We present preliminary measurements of time-dependent CP-violation parameters in the decays $B^0 \to \omega K^0_S$, $B^0 \to \eta' K^0_S$, $B^0 \to \pi^0 K^0_S$, $B^0 \to \phi K^0_S \pi^0$, and $B^0 \to K^+ K^- K^0_S$, which includes the resonant final states $\phi K^0_S$ and $J_0(980)K^0_S$. The data sample corresponds to the full BABAR dataset of $467 \times 10^6 B \bar{B}$ 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 $\phi K^0$, $\pi^0 K^0$, $\eta' K^0$, and $\omega K^0$ 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 $\beta = \arg(-V_{tb}^* V_{cb}/V_{td}^* V_{ub})$ 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 $\beta$ is accessible experimentally through interference between the direct decay of the $B$ meson to a CP eigenstate and $B^0/\bar{B}^0$ 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 $Y(4S) \to B^0\bar{B}^0$, which decays to the CP eigenstate $\omega K^0_S$, $\eta' K^0_S$, $\eta K^0_L$, $\pi^0 K^0_S$, $\phi K^0_S \pi^0$, 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 ($B_{tag}$) and identify its flavor. The difference $\Delta t \equiv t_{CP} - t_{tag}$ of the proper decay times $t_{CP}$ and $t_{tag}$ is obtained from the measured distance between the decay vertices of the $B_{CP}$ and $B_{tag}$ and the boost ($\beta\gamma = 0.56$) of the $Y(4S)$ system. In the $\pi^0 K^0_S$ analysis we compute $\Delta t$ and its uncertainty with a geometric fit to the $Y(4S) \to B^0\bar{B}^0$ 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 $\Delta t$ is given by

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

where $\eta_f$ is the CP eigenvalue of final state $f$, the upper (lower) sign denotes a decay accompanied by a $B^0$ ($\bar{B}^0$) tag, $\tau$ is the mean $B^0$ lifetime, $\Delta m_d$ is the mixing frequency, $w$ is the mistag rate, and $\Delta w \equiv w(B^0) - w(\bar{B}^0)$ is the difference in mistag rates for $B^0$ and $\bar{B}^0$ tag-side decays. The tagged flavor and mistag parameters $w$ and $\Delta w$ 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, 7, 8, 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 [2, 4, 14]. The estimates are channel dependent. Estimates of $\Delta S$ from QCDF are in the ranges ($0.0, 0.2), (-0.03, 0.03), and (0.01, 0.12)$ for $\omega K^0, \eta' K^0, \omega K^0_S, \phi K_S \pi^0$, 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 $\sin 2\beta$ [15]. The modification of the CP asymmetry due to the presence of suppressed tree

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**CP Violation in Hadronic Penguins at BABAR**

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We present preliminary measurements of time-dependent CP-violation parameters in the decays $B^0 \to \omega K^0_S$, $B^0 \to \eta' K^0_S$, $B^0 \to \phi K^0_S \pi^0$, and $B^0 \to K^+ K^- K^0_S$, which includes the resonant final states $\phi K^0_S$ and $J_0(980)K^0_S$. The data sample corresponds to the full BABAR dataset of $467 \times 10^6 B \bar{B}$ pairs produced at the PEP-II asymmetric-energy $e^+e^-$ collider at the Stanford Linear Accelerator Center.
amplitudes in $B^0 \to \phi(K^+K^-)K^0$ is at $O(0.01)$ \cite{13, 17}, while at higher $K^+K^-$ masses a larger contribution at $O(0.1)$ is possible \cite{18}.

In these proceedings, we summarize preliminary measurements of time-dependent $CP$ parameters in the aforementioned $b \to q\bar{q}\gamma$ penguin-dominated $B^0$ decays. The $\omega K^0_S$, $\eta' K^0_S$, $\pi^0 K^0_S$, and $K^+ K^- K^0_S$ results are updates of previous measurements \cite{19, 20, 21, 22}, while the $\phi K^0_S \pi^0$ results are first measurements. Detailed descriptions of each analysis are given in Refs. \cite{23, 24, 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 fb$^{-1}$ and $(467 \pm 5) \times 10^6 B\bar{B}$ pairs.

