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Measurement of branching fractions in radiative B decays to $\eta K\gamma$ and search for B decays to $\eta' K\gamma$

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We present measurements of the $B \to \eta K \gamma$ branching fractions and upper limits for the $B \to \eta' K \gamma$ branching fractions. For $B^+ \to \eta K^+ \gamma$ we also measure the time-integrated charge asymmetry. The data sample, collected with the *BABAR* detector at the Stanford Linear Accelerator Center, represents 232×10^6 produced $B\bar{B}$ pairs. The results for branching fractions and upper limits at 90% confidence level in units of 10^{-6} are: $\mathcal{B}(B^0 \to \eta K^0 \gamma) = 11.3^{+2.8}_{-2.6} \pm 0.6$, $\mathcal{B}(B^+ \to \eta K^+ \gamma) = 10.0 \pm 1.3 \pm 0.5$, $\mathcal{B}(B^0 \to \eta' K^0 \gamma) < 6.6$, $\mathcal{B}(B^+ \to \eta' K^+ \gamma) < 4.2$. The charge asymmetry in the decay $B^+ \to \eta K^+ \gamma$ is $\mathcal{A}_{ch} = -0.09 \pm 0.12 \pm 0.01$. The first errors are statistical and the second systematic.

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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) [1,2]. In the SM, flavor-changing neutral current processes such as $b \to s\gamma$ proceed via radiative loop (penguin) diagrams. The loop diagrams may also contain new heavy particles, and therefore are sensitive to NP. Measurements of the branching fractions of a few of the exclusive decay modes exist: $K^*(892)\gamma$ [3,4], $K_1(1270)\gamma$ [5], $K_2^*(1430)\gamma$ [3,6], $K\pi\pi\gamma$ [6], $\phi K \gamma$ [7] and $K\eta\gamma$ [8]. The measured branching fraction of inclusive $b \to s\gamma$ and exclusive radiative B decays are in agreement with SM predictions [2,9,10]. Direct [11] and mixing-induced [12] CP asymmetries in exclusive radiative B decays are expected to be very small in the SM. Measurement of direct CP asymmetries in exclusive radiative decays, and also mixing-induced CP asymmetries in the decays $B^0 \to \eta K^0 \gamma$ and $B^0 \to \eta' K^0 \gamma$ could provide a clear sign of NP [13]. We search for direct CP asymmetry in charged B decays, measuring the charge asymmetry $\mathcal{A}_{ch} \equiv (\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$, where Γ is the partial decay width of the B meson. The superscript on Γ corresponds to the sign of the $B^{\pm}$ meson.

The branching fraction of $B \to \eta' K$ is enhanced with respect to that of $B \to \eta K$ [14]. This behavior may be explained by a destructive interference between two penguin amplitudes [15]. It is important to verify whether this mechanism is also valid in radiative $B \to \eta K \gamma$ and $B \to \eta' K \gamma$ decays.

We present analyses of the exclusive decay modes $B^+ \to \eta K^+ \gamma$ and $B^0 \to \eta K^0 \gamma$ [16], which have previously been measured by the Belle Collaboration [8], and $B^+ \to \eta' K^+ \gamma$ and $B^0 \to \eta' K^0 \gamma$ which are studied for the first time. The results presented here are based on data collected with the *BABAR* detector [17] at the PEP-II asymmetric-energy e^+e^- collider [18] located at the Stanford Linear Accelerator Center. The analyses use an integrated luminosity of 211 fb^{-1}, corresponding to 232×10^6 $B\bar{B}$ pairs, recorded at the $\Upsilon(4S)$ resonance (at a center-of-mass energy of $\sqrt{s} = 10.58$ GeV).

Charged particles from e^+e^- interactions are detected, and their momenta measured, 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 of a superconducting solenoid. We identify photons and electrons 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. A K/π separation of better than 4 standard deviations is achieved for momenta below 3 GeV$/c$, decreasing to 2.5σ at the highest momenta in the B decay final states. A more detailed description of the reconstruction of charged tracks in *BABAR* can be found elsewhere [19].

