Search for CP Violation in $B \to \pi h$ decays and $B \to \rho h$ decays with BABAR Experiment

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Abstract. We present *BABAR* experiment studies to observe CP violation in the two-body decays (πK and $\pi\pi$) and the quasi two-body decays (ρK and $\rho\pi$) of B mesons. The results are obtained from data samples of about 89(123) million $\Upsilon(4S) \to B\overline{B}$ decays collected between 1999 and 2002(2003) with the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC.

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1 Introduction

The study of B meson decays into charmless hadronic final states ($b \to u$) plays an important role in the understanding of CP violation in the B system. In the Standard Model, CP violation arises from a single complex phase in the Cabibbo-Kobayashi-Maskawa quark-mixing matrix $V_{\rm ij}$ [1]. One of the central, unresolved questions is whether this mechanism is sufficient to explain the pattern of CP violation observed in nature.

Measurements of the time-dependent CP-violating asymmetry in the $B^0 \to \pi^+\pi^-$ and $B^0 \to \rho^\pm\pi^\mp$ decay modes provide information on the angle $\alpha \equiv \arg\left[-V_{\rm td}V^*_{\rm tb}/V_{\rm ud}V^*_{\rm ub}\right]$ of the Unitarity Triangle. Moreover, the measurements of the CP-violating charge asymmetry in the self-tagging modes $\pi^\pm K^\mp$ and $\rho^\pm K^\mp$ allow us to test direct CP violation. These asymmetries may arise from interference between the $b \to s$ penguin and $b \to u$ tree amplitudes.

However, in contrast to the theoretically clean determination of the angle β in B^0 decays to charmonium final states [2], the extraction of α in $B^0 \to \pi^+\pi^-$ is complicated by the interference of tree and penguin amplitudes with different weak phases. The shift between $\alpha^{\pi\pi}_{\rm eff}$, derived from the measured $B^0 \to \pi^+\pi^-$ asymmetry, and α may be evaluated or constrained using measurements of the branching fractions of the isospin-related decays $B^0(\overline{B}^0) \to \pi^0\pi^0$, $B^0 \to \pi^+\pi^-$ and $B^\pm \to \pi^\pm\pi^0$ [3]. A similar method [4] may be applied to $\rho\pi$ final states with measurements of the branching fractions of the five decays $B^0 \to \rho^+\pi^-$, $B^0 \to \rho^-\pi^+$, $B^0 \to \rho^0\pi^0$, $B^+ \to \rho^+\pi^0$ and $B^+ \to \rho^0\pi^+$.

In this paper, we report on measurements of CP-violating parameters for both $B \to \pi h$ and $B \to \rho h$ decays, and the first observation of $B^0 \to \pi^0\pi^0$, using 123×10^6 $B\overline{B}$ pairs collected collected between 1999 and 2003 with the *BABAR* detector. We also present measurements of the other $B \to \pi h$ and $B \to \rho h$ branching fractions performed with a smaller data set, 89×10^6 $B\overline{B}$ pairs recorded between 1999 and 2002.

2 Analysis Overview

This paper summarizes various analyses related to the determination of the α angle of *BABAR* experiment, already published or submitted to publication. Full descriptions of these analyses are available in Ref. [5–8].

BABAR is a solenoidal detector optimized for the asymmetric-energy beams at PEP-II and is described in detail in Ref. [9]. Charged particle (track) momenta are measured with a 5-layer double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) inside a 1.5 T superconducting solenoidal magnet. Photon (neutral cluster) positions and energies are measured with an electromagnetic calorimeter (EMC) consisting of 6580 CsI(Tl) crystals. Tracks are identified as pions or kaons by the Cherenkov angle θ_c measured with a detector of internally reflected Cherenkov light (DIRC).

