Developments in heavy quarkonium spectroscopy

S. Eidelman,1, 2 B. K. Heltsley,3 J. J. Hernández-Rey,4 S. Navas,5 and C. Patrignani6

1Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090, Russia
2Novosibirsk State University, Novosibirsk 630090, Russia
3Cornell University, Ithaca, NY 14853, USA
4Instituto de Física Corpuscular, Universitat de València-CSIC, Edificio de Investigación de Paterna, Apdo. 22085, E-46071 Valencia, Spain
5Departamento de Física Teórica y del Cosmos & CAFPE, Universidad de Granada, 18071 Granada, Spain
6Dipartimento di Fisica e INFN, Università di Genova. I-16146 Genova, Italy

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We summarize recent developments in heavy quarkonium spectroscopy, relying on previous review articles for the bulk of material available prior to mid-2010. This note is intended as a mini-review to appear in the 2012 Review of Particle Physics published by the Particle Data Group.

A golden age for heavy quarkonium physics dawned a decade ago, initiated by the confluence of exciting advances in quantum chromodynamics (QCD) and an explosion of related experimental activity. The subsequent broad spectrum of breakthroughs, surprises, and continuing puzzles had not been anticipated. In that period, the BESII program concluded only to give birth to BE-SIII; the B-factories and CLEO-c flourished; quarkonium production and polarization measurements at HERA and the Tevatron matured; and heavy-ion collisions at RHIC opened a window on the deconfinement regime. For an extensive presentation of the status of heavy quarkonium physics, the reader is referred to several reviews [1–7], the last of which covers developments through the middle of 2011, Springer). This note focuses solely on experimental developments in heavy quarkonium spectroscopy, and in particular on those too recent to have been included in [7].

Table 1 lists properties of newly observed conventional heavy quarkonium states, where “newly” is interpreted to mean within the past decade. The $h_c$ is the $1P_1$ state of charmonium, singlet partner of the long-known $\chi_{cJ}$ triplet $3P_1$. The $\eta_c(2S)$ is the first excited state of the pseudoscalar ground state $\eta_c(1S)$, lying just below the mass of its vector counterpart, $\psi(2S)$. The state originally dubbed $Z(3930)$ is now regarded by many as the first observed $2P$ state of $\chi_{cJ}$, the $\chi_{c2}(2P)$. The first $B$-meson seen that contains charm is the $B_s^+$. The ground state of bottomonium is the $\eta_b(1S)$, recently confirmed with a second observation of more than 5$\sigma$ significance. The $\Upsilon(1D)$ is the lowest-lying $D$-wave triplet of the $b\bar{b}$ system. Both the $h_b(1P)$, the bottomonium counterpart of $h_c(1P)$, and the next excited state, $h_b(2P)$, were very recently observed by Belle [31], as described further below, in dipion transitions from either the $\Upsilon(5S)$ or $Y_b(10888)$. All fit into their respective spectroscopies roughly where expected. Their exact masses, production mechanisms, and decay modes provide guidance to their descriptions within QCD. The $h_b(nP)$ states still need experimental confirmation at the 5$\sigma$ level, as does the $\chi_{bJ}(3P)$ triplet.

Correspondingly, the menagerie of new, heavy-quarkonium-like unanticipated states* is shown in Table 2; notice that just a handful have been experimentally confirmed. None can unambiguously be assigned a place in the hierarchy of charmonia or bottomonia; neither do any have a universally accepted unconventional origin. The $X(3872)$ occupies a unique niche among the unexplained states as both the first and the most intriguing. It is, by now, widely studied, yet its interpretation demands much more experimental attention. The $Y(4260)$ and $Y(4360)$ are vector states decaying to $\pi^+\pi^-J/\psi$ and $\pi^+\pi^-\psi(2S)$, respectively, yet, unlike most conventional vector charmonia, do not correspond to enhancements in the $e^+e^-$-hadronic cross section. The three $Z_c^+$ and two $Z_b^+$ states, each decaying to a charged pion and conventional heavy quarkonium state, would be manifestly exotic, but remain unconfirmed. Final states of the type $\Upsilon(nS)\pi^+\pi^-$ from $e^+e^-$ collisions acquired near the $\Upsilon(5S)$ have a lineshape differing somewhat from that of multi-hadronic events, which suggested a new state $Y_b(10888)$, distinct from $\Upsilon(5S)$, which could be analogous to $Y(4260)$. The nature of $Y_b(10888)$, if it does mimic the behavior of the charmonium-region $Y$’s, could help to explain the observed (and otherwise unexpected) high rate of dipion transitions to $\Upsilon(nS)$ and $h_b(nP)$ seen in $e^+e^-$ collisions near the $\Upsilon(5S)$ region. It could also provide insight into the $Z_b^+$ states, which appear to be intermediate resonances in the dipion transitions.

