 3. From an unbinned maximum

Tagging 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 ± 1.5	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

Table 1: 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}). Uncertainties are statistical only.

likelihood fit we obtain the preliminary result:

$$\Delta m_d = 0.519 \pm 0.020(\text{stat.}) \pm 0.016(\text{syst.})\hbar\,\text{ps}^{-1} \tag{5}$$

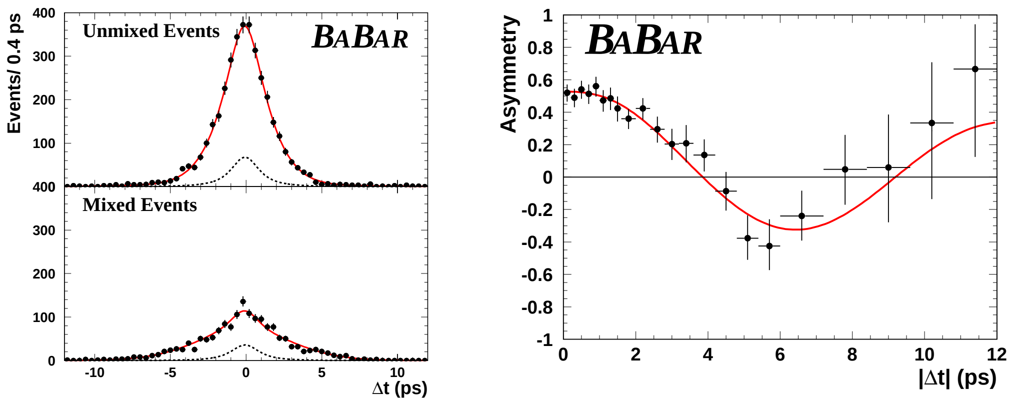

Figure 3: Left: Δt distributions of the selected neutral unmixed (top) and mixed (bottom) events. Right: The time dependent asymmetry between unmixed and mixed events. The fit results are shown superimposed in all distributions. The dashed curves on the Δt plots indicate the background contributions.

6 sin2β and the observation of CP violation

The data set of 32 million $B\overline{B}$ pairs collected between October 1999 and May 2001 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 $J/\psi K^{*0}(K^{*0} \to K^0_S\pi^0)$ final states. The last two modes have been added since our first sin2β publication [9]. There are several other significant changes in the analysis. Improvements in track and K^0_S reconstruction efficiency in 2001 data produce a ≈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. [9]. A sample B_{flav} of 7591 fully reconstructed B^0 events in definite flavor eigenstates has been used to determine the tagging performance and a sample of 6814 fully reconstructed charged B has been used for validations. Details of our samples are shown in Table 2. The samples are shown in Fig. 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 distributions 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 [7]. The distribution $\mathrm{f}_+(\mathrm{f}_-)$ of the decay rate when the tagging meson is a $B^0(\overline{B}^0)$ is given by

$$\mathrm{f}_\pm(\,\Delta t) = \frac{\mathrm{e}^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}(1+|\lambda|^2)} \times \left[\,\frac{1+|\lambda|^2}{2} \pm\ \mathcal{I}m\lambda \sin{(\Delta m_{B^0}\Delta t)} \mp \frac{1-|\lambda|^2}{2}\cos{(\Delta m_{B^0}\Delta t)}\right] \tag{6}$$

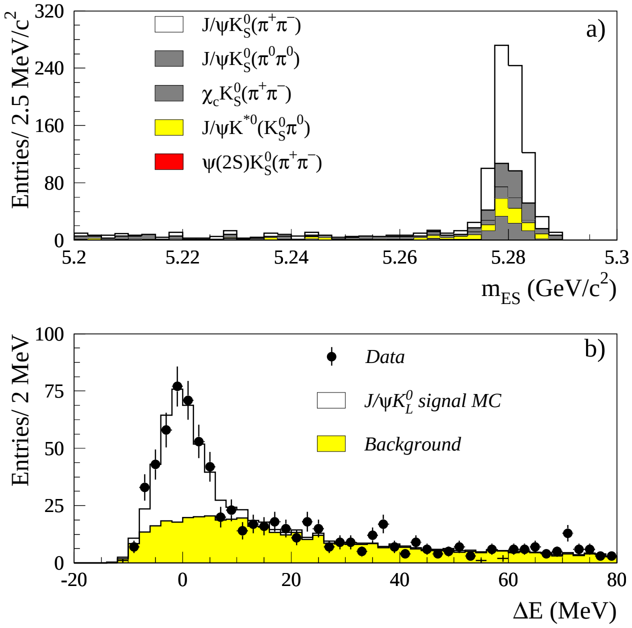

Figure 4: a) Distribution of $m_{\rm ES}$ for B_{CP} candidates having a K^0_S in the final state; b) distribution of ΔE for $J/\psi\, K^0_L$ candidates.

