Exotic Charmonium and Bottomonium-like Resonances

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Abstract. Many new states in the charmonium and bottomonium mass region were recently discovered by the BaBar, Belle and CDF Collaborations. We use the QCD Sum Rule approach to study the possible structure of some of these states. In particular we identify the recently observed bottomonium-like resonance $Z_b^{++}(10610)$ with the first excitation of the tetraquark $X_b^{++}(1^{++})$, the analogue of the $X(3872)$ state in the charm sector.

1. Introduction

Most of the new charmonium states discovered in recent years at the B factories and at the Tevatron, called X, Y, Z particles, do not seem to have a simple $c\bar{c}$ structure. Their production mechanism, masses, decay widths, spin-parity assignments and decay modes have been discussed in some reviews [1, 2, 3]. Although the masses of these states are above the corresponding thresholds of decays into a pair of open charm mesons, they decay into $J/\psi$ or $\psi'$ plus pions, which is unusual for $c\bar{c}$ states. Besides, their masses and decay modes are not in agreement with the predictions of potential models, which, in general, describe very well $c\bar{c}$ states. For these reasons, they are considered as candidates for exotic states such as hybrid, molecular or tetraquark states, with a more complex structure than the simple quark-antiquark states.

In the bottomonium mass region, the first particle that does not seem to have a simple $b\bar{b}$ structure was the $Y_b(10890)$, observed by the Belle Collaboration [4]. The Belle Collaboration also reported the observation of two charged narrow structures in the $\pi^\pm \Upsilon(nS)$ ($n = 1, 2, 3$) and $\pi^\pm h_b(mP)$ ($m = 1, 2$) mass spectra of the $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^\pm$ and $\Upsilon(5S) \rightarrow h_b(mP)\pi^\pm$ decay processes [5]. These narrow structures were called $Z_b(10610)$ and $Z_b(10650)$. Analysis of angular distribution favors the quantum numbers $I^G(J^P) = 1^+(1^+)$ for both states. Since the $Z_b$ are charged states, they are ideal candidates for exotic four-quark states, like the $Z^+(4430)$, also observed by the Belle Collaboration in $B^+ \rightarrow K\psi'/\pi^+$ through its decay into $\psi'/\pi^+$ [6].

2. Molecular States

As pointed out by the Belle Collaboration, the proximity of the $BB^*$ and $B^*B^*$ thresholds and the $Z_b(10610)$ and $Z_b(10650)$ masses suggests that these states could be interpreted as weakly bound $BB^*$ and $B^*B^*$ states [7, 8, 9, 10, 11]. They have also been interpreted as cusps at the $BB^*$ and $B^*B^*$ thresholds [12, 13] and as tetraquark states [14].
The molecular picture was also used to understand the well established \(X(3872)\), which was considered to be a \(D\bar{D}^*\) molecule. Of course, the actual physical state is probably rather complex, with a short-range component of \((c\bar{c})\) nature and a long-range component with a charmed meson and an anticharmed meson almost bound by attractive Yukawa forces. The idea of molecules with hidden charm has been proposed long ago by Okun and Voloshin [15]. A molecular interpretation was proposed for some high-lying \(1^{--}\) charmonium resonances [16], due to puzzling branching ratios into \(DD, DD^*\) and \(D^*D^*\), which turned out to be due to the node structure of these states as radial excitations of the \(J/\psi\) [17]. The possibility of hidden-charm meson molecules has been revisited in the 90s by Törnqvist [18], Ericson and Karl [19] and Manohar and Wise [20], and further developed by several authors after the discovery of the \(X(3872)\) [2]. The main idea is that the \(J/\psi\) interaction, that successfully binds nuclei, is not restricted to the nucleon-nucleon interaction. The exchange of light mesons also generates a potential between flavored mesons, which is sometimes attractive. Although usually weaker than the proton-neutron interaction that binds the deuteron, it is probed by much heavier particles, and thus can lead to bound states with a binding energy of a few MeV, or even a few tens of MeV, as shown by Törnqvist [18]. For the molecular \(B\bar{B}\) states, the study shows that the energy of isoscalars \(B\bar{B}^*\) with \(J^{PC} = 0^{-+}\), \(1^{++}, B^*\bar{B}^*\) with \(J^{PC} = 0^{-+}, 0^{-+}, 1^{-+}, 2^{++}\) are about 50MeV below the corresponding \(B\bar{B}^*\) and \(B^*\bar{B}^*\) thresholds. No bound state, however, appears for isovectors. Isovector states receive less attraction than the states with \(I = 0\), mainly because of the isospin dependence of the one-pion-exchange potential. The operator includes a factor \(\tau_1,\tau_2\) whose expectation value is \(-3\) for \(I = 0\) and \(+1\) for \(I = 1\). Hence, if the Belle \(Z_b\) states are identified as the isovector \(BB^*\) and \(B^*\bar{B}^*\) molecules, one should also have their isoscalar counterpart somewhat below (typically a few tens of MeV).

