Hadronic transitions in bottomonia at Belle

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Abstract. Recent Belle results on various hadronic transitions among bottomonia are presented. We observe transitions with the η and η' meson at the $\Upsilon(4S)$. Bottomonium production together with the η meson is also reported at the $\Upsilon(10860)$. We study $\pi^+\pi^-\pi^0$ transitions at the $\Upsilon(10860)$ and $\Upsilon(11020)$.

1 Introduction

Spectroscopy of heavy quarkonia provides crucial information for understanding strong interactions since QCD calculations become possible. Measurements of hadronic transitions ($\pi^+\pi^-$, η, ω, ...) between bottomonia yield important input for QCD. η transitions are believed to be suppressed compared to $\pi^+\pi^-$ because of the spin flip. $\pi^+\pi^-$ transitions and their peculiarities were studied by both BaBar and Belle. Large integrated luminosity collected by Belle above the $\Upsilon(4S)$ opened unique possibilities resulting in exciting observations of $h_b(1P)$, $h_b(2P)$, $\eta_b(2S)$, $Z_b(10610)$ and $Z_b(10650)$. In this work we discuss recent results on hadronic transitions in bottomonia.

2 Study of η and $\pi^+\pi^-$ transitions in $\Upsilon(4S)$ decays to lower $b\bar{b}$

Here we study the transitions $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(nS)$ ($n = 1, 2$) and $\Upsilon(4S) \to \eta\Upsilon(1S)$, by reconstructing $\Upsilon(nS) \to \mu^+\mu^-$, $\eta \to \pi^+\pi^-\pi^0$ using $(538 \pm 7) \times 10^6$ $\Upsilon(4S)$ mesons [1].

For the dipion transitions, the two-dimensional distribution of the invariant dimuon mass $M(\mu\mu)$ vs. ΔM for the selected events is shown in Fig. 1, where $\Delta M = M(\pi\pi\mu\mu) - M(\mu\mu)$. The signal yields are determined from the fit to the ΔM distribution in 6×4 (4×4) bins of $M(\pi^+\pi^-)$ and $cos\theta_{\rm hel}(\pi^+)$ in the regions (a) and (b) due to the initial-state radiation processes $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$, respectively (in (c) and (d) due to the decays of interest $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)$, respectively). The results are listed in Table 1 and the ΔM distributions integrated over the bins are shown in Fig. 2.

For the η transitions, the distributions of $\Delta M_\eta = M(\pi\pi\gamma\mu\mu) - M(\mu\mu) - M(\pi\pi\gamma\gamma)$ are shown in Fig. 3 for the $\Upsilon(4S) \to \eta\Upsilon(1S)$ (left) and $\Upsilon(1^3D_{1,2}) \to \eta\Upsilon(1S)$ (right).

All the results are compatible with the previous measurements with the slightly improved precision. We confirm the enhancement of the $\Upsilon(4S) \to \Upsilon(1S)$ transition via the spin-flip exchange of the η meson with respect to the dipion one.

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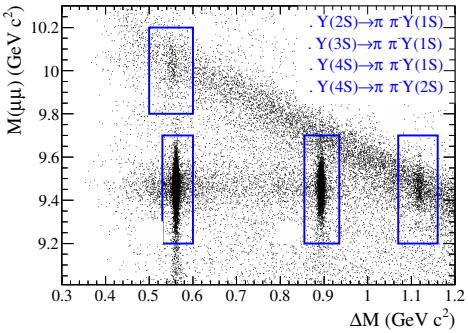

Figure 1. Distribution of $M(\mu\mu)$ vs. ΔM for the selected events. Fit regions are enclosed in boxes.

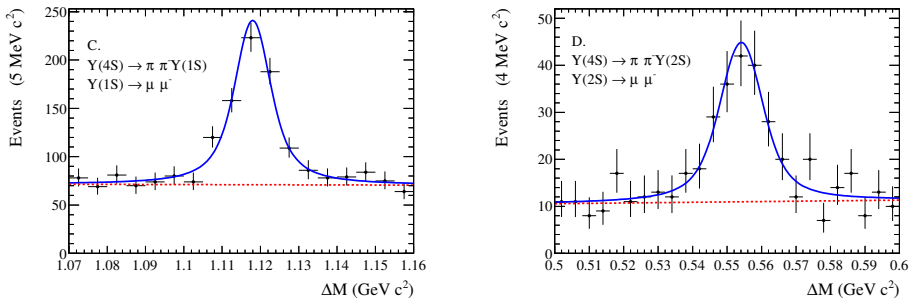

Figure 2. Fits to the ΔM distributions for: (left) $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$ and (right) $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)$.

