Observation of $B^+ \to K^+ \eta \gamma$

Belle Collaboration

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Abstract

We report measurements of radiative B decays with $K\eta\gamma$ final states, using a data sample of 253 fb^{-1} recorded at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB e^+e^- storage ring. We observe $B^+ \to K^+\eta\gamma$ for the first time with a branching fraction of $(8.4 \pm 1.5(\text{stat})^{+1.2}_{-0.9}(\text{syst})) \times 10^{-6}$ for $M_{K\eta} < 2.4$ GeV/c^2, and find evidence of $B^0 \to K^0\eta\gamma$. We also search for $B \to K_3^*(1780)\gamma$.

Radiative B decays, which proceed mainly through the $b \to s\gamma$ process,[2] have played an important role in a search for physics beyond the Standard Model (SM). Although the inclusive branching fraction has been measured to be $(3.3 \pm 0.4) \times 10^{-4}$ [1], we know little about its constituents. So far, measured exclusive final states such as $K^*(892)\gamma$ [2,3], $K_2^*(1430)\gamma$ [2,4], $K\pi\pi\gamma$ [4] and $K\phi\gamma$ [5] only explain one third of the inclusive rate. Detailed knowledge of exclusive final states reduces the theoretical uncertainty in the measurement of the inclusive $B \to X_s\gamma$ branching fraction using the pseudo-reconstruction technique, as well as in the measurement of $B \to X_s\ell^+\ell^-$ [6]. In this analysis, the decay mode $B \to K\eta\gamma$ is studied for the first time. In addition to improving the understanding of $b \to s\gamma$ final states, $B^0 \to K_S^0\eta\gamma$ can be used to study time-dependent CP asymmetry [7], which is sensitive to physics beyond the SM. The mode $B \to K\eta\gamma$ can also be used to search for radiative B decays through possible $K\eta$ resonances, e.g., $K_3^*(1780)$ observed by the LASS experiment [8].

The analysis is based on 253 fb^{-1} of data taken at the $\Upsilon(4S)$ resonance (on-resonance) and 28 fb^{-1} at an energy 60 MeV below the resonance (off-resonance), which were recorded by the Belle detector [9] at the KEKB asymmetric e^+e^- collider

(3.5 GeV on 8 GeV) [10]. The on-resonance data corresponds to 275 million $B\bar{B}$ events. The Belle detector is comprised of a silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel Čerenkov counters (ACC), time-of-flight scintillation counters (TOF) and an electromagnetic calorimeter of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An instrumented iron flux-return for K_L^0/μ detection is located outside the coil. Two different inner detector configurations were used. For the first sample of 152 million $B\bar{B}$ pairs, a 2.0 cm radius beampipe and a 3-layer silicon vertex detector were used; for the latter 123 million $B\bar{B}$ pairs, a 1.5 cm radius beampipe, a 4-layer silicon detector and a small-cell inner drift chamber were used [11].

We reconstruct $B^+ \to K^+\eta\gamma$ and $B^0 \to K_S^0\eta\gamma$ via $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$. All charged tracks used in the reconstruction (except charged pions from K_S^0) are required to have a center-of-mass (CM) momentum greater than 100 MeV/c and to have an impact parameter within ± 5 cm of the interaction point along the positron beam axis and within 0.5 cm in the transverse plane. In order to identify kaon and pion candidates, we use a likelihood ratio based on the light yield in the ACC, TOF information and specific ionization measurements in the CDC. For the requirement applied on the likelihood ratio, we obtain an efficiency (pion misidentification probability) of 90% (10%) for charged kaon candidates, and an efficiency

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[2] Throughout this Letter, the inclusion of the charge conjugate mode is implied unless otherwise stated.

(kaon misidentification probability) of 98% (10%) for charged pion candidates. Tracks identified as electrons are excluded.