In Ref. [9], the authors also did not find any isovector \(BB^*\) bound state. The only calculation that found loosely bound states in S-wave \(BB^*\) and \(B^*\bar{B}^*\) for isovectors was presented by Liu et al. [10], where the authors took, besides the pion, also scalar and vector mesons exchange into account, in the framework of the meson exchange model.

3. Tetraquark States

In the context of the tetraquark picture, using the chromomagnetic interaction, the authors of Ref. [14] studied the masses of the S-wave \([b\bar{q}][b\bar{q}]\) tetraquark states with \(J^{PC} = 1^{+}\). They found six states and two of them are consistent with the \(Z_b(10610)\) and \(Z_b(10650)\). However, it is important to mention that these two states are not the low-lying states in this channel. The lowest \([b\bar{q}][b\bar{q}]\) tetraquark state with \(J^{PC} = 1^{+}\) appears at 10167.9 MeV. This result is consistent with the findings of Ref. [21] where, using the color-magnetic interaction with the flavor symmetry breaking corrections, the \(bb\bar{q}\bar{q}\) tetraquark states were predicted to be around 10.2 \(\sim\) 10.3 GeV. These results are also consistent with the values extracted from the QCD sum rule approach [22, 23] for the \([b\bar{q}][b\bar{q}]\) tetraquark state with \(J^{PC} = 1^{++}\).

The first QCD sum rule (QCDSR) calculation for the tetraquark \([b\bar{q}][b\bar{q}]\) state with \(J^{PC} = 1^{++}\), which we call \(X_{b}\), was performed in Ref. [22]. At the sum rule stability point and using the perturbative MS-mass \(m_{b}(m_{b}) = 4.24\) GeV, the authors obtained \(M_{X_{b}} = (10250 \pm 200)\) MeV, for \(\sqrt{s_0} = (10500 \pm 300)\) MeV, where \(s_0\) is the continuum threshold. The authors of Ref. [23] have used different \(J^{PC} = 1^{++}\) and \(J^{PC} = 1^{--}\) tetraquark \([b\bar{q}][b\bar{q}]\) currents. They have obtained \(M_{X_{b}} = (10220 \pm 100)\) MeV, for \(\sqrt{s_0} = (10800 \pm 100)\) MeV which is in complete agreement with the result of Ref. [22]. The authors of Ref. [24] tried to reproduce the mass of \(Z_b(10610)\) using a \(B\bar{B}^*\) molecular current in the QCDSR calculation. They obtained \(M_{BB^*} = (10560 \pm 180)\) MeV, which they say is in agreement with the \(Z_b(10610)\) mass. However, to obtain such a big mass they were forced to use a continuum threshold of \(\sqrt{s_0} = (11400 \pm 200)\) MeV, which is much bigger than the values used in Refs. [22, 23]. As it was shown in Ref. [25], different currents with the same quantum numbers lead to approximately the same mass in the QCDSR approach, if
the same parameters are used. Therefore, from QCDSR studies one may say that the low-lying $X_b$ state has a mass around 10100 - 10200 MeV, which is in agreement with the results from chromomagnetic model calculations [14, 21].

It is very interesting to notice that the mass difference between the predicted $X_b$ and $\chi_b(9892)$:

$$M_{X_b} - M_{\chi_b} \sim 310 \text{ MeV}, \quad (1)$$

is of the same order of magnitude of the mass difference between the $X(3872)$ and $\chi_{c1}(3510)$:

$$M_X - M_{\chi_{c1}} \sim 360 \text{ MeV}. \quad (2)$$

This kind of similarity between the $c$ and $b$ sector is very interesting. One can see that $M_{\Psi(2S)} - M_{\Psi(1S)} = 590 \text{ MeV} \sim M_{\Upsilon(2S)} - M_{\Upsilon(1S)} = 560 \text{ MeV}$. Therefore, the results in Eqs. (1) and (2), could be used as an evidence that a 4-quark state, similar to $X(3872)$, should exist in the $b$ sector! This state should be searched for by the experimental groups.

