Bottomonium(-like) Spectroscopy at Belle

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We report the recent progresses in bottomonium spectroscopy obtained with the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(5S)$ samples collected by the Belle experiment. In particular, using the 121 fb^{-1} collected at the $\Upsilon(5S)$ resonance, the missing singlet states $h_b(1P)$ and $h_b(2P)$ are observed for the first time with high significance. The transition $\Upsilon(5S) \to \pi^+\pi^- h_b(1,2P)$ is found to be mediated by two new, bottomonium-like, charged state Z_b and Z_b', whose nature is still argument of discussion. We also report a new measurement of the hyperfine splitting in the $1S$ system, a new high significance observation of the $\eta_b(1S)$ state and a summary of the progresses archived in the study of the $\Upsilon(nS) \to \eta\Upsilon(mS)$ transition and in the Υ decay to charmonium and double charmonium.

1 New states observation in $\Upsilon(5S) \to \pi^+\pi^- X$

The Belle experiment [1] at the KEKB e^+e^- asymmetric collider [2] collected the world largest samples of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(5S)$. The $\Upsilon(5S)$ sample revealed a totally unexpected potential for the study of the lower bottomonium resonances, in particular the singlet states h_b and η_b.

1.1 Observation of $h_b(1P)$ and $h_b(2P)$

The observation of $h_b(1P)$ and $h_b(2P)$ is made with an inclusive analysis [3], studying the distribution of the missing mass $M_{miss}(\pi^+\pi^-)$ from the $\pi^+\pi^-$ pair in $\Upsilon(5S) \to \pi^+\pi^- + X$ final states. Once the large combinatorial background is fitted and subtracted, the remaining distribution (Figure 1) shows different peaks, due to different dipion transitions: the $h_b(1P)$ and $h_b(2P)$ signals are clearly visible with a significance of 6.2 σ and 12.4 σ respectively, together with the $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(nS)$ signals.
The measured masses of the h_b states are $M_{h_b(1P)} = 9898.3 \pm 1.1^{+1.0}_{-1.1}$ MeV/c^2 and $M_{h_b(2P)} = 10259.8 \pm 0.6^{+0.4}_{-1.0}$ MeV/c^2.

1.2 Observation of Z_b and Z_b'

The $\Upsilon(5S) \to \pi^+\pi^- h_b(1P)$ transition is expected to involve amplitudes related to a spin flip of the b quark, that are predicted by non-relativistic QCD (NRQCD) to be suppressed, while the dipion transition to a lower Υ resonance is not a spin flipping process and thus is predicted not to be suppressed. The measured ratio $\frac{\mathcal{B}(\Upsilon(5S)\to\pi^+\pi^- h_b(1P))}{\mathcal{B}(\Upsilon(5S)\to\pi^+\pi^- Y(1S))} = 0.77$, surprisingly indicates no significant suppression of the spin flip transition with respect to the non flipping processes. This unexpected behavior can be explained with the introduction of an intermediate charged

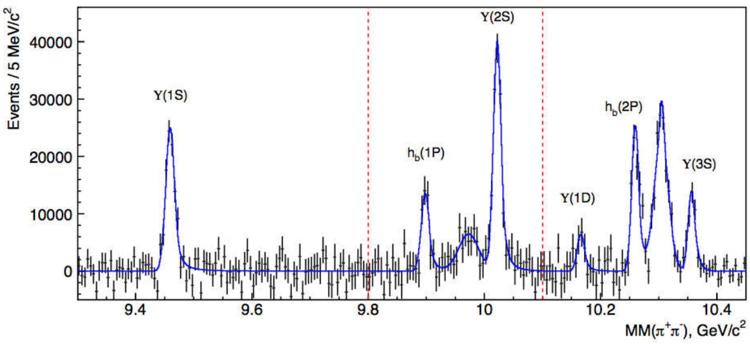

Figure 1: Missing mass in $\Upsilon(5S) \to \pi^+\pi^- + X$ events. The two peaks located at 9.95 GeV/c^2 and 10.3 GeV/c^2 are due to the known $\Upsilon(2,3S) \to \pi^+\pi^-\Upsilon(1S)$ transitions.

state that mediates the dipion transition; with this hypothesis the decay chain from the $\Upsilon(5S)$ to the h_b states should be $\Upsilon(5S) \to \pi^\pm Z_b^\mp \to \pi^+\pi^- h_b(1,2P)$, and the hypothetical Z_b state should be seen as a peak in the h_b yield distribution, when computed in bins of the missing mass form the single pion. A double peak observed in both the distributions of the $h_b(1P)$ (Figure 2) and $h_b(2P)$ (Figure 3) yields, is thus interpreted as a doublet of charged states Z_b and Z_b', with masses $M_{Z_b} = 10608 \pm 2.0$ MeV/c^2, $M_{Z_b'} = 10653 \pm 1.5$ MeV/c^2 and widths $\Gamma_{Z_b} = 15.6 \pm 2.5$ MeV, $\Gamma_{Z_b'} = 14.4 \pm 3.2$ MeV [4]. The same structures are also observed in the exclusive final states $\pi^+\pi^-\Upsilon(1,2,3S)$ where the Υ states are reconstructed in the leptonic final state $\Upsilon(nS) \to \mu^+\mu^-$. The Z_b and Z_b' parameters extracted in this five independent final states are in agreement, providing a strong observation of these states.