Signal decays are identified kinematically using two variables, the difference ΔE between the center-of-mass (CM) energy of the $B_{\rm rec}$ candidate and $\sqrt{s}/2$, and $m_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$, the beam-energy substituted mass, where $\sqrt{s}$ is the total CM energy, and the $B_{\rm rec}$ momentum $\mathbf{p_B}$ and the four-momentum of the initial state $(E_i, \mathbf{p_i})$ are defined in the laboratory frame.

The jet-like background from $e^+e^- \to q\bar{q}(q = u, d, s, c)$ (continuum) is suppressed by its topology. In the CM frame, we define discriminating variables based on the event shapes. These variables are combined in a single variable $x_{\rm sep}$, either a Fisher discriminant [5,6] or a neural network output [7,8]. In the latter case, some information related to reconstructed ρ, are added (mass and helicity).

The time difference Δt is obtained from the known boost of the e^+e^- system and the measured distance between the z positions of the $B_{\rm rec}$ and $B_{\rm tag}$ decay vertices. A detailed description of this algorithm is given in Ref. [10]. To determine the flavor of the $B^0_{\rm tag}$ we use the tagging algorithm of Ref. [10]. This produces five mutually exclusive tagging categories.

We use an unbinned extended maximum likelihood fit to extract yields and *CP* parameters. The likelihood for candidate j tagged in category k is obtained by summing the product of event yield N_i, tagging efficiency $\epsilon_{i,k}$, and probability $\mathcal{P}_{i,k}$ over the hypotheses i, signal and backgrounds (continuum and from other B decays). In the case of $\pi\pi$ mode [5], the potential backgrounds from other B decays are found to be negligible, whereas for final states containing π^0 [6–8] a specific PDF was added in the likelihood to represent each specific B background. The extended likelihood function for category k is

$$\mathcal{L}_k = e^{\left(-\sum_i N_i\epsilon_{i,k}\right)} \prod_j \left[\sum_i N_i \epsilon_{i,k} \mathcal{P}_{i,k}(\boldsymbol{x}_j;\boldsymbol{\alpha}_i)\right]. \qquad (1)$$

The probabilities $\mathcal{P}_{i,k}$ are evaluated as the product of PDFs for each of the independent variables $\boldsymbol{x}_j = \{m_{\rm ES}, \Delta E, x_{\rm sep}, \Delta t, \theta_c, ...\}$. Only the first three variables are used in all the analyses described in this paper [5–8].

3 Study of $B \to \pi h$

3.1 Time-dependent Analysis and Search for *CP* Violation

With $\Delta t \equiv t_{\pi\pi} - t_{\rm tag}$ defined as the proper time interval between the decay of the reconstructed $B^0_{\pi^+\pi^-}$ and that of the other meson $B^0_{\rm tag}$, the time-dependent decay rates are given by

$$f^{\pi^+\pi^-}_{Q_{\rm tag}} = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 + Q_{\rm tag} S_{\pi\pi}\sin(\Delta m_d \Delta t) - Q_{\rm tag} C_{\pi\pi}\cos(\Delta m_d\Delta t)], \qquad (2)$$

where where $Q_{\rm tag} = 1(-1)$ when the tagging meson $B^0_{\rm tag}$ is a $B^0(\overline{B}{}^0)$, τ is the mean B^0 lifetime and Δm_d is the mixing frequency due to the eigenstate mass difference. If the decay proceeds purely through the $b \to u$ tree amplitude, $C_{\pi\pi} = 0$ and $S_{\pi\pi} = \sin(2\alpha)$. In general, the $b \to d$ penguin amplitude are not negligible in $B^0 \to \pi^+\pi^-$ decays, so that $C_{\pi\pi}$ which probes direct *CP* violation, may be not equal to zero and $S_{\pi\pi} = \sqrt{1-C^2_{\pi\pi}}\sin 2\alpha^{\pi\pi}_{\rm eff}$, where $2\alpha^{\pi\pi}_{\rm eff} = \arg[(q/p)(\overline{A}_{\pi\pi}/A_{\pi\pi})]$, $\arg[q/p]$ is the $B^0\overline{B}{}^0$ mixing phase, and $A_{\pi\pi}(\overline{A}_{\pi\pi})$ are the transition amplitudes of the processes $B^0(\overline{B}{}^0) \to \pi^+\pi^-$, respectively.

