Recent bottomonium studies at Belle

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Abstract. We report the recent studies of bottomonium spectroscopy and transitions using the data sample collected with the Belle detector. Unambiguous $\pi^+\pi^-\pi^0\chi_{b1}$ $(J = 1,\ 2)$, $\omega\chi_{b1}$ signals are observed near the $\Upsilon(5S)$ resonance mass region. In the $\pi^+\pi^-\pi^0$ invariant mass distribution, some $(\pi^+\pi^-\pi^0)_{\mathrm{non}-\omega}$ events are observed besides clear ω signal events. A X(3872)-like state in bottom sector is search for in the final state $\omega\Upsilon(1S)$. The Belle collaboration also searches for the η transitions with the $\Upsilon(4S)$ and $\Upsilon(5S)$ data samples. The $\Upsilon(4S) \to \eta h_b(1P)$ process is observed and evidences of η transitions from $\Upsilon(5S)$ to lower bottomonium are found. The $\eta_b(1S)$ resonance parameters are updated based on the decay mode $h_b(1P) \to \gamma\eta_b(1S)$ in the same work.

1. Study of $e^+e^- \to \pi^0\pi^+\pi^-\gamma\Upsilon(1S)$ at $\Upsilon(5S)$

1.1. Observation of $e^+e^- \to \pi^0\pi^+\pi^-\chi_{bJ}$

Heavy quarkonium systems are basically non-relativistic and hadronic transition between them have largely been successfully described by the QCD multipole expansion model [1]. The Belle collaboration has observed the anomalously large width of the $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(mS)$ (m = 1, 2, 3) and $\pi^+\pi^-h_b(nP)$ $(n = 1,\ 2)$ transitions [2], which is interpreted as the rescattering of the B mesons [3] or the existence of a tetraquark state with a mass close to that of the $\Upsilon(5S)$ [4]. A detailed study [5] revealed the presence of two charged bottomonium-like states, $Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$. It is natural to investigate a similar of $\pi^0\pi^+\pi^-$ hadronic transitions between the $\Upsilon(5S)$ and χ_{bJ} $(J = 0,\ 1,\ 2)$.

The study [6] is based on a 118 fb^{-1} data sample at $\sqrt{s} \sim 10.867$ GeV collected with the Belle detector [7] at the KEKB asymmetric-energy e^+e^- collider [8]. Figure 1 shows the scatter plot of $M(\pi^0\pi^+\pi^-)$ versus $M(\gamma\Upsilon(1S))$ after event selection criteria. A unbinned two-dimensional fit is performed to extract signal yields. There is a clear ω signal and some $(\pi^+\pi^-\pi^0)_{\mathrm{non}-\omega}$ events, as shown in Fig. 2.

Figure 3 shows the $\gamma\Upsilon(1S)$ mass projections within and outside ω signal region. The signal statistical significance and the calculated Born cross sections and branching fractions are summarized in Table 1.

The measured branching fractions of $\Upsilon(5S) \to \pi^+\pi^-\pi^0\chi_{b1}$ and $\pi^+\pi^-\pi^0\chi_{b2}$ are at the same order as the $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(mS)$ $(m = 1,\ 2,\ 3)$ [2]. The ratio of the branching fractions of $\Upsilon(5S)$ decays or the cross sections of e^+e^- to $\omega\chi_{b2}$ and $\omega\chi_{b1}$ is $0.38 \pm 0.16(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})$. It is significantly lower than the expectation from the heavy quark symmetry [9].

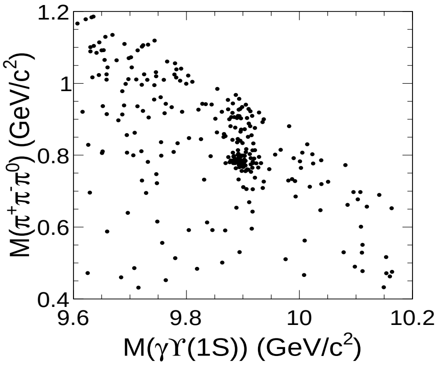

Figure 1. The scatter plot of $M(\pi^+\pi^-\pi^0)$ versus $M(\gamma\Upsilon(1S))$ for selected $e^+e^- \to \pi^+\pi^-\pi^0\gamma\Upsilon(1S)$ candidate events.