We reconstruct the primary photon, originating from the B decay candidate, using an EMC shower not associated with a track. We require that the photon candidate fall within the fiducial region of the EMC, has the expected lateral shower shape, and is well-separated from other tracks and showers in the EMC. The primary photon energy, calculated in the $\Upsilon(4S)$ frame, is required to be in the range 1.6–2.7 GeV. We veto photons from $\pi^0(\eta)$ decays by requiring that the invariant mass of the primary photon candidates combined with any other photon candidate of laboratory energy greater than 50 (250) MeV not be within the range 115–155 (507–587) MeV$/c^2$. 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 $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma(\eta_{\gamma\gamma})$, $\eta \to \pi^+\pi^-\pi^0(\eta_{3\pi})$, $\eta' \to \eta_{\gamma\gamma}\pi^+\pi^-(\eta'_{\eta\pi\pi})$, and $\eta' \to \rho^0\gamma(\eta'_{\rho\gamma})$, where $\rho^0 \to \pi^+\pi^-$. Here we require the laboratory energy of the photons to be greater than 50 MeV (200 MeV for $\eta'_{\rho\gamma}$). We impose the following requirements on the invariant mass in MeV$/c^2$ of these particles' final states: $120 < m(\gamma\gamma) < 150$ for π^0, $490 < m(\gamma\gamma) < 600$ for $\eta_{\gamma\gamma}$, $520 < m(\pi^+\pi^-\pi^0) < 570$ for $\eta_{3\pi}$, $930 < m(\pi^+\pi^-\eta) < 990$ for $\eta'_{\eta\pi\pi}$, $910 < m(\pi^+\pi^-\gamma) < 1000$ for $\eta'_{\rho\gamma}$, and $510 < m(\pi^+\pi^-) < 1000$ for ρ^0. For the η' and η these requirements are sufficiently loose as to include sidebands, since these observables are used in the maximum-likelihood (ML) fit described below. Secondary pions in η' and η candidates are rejected if their DIRC and dE/dx signatures satisfy tight requirements for being consistent with protons, kaons, or electrons.

Neutral K candidates are formed from pairs of oppositely-charged tracks with a vertex χ^2 probability larger than 0.001, $486 < m(\pi^+\pi^-) < 510\ \mathrm{MeV}/c^2$ and a reconstructed decay length greater than 3 times its uncertainty. We require the momentum of the η or η' in the $\Upsilon(4S)$ frame to be greater than $0.9\ \mathrm{GeV}/c$ ($0.6\ \mathrm{GeV}/c$ in modes with $\eta'_{\eta\pi\pi}$). The invariant mass of ηK and $\eta' K$ systems is required to be less than $3.25\ \mathrm{GeV}/c^2$. In $\eta' K\gamma$ final states, we suppress background from the decay $J/\psi K$, with $J/\psi \to \eta'\gamma$ by applying a veto on the reconstructed $\eta'\gamma$ invariant mass. Defining the helicity frame for a meson as its rest frame with polar axis along the direction of the boost from the parent rest frame, and the decay angle θ_{dec} as the polar angle of a daughter momentum in this helicity frame, we require for the $\eta'_{\rho\gamma}$ decays $|\cos\theta^{\rho}_{\mathrm{dec}}| < 0.9$, and for $\eta_{\gamma\gamma}$ decays $|\cos\theta^{\eta}_{\mathrm{dec}}| < 0.9$, to suppress combinatorial background.

A B meson candidate is reconstructed by combining an η or η' 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 $\Upsilon(4S)$ frame.

Background arises primarily from random track combinations in $e^+e^- \to q\bar{q}$ events. We reduce this background by using the angle θ_T between the thrust axis of the B candidate in the $\Upsilon(4S)$ frame and the thrust axis of the rest of the event. The distribution of $|\cos\theta_T|$ is sharply peaked near 1 for combinations drawn from jetlike $q\bar{q}$ events, and is nearly uniform for $B\bar{B}$ events. We require $|\cos\theta_T| < 0.9$. Furthermore events should contain at least the number of charged tracks in the candidate decay mode plus one. For $\eta_{\gamma\gamma}K^+\gamma$ we require at least 3 charged tracks in the event. The mean number of B candidates per event is in the range 1.09–1.25, depending on the decay mode. If an event has multiple B candidates, we select the candidate with the highest B vertex χ^2 probability, determined from a vertex fit that includes both charged and neutral particles.

We estimate $B\bar{B}$ backgrounds using simulated samples of B decays [20]. Signal and inclusive $b \to s\gamma$ events are simulated according to the Kagan-Neubert model [21]. The $B\bar{B}$ background is completely dominated by radiative B decays. Branching fractions in the simulation are based on measured values, where available [9].

