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BABAR Results on CP Violation in the B^0 system.

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Abstract

The *BABAR* detector, operating at the SLAC PEP-II asymmetric B Factory, has collected a sample of 32 million $B\overline{B}$ pairs by May 2001, at energies close to the $\Upsilon(4S)$ resonance. The measurement of $\sin 2\beta = 0.59 \pm 0.14(stat) \pm 0.05(syst)$, performed with a study of time-dependent CP-violating asymmetries in neutral B decays, establishes CP violation at the 4σ level. In addition, preliminary results on CP-violating asymmetries in the decay channel $B^0 \rightarrow \pi^+\pi^-$ are presented.

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1 Introduction

The *BABAR* experiment has performed the first observation ever of CP violation in the neutral B meson system, 37 years after its discovery in the kaon system [1]. CP violation is explained within the three-generations Standard Model by the non vanishing imaginary phase of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [2]. The primary goal of the experiment is to probe the validity of this picture by over-constraining the Unitarity Triangle through measurements of both its sides and angles (α, β, γ).

The angles can be determined measuring the decays of neutral B to CP eigenstates. The final state, f_{CP}, can be reached via a direct decay or a decay after oscillation in the opposite flavor. The interference between the two possible paths can produce different decay time distributions for B^0 and $\overline{B}^0$. A time-dependent CP asymmetry can then be defined as follows:

$$\begin{aligned} a_{CP}(t) &= \frac{\Gamma(B^0(t) \to f_{CP}) - \Gamma(\overline{B}^0(t) \to f_{CP})}{\Gamma(B^0(t) \to f_{CP}) + \Gamma(\overline{B}^0(t) \to f_{CP})} \\ &= \frac{(1-|\lambda|^2)\cos(\Delta m_d t)}{1+|\lambda|^2} + \frac{-2\mathrm{Im}(\lambda)\sin(\Delta m_d t)}{1+|\lambda|^2}\ . \end{aligned} \tag{1}$$

CP violation occurs when $\lambda = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} \neq 1$. By definition, λ is independent of phase convention, q and p are the parameters expressing the B mixing, while $\overline{A}_{f_{CP}}(A_{f_{CP}})$ is the decay amplitude for a $\overline{B}^0$ (B^0), Δm_d is instead a measure of the $B^0\overline{B}^0$ oscillation frequency. In B decays where there are no effects of direct CP violation, it results $|\lambda| = 1$ and the coefficient of the sin term of the above equation can be directly related to angles of the Unitarity Triangle. In particular, the so called *golden mode* $B^0 \to J/\psi K^0$ ($BF \sim 8 \times 10^{-4}$), leads to the measurement of β ($\eta_{J/\psi K^0_{S,L}}$ is the CP eigenvalue of the final state):

$$a_{CP}(t) = -\eta_{J/\psi K^0_{S,L}}\ \sin 2\beta\ \sin\,(\Delta m_d t) \tag{2}$$

1.1 PEP-II and *BABAR*

The PEP-II B Factory is an e^+e^- double ring collider designed to operate at a center-of-mass energy of 10.58 GeV ($\Upsilon(4S)$ resonance), with asymmetric beam energies (9 GeV e^- on 3.1 GeV e^+). This facility fulfills all the needs for measuring the asymmetries described in Eq (1). The cross sections for $\Upsilon(4S)$ and continuum $q\bar{q}$ production are in a ratio $\sim 1/4$ and the $\Upsilon(4S)$ decays almost exclusively in $B\overline{B}$ pairs, providing a large sample of B mesons with a good signal-to-noise ratio. The $B^0\overline{B}^0$ pairs evolve in coherent P-wave states until a decay occurs. If one of the neutral $B(B_{tag})$ decays in a state which unambiguously identifies its flavor at a certain time t_{tag}, the other $B(B_{CP})$ is, *at that time* known to be of the opposite flavor. As a consequence, a clear flavor tagging procedure is available and the asymmetry can be studied as a function of the difference between the two B decay times $\Delta t = t_{CP} - t_{tag}$. The boost ($\beta\gamma = 0.56$), provided to the $\Upsilon(4S)$ system by the different beam energies, yields an average decay length for the B mesons of $\beta\gamma c\tau \approx 260$ μm. Δt is then determined from the distance between the B decay vertices: $\Delta t = \Delta z/\langle\beta\gamma\rangle c$. The *BABAR* detector [3] is a cylindric detector, asymmetric with respect to the interaction point to account for the boost and maximize the acceptance in the center of mass system. The volume inside the 1.5 T super-conducting solenoid consists of a five layer double-sided silicon strip vertex detector (SVT), a drift chamber (DCH) filled with a Helium-Isobutane gas mixture, a quartz-bar

Cherenkov detector (DIRC), a CsI(Tl) crystal electromagnetic calorimeter (EMC) and two layers of cylindric resistive plate counters (RPC). Externally at the solenoid, the iron for the magnetic flux return has been instrumented with 19 layers of RPC's (IFR).