A detailed description of the BaBar detector can be found elsewhere \cite{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 ($dE/dx$) 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: $\pi^0 \to \gamma\gamma$; $\eta \to \gamma\gamma$ ($\eta(\gamma\gamma)$); $\eta \to \pi^+\pi^-\pi^0$ ($\eta_{3\pi}$); $\eta' \to \eta(\gamma\gamma)\pi$ ($\eta'_{\gamma\gamma}\pi$); $\eta' \to \eta_{3\pi}\pi$ ($\eta'_{3\pi}$); $\eta' \to \rho^0\pi$ ($\eta'_{\rho\pi}$), 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 $\eta'_{\gamma\gamma}\pi K^0_{\pi^+\pi^-}$, $\eta'_{3\pi}\pi K^0_{\pi^+\pi^-}$, $\eta'_{\gamma\gamma}\pi K^0_{\pi^0\pi^0}$, $\eta'_{3\pi}\pi K^0_{\pi^0\pi^0}$, and $\eta'_{\rho\pi} K^0_{\pi^0\pi^0}$. For the $B^0 \to \eta' K^0_S$ channel we reconstruct the $\eta'$ in two modes: $\eta'_{\gamma\gamma}\pi\pi$ and $\eta'_{3\pi}\pi\pi$.

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 $\omega K^0_S$, $\phi K^0_S \pi^0$, 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 $m_{\text{ES}} \equiv \sqrt{\left(\frac{1}{2}p_B + p_L^0\right)^2 / E_0^2 - p^2_B}$ and the energy difference $\Delta E \equiv E^*_B - \frac{1}{2}E_0^*$, where $(E_0, p_0)$ and $(E_B, p_B)$ 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 $m_{\text{miss}}$, the invariant mass of the $B_{\text{tag}}$ computed from the known beam energy and the measured $B_{CP}$ momentum with mass of $B_{CP}$ constrained to the nominal $B$ meson mass \cite{27}. In the $\eta' K^0_L$ analysis we use only the $\Delta E$ variable because a mass constraint on the $B$ meson during the vertex fit leaves $m_{\text{ES}}$ and $\Delta E$ 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 angle and second momentum-weighted angular moments $L_0$ and $L_2$, defined as $L_i = \sum_j p_j \times |\cos \theta_j|^i$, where $\theta_j$ 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.
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 | $-\eta_f S_f$ | $C_f$ |
|------|--------------|---------------|-------|
| $\omega K_S^0$ | 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 | $0.57 \pm 0.08 \pm 0.02$ | $-0.08 \pm 0.06 \pm 0.02$ |
| $\eta' K_S^0$ | 1950 ± 58 | $0.53 \pm 0.08 \pm 0.02$ | $-0.11 \pm 0.06 \pm 0.02$ |
| $\eta' K_L^0$ | 556 ± 38 | $0.82 \pm 0.19 \pm 0.02$ | $0.09 \pm 0.14 \pm 0.02$ |
| $\pi^+ K_S^0$ | 556 ± 32 | $0.55 \pm 0.20 \pm 0.03$ | $0.13 \pm 0.13 \pm 0.03$ |

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

The $K^+ K^- K_S^0$ 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 $\chi_{c0}$ to extract $\beta_{\text{eff}}$ 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 $\beta_{\text{eff}}$, which is accessible only through the $\phi K_S^0 \pi^0$ CP eigenstate in which we reconstruct just $\sim 60$ events, by constraining the other 26 parameters, including $A_{CP}$ for each partial wave, with $\sim 800$ 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 $\eta' K_S^0$ and $\eta' K_L^0$ in addition to the combined $\eta' K^0$ results. The $K^+ K^- K_S^0$ results come 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 $\phi K_S^0$ and $f_0(980)K_S^0$ events, is 421 $\pm$ 25. The $\phi K_S^0 \pi^0$ yield is the total for all partial waves; each $\phi K^+_f$ yield is the sum of $\phi K_S^0 \pi^0$ and $\phi K^+ \pi^-$ final states events since both contribute to the determination of each direct CP parameter $A_{CP}$.

All $S_f$ and $\beta_{\text{eff}}$ results are consistent with the value of $\sin 2\beta$ measured in $b \to c\bar{c}s$ decays [28, 29]. The current world averages are $\sin 2\beta = 0.67 \pm 0.02$ and $\beta = 0.37 \pm 0.02$. All $C_f$ and $A_{CP}$ results are consistent with zero direct CP-violation. These $K^+ K^- K_S^0$ results favor $\beta_{\text{eff}} \simeq 0.37$ and rule out at 4.8$\sigma$ the solution $\frac{\pi}{2} - \beta$ from the trigonometric ambiguity of $\beta$ 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 $B\bar{B}$ background; the dominant systematic uncertainty in the $K^+ K^- K_S^0$ 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 $B^0 \to \phi K_S^0 \pi^0$ decay. The $\phi K_S^0 \pi^0$ 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 $\omega K^0$, 20% more data for other analyses, and improved track reconstruction.

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