Branching fractions and CP-violating asymmetries in radiative $B$ decays to $\eta K\gamma$

BRANCHING FRACTIONS AND CP-VIOLATING ...

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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 via radiative loop diagrams. The loop diagrams may also contain new heavy particles, and therefore are sensitive to NP.

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 $CP$ asymmetries [2]. There are however NP scenarios predicting large values of mixing-induced $CP$ asymmetries [3,4]. We search also for direct $CP$ asymmetry in charged $B$ decays, measuring the charge asymmetry $A_{ch} \equiv (\Gamma^- - \Gamma^+)/\Gamma^+$, where $\Gamma$ 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 [5]. Observation of significant $CP$ violation in these radiative decay modes would provide a clear sign of NP [6].

In this paper, we present the first measurement of the mixing-induced $CP$ violation in the decay mode $B^0 \to \eta K^0 \gamma$. Branching fractions for the decay modes $B^0 \to \eta K^0 \gamma$ and $B^+ \to \eta K^+ \gamma$ [7] and time-integrated charge asymmetry for $B^+ \to \eta K^+ \gamma$ have been measured previously by the Belle [8] and BABAR [9] 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 [10] at the PEP-II asymmetric-energy $e^+e^-$ collider [11] located at the Stanford Linear Accelerator Center. We use an integrated luminosity of 423 fb$^{-1}$, corresponding to $(465 \pm 5) \times 10^{9}$ $B\bar{B}$ pairs, recorded at the $\Upsilon(4S)$ resonance (at a center-of-mass energy of $\sqrt{s} = 10.58$ GeV).

Charged particles are detected by a combination of a vertex tracker (SVT) consisting of five layers of double-sided silicon microstrip detectors, and a 40-layer central drift chamber (DCH), both operating in the 1.5 T magnetic field. Photons and electrons are identified using a CsI(Tl) electromagnetic calorimeter (EMC). Further charged-particle identification is provided by the average energy loss ($dE/dx$) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. We reconstruct the primary photon using an EMC shower not associated with a track. The primary photon energy, calculated in the $\Upsilon(4S)$ frame, is required to be in the range 1.6–2.7 GeV. Charged $K$ candidates are selected from tracks, by using particle identification from the DIRC and the $dE/dx$ measured in the SVT and DCH.

The $B$ decay daughter candidates are reconstructed through their decays $\pi^0 \to \gamma \gamma$, $\eta \to \gamma \gamma$ ($\eta_{\gamma\gamma}$), and $\eta \to \pi^+ \pi^- \pi^0$ ($\eta_{3\pi}$). Here we require the laboratory energy of the photons to be greater than 50 MeV. We impose the following requirements on the invariant mass in MeV/c$^2$ of these particles’ final states: $120 < m(\gamma\gamma) < 150$ for $\pi^0$, $490 < m(\gamma\gamma) < 600$ for $\eta_{\gamma\gamma}$, $520 < m(\pi^+ \pi^- \pi^0) < 570$ for $\eta_{3\pi}$. Secondary pions in $\eta$ candidates are rejected if their DIRC and $dE/dx$ signatures satisfy tight requirements for being consistent with protons, kaons, or electrons.

Neutron $K$ candidates are formed from pairs of oppositely charged tracks with a vertex $\chi^2$ probability larger than 0.001, $486 < m(\pi^+ \pi^-) < 510$ MeV/c$^2$ and a reconstructed decay length greater than 3 times its uncertainty. The invariant mass of $\eta K^0$ system is required to be less than 3.25 GeV/c$^2$. 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 $m_{ES} \equiv \sqrt{(s/2 + p_0 \cdot p_B)^2 - E_B^2 - p_B^2}$ and energy difference $\Delta E \equiv E^- - 1/2 \sqrt{s}$, 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 $\Upsilon(4S)$ 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 $\eta K^0 \gamma$ ($B_{\gamma\gamma}$). We also reconstruct the decay point of...
the other $B$ meson ($B_{\text{tag}}$) and identify its flavor. The differ-
ence $\Delta t \equiv t_{\text{rec}} - t_{\text{tag}}$ of the proper decay times $t_{\text{rec}}$ and $t_{\text{tag}}$
of the reconstructed and tag $B$ mesons, respectively, is obtained from the measured distance between the $B_{\text{rec}}$
and $B_{\text{tag}}$ decay vertices and from the boost ($\beta\gamma = 0.56$)
of the $e^+e^-$ system. The $\Delta t$ distribution [12] is given by
\[
F(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \pm \Delta w \pm (1 - 2w)(\delta \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t))].
\] (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 [13] there are six mutually
exclusive tagging categories of different response purities
and untagged events with no tagging informations.

