34th International Conference on High Energy Physics, Philadelphia, 2008

October 2008
SLAC-PUB-13441

BABAR-PROC-08/089
SLAC-PUB-13441
arXiv:0810.2966 [hep-ex]

CP Violation in Hadronic Penguins at *BABAR*

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We present preliminary measurements of time-dependent CP-violation parameters in the decays $B^0 \to \omega K^0_S$, $B^0 \to \eta' K^0$, $B^0 \to \pi^0 K^0_S$, $B^0 \to \phi K^0_S \pi^0$, and $B^0 \to K^+K^-K^0_S$, which includes the resonant final states ϕK^0_S and $f_0(980)K^0_S$. The data sample corresponds to the full *BABAR* dataset of 467 × 10^6 $B\overline{B}$ pairs produced at the PEP-II asymmetric-energy e^+e^- collider at the Stanford Linear Accelerator Center.

1. INTRODUCTION

Measurements of time-dependent CP asymmetries in B^0 meson decays through $b \to c\bar{c}s$ amplitudes have provided crucial tests of the mechanism of CP violation in the Standard Model (SM) [1]. These amplitudes contain the leading b-quark couplings, given by the Cabibbo-Kobayashi-Maskawa [2] (CKM) flavor mixing matrix, for kinematically allowed transitions. Decays to charmless final states such as ϕK^0, $\pi^0 K^0$, $\eta' K^0$, and ωK^0 are CKM-suppressed $b \to q\bar{q}s$ $(q = u, d, s)$ processes dominated by a single loop (penguin) amplitude. This amplitude has the same weak phase $\beta = arg(-V_{cd}V^*_{cb}/V_{td}V^*_{tb})$ of the CKM mixing matrix as that measured in the $b \to c\bar{c}s$ transition, but is sensitive to the possible presence of new heavy particles in the loop [3]. Due to the different non-perturbative strong-interaction properties of the various penguin decays, the effect of new physics is expected to be channel dependent.

The CKM phase β is accessible experimentally through interference between the direct decay of the B meson to a CP eigenstate and $B^0\overline{B}^0$ mixing followed by decay to the same final state. This interference is observable through the time evolution of the decay. In the present study, we reconstruct one B^0 from $\Upsilon(4S) \to B^0\overline{B}^0$, which decays to the CP eigenstate ωK^0_S, $\eta' K^0_S$, $\eta' K^0_L$, $\pi^0 K^0_S$, $\phi K^0_S \pi^0$, or $K^+K^-K^0_S$ (B_{CP}). From the remaining particles in the event we also reconstruct the decay vertex of the other B meson ($B_{\rm tag}$) and identify its flavor. The difference $\Delta t \equiv t_{CP} - t_{\rm tag}$ of the proper decay times t_{CP} and $t_{\rm tag}$ is obtained from the measured distance between the decay vertices of the B_{CP} and $B_{\rm tag}$ and the boost ($\beta\gamma = 0.56$) of the $\Upsilon(4S)$ system. In the $\pi^0 K^0_S$ analysis we compute Δt and its uncertainty with a geometric fit to the $\Upsilon(4S) \to B^0\overline{B}^0$ system taking into account the reconstructed K^0_S trajectory, the knowledge of the average interaction point (IP) [4], and the average B meson lifetime. The distribution of Δt is given by

$$F(\Delta t) \;=\; \frac{e^{-|\Delta t|/\tau}}{4\tau} 1 \mp \Delta w \pm (1-2w)\left[-\eta_f S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)\right],$$

where η_f is the CP eigenvalue of final state f, the upper (lower) sign denotes a decay accompanied by a B^0 ($\overline{B}^0$) tag, τ is the mean B^0 lifetime, Δm_d is the mixing frequency, w is the mistag rate, and $\Delta w \equiv w(B^0) - w(\overline{B}^0)$ is the difference in mistag rates for B^0 and $\overline{B}^0$ tag-side decays. The tagged flavor and mistag parameters w and Δw are determined with a neural network based algorithm [5].

