Bottomonium physics at \( \Upsilon(4S, 5S, 6S) \) energies with the Belle detector

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Abstract. The description of quarkonia as pure quark anti-quark bound states has been recently challenged by the observation of charged states in both the charmonium and bottomonium region and large violations of the heavy quark spin symmetry in hadronic transitions. All these effects can be ascribable to non-negligible contributions from the light quark degrees of freedom in the description of both charmonia and bottomonia. We will report the most recent experimental measurements performed by the Belle collaboration in the \( \Upsilon(4S) \), \( \Upsilon(5S) \) and \( \Upsilon(6S) \) regions, including the measurement of the ratio \( \sigma(e^+e^- \rightarrow b\bar{b})/\sigma(e^+e^- \rightarrow \mu^+\mu^-) \), the search for neutral states near the \( B^0\bar{B}^0 \) threshold, the first observation of the transition \( \Upsilon(4S) \rightarrow \eta h(1P) \) and the study of the \( \eta \) transitions at the \( \Upsilon(5S) \) energy. The contribution to the study of the structure of these states coming from the measurement of hadronic transitions will be discussed.

1. Quarkonium near the thresholds as a QCD laboratory

A new rich phenomenology consisting in new exotic states, unexpected transitions or sizable corrections to the energy levels above the threshold has been discovered in the last years, challenging the available theoretical models and triggering wide discussion in both the theoretical and experimental communities [1, 2, 3]. The common denominator of all the new, unexpected effects is the presence of light degrees of freedom not accounted by the simple \( b\bar{b} \) model. The fact that thresholds located nearby a resonant state can shift its mass [4, 5] or modify its decay modes is known since long time as coupled channel effect. The presence in the quarkonium of light degrees of freedom, more and more important approaching the open flavor threshold, is therefore not a new or unexpected phenomenon in the quarkonium sector, and the coupled channel effects were already included in early descriptions of the dipion transitions from the \( \Upsilon(3S) \) [6, 7]. What was surprising in the last years is the manifestation of light quark effects in a number of different ways, perhaps the most spectacular one being the appearance of large number of unpredicted states with exotic quantum numbers in both the bottomonium and charmonium sector. We present here the most recent results on the bottomonium states above the thresholds, \( \Upsilon(4S, 5S, 6S) \), obtained using the data samples collected by the Belle detector [8] at the KEKB \( e^+e^- \) collider [9].

2. The role of hadronic transitions

The study of charmonia and bottomonia, despite their similar structure, offer an insights into different dynamic regimes: while the charmonium spectrum is known to get significant relativistic correction, the dynamic of the \( b\bar{b} \) quarks in a bottomonium state lays completely in the non-relativistic regime. As a consequence, the heavy quark spin symmetry (HQSSS) is expected to
be a good symmetry that determines the selection rules for the hadronic transition. Therefore, violations of these selection rules can lead insights on the HQSS violation mechanisms related to the presence of light quarks. Experimentally the study of the exotic charmonium states is much easier than the bottomonium ones. The former one can both be produced in $e^+e^-$ collisions, $B$ meson decays or complete $pp$ annihilations. The study of charmonium in complete $pp$ annihilation in particular, already carried on at the CERN intersecting storage rings [10] and more recently at Fermilab [11, 12] until 2000, is now looked as the most promising way to finally disentangle the ambiguities left by the observations made at the B- and tau/cram factories and to measure the width of the exotic states, which are often not precisely measurable at the $e^+e^-$ colliders. The proposed Panda experiment [13] at the FAIR facility [14] should resume this kind of research in the future. On the other hand, the study of bottomonium is experimentally more challenging: the only feasible way to search for exotic states is the production of $1^{--}$ states at $e^+e^-$ collider, and the observation of other states with different quantum numbers through hadronic and radiative transition. Therefore the study of the hadronic transitions plays, from a certain point of view, a prominent role in the bottomonium sector.