We reconstruct the $B^0 \rightarrow \eta \gamma K^0_S \gamma$ decay point, using
the knowledge of the $K^0_S$ trajectory and the average interaction
point in a geometric fit [12]. 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 $\eta \gamma K^0_S \gamma$ and $\eta_{s\bar{s}} K^0_S \gamma$
modes we require $|\Delta t| < 20$ 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 para-
eters from unbinned extended maximum-likelihood (ML)
fits. We indicate with $j$ the species of event: signal, $q\bar{q}$
continuum background, $B\bar{B}$ peaking background ($BP$), and
$B\bar{B}$ nonpeaking 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 varia-
tables: the absolute values of the cosines of the polar angles
with respect to the beam axis in the $Y(4S)$ frame of the $B$
candidate momentum and the $B$ thrust axis, the ratio of the
second and zeroth Fox-Wolfram moments [14], and the
absolute value of the cosine of the angle $\theta_1$ 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
$Y(4S)$ frame.

For each species $j$ and tagging category $c$ and with $n_j$
definite 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 be-
longing to category $c$ as
\[
L_c = \exp\left(-\sum_j n_j f_{j,c}\right) \prod_i \left[n_{\text{sig}} f_{\text{sig},c} P^i_{\text{sig},c} + n_{q\bar{q}} f_{q\bar{q},c} P^i_{q\bar{q}}
+ n_{\text{BNP}} f_{\text{BNP},c} P^i_{\text{BNP}} + n_{BP} f_{BP,c} P^i_{BP}\right),
\] (2)

where $P^i_{j,c}$ is the total probability function (PDF) for event
$i$ and $N_c$ the number of events of category $c$ in the sample.
We fix $f_{\text{sig},c}$, $f_{\text{BNP},c}$, and $f_{BP,c}$ to $f_{B_{\text{flav}},c}$, the values mea-
sured with a large sample of $B$-decays to fully recon-
structed flavor eigenstates ($B_{\text{flav}}$) [15]. 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 grand likelihood $L =
\prod_d L_d$.

The PDF $P_{\text{sig}}(\Delta t, \sigma_{\Delta t}, c)$, for each category $c$, is the
convolution of $P(\Delta t; c)$ [Eq. (1)] with the signal resolution
function (sum of three Gaussians) determined from the
$B_{\text{flav}}$ sample. The other PDF forms are the sum of two
Gaussians for $P_{q\bar{q}}(m_{ES})$, $P_{q\bar{q}}(\Delta E)$, and $P_{q\bar{q}}(m_{\eta})$; the sum
of three Gaussians for $P_{q\bar{q}}(\Delta t)$, $P_{BNP}(\Delta t)$, and $P_{BP}(\Delta t)$; a
nonparametric step function for $P_{j}(NN)$ [16]; a linear
dependence for $P_{q\bar{q}}(\Delta E)$, $P_{BNP}(\Delta E)$, and $P_{BP}(\Delta E)$; a
first-order polynomial plus a Gaussian for $P_{q\bar{q}}(m_{\eta})$,
$P_{BNP}(m_{\eta})$, and $P_{BP}(m_{\eta})$; and for $P_{q\bar{q}}(m_{ES})$, $P_{BNP}(m_{ES})$, and $P_{BP}(m_{ES})$, the function $x \sqrt{1-x^2} \exp[-\xi(1-x^2)]$, with $x = 2m_{ES}/\sqrt{5}$ [17], where for the
$BP$ PDFs we add a Gaussian. We allow $q\bar{q}$ background
PDF parameters to vary in the fit.

We determine the PDF parameters from Monte Carlo
(MC) simulation for the signal and $B\bar{B}$ 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 back-
ground. 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 $\Delta E$. 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.

We compute the branching fractions and charge asym-
metry from fits made without $\Delta t$ and flavor tagging. The
free parameters in the fit are the signal, $q\bar{q}$, $BNP$ and $BP$
background yields; the bin weights of the step function for
$P_{q\bar{q}}(NN)$; the slopes of $P_{q\bar{q}}(\Delta E)$ and $P_{q\bar{q}}(m_{\eta}); \xi$; and for
charged modes the signal and background $A_{c,cb}$. As free
parameters we have also $S$, $C$, the parameters of the
$P_{q\bar{q}}(\Delta t)$ PDF, and the $f_{q\bar{q}}$ fractions.