K_S^0 candidates are formed from $\pi^+\pi^-$ combinations with invariant mass within 8 MeV/c^2 ($\sim 2\sigma$) of the nominal K_S^0 mass. The two pions are required to have a common vertex displaced from the interaction point. The K_S^0 momentum direction is required to be consistent with the K_S^0 flight direction. Neutral pion candidates are formed from pairs of photons that have an invariant mass within 16 MeV/c^2 ($\sim 3\sigma$) of the nominal π^0 mass and a momentum greater than 100 MeV/c in the CM frame. Each photon is required to have an energy greater than 50 MeV in the laboratory frame. A mass-constrained fit is then performed to obtain the π^0 momentum.

For $\eta \to \gamma\gamma$ reconstruction, we require that the invariant mass of the two photons satisfy $0.515 < M_{\gamma\gamma} < 0.570$ GeV/c^2 and that each photon have an energy greater than 50 MeV in the laboratory frame. We also require $|\cos\theta_{\text{hel}}^\eta| < 0.9$, where θ_{hel}^η is the angle between the photon momentum and η boost direction from the laboratory frame in the η rest frame. A mass-constrained fit is then performed to obtain the η momentum. For $\eta \to \pi^+\pi^-\pi^0$, we apply a requirement on the three-pion invariant mass, $0.532 < M_{\pi^+\pi^-\pi^0} < 0.562$ GeV/c^2.

We reconstruct B meson candidates from an η, a charged or neutral kaon and the highest energy photon within the acceptance of the barrel ECL ($33° < \theta_\gamma < 128°$, where θ_γ is the polar angle of the photon with respect to the electron beam in the laboratory frame). Here, the invariant mass of the $K\eta$ system is required to be less than 2.4 GeV/c^2. This selection corresponds to $E_\gamma^{(B)} > 2.1$ GeV, where $E_\gamma^{(B)}$ is the photon energy in the B rest frame, and includes 84% of events from the $b \to s\gamma$ process. The highest energy photon candidate is required to be consistent with an isolated electromagnetic shower, i.e., 95% of the energy in an array of 5×5 crystals should be concentrated in an array of 3×3 crystals and no charged tracks should be associated with it. In order to reduce the background from decays of π^0 and η mesons, we combine the photon candidate with each of the other photons that have CM energy greater than 30 MeV (200 MeV) in the event and reject the event if the invariant mass of any pair is within 18 MeV/c^2 (32 MeV/c^2) of the nomi-

nal π^0 (η) mass. This condition is referred to as the π^0/η veto.

We use two independent kinematic variables for the B reconstruction: the beam-energy constrained mass $M_{\text{bc}} \equiv \sqrt{(E_{\text{beam}}^*/c^2)^2 - (|\vec{p}_{K\eta}^* + \vec{p}_\gamma^*|/c)^2}$ and $\Delta E \equiv E_{K\eta}^* + E_\gamma^* - E_{\text{beam}}^*$, where E_{beam}^* is the beam energy, and $\vec{p}_\gamma^*$, E_γ^*, $\vec{p}_{K\eta}^*$, $E_{K\eta}^*$ are the momenta and energies of the photon and the $K\eta$ system, respectively, calculated in the CM frame. In the M_{bc} calculation, the photon momentum is rescaled so that $|\vec{p}_\gamma^*| = (E_{\text{beam}}^* - E_{K\eta}^*)/c$ is satisfied. We require $M_{\text{bc}} > 5.2$ GeV/c^2 and $-150 < \Delta E < 80$ MeV. We define the B signal region to be $M_{\text{bc}} > 5.27$ GeV/c^2. In the case that multiple candidates are found in the same event, we take the candidate that has the η mass closest to the nominal mass[3] after applying the background suppression described later.

The largest source of background originates from continuum $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) production including contributions from initial state radiation ($e^+e^- \to q\bar{q}\gamma$). In order to suppress this background, we use the likelihood ratio (LR) described in Ref. [4], which utilizes the information from a Fisher discriminant [12] formed from six modified Fox–Wolfram moments [13] and the cosine of the angle between the B meson flight direction and the beam axis. The LR requirement retains 44% of the signal, while rejecting 98% of the continuum background.