3. $\sigma[e^+e^- \rightarrow hadrons]$ in the $\Upsilon(5S,6S)$ region

The first striking anomaly in the region above the open beauty threshold was reported by the Belle collaboration, that measured a branching fraction for the transition $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ several orders of magnitude larger than the expectations [15]. Furthermore, the $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(1S)$ and $e^+e^- \rightarrow hadrons$ cross sections were reported not to be peaking at the same energy, leading to speculations about the presence of two overlapping resonances instead of one single bottomonium state [16]. Belle performed a new scan of the region during the final phase of the data taking, and re-measured more precisely the cross section for the production of both the inclusive $bb$ pairs, $\sigma[e^+e^- \rightarrow bb]$, and $\Upsilon(nS)$ via a dipion transition, $\sigma[e^+e^- \rightarrow \pi^+\pi^-\Upsilon(1S,2S,3S)]$ [17], in the form of the ratios $R_b = \frac{\sigma[e^+e^- \rightarrow bb]}{\sigma[e^+e^- \rightarrow \mu^+\mu^-]}$ and $R_{\pi\pi} = \frac{\sigma[e^+e^- \rightarrow \pi^+\pi^-\Upsilon(1S,2S,3S)]}{\sigma[e^+e^- \rightarrow \mu^+\mu^-]}$. Thanks to the previous studies on the $\Upsilon(nS)$ and $Z_b$ production from $\Upsilon(5S)$ [18], $R_b$ can for the first time be analyzed into its different components. Surprisingly, the known contributions of the hadronic transitions $\Upsilon(5S) \rightarrow \pi^+Z_b^- \rightarrow \pi^+[B^*\bar{B}(l)]$, $\Upsilon(5S) \rightarrow \pi^+\pi^-h_b(1P,2P)$ and $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(nS)$ saturate the cross section at the $\Upsilon(5S)$ energy, leaving no space for direct decays of $\Upsilon(5S)$ into $B$ meson pairs. This observation is obviously inconsistent with the copious production of $B_s$ known to occur at the $\Upsilon(5S)$ energy. If it is not due to $\Upsilon(5S)$ annihilations as the decomposition of $R_b$ suggests, it must come directly from the continuum. However, if the $\Upsilon(5S)$ really decays entirely into other bottomonium states and the two-body $B$ meson production is completely due to the $bb$ continuum, then there should be no or little interference between the $\Upsilon(5S)$ resonance and the continuum itself, in contrast with the results of the fit that show a sizable interference effect. All these evidences strongly suggest that the complex threshold structure above the open flavor threshold cannot be simply approximated by a constant distribution, and that the resonance parameters extracted with this fit could be affected by some unknown bias. This bias however can be avoided measuring the resonance parameters with $R_{\pi\pi}$ instead of $R_b$.

The study of $R_{\pi\pi}$ is done reconstructing the exclusive $\Upsilon(nS)$ annihilations into muon pairs. The parameters fitted in the different $\Upsilon$ final states are in agreement, therefore a simultaneous fit is performed to increase the overall precision. No $\pi\pi\Upsilon$ final states are expected to be produced directly by the continuum reaction, therefore the fitting function can be simplified removing the continuum-components, but introducing additional factors to account for the different phase space sizes due to the different $\Upsilon(nS)$ masses.

For the first time, we report the observation of the $\pi\pi$ transitions from the $\Upsilon(6S)$. The resonance parameters obtained in the two analyses have a $2\sigma$ level discrepancy, but this can be
ascribed to the mismodelling of the continuum contribution in the fit of $R_b$.

4. Hadronic transitions from $\Upsilon(5S)$ and $\Upsilon(6S)$

We saw that unexpected dipion transitions from the $\Upsilon(5S)$ challenged our understanding of the $\Upsilon(5S)$ nature and lead to the discovery of the first tetraquark-like bottomonium states, the $Z_b$. In addition, the hadronic transitions are challenging the most common theoretical models developed for their description, in particular the QCD multipole expansion (QCDME) [19, 20, 21, 22, 23, 24, 25, 26], in which the HQSS is preserved. The HQSS violation effects in bottomonium are expected to be of the order of $\Lambda^2_{QCD}/m_b^2$. To study these effects it is required to measure both the $\eta$ and the $\pi\pi$ transitions rates between two states: the $\eta$ meson transitions among vector states are HQSS violating since, in the QCDME framework, they are described by the emission of a chromo-magnetic gluon, while the corresponding di-pion transitions are HQSS preserving. Therefore the ratios between the $\eta$ and $\pi\pi$ transitions among $\Upsilon(3S)$, $\Upsilon(2S)$ and $\Upsilon(1S)$, $\mathcal{R}_{\eta,\pi\pi}^{3S,2S\rightarrow 1S}$ are expected to be of the order of $\Lambda^2_{QCD}/m_b^2 \approx 4 \times 10^{-3}$. This QCDME prediction meets, at least qualitatively the experimental measurements in the sector of narrow bottomonia, indicating that the HQSS is indeed a good symmetry: $\mathcal{R}_{\eta,\pi\pi}^{2S\rightarrow 1S} = (1.6 \pm 0.2) \times 10^{-3}$ [27, 28, 29] and $\mathcal{R}_{\eta,\pi\pi}^{3S\rightarrow 1S} < 2.1 \times 10^{-3}$ [28]. At the $\Upsilon(4S)$ energy however the situation is completely reversed. The BaBar collaboration measured $\mathcal{R}_{\eta,\pi\pi}^{3S\rightarrow 1S} < 2.4 \pm 0.5$ [30], therefore the spin fliping process is even enhanced with respect to the non spin-flipping one. Soon after a similar behavior was also observed in the $\Upsilon(5S)$ decays, where the $\eta$ transitions [31] are of the same order of magnitude of the $\pi\pi$ ones: $\mathcal{R}_{\eta,\pi\pi}^{5S\rightarrow 1S} = 0.13 \pm 0.10$ and $\mathcal{R}_{\eta,\pi\pi}^{5S\rightarrow 2S} = 0.49 \pm 0.37$. Even if the QCDME model is expected to be not reliable for wide states, such a large violation of the HQSS triggered the interest of the theoretical community.

