Review of bottomonium studies at Belle

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Abstract. We review recent bottomonium studies at Belle. The results include the new measurement of the $\eta_b(1S)$ mass, the observation of the $\Upsilon(4S) \to \Upsilon(1S)\eta'$ transition, and the observation of the $e^+ e^- \to \chi_{bJ}(1P)\pi^+ \pi^- \pi^0$ process in the $\Upsilon(11020)$ region.

1 Introduction

B-factories, the BaBar and Belle experiments, produced many highlights in the bottomonium physics. Among them are:

- observation of the spin-singlet states $\eta_b(1S), \eta_b(2S), h_b(1P)$ and $h_b(2P)$;
- observation of charged bottomonium-like states $Z_b(10610)$ and $Z_b(10650)$ with exotic quark content;
- observation of anomalous transitions from the $\Upsilon(4S), \Upsilon(10860)$ and $\Upsilon(11020)$.

Here we present three recent results from Belle: the new measurement of the $\eta_b(1S)$ mass [1], the observation of the $\Upsilon(4S) \to \Upsilon(1S)\eta'$ transition [2], and the observation of the $e^+ e^- \to \chi_{bJ}(1P)\pi^+ \pi^- \pi^0$ process in the $\Upsilon(11020)$ region [3].

2 New measurement of the $\eta_b(1S)$ mass

There is a substantial disagreement between various measurements of the $\eta_b(1S)$ mass [4]. Those from the $\Upsilon(2S, 3S) \to \eta_b(1S)\gamma$ transitions measured by BaBar and CLEO are grouped near 9390 MeV/$c^2$, while those from the $h_b(1P, 2P) \to \eta_b(1S)\gamma$ transitions measured by Belle are clustered near 9400 MeV/$c^2$. To improve on this, Belle studied the $\Upsilon(4S) \to \Upsilon(1S)\eta'$ transition using the 24.7 fb$^{-1}$ $\Upsilon(2S)$ data sample.

Like previous measurements, Belle used inclusive reconstruction: the energy spectrum of all photons was investigated. Selection requirements include suppression of the light quark production using event topology and $\pi^0$ veto. The $\gamma$ spectrum after subtraction of the smooth component of the fit function is shown in figure 1. The significance of the $\eta_b(1S)$ signal exceeds 7 standard deviations ($\sigma$), and this is the first observation of the $\Upsilon(2S) \to \eta_b(1S)\gamma$ transition. The $\eta_b(1S)$ width is fixed to the world-average value, and only the branching fraction and the mass are reported. For the branching fraction measurement, a non-relativistic Breit-Wigner (BW) signal shape is used, like in all previous measurements. The result $B(\Upsilon(2S) \to \eta_b(1S)\gamma) = (6.1^{+0.6+0.9}_{-0.7-0.6}) \times 10^{-4}$ agrees with the world average [4]. For the mass measurement, the BW shape multiplied by the photon energy to the third power is used.

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The result $M(\eta_b(1S)) = 9394.8^{+2.7+3.1}_{-2.7-1.1}$ MeV/$c^2$ is just between the two groups of measurements mentioned above, consistent with both of them within the uncertainties. If the $E_\gamma^2$ term is not used, the mass shifts by 2.6 MeV/$c^2$ to higher values. We conclude that more precise measurement is needed to solve the puzzle of the $\eta_b(1S)$ mass.

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

Both BaBar and Belle observed many decays of the $\Upsilon(4S)$, $\Upsilon(10860)$ and $\Upsilon(1120)$ states that do not agree with the expectations for pure bottomonium states (for review see, e.g., [5]). Puzzling properties correspond to a violation of the OZI rule and Heavy Quark Symmetry; their explanation might be a contribution of hadron loops or, equivalently, the $B$ hadron admixture in the $\Upsilon$ states. Recently, Belle reported the observation of a new transition, $\Upsilon(4S) \to \Upsilon(1S)\eta'$, using the 496 fb$^{-1}$ data sample collected at the $\Upsilon(4S)$.

The decay chains $\Upsilon(4S) \to \Upsilon(1S)\eta'$, $\Upsilon(1S) \to \mu^+\mu^-$ or $e^+e^-$, $\eta' \to \pi^+\pi^-\gamma$ or $\pi^+\pi^-\eta$, $\eta \to \gamma\gamma$ were used. The signals were identified using the $\Delta M = M(\Upsilon(4S)) - M(\Upsilon(1S)) - M(\eta')$ variable, where $M(X)$ is the mass of all the particles comprising the $X$ candidate. The distributions in the $\Delta M$ for the $\eta' \to 2\pi\gamma$ and $2\pi2\gamma$ final states are shown in figure 2. Each distribution shows a clear signal with a significance of about 4$\sigma$; the combined significance including systematic uncertainty is 5.7$\sigma$. The branching fraction is measured to be $B(\Upsilon(4S) \to \Upsilon(1S)\eta') = (3.43 \pm 0.88 \pm 0.21) \times 10^{-5}$. Belle also reported the $\eta'$ to $\eta$ production ratio of 0.20 $\pm$ 0.06, which agrees with the expectations of the $B$ hadron admixture model [6].