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 [8]. The first oscillatory term in Eq. 6 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 $\overline{B}^0$ Δt distributions or a Δt asymmetry for either flavor tag is evidence for CP violation.

In the Standard Model $\lambda = \eta_f e^{-2i\beta}$ for charmonium-containing $b \to c\overline{c}s$ decays, 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. Thus, the time-dependent CP-violating asymmetry is

$$A_{CP}(\Delta t) \;\equiv\; \frac{{\rm f}_+(\Delta t) - {\rm f}_-(\Delta t)}{{\rm f}_+(\Delta t) + {\rm f}_-(\Delta t)} = -\eta_f \sin 2\beta \sin\left(\Delta m_{B^0}\, \Delta t\right), \qquad (7)$$

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 $J/\psi\, K^{*0} (K^{*0} \to K^0_S \pi^0)$ 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 $D_\perp = 1 - 2R_\perp$, where $R_\perp$ is the fraction of the L=1 component. We have measured $R_\perp = (16 \pm 3.5)\%$ [6] which, after acceptance corrections, leads to an effective $\eta_f = 0.65 \pm 0.07$ for the $J/\psi\, K^{*0}$ mode.

The B_{CP} and B_{flav} samples are used together in the unbinned maximum likelihood fit for the extraction of $\sin 2\beta$. A total of 45 parameters are varied in the fit, including $\sin 2\beta$ (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 large $B_{\rm flav}$ sample. Background parameters are governed by events with $m_{\rm ES} < 5.27\,{\rm GeV}/c^2$. As a result, the largest correlation between $\sin 2\beta$

Table 2: 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 (%)	$\sin2\beta$
$J/\psi K^0_S$,$\psi(2S)K^0_S$,$\chi_{c1}K^0_S$	480	96	0.56 ± 0.15
$J/\psi K^0_L$ ($\eta_f = +1$)	273	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	803	80	0.59 ± 0.14
$J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$ only ($\eta_f = -1$)			
$J/\psi K^0_S$ ($K^0_S \to \pi^+\pi^-$)	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	$2.59 \pm ^{0.55}_{0.67}$
`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
$B_{\rm flav}$ non-CP sample	7591	86	0.02 ± 0.04
Charged B non-CP sample	6814	86	0.03 ± 0.04

and any linear combination of the other free parameters is only 0.13. We fix $\tau_{B^0} = 1.548\,{\rm ps}$ and $\Delta m_{B^0} = 0.472\,\hbar\,{\rm ps}^{-1}$ [8]. The value of $\sin2\beta$ and the CP asymmetry in the Δt distribution were hidden (blind analysis) following our previous publication [9], until the event selection was optimized and all other aspects of the present analysis were complete.

Figure 5 shows the Δt distributions and A_{CP} as a function of Δt 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 parameterized simulation of a large number of data-sized experiments, is 27%. Our result is:

$$\sin2\beta = 0.59 \pm 0.14\ ({\rm stat}) \pm 0.05\ ({\rm syst}).$$

Repeating the fit with all parameters except $\sin2\beta$ 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, Δt resolution and background parameters. The dominant sources of systematic error are the 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_{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 $B_{\rm flav}$ sample are small; an increase of $0.02\,\hbar\,{\rm ps}^{-1}$ in the value for Δm_{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 $B_{\rm tag}$ flavor. The results of fits to these

