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Measurement of branching fractions for $B \to J/\psi\eta K$ decays and search for a narrow resonance in the $J/\psi\eta$ final state

Tomoko Iwashita[*†]
Department of Physics, Nara Women's University

We report an observation of the $B^{\pm} \to J/\psi\eta K^{\pm}$ and $B^0 \to J/\psi\eta K^0_S$ decays at Belle and corresponding branching fractions are obtained to be $\mathscr{B}(B^{\pm} \to J/\psi\eta K^{\pm}) = (1.27 \pm 0.11(\text{stat.}) \pm 0.11(\text{syst.})) \times 10^{-4}$ and $\mathscr{B}(B^0 \to J/\psi\eta K^0_S) = (5.22 \pm 0.78(\text{stat.}) \pm 0.49(\text{syst.})) \times 10^{-5}$. We search for a new narrow charmonium(-like) state X in the $J/\psi\eta$ mass spectrum and find no significant excess. We set upper limits on the product of branching fractions, $\mathscr{B}(B^{\pm} \to XK^{\pm})\mathscr{B}(X \to J/\psi\eta)$, at 3872 MeV/$c^2$ where a C-odd partner of $X(3872)$, denoted as $X^{C-\text{odd}}$, may exist, as well as $\psi(4040)$ and $\psi(4160)$ and over arange from 3.8 to 4.8 GeV/c^2. The obtained upper limits on the product of the branching fractions at 90% confidence level for $X^{C-\text{odd}}$ at 3872MeV/c^2, $\psi(4040)$ and $\psi(4160)$ are 3.8×10^{-6}, 15.5×10^{-6} and 7.4×10^{-6}, respectively.

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[*]Speaker.
[†]for the Belle collaboration

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The narrow charmonium-like resonance, $X(3872)$ were discovered in the $J/\psi\pi^+\pi^-$ final state by the Belle collaboration in 2003 [1]. It opened a new era in the spectroscopy of quarkonium-like exotic states [2]. The X(3872) is confirmed to be C-even because of its decay to $J/\psi\gamma$ [3, 4]. The studies of angular distributions of the decay products in the $X(3872) \to J/\psi\pi^+\pi^-$ mode by CDF [5] and Belle [6] as well as the 3π invariant mass spectrum in $J/\psi\pi^+\pi^-\pi^0$ mode by BaBar [7] restrict J^{PC} to be either 1^{++} and 2^{-+}. Finally, the LHCb collaboration performed a full five-dimensional amplitude analysis of the angles among the decay products in $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\pi^+\pi^-$ and consequently has unambiguously assigned $J^{PC} = 1^{++}$ to the $X(3872)$ [8].

It is also important to search for the missing C-odd partner of the $X(3872)$ denoted as $X^{C-\mathrm{odd}}$ which might appear in the $J/\psi\eta$ final state. The photon energy in $\eta \to \gamma\gamma$ is well above the threshold to be detected in B-factory experiments even in the case where the resonance is just above the $J/\psi\eta$ mass threshold. Therefore, the $J/\psi\eta$ system in the three-body $B \to J/\psi\eta K$ decay is suitable to search for the $X^{C-\mathrm{odd}}$ as well as any yet-unseen charmonium(-like) resonances.

A previous study by the BaBar collaboration [9] based on 90×10^6 $B\overline{B}$ pairs ($N_{B\bar{B}}$) showed no signal of a narrow resonance in the $J/\psi\eta$ spectrum. We present a study of $B \to J/\psi\eta K$ decay based on a data sample of $772{\times}10^6$ $B\overline{B}$ events collected with the Belle detector [10] at the KEKB asymmetric-energy e^+e^- collider [11] at the $\Upsilon(4S)$ resonance. More detail of this work can be found in Ref. [12]. The J/ψ meson is reconstructed in its decay to $\ell^+\ell^-$ ($\ell = e$ or μ). Pairs of photons are combined to form η candidates. Charged kaons are identified by combining information from the central drift chamber (CDC), time-of-flight scintillation counters (TOF) and aerogel Cherenkov counter (ACC) systems. K^0_S mesons are reconstructed by combining two oppositely charged tracks with assuming both to be pions.