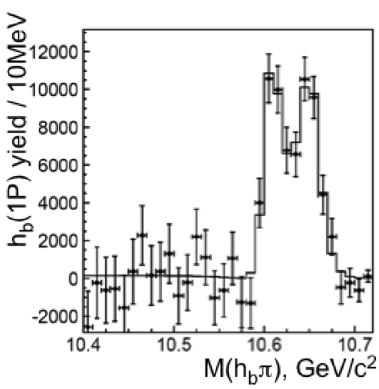

Figure 2: $h_b(1P)$ yield in bins of recoil mass against the single charged pion, in $\Upsilon(5S) \to \pi^+\pi^- + X$ events.

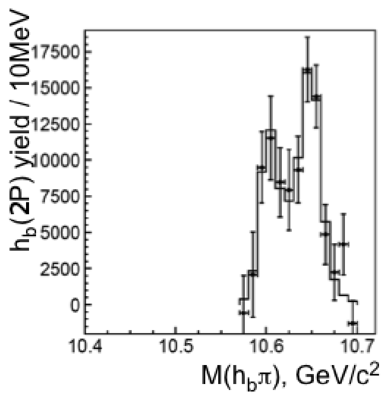

Figure 3: $h_b(2P)$ yield in bins of recoil mass against the single charged pion, in $\Upsilon(5S) \to \pi^+\pi^- + X$ events.

1.3 Observation of $h_b(1P) \to \gamma\eta_b(1S)$

The unexpected high number of h_b and the strong experimental signature provided by the observation of the Z_b allow, for the first time, the study of the radiative decay $h_b(1P) \to \gamma\eta_b(1S)$, opening new prospectives on the study of the $\eta_b(1S)$ itself [5]. This resonance, the ground state of bottomonium, was observed both by CLEO and BaBar studying the radiative transition $\Upsilon(2,3S) \to \gamma\eta_b(1S)$. This kind of studies are affected by large resonant background, mainly due to $\Upsilon(1S)$ ISR production, $\Upsilon(2S) \to \gamma\chi_b(1P)$ and $\Upsilon(2,3S) \to \pi^0\pi^0\Upsilon(1S)$ transitions. The $h_b(1P) \to \gamma\eta_b(1P)$ transition is studied requiring a single pion missing mass compatible with Z_b mass and fitting the h_b yield, extracted form the missing mass from the $\pi^+\pi^-$ system $M_{miss}(\pi^+\pi^-)$, in bins of ΔM_{miss}, where $\Delta M_{miss} = M_{miss}(\pi^+\pi^-\gamma) - M_{miss}(\pi^+\pi^-) + M(h_b)$, $M_{miss}(\pi^+\pi^-\gamma)$ is the missing mass from the $\pi^+\pi^-\gamma$ system, and $M(h_b)$ is the measured h_b mass. ΔM_{miss} peaks, by construction, at the η_b mass value, as shown in Figure 4.

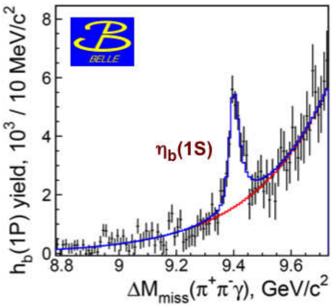

Figure 4: h_b yield in bins of ΔM_{miss}, in $\Upsilon(5S) \to \pi^\pm Z_b \to \pi^+\pi^- + X$ events.

The significance of the $\eta_b(1S)$ peak is 15 σ, and such a clean observation allows to measure with unprecedented precision the parameters of this resonance, obtaining $M_{\eta_b(1S)} = 9401.0 \pm 1.9^{+1.4}_{-2.4}$ MeV/c^2 and $\Gamma_{\eta_b(1S)} = 12.4^{+5.5+11.5}_{-5.6-3.4}$ MeV. The theoretical importance of such measurements is connected to the hyperfine splitting in the $1S$ system, defined as the mass difference between the $\Upsilon(1S)$ and the $\eta_b(1S)$. Previous measurement fixed this value slightly above the theoretical prediction obtained from both NRQCR and potential based models. The new value $\Delta M_{HF}(1S) = (59.3 \pm 1.9^{+1.6}_{-1.2})$ MeV/c^2 obtained by the Belle collaboration is lower than the previous ones and in agreement with the non-relativistic QCD predictions.

