Heavy quarkonia: the beauty and the beasts

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Abstract. New enhancements in the charmonium and bottomonium spectra observed since 2003 are very briefly reviewed. Special attention is paid to $c \bar{c}_1(3872)$ (formerly $X(3872)$) owing to its remarkable proximity to the $D^0\bar{D}^0$ threshold, which allows modelling as a quasibound axial-vector $c \bar{c}$ state with a large $D^0\bar{D}^0$ admixture. In contrast, the interpretation of many other charmonium-like and bottomonium-like states is still very controversial and some may not even correspond to genuine resonances. Accordingly, several entries in the PDG tables have been wildly changing over the years. Three representative states are reviewed here as non-resonant enhancements due to threshold effects, viz. $\psi(4260)$, $\psi(4660)$, and $\Upsilon(10580)$.

1. Introduction

Meson spectroscopy has witnessed a true revolution since the year 2003, when a first unusual charmonium-like state was observed [1] by the Belle Collaboration, extremely close to the $D^0\bar{D}^0$ threshold at 3872 MeV. For this reason, the collaboration suggested the state might correspond to a (quote) loosely bound $D\bar{D}^*$ multiquark “molecular” state, as proposed by some authors (unquote). The designation $X(3872)$ employed in Ref. [1] was then also adopted by the PDG in 2004 [2] and maintained till 2017. In the very recent 2018 edition [3] the name was finally changed into $\chi_{c1}(3872)$, based on unmistakable evidence favouring $J^{PC} = 1^{++}$ quantum numbers. However, despite being the obvious candidate for $\chi_{c1}(2P)$, its spectroscopic assignment is still controversial, with several authors insisting on a non-$c\bar{c}$ configuration, the molecular hypothesis being the most popular. Whatever the description, though, $\chi_{c1}(3872)$ is absolutely unique among the newly discovered heavy quarkonia, owing to its accurately known mass, very small width, and well-established $J^{PC}$. This allows a detailed and selective modelling, as well as dedicated experiments aiming at pinning down its properties even more precisely. In Sec. 3 below we shall succinctly revisit some of our model results on $\chi_{c1}(3872)$.

On the other hand, many of the other enigmatic heavy-quarkonium states observed in recent years are much less firmly established and some are even questionable as genuine resonances. Checking their entries in the PDG tables since 2004, one observes frequent changes of listed masses and names, with an occasional state being eliminated altogether (see Sec. 2 below for details). Most of the model activity has focused on charged states like e.g. $X(3900)^\pm$ (now [3] called $Z_c(3900)^\pm$) and $X(10610)^\pm$ (now [3] $Z_b(10610)^\pm$), which cannot be purely $c\bar{c}$ or $b\bar{b}$, of course. For a short review on such “XYZ” states, see Ref. [4], in particular concerning non-resonant assignments. Another very puzzling state is $X(4260)$ (now [3] $\psi(4260)$) which has not
beaten observed in any open-charm decay channel. In Sec. 4 we shall very briefly review our non-resonant model description of $\psi(4260)$, as well as that of $\psi(4660)$ and $\Upsilon(10580)$.

2. Charmonium and bottomonium states in the PDG tables since 2002

Up to the 2002 PDG edition [5], the list of charmonia and bottomonia had remained largely unaltered, with all states being considered compatible with mainstream quark models. Things changed dramatically in 2003 with the discovery [1] of $X(3872)$, whose mass is almost 100 MeV lower than was expected then (also see Sec. 3 below). Over the following years many more new charmonium-like states were observed and included in the PDG listings, as summarised next.

In the following charmonium and bottomonium enumerations, normal entries refer to states already present in the preceding PDG edition, boldface ones to new entries, designations in quotation marks to mere name changes, and states in square brackets to freshly removed entries.

Charmonium

2002: $\eta_c(1S) J/\psi(1S) \chi_{c0}(1P) \chi_{c1}(1P) h_c(1P) \chi_{c2}(1P) \eta_c(2S) \psi(2S) \psi(3770) \psi(3836) \psi(4040) \psi(4160) \psi(4415)$

2004: $\eta_c(1S) J/\psi(1S) \chi_{c0}(1P) \chi_{c1}(1P) h_c(1P) \chi_{c2}(1P) \eta_c(2S) \psi(2S) \psi(3770) \psi(3836) X(3872) \psi(4040) \psi(4160) \psi(4415)$

