Branching Fractions and CP-Violating Asymmetries in Radiative B Decays to ηKγ

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We present measurements of the CP-violation parameters $S$ and $C$ for the radiative decay $B^0 \to \eta K_S^0 \gamma$; 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 Stanford
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) \[1,2\]. In the SM, flavor-changing neutral current processes, such as $b \to s\gamma$, proceed via radiative loop diagrams. The loop diagrams may also contain new heavy particles, and therefore are sensitive to NP. The measured branching fractions of inclusive $b \to s\gamma$ and exclusive radiative $B$ decays are in agreement with SM predictions \[2,3,4\]. Recent estimates of the branching fraction of the inclusive $b \to s\gamma$ decay are affected by a theoretical uncertainties as large as the experimental ones \[3\].

In the SM the photon polarization in radiative decays is dominantly left (right) handed for $b (\bar{b})$ decays, resulting in the suppression of mixing-induced \[3\] CP asymmetries. Because we do not measure the photon helicity, we sum the decay rates for the left-handed and right-handed helicity states. Observation of significant CP-violation in these radiative decay modes would provide a clear sign of NP \[3\]. We search also for direct CP asymmetry in charged $B$ decays, measuring the charge asymmetry $A_{ch} \equiv (\Gamma^- - \Gamma^+)/\langle \Gamma^- + \Gamma^+ \rangle$, where $\Gamma$ is the partial decay width of the $B$ meson, and the superscript corresponds to its charge. This asymmetry in the SM is expected to be very small \[3\].

In this letter, we present the first measurement of the mixing-induced CP violation in the decay mode $B^0 \to \eta K^{\pm}\gamma$. Branching fractions for the decay modes $B^0 \to \eta K^{0}\gamma$ and $B^+ \to \eta K^{+}\gamma$ \[3\] and time-integrated charge-asymmetry for $B^+ \to \eta K^{+}\gamma$ have been measured previously by the Belle \[10\] and BABAR \[11\] Collaborations. We update our previous measurements with a data sample that is twice as large.

The results presented here are based on data collected with the BABAR detector \[12\] at the PEPII asymmetric-energy $e^+e^-$ collider \[13\] located at the Stanford Linear Accelerator Center. We use an integrated luminosity of 423 fb$^{-1}$, corresponding to 465 ± 5 million $B\bar{B}$ pairs, recorded at the $\Upsilon(4S)$ resonance (at a center-of-mass energy of $\sqrt{s} = 10.58$ GeV).

Description of the BABAR detector and of the reconstruction of charged and neutral particles can be found elsewhere \[14\]. The $B$ decay daughter candidates are reconstructed through their decays $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$ ($\eta_{\gamma\gamma}$), and $\eta \to \pi^+\pi^-\pi^0$ ($\eta_{\pi\pi\pi}$). Reconstruction and selection criteria of charged and neutral mesons, and primary photons and the study of continuum and $B\bar{B}$ backgrounds are described in our previous paper \[11\].

A $B$ meson candidate is reconstructed by combining an $\eta$ candidate, a charged or neutral kaon and a primary photon candidate. It is characterized kinematically by the energy-substituted mass $m_{ES} = \sqrt{(s/2 + p_0 \cdot p_B)^2/E_B^2 - p_E^2}$ and energy difference $\Delta E = E_B^2 - E_{\gamma}^2 - \frac{1}{2}m_{BS}^2$, 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 $\Upsilon(4S)$ rest frame. We require $5.25 < m_{ES} < 5.29$ GeV/c$^2$ and $|\Delta E| < 0.2$ GeV.

From a candidate $B\bar{B}$ pair we reconstruct a $B^0$ decaying into $\eta K^{0}\gamma$ ($B_{rec}$). We also reconstruct the decay point of the other $B$ meson ($B_{tag}$) and identify its flavor. The difference $\Delta t \equiv t_{rec} - t_{tag}$ of the proper decay times $t_{rec}$ and $t_{tag}$ of the reconstructed and tagged $B$ 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. The $\Delta t$ distribution \[11\] is given by:

$$F(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\pi} [1 \pm \Delta w \pm (1 - 2w)(S\sin(\Delta m_d\Delta t) - C\cos(\Delta m_d\Delta t))]. \quad (1)$$

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, and the mistag parameters $w$ and $\Delta w$ are the average and difference, respectively, of the probabilities that a true $B^0$ is incorrectly tagged as a $\bar{B}^0$ or vice versa. In the flavor tagging algorithm \[10\] there are six mutually exclusive tagging categories of different response purities and untagged events with no tagging informations. Tagging and $\Delta t$ informations are used for the measurement of the CP-violation parameters $S$ and $C$ in the decay mode $B^0 \to \eta K^{0}\gamma$.