We obtain signal event yields separately for each decay mode from unbinned extended maximum-likelihood fits. The principal input observables are ΔE, m_{ES} and a Fisher discriminant $\mathcal{F}$. Where relevant, the invariant masses m_{res} of the intermediate η and η' resonances and $|\cos\theta^{\rho}_{\mathrm{dec}}|$ are also used. The Fisher discriminant $\mathcal{F}$ combines four variables: the angles with respect to the beam axis of the B momentum and the thrust axis of the B decay products (in the $\Upsilon(4S)$ frame), and the zeroth and second angular moments $L_{0,2}$ of the energy flow about the B thrust axis. The moments are defined by $L_j = \sum_i p_i \times |\cos\theta_i|^j$, where θ_i is the angle with respect to the B thrust axis of track or neutral cluster i, p_i is its momentum, and the sum excludes the B candidate daughters.

For each event i and hypothesis j (signal, continuum or $B\bar{B}$ background), the likelihood function is

$$\mathcal{L} = e^{-(\sum n_j)} \prod_{i=1}^{N} \left[\sum_{j=1}^{3} n_j \mathcal{P}_j(\mathbf{x}_i) \right], \qquad (1)$$

where N is the number of input events, n_j is the number of events for hypothesis j and $\mathcal{P}_j(\mathbf{x}_i)$ is the corresponding probability density function (PDF), evaluated with the observables $\mathbf{x}_i$ of the ith event. Since correlations among the observables are small (2–5%), we take each $\mathcal{P}$ as the product of the PDFs for the separate variables. We determine the PDF parameters from Monte Carlo simulation for the signal and $B\bar{B}$ background, while using sideband data ($5.25 < m_{\mathrm{ES}} < 5.27\ \mathrm{GeV}/c^2$; $0.1 < |\Delta E| < 0.2\ \mathrm{GeV}$) to model the PDFs of continuum background. We parameterize each of the functions $\mathcal{P}_{\mathrm{sig}}(m_{\mathrm{ES}})$, $\mathcal{P}_{\mathrm{sig}}(\Delta E)$, $\mathcal{P}_j(\mathcal{F})$, and the components of $\mathcal{P}_j(m_{\mathrm{res}})$ that peak in m_{ES} with either a Gaussian, the sum of two Gaussian distributions, or an asymmetric Gaussian function, as required, to describe the distribution. Distributions of ΔE for $B\bar{B}$ and continuum background and $|\cos\theta^{\rho}_{\mathrm{dec}}|$ are represented by linear or quadratic functions. The $B\bar{B}$ and continuum background in m_{ES} is described by the ARGUS function $x\sqrt{1 - x^2}\exp[-\xi(1 - x^2)]$, with $x \equiv 2m_{\mathrm{ES}}/\sqrt{s}$ and a parameter ξ [22]. We allow continuum background PDF parameters to vary in the fit.

Large control samples of B decays to charmed final states of similar topology and a smearing procedure applied to photons during the event resonstruction are used to verify the simulated resolutions in m_{ES} and ΔE. Where the control data samples reveal differences from the Monte Carlo (MC) in mass resolution, we shift or scale the resolution used in the likelihood fits. The largest shift in m_{ES} is $0.8\ \mathrm{MeV}/c^2$. Any bias in the fit, which arises mainly from neglecting the small correlations among the discriminating variables, is determined from a large set of simulated experiments in which the $q\bar{q}$ background is generated from the PDFs, and into which we have embedded the expected number of $B\bar{B}$ background and signal events chosen randomly from fully simulated Monte Carlo samples.

In Table I we show the number of events in the sample, the fitted signal yield and measured bias, the efficiency, and the product of daughter branching fractions for each decay

TABLE I. Number of events N in the sample, fitted signal yield and measured fit bias in events, detection efficiency ϵ, daughter branching fraction product $\prod \mathcal{B}_i$, significance $\mathcal{S}(\sigma)$ (including systematic uncertainties), measured branching fraction $\mathcal{B}$ with statistical error for each decay mode. For the combined measurements we give the significance (with systematic uncertainties included) and the branching fraction with statistical and systematic uncertainty (in parentheses the 90% CL upper limit). For the $\eta K^+\gamma$ mode we also list the measured signal charge asymmetry $\mathcal{A}_{\rm ch}$.