Table 1. The signal yields and branching fractions compared to PDG [2] for the decay modes studied.

Decay	Events	$\mathcal{B}$, 10^{-5}	$\mathcal{B}_{\rm PDG}$, 10^{-5}
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$	1095 ± 74	$8.2 \pm 0.5 \pm 0.4$	8.1 ± 0.6
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)$	821 ± 107	$7.9 \pm 1.0 \pm 0.4$	8.6 ± 1.3
$\Upsilon(4S) \to \eta\Upsilon(1S)$	49 ± 7	$1.70 \pm 0.23 \pm 0.08$	1.96 ± 0.28
$\Upsilon(1^3D_{1,2}) \to \eta\Upsilon(1S)$	2.1 ± 3.0	< 0.23	–

3 Observation of $\Upsilon(4S) \to \eta'\Upsilon(1S)$

This observation is based on the same data sample of $(538 \pm 7) \times 10^6$ $\Upsilon(4S)$ mesons as in Sect. 2. We reconstruct $\Upsilon(1S) \to \mu^+\mu^-$ and $\eta' \to \rho\gamma$, $\eta\pi^+\pi^-$, $\eta \to 2\gamma$ [3].

Signal events are identified by the variable $\Delta M_{\eta'} = M(\Upsilon(4S)) - M(\Upsilon(1S)) - M(\eta')$, where $M(\Upsilon(1S)) = M(\mu\mu)$, $M(\Upsilon(4S)) = M(\mu\mu\pi\pi\gamma)[M(\mu\mu\pi\pi\gamma\gamma)]$ and $M(\eta') = M(\pi\pi\gamma)[M(\pi\pi\gamma\gamma)]$. The signal and background yields are obtained by the fit to the $\Delta M_{\eta'}$ distributions shown in Fig. 4 and are also listed in Table 2.

The combined branching fraction is $\mathcal{B}(\Upsilon(4S) \to \eta'\Upsilon(1S)) = (3.43 \pm 0.88 \pm 0.21) \times 10^{-5}$ and corresponds to the 5.7σ statistical significance.

We also determine the ratios of branching fractions:

$$R_{\eta'/h} = \frac{\mathcal{B}(\Upsilon(4S) \to \eta'\Upsilon(1S))}{\mathcal{B}(\Upsilon(4S) \to h\Upsilon(1S))},$$

Table 2. The signal and background yields as well as significances for two η' decay modes.

η' decay mode	$N_{\rm sig}$	$N_{\rm bkg}$	Sign., σ
$2\pi 1\gamma$	22±7	96±11	4.2
$2\pi 2\gamma$	5.0±2.3	2.0±1.6	4.1

where the decay is mediated by $h = \eta$ or $h = \pi^+\pi^-$ and using the values from our work [1] obtain $R_{\eta'/\eta} = 0.20 \pm 0.06$ and $R_{\eta'/\pi^+\pi^-} = 0.42 \pm 0.11$. The former ratio agrees with the predicted 0.2 [4].

4 Observation of $\Upsilon(4S) \to \eta h_b(1P)$

From a sample of 771.6×10^6 $\Upsilon(4S)$ decays (711 fb^{-1}) Belle observed for the first time the decay $\Upsilon(4S) \to \eta h_b(1P)$ using the η missing mass, $M_{\rm miss}(\eta) = \sqrt{(P_{e^+e^-} - P_\eta)^2}$ and $\eta \to \gamma\gamma$ [5]. The $M_{\rm miss}(\eta)$ distribution is shown in Fig. 5 (left). The clear $h_b(1P)$ signal is observed with the fit yield of 112469 ± 5537 events (11σ significance).

The obtained branching fraction $\mathcal{B}(\Upsilon(4S) \to \eta h_b(1P)) = (2.18 \pm 0.11 \pm 0.18) \times 10^{-3}$ agrees with the theoretical prediction of Ref. [6].