We use the same technique developed for $B^0 \to \pi^0 K_S^{0}\gamma$ decays \[15\] to reconstruct the $B^0 \to \eta_{\pi\pi\pi} K_S^{0}\gamma$ decay point, using the knowledge of the $K_S^{0}$ trajectory and the average interaction point in a geometric fit. The extraction of $\Delta t$ has been extensively validated in data \[17\] and in a full detector simulation. In about 70% of the selected events the $\Delta t$ resolution is sufficient for the time-dependent CP-violation measurement. For the remaining events the $\Delta t$ information is not used. For both $\eta_{\gamma\gamma} K_S^{0}\gamma$ and $\eta_{\pi\pi\pi} K_S^{0}\gamma$ modes we use the events which satisfy the requirements $|\Delta t| < 20$ ps and $\sigma_{\Delta t} < 2.5$ ps, where $\sigma_{\Delta t}$ is the per-event error on $\Delta t$.

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, $qq$
current background, $B\overline{B}$ peaking background ($BP$), and $B\overline{B}$ non-peaking background (BNP). The input observables are $m_{ES}$, $\Delta E$, the output of a Neural Network (NN), the $\eta$ invariant mass $m_{\eta}$, and $\Delta t$. The NN combines four variables: the absolute values of the cosines of the polar angles with respect to the beam axis in the $\Upsilon(4S)$ frame of the $B$ candidate momentum and the $B$ thrust axis, the ratio of the second and zeroth Fox-Wolfram moments [15], and the absolute value of the cosine of the angle $\theta_B$ between the thrust axis of the $B$ candidate and that of the rest of the tracks and neutral clusters in the event, calculated in the $\Upsilon(4S)$ frame.

For each species $j$ and tagging category $c$, we define a total probability density function (PDF) for event $i$ as

$$P_{j,c}^i = P_j(m_{ES}^i) \cdot P_j(\Delta E^i) \cdot P_j(NN^i) \cdot P_j(m_{\eta}^i) \cdot P_j(\Delta t^i, \sigma_{\Delta t}; c).$$

The factored form of the PDF is a good approximation since correlations between input observables are small. With $n_j$ defined to be the number of events of the species $j$ and $f_{j,c}$ the fraction of events of species $j$ for each category $c$, we write the extended likelihood function for all events belonging to category $c$ as

$$L_c = \exp \left( -\sum_{j} n_{j,c} \prod_{i} (n_{\text{sig}} f_{\text{sig},c} P_{\text{sig},c}^i + n_{q\overline{q}} f_{q\overline{q},c} P_{q\overline{q}}^i + n_{\text{BNP}} f_{\text{BNP},c} P_{\text{BNP}}^i + n_{\text{BP}} f_{\text{BP},c} P_{\text{BP}}^i) \right),$$

where $n_{j,c}$ is the yield of events of species $j$ found by the fitter in category $c$ and $N_c$ the number of events of category $c$ in the sample. We fix $f_{\text{sig},c}$, $f_{\text{BNP},c}$, and $f_{\text{BP},c}$ to $f_{\text{baseline},c}$, the values measured with a large sample of $B$-decays to fully reconstructed flavor eigenstates ($B_{\text{baseline}}$) [19]. The total likelihood function $L_d$ for decay mode $d$ is given as the product over the seven tagging categories. Finally, when combining decay modes we form the joint likelihood $L = \prod L_d$.

The PDF $P_{\text{sig}}(\Delta t, \sigma_{\Delta t}; c)$, for each category $c$, is the convolution of $F(\Delta t; c)$ (Eq. [1]) with the signal resolution function (sum of three Gaussians) determined from the $B_{\text{baseline}}$ sample. The other PDF forms are: the sum of two Gaussians for $P_{\text{sig}}(m_{ES})$, $P_{\text{sig}}(\Delta E)$, and $P_{\text{sig}}(m_{\eta})$; the sum of three Gaussians for $P_{q\overline{q}}(\Delta t)$, $P_{\text{BNP}}(\Delta t)$, and $P_{\text{BP}}(\Delta t)$; a non-parametric step function for $P_j(NN)$ [20]; a linear dependence for $P_{q\overline{q}}(\Delta E)$, $P_{\text{BNP}}(\Delta E)$, and $P_{\text{BP}}(\Delta E)$; a first-order polynomial plus a Gaussian for $P_{q\overline{q}}(m_{\eta})$, $P_{\text{BNP}}(m_{\eta})$, and $P_{\text{BP}}(m_{\eta})$; and for $P_{q\overline{q}}(m_{ES})$, $P_{\text{BNP}}(m_{ES})$, and $P_{\text{BP}}(m_{ES})$, the function $x \sqrt{1 - x^2} \exp[-\xi(1 - x^2)]$, with $x = 2m_{ES}/\sqrt{s}$ [21], where for the $BP$ PDFs we add a Gaussian. We allow $q\overline{q}$ background PDF parameters to vary in the fit.