A nonzero value of the parameter C_f would indicate direct CP violation. In these modes we expect $C_f = 0$ and $-\eta_f S_f = \sin 2\beta$, assuming penguin dominance of the $b \to s$ transition and neglecting other CKM-suppressed amplitudes with a different weak phase. However, these CKM-suppressed amplitudes and the color-suppressed tree diagram introduce additional weak phases whose contributions may not be negligible [6–9]. As a consequence, the measured S_f may differ from $\sin 2\beta$ even within the SM. This deviation $\Delta S_f = S_f - \sin 2\beta$ is estimated in several theoretical approaches: QCD factorization (QCDF) [6, 10], QCDF with modeled rescattering [11], soft collinear effective theory [12], and SU(3) symmetry [7, 9, 14]. The estimates are channel dependent. Estimates of ΔS from

Work supported in part by US Department of Energy contract DE-AC02-76SF00515

QCDF are in the ranges $(0.0, 0.2)$, $(-0.03, 0.03)$, and $(0.01, 0.12)$ for ωK^0_S, $\eta' K^0$, and $\pi^0 K^0_S$, respectively [10, 12, 13]; SU(3) symmetry provides bounds of $(-0.05, 0.09)$ for $\eta' K^0$ and $(-0.06, 0.12)$ for $\pi^0 K^0_S$ [14]. Predictions that use isospin symmetry to relate several amplitudes, including the $I = \frac{3}{2}$ $B \to K\pi$ amplitude, give an expected value for $S_{\pi^0 K^0_S}$ near 1.0 instead of sin2β [15]. The modification of the *CP* asymmetry due to the presence of suppressed tree amplitudes in $B^0 \to \phi(K^+K^-)K^0$ is at $\mathcal{O}(0.01)$ [16, 17], while at higher K^+K^- masses a larger contribution at $\mathcal{O}(0.1)$ is possible [18].

In these proceedings, we summarize preliminary measurements of time-dependent *CP* parameters in the aforementioned $b \to q\bar{q}s$ penguin-dominated B^0 decays. The ωK^0_S, $\eta' K^0$, $\pi^0 K^0_S$, and $K^+K^-K^0_S$ results are updates of previous measurements [19–22], while the $\phi K^0_S \pi^0$ results are first measurements. Detailed descriptions of each analysis are given in Refs. [23], [24], and [25].

2. DETECTOR AND DATASET

The data used in this analysis were collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage ring operating at the Stanford Linear Accelerator Center. We analyze the entire *BABAR* dataset collected at the $\Upsilon(4S)$ resonance, corresponding to an integrated luminosity of 426 $\rm fb^{-1}$ and $(467 \pm 5) \times 10^6$ $B\overline{B}$ pairs.

A detailed description of the *BABAR* detector can be found elsewhere [26]. Charged particle (track) momenta are measured with a 5-layer double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) coaxial with a 1.5-T superconducting solenoidal magnet. Neutral cluster (photon) positions and energies are measured with an electromagnetic calorimeter, which also provides partial K^0_L reconstruction. Charged hadrons are identified with a detector of internally reflected Cherenkov light and specific ionization measurements ($\mathrm{d}E/\mathrm{d}x$) in the tracking detectors (DCH, SVT). Finally, the instrumented flux return of the magnet allows discrimination of muons from pions and additional detection of K^0_L mesons.

3. ANALYSIS TECHNIQUE

In the $\eta' K^0_S$ and $K^+K^-K^0_S$ analyses we reconstruct the K^0_S in the final states $\pi^+\pi^-$ ($K^0_{\pi^+\pi^-}$) and $\pi^0\pi^0$ ($K^0_{\pi^0\pi^0}$); in the other analyses we use only the $\pi^+\pi^-$ final state. Other B-daughter candidates are reconstructed with the following decays: $\pi^0 \to \gamma\gamma$; $\eta \to \gamma\gamma$ ($\eta_{\gamma\gamma}$); $\eta \to \pi^+\pi^-\pi^0$ ($\eta_{3\pi}$); $\eta' \to \eta_{\gamma\gamma}\pi^+\pi^-$ ($\eta'_{\eta(\gamma\gamma)\pi\pi}$); $\eta' \to \eta_{3\pi}\pi^+\pi^-$ ($\eta'_{\eta(3\pi)\pi\pi}$); $\eta' \to \rho^0\gamma$ ($\eta'_{\rho\gamma}$), where $\rho^0 \to \pi^+\pi^-$; and $\omega \to \pi^+\pi^-\pi^0$. The five final states used for $B^0 \to \eta' K^0_S$ are $\eta'_{\eta(\gamma\gamma)\pi\pi} K^0_{\pi^+\pi^-}$, $\eta'_{\rho\gamma} K^0_{\pi^+\pi^-}$, $\eta'_{\eta(3\pi)\pi\pi} K^0_{\pi^+\pi^-}$, $\eta'_{\eta(\gamma\gamma)\pi\pi} K^0_{\pi^0\pi^0}$, and $\eta'_{\rho\gamma} K^0_{\pi^0\pi^0}$. For the $B^0 \to \eta' K^0_L$ channel we reconstruct the η' in two modes: $\eta'_{\eta(\gamma\gamma)\pi\pi}$ and $\eta'_{\eta(3\pi)\pi\pi}$.