We reconstruct the $h_b(1P) \to \gamma\eta_b(1S)$ decay by measuring the number of events of $\Upsilon(4S)$ decay as a function of the variable $\Delta M_{\rm miss} = M_{\rm miss}(\eta\gamma) - M_{\rm miss}(\eta)$. Its distribution (Fig. 5 (right)) shows a clear excess at $\Delta M_{\rm miss} = M_{\eta_b(1S)} - M_{h_b(1P)}$, with a yield of 33116 ± 4741 events (9σ significance). The corresponding branching fraction $\mathcal{B}(h_b(1P) \to \gamma\eta_b(1S)) = (56 \pm 8 \pm 4)\%$ agrees with predictions [7, 8]. The results are summarized in Table 3.

Table 3. Summary of the searches for $\Upsilon(4S) \to \eta h_b(1P)$ and $h_b(1P) \to \gamma\eta_b(1S)$.

Observable	Value, MeV
$M_{h_b(1P)}$	$9899.3 \pm 0.4 \pm 1.0$
$M_{\eta_b(1S)}$	$9400.7 \pm 1.7 \pm 1.6$
$\Gamma_{\eta_b(1S)}$	$8^{+6}_{-5} \pm 5$
$\Delta M_{\rm HF}(1P) = M^{\rm sa}_{\chi_{bJ}}(1P) - M_{h_b(1P)}$	$+0.6 \pm 0.4 \pm 1.0$
$\Delta M_{\rm HF}(1S) = M_{\Upsilon(1S)} - M_{\eta_b(1S)}$	$59.6 \pm 1.7 \pm 1.6$

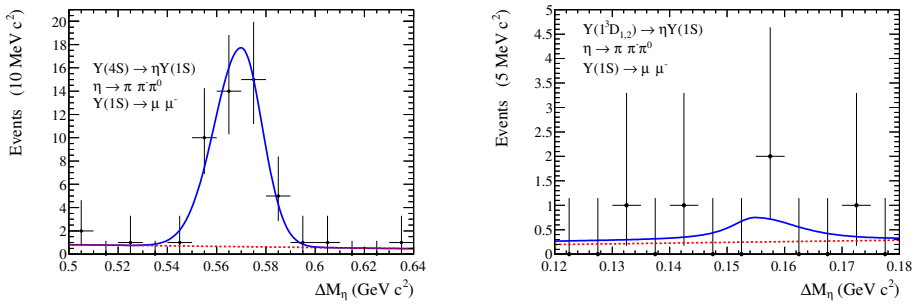

Figure 3. Fits to the ΔM_η distributions for: (left) $\Upsilon(4S) \to \eta\Upsilon(1S)$ and (right) $\Upsilon(1^3D_{1,2}) \to \eta\Upsilon(1S)$.

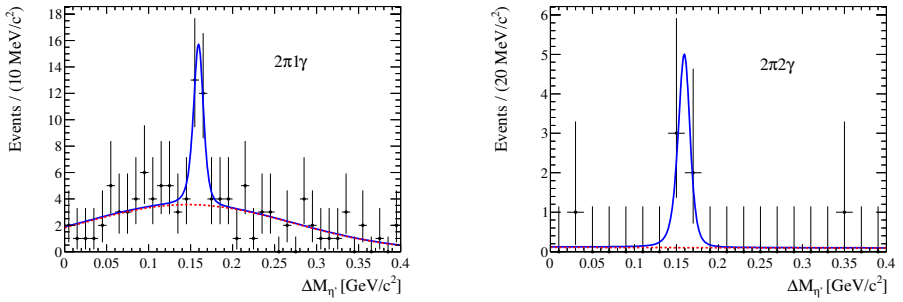

Figure 4. Fit to the $\Delta M_{\eta'}$ distribution for $\Upsilon(4S) \to \eta'\Upsilon(1S)$ candidates in the $2\pi1\gamma$ (left) and $2\pi2\gamma$ (right) modes.

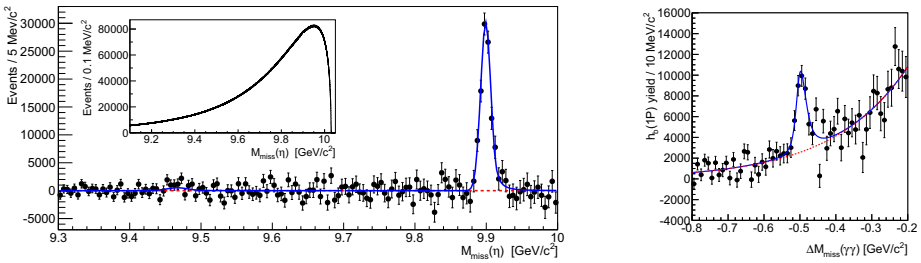

Figure 5. Distributions of: (left) $M_{\rm miss}(\eta)$ after background subtraction, (right) $\Delta M_{\rm miss}$.