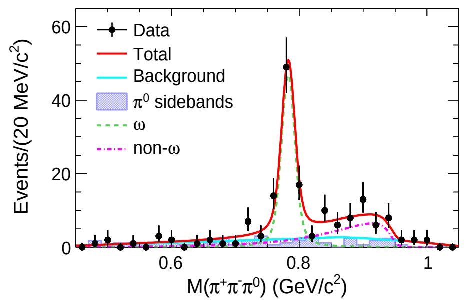

Figure 2. The $M(\pi^+\pi^-\pi^0)$ invariant mass distribution, where the dashed and dash-dotted curves represent the ω and $(\pi^+\pi^-\pi^0)_{\rm non-\omega}$ events; the hatched histogram is the normalized π^0 sideband events.

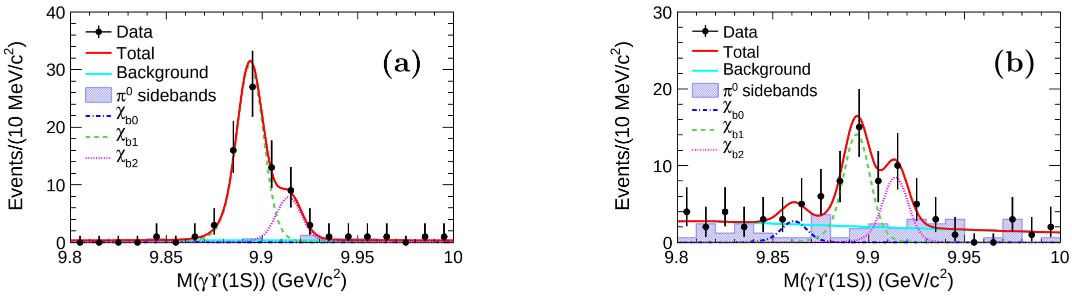

Figure 3. Projections of $M(\gamma\Upsilon(1S))$ (a) in the ω signal region and (b) outside of ω signal region, where the dash-dotted, dashed and dotted curves represent the χ_{b0}, χ_{b1} and χ_{b2} signals, respectively.

Table 1. The signal significance (Σ), Born cross section (σ_B) and branching fraction ($\mathcal{B}$). The upper limits are given at 90% confidence level (C.L.) if the significance is lower than 3σ.

Mode	Σ (σ)	σ_B (pb)	$\mathcal{B}$ (10^{-3})
$(\pi^+\pi^-\pi^0)\chi_{b0}$	1.0	< 3.1	< 6.3
$(\pi^+\pi^-\pi^0)\chi_{b1}$	12	$0.90 \pm 0.11 \pm 0.13$	$1.85 \pm 0.23 \pm 0.23$
$(\pi^+\pi^-\pi^0)\chi_{b2}$	5.9	$0.57 \pm 0.13 \pm 0.08$	$1.17 \pm 0.27 \pm 0.14$
$\omega\chi_{b0}$	0.5	< 1.9	< 3.9
$\omega\chi_{b1}$	12	$0.76 \pm 0.11 \pm 0.11$	$1.57 \pm 0.22 \pm 0.21$
$\omega\chi_{b2}$	3.5	$0.29 \pm 0.11 \pm 0.08$	$0.60 \pm 0.23 \pm 0.15$
$(\pi^+\pi^-\pi^0)_{\rm non-\omega}\chi_{b0}$	0.4	< 2.3	< 4.8
$(\pi^+\pi^-\pi^0)_{\rm non-\omega}\chi_{b1}$	4.9	$0.25 \pm 0.07 \pm 0.06$	$0.52 \pm 0.15 \pm 0.11$
$(\pi^+\pi^-\pi^0)_{\rm non-\omega}\chi_{b2}$	3.1	$0.30 \pm 0.11 \pm 0.14$	$0.61 \pm 0.22 \pm 0.28$

1.2. Search for X_b decaying to $\omega\Upsilon(1S)$

The CMS Collaboration reported a null search of the $X(3872)$ counterpart in bottomonium sector (called X_b) in the $\pi^+\pi^-\Upsilon(1S)$ final state [10]. Unlike the $X(3872)$, the $X_b \to \omega\Upsilon(1S)$ is a isospin-conserving process.