2 Time-dependent measurements with exclusively reconstructed B events

The measurements of both $B^0\overline{B}^0$ mixing and CP asymmetries can be performed using events where the decay of one B meson into a flavor or CP eigenstate respectively is fully reconstructed (the two samples are referred to as B_{flav} and B_{CP}). In order to maximize the data sample, the other B is only partially reconstructed to determine its decay vertex and its flavor at the decay time. The selections for the different decay modes have been optimized to give maximum sensitivity to the final measurement. The signal is identified in the two-dimensional distribution of the almost uncorrelated kinematic variables ΔE and m_{ES}. $\Delta E = E^*_B - E^*_{beam}$ is the difference between the reconstructed B candidate energy and the beam energy in the center of mass system. The energy substituted mass, $m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$, is the mass of a particle with a reconstructed momentum of p^*_B assumed to have the beam energy, as it should be for a true B meson. The resolution on m_{ES} is ≈ 3 MeV/c^2, dominated by the beam energy spread, while the resolution on ΔE is mode dependent (ranging from 12 to 40 MeV). For each mode a signal region is defined as $\pm 3\sigma$ about the nominal values (5.279,0.) in the $m_{ES}, \Delta E$ plane. The signal purities are determined by fitting the m_{ES} distribution, for candidates within the ΔE signal region, to the sum of a single Gaussian representing the signal and a background function first introduced by the ARGUS collaboration [4].

2.1 Δt measurement and B flavor tagging

The difference of proper decay times of the B mesons is determined from the separation along the boost direction of the vertices, $\Delta z = z_1 - z_2$. An event-by-event correction for the direction of the B with respect to the z direction in the $\Upsilon(4S)$ frame is applied. The error on Δz is dominated by the vertex of the partially reconstructed B_{tag}, which is determined by a fit to a common vertex of all the tracks not assigned to the fully reconstructed B, using also the knowledge of the beam spot location, the $\Upsilon(4S)$ momentum and the direction of the fully reconstructed B. The Δz reconstruction efficiency is 97%, with a r.m.s. measured in data of 180 μm. Only events with converged fits for the two vertices, an error on Δz less than 400 μm and a measured $|\Delta t| < 20$ ps are accepted.

The Δt resolution function $\mathcal{R}(\Delta t)$ for both B_{CP} and B_{flav} samples, is parametrized as a sum of three Gaussian distributions (core, tail and outliers) with different means. The core and tail widths are scaled by the per-event Δt error derived from the vertex fit. The third Gaussian, whose width is fixed to 8 ps, accounts for the $< 1\%$ of events with incorrectly reconstructed vertices. Separate resolution function parameters have been used for data collected in 1999-2000 and 2001, due to a significant improvement in the SVT alignment.

For flavor tagging we look at the decay modes of the other, partially reconstructed, B in the event. Each event is assigned to one of four hierarchical, mutually exclusive tagging categories. The **Lepton** and **Kaon** categories determine the flavor using the charge of a high momentum leptons from semileptonic B decays or the charge of the kaon produced in the hadronization of the s quark coming from the $b \to c \to s$ transitions (e.g. 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 $Q \equiv \sum_i \varepsilon_i(1-2w_i)^2$, where ε_i and w_i are the efficiency and wrong tag fractions for the i^{th} category. The statistical error on sin2β is in fact proportional to $1/\sqrt{Q}$. The tagging performances measured from real data are reported in Table 1.

Table 1: Efficiencies ϵ_i, mistag fractions w_i and effective tagging efficiencies for each tagging category. The w_i are extracted from the global maximum likelihood fit to the time distribution of the fully reconstructed B^0 sample ($B_{flav} + B_{CP}$).

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

2.2 sin2β measurements

The B_{CP} sample used for the sin2β analysis consists 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 $J/\psi K^*$. The last two modes have been added since our first sin2β publication [5]. There are several other significant changes and optimizations in the present analysis, the details can be found in the published paper [6]. With all the improvements, the final B_{CP} tagged sample contains about 640 signal events and the statistical power of the analysis is almost doubled. B_{flav} sample, used to determine the tagging performance, consists of 7591 events, while a sample of 6814 fully reconstructed charged B has been used for analysis validations. Table 2 reports the details about the collected samples, while figure 1 shows on the left the m_{ES} distribution in the ΔE window for $\eta_{CP} = -1$ modes and the ΔE distribution for $J/\psi K^0_L$ candidates.