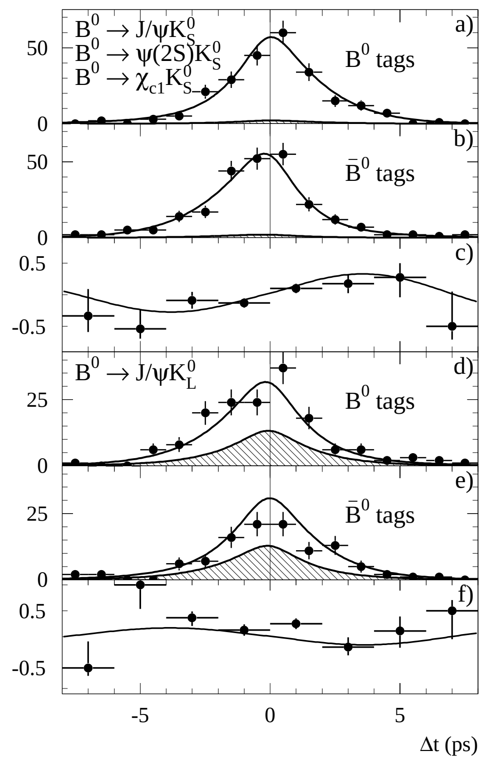

Figure 5: Number of $\eta_f = -1$ candidates ($J/\psi K^0_S$, $\psi(2S)K^0_S$, and $\chi_{c1}K^0_S$) in the signal region a) with a B^0 tag N_{B^0} and b) with a $\overline{B}^0$ tag $N_{\overline{B}^0}$, and c) the asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$, as functions of Δt. The solid curves represent the result of the combined fit to all selected *CP* events; the shaded regions represent the background contributions. Figures d)–f) contain the corresponding information for the $\eta_f = +1$ mode ($J/\psi K^0_L$). The likelihood is normalized to the total number of B^0 and $\overline{B}^0$ tags. The value of sin2β is independent of the individual normalizations and therefore of the difference between the number of B^0 and $\overline{B}^0$ tags.

subsamples are shown in Table 2. Table 2 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 sin2β =0.32±0.18, consistent with the published value [9]. For only these decay modes, the year 2001 data yield sin2β =0.83±0.23, consistent with the 1999-2000 results at the 1.8σ level; for the $J/\psi K^0_S(K^0_S \to \pi^+\pi^-)$ channel the consistency is at the 1.4σ level.

If $|\lambda|$ is allowed to float in the fit to the $\eta_f = -1$ 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 sin2β analysis. In this fit, the coefficient of the $\sin(\Delta m_{B^0}\Delta t)$ term in Eq. 6 is measured to be 0.56 ± 0.15 (stat) in agreement with Table 2.

The measurement of sin2β = 0.59 ± 0.14 (stat) $\pm$ 0.05 (syst) establishes *CP* violation in the B^0 meson system at the 4.1σ 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 3×10^{-5}. This direct measurement is consistent with the range implied by measurements and theoretical estimates of the magnitudes of CKM matrix elements [10].

7 Conclusions and prospects

37 years after the discovery of *CP* violation in the Kaon system, *BABAR* has established *CP* violation in the B system with the measurement:

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

By the summer of 2002 *BABAR* will have a data sample of more than 100 million $B\overline{B}$ pairs, bringing the precision on $\sin 2\beta$ to less than 0.1 and allowing searches for other manifestations of *CP* violation in the B system.

References

[1] J.H. Christenson *et al.*, Phys. Rev. Lett. **13**, 138 (1964).

[2] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Th. Phys. **49**, 652 (1973).

[3] *BABAR* Collaboration, B. Aubert *et al.*, SLAC-PUB-8569, hep-ex/0105044, to appear in Nucl. Instr. and Methods.

[4] CPLEAR Collabration, A. Apostolakis *et al.*, Phys. Lett. **456**, 297 (1999).

[5] ARGUS collaboration, H. Albrecht *et al.*, Phys. Lett. **185**, 218(1987).

[6] *BABAR* Collaboration, B. Aubert *et al.*, SLAC-PUB-8898, hep-ex/0107049, submitted to Phys. Rev. Lett.

[7] See, for example, L. Wolfenstein, Eur. Phys. Jour. C **15**, 115 (2000).

[8] Particle Data Group, D.E. Groom *et al.*, Eur. Phys. Jour. C **15**, 1 (2000).

[9] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **86**, 2515 (2001).

[10] See, for example, F.J. Gilman, K. Kleinknecht and B. Renk, Eur. Phys. Jour. C **15**, 110 (2000); for some further interpretation, with different statistical approaches, see A. Höcker *et al.*, Eur. Phys. Jour. C **21**,1 225-259 (2001) and M. Ciuchini *et al.*, JHEP, 07(2001)013, and references therein.