In order to extract the signal yield, we perform a binned likelihood fit to the M_{bc} distribution. The M_{bc} distribution of the signal component is modeled by a Crystal Ball line shape [14], with the parameters determined from the signal Monte Carlo (MC) and calibrated using control samples of $B^+ \to \bar{D}^0(\to K^+\pi^-\pi^0)\pi^+$ and $B^0 \to D^-(\to K_S^0\pi^-\pi^0)\pi^+$ decays. The M_{bc} distribution of the continuum background is modeled by an ARGUS function [15] whose shape is determined from the off-resonance data. Here, the LR requirement is not applied to the off-resonance data in order to compensate for the limited amount of data in that sample. The possible bias due to this is taken as systematic error on the fitted yield. Background from hadronic B decays is divided into two

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[3] In case multiple candidates share such an η candidate, the candidate with the smallest $|\Delta E|$ is chosen.
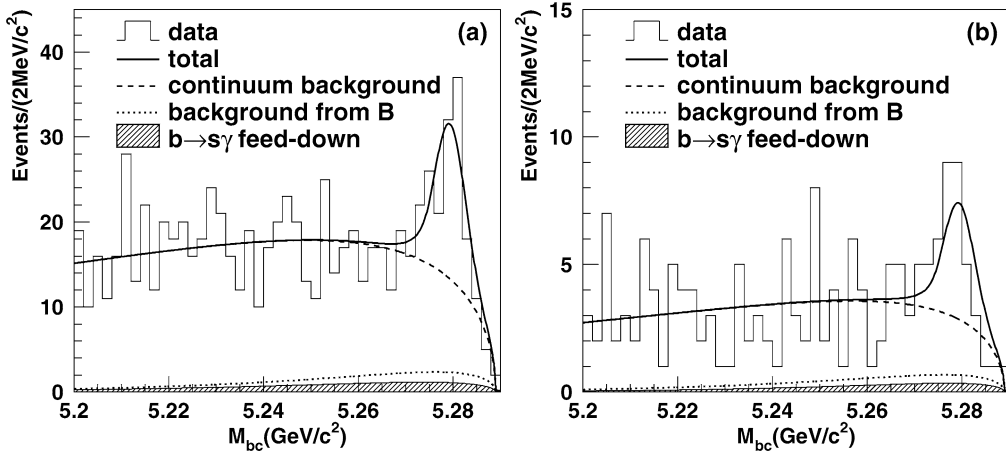
Fig. 1. M_{bc} distributions for (a) $B^+ \to K^+ \eta \gamma$, (b) $B^0 \to K_S^0 \eta \gamma$. Fit results are overlaid.

components, which we refer to as generic $B\bar{B}$ background and rare B background in this Letter. The former comprises B decays through $b \to c$ transitions including color-suppressed B decays such as $B^0 \to \bar{D}^0 \pi^0$, and the latter covers charmless B decays. Each of them is modeled by another ARGUS function. The shape of these distributions is determined using corresponding MC samples. In order to study the contamination from other $b \to s\gamma$ decays, we examine a $B \to K^*(892)\gamma$ MC sample and an inclusive $b \to s\gamma$ MC sample that is modeled as an equal mixture of $s\bar{d}$ and $s\bar{u}$ quark pairs and is hadronized using JETSET [16], where the X_s mass spectrum is fitted to the model of Kagan and Neubert [17]. We find that feed-down from other $b \to s\gamma$ decays is small, but not negligible, and model its M_{bc} distribution with an ARGUS function.

