Bottomonium(-like) states at $e^+e^-$ colliders

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Abstract. We review recent results on bottomonium(-like) states from $e^+e^-$ colliders. They include energy scan of the $e^+e^-$ annihilation cross sections into $\Upsilon(nS)\pi^+\pi^-$ and $h_b(nP)\pi^+\pi^-$ final states, studies of transitions from $\Upsilon(4S)$ resonance with emission of $\eta$ meson and update of $\Upsilon(5S) \rightarrow B(\ast)\bar{B}(\ast)\pi$ analysis from Belle.

1. Introduction
Studies of bottomonium were always considered to be an important test of our understanding of hadron spectroscopy [1]. Indeed, bottomonium represents one of the simplest hadronic systems that can be considered as approximately non-relativistic due to high mass of $b$ quarks. In addition, there are many narrow and well separated states, thus the system provides a rich phenomenological material. Recently, several low-lying spin-singlet states were observed by the Belle experiment [2, 3].

In this review we will concentrate on the properties of highly excited states with masses above the $BB$ threshold. During last decade it became clear that such states possess unexpected for quarkonium properties. We will consider energy scans in the $\Upsilon(10860)$ and $\Upsilon(11020)$ regions, $\eta$ transitions between bottomonium states and properties of charged exotic bottomonium-like states $Z_b(10610)$ and $Z_b(10650)$.

2. Energy scan in the $\Upsilon(10860)$ and $\Upsilon(11020)$ region
In the data collected at the $\Upsilon(10860)$ resonance, the Belle collaboration observed numerous hadronic processes that involve production of bottomonia or charged bottomonium-like states. These are $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$ ($n = 1, 2, 3$) and $\Upsilon(1S)K^+K^-$ [4], $h_b(nP)\pi^+\pi^-$ ($n = 1, 2$) [2], $\chi_bJ(1P)\omega$ [5], $\Upsilon(nS)\eta$ ($n = 1, 2$) and $\Upsilon(1D)\eta$, $Z_b(10610, 10650)\pi^+\pi^-$ [6, 7, 8]. The energy dependence of the cross section was measured only for the $\Upsilon(nS)\pi^+\pi^-$ channels [9, 10], with an observation of clear $\Upsilon(10860)$ peak. For other channels the question of whether the final states are produced from resonances, the continuum, or both, remains open.

An energy scan of the $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$ cross sections revealed that they peak also at the $\Upsilon(11020)$ resonance [10]. Thus one can expect that other processes that were observed at $\Upsilon(10860)$ are also enhanced at the $\Upsilon(11020)$.

The rates of all the above processes are anomalously large, which suggests exotic multiquark admixtures in the $\Upsilon(10860)$ and $\Upsilon(11020)$ wave functions [1]. Further studies, in particular the comparison of the $\Upsilon(10860)$ and $\Upsilon(11020)$ properties, may be helpful for a better understanding of highly excited quarkonium(-like) states. Since the $\Upsilon(10860)$ [$\Upsilon(11020)$] is expected to contain...
a $b\bar{b}$ pair in the $5S \ [6S]$ spin-triplet state, in this paper it is referred to for brevity as the $\Upsilon(5S)$ [$\Upsilon(6S)$].

The Belle experiment reported preliminary results on the energy dependence of the $e^+e^- \rightarrow h_b(nP)\pi^+\pi^-$ ($n = 1, 2$) cross sections [11]. The $h_b(nP)\pi^+\pi^-$ final states were reconstructed inclusively using missing mass of the $\pi^+\pi^-$ pairs. The requirement that the reaction proceeds via intermediate $Z_b$ states, $e^+e^- \rightarrow Z_b\pi \rightarrow h_b(nP)\pi^+\pi^-$, was also applied: $10.59 \text{GeV}/c^2 < M_{\text{miss}}(\pi^+) < 10.67 \text{GeV}/c^2$. The measured Born cross sections are shown in figure 1. The energy dependence of the $h_b(1P)\pi^+\pi^-$ and $h_b(2P)\pi^+\pi^-$ cross sections looks very similar. It shows a two-peak structure without any significant non-resonant continuum contribution. A simultaneous fit to the energy dependence of the $e^+e^- \rightarrow h_b(nP)\pi^+\pi^-$ ($n = 1, 2$) cross sections is performed. A fit function is a coherent sum of two Breit-Wigner amplitudes and (optionally) a constant with an energy continuum contribution. The significance of the non-resonant continuum contribution is found to be 1.5$\sigma$ only. Thus the default fit function does not include the continuum contribution, and it is considered only for estimation of a systematic uncertainty on the resonance parameters. The fit results for the default model are given in table 1. Resonance parameters are consistent with those of the $\Upsilon(5S)$ and $\Upsilon(6S)$ measured in the $\Upsilon(nS)\pi^+\pi^-$ final state, so the observed structures are identified as $\Upsilon(5S)$ and $\Upsilon(6S)$.

