SLAC-PUB-8835
BABAR-PROC-01/29
hep-ex/0105073
May 23, 2001

CP VIOLATION, B MIXING AND B LIFETIME RESULTS FROM THE BABAR EXPERIMENT

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Abstract

The *BABAR* detector at the PEP-II asymmetric B Factory at SLAC collected a sample of $23 \cdot 10^6$ $B\overline{B}$ pairs in the years 1999 and 2000. Using this data sample, we measure the amplitude of the time-dependent CP-violating asymmetry in neutral B decays to the CP eigenstates $J/\psi K^0_S$, $\psi(2S)K^0_S$ and $J/\psi K^0_L$. We find a value of $\sin 2\beta = 0.34 \pm 0.20(stat) \pm 0.05(syst)$. We also present preliminary measurements of the $B^0\overline{B}^0$ oscillation frequency and of the lifetimes of charged and neutral B mesons.

Invited talk given at the
36th Rencontres de Moriond on QCD and Hadronic Interactions
17-24 March 2001, Les Arcs, France

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

Work supported in part by Department of Energy contract DE-AC03-76SF00515.

The measurement of CP–violating asymmetries in the time distribution of decays of neutral B mesons can provide a direct test of the standard model of electroweak interactions [1] and is the primary goal of the *BABAR* experiment at the PEP-II asymmetric–energy e^+e^- collider at SLAC. Decays of B^0 and $\overline{B}^0$ mesons into charmonium CP eigenstates due to $b \to c\bar{c}s$ transitions (e.g. $B^0 \to J/\psi\, K^0_S$) can be used to measure sin2β (where β is one of the interior angles of the unitarity triangle) with negligible corrections from strong interactions.

In the years 1999 and 2000, *BABAR* [2] collected a sample of $23 \cdot 10^6$ $B\overline{B}$ pairs ($20.7\,\mathrm{fb}^{-1}$ on–peak) at PEP-II, where $B\overline{B}$ mesons are produced at the $\Upsilon(4S)$ resonance in collisions of 9.0 GeV electrons and 3.1 GeV positrons. The boost $\langle\beta\gamma\rangle = 0.56$ along the collision axis (z) resulting from the asymmetric beam energies allows the determination of the proper decay time difference Δt of the two B mesons from the measurement of the decay length difference Δz, whose average value is $\langle\beta\gamma\rangle\, c\tau_{B^0} \simeq 260\,\mu$m.

In $\Upsilon(4S)$ decays, $B^0\overline{B}^0$ pairs are produced in a P–wave state and evolve coherently until one of the B meson decays. At that time ($\Delta t = 0$) the other B meson has the opposite flavor. In events where one of the B mesons, B_{CP}, decays into a charmonium CP eigenstate and the other, B_{tag}, decays such that its flavor can be determined, the expected decay–time distribution $\mathcal{F}_+$ ($\mathcal{F}_-$) for events where the flavor tag is a B^0 ($\overline{B}^0$) is given by

$$\mathcal{F}_\pm(\Delta t_{\rm rec}; \Gamma, \Delta m_d, w, \sin 2\beta) = \frac{1}{4}\Gamma \mathrm{e}^{-\Gamma|\Delta t|}\,[1 \mp \eta_{CP}(1-2w)\sin 2\beta \sin \Delta m_d \Delta t] \otimes \mathcal{R}(\delta_{\rm t}; \hat{a})\,. \quad (1)$$

The mistag rate w is the probability to wrongly determine the flavor of B_{tag}. The decay–time distribution is convoluted with a time resolution function $\mathcal{R}(\delta_{\rm t} = \Delta t_{\rm rec} - \Delta t; \hat{a})$ with parameters $\hat{a}$ in order to account for the finite resolution of the detector. η_{CP} is the CP eigenvalue of the final state (-1 for decay modes with K^0_S, +1 for modes with K^0_L).

For events where one of the B mesons decays into a fully reconstructed flavor eigenstate $B_{\rm flav}$, the decay–time distribution for unmixed ($\mathcal{H}_+$) and mixed ($\mathcal{H}_-$) signal events is

$$\mathcal{H}_\pm(\Delta t_{\rm rec}; \Gamma, \Delta m_d, w, \hat{a}) = \frac{1}{4}\,\Gamma\,\mathrm{e}^{-\Gamma|\Delta t|}\,[1 \pm (1-2w)\cos \Delta m_d \Delta t] \otimes \mathcal{R}(\delta_{\rm t}; \hat{a})\,, \quad (2)$$

where an unmixed event is one where the $B_{\rm flav}$ and B_{tag} mesons have opposite flavor. The mistag rate and resolution function (the latter is dominated by the reconstruction of the B_{tag} vertex) are the same as for the B_{CP} sample, and both can be determined from the $B_{\rm flav}$ sample.