We suggest that the recently observed $Z_b$ states are not ground states of the $1^+$ bottomonium 4-quark states, but excitations of a ground state with a mass around 10.2 GeV. A similar suggestion was made by Maiani, Polosa and Riquer [26], to explain the $Z^+(4430)$ as an excitation of a charged $X$ state. Although the Babar Collaboration found no conclusive evidence of the existence of $Z^+(4430)$ [27], Belle has confirmed its observation. Using the same data sample of Ref. [6], Belle also performed a full Dalitz plot analysis [28] and has confirmed the observation of the $Z^+(4430)$ signal with a 6.4 σ peak significance. Therefore, if one believes in the $Z_b$ states observed by Belle, one should also believe in the existence of the $Z^+(4430)$.

4. $Z_b$ is not $X_b$. Is that a question?

In [29] it was conjectured that the $X(3872)$ must have a charged partner $X^+$ with $J^{PC} = 1^{+-}$ with a similar mass. In [26] it was pointed out that since the mass difference

$$M_{Z^+(4430)} - M_{X^+(3872)} \sim 560 \text{ MeV} \quad (3)$$

is close to the mass difference $M_{\Psi(2S)} - M_{\Psi(1S)}$ given above, the $Z^+(4430)$ may well be the first radial excitation of the $X^+$. In a straightforward extension of this reasoning to the bottom case, we may conjecture that the $Z_b(10610)$ is also a radial excitation of an yet unmeasured $X^+_b$ ($J^P = 1^+$) state, such that the mass difference

$$M_{Z_b(10610)} - M_{X^+_b(10100)} \sim 510 \text{ MeV} \quad (4)$$

very close to the mass difference $M_{\Upsilon(2S)} - M_{\Upsilon(1S)} = 560 \text{ MeV}$. For the sake of clarity the above mentioned numbers are displayed in Fig. 1, where we compare the charm and bottom spectra in the mass region of interest. On the left (right) we show the charm (bottom) states with their mass differences in MeV. The comparison between the two left lines with the two lines on the right emphasizes the similiraty between the conjecture made in this note, namely the existence of $X_b^+$ as a ground state of the measured $Z_b^+(1610)$, and the conjecture made in Ref. [26] on the existence of the charged partner $X^+$ of the $X(3872)$ as the ground states of the $Z^+(4430)$.

The conjecture presented above should encourage searches both in the charm and bottom sectors in the mass regions around $3870 \text{ MeV}$ and $10200 \text{ MeV}$ respectively. The reason for these searches would be not only to find the unobserved states shown in Fig. 1, $X^+(?)$, $X_b(?)$ and $X_b^+(?)$. In fact there are even more striking states to be detected in these mass regions. In the molecular approach, there is also attraction in the flavor exotic $DD$ or $D^*D^*$ and $BB^*$ or $B^*B^*$ channels. In the vector-vector case, the Fermi–Yang rule of $G$-parity [30] holds and the pion-exchange potential flips sign (for a given isospin $I$). Hence $B^*B^*$ channels with repulsive
interaction are transformed into $B^*B^*$ with attraction. The pseudoscalar-vector case is more subtle. Pion-exchange induces a transition from $|1\rangle = B\bar{B}^*$ to $|2\rangle = B^*\bar{B}$, and by linear combination, the potential is attractive in one of the channels, say $|1\rangle \pm |2\rangle$. In the flavor-exotic sector, one deals with $|1\rangle' = BB^*$ and $|2\rangle' = B^*B$. The pion-exchange potential still flips signs, but this simply means that the very same attraction is observed now in the combination $|1\rangle' \pm |2\rangle'$, if it exists in the partial wave one looks at.

For tetraquark systems, constituent model calculations have always favored $(QQ\bar{q}\bar{q})$ configurations, where the pair of heavy quarks benefits from their attraction. In the threshold $(Q\bar{q}) + (Q\bar{q})$, instead, the heavy quarks interact only with light quarks, and no heavy reduced mass enters. For a review, see, e.g., [31]. This peculiarity of $(QQ\bar{q}\bar{q})$ channels is confirmed in some studies based on lattice QCD [32] and QCD sum rules [33]. Experimentally the sector with charm $+2$ or beauty $-2$ is almost virgin. Theoretically, the question is whether charm is heavy enough to make $(cc\bar{q}\bar{q})$ stable against spontaneous dissociation or $b$ quarks are necessary. Two $b$ or not two $b$, that is the question!

