Measurements of Branching Fractions and CP Asymmetries in B → ηh Decays

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We report measurements of $B$ to pseudoscalar-pseudoscalar decays with at least one $\eta$ meson in the final state using 140 fb$^{-1}$ of data collected by the Belle detector at KEKB $e^+e^-$ collider. We observe the decay $B^+ \rightarrow \eta\pi^+$ and find evidence of $B^+ \rightarrow \eta K^+$; the measured branching fractions are $\mathcal{B}(B^+ \rightarrow \eta\pi^+) = (4.8^{+0.5}_{-0.3}(\text{stat}) \pm 0.3(\text{sys})) \times 10^{-6}$ and $\mathcal{B}(B^+ \rightarrow \eta K^+) = (2.1 \pm 0.6(\text{stat}) \pm 0.2(\text{sys})) \times 10^{-6}$. Their corresponding $CP$ violating asymmetries are measured to be $0.07 \pm 0.15(\text{stat}) \pm 0.03(\text{sys})$ for $\eta\pi^\pm$ and $-0.40 \pm 0.31(\text{stat}) \pm 0.07(\text{sys})$ for $\eta K^{\pm}$. No significant signals are found for neutral $B \rightarrow h\eta$ decays. We report the following upper limits on branching fractions at the 90% confidence level: $\mathcal{B}(B^0 \rightarrow \eta K^0) < 2.0 \times 10^{-6}$, $\mathcal{B}(B^0 \rightarrow \pi\pi^0) < 2.5 \times 10^{-6}$ and $\mathcal{B}(B^0 \rightarrow \eta\eta) < 2.0 \times 10^{-6}$.

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Charmless $B$ decays provide a rich sample to understand $B$ decay dynamics and to search for $CP$ violation. An unexpectedly large $B \rightarrow \eta'K$ branching fraction\cite{1,2} has stimulated much theoretical interest. It was suggested even before the $\eta'K$ measurement that two $b \rightarrow s$ penguin amplitudes are constructive in $B \rightarrow \eta'K$ decays but destructive in $B \rightarrow \eta K$ \cite{3}. The situation is reversed for $B \rightarrow \eta'K^*$ and $B \rightarrow \eta K^*$ decays. Experimental results have more or less confirmed this picture; however, precise measurements of branching fractions are needed to quantitatively understand the contribution of each diagram. It was also pointed out that in the $\eta K$ mode the suppressed penguin amplitudes may interfere with the CKM suppressed $b \rightarrow u$ (tree) amplitude and result in direct $CP$ violation \cite{4}. The penguin-tree interference may also be large in $B^+ \rightarrow \eta'\pi^+$ \cite{5} and $B^+ \rightarrow \eta\pi^+$ decays; however, theoretical expectations for the partial rate asymmetry ($A_{CP}$) can be either positive or negative \cite{4,5,6}. Recently, the BaBar Collaboration has reported large negative $A_{CP}$ values in both $\eta K^+$ and $\eta\pi^+$, which are $\sim 2\sigma$ away from zero \cite{7}. However, more data are needed to verify these large $CP$ violating asymmetries. Furthermore, branching fractions and partial rate asymmetries in charmless $B$ decays can be used to understand the tree and penguin contributions and provide constraints on the third unitarity triangle angle $\phi_2$ \cite{8}.

In this paper, we report measurements of branching fractions and partial rate asymmetries for $B \rightarrow h\eta$ decays, where $h$ could be a $K$, $\pi$ or $\eta$ meson. The partial rate asymmetry is measured for the charged $B$ decays and defined to be:

$$A_{CP} = \frac{N(B^- \rightarrow \eta h^-) - N(B^+ \rightarrow \eta h^+)}{N(B^- \rightarrow \eta h^-) + N(B^+ \rightarrow \eta h^+)}$$

where $N(B^-)$ is the yield for the $B^- \rightarrow \eta h^-$ decay and $N(B^+)$ denotes that of the charge conjugate mode. The data sample consists of 152 million $BB$ pairs (140 fb$^{-1}$) collected with the Belle detector at the KEKB $e^+e^-$ asymmetric-energy (3.5 on 8 GeV) collider\cite{10} operating at the $Y(4S)$ resonance.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K_L^0$ mesons and to identify muons (KLM). The detector is described in detail elsewhere\cite{11}.

