Recent Belle results in quarkonium physics

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We review selected recent Belle results in quarkonium physics, including precision measurement of the $\eta_b(1S)$ parameters, evidence for the $\eta_b(2S)$; evidence for the $\psi_2(1D)$; observation of the $\psi(4040)$ and $\psi(4160)$ transitions to $J/\psi\eta$ with anomalously high rates; observation of the $\Upsilon(5S)$ transitions to $\Upsilon(1D)\pi^+\pi^-$ and $\Upsilon(1S, 2S)\eta$. The low excitations of charmonium and bottomonium are in agreement with the Lattice QCD and effective theories calculations, while high excitations show unexpected properties.

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B-factories have made a significant contribution to the quarkonium physics, in particular, the observation of several missing low excitations and of many highly excited states with unexpected properties. In this review of recent Belle results we consider charmonium and bottomonium states in parallel to stress similarity between the two sectors. We start from low excitations and then move beyond the open flavor threshold.

1. Heavy quarkonia below open flavor thresholds

1.1 $\eta_b(1S)$ and $\eta_b(2S)$

Spin-singlet states provide information on spin-spin interaction between quark and antiquark. Observed in 2008, $\eta_b(1S)$ remained the only known bottomonium spin-singlet state [1]. Recently Belle observed the $h_b(1P)$ and $h_b(2P)$ states using transitions $\Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-$ [2]. The P-wave hyperfine splittings $\Delta M_{HF}(nP) = \sum_{J=0}^{2} \frac{2J+1}{9} m_{\chi_{bJ}(nP)} - m_{h_b(nP)}$ are measured to be $(+0.8 \pm 1.1)\,\text{MeV}/c^2$ for $n = 1$ and $(+0.5 \pm 1.2)\,\text{MeV}/c^2$ for $n = 2$ [3]; consistent with zero values are in agreement with expectations [4].

The $h_b(nP)$ production is found to be unsuppressed relative to the $\Upsilon(nS)$ production despite involved spin-flip of heavy quark. Further studies resulted in the observation of charged bottomonium-like states $Z_b(10610)$ and $Z_b(10650)$ [5, 6, 7, 8], that are discussed in a separate talk at this conference.

Large samples of the $h_b(1P)$ and $h_b(2P)$ enable the study of the $\eta_b(1S)$ and $\eta_b(2S)$ states, since the electric-dipole transitions $h_b(nP) \rightarrow \eta_b(mS)\gamma$ are expected to be prominent [9]. To reconstruct these transitions Belle measured the $h_b(nP)$ yield as a function of the $\pi^+\pi^-\gamma$ missing mass [3]. The radiative transitions from the $h_b(1P)$ and $h_b(2P)$ to the $\eta_b(1S)$ are observed with significances of 15σ and 9σ, respectively [see Fig. 1 (a) and (b)]. From simultaneous fit the
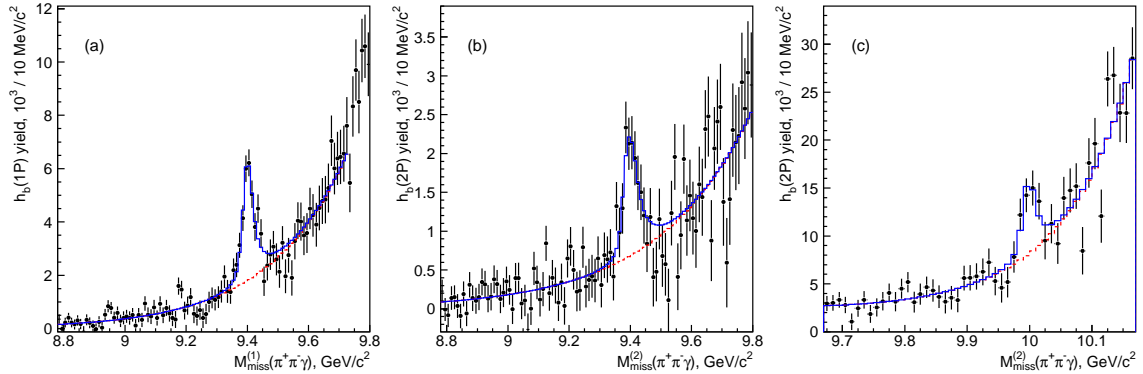

Figure 1: The $h_b(1P)$ (a) and $h_b(2P)$ (b), (c) yields as a function of the $\pi^+\pi^-\gamma$ missing mass.