Fig. 1 shows the M_{bc} distributions for $B^+ \to K^+ \eta \gamma$ and $B^0 \to K_S^0 \eta \gamma$, respectively. These distributions, as well as the distribution for the combined mode, are fitted to the sum of signal, continuum, generic $B\bar{B}$, rare B background and $b \to s\gamma$ feed-down components. In the fit, the normalization of generic $B\bar{B}$, rare B and $b \to s\gamma$ are fixed according to the luminosity and $b \to s\gamma$ branching fraction, while the normalization of the continuum component is allowed to float. We find signal yields of 81 ± 14, $20.9^{+7.3}_{-6.5}$ and 102 ± 16 events with statistical significances of 7.1σ, 3.7σ and 8.1σ, for the charged, neutral and combined modes, respectively. Here, the significance is defined as $\sqrt{-2\ln(\mathcal{L}(0)/\mathcal{L}_{max})}$, where $\mathcal{L}_{max}$
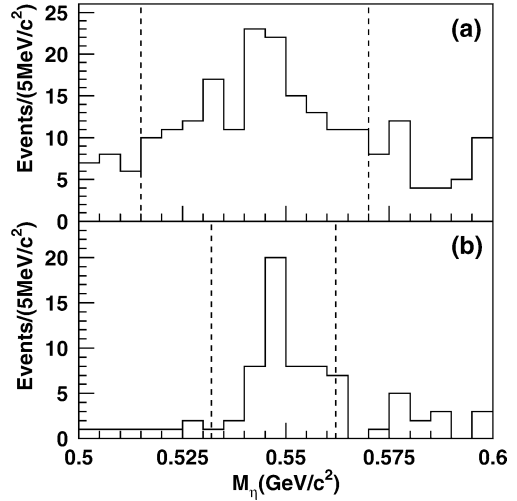

Fig. 2. η invariant mass distributions for (a) $\eta \to \gamma\gamma$ and (b) $\eta \to \pi^+\pi^-\pi^0$ inside the B signal region for combined $B \to K\eta\gamma$. Dashed lines show the selection applied in the analysis.

and $\mathcal{L}(0)$ are the maximum values of the likelihood when the signal yield is left free or fixed to zero, respectively.

Fig. 2 shows the $\gamma\gamma$ and $\pi^+\pi^-\pi^0$ invariant mass distributions for events inside the B signal region. Here, we do not apply the best candidate selection. We observe clear peaks at the nominal η mass. The $K\eta$ invariant mass distribution for events inside the B signal region is shown in Fig. 3. Here, the background distributions are obtained from the off-resonance data without the LR requirement or from the corresponding
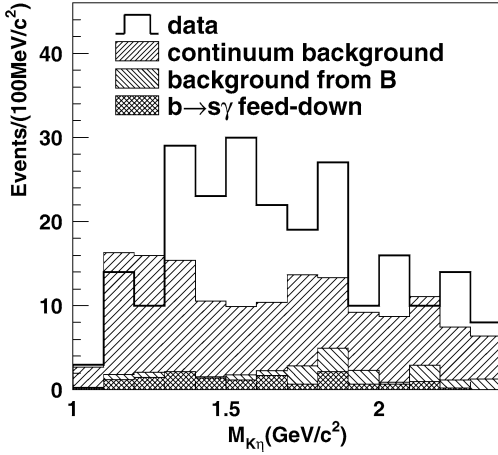
Fig. 3. $K\eta$ invariant mass distribution for events inside the B signal region for combined $B \to K\eta\gamma$.

Table 1

Measured signal yields, efficiencies, branching fractions ($\mathcal{B}$) and significances including systematic error ($\mathcal{S}$) for $B \to K\eta\gamma$. The first and second errors are statistical and systematic, respectively. Efficiencies include the sub-decay branching fractions

