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Measurements of Time-Dependent *CP* Violation in Radiative *B* Meson Decays at *BABAR*

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Abstract. We present measurements of the *CP*-violation parameters S and C for the radiative decays $B^0 \to \pi^0 K_S^0 \gamma$ and $B^0 \to \eta K_S^0 \gamma$; for $B \to \eta K \gamma$ we also measure the branching fractions and for $B^+ \to \eta K^+ \gamma$ the time-integrated charge asymmetry A_{ch}. The data, collected with the *BABAR* detector at the SLAC National Accelerator Laboratory, represent 467×10^6 $B\overline{B}$ pairs produced in e^+e^- annihilation at the PEP-II collider. For $B^0 \to \pi^0 K_S^0 \gamma$ we report results in two $m(\pi^0 K_S^0)$ mass regions: $S_{K^*(892)\gamma} = -0.03 \pm 0.29 \pm 0.03$, $C_{K^*(892)\gamma} = -0.14 \pm 0.16 \pm 0.03$ for $0.8 < m(\pi^0 K_S^0) < 1.0$ GeV/c^2; and $S_{\pi^0 K_S^0 \gamma} = -0.78 \pm 0.59 \pm 0.09$, $C_{\pi^0 K_S^0 \gamma} = -0.36 \pm 0.33 \pm 0.04$ for $1.1 < m(\pi^0 K_S^0) < 1.8$ GeV/c^2. For $B \to \eta K \gamma$ we find $S_{\eta K_S^0 \gamma} = -0.18^{+0.49}_{-0.46} \pm 0.12$, $C_{\eta K_S^0 \gamma} = -0.32^{+0.40}_{-0.39} \pm 0.07$, $\mathscr{B}(B^0 \to \eta K^0 \gamma) = (7.1^{+2.1}_{-2.0} \pm 0.4) \times 10^{-6}$, $\mathscr{B}(B^+ \to \eta K^+ \gamma) = (7.7 \pm 1.0 \pm 0.4) \times 10^{-6}$, and $A_{ch} = (-9.0^{+10.4}_{-9.8} \pm 1.4) \times 10^{-2}$. The first error quoted is statistical and the second systematic.

Keywords: Time-Dependent *CP* Violation, Radiative *B* Meson
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INTRODUCTION

Radiative B meson decays have long been recognized as a sensitive probe to test the standard model (SM) and to look for new physics (NP) [1]. In the SM, flavor-changing neutral current processes, such as $b \to s\gamma$, proceed at leading order through a loop diagram, making it sensitive to possible virtual contributions from as yet undiscovered particles. In the SM the photon polarization in radiative decays is dominantly left (right) handed for b ($\overline{b}$) decays, resulting in the suppression of time-dependent *CP* asymmetry due to the interference between B^0 mixing and decay diagrams [2]. The parameter S, which measures such an asymmetry, is expected to be approximately -0.02 [2, 3]. There are however NP scenarios predicting large values of this parameter; these include left-right symmetric models [2, 4] and supersymmetric models [5]. We search also for direct *CP* asymmetry in charged B decays, measuring the charge asymmetry $A_{ch} \equiv (\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$, where Γ is the partial decay width of the B meson, and the superscript corresponds to its charge. Direct *CP* asymmetry in the SM is expected to be very small [6]. Observation of significant *CP*-violation in these radiative decay modes would provide a clear sign of NP [7].

In this summary we present an updated measurement of the time-dependent *CP* asymmetry in $B^0 \to \pi^0 K_S^0 \gamma$ decay mode and the first measurement of the time-dependent *CP* asymmetry in $B^0 \to \eta K_S^0 \gamma$ decay mode [8]. Hadronic corrections in $B^0 \to \pi^0 K_S^0 \gamma$

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decay mode might permit S to be as large as ± 0.1 [9]. Such corrections and NP effects could depend on $m(\pi^0 K_S^0)$, so we split the data into two parts: the $K^*(892)$ region with $0.8 < m(\pi^0 K_S^0) < 1.0\,\mathrm{GeV}/c^2$ and the non-$K^*(892)$ region with $1.1 < m(\pi^0 K_S^0) < 1.8\,\mathrm{GeV}/c^2$. We also report updated measurements of branching fractions for the decay modes $B^0 \to \eta K^0 \gamma$ and $B^+ \to \eta K^+ \gamma$ and time-integrated charge-asymmetry for $B^+ \to \eta K^+ \gamma$.