### 4 Observation of $e^+e^- \to \chi_{bJ}(1P)\pi^+\pi^-\pi^0$ in the $\Upsilon(11020)$ region

Among about ten known anomalous hadronic transitions from the $\Upsilon(10860)$ [5], the energy dependence was measured only for the $e^+e^- \to \Upsilon(nS)\pi^+\pi^- \ (n = 1, 2, 3)$ [7] and $e^+e^- \to \eta_b(nP)\pi^+\pi^- \ (n = 1, 2)$ [8]. Recently Belle studied also the $e^+e^- \to \chi_{bJ}(1P)\pi^+\pi^-\pi^0$ processes in the energy region above the $\Upsilon(10860)$ using scan data with about 1 fb$^{-1}$ per point.
Full reconstruction was used, with the $\chi_{bJ}(1P)$ reconstructed in the $\mu^+\mu^-\gamma$ final state. A scatter plot of $M(\pi^+\pi^-\pi^0)$ versus $M(\gamma\Upsilon(1S))$ for six energy scan data samples near the $\Upsilon(11020)$ is shown in figure 3. There is a clear clustering of events in the $\chi_{bJ}(1P)$ signal region. Along the $M(\pi^+\pi^-\pi^0)$ axis, there is a cluster of events in the $\omega$ region and there are many events at higher masses. It is evident that there is a correlation between the $M(\pi^+\pi^-\pi^0)$ and $M(\gamma\Upsilon(1S))$ variables: $\omega$ candidates are produced together with $\chi_{b2}$, while higher mass $\pi^+\pi^-\pi^0$ combinations are accompanied by $\chi_{b1}$. The significance of the $e^+e^- \rightarrow \chi_{b1}(1P)(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$ signal is 5.3 $\sigma$, thus it is the first observation of this process in the energy region of the $\Upsilon(11020)$. The significance of the $e^+e^- \rightarrow \chi_{b2}(1P)\omega$ is 4.0 $\sigma$. These values are obtained from a 2D fit of the $M(\pi^+\pi^-\pi^0)$ versus $M(\gamma\Upsilon(1S))$ distribution.

To estimate the energy dependence of the $e^+e^- \rightarrow \chi_{bJ}(1P)\pi^+\pi^-\pi^0$ cross section, the 2D fit is not repeated at every scan point. Instead, the number of signal events is counted in the combined $\chi_{b1}$ and $\chi_{b2}$ signal region and background is subtracted using sidebands. The events are not separated into the $\omega$ or higher $\pi^+\pi^-\pi^0$ mass samples. The resulting cross sections are presented in figure 4. There are three points with very high accuracy; these are the

Figure 2. Fit to the $\Delta M_\eta$ distribution for $\Upsilon(4S) \rightarrow \eta'\Upsilon(1S)$ candidates reconstructed in the $2\pi1\gamma$ (left) and $2\pi2\gamma$ (right) final states. Data are shown as points, the solid blue line shows the best fit to the data, while the dashed red line shows the background contribution.

Figure 3. (Left) A scatter plot of $M(\pi^+\pi^-\pi^0)$ versus $M(\gamma\Upsilon(1S))$ from data. Red dashed lines indicate signal regions of the $\chi_{bJ}(1P)$ and $\omega$. (Right) The projections of the 2D fit for events in the $\chi_{bJ}$ signal region. Points with error bars are data, solid lines are the best fit, dashed lines are the $\chi_{b1}$ signals, dotted lines are $\chi_{b2}$ signals, and the dash-dotted lines are the fitted background.
measurements in the $\Upsilon(10860)$ on-resonance data that were reported by Belle previously [9]. The accuracy is insufficient to conclude whether the production mechanism is resonant, non-resonant or both. Assuming that the mechanism is resonant, the cross sections are fitted using a sum of Breit-Wigner amplitudes to represent the $\Upsilon(10860)$ and $\Upsilon(11020)$ contributions. The fit results are presented in figure 4. Belle finds $\mathcal{B}(\Upsilon(10860) \to \chi_{bJ}(1P)\pi^+\pi^-\pi^0) = (2.5 \pm 0.6 \pm 2.0 \pm 0.7) \times 10^{-3}$ and $\mathcal{B}(\Upsilon(11020) \to \chi_{bJ}(1P)\pi^+\pi^-\pi^0) = (8.7 \pm 4.3 \pm 6.1_{-2.5}^{+4.5}) \times 10^{-3}$. These results agree with the expectations of the $B$ hadron loops model [10].

Belle searched also for the $e^+e^- \to \chi_{bJ}(1P)\phi$ processes in the $\Upsilon(11020)$ region using the data of six scan points and found no significant signal. These processes are expected to be strongly suppressed (factor $10^3$) compared to the $e^+e^- \to \chi_{bJ}(1P)\omega$ [10].

5 Conclusions

We presented here three recent Belle results on bottomonium. Among on-going analyses to be reported soon are the measurement of the energy dependence of the $e^+e^- \to B^*(\pi)\bar{B}^*(\pi)$ cross sections, update of the $Z_b(10610)$ and $Z_b(10650)$ lineshapes in the $B\bar{B}$ and $B\bar{B}^*$ channels, search for the $W_{bJ}$ states in the $\Upsilon(10860) \to W_{bJ}\gamma \to (\Upsilon(1S)\pi^+\pi^-)\gamma$ transitions, search for the $\Upsilon(4S,5S) \to \eta_b(1S,2S)\omega$ transitions and others.

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References