Even if less pure, the $J/\psi K^0_L$ mode is very important because its CP eigenvalue ($\eta_{CP} = +1$) is opposite to the other modes. Due to the presence of even (L=0, 2) and odd ($L = 1$) orbital angular momenta in the $J/\psi K^*$ final state, its CP content is a mixture of CP-even and CP-odd states. When an angular analysis is not performed, the measured CP asymmetry in this channel is diluted by a factor $D_\perp = 1 - 2R_\perp$, where $R_\perp$ is the fraction of the $L = 1$ component. We have measured $R_\perp = (16 \pm 3.5)\%$ [7], which after acceptance corrections leads to an effective $\eta_{CP} = 0.65 \pm 0.07$.

The sin2β value is extracted from a simultaneous unbinned maximum likelihood fit to the Δt distributions of the B_{CP} and B_{flav} tagged samples. The latter evolve according to the known rate for flavor oscillation in neutral B mesons [8]. The Δt distribution of the B_{CP} sample, in the most general case, is written as:

$$f_\pm(\Delta t) = \frac{\Gamma e^{-\Gamma|\Delta t|}}{2(1+|\lambda|^2)}\left[\frac{1+|\lambda|^2}{2} \pm Im(\lambda)\sin(\Delta m_d \Delta t) \mp \frac{1-|\lambda|^2}{2}\cos(\Delta m_d \Delta t)\right] \quad (3)$$

where $f_+(f_-)$ refers to events with B^0 ($\overline{B}^0$) tag. The quark subprocess for the B decays considered here is a transition $b \to c\bar{c}s$, which, according to the SM, occurs with the same weak phase for all the dominant diagrams. As a consequence $\lambda = \eta_{CP} e^{-2i\beta}$ and the CP asymmetry gives directly the value of sin2β, as show in Eq.(2).

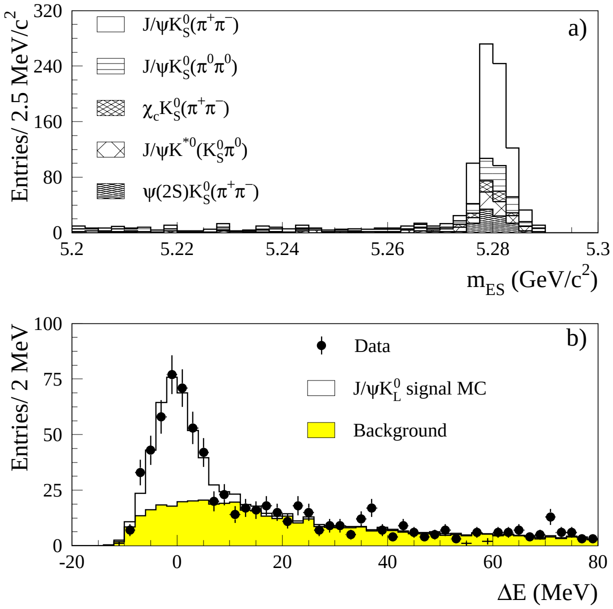

Figure 1: Distributions of m_{ES} for B_{CP} candidates having a K^0_S in the final state and of ΔE for $J/\psi\, K^0_L$ candidates.

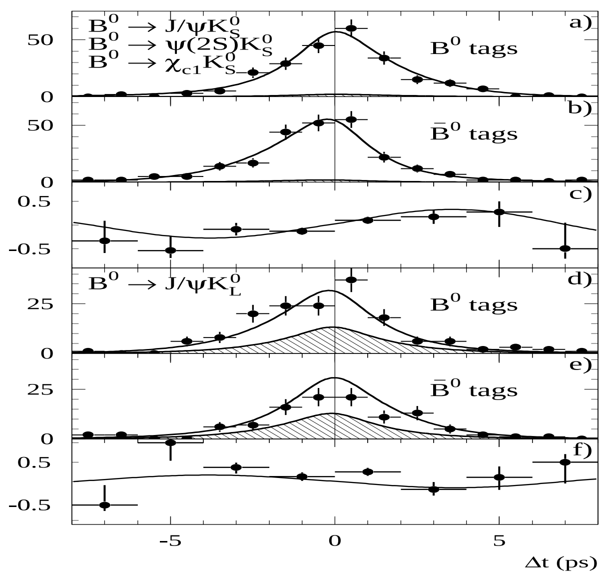

Figure 2: Number of $\eta_{CP} = -1$ candidates with a) a B^0 tag, N_{B^0} and b) a $\overline{B}^0$ tag, $N_{\overline{B}^0}$, figure c) shows the asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$ as a function of Δt. The solid curve represent the fit result and the shaded region the background contributions; figures d) to f) contain the same information for the $J/\psi\, K^0_L$ sample.