5 Production of $b\bar{b}$ and η near $\Upsilon(5S)$

For this study we used a sample of 121.4 fb^{-1} collected near the $\Upsilon(5S)$ energy [9]. The approach is based on the missing mass $M_{\rm miss}(\eta)$ similar to that in Sect. 4. The corresponding distribution is shown in Fig. 6 with the results listed in Table 4.

Table 4. Summary of the studies of $e^+e^- \to \eta(b\bar{b})$ near $\Upsilon(5S)$.

Process	Sign., σ	$N, 10^3$	Process	Sign., σ	$N, 10^3$
$\eta\Upsilon(1S)$	1.5σ	1.7 ± 1.0	$\eta\Upsilon(2S)$	3.3σ	5.6 ± 1.6
$\eta\, h_b(1P)$	2.7σ	3.9 ± 1.5	$\eta\Upsilon(1D)$	5.3σ	9.3 ± 1.8

We observe for the first time the process $e^+e^- \to \eta\Upsilon_J(1D)$ and find evidence for $e^+e^- \to \eta\Upsilon(2S)$. Assuming that the process proceeds entirely via the $\Upsilon(5S)$ and taking $\sigma(e^+e^- \to \Upsilon(5S)) = \sigma(e^+e^- \to b\bar{b}) = (0.340 \pm 0.016)$ nb from our measurement [10], we obtain $\mathcal{B}(\Upsilon(5S) \to \eta\Upsilon_J(1D)) = (4.82 \pm 0.92 \pm 0.67) \times 10^{-3}$. This result agrees with theoretical estimates accounting for the effect of virtual B-meson loops [11]. We do not have significant evidence for $e^+e^- \to \eta h_b(1P, 2P)$ nor $e^+e^- \to \eta\Upsilon(1S)$. We do not have direct evidence for the presence of the three states of the $\Upsilon_J(1D)$ triplet and derive 90% CL upper limits on the fraction of $J = 1$ and $J = 3$ states with respect to the $J = 2$ state.

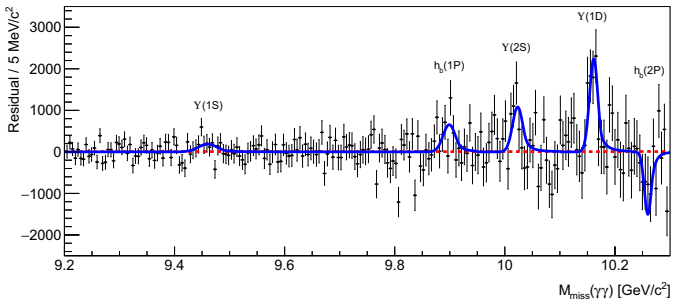

Figure 6. $M_{\rm miss}(\eta)$ distribution after subtraction of the fitted background.

6 Observation of $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bJ}$ at 10.867 GeV

A data sample of 118 fb^{-1} collected at 10.867 GeV has been used to study $\pi^+\pi^-\pi^0$ transitions between the $\Upsilon(5S)$ and χ_{bJ}, $J = 0, 1, 2$, with subsequent $\chi_{bJ} \to \gamma\Upsilon(1S)$, $\Upsilon(1S) \to l^+l^-$, $l = e, \mu$ decays [12].

Figure 7 shows the scatter plot of $M(\pi^+\pi^-\pi^0)$ vs. $M(\gamma\Upsilon(1S))$. In addition to the clear ω signal in the χ_{bJ} mass region, there is an obvious accumulation of $(\pi^+\pi^-\pi^0)_{\rm non-\omega}$ events above the ω mass. A two-dimensional fit gives the $\omega\chi_{bJ}$ and $(\pi^+\pi^-\pi^0)_{\rm non-\omega\chi_{bJ}}$ yields. Figure 8 shows the $\pi^+\pi^-\pi^0$ mass projection (left) with the obvious ω signal and evidence for non-ω events, and the $\gamma\Upsilon(1S)$ mass projection within (center) and outside (right) the ω region with clear χ_{b1} and χ_{b2} signals. The fit results are summarized in Table 5. No excess of χ_{b0} events above expected backgrounds is observed. The branching fractions of the three-pion transitions are large and of the same order as two-pion processes.