The shapes of the $e^+e^- \rightarrow h_b(nP)\pi^+\pi^-$ and $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$ [10] cross sections look very similar. The most prominent difference is a smaller relative yield of the $\Upsilon(6S)$ compared to the $\Upsilon(5S)$ in the $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$ cross section. Since the $h_b(nP)\pi^+\pi^-$ channel is produced only via intermediate $Z_b$ states, while in the $\Upsilon(nS)\pi^+\pi^-$ channel there are both $Z_b$ and non-resonant contributions, this difference can be explained if the non-resonant contribution in the $\Upsilon(nS)\pi^+\pi^-$ channel is suppressed at $\Upsilon(6S)$.

In the charmonium region the difference between the shapes of the $e^+e^- \rightarrow h_c\pi^+\pi^-$ and $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ cross sections is much more pronounced, with possible new peaks and a non-resonant contribution to the $h_c\pi^+\pi^-$ process [12]. There is at this time no clear explanation of

Figure 1. (colored online) Cross sections for the $e^+e^- \rightarrow h_b(1P)\pi^+\pi^-$ (top) and $e^+e^- \rightarrow h_b(2P)\pi^+\pi^-$ (bottom) processes as a function of center-of-mass energy [11]. Points with error bars are the data, red solid curves are the fit results.
this difference between charmonium and bottomonium.

### 3. Observation of the $\Upsilon(4S) \rightarrow h_b(1P) \eta$ transitions

Hadronic transitions between the lowest mass quarkonium levels can be described using the QCD multipole expansion (ME) [13]. In this approach, the heavy quarks emit two gluons that subsequently transform into light hadrons. The $\pi\pi$ and $\eta$ transitions between the vector states proceed via emission of $E1E1$ and $E1M2$ gluons, respectively. Indeed, the ratio of branching fractions

$$R_{\pi\pi S}(n, m) = \frac{B[\Upsilon(nS) \rightarrow \eta \Upsilon(mS)]}{B[\Upsilon(nS) \rightarrow \pi^+\pi^- \Upsilon(mS)]}$$

is measured to be small for low-lying states: $R_{\pi\pi S}(2, 1) = (1.64 \pm 0.23) \times 10^{-3}$ [15, 16, 17] and $R_{\pi\pi S}(3, 1) < 2.3 \times 10^{-3}$ [16].

Above the $B\bar{B}$ threshold, BaBar observed the transition $\Upsilon(4S) \rightarrow \eta \Upsilon(1S)$ with the unexpectedly large branching fraction of $(1.96 \pm 0.28) \times 10^{-4}$, corresponding to $R_{\pi\pi S}(4, 1) = 2.41 \pm 0.42$ [18]. This apparent violation of the heavy quark spin-symmetry was explained by the contribution of $B$ meson loops or, equivalently, by the presence of a four-quark $B\bar{B}$ component inside the $\Upsilon(4S)$ wave function [19, 20]. At the $\Upsilon(5S)$ energy, the anomaly is even more striking. The spin-flip processes $\Upsilon(5S) \rightarrow \pi\pi h_b(1P, 2P)$ are found not to be suppressed with respect to the spin-symmetry preserving reactions $\Upsilon(5S) \rightarrow \pi\pi \Upsilon(1S, 2S)$ [2], and all the $\pi\pi$ transitions show the presence of new resonant structures [6] that cannot be explained as conventional bottomonium states. Further insight into the mechanism of the hadronic transitions above the threshold can be gained by searching for the $E1M1$ transition $\Upsilon(4S) \rightarrow \eta h_b(1P)$, which is predicted to have a branching fraction of the order of $10^{-3}$ [23].