In order to complete the exploration of the possible $\eta$ $\pi\pi$ transitions, the Belle collaboration recently studied extensively the last class of process left unexplored: the $\eta$ transitions from $\Upsilon(4S)$ and $\Upsilon(5S)$ to the spin-singlets $h_b(nP)$. Since no $h_b(1,2P)$ exclusive decay modes are known to have a significant branching fraction and a clear experimental signature, the analysis is performed inclusively: the signals of $\Upsilon(4,5S) \rightarrow \eta(h_b)$ transitions are expected to appear as peaks in the recoil mass spectrum of the $\eta$ candidates in the samples of hadronic events collected at the $\Upsilon(4,5S)$ energies. We reconstruct the $\eta$ meson in the $\gamma\gamma$ decay mode, that guarantees the lowest combinatorial background.

By this mean the $\Upsilon(4S) \rightarrow \eta h_b(1P)$ transition is observed for the first time, with a statistical significance greater than 5$\sigma$, and the corresponding branching ratio is $\mathcal{B}[\Upsilon(4S) \rightarrow \eta h_b(1P)] = (2.18 \pm 0.11 \pm 0.18) \times 10^{-3}$ [32], in agreement with the available theoretical predictions [33, 34]. This is by far the largest known hadronic transition from the $\Upsilon(4S)$, and offers a new, unexpected gateway to the bottomonium spin-singlet states. The same analysis performed at the $\Upsilon(5S)$ energy shows significant peaks in correspondence of the $\Upsilon(5S) \rightarrow \eta \Upsilon(2S)$, and $\Upsilon(5S) \rightarrow \eta \Upsilon(31D)$, with statistical significance of 3.1$\sigma$ and 4.4$\sigma$, respectively.

With these new results, we are able to improve the overall knowledge of the hadronic transitions and make a comprehensive comparison between the experimental measurements and the theoretical predictions. Figure 1 and 2 show a comparison between some theoretical prediction based on different approaches [26, 35, 36, 37, 38, 41, 40] and the experimental measurements. Each branching ratio is, individually, well predicted by at least one author. Nevertheless, no model is able to correctly reproduce the branching ratios observed below and above threshold in a single framework. \textit{W} are still lacking a unified approach to all the hadron transitions from the different states due to theoretical incomprehensions, or the physical mechanism generating the transitions is strikingly different in the two mass regions. Furthermore, while the transitions from above the threshold seems to be overall well described by the introduction of coupled channel effects, loops or hybrid states as HQSS breaking mechanism in the QCDME, the theoretical landscape is surprisingly confused in the region below the
threshold, where these effects are expected to be small and the HQSS should be dominant.