The $\omega\Upsilon(1S)$ invariant mass distribution is shown in Fig.4, where the solid histogram represents the reflection from the contribution of $e^+e^- \to \omega\chi_{bJ}$ ($J = 0,\ 1,\ 2$), the shaded histogram is the normalized ω sideband events and the dashed histogram is from the MC signal sample with X_b mass fixed at 10.6 GeV/c^2 and yield fixed at the upper limit at 90% C.L. No significant signal is observed for X_b with mass between 10.55 and 10.65 GeV/c^2. The 90% C.L. upper limits on the product branching fraction $\mathcal{B}(\Upsilon(5S) \to \gamma X_b)\mathcal{B}(X_b \to \omega\Upsilon(1S))$ varies from 2.6×10^{-5} to 3.8×10^{-5}.

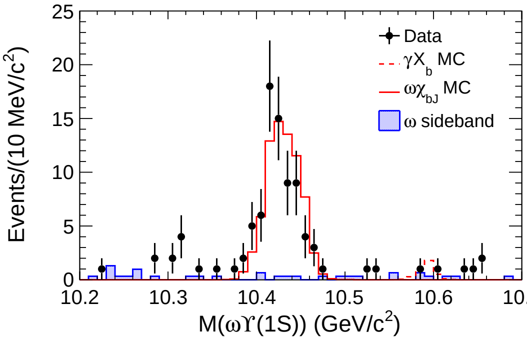

Figure 4. The $\omega\Upsilon(1S)$ invariant mass distribution from selected $\pi^0\pi^+\pi^-\gamma\Upsilon(1S)$ events.

2. Study on the η transitions

The processes $\Upsilon(nS) \to \eta\Upsilon(mS)$ are spin flipping, which the branch fractions should be suppressed with respect to the $\pi^+\pi^-$ transitions in QCD mutipole expansion approach. For $\Upsilon(4S)$ case, the ratio $\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S))/\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$ is 2.4 [11], which shows the strong discrepancy with the theoretical prediction [12]. However, for $\Upsilon \to h_b$ transitions, the similar ratio should be not less than 1.0.

Recently, Belle collaboration searches for the η transitions from $\Upsilon(4S)$ and $\Upsilon(5S)$ to the $h_b(nP)$. The results presented here is preliminary. Figure 5 shows η recoil mass distribution with the combinatorial background subtracted in the $\Upsilon(4S)$ dataset. A clear $h_b(1P)$ peak is observed, with a statistical significance greater than 5σ. The corresponding branching fraction is $\mathcal{B}(\Upsilon(4S) \to \eta h_b(1P)) = (1.83 \pm 0.16 \pm 0.17)\times 10^{-3}$. The ratio $\mathcal{B}(\Upsilon(4S) \to \eta h_b(1P))/\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^- h_b(1P))$ is greater than 2.0 at 90% C.L., which is in reasonable agreement with the QCD multipole expansion model expectation.

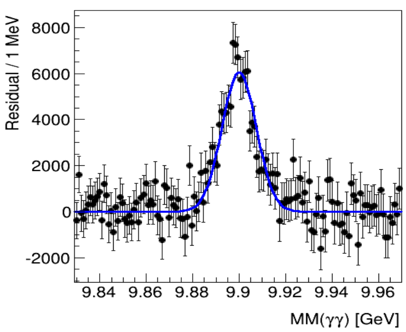

Figure 5. The η recoil mass distribution with the background subtracted in the $\Upsilon(4S)$ dataset. The blue curve represents the best fit.