Following the approach used for the observation of the $h_b(1P, 2P)$ production at the $\Upsilon(5S)$ energy [2], Belle investigated the missing mass spectrum of $\eta$ mesons in the $\Upsilon(4S)$ data sample [24]. Figure 2 shows the $M_{\text{miss}}(\eta)$ distribution, where the transition $\Upsilon(4S) \rightarrow \eta h_b(1P)$ is observed with a statistical significance of $11\sigma$. From the position of the peak, the $h_b(1P)$ mass is measured to be $M_{h_b(1P)} = (9899.3 \pm 0.4 \pm 1.0) \text{ MeV}/c^2$, that corresponds to the $1P$ hyperfine splitting $\Delta M_{HF}(1P) = (+0.6 \pm 0.4 \pm 1.0) \text{ MeV}/c^2$. The value is compatible with zero, which agrees with the previous Belle measurement [3] and can be interpreted as evidence of the absence of sizable long range spin-spin interactions. The branching fraction of the transition is measured to be $B[\Upsilon(4S) \rightarrow \eta h_b(1P)] = (2.18 \pm 0.11 \pm 0.18) \times 10^{-3}$, in agreement with the available theoretical prediction [23]. This process is found to be the strongest known transition from the $\Upsilon(4S)$ meson to lower bottomonium states.

Exploiting the radiative transition $h_b(1P) \rightarrow \gamma \eta_b(1S)$, Belle performed a new measurement of the $\eta_b(1S)$ mass $M_{\eta_b(1S)} = (9400.7 \pm 1.7 \pm 1.6) \text{ MeV}/c^2$. This result is in agreement with the value obtained by Belle with the $\Upsilon(5S) \rightarrow \pi^+\pi^- h_b(1P) \rightarrow \pi^+\pi^- \gamma \eta_b(1S)$ process [3] but exhibits

| Parameter | $h_b(nP)\pi^+\pi^-$ | $\Upsilon(nS)\pi^+\pi^-$ |
|-----------|----------------------|------------------------|
| $M_{\Upsilon(5S)}$, MeV/$c^2$ | 10884.7$^{+3.2+8.6}_{-2.9-0.6}$ | 10891.1$^{+3.2+0.5}_{-2.1-1.5}$ |
| $\Gamma_{\Upsilon(5S)}$, MeV | 44.2$^{+11.9+2.2}_{-7.8-15.8}$ | 53$^{+7.1+0.9}_{-5.6-5.4}$ |
| $M_{\Upsilon(6S)}$, MeV/$c^2$ | 10998.6$^{+20+2}_{-6.1-1.1}$ | 10987.5$^{+4.4+0.0}_{-2.5-2.1}$ |
| $\Gamma_{\Upsilon(6S)}$, MeV | 29$^{+20+2}_{-12-7}$ | 61$^{+9+2}_{-19-20}$ |
Figure 2. $M_{\text{miss}}(\eta)$ distribution after the background subtraction. The solid blue curve shows the fit with the signal PDFs, while the dashed red curve represents the background only hypothesis. The inset shows the $M_{\text{miss}}(\eta)$ distribution before the background subtraction.

a discrepancy with the $M1$-based measurements by BaBar and CLEO [25, 26, 27]. From the theoretical point of view, the Belle measurements are in agreement with the predictions of many potential models and lattice calculations [28], including the recent lattice result in Ref. [29].