2006: $\eta_c(1S) J/\psi(1S) \chi_{c0}(1P) \chi_{c1}(1P) h_c(1P) \chi_{c2}(1P) \eta_c(2S) \psi(2S) \psi(3770) [\psi(3836)] X(3872) \chi_{c2}(2P) X(3940) \psi(4040) \psi(4160) \psi(4620) \psi(4415)$

2008: $\eta_c(1S) J/\psi(1S) \chi_{c0}(1P) \chi_{c1}(1P) h_c(1P) \chi_{c2}(1P) \eta_c(2S) \psi(2S) \psi(3770) X(3872) \chi_{c2}(2P) X(3940) X(3945) \psi(4040) \psi(4160) \psi(4260) \psi(4620) \psi(4415)$

2010: $\eta_c(1S) J/\psi(1S) \chi_{c0}(1P) \chi_{c1}(1P) h_c(1P) \chi_{c2}(1P) \eta_c(2S) \psi(2S) \psi(3770) X(3872) \chi_{c2}(2P) X(3940) X(3945) \psi(4040) X(4140) \psi(4160) X(4160) X(4250) \pm X(4260) X(4350) \psi(4415) X(4430) \pm X(4660)$

2012: $\eta_c(1S) J/\psi(1S) \chi_{c0}(1P) \chi_{c1}(1P) h_c(1P) \chi_{c2}(1P) \eta_c(2S) \psi(2S) \psi(3770) X(3872) X(3915) \chi_{c2}(2P) X(3940) \psi(4040) X(4050) \pm X(4140) \pm X(4160) \psi(4415) \pm X(4430) \pm X(4460)$

2014: $\eta_c(1S) J/\psi(1S) \chi_{c0}(1P) \chi_{c1}(1P) h_c(1P) \chi_{c2}(1P) \eta_c(2S) \psi(2S) \psi(3770) X(3872) X(3900) \pm X(3900) \pm X(3915) \chi_{c0}(2P) \chi_{c2}(2P) X(3940) X(4020) \psi(4040) X(4050) \pm X(4140) \psi(4160) X(4160) X(4250) \pm X(4260) X(4350) \psi(4415) X(4430) \pm X(4460)$

2016: $\eta_c(1S) J/\psi(1S) \chi_{c0}(1P) \chi_{c1}(1P) h_c(1P) \chi_{c2}(1P) \eta_c(2S) \psi(2S) (\psi(3823)) \psi(3823) X(3872) X(3900) \pm X(3915) \chi_{c0}(2P) X(3940) X(4020) \pm X(4050) \pm X(4055) \pm X(4140) \psi(4160) X(4160) \pm X(4200) \pm X(4230) \pm X(4260) \pm X(4250) \pm X(4260) \pm X(4350) \pm X(4415) \pm X(4430) \pm X(4460)$

2018: $\eta_c(1S) J/\psi(1S) \chi_{c0}(1P) \chi_{c1}(1P) h_c(1P) \eta_c(2S) \psi(2S) \psi(3770) \psi(3770) X(3872) X(3900) \pm X(3915) \chi_{c2}(2P) X(3940) X(4020) \pm X(4050) \pm X(4055) \pm X(4140) \pm X(4160) \pm X(4200) \pm X(4230) \pm X(4260) \pm X(4250) \pm X(4260) \pm X(4350) \pm X(4415) \pm X(4430) \pm X(4460)$

The above PDG entries over the period 2002–2018 show an increasingly confusing situation of well-established charmonia, puzzling charmonium-like resonances though with non-exotic quantum numbers, and clear non-$c\bar{c}$-only states, either for being charged or having exotic quantum numbers (cf. $R_{0}(4240)$, with tentative $J^{PC} = 0^{+} - [3]$). Among the several questionable assignments made by the PDG [3], one should stress the regressive designation of $X(3915)$, previously named $\chi_{c0}(2P)$ [10] or $\chi_{c0}(3915)$ [12], and to be contrasted with the new $\chi_{c0}(4500)$ and $\chi_{c0}(4700)$. 