The amplitudes for B_{CP} asymmetries and for B_{flav} oscillations are diluted by the same factor $\mathcal{D} = 1 - 2w$ due to mistags. In order to reproduce the observed decay rates for tagged B^0 mesons, both Δt distributions must also be convoluted with the time resolution function $\mathcal{R}(\Delta t)$ mentioned

Table 2: Number of tagged events, signal purity and result of fitting for *CP* in the full *CP* sample and in various subsamples and control samples. Errors are statistical only.

Sample	N_{tag}	Purity(%)	sin2β
$J/\psi K^0_S$,$\psi(2S)K^0_S$,$\chi_{c1}K^0_S$	480	96	0.56 ± 0.15
$J/\psi K^0_L$	273	51	0.70 ± 0.34
$J/\psi K^*$	50	74	0.82 ± 1.00
Full *CP* sample	803	80	0.59 ± 0.14
B_{flav} non-*CP* sample	7591	86	0.02 ± 0.04
Charged B non-*CP* sample	6814	86	0.03 ± 0.04

earlier. The background are accounted for by adding terms to the likelihood function incorporated with different assumptions about their Δt evolution and convoluted with a separate resolution function. Events are assigned signal and backgrounds probabilities based on fits to m_{ES} (all modes except $J/\psi K^0_L$) or ΔE ($J/\psi K^0_L$) distributions.

There are 45 free parameters in the fit, including sin2β, the average mistag fraction w_i and the difference between B^0 and $\overline{B}^0$ mistags for each tagging category (8), the set of parameters for the signal Δt resolution (16) and other 20 parameters describing the background. The B lifetime and Δm_d are instead fixed to the PDG values [8]. The determination of the wrong tag fractions and signal Δt resolution function is dominated by the large b_{flav} sample. Background parameters are determined by events with $m_{ES} < 5.27$ GeV/c^2. As a result, the largest correlation between sin2β and any linear combination of the other parameters is only 0.13.

Figure 1 shows the observed Δt distributions and $a_{CP}(\Delta t)$ overlaid with the likelihood fit results for the $\eta_{CP} = -1$ and $\eta_{CP} = +1$ samples. The simultaneous fit to the full sample gives (including the systematic error discussed below):

$$\sin 2\beta \ = \ 0.59 \pm 0.14(stat) \pm 0.05(syst) \ . \tag{4}$$

2.3 Systematic errors and consistency checks

The large size of the collected samples 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 reported in Table 2

The main contributions to the total systematic error arise from the parameterization of the time resolution function, due in part to residual uncertainties in SVT alignment (0.03), 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 (0.02). The last systematic error affects mainly the $J/\psi K^0_L$ and $J/\psi K^*$modes.

We search for direct *CP* violation effects allowing $|\lambda|$ to float in the fit to the $\eta_{CP} = -1$ sample, which has high purity and requires minimal assumptions on the effect of backgrounds. The value obtained, $|\lambda| = 0.93 \pm 0.09(stat) \pm 0.03(syst)$, is consistent with the SM predictions of $|\lambda| = 1$. The sources of the systematic error in this measurement are the same as in the sin2β analysis.

3 Measurement of CP asymmetry in $B^0 \to \pi^+\pi^-$ decays

In neutral B decays to two light mesons there is a significant contribution to the final amplitude from penguin diagrams with weak and strong phases different from the tree diagram. Thus, the fit to the Δt distributions should allow for direct CP violation and in general $|\lambda| \neq 1$. Both the sine and cosine terms of Eq.(3) are present. The coefficient of the sine term does not provide directly the value of the Unitarity Triangle angle α, as in the case of the sin2β analysis. The exact determination of α, which depends on the magnitudes and strong phases of the tree and penguins diagrams, can be obtained by experimentally challenging isospin analysis [9], which requires the separate evaluation of the amplitudes of the rare decays $B^0 \to \pi^0\pi^0$ and $\overline{B}^0 \to \pi^0\pi^0$, other than the corresponding decays in charged pions.