Mode	N	Yield	Bias	ϵ (%)	$\prod \mathcal{B}_i$ (%)	$\mathcal{S}$ (σ)	$\mathcal{B}(10^{-6})$	$\mathcal{A}_{\rm ch}$ (10^{-2})
$\eta_{3\pi}K^0\gamma$	786	40^{+13}_{-12}	+4	10.2	13.6	4.6	$11.2^{+4.0}_{-3.7}$	
$\eta_{3\pi}K^0\gamma$	310	15^{+8}_{-7}	+1	7.0	7.8	2.9	$11.5^{+6.1}_{-5.3}$	
$\boldsymbol{\eta K^0\gamma}$						**5.3**	$\mathbf{11.3^{+2.8}_{-2.6} \pm 0.6}$	
$\eta_{\gamma\gamma}K^+\gamma$	2391	119^{+22}_{-21}	+9	12.9	39.4	8.0	$9.4^{+1.8}_{-1.7}$	-1.3 ± 15.3
$\eta_{3\pi}K^+\gamma$	1108	55^{+14}_{-13}	+2	8.8	22.6	6.6	$11.4^{+3.0}_{-2.8}$	-21.9 ± 20.5
$\boldsymbol{\eta K^+\gamma}$						**10.0**	$\mathbf{10.0 \pm 1.3 \pm 0.5}$	$\mathbf{-8.6 \pm 12.0 \pm 1.0}$
$\eta'_{\eta\pi\pi}K^0\gamma$	119	-5^{+2}_{-2}	−6	6.2	6.0	0.4	$0.6^{+2.8}_{-2.0}$	
$\eta'_{\rho\gamma}K^0\gamma$	2464	19^{+16}_{-14}	+5	5.3	10.2	10.2	$11.2^{+12.8}_{-11.0}$	
$\boldsymbol{\eta' K^0\gamma}$						**0.6**	$\mathbf{1.1^{+2.8}_{-2.0} \pm 0.1}$ ($\mathbf{< 6.6}$)	
$\eta'_{\eta\pi\pi}K^+\gamma$	401	7^{+6}_{-5}	+1	8.2	17.5	1.6	$1.9^{+1.8}_{-1.4}$	
$\eta'_{\rho\gamma}K^+\gamma$	8792	17^{+27}_{-24}	+7	9.9	29.5	0.5	$1.5^{+3.9}_{-3.6}$	
$\boldsymbol{\eta' K^+\gamma}$						**1.7**	$\mathbf{1.9^{+1.5}_{-1.2} \pm 0.1}$ ($\mathbf{< 4.2}$)	

mode. The efficiency is calculated as the ratio of the number of signal MC events entering into 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, assuming equal production rates of charged and neutral B pairs. The corrected signal yield is the fitted yield minus the fit bias. We combine results from different channels by combining their likelihood functions, taking into account the correlated and uncorrelated systematic errors. We report the statistical significance and branching fraction for the individual decay channel; for combined measurements having a significance smaller than 5σ, we also report the 90% confidence level (CL) upper limit.

The statistical error on the signal yield is taken as the change in the central value when the quantity $-2\ln\mathcal{L}$ increases by one unit from its minimum value. The significance is the square root of the difference between the value of $-2\ln\mathcal{L}$ (with systematic uncertainties included) for zero signal and the value at its minimum. The 90% CL upper limit is taken to be the branching fraction below which lies 90% of the total likelihood integral in the positive branching fraction region.

The measured charge asymmetry in the decay $B^+ \to \eta K^+\gamma$ is corrected for an estimated bias of -0.005, determined from studies of signal Monte Carlo events and data control samples and from calculation of the asymmetry due to particles interacting in the detector. The result is $\mathcal{A}_{\rm ch} = -0.09 \pm 0.12 \pm 0.01$ with an asymmetry interval $[-0.282, 0.113]$ at 90% CL.

Figure 1 shows, as representative fits, the projections onto $m_{\rm ES}$ and ΔE for the decays $\eta K^+\gamma$, $\eta K^0\gamma$, $\eta' K^+\gamma$ and $\eta' K^0\gamma$ for a subset of the data for which the signal likelihood (computed without using the variable plotted) exceeds a mode-dependent threshold that optimizes the sensitivity.

Figure 2 shows the distribution of the ηK invariant mass for signal events obtained by the event-weighting technique (sPlot) described in Ref. [23]. We use the covariance matrix and PDFs from the ML fit to determine a probability for each signal event. The resulting distributions (points with errors) are normalized to the signal yield. This mass