The fit of the likelihood function defined in Eq. 1 gives for the *CP*-violating parameters $S_{\pi\pi} = -0.40 \pm 0.22 \pm 0.03$ and $C_{\pi\pi} = -0.19 \pm 0.19 \pm 0.05$, where the first error is statistical and the second is systematic.

For the $K^\mp\pi^\pm$ decay mode, the *CP*-violating charge asymmetry is defined by $A^{K\pi}_{CP} = (N_{K^-\pi^+} - N_{K^+\pi^-})/(N_{K^-\pi^+} + N_{K^+\pi^-})$. With a maximum likelihood fit including only kinematic and topological information, we obtain $A^{K\pi}_{CP} = -0.107 \pm 0.041 \pm 0.013$.

3.2 Branching Fraction Measurements and Isospin Analysis

From a maximum likelihood fit excluding tagging or Δt information, we measure the following branching fractions: $\mathcal{B}(B^0 \to \pi^+\pi^-) = (4.7 \pm 0.6 \pm 0.2) \times 10^{-6}$ [5], $\mathcal{B}(B^\pm \to \pi^\pm\pi^0) = (5.5^{+1.0}_{-0.9} \pm 0.6) \times 10^{-6}$ and $\mathcal{B}(B^0 \to \pi^0\pi^0) = (2.1 \pm 0.6 \pm 0.3) \times 10^{-6}$ [6]. Assuming isospin relations for $B \to \pi\pi$ [3], these branching fractions correspond to an upper limit of $|\alpha^{\pi\pi}_{\rm eff} - \alpha| < 48^{\rm o}$. On Fig. 1 we can see both for $m_{\rm ES}$ and ΔE an excess of $\pi^0\pi^0$ events which is the first observation of $B^0 \to \pi^0\pi^0$ decays.

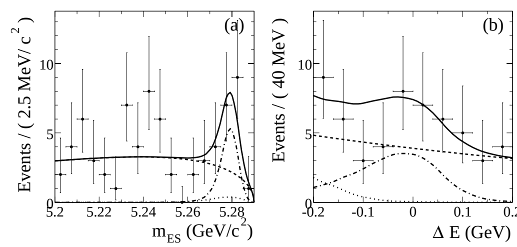

Fig. 1. The distributions of a) $m_{\rm ES}$, b) ΔE, for events selected to enhance the $\pi^0\pi^0$ signal. The PDF projections are shown as a dashed line for continuum background, a dotted line for $B^\pm \to \rho^\pm\pi^0$, and a dashed-dotted line for $B^0 \to \pi^0\pi^0$ signal. The solid line shows the sum of all PDF projections.

4 Study of $B \to \rho h$

4.1 Time-dependent Analysis and Search for *CP* Violation

Unlike $\pi^+\pi^-$ final state, $\rho^\pm\pi^\mp$ is not a *CP* eigenstate, and four flavor-charge configurations $(B^0(\overline{B}{}^0) \to \rho^\pm\pi^\mp)$ must be considered. Although this leads to a more complicated analysis, it benefits from a branching fraction that is nearly five times larger. Following a quasi-two-body approach [11], we restrict the analysis to the two regions of the $\pi^\mp\pi^0 h^\pm$ Dalitz plot ($h = \pi$ or K) that are dominated by either ρ^+h^- or ρ^-h^+. With $\Delta t \equiv t_{\rho h} - t_{\rm tag}$, the time-dependent decay rates are given by

$$f^{\rho^\pm h^\mp}_{Q_{\rm tag}}(\Delta t) = (1 \pm A^{\rho h}_{CP})\frac{e^{-|\Delta t|/\tau}}{4\tau} \times \Big[1 + Q_{\rm tag}(S_{\rho h} \pm \Delta S_{\rho h})\sin(\Delta m_d \Delta t) - Q_{\rm tag}(C_{\rho h} \pm \Delta C_{\rho h})\cos(\Delta m_d \Delta t)\Big], \qquad (3)$$

where $Q_{\rm tag} = 1(-1)$ when the meson $B^0_{\rm tag}$ is a $B^0(\overline{B}{}^0)$.