BaBar [59, 71] has searched for the three $Z_c^+$ states in the charmonium mass region seen by Belle, and failed to observe any significant signals. The approach taken in searching for $B \to Z_c^+K \to (c\bar{c})K\pi$, where (c\bar{c}) is $\psi(2S)$ or $\chi_{c1}$, is to first fit the data for all reasonable $K\pi$ mass or angular structure, having demonstrated that the presence of one or more $Z$’s cannot be accommodated by this procedure. After doing so, the finding is that

* For consistency with the literature, we preserve the use of $X, Y, Z,$ and $G$, contrary to the practice of the PDG, which exclusively uses $X$ for unidentified states.
TABLE 1: New conventional states in the \( c\bar{c}, b\bar{c}, \) and \( b\bar{b} \) regions, ordered by mass. Masses \( m \) and widths \( \Gamma \) represent the weighted averages from the listed sources. Quoted uncertainties reflect quadrature summation from individual experiments. In the Process column, the decay mode of the new state claimed is indicated in parentheses. Ellipses (...) indicate inclusively selected event topologies; i.e., additional particles not required by the Experiments to be present. A question mark (?) indicates an unmeasured value. For each Experiment a citation is given, as well as the statistical significance in number of standard deviations \((\#\sigma)\), or "(np)" for "not provided". The Year column gives the date of first measurement cited. The Status column indicates if the state has been observed at least by one result (NC!-needs confirmation) or at least two independent experiments with significance of \( >5\sigma \) (OK). The state labelled \( \chi_{c2}(2P) \) has previously been called \( Z(3930) \). See also the reviews in [1–7]. Adapted from [7] with kind permission, copyright (2011), Springer.

| State       | \( m \) (MeV) | \( \Gamma \) (MeV) | \( J^{PC} \) | Process (mode)                                                                 | Experiment \((\#\sigma)\) | Year | Status |
|-------------|---------------|---------------------|-------------|--------------------------------------------------------------------------------|----------------------------|------|--------|
| \( h_c(1P) \) | 3525.41 ± 0.16 | <1 \( 1^{-+} \)   | \( \psi(2S) \to \pi^0(\gamma\eta_c(1S)) \) | CLEO [8–10] \((13.2)\)                                               | 2004 OK                   |
| \( \eta_c(2S) \) | 3638.9 ± 1.3   | 10±4 \( 0^{-+} \)  | \( B \to K (K_S^0 K^− \pi^+) \) \( e^+ e^- \to e^+ e^- (K_S^0 K^− \pi^+) \) | Belle [13, 14] \((6.0)\)                        | 2002 OK                   |
| \( \chi_{c2}(2P) \) | 3927.2 ± 2.6   | 24±6 \( 2^{++} \)  | \( e^+ e^- \to J/\psi (D\bar{D}) \) | Belle [21] \((5.3)\), BABAR [22, 23] \((5.8)\)   | 2005 OK                   |
| \( B_s^+ \)   | 6277 ± 6       | 0 \( 0^- \)        | \( p\bar{p} \to (\pi^+ J/\psi) ... \) | CDF [24, 25] \((8.0)\), DO [26] \((5.2)\) | 2007 OK                   |
| \( \eta_b(1S) \) | 9395.8 ± 3.0   | 12.4±12.7 \( 0^{-+} \) | \( \Upsilon(3S) \to \gamma (...) \) \( \Upsilon(5S) \to \pi^+ \pi^- \gamma (...) \) | BABAR [27] \((10)\), CLEO [28] \((4.0)\) | 2008 OK                   |
| \( h_b(1P) \)  | 9898.6 ± 1.4   | ? \( 1^{-+} \)     | \( \Upsilon(5S) \to \pi^+ \pi^- (...) \) \( \Upsilon(3S) \to \pi^0 (...) \) | Belle [30, 31] \((5.5)\), BABAR [32] \((3.0)\) | 2011 NC!                   |
| \( \Upsilon(1D_2) \) | 10163.7 ± 1.4 | ? \( 2^{--} \)     | \( \Upsilon(3S) \to \gamma \gamma(\gamma \Upsilon(1S)) \) \( \Upsilon(5S) \to \pi^+ \pi^- \Upsilon(1S) \) | CLEO [33] \((10.2)\)                       | 2004 OK                   |
| \( h_b(2P) \)  | 10259.8±1.5 \( 1^{-+} \) | ? \( 1^{-+} \)     | \( \Upsilon(5S) \to \pi^+ \pi^- (...) \) | Belle [31] \((11.2)\)                     | 2011 NC!                   |
| \( \chi_{bJ}(3P) \) | 10530 ± 10     | ? \( ? \)          | \( pp \to (\gamma \mu^+ \mu^-) ... \) | ATLAS [35] \((>6)\)                  | 2011 NC!                   |
detected production mechanism, \( \Upsilon(3S) \to \pi^0 h_b(1P) \). In early 2011 \textit{BaBar} presented marginal evidence for this transition at the 3\( \sigma \) level, at a mass near that expected for zero hyperfine splitting.