A $B \to J/\psi\eta K$ candidate is formed from the J/ψ, η and kaon candidates and is identified by two kinematic variables defined in the $\Upsilon(4S)$ rest frame (cms): the energy difference ($\Delta E \equiv E^*_B - E^*_{\mathrm{beam}}$) and the beam-energy constrained mass ($M_{\mathrm{bc}} \equiv \sqrt{(E^*_{\mathrm{beam}})^2 - (P^*_B)^2}$). Here, E^*_{beam} is the cms beam energy and E^*_B and P^*_B are the cms energy and momentum, respectively, of the reconstructed B candidate. The B candidates satisfying $M_{\mathrm{bc}} > 5.27$ GeV/c^2 and $|\Delta E| < 0.2$ GeV are retained for further analysis.

To suppress continuum background, we require events to have a ratio R_2 of the second to zeroth Fox-Wolfram moments [13] less than 0.5. The backgrounds from $B\overline{B}$ events containing a real $J/\psi \to \ell^+\ell^-$ decay dominate. Among them, when ψ' decays to the final states other than $J/\psi\eta$, the $B \to \psi' K$ decay mode forms a significant portion of the background. We denote this contribution as the $B \to \psi'(\not\to J/\psi\eta)K$ process. In order to reduce this background, we reject a J/ψ that, when combined with a $\pi^+\pi^-$ pair, forms a ψ' candidate.

The B decay signal extraction is done by an extended unbinned maximum likelihood (UML) fit to the ΔE distribution. Figure. 1 shows the ΔE distribution for the charged and neutral B decay candidates together with the fit results. Signal yields are obtained to be 428 ± 37 events and 94 ± 14 events for the $B^\pm \to J/\psi\eta K^\pm$ and $B^0 \to J/\psi\eta K^0_S$ decay modes, respectively. Their branching fractions are $(1.27 \pm 0.11 \pm 0.11) \times 10^{-4}$ and $(5.22 \pm 0.78 \pm 0.49) \times 10^{-5}$, where the first uncertainty is statistical and the second is systematic uncertainty. The statistical significance is found to be 17σ (7σ) for the $B^\pm \to J/\psi\eta K^\pm$ ($B^0 \to J/\psi\eta K^0_S$) decay mode. We observe the $B^0 \to J/\psi\eta K^0_S$ decay mode for the first time with the significance more than 5 σ. Equal production of neutral and charged B meson pairs in the $\Upsilon(4S)$ decay is assumed and we used the secondary branching fractions reported in Ref. [14]. The results of the fits are presented in Table 1.

Table 1: Summary of the detection efficiency (ε), signal yield ($N_{\rm sig}$) and branching fraction ($\mathscr{B}$) in -0.2 GeV$/c^2 < \Delta E < 0.2$ GeV$/c^2$, where the first and second errors are statistical and systematic.

Decay mode	$\varepsilon(\%)$	$N_{\rm sig}$	$\mathscr{B}$
$B^{\pm} \to J/\psi\eta K^{\pm}$	9.37	428±37	$(1.27\pm0.11\pm0.11)\times10^{-4}$
$B^0 \to J/\psi\eta K^0_S$	7.23	94±14	$(5.22\pm0.78\pm0.49)\times10^{-5}$