The time- and flavor-integrated charge asymmetries $A^{\rho\pi}_{CP}$ and $A^{\rho K}_{CP}$ measure direct *CP* violation. For the $\rho\pi$ mode, the quantities $S_{\rho\pi}$ and $C_{\rho\pi}$ parameterize mixing-induced *CP* violation related to the angle α, and flavor-dependent direct *CP* violation, respectively. The parameters $\Delta C_{\rho\pi}$ and $\Delta S_{\rho\pi}$ are insensitive to *CP* violation.

$\Delta C_{\rho\pi}$ describes the asymmetry between the rates $\Gamma(B^0 \to \rho^+\pi^-) + \Gamma(\overline{B}^0 \to \rho^-\pi^+)$ and $\Gamma(B^0 \to \rho^-\pi^+) + \Gamma(\overline{B}^0 \to \rho^+\pi^-)$, while $\Delta S_{\rho\pi}$ is related to the strong phase difference between the amplitudes contributing to $B^0 \to \rho\pi$ decays. More precisely, one finds the relations $S_{\rho\pi} \pm \Delta S_{\rho\pi} = \sqrt{1-(C_{\rho\pi} \pm \Delta C_{\rho\pi})^2}\,\sin(2\alpha_{\rm eff}^{\pm} \pm \delta)$, where $2\alpha_{\rm eff}^{\pm} = \arg[(q/p)(\overline{A}_{\rho\pi}^{\pm}/A_{\rho\pi}^{\mp})]$, $\delta = \arg[A_{\rho\pi}^{-}/A_{\rho\pi}^{+}]$, $\arg[q/p]$ is the $B^0\overline{B}^0$ mixing phase, and $A_{\rho\pi}^{+}(\overline{A}_{\rho\pi}^{+})$ and $A_{\rho\pi}^{-}(\overline{A}_{\rho\pi}^{-})$ are the transition amplitudes of the processes $B^0(\overline{B}^0) \to \rho^+\pi^-$ and $B^0(\overline{B}^0) \to \rho^-\pi^+$, respectively. The angles $\alpha_{\rm eff}^{\pm}$ are equal to α in the absence of contributions from penguin amplitudes. For the self-tagging ρK mode, the values of the four time-dependent parameters are $C_{\rho K} = 0$, $\Delta C_{\rho K} = -1$, $S_{\rho K} = 0$, and $\Delta S_{\rho K} = 0$.

With a maximum likelihood fit, we obtain

$$\begin{aligned}
A_{CP}^{\rho\pi} &= -0.114 \pm 0.062 \pm 0.027 & A_{CP}^{\rho K} &= 0.18 \pm 0.12 \pm 0.08 \\
C_{\rho\pi} &= 0.35 \pm 0.13 \pm 0.05 & S_{\rho\pi} &= -0.13 \pm 0.18 \pm 0.04 \\
\Delta C_{\rho\pi} &= 0.20 \pm 0.13 \pm 0.05 & \Delta S_{\rho\pi} &= 0.33 \pm 0.18 \pm 0.03\ .
\end{aligned}$$

The raw time-dependent asymmetry $A_{B^0/\overline{B}^0} = (N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$ in the tagging categories dominated by kaons and leptons is represented in Fig. 2.