We select $B \to h^+h'^-$ candidates in the region $5.2 < m_{ES} < 5.3$ GeV/c^2 and $|\Delta E| < 0.15$ GeV and apply requirements on track multiplicity and event topology. About 10000 events satisfy these criteria. This sample contains 97% of background mainly from $e^+e^- \to q\bar{q}$ events. We extract yields for $\pi^\pm, K^+\pi^-, K^-\pi^+$ and K^+K^- events and the amplitudes of the $\pi\pi$ sine ($S_{\pi\pi}$) and cosine ($C_{\pi\pi}$) oscillation terms simultaneously from an unbinned maximum likelihood fit. The likelihood function [11] includes the Δt distributions both for signal and backgrounds, taking into account the mistag probabilities in each tagging category. Dilutions and resolution functions for the signal are taken from the sin2β analysis. Discrimination between signal and background is obtained using kinematic variables and particle identification information, mainly from the Cherenkov detector.

In the full sample of about 33 million $B\overline{B}$ pairs we find 65^{+12}_{-11} $\pi\pi$, 217 ± 18 $K\pi$ and $4.3^{+6.3}_{-4.3}$ KK events. The results obtained on CP parameters are reported in Table 3, while Figure 3 shows the Δt distributions and CP raw asymmetry for tagged events where the signal $\pi\pi$ has been enhanced through likelihood ratios between signal and background hypothesis.

Table 3: Central values and 90% confidence level intervals for CP asymmetries in $b \to h^+h'^-$ decays. A charge asymmetry $A_{K\pi} \equiv (N_{K^-\pi^+} - N_{K^+\pi^-})/(N_{K^-\pi^+} + N_{K^+\pi^-})$ different from zero in $B^0 \to K^\pm\pi^\mp$ decays will indicate a direct CP violation effect.

Parameter	Central Value	90% C.L. Interval
$S_{\pi\pi}$	$0.03^{+0.53}_{-0.56} \pm 0.11$	$[-0.89, +0.85]$
$C_{\pi\pi}$	$-0.25^{+0.45}_{-0.47} \pm 0.14$	$[-1.0, +0.47]$
$A_{K\pi}$	$-0.07 \pm 0.08 \pm 0.02$	$[-0.21, +0.07]$

4 Conclusions and perspectives

BABAR has observed CP violation in the neutral B system, 37 years after its discovery in the Kaon system. The measurement of

$$\sin 2\beta = 0.59 \pm 0.14(stat) \pm 0.05(syst)$$

establishes CP violation at 4.1σ level. The probability of obtaining this value or higher in absence of CP violation is less than 3×10^{-5}. This direct measurements is consistent with the range implied by measurements and theoretical estimates of the magnitudes of CKM matrix elements.The measurement error is still statistically dominated, but with the data sample of more than 100 million

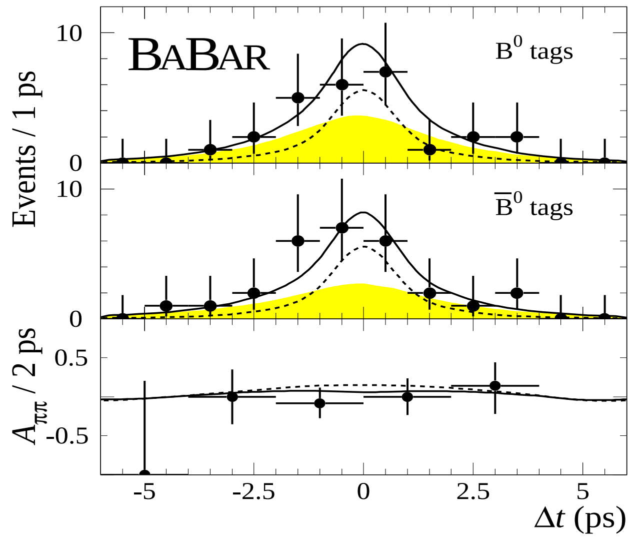

Figure 3: Δt distributions for events enhanced in signal $\pi\pi$ decays with $B_{tag} = B^0$ or $\overline{B}^0$. Solid curves represent the projections of the fit result, while dashed curves represent the sum of $q\bar{q}$ and $K\pi$ background events and the shaded region the contribution from signal events. On the bottom the *CP*-violating asymmetry $A_{\pi\pi}(\Delta t) = (N_{B^0}(\Delta t) - N_{\overline{B}^0}(\Delta t))/(N_{B^0}(\Delta t) - N_{\overline{B}^0}(\Delta t))$ overlaid with the global fit result (solid curve) and signal events only (dashed curve).

$B\overline{B}$ pairs, expected by the summer 2002, sin2β will be measured with a precision of less than 0.1.

A first measurement of the *CP*-violating asymmetries in the decays $B^0 \to \pi^+\pi^-$ and $B^0 \to K\pi$ has been also presented. Also in this case significant improvement on the errors are expected by the summer 2002.

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