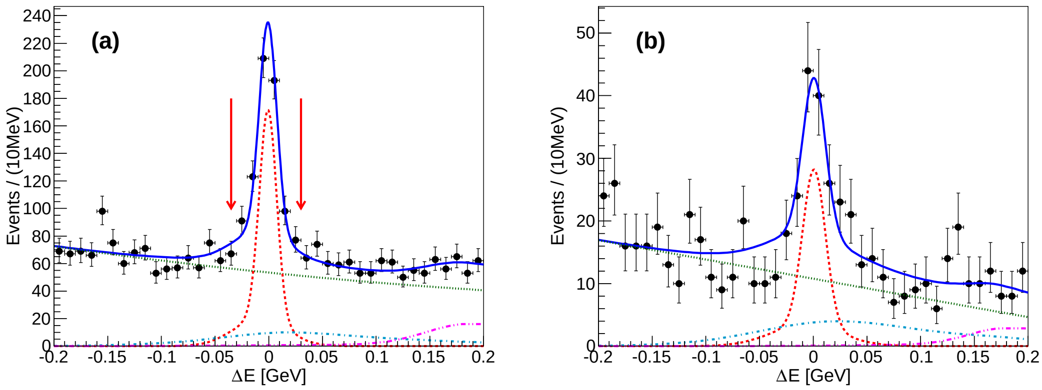

Figure 1: ΔE distribution of (a) $B^{\pm} \to J/\psi\eta K^{\pm}$ and (b) $B^0 \to J/\psi\eta K^0_S$ candidates in $M_{\rm bc} > 5.27$ GeV/c^2. Signal-enhanced region for $B^{\pm} \to J/\psi\eta K^{\pm}$ is shown by the the red arrows in (a). Data are shown by points with error bars. The red dashed line is signal, the cyan dot-dashed line is $B \to \psi'(\not\to J/\psi\eta)K$ background, the magenta dot-dot-dashed line is $B \to \chi_{c1}K$ background and the green dotted line is other backgrounds.

Since the $B^{\pm} \to J/\psi\eta K^{\pm}$ signal has enough statistics, we use the $J/\psi\eta$ mass spectrum ($M_{J/\psi\eta}$) to resolve the intermediate states. For this purpose, we select events having -35 MeV $< \Delta E < 30$ MeV. The B decay signal yield in this signal-enhanced region is 403 ± 35 events. Fig. 2(a) shows the $M_{J/\psi\eta}$ distribution for this subsample. We find a clear peak corresponding to the $\psi' \to J/\psi\eta$ decay at 3686 MeV/c^2 with a yield of 46±8 events as shown in Fig. 2(b). We obtain $\mathscr{B}(B^{\pm} \to \psi' K^{\pm})\mathscr{B}(\psi' \to J/\psi\eta) = (0.15\pm0.03(\text{stat.})\pm0.01(\text{syst.}))\times10^{-4}$, which is in agreement with the PDG value [14]. The rest of the B decay signal does not show any significant excess from with three-body phase space distribution.

After subtracting the yield of 46±8 events for $B^{\pm} \to \psi' K^{\pm}$ followed by $\psi' \to J/\psi\eta$, the rent of B decay signal yield is 357±38 events and is used to extract the branching fraction in Table 2.

The largest systematic uncertainty source in the branching fraction measurements is the PDF uncertainty. It is estimated by varying all fixed parameters by $\pm1\sigma$ and summing all the variations in quadrature; it amounts to 7.3% for $B^{\pm} \to J/\psi\eta K^{\pm}$ and 8.4% for $B^0 \to J/\psi\eta K^0_S$. Together with all other sources, the overall systematic error is obtained to be 8.6% for $B^{\pm} \to J/\psi\eta K^{\pm}$ and 9.4% for $B^0 \to J/\psi\eta K^0_S$ [12].

As shown in Fig. 2(c), the result for the $X^{C-\rm odd}$ yield is found to be 2.3±5.2 events and we determine a 90% confidence level (C.L.) upper limit (U.L.) on the product of the branching fractions, $\mathscr{B}(B^{\pm} \to X^{C-\rm odd}K^{\pm})\mathscr{B}(X^{C-\rm odd} \to J/\psi\eta) < 3.8\times10^{-6}$, using a frequentist approach. For the $\psi(4040)$ and $\psi(4160)$ cases, a Breit-Wigner function with the mass and width fixed to the