We also search for the $X(3872)$-like state X_b in the process $e^+e^- \to \gamma X_b$, $X_b \to \omega\Upsilon(1S)$ and observe no excess of events over the expectation from the $\omega\chi_{bJ}$ final states. The upper limit is $\mathcal{B}(\Upsilon(5S) \to \gamma X_b)\,\mathcal{B}(X_b \to \omega\Upsilon(1S)) < 2.9 \times 10^{-5}$ at 90% CL.

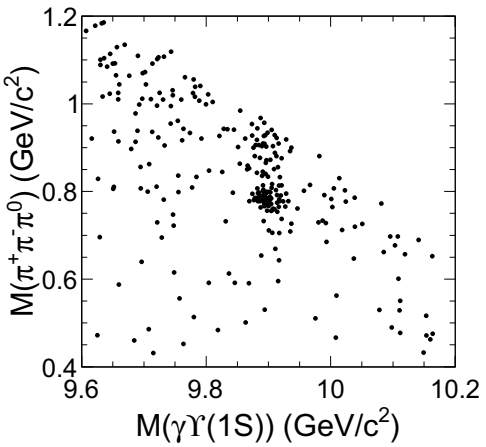

Figure 7. Scatter plot of $M(\pi^+\pi^-\pi^0)$ vs. $M(\gamma\Upsilon(1S))$ for selected $e^+e^- \to \pi^+\pi^-\pi^0\gamma\Upsilon(1S)$ events.

Table 5. Results of the fits

Mode	Yield	Sign., (σ)	$\mathcal{B}, 10^{-3}$
$3\pi\chi_{b1}$	80.1 ± 9.9	12	1.85 ± 0.23 ± 0.23
$3\pi\chi_{b2}$	28.6 ± 6.5	5.9	1.17 ± 0.27 ± 0.14
$\omega\chi_{b1}$	59.9 ± 8.3	12	1.57 ± 0.22 ± 0.21
$\omega\chi_{b2}$	12.9 ± 4.8	3.5	0.60 ± 0.23 ± 0.15
(3π)non$-\omega\chi_{b1}$	23.6 ± 6.4	4.9	0.52 ± 0.15 ± 0.11
(3π)non$-\omega\chi_{b2}$	15.6 ± 5.4	3.1	0.61 ± 0.22 ± 0.28

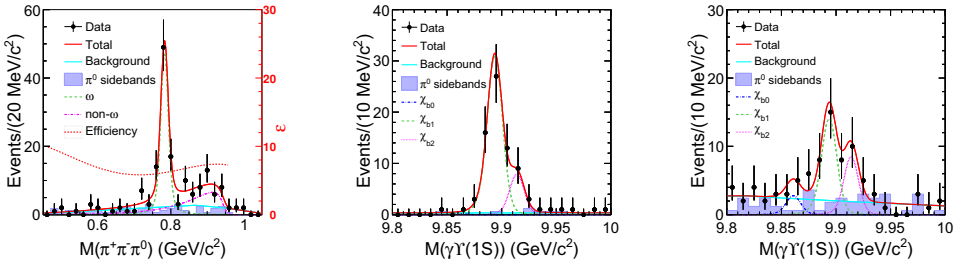

Figure 8. Projections of: (left) $M(\pi^+\pi^-\pi^0)$ for 9.8< $M(\gamma\Upsilon(1S))$ <10 GeV, (center) $M(\gamma\Upsilon(1S))$ in the ω region, (right) $M(\gamma\Upsilon(1S))$ outside of the ω region.

Finally, we search for $\Upsilon(6S) \to \omega\chi_{bJ}$, $\phi\chi_{bJ}$ using scan data near 10.867 and 11.020 GeV [13]. We observe $e^+e^- \to \pi^+\pi^-\pi^0\chi_{b1}$ near $\Upsilon(6S)$ and find evidence for $\omega\chi_{bJ}$ while there is no significant signals for $\phi\chi_{bJ}$ from 10.96 to 11.05 GeV.

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