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,
daugther branching fractions, and the number of produced
$B$ mesons. We assume that the branching fractions of the
$Y(4S)$ to $B^+B^-$ and $B^0\bar{B}^0$ are each equal to 50%. We
combine results from different channels by adding the values
of $-2 \ln L$ (parameterized in terms of the branching
fractions), taking into account the correlated and uncor-
related 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 1 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 \(\bar{B}^0\) tags. In these projections a subset of the data is used for when 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. [18]. There is some evidence of a structure near 1.5 GeV/c^2.

The main sources of systematic uncertainties for the time-dependent measurements come from the variation of the signal PDF shape parameters within their errors (0.08 for \(S\), 0.04 for \(C\), and from \(B\bar{B}\) backgrounds (0.09 for \(S\), 0.06 for \(C\)). Other minor sources are SVT alignment, beam spot position and size, and interference between the CKM-suppressed \(b \to u\bar{c}\bar{d}\) amplitude and the favored \(b \to c\bar{d}d\) amplitude for some tag-side \(B\) decays [19]. The \(B_{flav}\) sample is used to determine the errors associated with the signal \(\Delta t\) resolutions, tagging efficiencies, and mistag rates. We use specific signal MC samples to evaluate the systematic uncertainty associated with the appropriateness of using \(B_{flav}\) parameters for the signal \(\Delta t\) resolution (0.02 for \(S\), 0.01 for \(C\)). Published measurements [20] for \(\tau\) and \(\Delta m_d\) are used to determine the errors associated with them. Summing all systematic errors in quadrature, we obtain \(\pm 0.12\) for \(S\) and \(\pm 0.07\) 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 [21], include 0.4% \(\times N_t\) and 1.8% \(\times N_\gamma\), where \(N_t\) and \(N_\gamma\) are the numbers of tracks

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**TABLE I. Number of events \(N\) in the sample, corrected signal yield, detection efficiency \(\epsilon\), daughter branching fraction product \(\prod B_t\), 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 \(A_{ch}\).**

<table>
<thead>
<tr>
<th>Mode</th>
<th>(N)</th>
<th>Yield</th>
<th>(\prod B_t) (%)</th>
<th>(S(\sigma))</th>
<th>(B(10^{-6}))</th>
<th>(A_{ch} (10^{-2}))</th>
<th>(S)</th>
<th>(C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta\gamma K^{0}\gamma)</td>
<td>3690</td>
<td>58(^{+18}_{-18})</td>
<td>12</td>
<td>13.6</td>
<td>3.3</td>
<td>7.4(^{+2.5}_{-2.3})</td>
<td>-0.04</td>
<td>-0.24</td>
</tr>
<tr>
<td>(\eta\pi K^{0}\gamma)</td>
<td>2282</td>
<td>24(^{+12}_{-12})</td>
<td>10</td>
<td>7.8</td>
<td>2.1</td>
<td>6.6(^{+3.0}_{-3.2})</td>
<td>-0.45</td>
<td>-0.71</td>
</tr>
<tr>
<td>(\eta K^{+}\gamma)</td>
<td>3.9</td>
<td>7.1(^{+2.4}_{-2.0})</td>
<td>-0.18(^{+0.40}_{-0.39})</td>
<td>-0.32(^{+0.40}_{-0.07})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**FIG. 1 (color online).** 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 (color online).** 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) \(\bar{B}^0\) tagged events, and (c) the raw asymmetry \((N_{\gamma} - N_{\bar{\gamma}})/(N_{\gamma} + N_{\bar{\gamma}})\) between \(B^0\) and \(\bar{B}^0\) tags.
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 [20] provide the uncertainties in the $B$ daughter branching fraction products (0.7%–1.8%).

A systematic uncertainty of 0.014 is assigned to $\mathcal{A}_{\chi,h}$. 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 $B^0\rightarrow \eta K^0\gamma$: $S = -0.18^{+0.49}_{-0.46} \pm 0.12$ and $C = -0.32^{+0.40}_{-0.39} \pm 0.07$. We also measure the branching fractions, in units of $10^{-6}$, $\mathcal{B}(B^0\rightarrow \eta K^0\gamma) = 7.1^{+2.1}_{-1.6} \pm 0.4$ and $\mathcal{B}(B^0\rightarrow \eta K^+\gamma) = 7.7 \pm 1.0 \pm 0.4$, in agreement with the results from Belle [8] and the previous BABAR results [9]. The measured charge asymmetry in the decay $B^+\rightarrow \eta K^+\gamma$ is consistent with zero. Its confidence interval at 90% confidence level is $[-0.25, 0.08]$. All the results are consistent with SM expectations. Because of the large statistical uncertainties, interesting constraints on NP in these decay modes need a data sample available only at higher luminosity $B$ factories (as proposed at KEK [22] and Frascati [23]).

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[7] Charge-conjugate modes are implied throughout.