1.4 Observation of $\Upsilon(5S) \to \Upsilon(1D)\pi^+\pi^-$

A 2.5 σ $\Upsilon(1D)$ signal is visible in the dipion recoil mass distribution in $\Upsilon(5S) \to \pi^+\pi^- X$ events (Figure 1). Requiring the exclusive reconstruction of the double radiative decay $\Upsilon(1D) \to \gamma_1\chi_b(1P) \to \gamma_1\gamma_2\Upsilon(1S)$ an high significance signal of $\Upsilon(1D)$ is observed. The measured branching ratio for the complete decay chain is:
$\mathcal{B}[\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1D) \to \pi^+\pi^-\gamma_1\chi_b(1P) \to \pi^+\pi^-\gamma_1\gamma_2\Upsilon(1S)] = (2.0 \pm 0.4 \pm 0.3) \times 10^{-4}$

2 Progresses in $\Upsilon(nS) \to \eta\Upsilon(mS)$

In the QCDME formalism [6] the η transitions between Υ states should be mediated either by two M1 gluons, or by one E1 and one M2 gluon: both cases imply a spin flip of the b quark. The corresponding amplitude should scale as $1/m_b$, leading to a suppression of these processes. By scaling from the $\psi' \to \eta J/\psi$ transition, one expects $\mathbf{B}[\Upsilon(2S) \to \eta\Upsilon(1S)] = 8 \times 10^{-4}$. $\Upsilon(2,3,4S) \to \eta\Upsilon(1S)$ branching ratios have been measured by BaBar [7, 8] and CLEO [9]: they are either unexpectedly large ($\Upsilon(4S)$), or too small ($\Upsilon(2S)$ and $\Upsilon(3S)$). We search for the $\Upsilon(2S) \to \eta\Upsilon(1S)$ process with the exclusive reconstruction of the η in both the $\gamma\gamma$ and the $\pi^+\pi^-\pi^0$ mode. The $\Upsilon(1S)$ is reconstructed in the leptonic modes e^+e^- and $\mu^+\mu^-$. The measured branching ratio is $\mathcal{B}[\Upsilon(2S) \to \eta\Upsilon(1S)] = (3.41 \pm 0.28 \pm 0.35) \times 10^{-4}$, with an high

significance η signal observed.
The isospin violating transition $\Upsilon(2S) \to \pi^0\Upsilon(1S)$ is investigated too, with the same technique, but no signal is observed and and upper limit is set: $\mathcal{B}(\Upsilon(2S) \to \pi^0\Upsilon(1S)) < 4.6$ (90% CL).
The η transition is observed for the first time from $\Upsilon(5S)$ too, requiring also in this case the exclusive reconstruction of $\Upsilon(1,2S) \to \mu^+\mu^-$. We measure the branching ratios $\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon(1S)] = (7.3 \pm 1.6(stat) \pm 0.8(syst)) \times 10^{-4}$ and $\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon(2S)] = (38 \pm 4(stat) \pm 5(syst)) \times 10^{-4}$.

3 Charmonium in $\Upsilon(1,2S)$ and $\chi_b(1P)$ decays

A large study of the charmonium production in bottomonium decays was carried on by Belle during last year. In particular intensive studies of the radiative transitions $\Upsilon(1,2S) \to \gamma c\bar{c}$ and of the double charmonium production $b\bar{b} \to (c\bar{c})(c\bar{c})$ led to a large set of upper limits. In details a systematic search for η_c, χ_{cJ}, $X(3872)$, $X(3915)$, $X(4350)$, and $Y(4140)$ signals in $\Upsilon(2S)$ radiative decays is performed by Belle [10], extending a previous work on the $\Upsilon(1S)$ transitions to charmonium states [11]. A search for new resonances is performed too, looking for the $\gamma_R\gamma\psi'$ final state where γ_R is the radiative photon from the $\Upsilon(2S)$ decay. No signal is observed and upper limits are set for all the transitions at the 10^{-4} level.
The second field of research is the double charmonium production, i.e. the $b\bar{b} \to (c\bar{c})(c\bar{c})$ decays [12]. Recent studies report theoretical prediction on $b\bar{b} \to J/\psi J/\psi, J/\psi\psi', \psi'\psi'$, where $b\bar{b} = \Upsilon(1S), \Upsilon(2S), \chi_{bJ}(1P)$, obtained with different frameworks: light cone formalism (LCF), potential QCD (pQCD), and non-relativistic QCD (NRQCD). The J/ψ candidates are reconstructed in the $\mu^+\mu^-$ and e^+e^- final states, while the ψ' is reconstructed in the dominant decay $\pi^+\pi^- J/\psi$. $\chi_{b0}(1P)$,$\chi_{b1}(1P)$, and $\chi_{b2}(1P)$ are distinguished by the energy of the photon from the radiative transition $\Upsilon(2S) \to \gamma\chi_{bJ}(1P)$. Signals are observed neither in the full reconstruction of the bottomonium decays, nor in the missing mass from the J/ψ candidate distribution, and stringent upper limits are set. This upper limits are in agreement with the NRQCD predictions, while they are significantly below the light cone formalism and pQCD ones.

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