mass and width of the $\eta_b(1S)$ are measured to be $m_{\eta_b(1S)} = (9402.4 \pm 1.5 \pm 1.8)\,\text{MeV}/c^2$ and $\Gamma_{\eta_b(1S)} = (10.8\,^{+4.0}_{-3.7}\,^{+4.5}_{-2.0})\,\text{MeV}$. The $\Gamma_{\eta_b(1S)}$ is a first measurement; the $m_{\eta_b(1S)}$ measurement is more precise than the current world average and is $(11.4 \pm 3.6)\,\text{MeV}/c^2$ above the central value [10]. The hyperfine splitting, $\Delta M_{HF}(1S) = (57.9 \pm 2.3)\,\text{MeV}/c^2$, is in agreement with perturbative NRQCD $(41 \pm 14)\,\text{MeV}/c^2$ [11] and Lattice $(60 \pm 8)\,\text{MeV}/c^2$ [12] calculations.

Belle found first evidence for the $\eta_b(2S)$ using radiative transition from the $h_b(2P)$ [see Fig. 1 (c)]. The $\eta_b(2S)$ significance is $4.4\,\sigma$ including systematic uncertainties and trial factor. The mass of the $\eta_b(2S)$ was measured to be $m_{\eta_b(2S)} = (9999.0 \pm 3.5\,^{+2.8}_{-1.9})\,\mathrm{MeV}/c^2$, the hyperfine splitting is $\Delta M_{\mathrm{HF}}(2S) = (24.3^{+4.0}_{-4.5})\,\mathrm{MeV}/c^2$. For the ratio of hyperfine splittings many theoretical uncertainties cancel. Belle measurement $\Delta M_{\mathrm{HF}}(2S)/\Delta M_{\mathrm{HF}}(1S) = 0.420^{+0.071}_{-0.079}$ is in agreement with NRQCD, Lattice and model-independent calculations [11, 12, 13, 14].

Belle measured also branching fractions $\mathscr{B}[h_b(1P) \to \eta_b(1S)\gamma] = (49.2 \pm 5.7\,^{+5.6}_{-3.3})\%$, $\mathscr{B}[h_b(2P) \to \eta_b(1S)\gamma] = (22.3 \pm 3.8\,^{+3.1}_{-3.3})\%$ and $\mathscr{B}[h_b(2P) \to \eta_b(2S)\gamma] = (47.5 \pm 10.5\,^{+6.8}_{-7.7})\%$. These branching fractions are somewhat higher than the quark model predictions [9].

There is another claim of the $\eta_b(2S)$ signal by the group of K. Seth from Northwestern University, that used CLEO data [15]. The $\Upsilon(2S) \to \eta_b(2S)\gamma$ production channel was considered and the $\eta_b(2S)$ was reconstructed in 26 exclusive channels with up to 10 charged tracks in the final state. This analysis requires reconstruction of low energy photon, $E_\gamma \approx \Delta M_{\mathrm{HF}}(2S)$. Claimed significance of the $\eta_b(2S)$ is $4.6\,\sigma$. The group measured $\Delta M_{\mathrm{HF}}(2S) = (48.7 \pm 2.7)\,\mathrm{MeV}/c^2$. This value is two times higher then the Belle measurement and inconsistent with Belle at the $5\,\sigma$ level. We would like to stress, that for the Belle value of the $\Delta M_{\mathrm{HF}}(2S)$ the background in the $\Upsilon(2S) \to \eta_b(2S)\gamma$ channel is very high, thus this reaction has no sensitivity to low values of the $\Delta M_{\mathrm{HF}}(2S)$ and the two reported signals can not have the same origin. We point out that in [15] the background is assumed to depend exponentially on the γ energy, while it is known that the final state radiation contributes power law tail, thus the background model is incomplete and the claimed significance is overestimated. In addition, counting the event yields in the figure from [15] one can conclude that $N[\Upsilon(2S) \to \eta_b(2S)\gamma] \approx 0.2\,N[\Upsilon(2S) \to \chi_{b1}(1P)\gamma]$. Analogous process in charmonium sector $\psi(2S) \to \eta_c(2S)\gamma$ was recently observed by BESIII [16] and the relevant ratio $\mathscr{B}[\psi(2S) \to \eta_c(2S)\gamma] \approx 0.005\,\mathscr{B}[\psi(2S) \to \chi_{c1}\gamma]$ is a factor 30 lower. We conclude that the signal claimed in [15] is unlikely to originate from the $\eta_b(2S)$.