The \textit{Belle} \( h_b \) discovery analysis [31] selects hadronic events and looks for peaks in the mass recoiling against \( \pi^+ \pi^- \) pairs, the spectrum for which, after subtraction of smooth combinatoric and \( K^0_{S} \to \pi^+ \pi^- \) backgrounds, appears in Fig. 1. Prominent and unmistakable \( h_b(1P) \) and \( h_b(2P) \) peaks are present. This search was directly inspired by a new \textit{CLEO} result [77], which found the surprisingly copious transitions \( \psi(4160) \to \pi^+ \pi^- h_b(1P) \) and an indication that \( Y(4260) \to \pi^+ \pi^- h_b(1P) \) occurs at a comparable rate as the signature mode, \( Y(4260) \to \pi^+ \pi^- h_b(1P) \)
The presence of $\Upsilon(nS)$ peaks in Fig. 1 at rates two orders of magnitude larger than expected for transitions requiring a heavy-quark spin-flip, along with separate studies with exclusive decays $\Upsilon(nS) \rightarrow \mu^+\mu^-$, allow precise calibration of the $\pi^+\pi^-$ recoil mass spectrum and very accurate measurements of $h_b(1P)$ and $h_b(2P)$ masses. Both corresponding hyperfine splittings are consistent with zero within an uncertainty of about 1.5 MeV (lowered to $\pm 1.1$ MeV for $h_b(1P)$ in [30]).

Belle soon noticed that, for events in the peaks of Fig. 1, there seemed to be two intermediate charged states nearby. For example, Fig. 2 shows a Dalitz plot for events restricted to the $\Upsilon(2S)$ region of $\pi^+\pi^-$ recoil mass. The two bands observed in the maximum of the two $M[\pi^+\Upsilon(2S)]^2$ values also appear for $\Upsilon(1S)$, $\Upsilon(3S)$, $h_b(1P)$, and $h_b(2P)$ samples, but do not appear in the respective $[b\bar{b}]$ sidebands. Belle fits all subsamples to resonant plus non-resonant amplitudes, allowing for interference (notably, between $\pi^-Z_b^+$ and $\pi^+Z_b^-$), and finds consistent pairs of $Z_b^+$ masses for all bottomonium transitions, and comparable strengths of the two states. Angular analysis favors a $J^P = 1^+$ assignment for both $Z_b^+$ states, which must also have negative $G$-parity. Transitions through $Z_b^+$ to the $h_b(nP)$ saturate the observed $\pi^+\pi^-h_b(nP)$ cross sections. The two masses of $Z_b^+$ states are just a few MeV above the $B^*\bar{B}$ and $B^*B^*$ thresholds, respectively. The $Z_b^+$ cannot be simple mesons because they are charged and have $b\bar{b}$ content.