After applying loose selection criteria to reduce the dominant continuum $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) background, we perform an unbinned maximum likelihood (ML) fit to the data to separate signal from background and obtain the *CP*-violation parameters for each decay channel. As input to the ML fit, we use two kinematic variables, an event-shape Fisher discriminant, and, in the ωK^0_S, $\phi K^0_S \pi^0$, and $K^+K^-K^0_S$ analyses, resonance masses and decay angles.

In all analyses but $\pi^0 K^0_S$ and $\eta' K^0_L$, we use, as kinematic variables, the beam-energy-substituted mass $m_{\rm ES} \equiv \sqrt{(\frac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$ and the energy difference $\Delta E \equiv E^*_B - \frac{1}{2}E^*_0$, where $(E_0, \mathbf{p}_0)$ and $(E_B, \mathbf{p}_B)$ are the laboratory four-momenta of the $\Upsilon(4S)$ and the B_{CP} candidate, respectively, and the asterisk denotes the $\Upsilon(4S)$ rest frame. In the $\pi^0 K^0_S$ analysis we use m_B, the invariant mass of the reconstructed B_{CP}, and $m_{\rm miss}$, the invariant mass of the $B_{\rm tag}$ computed from the known beam energy and the measured B_{CP} momentum with mass of B_{CP} constrained to the nominal B meson mass [27]. In the $\eta' K^0_L$ analysis we use only the ΔE variable because a mass constraint on the B meson during the vertex fit leaves $m_{\rm ES}$ and ΔE completely correlated.

Further discrimination from continuum background is obtained with the combination of four event-shape variables in a Fisher discriminant: the angle with respect to the beam axis of the B momentum, the angle with respect to the beam axis of the B thrust axis, and the zeroth and second momentum-weighted angular moments L_0 and L_2,

Table I: Preliminary fit results for signal yields and *CP* parameters. The first errors are statistical and the second are systematic. See Sec. 4 for explanation of results.

Mode	**Signal Yield**	$-\boldsymbol{\eta_f S_f}$	$\boldsymbol{C_f}$
ωK^0_S	163 ± 18	$0.55^{+0.26}_{-0.29} \pm 0.02$	$-0.52^{+0.22}_{-0.20} \pm 0.03$
$\eta' K^0$	2515 ± 69	$0.57 \pm 0.08 \pm 0.02$	$-0.08 \pm 0.06 \pm 0.02$
$\eta' K^0_S$	1959 ± 58	$0.53 \pm 0.08 \pm 0.02$	$-0.11 \pm 0.06 \pm 0.02$
$\eta' K^0_L$	556 ± 38	$0.82 \pm 0.19 \pm 0.02$	$0.09 \pm 0.14 \pm 0.02$
$\pi^0 K^0_S$	556 ± 32	$0.55 \pm 0.20 \pm 0.03$	$0.13 \pm 0.13 \pm 0.03$