Two $\eta$ decay channels are considered in this analysis: $\eta \rightarrow \gamma\gamma$ ($\eta_{\gamma\gamma}$) and $\eta \rightarrow \pi^+\pi^-\pi^0$ ($\eta_{\pi\pi}$). In the $\eta_{\gamma\gamma}$ reconstruction, each photon is required to have a minimum laboratory energy of 50 MeV and the energy asymmetry, defined as the absolute value of the energy difference in the laboratory frame between the two photons divided by their energy sum, must be less than 0.9. Furthermore, we remove $\eta$ candidates if either one of the daughter photons can pair with
any other photon to form a $\pi^0$ candidate. Candidate $\eta\pi$ mesons are reconstructed by combining a $\pi^0$ with a pair of oppositely charged tracks that originate from the interaction point (IP). We make the following requirements for the invariant mass on the $\eta$ candidates: $516 \text{ MeV}/c^2 < M_{\gamma\gamma} < 569 \text{ MeV}/c^2$ for $\eta\gamma\gamma$ and $539 \text{ MeV}/c^2 < M_{3\pi} < 556 \text{ MeV}/c^2$ for $\eta\pi\pi$. After the selection of each candidate, an $\eta$ mass constraint is implemented by readjusting the momenta of the daughter particles.

Candidate neutral pions are selected by requiring the two-photon invariant mass to be in the mass window between 115 MeV/$c^2$ and 152 MeV/$c^2$. The momentum of each photon is then readjusted to constrain the mass of the photon pair to be the nominal $\pi^0$ mass. To reduce the low energy photon background, each photon is required to have a minimum energy of 50 MeV and the $\pi^0$ momentum must be above 250 MeV/c in the laboratory frame. Charged tracks are required to come from the IP. Charged kaons and pions that form $B$ candidates with $\eta$ mesons are identified by combining information from the CDC ($dE/dx$), the TOF and the ACC to form a $K(\pi)$ likelihood $L_K(L_\eta)$. Discrimination between kaons and pions is achieved through the likelihood ratio $L_K/(L_\pi + L_K)$. Charged tracks with likelihood ratios greater than 0.6 are regarded as kaons, and less than 0.4 as pions. The typical kaon and pion identification efficiencies for 2.5 GeV/$c$ tracks are (85.0 ± 0.2)% and (89.3 ± 0.2)% respectively. With the same track momentum, the rate for pions to be misidentified as kaons is (7.3 ± 0.2)% while the rate for kaons to be misidentified as pions is (10.6 ± 0.2)%.

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the continuum PDF is the product of an ARGUS function and a polynomial, where \( \xi \) and the coefficients of the polynomial are free parameters. Since \( B \to \eta K^* \) branching fractions are well measured \( (\sim 20 \times 10^{-6}) \), their feed-down to the \( \eta K \) modes are fixed from MC in the likelihood fit. Since the decay \( B^+ \to \eta \rho^0 \) is experimentally poorly constrained, the amount of this background in the \( \eta \pi \) modes is allowed to float in the fit. In the charged \( B \) modes, the normalizations of the reflections are fixed to expectations based on the \( B^+ \to \eta K^+ \) and \( B^+ \to \eta \pi^+ \) branching fractions and \( K^+ \to \pi^+ \) fake rates, measured using \( D^0 \to K^+ \pi^- \) data. The reflecting yield is first estimated with the assumed \( \eta K^+ \) and \( \eta \pi^+ \) branching fractions and is then recalculated according to our measured branching fractions. No \( B\bar{B} \) contributions are included for the \( B^0 \to \eta \eta \) mode.

**TABLE I:** Detection efficiency \( (\epsilon) \), product of daughter branching fractions \( (\prod \mathcal{B_i}) \), yield, significance \( (\text{Sig.}) \), measured branching fraction \( (\mathcal{B}) \), the 90% C.L. upper limit \( (\text{UL}) \) and \( A_{CP} \) for the \( B \to \eta \rho \) decays. The first errors in columns 4 and 6 and 8 are statistical and the second errors are systematic.