CP candidates are reconstructed in the decay modes $J/\psi\, K^0_S$, $\psi(2S)K^0_S$, and $J/\psi\, K^0_L$ and are required to have a difference ΔE between the energy of the B_{CP} candidate and the beam energy in the center–of–mass frame of less than 3 standard deviations from zero. In addition, modes with a K^0_S must have a beam–energy substituted mass $m_{\rm ES} = \sqrt{(E^{\rm cm}_{\rm beam})^2 - (p^{\rm cm}_B)^2} > 5.2\,\mathrm{GeV}/c^2$ ($m_{\rm ES} > 5.27\,\mathrm{GeV}/c^2$ for candidates counted as signal). The distributions of $m_{\rm ES}$ and ΔE for the B_{CP} candidates are shown in figure 1. A sample of B decays, $B_{\rm flav}$, reconstructed in the flavor eigenstate modes [a] $D^{(*)-}h^+(h^+ = \pi^+, \rho^+, a_1^+)$ and $J/\psi\, K^{*0}$ ($K^{*0} \to K^+\pi^-$) is used to measure the B^0 lifetime and Δm_d. A sample of charged B decays, $B_{\rm ch}$, in the final states $J/\psi\, K^{(*)+}$, $\psi(2S)K^+$ and $\overline{D}^{(*)0}\pi^+$ is used to measure the B^+ lifetime and serves as a control sample. Yields and purities for events with a flavor tag are summarized in table 1.

The vertex of the other B in the event (B_{tag}) is determined by fitting the tracks not belonging to the reconstructed B_{CP}, $B_{\rm flav}$ or $B_{\rm ch}$ to a common vertex. Tracks from γ conversion are removed and reconstructed K^0_S and Λ candidates are used as input to the fit in place of their daughters.

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

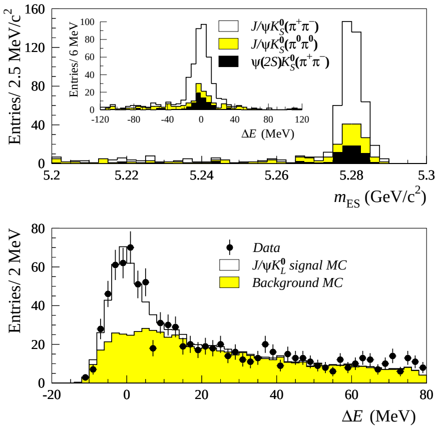

Figure 1: $m_{\rm ES}$ and ΔE distribution for B_{CP} candidates with K^0_S (top) and K^0_L (bottom).

Sample	$N_{\rm tag}$	Purity (%)	sin2β
Full CP sample	529	69 ± 2	0.34 ± 0.20
$J/\psi\, K^0_L$	256	39 ± 6	0.87 ± 0.51
$J/\psi\, K^0_S$, $\psi(2S) K^0_S$	273	96 ± 1	0.25 ± 0.22
- `Lepton` tags	34	99 ± 2	0.07 ± 0.43
- `Kaon` tags	156	96 ± 2	0.40 ± 0.29
- `NT1` tags	28	97 ± 3	-0.03 ± 0.67
- `NT2` tags	55	96 ± 3	0.09 ± 0.76
- B^0 tags	141	96 ± 2	0.24 ± 0.31
- $\overline{B}^0$ tags	132	97 ± 2	0.25 ± 0.30
$B_{\rm flav}$ sample	4637	86 ± 1	0.03 ± 0.05
Charged B sample	5165	90 ± 1	0.02 ± 0.05

Table 1: Number of tagged events, signal purity, and result of fitting for CP asymmetries in the full B_{CP} sample, in various subsamples, and in the $B_{\rm flav}$ and charged B samples.

Tracks with a large (> 6) χ^2 contribution are removed to reduce the bias from charm decays. We require $\sigma(\Delta z) < 400\,\mu$m and $|\Delta z| < 3\,$mm. The average resolution of Δz is $190\,\mu$m.