1.2 Evidence for $\psi_2(1D)$

The D-wave charmonium levels are expected to lie between the $D\bar{D}$ and $D\bar{D}^*$ thresholds [17]. Among them, the η_{c2} with $J^{PC} = 2^{-+}$ and ψ_2 with $J^{PC} = 2^{--}$ have unnatural spin-parities and can not decay to $D\bar{D}$. Thus they remain the only undiscovered narrow charmonia.

Belle reported preliminary results on the resonant structure of the $B^+ \to K^+ \chi_{c1}\gamma$ decays, with χ_{c1} reconstructed in the $J/\psi\gamma$ mode. In the channel $\chi_{c1}\gamma$ Belle finds the first evidence for the $\psi_2(1D)$ charmonium state (see Fig. 2), with the mass of $M = (3823.5 \pm 2.8)\,\mathrm{MeV}/c^2$ and the significance of $4.2\,\sigma$ including systematic uncertainty. Measured width is consistent with zero, $\Gamma = (4 \pm 6)\,\mathrm{MeV}$; it is likely that the width is very small, since the state is observed in the radiative decay and the typical charmonium radiative decay widths are at the $O(100)\,\mathrm{keV}$ level. The odd C-parity (fixed by decay products) allows to discriminate between the η_{c2} and ψ_2 hypotheses. No signal is found in the $\chi_{c2}\gamma$ channel, in agreement with expectations for the ψ_2 [17].

Belle measures $\mathscr{B}[B^+ \to K^+ \psi_2] \times \mathscr{B}[\psi_2 \to \chi_{c1}\gamma] = (9.7^{+2.8}_{-2.5}\,^{+1.1}_{-1.0}) \times 10^{-6}$. Given expected $\mathscr{B}[\psi_2 \to \chi_{c1}\gamma] \sim \frac{2}{3}$ [17], the $\mathscr{B}[B^+ \to K^+ \psi_2]$ is a factor 50 smaller than corresponding branching fractions for the J/ψ, $\psi(2S)$ and χ_{c1} due to the factorization suppression [18].
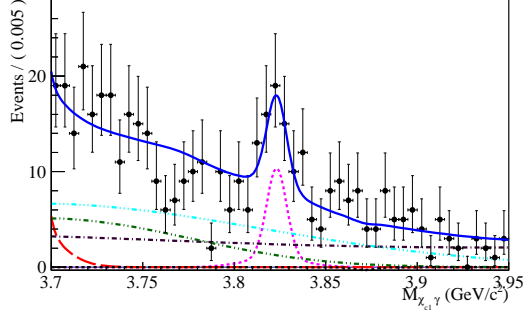
Figure 2: The $M(\chi_{c1}\gamma)$ spectrum for the $B^+ \to K^+ \chi_{c1}\gamma$ candidates.

2. Quarkonium(-like) states above open flavor thresholds

Many recently observed states above the open flavor thresholds exhibit anomalously large rates of transitions to lower quarkonia with emission of hadrons.

2.1 Observation of $\psi(4040)$ and $\psi(4160)$ transitions to $J/\psi\eta$

There are five such states in charmonium sector: the $Y(3915) \to J/\psi\omega$ observed in B meson decays and in $\gamma\gamma$ fusion [19], and four states observed in the initial state radiation (ISR) process: $Y(4008, 4260) \to J/\psi\pi^+\pi^-$ [20] and $Y(4360, 4660) \to \psi(2S)\pi^+\pi^-$ [21]. Charged charmonium-like states [22] possibly also belong to this category.

Contrary to the Y states, the ψ states were known to decay to the open flavor channels.

Belle observed transitions from $\psi(4040)$ and $\psi(4160)$ to $J/\psi\eta$ (see Fig. 3) using the ISR scan of the $e^+e^- \to J/\psi\eta$ cross-section [23]. The partial widths of these transitions are $\Gamma \sim$
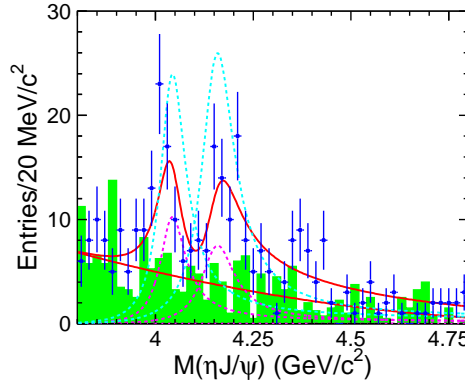

Figure 3: The $\eta J/\psi$ invariant mass distribution and the fit results. The points with error bars show the data while the shaded histogram is the normalized η and J/ψ background from the sidebands. The curves show the best fit on signal candidate events and sideband events simultaneously and the contribution from each Breit-Wigner component.