| Mode          | \( \epsilon(\%) \) | \( \prod \mathcal{B_i}(\%) \) | Yield | Sig. | \( \mathcal{B}(10^{-6}) \) | \( \text{UL}(10^{-6}) \) | \( A_{CP} \) |
|---------------|---------------------|---------------------------------|-------|------|-----------------|-----------------|---------|
| \( B^+ \to \eta \pi^+ \) | 23.3                | 39.4                           | 73.4±13.5 | ±0.7 | ±0.3            | 0.07±0.15±0.03 |
| \( \eta_{\gamma \pi} \to \pi^+ \) | 14.8                | 22.6                           | 19.6±7.0 | ±0.7 | ±0.3            | -0.11±0.33±0.04 |
| \( B^+ \to \eta K^+ \) | 21.1                | 39.4                           | 28.0±10.0 | ±1.6 | ±0.2            | -0.49±0.31±0.07 |
| \( B^+ \to \eta \pi^0 \) | 13.8                | 22.6                           | 7.4±4.5  | ±0.5 | ±0.2            | -0.78±0.76±0.12 |
| \( B^0 \to \eta K^0 \) | 22.9                | 13.6                           | -1.9±4.3 | ±0.3 | ±0.1            | 1.8±0.7±0.1     |
| \( B^0 \to \eta K^0 \) | 12.2                | 7.8                            | 3.5±2.6  | ±0.2 | ±0.1            | 2.4±0.9±0.3     |
| \( B^0 \to \eta \eta \) | 17.0                | 39.0                           | 18.5±8.9 | ±0.8 | ±0.2            | 2.4±0.9±0.3     |
| \( B^0 \to \eta \eta \) | 11.2                | 22.3                           | -3.0±5.0 | ±0.3 | ±0.1            | -0.8±1.3±0.8    |
| \( B^0 \to \eta \eta \) | 16.9                | 15.5                           | -1.5±4.2 | ±0.1 | ±0.1            | 0.7±0.6±0.1     |
| \( B^0 \to \eta \eta \) | 11.3                | 17.8                           | 7.3±4.2  | ±0.2 | ±0.2            | 2.3±1.2±0.2     |
| \( B^0 \to \eta \eta \) | 7.7                 | 5.1                            | 0.3±2.0  | ±0.1 | ±0.1            | 0.5±3.1±0.1     |

In Table I we show the measured branching fractions for each decay mode as well as other quantities associated with the measurements. The efficiency for each mode is determined using MC simulation and corrected for the discrepancy between data and MC using the control samples. The only discrepancy we find is the performance of particle identification, which results in a 4.3% correction for the \( \eta \pi^+ \) mode and 1.7% for \( B \to \eta K^+ \). The combined branching fraction of the two \( \eta \) decay modes is obtained from a simultaneous likelihood fit to all the sub-samples with a common branching fraction. Systematic uncertainties in the fit due to the uncertainties in the signal PDFs are estimated by performing the fit after varying their peak positions and resolutions by one standard deviation. In the \( \eta K \) modes, we also vary the expected \( \eta K^+ \) feed-down by one standard deviation to check the yield difference. The quadratic sum of the deviations from the central value gives the systematic uncertainty in the fit, which ranges from 3% to 6%. For each systematic check, the statistical significance is taken as the square root of the difference between the value of \(-2\ln \mathcal{L}\) for zero signal yield and the best-fit value. We regard the smallest value as our significance incuding the systematic uncertainty. The number of \( B^+ B^- \) and \( B^0 \bar{B}^0 \) pairs are assumed to be equal.

The performance of the \( R \) requirement is studied by checking the data-MC efficiency ratio using the \( B^+ \to D^0 \pi^+ \) control sample. The obtained error is 2.4–3.5%. The systematic errors on the charged track reconstruction are estimated to be around 1% per track using partially reconstructed \( D^* \) events, and verified by comparing the ratio of \( \eta \to \pi^+ \pi^- \pi^0 \) to \( \eta \to \gamma \gamma \) in data with MC expectations. The \( \pi^0 \) and \( \eta \gamma \) reconstruction efficiency is verified by comparing the \( \pi^0 \) decay angular distribution with the MC prediction, and by measuring the ratio of the branching fractions for the two \( \eta \) decay channels: \( \eta \to \gamma \gamma \) and \( \eta \to \pi^0 \pi^0 \). We assign 3.5% error for the \( \pi^0 \) and \( \eta \gamma \) reconstruction. The \( K^0_S \) reconstruction is verified by comparing the ratio of \( D^+ \to K^0_S \pi^+ + \pi^- \) and \( D^+ \to K^- \pi^+ \pi^- \) yields. The resulting \( K^0_S \) detection systematic error is 4.4%. The uncertainty in the number of \( B \bar{B} \) events is 1%. The final systematic error is obtained by first summing all correlated errors linearly and then quadratically summing the uncorrelated errors.