2
Bottomonium

2002: $\eta_b(1S) \ U(1S) \ \chi_{b0}(1P) \ \chi_{b1}(1P) \ \chi_{b2}(1P) \ \Upsilon(2S) \ \chi_{b0}(2P) \ \chi_{b1}(2P) \ \chi_{b2}(2P) \ \Upsilon(3S) \ \Upsilon(4S) \ \Upsilon(10860) \ \Upsilon(11020)$

2006: $\eta_b(1S) \ U(1S) \ \chi_{b0}(1P) \ \chi_{b1}(1P) \ \chi_{b2}(1P) \ \Upsilon(2S) \ \Upsilon(1D) \ \chi_{b0}(2P) \ \chi_{b1}(2P) \ \chi_{b2}(2P) \ \Upsilon(3S) \ \Upsilon(4S) \ \Upsilon(10860) \ \Upsilon(11020)$

2012: $\eta_b(1S) \ U(1S) \ \chi_{b0}(1P) \ \chi_{b1}(1P) \ \eta_b(2S) \ \Upsilon(2S) \ \Upsilon(1D) \ \chi_{b0}(2P) \ \chi_{b1}(2P) \ \chi_{b2}(2P) \ \eta_b(2P) \ \chi_{b2}(2P) \ \Upsilon(3S) \ \chi_{b0}(3P) \ \Upsilon(4S) \ X(10610)^{\pm} \ X(10650)^{\pm} \ U(10860) \ U(11020)$

2014: $\eta_b(1S) \ U(1S) \ \chi_{b0}(1P) \ \chi_{b1}(1P) \ \eta_b(2S) \ \Upsilon(2S) \ \Upsilon(1D) \ \chi_{b0}(2P) \ \chi_{b1}(2P) \ \chi_{b2}(2P) \ \eta_b(2P) \ \chi_{b2}(2P) \ \Upsilon(3S) \ \chi_{b0}(3P) \ \Upsilon(4S) \ X(10610)^{\pm} \ X(10650)^{\pm} \ U(10860) \ U(11020)$

2016: $\eta_b(1S) \ U(1S) \ \chi_{b0}(1P) \ \chi_{b1}(1P) \ \eta_b(2S) \ \Upsilon(2S) \ \Upsilon(1D) \ \chi_{b0}(2P) \ \chi_{b1}(2P) \ \chi_{b2}(2P) \ \eta_b(2P) \ \chi_{b2}(2P) \ \Upsilon(3S) \ \chi_{b0}(3P) \ \Upsilon(4S) \ X(10610) \ X(10650) \ U(10860) \ U(11020)$

2018: $\eta_b(1S) \ U(1S) \ \chi_{b0}(1P) \ \chi_{b1}(1P) \ \eta_b(2S) \ \Upsilon(2S) \ \Upsilon(2D) \ \chi_{b0}(2P) \ \chi_{b1}(2P) \ \chi_{b2}(2P) \ \eta_b(2P) \ \chi_{b2}(2P) \ \Upsilon(3S) \ \chi_{b0}(3P) \ \Upsilon(4S) \ \chi_{b0}(10610)^{\pm} \ \chi_{b1}(10650)^{\pm} \ U(10860) \ U(11020)$

In the $b\bar{b}$ sector the successive PDG updates have followed a more conservative pattern, also owing to the reduced number of newly discovered states. (Only PDG editions with changes given here). Nevertheless, the designation $\chi_{b0}(3P)$ [9, 10] is incomprehensible and even unacceptable, as it refers to 3 different bottomonia, with $J = 0, 1, 2$. Impossibility to disentangle them, due to insufficient experimental resolution [13], should have imposed an “X” naming.