Mode	Yield	Efficiency (%)	$\mathcal{B}\,(\times 10^{-6})$	$\mathcal{S}$
$B^+ \to K^+\eta\gamma$	$81 \pm 14^{+10}_{-6}$	3.50 ± 0.27	$8.4 \pm 1.5^{+1.2}_{-0.9}$	6.8
$B^0 \to K^0\eta\gamma$	$20.9^{+7.3}_{-6.5}{}^{+4.2}_{-3.2}$	0.87 ± 0.08	$8.7^{+3.1}_{-2.7}{}^{+1.9}_{-1.6}$	3.4
$B \to K\eta\gamma$	$102 \pm 16^{+13}_{-8}$	4.37 ± 0.31	$8.5 \pm 1.3^{+1.2}_{-0.9}$	7.7

MC samples, and are normalized using the fit result. We find that the signal is concentrated between 1.3 and 1.9 GeV/c^2 and is falling above 1.9 GeV/c^2. Therefore, our requirement $M_{K\eta} < 2.4$ GeV/c^2 is expected to include most of the $B \to K\eta\gamma$ signal. We do not see any clear resonant structure in the $M_{K\eta}$ distribution.

The systematic error on the signal yield due to the fitting procedure is estimated by varying the value of each fixed parameter by $\pm 1\sigma$ and extracting the new signal yield for each case. The difference between the background shape for the continuum MC with and without the LR requirement is taken as an additional error to the continuum background shape. We set the normalization of either the generic $B\bar{B}$ or rare B backgrounds to zero and to twice its nominal value to account for its uncertainty. The changes of the yields for each procedure are added in quadrature, and are regarded as the systematic error on the signal yield. We also calculate a statistical significance for each case, and regard the smallest value as the significance including the systematic error. The result is listed in Table 1.

The signal reconstruction efficiency is estimated using the MC simulation and is corrected for discrepancies between data and MC using control samples. The signal MC has uniform $K\eta$ invariant mass and $\cos\theta_{hel}$ distributions, where θ_{hel} is the decay helicity angle between the kaon momentum and opposite to B momentum in the $K\eta$ rest frame. We find that the efficiency is almost independent of the $K\eta$ invariant

mass and $\cos\theta_{hel}$. Table 1 shows the signal efficiencies and the branching fractions for each $B \to K\eta\gamma$ mode. Here, we assume an equal production rate for $B^0\bar{B}^0$ and B^+B^-. The error on the branching fraction includes the following systematic uncertainties: photon detection (2.8%), tracking (1.0% to 1.2% per track), kaon identification (0.8%), pion identification (0.5% per pion), K^0_S detection (4.5%), π^0 detection (1.5%), η detection in $\eta \to \gamma\gamma$ mode (2.0%), π^0/η veto and LR (5.9% and 4.4% for charged and neutral modes, respectively), possible $K\eta$ mass dependence of the efficiency (2.1% and 4.4% for charged and neutral modes, respectively), possible $\cos\theta_{hel}$ dependence of the efficiency (2.5% and 3.4% for charged and neutral modes, respectively), uncertainty in the η branching fraction (0.7% for $\eta \to \gamma\gamma$ and 1.8% for $\eta \to \pi^+\pi^-\pi^0$), and uncertainty in the number of $B\bar{B}$ events (1.1%). The systematic errors from the π^0/η veto and LR requirement are estimated using control samples of $B^+ \to \bar{D}^0(\to K^+\pi^-\pi^0)\pi^+$ and $B^0 \to D^-(\to K^0_S\pi^-\pi^0)\pi^+$ decays, treating the primary pion as a high energy photon.

We search for the decay $B \to K^*_3(1780)\gamma$ by applying the additional requirements $1.60 < M_{K\eta} < 1.95$ GeV/c^2 and $|\cos\theta_{hel}| < 0.2$ or $|\cos\theta_{hel}| > 0.7$. The expected $\cos\theta_{hel}$ distribution for $B \to K^*_3(1780)\gamma$ is proportional to $1 - 11\cos^2\theta_{hel} + 35\cos^4\theta_{hel} - 25\cos^6\theta_{hel}$. The fits to the M_{bc} distributions yield $4.4^{+5.2}_{-4.5}{}^{+2.6}_{-2.4}$, $0.2^{+3.1}_{-2.4}{}^{+1.3}_{-1.4}$ and $5.2^{+5.9}_{-5.2}{}^{+3.5}_{-3.2}$ events for the charged, neutral and combined modes, respectively. Here and in the following, we quote statistical and systematic errors in the first and second position. The M_{bc} distribution and fit result for the combined mode is shown in Fig. 4. We provide only upper limits due to our inability to distinguish $B \to K^*_3(1780)\gamma$ from non-resonant decays. The 90% confidence level upper limit N is calcu-