$1\,\mathrm{MeV}$, which is anomalously large. For the first time the "ordinary" ψ states that were successfully described so far as simple $c\bar{c}$ bound states, show anomalous properties.

Similar phenomenon was found also in bottomonium sector.

2.2 Anomalous hadronic transitions from $\Upsilon(5S)$

In 2008 Belle observed anomalously large rates of the $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$ ($n = 1, 2, 3$) transitions with partial widths of $\Gamma = 300 - 400\,\text{keV}$ [24]. This can be compared with $\Gamma = 1 - 6\,\text{MeV}$ for transitions from lower $\Upsilon(nS)$ states ($n = 2, 3, 4$). Recently Belle found more hadronic transitions from the $\Upsilon(5S)$.

2.2.1 Observation of $\Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^-$

Already in the $h_b(nP)$ analysis [2] Belle found signal of the inclusively reconstructed decay $\Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^-$ with the significance of $2.6\,\sigma$. The ratio of the $\Upsilon(1D)$ and $\Upsilon(2S)$ yields was found to be $\sim 1/7$, thus partial decay width $\Gamma[\Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^-]$ is at the level of $60\,\text{keV}$, which is anomalously large.

Exclusive reconstruction of the decay chain $\Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^-$, $\Upsilon(1D) \rightarrow \chi_{bJ}(1P)\gamma$, $\chi_{bJ}(1P) \rightarrow \Upsilon(1S)\gamma$, $\Upsilon(1S) \rightarrow \mu^+\mu^-$ allowed to observe this transition with the significance of $9\,\sigma$, according to preliminary Belle results (see Fig. 4 left panel). Belle measures product of branching
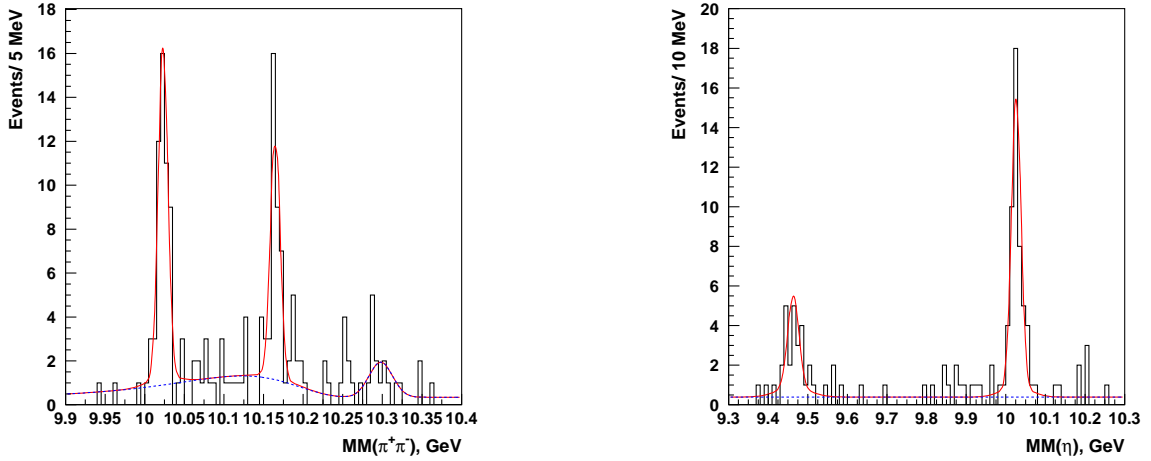

Figure 4: The missing mass spectra of $\pi^+\pi^-$ (left) and η (right) for the exclusively reconstructed hadronic transitions from the $\Upsilon(5S)$.

fractions: $\mathscr{B}[\Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^-] \times (\sum_{J=1,2} \mathscr{B}[\Upsilon(1D) \rightarrow \chi_{bJ}\gamma] \times \mathscr{B}[\chi_{bJ} \rightarrow \Upsilon(1S)\gamma]) = (2.5 \pm 0.5 \pm 0.5) \times 10^{-5}$. This is 10 times larger than a similar product for the $\Upsilon(3S) \rightarrow \Upsilon(1D)\gamma\gamma$ production channel that was measured by CLEO [25].