5. Conclusions
We have discussed the masses of some $X$, $Y$ and $Z$ states, recently observed by BaBar and Belle Collaborations. In some cases a tetraquark configuration was favored, as the $Y_b(10890)$ [34], and in some other cases a molecular configuration was favored. In the case of $Z_{b^+}^*(10610)$ we identify it as the first excitation of the tetraquark $X_b(1^{++})$, the analogue of the $X(3872)$ state in the charm sector.
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References

[1] N. Brambilla, et al., Eur. Phys. J. C 71, 1534 (2011) [arXiv:1010.5827].
[2] M. Nielsen, F. S. Navarra, S. H. Lee, Phys. Rept. 497, 41-83 (2010) [arXiv:0911.1958].
[3] S. L. Olsen, Nucl. Phys. A 827, 53C-60C (2009) [arXiv:0901.2371].
[4] K. -F. Chen et al. [ Belle Collaboration ], Phys. Rev. D 82, 091106 (2010) [arXiv:0810.3829].
[5] I. Adachi et al. [Belle Collaboration], arXiv:1105.4583.
A. Bondar et al. [Belle Collaboration] arXiv:1110.2251.
[6] S. K. Choi et al. [ Belle Collaboration ], Phys. Rev. Lett. 100, 142001 (2008).
[7] A. E. Bondar, A. Garmash, A. I. Milstein, R. Mizuk and M. B. Voloshin, arXiv:1105.4473.
[8] Y. Yang, J. Ping, C. Deng and H. S. Zong, arXiv:1105.5935.
[9] J. Nieves and M. P. Valderrama, arXiv:1106.0600.
[10] Z.-F. Sun, J. He, X. Liu, Z.-G. Luo and S.-L. Zhu, arXiv:1106.2968.
[11] M. Cleven, F.-K. Guo, C. Hanhar and U.-G. Meissner, arXiv:1107.0254.
[12] D. V. Bugg, Europhys. Lett. 96, 11002 (2011). [arXiv:1105.5492].
[13] I. V. Danilkin, V. D. Orlovsky and Yu. A. Simonov, arXiv:1106.1552.
[14] T. Guo, L. Cao, M. Z. Zhou and H. Chen, arXiv:1106.2284.
[15] M. B. Voloshin and L. B. Okun, JETP Lett. 23, 333 (1976) [Pisma Zh. Eksp. Teor. Fiz. 23, 369 (1976)].
[16] A. De Rujula, H. Georgi and S. L. Glashow, Phys. Rev. Lett. 38, 317 (1977).
[17] A. Le Yaouanc, L. Oliver, O. Pene and J. C. Raynal, Phys. Lett. B 71, 397 (1977); 72, 57 (1977);
E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane and T. M. Yan, Phys. Rev. D 21, 203 (1980).
[18] N. A. Tornqvist, Z. Phys. C 61, 525 (1994).
[19] T. E. O. Ericson and G. Karl, Phys. Lett. B 309, 426 (1993).
[20] A. V. Manohar and M. B. Wise, Nucl. Phys. B 399, 17 (1993).
[21] Y. Cui, X. L. Chen, W. Z. Deng and S. L. Zhu, High Energy Phys. Nucl. Phys. 31, 7 (2007).
[22] R. D. Mathews, S. Narison, M. Nielsen, J.M. Richard, Phys. Rev. D75, 014005 (2007).
[23] W. Chen and S. L. Zhu, Phys. Rev. D 83, 034010 (2011).
[24] J. R. Zhang, M. Zhong and M. Q. Huang, Phys. Lett. B704, 312-315 (2011). [arXiv:1105.5472].
[25] S. Narison, F.S. Navarra, M. Nielsen, Phys. Rev. D83, 016004 (2011).
[26] L. Maiani, A. D. Polosa and V. Riquer, arXiv:0708.3997, and New Journal of Physics, 10 073004 (2008).
[27] B. Aubert et al. [BaBar Collaboration], Phys. Rev. D 79, 112001 (2009).
[28] R. Mizuk et al. [Belle Collaboration], Phys. Rev. D 80, 031104(R) (2009).
[29] L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. D 71, 014028 (2005).
[30] It was much used in the time of baryonium to relate the nucleon–antinucleon interaction to the nucleon–nucleon one.
[31] J. Vijande, A. Valcarce, J. M. Richard and N. Barnea, Few Body Syst. 45, 99 (2009).
[32] C. Michael and P. Pennanen [UKQCD Collaboration], Phys. Rev. D 60, 054012 (1999). M. Wagner [ETM Collaboration], arXiv:1103.5147.
[33] F. S. Navarreta, M. Nielsen and S. H. Lee, Phys. Lett. B 649, 166 (2007).
[34] R. M. Albuquerque, M. Nielsen, R. R. da Silva, arXiv:1110.2113.