The third Belle result to flow from these data is confirmation of the $\eta_b(1S)$ and measurement of the $h_b(1P) \rightarrow \gamma\eta_b(1S)$ branching fraction, expected to be several tens of percent. To accomplish this, events with the $\pi^+\pi^-$ recoil mass in the $h_b(1P)$ mass window and a radiative photon candidate are selected, and the $\pi^+\pi^-\gamma$ recoil mass queried for correlation with non-zero $h_b(1P)$ population in the $\pi^+\pi^-$ missing mass spectrum, as shown in Fig. 3. A clear peak is observed, corresponding to the $\eta_b(1S)$. A fit is performed to extract the $\eta_b(1S)$ mass, and first measurements of its width and the branching fraction for $h_b(1P) \rightarrow \gamma\eta_b(1S)$ (the latter of which is $49.8 \pm 6.8^{+10.0}_{-5.2}$%). The mass determination has comparable uncertainty to and a larger central value (by 10 MeV, or 2.4$\sigma$) than the average of previous measurements, thereby reducing the new world average hyperfine splitting by nearly 5 MeV, as shown in Table 3.

The $\chi_{bJ}(nP)$ states have recently been observed at the LHC by ATLAS [35] for $n = 1, 2, 3$, although in each case
the three $J$ states are not distinguished from one another. Events are sought which have both a photon and an $\Upsilon(1S,2S) \rightarrow \mu^+\mu^-$ candidate which together form a mass in the $\chi_b$ region. Observation of all three $J$-merged peaks is seen at significance in excess of 6$\sigma$ for both unconverted and converted photons. The mass plot for converted photons, which provide better mass resolution, is shown in Fig. 4. This marks the first observation of the $\chi_bJ(3P)$ triplet, quite near the expected mass.

**TABLE 3**: Measured $\eta_b(1S)$ masses and hyperfine splittings, by experiment and production mechanism.

| $m(\eta_b)$ | $\Delta m_{hf}$ | Process | Ref. | ($\chi^2$/d.o.f.) |
|-------------|-----------------|---------|------|-------------------|
| 9394.2$^{+4.8}_{-4.5}$±2.0 | 66.1$^{+1.0}_{-1.1}$±2.0 | $\Upsilon(2S) \rightarrow \gamma \eta_b$ | BABAR [29] |
| 9388.9$^{+3.1}_{-3.3}$±2.7 | 71.4$^{+2.4}_{-3.2}$±2.7 | $\Upsilon(3S) \rightarrow \gamma \eta_b$ | BABAR [27] |
| 9391.8±6.6±2.0 | 68.5±6.6±2.0 | $\Upsilon(3S) \rightarrow \gamma \eta_b$ | CLEO [28] |
| 9391.0±2.8 | 69.3±2.9 | Above [7] Avg$^a$ (0.6/2) |
| 9401.0±1.9$^{+1.4}_{-2.4}$ | 59.3±1.9$^{+2.4}_{-2.4}$ | $h_b(1P) \rightarrow \gamma \eta_b$ | Belle [30] |
| 9395.8±3.0 | 64.5±3.0 | All Avg$^a$ (6.1/3) |

$^a$An inverse-square-error-weighted average of the individual measurements appearing above, for which all statistical and systematic errors were combined in quadrature without accounting for any possible correlations between them. The uncertainty on this average is inflated by the multiplicative factor $S$ if $S^2 \equiv \chi^2$/d.o.f.>1

shown in Fig. 4. From ATLAS [35] pp collision data (points with error bars) taken at $\sqrt{s} = 7$ TeV, the effective mass of $\chi_bJ(1P,2P,3P) \rightarrow \gamma \Upsilon(1S,2S)$ candidates in which $\Upsilon(1S,2S) \rightarrow \mu^+\mu^-$ and the photon is reconstructed as an $e^+e^-$ conversion in the tracking system. Fits (smooth curves) show significant signals for each triplet (merged-$J$) on top of a smooth background. From [35] with kind permission, copyright (2012) The American Physical Society.

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