To a very good approximation $\Delta t \approx \Delta z / c\,\langle\beta\gamma\rangle$, but event–by–event corrections are made for the direction of the B with respect to the z direction in the $\Upsilon(4S)$ frame. The resolution function $\mathcal{R}(\delta_{\rm t}; \hat{a})$ is parameterized either as the sum of three Gaussian distributions (sin2β and Δm_d measurements) or as the sum of a zero–mean Gaussian distribution and its convolution with a decaying exponential (lifetime measurements). In both cases, the event–by–event errors calculated by the vertex fits are used to scale some of the contributions to $\mathcal{R}(\delta_{\rm t}; \hat{a})$. From an unbinned maximum likelihood fit to the Δt_{rec} distribution in the $B_{\rm flav}$ and $B_{\rm ch}$ samples, including also events without a flavor tag, we obtain the preliminary results

$$\tau_{B^0} = 1.546 \pm 0.032\,({\rm stat}) \pm 0.022\,({\rm syst})\ {\rm ps} \quad (3)$$

$$\tau_{B^+} = 1.673 \pm 0.032\,({\rm stat}) \pm 0.022\,({\rm syst})\ {\rm ps} \quad (4)$$

$$\tau_{B^+}/\tau_{B^0} = 1.082 \pm 0.026\,({\rm stat}) \pm 0.011\,({\rm syst})\,. \quad (5)$$

The fit takes into account contributions from signal, background and outliers. The probability of each candidate to be signal is determined from the $m_{\rm ES}$ distribution. An empirical description based on $m_{\rm ES}$ sidebands and including both prompt and lifetime components is used to describe the Δt shape of the combinatoric background from other B decays and from continuum events.

In order to determine the B_{tag}'s flavor tag for the sin2β and Δm_d measurements, we use the flavor information carried by the charge of high momentum leptons (e, μ) from semileptonic B decays, of kaons from $b \to c \to s$ transitions, of soft pions from D^* decays and of high momentum charged particles not coming from the reconstructed B_{CP} or $B_{\rm flav}$ candidate. Each event is assigned to one of four hierarchical mutually exclusive tagging categories (or else not assigned a flavor tag). The `Lepton` and `Kaon` categories are characterized by the presence of an electron or muon with a center–of–mass momentum $p^*_e > 1.0\,{\rm GeV}/c$ or $p^*_\mu > 1.1\,{\rm GeV}/c$, and of one or more kaons with a non–zero charge sum, respectively. The remaining two categories, `NT1` and `NT2`, are based on the output of a neural network algorithm whose performance relies primarily on soft pions and on recovering isolated electrons and muons from semileptonic B decays. The tagging performance measured on data is shown in table 2.

Based on the flavor of the reconstructed $B_{\rm flav}$ candidate and the flavor tag, events in the $B_{\rm flav}$

Category	ε (%)	w (%)	Δw (%)	Q (%)
Lepton	10.9 ± 0.4	11.6 ± 2.0	3.1 ± 3.1	6.4 ± 0.7
Kaon	36.5 ± 0.7	17.1 ± 1.3	-1.9 ± 1.9	15.8 ± 1.3
NT1	7.7 ± 0.4	21.2 ± 2.9	7.8 ± 4.2	2.6 ± 0.5
NT2	13.7 ± 0.5	31.7 ± 2.6	-4.7 ± 3.5	1.8 ± 0.5
All	68.9 ± 1.0			26.7 ± 1.6

Table 2: 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 in the $B_{\rm flav}$ $+B_{CP}$ sample. The figure of merit for tagging is $Q_i = \varepsilon_i(1-2w_i)^2$, where ε_i is the fraction of events in the i^{th} category. The statistical error on sin2β is proportional to $1/\sqrt{Q}$, where $Q = \sum Q_i$.

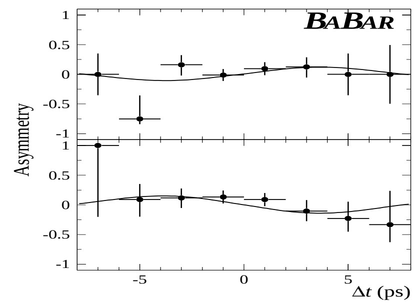

Figure 2: Raw asymmetry in the number of B^0 and $\overline{B}^0$ tags for $J/\psi\ K^0_S$, $\psi(2S)\ K^0_S$ (top) and $J/\psi\ K^0_L$ modes (bottom). The solid curve is the sin2β fit to these samples.

sample are classified as mixed or unmixed. The time–dependent mixing asymmetry $A(\Delta t_{rec}) = (N_{unmixed} - N_{mixed})/(N_{unmixed} + N_{mixed})$ is shown in figure 3. Δm_d is determined from an unbinned maximum likelihood fit in which the mistag fractions w_i and Δw_i (8 parameters), signal resolution function parameters (9 parameters) and the fractions, lifetimes, dilutions and resolution function parameters of different background components (16 parameters) are determined simultaneously with Δm_d. The correlation between Δm_d and w_i is small because the latter are determined by events at low values of Δt where the mixing probability is small.