We determine the PDF parameters from Monte Carlo (MC) simulation for the signal and $B\overline{B}$ backgrounds, while using sideband data ($5.25 < m_{ES} < 5.27$ GeV/$c^2$; $0.1 < |\Delta E| < 0.2$ GeV) to model the PDFs of continuum background. Large control samples of $B$ decays to charmed final states with similar topology and a smearing procedure applied to photons during the event reconstruction are used to verify the simulated resolutions in $m_{ES}$ and $\Delta E$. Where the control data samples reveal differences from the MC in mass resolution, we shift or scale the resolution used in the likelihood fits. The largest shift in $m_{ES}$ is 0.6 MeV/$c^2$. Any bias in the fit is determined from a large set of simulated experiments in which the $q\overline{q}$ and BNP backgrounds are generated from the PDFs, and into which we have embedded the expected number of $BP$ and signal events chosen randomly from fully simulated MC samples.

We compute the branching fractions and charge asymmetry from fits made without $\Delta t$ or flavor tagging. The free parameters in the fit are: the signal, $q\overline{q}$, BNP and $BP$ background yields; the bin weights of the step function for $P_{q\overline{q}}(NN)$; the slopes of $P_{q\overline{q}}(\Delta E)$ and $P_{q\overline{q}}(m_{\eta}); \xi$; and for charged modes the signal and background $\mathcal{A}_c$. We apply the same procedure to extract $S$ and $C$. In this case we add in the fit the $\Delta t$ variable and the flavor-tagging information. As free parameters we have also $S$, $C$, and the parameters of the $P_{q\overline{q}}(\Delta t)$ PDF.

Table I lists the results of the fits. The corrected signal yield is the fitted yield minus the fit bias which is in the range $2 - 4\%$. The efficiency is calculated as the ratio of the number of signal MC events entering the ML fit to the total generated. We compute the branching fractions from the corrected 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 $B^0\overline{B}^0$ are each equal to 50%. We combine results from different channels by adding their likelihood functions, taking into account the correlated and uncorrelated systematic errors.

The statistical error on the signal yield, $S$, $C$ and the signal charge asymmetry is taken as the change in the central value when the quantity $-2 \ln L$ increases by one unit from its minimum value. The significance $S(\sigma)$ is the square root of the difference between the value of $-2 \ln L$ (with systematic uncertainties included) for zero signal and the value at its minimum.

Figure 4 shows, as representative fits, the projections onto $m_{ES}$ and $\Delta E$ while Fig. 2 shows the projections onto $\Delta t$ and the raw asymmetry between $B^0$ and $B^0\overline{B}^0$ tags. In these projections a subset of the data is used for which the signal likelihood (computed without the variable plotted) exceeds a threshold that optimizes the sensitivity.

Figure 3 shows the distribution of the $\eta K$ invariant mass for signal events obtained by the event-weighting technique (sPlot) described in Ref. [22]. We use the covariance matrix and PDFs from the ML fit to determine a probability for each signal event. The resulting distri-
TABLE I: Number of events $N$ in the sample, corrected signal yield, detection efficiency $\epsilon$, daughter branching fraction product $\prod B_i$, significance $S$ ($\sigma$) (including systematic uncertainties), and measured branching fraction $B$ with statistical error for each decay mode. For the combined measurements we give $S$ ($\sigma$) and the branching fraction with statistical and systematic uncertainty. For the neutral mode we give the $S$ and $C$ parameters for each decay mode and for their combination. For the charged modes we also give the measured signal charge asymmetry $A_\beta$.