Table 2
Measured signal yields, efficiencies and products of branching fractions of $B \to K_3^*(1780)\gamma$ and $K_3^*(1780) \to K\eta$ ($\mathcal{B} \times \mathcal{B}(K_3^* \to K\eta)$). Efficiencies include the sub-decay branching fractions of η and K^0, but not of $K_3^*(1780)$. Upper limits are calculated at the 90% confidence level and include systematics

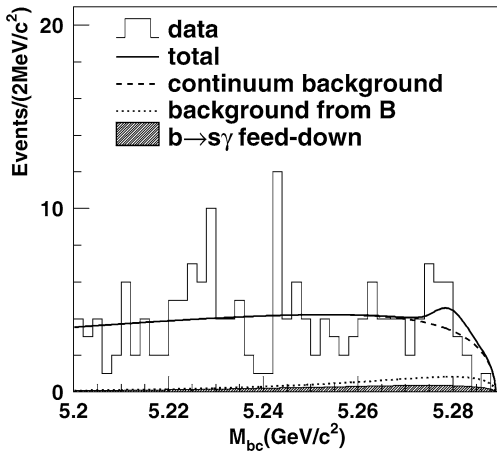| Mode	Yield	Efficiency (%)	$\mathcal{B} \times \mathcal{B}(K_3^* \to K\eta)$ ($\times 10^{-6}$)
$B^+ \to K_3^*(1780)^+\gamma$	< 15.0	2.03 ± 0.16	< 2.9
$B^0 \to K_3^*(1780)^0\gamma$	< 7.5	0.48 ± 0.05	< 6.4
$B \to K_3^*(1780)\gamma$	< 17.7	2.51 ± 0.18	< 2.8

Fig. 4. M_{bc} distribution for combined $B \to K\eta\gamma$ with the $B \to K_3^*(1780)\gamma$ selection. Fit results are overlaid.

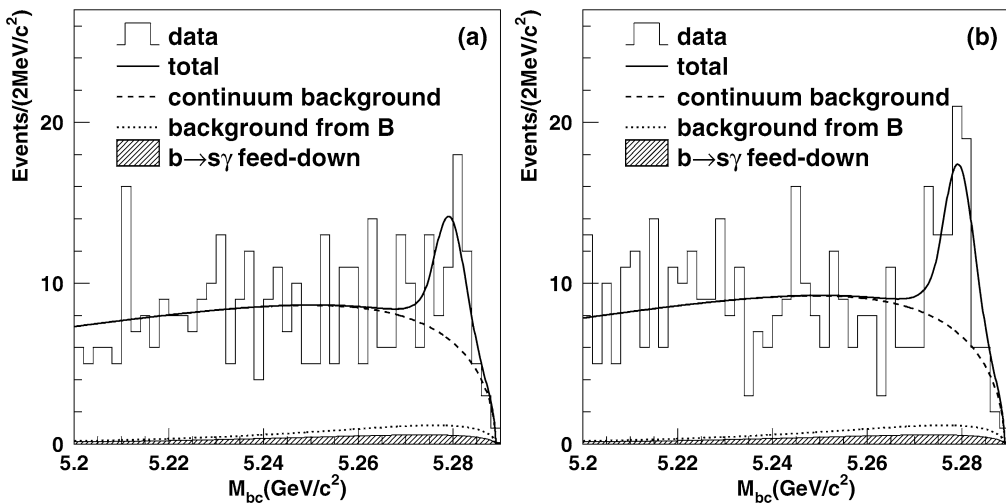lated from the relation $\int_0^N \mathcal{L}(n) \, dn = 0.9 \int_0^\infty \mathcal{L}(n) \, dn$, where $\mathcal{L}(n)$ is the maximum likelihood in the M_{bc} fit with the signal yield fixed at n. In order to include the systematic errors from the fitting procedure in the upper limit for the yield, the positive systematic error is added to N. The obtained yield upper limits, efficiencies and products of branching fractions $\mathcal{B}(B \to K_3^*(1780)\gamma) \times \mathcal{B}(K_3^*(1780) \to K\eta)$ are listed in Table 2. Here, the number of $B\bar{B}$ events and the reconstruction efficiency are lowered by 1σ when we calculate the upper limit for the branching fractions. If we assume $\mathcal{B}(K_3^*(1780) \to K\eta) = (11^{+5}_{-4})\%$ [18], the 90% confidence level limits correspond to $B \to K_3^*(1780)\gamma$ branching fractions of 3.9×10^{-5}, 8.3×10^{-5} and 3.7×10^{-5}, respectively for charged, neutral and combined modes, which substantially improve the limits set by the ARGUS Collaboration [19].