An alternative method for measuring Δm_d is to use inclusively reconstructed dilepton events, i.e. events where both B mesons decay semileptonically and the flavor of each B is given by the charge of the high momentum electron or muon produced in its decay. Because of the relatively large semileptonic branching ratio and the high lepton identification efficiency, this method is statistically more powerful. The non–negligible backgrounds due to leptons from charm decays are minimized with a neural network technique which uses the lepton momenta and opening angle, and the total and missing energy as input. The resulting dilepton sample has about equal contributions from neutral and charged B mesons, but the former can be enhanced by an inclusive reconstruction of $\overline{B}^0 \to D^{*+}\ell^-\nu$ decays. The mixing asymmetry obtained with this technique is shown in figure 3.

The preliminary results obtained for Δm_d with the two methods are:

$$\Delta m_d = 0.519 \pm 0.020\,(\text{stat}) \pm 0.016\,(\text{syst})\,\hbar\,\text{ps}^{-1} \qquad (\text{B}_{\text{flav}}\text{ sample}) \qquad (6)$$

$$\Delta m_d = 0.499 \pm 0.010\,(\text{stat}) \pm 0.012\,(\text{syst})\,\hbar\,\text{ps}^{-1} \qquad (\text{dilepton sample}) \qquad (7)$$

The sin2β measurement is made with an unbinned maximum likelihood fit to the Δt_{rec} distribution of the tagged candidates from the combined B_{CP} and $B_{\rm flav}$ samples with parameters similar to the ones used in the fit for Δm_d. The values of the B^0 lifetime and Δm_d are fixed to their world average [3]. We find a value of [4]

$$\sin2\beta = 0.34 \pm 0.20\,(\text{stat}) \pm 0.05\,(\text{syst})\,. \qquad (8)$$

The raw asymmetry in the number of B^0 and $\overline{B}^0$ tags as a function of $\Delta t_{\rm rec}$ is shown in figure 2 and has, as expected from eq. 1, the opposite sign for CP even and CP odd modes.

The determination of the mistag rates and Δt resolution function function is dominated by the high statistics $B_{\rm flav}$ sample. The largest correlation between sin2β and any linear combination of the other 34 free parameters is 0.076. The dominant sources of systematic error are the assumed parameterization of the Δt resolution function, due in part to residual uncertainties in the alignment

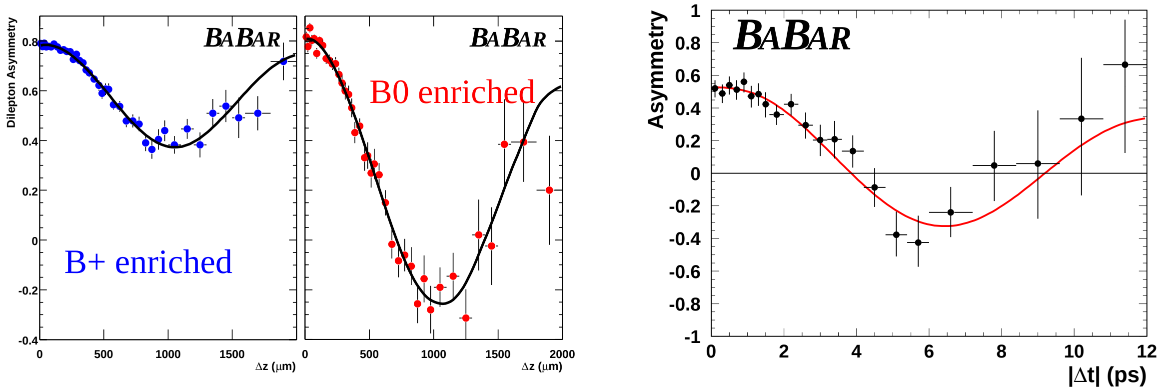

Figure 3: Mixing asymmetry $A(\Delta t_{rec})$ in the dilepton (left) and the B_{flav} (right) sample (preliminary).

of the silicon vertex tracker, and uncertainties in the level, composition and CP asymmetry of the background in the selected CP events. The large B_{CP} sample allows a number of consistency checks, including fits to subsamples of the data by decay mode, tagging category and flavor of the B_{tag} as shown in table 1. No statistically significant asymmetry is found in fits to control samples where no asymmetry is expected.

The measured value of sin2β is consistent with the range implied by measurements and theoretical estimates of the magnitudes of CKM matrix elements [5]. It is also consistent with no CP asymmetry at the 1.7σ level.

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