The results presented here have been published in Ref. [10] for $B^0 \to \pi^0 K_S^0 \gamma$ decay mode and in Ref. [11] for $B \to \eta K \gamma$ decay modes.

DATA SAMPLE AND EVENTS SELECTION

The results are based on data collected with the *BABAR* detector [12] at the PEP-II asymmetric-energy e^+e^- collider [13] located at the SLAC National Accelerator Laboratory. We use an integrated luminosity of 423 fb^{-1}, corresponding to 467 ± 5 million $B\bar{B}$ pairs, recorded at the $\Upsilon(4S)$ resonance (at a center-of-mass (CM) energy of $\sqrt{s} = 10.58$ GeV).

The B decay daughter candidates are reconstructed through their decays $\pi^0 \to \gamma\gamma$, $K_S^0 \to \pi^+\pi^-$, $\eta \to \gamma\gamma$ ($\eta_{\gamma\gamma}$), and $\eta \to \pi^+\pi^-\pi^0$ ($\eta_{3\pi}$). Selection requirements on these candidates and on the primary photon from the B decay are described in Refs. [10, 11].

A B meson candidate (B_{rec}) is reconstructed by combining an η or π^0 candidate, a charged or neutral kaon and a primary photon candidate. It is characterized kinematically by the energy-substituted mass $m_{\mathrm{ES}} \equiv \sqrt{(s/2 + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$ and energy difference $\Delta E \equiv E_B^* - \frac{1}{2}\sqrt{s}$, where the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and to the B candidate in the lab-frame, respectively, and the asterisk denotes the CM frame. We require $5.2 < m_{\mathrm{ES}} < 5.3\,\mathrm{GeV}/c^2$ and $|\Delta E| < 0.250$ GeV for $B^0 \to \pi^0 K_S^0 \gamma$ decay mode, and $5.25 < m_{\mathrm{ES}} < 5.29$ GeV/c^2 and $|\Delta E| < 0.200$ GeV for $B \to \eta K \gamma$ decay modes. Furthermore, to suppress the continuum $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) background in the $B^0 \to \pi^0 K_S^0 \gamma$ candidates selection, we require $|\cos\theta_B^*| < 0.9$, where θ_B^* is the CM angle between the B candidate and the e^- beam direction, and the ratio of event-shape moments L_2/L_0 to be less than 0.55, where $L_i = \sum_j |p_j^*||\cos\theta_j^*|^i$, p_j^* is the CM momentum of each particle j not used to reconstruct the B candidate, and θ_j^* is the CM angle between p_j^* and the thrust axis of the reconstructed B candidate.

For each reconstructed signal candidate we use the remaining tracks in the event to reconstruct the decay vertex of the other B meson (B_{tag}) and identify its flavor. The difference $\Delta t \equiv t_{\mathrm{rec}} - t_{\mathrm{tag}}$ of the proper decay times t_{rec} and t_{tag} of the B_{rec} and B_{tag} mesons, respectively, is obtained from the measured distance between the B_{rec} and B_{tag} decay vertices and from the boost ($\beta\gamma = 0.56$) of the e^+e^- system. Due to the K_S^0 lifetime, the Δt for the modes $B^0 \to \pi^0 K_S^0 \gamma$ and $B^0 \to \eta_{\gamma\gamma} K_S^0 \gamma$ is obtained reliably by exploiting the knowledge of the average interaction point and from a global constrained fit to the entire $\Upsilon(4S) \to B^0\bar{B}^0$ decay tree, including the constraint from the lifetime of the B^0 meson. The Δt distribution is given by:

$$F(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \pm S\sin(\Delta m_d \Delta t) \mp C\cos(\Delta m_d \Delta t)], \quad (1)$$

where the upper (lower) sign denotes a decay accompanied by a B^0 ($\bar{B}^0$) tag, τ is the mean B^0 lifetime, and Δm_d is the $B^0\bar{B}^0$ mixing frequency. The C coefficient corresponds to the direct *CP* asymmetry in decay, expected to be smaller than 1% in the SM [6]. We require $|\Delta t| < 20$ ps and $\sigma_{\Delta t} < 2.5$ ps, where $\sigma_{\Delta t}$ is the per-event error on Δt.