For $\Upsilon(5S)$ dataset case, the η recoil mass, after the subtraction of combinatorial background, shows significant signals corresponding to the $\Upsilon(5S) \to \eta\Upsilon(2S)$ and $\Upsilon(5S) \to \eta\Upsilon(1D)$, as shown in Fig. 6. The statistical significance are 3.1σ and 4.4σ for the two processes, respectively. The measured branching fractions are

$$\mathcal{B}(\Upsilon(5S) \to \eta\Upsilon(2S)) = 2.1 \pm 0.7 \pm 0.3,$$
$$\mathcal{B}(\Upsilon(5S) \to \eta\Upsilon(1D)) = 2.8 \pm 0.7 \pm 0.4,$$
$$\mathcal{B}(\Upsilon(5S) \to \eta h_b(1P)) < 3.3 \times 10^{-3},$$
$$\mathcal{B}(\Upsilon(5S) \to \eta h_b(2P)) < 3.7 \times 10^{-3},$$

where the upper limits are obtained at 90% C.L. Since the $\Upsilon(5S) \to \pi^+\pi^- h_b(nP)$ proceed mainly through the charged Z_bs, the interpretation of $\mathcal{B}(\Upsilon(5S) \to \eta h_b(nP))/\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^- h_b(nP))$ of $\Upsilon(5S)$ results is not straightforward.

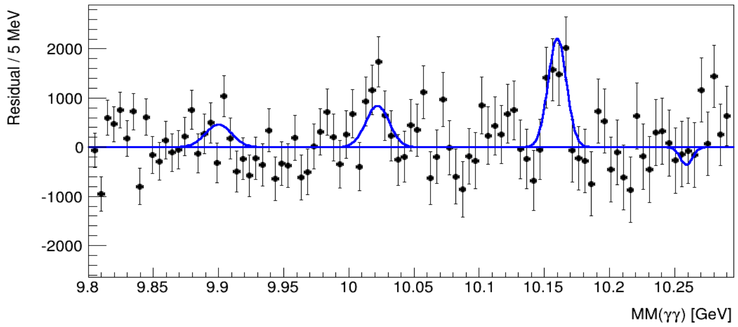

Figure 6. The η recoil mass distribution with the combinatorial background subtracted in the $\Upsilon(5S)$ dataset. The blue curve represent the best fit.

The $\eta_b(1S)$ resonance parameters are measured using the process $\Upsilon(4S) \to \eta h_b(1P) \to \eta\gamma\eta_b(1S)$. A variable $\Delta MM = MM(\gamma\eta) - MM(\eta)$ is defined, where $MM(\gamma\eta)$ and $MM(\eta)$ are the missing masses of $\gamma\eta$ and η. The ΔMM distribution is shown in Fig. 7. The measured $M(\eta_b(1S))$ is $9405.3 \pm 1.3 \pm 3.0$ MeV/c^2 and corresponding hyperfine splitting $\Delta M_{HF}(1S) = M(\Upsilon(1S)) - M(\eta_b(1S))$ is $55.0 \pm 1.3 \pm 3.2$ MeV/c^2 which is in agreement with the lattice and potential non-relativistic QCD expactations [13]. The measured width is $\Gamma(\eta_b(1S)) = 11^{+8}_{-6} \pm 3$ MeV/c^2.

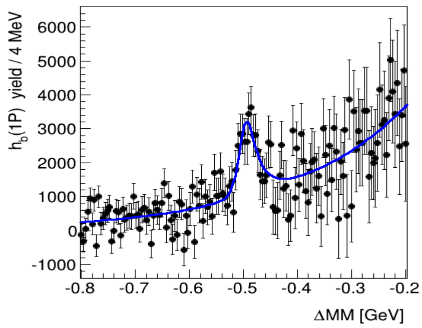

Figure 7. The ΔMM distribution. The blue curve represents the best fit.

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