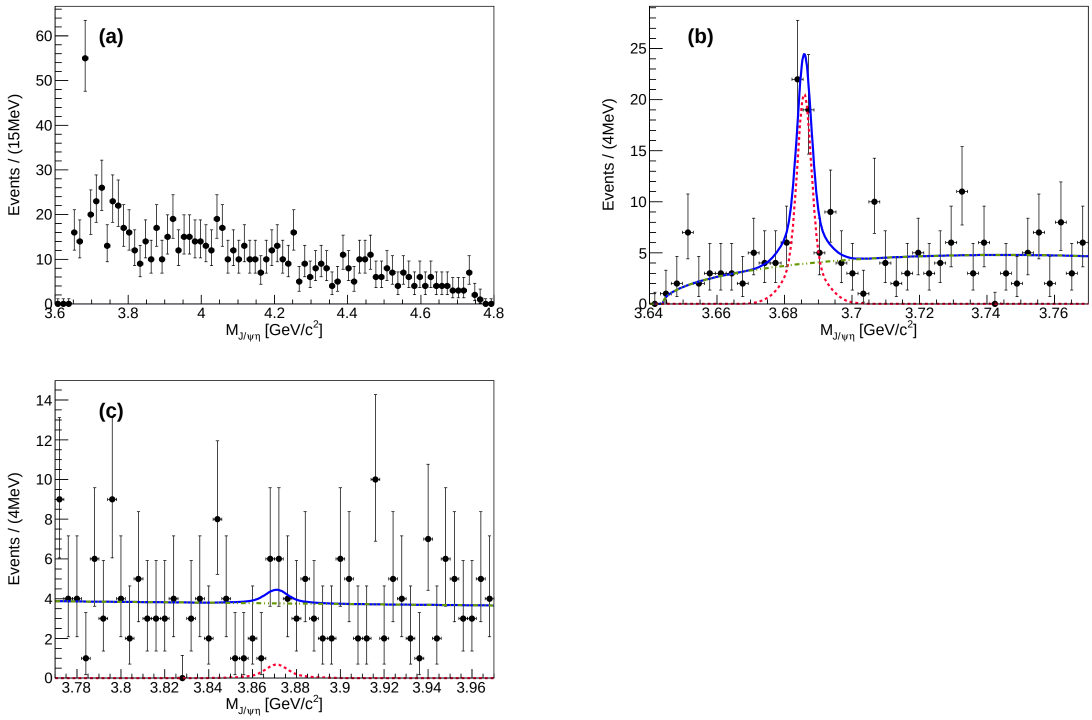

Figure 2: The $J/\psi\eta$ invariant mass ($M_{J/\psi\eta}$) distribution of $B^{\pm} \to J/\psi\eta K^{\pm}$ candidates for: (a) the entire mass distribution, (b) the region around the ψ' and (c) the $X(3872)$ region. Data is shown by points with error bars; overall fit is shown by blue solid line. For (b) and (c), the red dashed line is for signal (ψ' and $X(3872)$ in (b) and (c), respectively) and the green two dotted-dashed line is for the remainder.

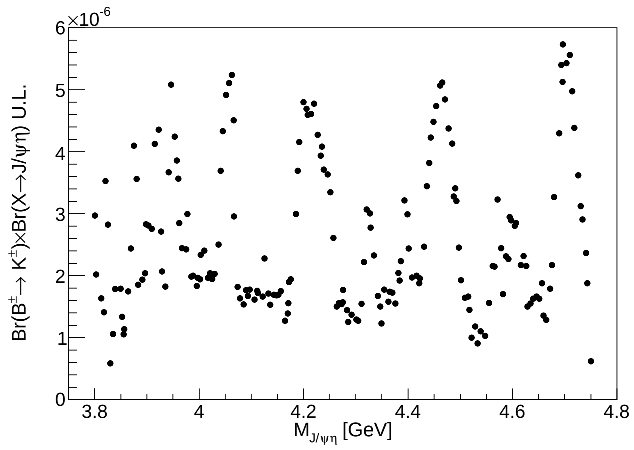

Figure 3: 90% C.L. upper limit of the $\mathscr{B}(B^{\pm} \to XK^{\pm})\mathscr{B}(X \to J/\psi\eta)$ for a narrow resonance X as a function of the mass, with a 5 MeV/c^2 interval.

values reported in Ref.[14] is used. Table 3 summarizes the U.L. for the $X^{C-\mathrm{odd}}$ and $\psi(4040, 4160)$. As shown in Fig. 3, We also provide the U.L. at 90% C.L. of narrow resonances over a range from 3.8 to 4.8 GeV$/c^2$, with 5 MeV$/c^2$ steps.