Mode	**Signal Yield**	$\boldsymbol{\beta_{eff}}$	$\boldsymbol{A_{CP}}$
$K^+K^-K^0_S$	1011 ± 39	$0.52 \pm 0.08 \pm 0.03$	$0.05 \pm 0.09 \pm 0.04$
ϕK^0_S	(see text)	$0.13 \pm 0.13 \pm 0.02$	$0.14 \pm 0.19 \pm 0.02$
$f_0(980) K^0_S$	(see text)	$0.15 \pm 0.13 \pm 0.03$	$0.01 \pm 0.26 \pm 0.07$
$\phi K^0_S \pi^0$	58 ± 3	$0.97^{+0.03}_{-0.52}$	(see text)
$\phi(K\pi)^{*0}_0$	172 ± 24	(see text)	$0.20 \pm 0.14 \pm 0.06$
$\phi K^*(892)^0$	535 ± 38	(see text)	$0.01 \pm 0.06 \pm 0.03$
$\phi K^*_2(1430)^0$	167 ± 21	(see text)	$-0.08 \pm 0.12 \pm 0.04$

defined as $L_i = \sum_j p_j \times |\cos\theta_j|^i$, where θ_j is the angle with respect to the B thrust axis of daughter particle j, p_j is its momentum, and the sum excludes the daughters of the B candidate. In the $\eta' K^0_L$ analysis we also use the continuous output of the flavor tagging algorithm as input to the discriminant.

The $K^+K^-K^0_S$ analysis is designed to account for variations of *CP* structure and interference over the Dalitz plot. We use an isobar model that includes the K^+K^- resonances $f_0(980)$, $\phi(1020)$, $X_0(1550)$, and χ_{c0} to extract $\beta_{\rm eff}$ and A_{CP} $(-C_f)$ from the amplitude and phase information over the Dalitz plot. In the $\phi K\pi$ analysis we measure 27 parameters that characterize the interference of S, P, and D $K\pi$ partial wave amplitudes. We are able to measure the single mixing-induced *CP*-violation parameter $\beta_{\rm eff}$, which is accessible only through the $\phi K^0_S\pi^0$ *CP* eigenstate in which we reconstruct just ~ 60 events, by constraining the other 26 parameters, including A_{CP} for each partial wave, with ~ 800 events from the $\phi K^+\pi^-$ self-tagging final state.

4. RESULTS

The preliminary fit results for signal event yields and *CP* parameters are shown in Table I. We report separate results for $\eta' K^0_S$ and $\eta' K^0_L$ in addition to the combined $\eta' K^0$ results. The $K^+K^-K^0_S$ results comes from the high-mass, non-resonant region of the Dalitz plot ($m_{K^+K^-} > 1.1$ GeV). The total yield in the low-mass region of the Dalitz plot ($m_{K^+K^-} < 1.1$ GeV), which are mostly ϕK^0_S and $f_0(980)K^0_S$ events, is 421 ± 25. The $\phi K^0_S\pi^0$ yield is the total for all partial waves; each ϕK^*_J yield is the sum of $\phi K^0_S\pi^0$ and $\phi K^+\pi^-$ final states events since both contribute to the determination of each direct *CP* parameter A_{CP}.

All S_f and $\beta_{\rm eff}$ results are consistent with the value of sin2β measured in $b \rightarrow c\bar{c}s$ decays [28, 29]. The current world averages are sin2$\beta = 0.67 \pm 0.02$ and $\beta = 0.37 \pm 0.02$. All C_f and A_{CP} results are consistent with zero direct *CP*-violation. These $K^+K^-K^0_S$ results favor $\beta_{\rm eff} \simeq 0.37$ and rule out at 4.8σ the solution $\frac{\pi}{2} - \beta$ from the trigonometric ambiguity of β from the measurement of $\sin 2\beta$. All results are statistics limited. The dominant systematic uncertainty in the $\eta' K^0$ analysis is related to *CP* structure in the $B\overline{B}$ background; the dominant systematic uncertainty in the $K^+K^-K^0_S$ analysis is related to the Dalitz model.

5. CONCLUSIONS

We present preliminary updates of our measurements of mixing-induced *CP*-violation parameters in several $b \to q\bar{q}s$ penguin-dominated B^0 decays and the first measurement in the $B^0 \to \phi K^0_S \pi^0$ decay. The $\phi K^0_S \pi^0$ analysis demonstrates a novel technique for extracting *CP* parameters from interfering amplitudes with relatively few signal events. Significant changes to previous analyses include twice as much data for ωK^0_S, 20% more data for other analyses, and improved track reconstruction.

Acknowledgments

I thank the organizers of ICHEP 08 for a well-organized and interesting conference. I also thank my *BABAR* collaborators for their support, especially my thesis advisors, Bill Ford and Jim Smith.

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