| Mode | $N$ (Events / 100 MeV/c) | Yield | $\epsilon$ (%) | $\prod B_i$ | $S$ ($\sigma$) | $B(10^{-6})$ | $A_\beta$ ($10^{-2}$) | $S$ (%) | $C$ (%) |
|------|----------------|------|------------|--------------|---------------|----------------|----------------|--------|--------|
| $\eta_{\gamma} K^0 \gamma$ | 3600 | 58 | 12 | 3.3 | 7.4$^{+2.5}_{-2.6}$ | $-0.04 \pm 0.62$ | $-0.24 \pm 0.44$ |
| $\eta_{3\pi} K^0 \gamma$ | 2282 | 24 | 10 | 2.1 | 6.6$^{+3.4}_{-3.2}$ | $-0.45 \pm 0.81$ | $-0.71 \pm 0.87$ |
| $\eta K^0 \gamma$ | 3.9 | 7.1$^{+2.1}_{-2.0}$ | 0.4 | 0.4 | $0.018^{+0.40}_{-0.46}$ | $0.12 \pm 0.07$ | $0.32^{+0.40}_{-0.39}$ |
| $\eta_{\gamma} K^+ \gamma$ | 11620 | 266$^{+37}_{-30}$ | 19 | 6.5 | 7.8$^{+1.1}_{-1.0}$ | $-4 \pm 12$ |
| $\eta_{3\pi} K^+ \gamma$ | 10738 | 111$^{+26}_{-24}$ | 14 | 4.5 | 7.4$^{+1.7}_{-1.6}$ | $-24 \pm 20$ |
| $\eta K^+ \gamma$ | 8.0 | 7.7$^{+1.0}_{-1.0}$ | 0.4 | 0.4 | $-9.0^{+10.4}_{-9.8}$ | $1.4$ |

FIG. 1: The $B$ candidate $m_{ES}$ and $\Delta E$ projections (see text) for $\eta K^+ \gamma$ (a, b), $\eta K^0 \gamma$ (c, d). Points with error bars (statistical only) represent the data, the solid line the full fit function, and the dashed line its background component.

FIG. 2: Projections (see text) onto $\Delta t$ of the data (points with error bars), fit function (solid line), and background function (dashed line), for (a) $B^0$ and (b) $\overline{B}^0$ tagged events, and (c) the raw asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$ between $B^0$ and $\overline{B}^0$ tags.

FIG. 3: Plot of $\eta K$ invariant mass for signal using the weighting technique described in the text for the combined sub-decay modes: (a) $B^+ \rightarrow \eta K^+ \gamma$, (b) $B^0 \rightarrow \eta K^0 \gamma$. Errors are statistical only.

The main sources of systematic uncertainties for the branching fraction measurements include uncertainties in the PDF parameterization and ML fit bias. For the signal, the uncertainties in PDF parameters are estimated by comparing MC and data in control samples. Varying the signal PDF parameters within these errors, we estimate yield uncertainties of 3–23 events, depending on the mode. The $B_{Bav}$ sample is used to determine the errors associated with the signal $\Delta t$ resolutions, tagging efficiencies, and mistag rates. Published measurements for $\tau$ and $\Delta m_d$ are used to determine the errors associated with them. Summing all systematic errors in quadrature, we obtain $0.12$ for $S$ and $0.07$ for $C$.

The main sources of systematic uncertainties for the branching fraction measurements include uncertainties in the PDF parameterization and ML fit bias. For the signal, the uncertainties in PDF parameters are estimated by comparing MC and data in control samples. Varying the signal PDF parameters within these errors, we estimate yield uncertainties of 3–23 events, depending on the mode. The uncertainty (1–3 events) from fit bias is taken as half the correction itself. Systematic uncertainties due to lack of knowledge of the primary photon spectrum are estimated to be in the range 2–3% depending on the decay mode. Uncertainties in our knowledge of the efficiency, found from auxiliary studies, include $0.4\% \times N_t$ and $1.8\% \times N_c$, where $N_t$ and $N_c$ are the numbers of tracks and photons, respectively, in the $B$ candidate. There is a systematic error of 2.1% in the efficiency of $K^0_S$ reconstruction. The uncertainty in the total
number of $B\bar{B}$ pairs in the data sample is 1.1%. Published data [4] provide the uncertainties in the $B$ daughter branching fraction products (0.7–1.8%).

A systematic uncertainty of 0.014 is assigned to $A_{ch}$. 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.

In conclusion, we measure the time-dependent $CP$ violation parameters in the decay mode $B^0 \to \eta K^0_S$: $S = -0.18^{+0.49}_{-0.46} \pm 0.12$ and $C = -0.32^{+0.40}_{-0.39} \pm 0.07$. These results are consistent with no $CP$-violation in this mode. We also measure the branching fractions, in units of $10^{-6}$, $B(B^0 \to \eta K^0_S) = 7.1^{+2.1}_{-2.0} \pm 0.4$ and $B(B^+ \to \eta K^+\gamma) = 7.7 \pm 1.0 \pm 0.4$, in agreement with the results from Belle [10] and the previous $BABAR$ results [11]. The measured charge asymmetry in the decay $B^+ \to \eta K^+\gamma$ is consistent with zero. Its confidence interval at 90% confidence level is $[-0.25, 0.08]$.

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