2.2.2 Observation of $\Upsilon(5S) \rightarrow \Upsilon(1S, 2S)\eta$

In the multipole expansion the η transition is dominated by emission of $E1M2$ gluons, while the $\pi^+\pi^-$ transition is dominated by $E1E1$ gluons, thus the ratio $R_{n\rightarrow m} = \frac{\Upsilon(nS)\rightarrow\Upsilon(mS)\eta}{\Upsilon(nS)\rightarrow\Upsilon(mS)\pi^+\pi^-}$ is expected to be small [26]. This was indeed observed for low Υ states, *e.g.* Belle recently measured $R_{2\rightarrow 1} = (1.99 \pm 0.14^{+0.12}_{-0.08}) \times 10^{-3}$ [27]. In 2008 BaBar observed the $\Upsilon(4S) \rightarrow \eta\Upsilon(1S)$ transition and measured $R_{4\rightarrow 1} = 2.41 \pm 0.40 \pm 0.21$ [28]. This unexpectedly large value pointed out to the breakdown of the multipole expansion approach.

Recently Belle reported preliminary results on the observation of the $\Upsilon(5S) \rightarrow \Upsilon(1S, 2S)\eta$ transitions (see Fig. 4 right panel). Belle measures the branching fractions $\mathscr{B}[\Upsilon(5S) \rightarrow \Upsilon(1S)\eta] = (0.73 \pm 0.16 \pm 0.08) \times 10^{-3}$, $\mathscr{B}[\Upsilon(5S) \rightarrow \Upsilon(1S)\eta] = (3.8 \pm 0.4 \pm 0.5) \times 10^{-3}$ which translate to $40 - 200\,\mathrm{keV}$ partial widths; such widths are anomalously high. For the relative rates Belle found $R_{5 \rightarrow 1} = 0.16 \pm 0.04 \pm 0.02$ and $R_{5 \rightarrow 2} = 0.48 \pm 0.05 \pm 0.09$. Thus, there is no strong suppression of η transitions from the $\Upsilon(5S)$ relative to $\pi^+\pi^-$ transitions.

2.3 Interpretation

It is proposed that the anomalously large rates of the hadronic transitions from the quarkonia above open flavor thresholds are due to the contribution of the hadron loops [29, 30]. The phenomenon can be considered either as a rescattering of the $D\bar{D}$ or $B\bar{B}$ mesons, or as a contribution of the four-quark molecular component to the quarkonium wave-function. Unsuppressed η transitions could have similar explanation [31].

Despite striking similarity between the observations in the charmonium and bottomonium sectors, there is also some difference. In charmonium, each of the $Y(3915)$, $Y(4008)$, $\psi(4040)$, $\psi(4160)$, $Y(4260)$, $Y(4360)$ and $Y(4660)$ decays to only one particular channel [$J/\psi\omega$, $J/\psi\eta$, $J/\psi\pi^+\pi^-$ or $\psi(2S)\pi^+\pi^-$]. In bottomonium, we know only one state with anomalous properties, the $\Upsilon(5S)$, that decays to many different channels [$\Upsilon(nS)\pi^+\pi^-$, $h_b(mP)\pi^+\pi^-$, $\Upsilon(1D)\pi^+\pi^-$, $\Upsilon(nS)\eta$] with similar probabilities for each channel. There is no general model giving explanation to this difference between charmonium and bottomonium. To explain affinity of the charmonium-like states to some particular channels, the notion of "hadrocharmonium" was proposed [32]. It is a heavy quarkonium embedded into a cloud of light hadron(s), thus the fall-apart decay could be dominant. Hadrocharmonium could also provide an explanation for the charged charmonium-like states observed by Belle.

3. Summary

There are many new results from Belle on the heavy quarkonium. The number of spin-singlet bottomonium states has increased from one to four over the last two years, including more precise measurement of the $\eta_b(1S)$ mass which appeared to be $11\,\mathrm{MeV}/c^2$ away from the PDG2012 average. There is an evidence of one of the two still missing narrow charmonium states expected in the region between the $D\bar{D}$ and $D\bar{D}^*$ thresholds.

Observation and detailed studies of the *charged* bottomonium-like states $Z_b(10610)$ and $Z_b(10650)$ (discussed in a separate talk) open reach phenomenological field to study exotic states near open flavor thresholds.

Belle observed new decay channels of the charmonium- and bottomonium-like states above open flavor thresholds. General feature of these states is the large rates of transitions to lower quarkonia with the emission of light hadrons. Hadron loops are important for understanding of their properties, however, there is no general theoretical model for these highly excited states yet.

We conclude that properties of low excitations are in agreement with the Lattice QCD and effective theories calculations, while high excitations show some unexpected properties, which are still not well understood. Interestingly, similar phenomena near and above open flavor thresholds are found in bottomonium and charmonium sectors.

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