Table 2: Summary of the detection efficiency (ε), signal yield ($N_{\rm sig}$) and branching fraction ($\mathscr{B}$), where the first and second errors are statistical and systematic, respectively. For $B^{\pm} \to \psi' K^{\pm}$, followed by $\psi' \to J/\psi\eta$, $\mathscr{B}$ denotes the products of the branching fractions, $\mathscr{B}(B^{\pm} \to \psi' K^{\pm})\mathscr{B}(\psi' \to J/\psi\eta)$. For the $B^{\pm}$ decays, all relevant numbers are defined in the signal enhanced region, -35 MeV $< \Delta E <$ 30 MeV.

Decay mode	ε(%)	$N_{\rm sig}$	$\mathscr{B}$
$B^{\pm} \to J/\psi\eta K^{\pm}$ (Total)	8.82	403±35	(1.27±0.11±0.11)×10^{-4}
$B^{\pm} \to \psi' K^{\pm}$, $\psi' \to J/\psi\eta$	8.42	46±8	(0.15±0.03±0.01)×10^{-4}
$B^{\pm} \to J/\psi\eta K^{\pm}$ (excl. $\psi' K^{\pm}$)	8.88	357±38	(1.12±0.11±0.10)×10^{-4}

Table 3: The U.L. for the product of the branching fractions $\mathscr{B}(B^{\pm} \to X(\to J/\psi\eta)K^{\pm}) \equiv \mathscr{B}(B^{\pm} \to XK^{\pm})\mathscr{B}(X \to J/\psi\eta)$ at 3872 and the ψ states recently found to decay into $J/\psi\eta$. Note that ε is the corrected detection efficiency and the signal yield $N_{\rm sig}$ is given as an U.L. at 90% confidence level.

M_X or ψ	ε(%)	$N_{\rm sig}$	$\mathscr{B}(B^{\pm} \to X(\to J/\psi\eta)K^{\pm})$
3872	8.1	< 10.6	$< 3.8 \times 10^{-6}$
$\psi(4040)$	9.2	< 51.4	$< 1.55 \times 10^{-5}$
$\psi(4160)$	9.2	< 24.3	$< 0.74 \times 10^{-5}$

In summary, we observe the $B^{\pm} \to J/\psi\eta K^{\pm}$ and $B^0 \to J/\psi\eta K_S^0$ decay modes and obtain the most precise branching fractions, $\mathscr{B}(B^{\pm} \to J/\psi\eta K^{\pm}) = (1.27 \pm 0.11(\text{stat.}) \pm 0.11(\text{syst.})) \times 10^{-4}$ and $\mathscr{B}(B^0 \to J/\psi\eta K_S^0) = (5.22 \pm 0.78(\text{stat.}) \pm 0.49(\text{syst.})) \times 10^{-5}$. Using the $B^{\pm} \to J/\psi\eta K^{\pm}$ sample, the $M_{J/\psi\eta}$ distribution is looked to resolve each possible contribution to search for a resonance in the $J/\psi\eta$ final state. Except for the known $\psi' \to J/\psi\eta$ decay, the $M_{J/\psi\eta}$ spectrum is found to be featureless. Therefor we obtain an U.L. on the product of the branching fractions, $\mathscr{B}(B^{\pm} \to X^{C-\text{odd}}K^{\pm})\mathscr{B}(X^{C-\text{odd}} \to J/\psi\eta) < 3.8 \times 10^{-6}$ at 90% C.L.; this is less than one half of the corresponding value in $X(3872) \to J/\psi\pi^+\pi^-$ [14]. Also we don't see $\psi(4040)$ and $\psi(4160)$ signuature in the $J/\psi\eta$ final state in B decays through they are seen in the initial state radiation process [15]. Our results show that either the production of the C-odd partner of the $X(3872)$ resonance in two-body B decay and/or its decay into $J/\psi\eta$ is suppressed.

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