RESULTS

We obtain signal event yields and *CP*-violation parameters from unbinned extended maximum-likelihood (ML) fits. We indicate with j the species of event: signal, $q\bar{q}$ continuum background, background from other B decays. The input observables in common for all modes are are m_{ES}, ΔE and Δt. Then we also use L_2/L_0 and, in the $K^*(892)$ region, $m(\pi^0 K_S^0)$ for the mode $B^0 \to \pi^0 K_S^0 \gamma$, or the output of a Neural Network (*NN*) and the η invariant mass m_η for the modes $B \to \eta K \gamma$. The *NN* combines four variables: $|\cos\theta_B^*|$, L_2/L_0, the absolute value of the cosine of the CM angle between the B thrust axis and the e^- beam direction, and the absolute value of the cosine of the angle between the B thrust axis and that of the rest of the tracks and neutral clusters in the event, calculated in the CM frame. We construct the likelihood function for each specie of event as the product of one-dimensional probability density functions (PDFs). The parameterizations of the PDFs are described in the Refs. [10, 11]. We compute the branching fractions and charge asymmetry from fits made without Δt.

Table 1 lists the results of the fits. We compute the branching fractions from the signal yields, reconstruction efficiencies, daughter branching fractions, and the number of produced B mesons. We assume that the branching fractions of the $\Upsilon(4S)$ to B^+B^- and $B^0\bar{B}^0$ are each equal to 50%.

The main sources of systematic uncertainties for the time-dependent measurements come from the variation of the signal PDF shape parameters within their errors, and from the *CP* content of $B\bar{B}$ background. The main sources of systematic uncertainties for the branching fraction measurements include uncertainties in the PDF parameterization and ML fit bias, uncertainties due to lack of knowledge of the primary photon spectrum, and uncertainties in our knowledge of the reconstruction efficiency. A systematic uncertainty of 0.014 is assigned to $\mathscr{A}_{ch}$. This uncertainty is estimated from studies with signal MC events and data control samples and from calculation of the asymmetry due to particles interacting in the detector.

CONCLUSION

We have measured the time-dependent *CP* asymmetry in $B^0 \to \pi^0 K_S^0 \gamma$ and $B^0 \to \eta K_S^0 \gamma$ decay modes. We have also measured the branching fractions for $B \to \eta K \gamma$ and the time-integrated charge asymmetry for $B^+ \to \eta K^+ \gamma$.

All measurements reported here are statistical limited. The *CP* asymmetry parameters are consistent within uncertainties with the predictions of the standard model. Due to the large statistical uncertainties, interesting constraints on NP in these decay modes need data sample available only at higher luminosity B factories (as proposed at KEK [15] and Frascati [16]).

TABLE 1. Number of signal yield, measured branching fraction $\mathscr{B}$, S and C parameters (only for neutral modes), and signal charge asymmetry $\mathscr{A}_{ch}$ (only for charged modes). First error quoted (or in case of single error) is statistical and the second systematic.

Mode	Signal	$\mathscr{B}(10^{-6})$	$\mathscr{A}_{ch}(10^{-2})$	S	C
$K^*(892)\gamma$	339 ± 24			$-0.03\pm0.29\pm0.03$	$-0.14\pm0.16\pm0.03$
$\pi^0 K_S^0\gamma$	133 ± 20			$-0.78\pm0.59\pm0.09$	$-0.36\pm0.33\pm0.04$
$\eta_{\gamma\gamma}K_S^0\gamma$	58^{+19}_{-18}	$7.4^{+2.5}_{-2.3}$		-0.04 ± 0.62	-0.24 ± 0.44
$\eta_{3\pi}K_S^0\gamma$	24^{+13}_{-12}	$6.6^{+3.6}_{-3.2}$		-0.45 ± 0.81	-0.71 ± 0.87
$\eta K^0\gamma$		$7.1^{+2.1}_{-2.0}\pm0.4$		$-0.18^{+0.49}_{-0.46}\pm0.12$	$-0.32^{+0.40}_{-0.39}\pm0.07$
$\eta_{\gamma\gamma}K^+\gamma$	266^{+37}_{-36}	$7.8^{+1.1}_{-1.0}$	-4 ± 12		
$\eta_{3\pi}K^+\gamma$	111^{+26}_{-24}	$7.4^{+1.7}_{-1.6}$	-24 ± 20		
$\eta K^+\gamma$		$7.7\pm1.0\pm0.4$	$\mathbf{-9.0^{+10.4}_{-9.8}\pm1.4}$		

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