4. Observation of $Z_b(10610) \rightarrow B \bar{B}^*$ and $Z_b(10650) \rightarrow B^* \bar{B}^*$
In the $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^- (n = 1, 2, 3)$ and $\Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^- (n = 1, 2)$ transitions Belle observed intermediate charged resonances $Z_b(10610)$ and $Z_b(10650)$ that decay to bottomonium and charged pion [6]. The minimal quark content of these states is obviously exotic, it is a four-quark combination $|b\bar{b}u\bar{d}\rangle$. However, the configuration of these quarks was unclear. The two proposed possibilities are $B^{(*)}B^{(*)}$ molecules or compact diquark-antidiquark objects [1]. The fact that the masses of $Z_b(10610)$ and $Z_b(10650)$ are very close to the $B\bar{B}$ and $B^*\bar{B}^*$ thresholds, respectively, supports the molecular hypothesis. Also, measured spin-parity of $J^P = 1^+$ [8] agrees with this hypothesis, as well as other properties of these states [30]. However, the “smoking gun” test is provided by the $Z_b$ decays to the open flavor channels: they should be suppressed in case of the diquark-antidiquark structure and enhanced for the molecules [1].

Belle performed reconstruction of the $\Upsilon(5S) \rightarrow BB^*\pi$ and $\Upsilon(5S) \rightarrow B^*B^*\pi$ decays using full reconstruction of one $B$ meson and pion and examining the missing mass spectrum of $B\pi$ combinations. The spectrum of $M_{\text{miss}}(\pi)$ for $\Upsilon(5S) \rightarrow BB^*\pi$ decays shows clear $Z_b(10610)$ signal without significant contribution of the $Z_b(10650)$, while in the case of $\Upsilon(5S) \rightarrow B^*B^*\pi$ one finds the $Z_b(10650)$ signal. The fact that the $Z_b(10650) \rightarrow B\bar{B}^*$ decay is suppressed compared to the $Z_b(10650) \rightarrow B^*\bar{B}^*$ decay despite a much larger phase space can not be explained in the diquark-antidiquark picture, while it qualitatively agrees with the molecular hypothesis. The branching fraction of the open flavor channels is found to be at the level of 80%, thus these channels dominate, which disfavors the tetraquark hypothesis too. Preliminary results of the presented study are available in Ref. [31]. Belle will publish final results soon.
5. Conclusions

Recently it was established that the anomalous production of \(e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-\) and \(e^+e^- \rightarrow h_b(nP)\pi^+\pi^-\) reactions is related to the \(\Upsilon(5S)\) and \(\Upsilon(6S)\) resonances, with little or no continuum contribution. The anomalous transitions from \(\Upsilon(6S)\) were observed for the first time. Resonant structure studies of the \(\Upsilon(6S) \rightarrow h_b(nP)\pi^+\pi^-\) decays indicates that they proceed via intermediate \(Z_b(10610)\) and/or \(Z_b(10650)\) states. One more channel where statistics is probably sufficient to measure energy dependence of the cross section at Belle is \(\Upsilon(2S)\). This result is to come. More precise energy scan in the \(\Upsilon(5S)\) and \(\Upsilon(6S)\) energy regions and above are expected at the new experiment Belle-II, which is under construction.

Belle observed \(\Upsilon(4S) \rightarrow h_b(1P)\eta\) decays with very high branching fraction and performed a new measurement of the \(h_b(1P)\) and \(\eta_b(1S)\) parameters, that agree with previous Belle measurements. These results are important for understanding of hadronic transitions from \(\Upsilon\) states above open flavor threshold. Also, since at Belle-II a 50 times larger sample of \(\Upsilon(4S)\) decays will be collected, it opens new perspectives for studies of spin-singlet states, in particular, the search for exclusive \(\eta_b(1S)\) decays.

Belle also updated the study of \(Z_b(10610)\) and \(Z_b(10650)\) decays to open flavor channels. Dominance of the \(Z_b(10610) \rightarrow BB^{\ast}\) and \(Z_b(10650) \rightarrow B^{\ast}\bar{B}^{\ast}\) is confirmed, while the \(Z_b(10650) \rightarrow BB^{\ast}\) decay is found to be suppressed despite relatively large phase space. These results are in agreement with the hypothesis, that \(Z_b\) states have molecular structure, and strongly disfavor the diquark-antidiquark hypothesis. Further improvement in the lineshape measurement is crucial to determine couplings in molecular models [32].

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