Some extensions of the SM predict a large CP asymmetry in the $b \to s\gamma$ process [20]. We measure the partial rate asymmetry $A_{CP} = (1/(1-2w))(N_- - N_+)/(N_- + N_+)$ for $B^+ \to K^+\eta\gamma$, where $N_\mp$ is the signal yield for $B^\mp \to K^\mp\eta\gamma$ and w is the probability that a signal event is reconstructed with the wrong kaon (and hence B) charge. This probability is found to be less than 1% in our signal MC sample, and hence we ignore its negligible effect on A_{CP}. $N_\mp$ is obtained by fitting separately the M_{bc} distributions for the negatively and positively charged modes shown in Fig. 5. We find $N_- = 34.0^{+9.8}_{-9.0}$ and $N_+ = 46.7^{+10.5}_{-9.8}$. The sys-

Fig. 5. M_{bc} distributions for (a) negative charged $B^- \to K^-\eta\gamma$, (b) positive charged $B^+ \to K^+\eta\gamma$. Fit results are overlaid.

tematic error on A_{CP} consists of the following contributions. The error from the fitting procedure is estimated to be 0.045 by varying each fixed parameter one by one, and extracting A_{CP} for each procedure, in the same way as before. Here, we assume no asymmetry for the generic $B\bar{B}$ background, but allow 100% asymmetry for the rare B and 6% asymmetry for $b \to s\gamma$ [21]. The error from the overall detector bias is studied with the $B^0 \to D^-(K^-\pi^+\pi^0)\pi^+$ control sample and is found to be 0.035. By adding these errors and the possible asymmetry in kaon identification (0.014) in quadrature, we obtain $A_{CP} = -0.16 \pm 0.09 \pm 0.06$.

In conclusion, we observe the decay mode $B^+ \to K^+\eta\gamma$ and find the first evidence of $B^0 \to K^0\eta\gamma$. The branching fraction and partial rate asymmetry of $B^+ \to K^+\eta\gamma$ are measured to be $(8.4 \pm 1.5^{+1.2}_{-0.9}) \times 10^{-6}$ and $-0.16 \pm 0.09 \pm 0.06$ for $M_{K\eta} < 2.4$ GeV/c^2. The branching fraction of $B^0 \to K^0\eta\gamma$ is measured to be $(8.7^{+3.1}_{-2.7}{}^{+1.9}_{-1.6}) \times 10^{-6}$. We also search for $B \to K_3^*(1780)\gamma$, but find no evidence. Although the signal yield for $B^0 \to K_S^0\eta\gamma$ is small, this mode can be used in the near future to study time-dependent CP asymmetries in radiative B decays and to search for new physics.

Acknowledgements

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