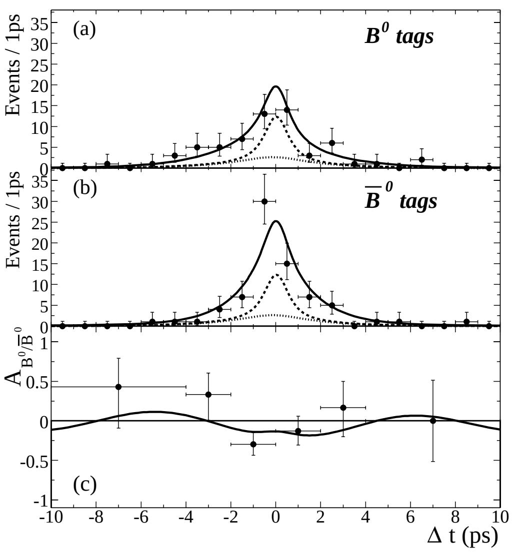

Fig. 2. Time distributions for events selected to enhance the $\rho\pi$ signal tagged as (a) $B^0_{\rm tag}$ and (b) $\overline{B}^0_{\rm tag}$, and (c) time-dependent asymmetry between $B^0_{\rm tag}$ and $\overline{B}^0_{\rm tag}$. The solid curve is a likelihood projection of the fit result. The dashed and dotted lines are the continuum and B background contributions, respectively.

A useful redefinition of the parameters, involving the parameters $A_{CP}^{\rho\pi}$, $C_{\rho\pi}$ and $\Delta C_{\rho\pi}$ is provided by the time-integrated asymmetries A_{-+} and A_{+-}, which probe direct CP. These asymmetries are written as

$$\begin{aligned}
A_{-+} &= \frac{N(\overline{B}^0 \to \rho^+\pi^-) - N(B^0 \to \rho^-\pi^+)}{N(\overline{B}^0 \to \rho^+\pi^-) + N(B^0 \to \rho^-\pi^+)} \\
&= -0.52\,^{+0.17}_{-0.19} \pm 0.07
\end{aligned}$$

$$\begin{aligned}
A_{+-} &= \frac{N(\overline{B}^0 \to \rho^-\pi^+) - N(B^0 \to \rho^+\pi^-)}{N(\overline{B}^0 \to \rho^-\pi^+) + N(B^0 \to \rho^+\pi^-)} \\
&= -0.18 \pm 0.13 \pm 0.05\ .
\end{aligned}$$

Including systematic errors, the confidence level of obtaining the observed values or less in the absence of CP violation, is $\mathrm{CL} = 1.45 \cdot 10^{-2}$, corresponding to 2.5σ.

4.2 Branching Fraction Measurements

With the same maximum likelihood fit including Δt and tagging information, we measure simultaneously $\mathcal{B}(B^0 \to \rho^\pm\pi^\mp) = (22.6 \pm 1.8 \pm 2.2) \times 10^{-6}$ and $\mathcal{B}(B^0 \to \rho^- K^+) = (7.3\,^{+1.3}_{-1.2} \pm 1.3) \times 10^{-6}$ [7]. With a similar method [8], we observe for the first time, $B^\pm \to \rho^\pm\pi^0$ decays with a branching fraction equal to $\mathcal{B}(B^+ \to \rho^+\pi^0) = (11.0 \pm 1.9 \pm 1.9) \times 10^{-6}$ and we find $\mathcal{B}(B^+ \to \rho^0\pi^+) = (9.3 \pm 1.0 \pm 0.8) \times 10^{-6}$. We set a 90% confidence-level upper limit of $\mathcal{B}(B^0 \to \rho^0\pi^0) < 2.5 \times 10^{-6}$.

5 Conclusion

In summary, we have not observed large mixing-induced or direct CP violation in the time-dependent asymmetry of both $B^0 \to \pi^\pm h^\mp$ and $B^0 \to \rho^\pm h^\mp$ decays. Moreover, we have presented the measurements of branching fractions useful for performing an isospin analysis. In particular, for the first time, we have observed a signal for $B^0 \to \pi^0\pi^0$ and for $B^\pm \to \rho^\pm\pi^0$.

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