Figure II shows the \( M_{bc} \) and \( \Delta E \) projections after requiring events to satisfy \(-0.10 \text{ GeV} < \Delta E < 0.08 \text{ GeV} \) \((-0.15 \text{ GeV} < \Delta E < 0.10 \text{ GeV} \) for the \( \eta \gamma \) and \( \eta \pi \) modes) and \( M_{bc} > 5.27 \text{ GeV}/c^2 \), respectively. No significant signals are observed for the neutral \( B \) meson modes; for these modes we set branching fraction upper limits at the 90% confidence.
FIG. 1: $M_{bc}$ and $\Delta E$ projections for (a,b) $B^+ \to \eta \pi^+$, (c,d) $B^+ \to \eta K^+$, (e,f) $B^0 \to \eta K^0$, (g,h) $B^0 \to \eta \pi^0$ and (i,j) $B^0 \to \eta \eta$ decays with the $\eta_{\gamma\gamma}$ and $\eta_{3\pi}$ modes combined. Open histograms are data, solid curves are the fit functions, dashed lines show the continuum contributions and shaded histograms are the $\eta K^*/\eta \rho$ contributions. The small contributions around $M_{bc} = 5.28$ GeV/$c^2$ and $\Delta E = \pm 0.05$ GeV in (a)-(d) are the backgrounds from $B^+ \to \eta K^+$ and $B^+ \to \eta \pi^+$. The upper limit for each mode is determined using the combined likelihood for the two $\eta$ decay channels with the reconstruction efficiency reduced by 1σ. We vary the signal PDF and the expected $\eta K^*$ feed-down in the $\eta K^0$ mode to compute the likelihood as a function of branching fraction; the largest branching fraction that covers 90% of the likelihood area is chosen to be the upper limit.

Significant signals are observed for charged $B$ decays. We investigate their partial rate asymmetries by extracting signal yields separately from the $B^+$ and $B^-$ samples. Unbinned maximum likelihood fits are performed independently for the two $\eta$ decay modes in order to reduce the systematic uncertainties. The same signal and background PDFs as used in the branching fraction measurement are applied. The parameters of the continuum PDF are fixed according to the branching fraction results. Contributions from $B\bar{B}$ backgrounds are required to be equal for the $B^+$ and $B^-$ samples. Figure 2 shows the $M_{bc}$ and $\Delta E$ projections. The $A_{CP}$ results for the two $\eta$ decay modes are combined assuming that the errors are Gaussian. Systematic errors due to uncertainties in the signal PDF are estimated by varying the peak positions and resolutions. We also check the $A_{CP}$ values after varying the amount of the expected $\eta K^*$ feed-down and the reflection background. The $B\bar{B}$ contributions are allowed to be different for the two samples to obtain the systematic error. The largest uncertainty is the asymmetry of the reflection. A possible detector bias in $A_{CP}$ is studied using $B \to D\pi^+$ decays. The obtained uncertainty is 0.5%. Each $A_{CP}$ deviation is added quadratically to provide the total systematic uncertainty.

In summary, we have observed $B^+ \to \eta \pi^+$ and found evidence for $B^+ \to \eta K^+$; the measured branching fractions and partial rate asymmetries are summarized in Table I. We conclude that the $B^+ \to \eta \pi^+$ branching fraction is larger than that of $B^+ \to \eta K^+$. The measured $B^+ \to \eta \pi^+$ branching fraction is consistent with an earlier result published by the BaBar Collaboration; however, unlike the large negative $A_{CP}$ measured by BaBar, the central value
in this analysis is small and positive, and is consistent with no asymmetry. For the decay \( B^+ \rightarrow \eta K^+ \), the measured branching fraction is 40\% lower than the published result of the BaBar experiment, corresponding to a 1.3 \( \sigma \) deviation. It is interesting to note that although the errors are still large, both experiments suggest a large negative \( A_{CP} \) value for \( B^+ \rightarrow \eta K^+ \), which is anticipated by some theories \[18\]. No significant signals are found in neutral \( B \rightarrow \eta h \) decays and upper limits at the 90\% confidence level are given.

![Graph](image)

**FIG. 2:** \( M_{bc} \) and \( \Delta E \) projections for (a,b) \( B^+ \rightarrow \eta \pi^+ \), (c,d) \( B^- \rightarrow \eta \pi^- \), (e,f) \( B^+ \rightarrow \eta K^+ \), and (g,h) \( B^- \rightarrow \eta K^- \) with the \( \eta_{\gamma\gamma} \) and \( \eta_{3\pi} \) modes combined. Open histograms are data, solid curves are the fit functions, dashed lines show the continuum contributions and shaded histograms are the \( \eta K^*/\eta \rho \) contributions. Small curves around \( M_{bc} = 5.28 \text{ GeV}/c^2 \) and \( \Delta E = \pm 0.05 \text{ GeV} \) are the reflection background on \( B^+ \rightarrow \eta \pi^+ \) and \( B^+ \rightarrow \eta K^+ \).

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