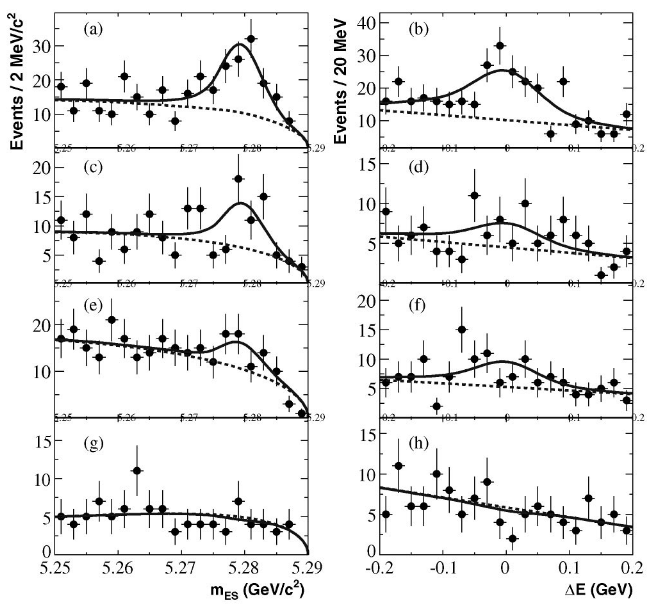

FIG. 1. The B candidate $m_{\rm ES}$ and ΔE projections for $\eta K^+\gamma$ (a), (b), $\eta K^0\gamma$ (c), (d), $\eta' K^+\gamma$ (e), (f) and $\eta' K^0\gamma$ (g), (h). Points with error bars (statistical only) represent the data, the solid line the full fit function, and the dashed line its background component.

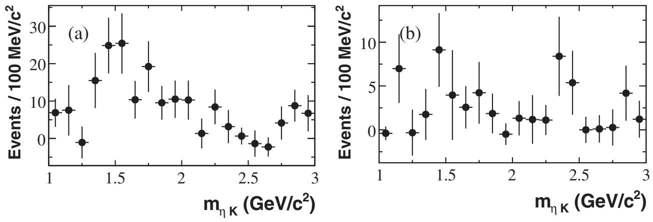

FIG. 2. Plot of ηK invariant mass for signal using the weighting technique described in the text for the combined subdecay modes: (a) charged modes, (b) neutral modes. Errors are statistical only.

distribution is useful to compare with theoretical predictions for radiative decays.

The main sources of systematic error 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 1–2 events, depending on the mode. The uncertainty from fit bias is taken as half the correction itself (1–3 events). Systematic uncertainties due to lack of knowledge of the primary photon spectrum are estimated to be in the range 2–6% depending on the decay mode. Uncertainties in our knowledge of the efficiency, found from auxiliary studies [19], include $0.8\% \times N_t$ and $1.5\% \times N_\gamma$, where N_t and N_γ 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_S^0 reconstruction. The uncertainty in the total number of $B\bar{B}$ pairs in the data sample is 1.1%. Published data [9] provide the uncertainties in the B daughter product branching fractions (0.7–3.4%). The uncertainty of 0.010 on the estimated bias correction is assigned as a systematic uncertainty to $\mathcal{A}_{\rm ch}$.

In conclusion, we have measured the central values and 90% CL upper limits in units of 10^{-6} for the branching fractions: $\mathcal{B}(B^0 \to \eta K^0 \gamma) = 11.3^{+2.8}_{-2.6} \pm 0.6$, $\mathcal{B}(B^+ \to \eta K^+ \gamma) = 10.0 \pm 1.3 \pm 0.5$, $\mathcal{B}(B^0 \to \eta' K^0 \gamma) = 1.1^{+2.8}_{-2.0} \pm 0.1 (<6.6)$, $\mathcal{B}(B^+ \to \eta' K^+ \gamma) = 1.9^{+1.5}_{-1.2} \pm 0.1 (<4.2)$. The measured branching fractions of the decay modes $B^+ \to \eta K^+ \gamma$ and $B^0 \to \eta K^0 \gamma$ are in good agreement with the values reported by the Belle Collaboration [8]. The decay mode $B^0 \to \eta K^0 \gamma$ is observed for the first time with greater than 5σ significance. We do not find evidence of the decays $B^0 \to \eta' K^0 \gamma$ and $B^+ \to \eta' K^+ \gamma$. We conclude that no mixing-induced *CP* study is feasible in these radiative B decays with the currently available data sample. The $B \to \eta' K \gamma$ decays may be suppressed with respect to $B \to \eta K \gamma$ decays due to destructive interference between two penguin amplitudes. This effect has been observed in B decays to $\eta' K$ and ηK, for which the branching fraction of the former is enhanced with respect to that of the latter [15]. We have also measured the charge asymmetry in the decay $B^+ \to \eta K^+ \gamma$ to be $\mathcal{A}_{\rm ch} = -0.09 \pm 0.12 \pm 0.01$, consistent with zero. The $\mathcal{A}_{\rm ch}$ interval at 90% CL is $[-0.28, 0.11]$.

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