3. $\chi_{c1}(3872)$ as a unitarised $\chi_{c1}(2P)$ state

Hardly any other meson has been attracting more attention from model builders than $\chi_{c1}(3872)$ (alias $X(3872)$, as it was called [11] before the 2018 PDG edition [3]. Among the various interpretations of this meson, the molecular picture is probably the most popular. However, any non-exotic hypothetical molecular state will inevitably mix with a bare $c\bar{c}$ state having the same quantum numbers, via light $q\bar{q}$ creation/annihilation and the $3P_0$ mechanism, even if the $c\bar{c}$ state lies at a quite different energy [14]. Much more straightforward is to consider $\chi_{c1}(3872)$ a unitarised and so mass-shifted $\chi_{c1}(2P)$ state, a consequence of its naturally large coupling to the $S$-wave $D^0\bar{D}^0$ threshold. In Ref. [15] a successful description was indeed achieved in a momentum-space multichannel calculation with all the relevant meson-meson channels included. The simplified coordinate-space calculation carried out in Ref. [14] aimed at studying the molecular scenario with a two-component wave function ($c\bar{c}$ and $D^0\bar{D}^0$). The conclusion was that in the inner region both components are of similar magnitude, although the $D^0\bar{D}^0$ one strongly dominates the overall probability due to its very long tail for the then listed [8] small binding energy of 0.16 MeV. Also, the $\chi_{c1}(3872)$ pole was found both as a dynamical resonance and an intrinsic one, depending on details of the bare $c\bar{c}$ state’s mass. Finally, in Ref. [16] the latter $r$-space model was generalised so as to include all relevant OZI channels, in order to obtain realistic multicomponent wave functions of $J/\psi, \psi(2S)$ and $\chi_{c1}(3872)$, allowing to compute the measured [10] electromagnetic transitions $\chi_{c1}(3872) \rightarrow J/\psi, \psi(2S)$. The resulting $\chi_{c1}(3872)$ wave function is shown in Fig. 1. We see that now the $c\bar{c}$ state is clearly dominant in the interior region, although the $D^0\bar{D}^0$ component still accounts for most of the total probability (65% [16]) because of its mentioned long tail. The latter probability will even be close to 99% for the recently [3] adjusted $\chi_{c1}(3872)$ binding of only about 0.01 MeV. Yet the ratio of the $c\bar{c}$ and $D^0\bar{D}^0$ components in the inner region will hardly change [14]. From all this we conclude that $\chi_{c1}(3872)$ should not be considered a meson-meson molecule [14]. More generally, the effects of unitarisation are often underestimated and should really be taken into account in modern meson spectroscopy.
4. Non-resonant $\psi(4260)$, $\psi(4660)$ and $\Upsilon(10580)$

To conclude, we very succinctly review three heavy quarkonia, listed as established $\psi$ and $\Upsilon$ resonances by the PDG [3], in an unconventional way, viz. through data analyses that focus on threshold effects. The latter are also usually ignored in hadron spectroscopy.

4.1. $\psi(4260)$

The $\psi(4260)$ resonance, still called $X(4260)$ up to 2016 [11], has 47 listed [3] decay modes, of which 38 are “not seen”. No decay into pairs of charmed mesons has ever been observed, with $J/\psi\pi^+\pi^-$ being the principal mode. Instead of the usual explanations in terms of (crypto-)exotic non-$c\bar{c}$ configurations, we looked [17] more closely at the data. Assuming a very broad threshold structure in the $J/\psi\pi^+\pi^-$ channel dominated by $J/\psi f_0(500)$, we interpreted the various dips in the $J/\psi\pi^+\pi^-$ event distribution as strong inelasticity effects from the opening of OZI-allowed channels with pairs of charmed mesons as well as established vector charmonia in these channels. This also helps to explain the very pronounced and puzzling dip precisely at the mass of $\psi(4415)$. Thereabove, the opening of the $\Lambda_c\bar{\Lambda}_c$ threshold and a tentative, so far unlisted $(3D)$ resonance are fundamental to explain the data. These large inelasticity effects we called depletion, which give rise to the resonant-like but — in our opinion — non-resonant $\psi(4260)$ enhancement.

4.2. $\psi(4660)$

The situation with $\psi(4660)$ [3] ($X(4660)$ up until 2016 [11]) is related, as we consider [18] it a non-resonant threshold enhancement due to the opening of the $\Lambda_c\bar{\Lambda}_c$ channel (also see Ref. [17]). We also found [18] indications of the higher vector charmonia $\psi(5S)$, $\psi(4D)$, $\psi(6S)$ and $\psi(5D)$. As mentioned above, we identified a $\psi(3D)$ signal in Ref. [17].
4.3. \( \Upsilon(10580) \)

Finally, we discuss a very well established bottomonium state, namely \( \Upsilon(10580) \), included in the PDG tables since many years and listed as \( \Upsilon(4S) \). However, we interpret [19] it as a non-resonant threshold bump right between the \( BB \) and \( BB^* \) thresholds. The crucial point is that the data show a small yet clear enhancement on top of the \( B_sB \) threshold, whereas there are unmistakable dips at the openings of the \( BB^* \) and \( B^*B^* \) thresholds (see Fig. 2). This pattern can be understood by assuming an \( \Upsilon(4S) \) resonance somewhat above the \( B_sB \) threshold, which also allows to indentify \( \Upsilon(10860) \) as \( \Upsilon(3D) \) and \( \Upsilon(11020) \) as \( \Upsilon(5S) \).

![Figure 2. Interpretation [19] of bottomonium vector states, including non-resonant \( \Upsilon(10580) \).](image)

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