5. References
[1] N. Brambilla et al., Eur. Phys. J. C 74, no. 10, 2981 (2014) doi:10.1140/epjc/s10052-014-2981-5 [arXiv:1404.3723 [hep-ph]].
[2] N. Brambilla et al. [Quarkonium Working Group Collaboration], hep-ph/0412158.
[3] N. Brambilla et al., Eur. Phys. J. C 71, 1534 (2011) doi:10.1140/epjc/s10052-010-1534-9 [arXiv:1010.5827 [hep-ph]].
[4] N. A. Tornqvist, Phys. Rev. Lett. 53, 878 (1984). doi:10.1103/PhysRevLett.53.878
[5] N. A. Tornqvist, Acta Phys. Polon. B 16, 503 (1985) [Acta Phys. Polon. B 16, 683 (1985)].
[6] P. Moxhay, Phys. Rev. D 39, 3497 (1989). doi:10.1103/PhysRevD.39.3497
[7] H. Y. Zhou and Y. P. Kuang, Phys. Rev. D 44, 756 (1991). doi:10.1103/PhysRevD.44.756
[8] A. Abashian et al., Nucl. Instrum. Meth. A 479, 117 (2002). doi:10.1016/S0168-9002(01)02013-7
[9] S. Kurokawa, E. Kikutani, Nucl. Instrum. Meth. A 499, 1 (2003). and other papers included in this volume.
[10] C. Baglin et al. [R704 and Annecy(LAPP)-CERN-Genoa-Lyon-Oslo-Rome-Strasbourg-Turin Collaborations], Phys. Lett. B 171, 135 (1986). doi:10.1016/0370-2693(86)91013-0
[11] T. A. Armstrong et al. [E760 Collaboration], Phys. Rev. Lett. 68, 1468 (1992). doi:10.1103/PhysRevLett.68.1468
[12] C. Patrignani et al. [FNAL-ES35 Collaboration], AIP Conf. Proc. 717, 581 (2004) [Nucl. Phys. Proc. Suppl. 142, 98 (2005)]. doi:10.1016/j.nuclphysbps.2005.01.017
[13] M. F. M. Lutz et al. [PANDA Collaboration], arXiv:0903.3905 [hep-ex].
[14] P. Spiller and G. Franchetti, Nucl. Instrum. Meth. A 561, 305 (2006). doi:10.1016/j.nima.2006.01.043
[15] K.-F. Chen et al. [Belle Collaboration], Phys. Rev. D 82, 091106 (2010) doi:10.1103/PhysRevD.82.091106 [arXiv:0810.3829 [hep-ex]].
[16] A. Ali, C. Hambrock, I. Ahmed and M. J. Aslam, Phys. Lett. B 684, 28 (2010) doi:10.1016/j.physletb.2009.12.053 [arXiv:0911.2787 [hep-ph]].
[17] D. Santel et al. [Belle Collaboration], arXiv:1501.01137 [hep-ex].
[18] A. Bondar et al. [Belle Collaboration], Phys. Rev. Lett. 108, 122001 (2012) doi:10.1103/PhysRevLett.108.122001 [arXiv:1110.2251 [hep-ex]].
[19] K. Gottfried, Phys. Rev. Lett. 40, 598 (1978).
[20] G. Bhanot, W. Fischler and S. Rudaz, Nucl. Phys. B 155, 208 (1979).
[21] M. E. Peskin, Nucl. Phys. B 156, 365 (1979).
[22] G. Bhanot and M. E. Peskin, Nucl. Phys. B 156, 391 (1979).
[23] M. B. Voloshin, Nucl. Phys. B 154, 365 (1979).
[24] M. B. Voloshin and V. I. Zakharov, Phys. Rev. Lett. 45, 688 (1980).
[25] Y. P. Kuang and T. M. Yan, Phys. Rev. D 24, 2874 (1981). doi:10.1103/PhysRevD.24.2874
[26] Y. P. Kuang, Front. Phys. China 1, 19 (2006) doi:10.1007/s11467-005-0012-6 [hep-ph/0601044].
[27] Q. He et al. (CLEO Collaboration), Phys. Rev. Lett. 101, 192001 (2008).
[28] J. P. Lees et al. (BaBar Collaboration), Phys. Rev. D 84, 092003 (2011).
[29] U. Tamponi et al. (Belle Collaboration), Phys. Rev. D 87, 011104 (2013).
[30] B. Aubert et al. (BaBar Collaboration), Phys. Rev. D 78, 112002 (2008).
[31] U. Tamponi, EPJ Web Conf. 70, 00034 (2014). doi:10.1051/epjconf/2014700034
[32] U. Tamponi et al. [Belle Collaboration], Phys. Rev. Lett. 115, no. 14, 142001 (2015) doi:10.1103/PhysRevLett.115.142001 [arXiv:1506.08914 [hep-ex]].
[33] F. K. Guo, C. Hanhart and U. G. Meissner, Phys. Rev. Lett. 105, 162001 (2010) doi:10.1103/PhysRevLett.105.162001 [arXiv:1007.4682 [hep-ph]].
[34] J. Segovia, F. Fernandez and D. R. Entem, arXiv:1507.01607 [hep-ph].
[35] Y. A. Simonov and A. I. Veselov, Phys. Rev. D 79, 034024 (2009) doi:10.1103/PhysRevD.79.034024 [arXiv:0804.4635 [hep-ph]].
[36] Y. A. Simonov and A. I. Veselov, Phys. Lett. B 671, 55 (2009) doi:10.1016/j.physletb.2008.12.001 [arXiv:0805.4499 [hep-ph]].
[37] Y. A. Simonov and A. I. Veselov, arXiv:0806.2919 [hep-ph].
[38] Y. A. Simonov, Phys. Atom. Nucl. 71, 1048 (2008) doi:10.1134/S1063778808060004 [arXiv:0711.3626 [hep-ph]].
[39] C. Meng and K. T. Chao, Phys. Rev. D 77, 074003 (2008) doi:10.1103/PhysRevD.77.074003 [arXiv:0712.3595 [hep-ph]].
[40] J. Segovia, D. R. Entem and F. Fernandez, Phys. Rev. D 91, no. 1, 014002 (2015) doi:10.1103/PhysRevD.91.014002 [arXiv:1409.7079 [hep-ph]].
[41] C. Meng and K. T. Chao, Phys. Rev. D 77, 074003 (2008) doi:10.1103/PhysRevD.77.074003 [arXiv:0712.3595 [hep-ph]].