

On the proliferation of X's, Y's and Z's candidates

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Abstract Heavy meson spectroscopy above open flavor thresholds has become a challenge both from the experimental and theoretical points of view. Experimentally, several signals have been interpreted as meson resonances with unusual properties; theoretically, such signals may be identified with meson-meson molecules or compact multiquark structures. We analyze the influence of thresholds on heavy meson spectroscopy comparing different flavor sectors and quantum numbers. The validity of a quark-model picture above open-flavor thresholds would severely restrict the number of channels that may lodge multiquark structures as meson-meson molecules.

Keywords Heavy meson spectroscopy · Exotics · Multiquark states

The discoveries in 1974 of the so-called *November revolution* [1], as the name 'revolution' implies, were not just additions to our knowledge of nature. Instead they signalled a change in our understanding of the structure of matter. Of course, this change did not occur completely overnight. Many of the ideas were there before, accepted by some and doubted by others. As always, there were also plenty of wrong ideas and irrelevant pieces of information. Why were these discoveries so exciting and so significant? First, because those particles were made of an unknown charm quark, and second because the spectrum of such particles could be studied with great precision and it was just the spectrum one would expect on the basis of

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quark constituents [2]. We had a stunning example which showed the quark layer of substructure to matter [3].

Since 1974 to 2003 all states discovered on charmonium spectroscopy fitted nicely into the simple spectroscopic models based on the one-gluon exchange postulated in 1975 [4]. The same theoretical ideas were applied to mesons made of a light and a heavy quark with great success [5]. In 2003 we relived a kind of revolution with the discovery by BABAR [6] of an open-charm meson, the $D_{s0}^*(2317)$, whose mass seemed to contradict current spectroscopic models; and by Belle [7] of a charmonium-like state, the $X(3872)$, with intriguing properties to be a simple quark-antiquark pair. Since then, the closely tended garden of heavy mesons is abloom with exotic new growths. These discoveries are offering exciting new insights into the subtleties of the strong interaction, awaiting for a general explanation that could lead to a more unified and mature picture of hadron spectroscopy. A recurring old question arises again: being some of these new states firmly established (as it is the case of the $X(3872)$), could they be fitted into the quark model scheme or are we in front of the breakdown of such a pattern?

The question above has been the flagship of many experimental and theoretical efforts during the last two decades [8]. It was already in May 1993, being N. Isgur the Cebaf theory group leader, when he invited the few students participating at the Hugs@Cebaf summer-school for lunch. He confessed that what he would like more to learn from Cebaf was the reason why the constituent quark model was wrong. Some of the students had to write a proceeding paper based on Isgur's lectures, it was entitled *Before the breakdown of the non-relativistic quark-model* [9]. We had the chance to talk to Isgur a few years later, in the 1996 Confinement conference. He laughed remembering that anecdote and he said *I keep trying*. In fact, one of his last papers dealt with the impact of thresholds on the hadronic spectrum, in an attempt to go beyond the adiabatic approximation within the constituent quark model [10].

Ten years later, F. Close entitled the summary talk at Hadron03 [11] *The end of the constituent quark model?* These were the hectic times of the θ^+ affair. He also pointed out that listing all of the mesons from the PDG as a function of J^{PC} indicated that the light hadron dynamics is clearly overpopulated, showing that not all of the data could be correct. The question of when does the constituent quark model work was once again made, noting that its successful picture for charmonium gets significant distortion from the $D\bar{D}$ threshold region. Thus, the relevance of thresholds was posed as an important potential distortion for the predictions of the constituent quark model.

Two final comments on this historical perspective. C. Quigg in the theory summary talk at Hadron11 [12], *The future of hadrons*, put some caution about the proliferation of low-statistics experimental data, pointing out that an experimental signal of 3σ means that it will probably disappear 80% of times. Finally, the difficulty of disentangling resonances from cusps due to the opening of thresholds has been the matter of study to give an alternative explanation to some of the recently reported new states [13].

Our purpose in this talk is to discuss how the new set of states reported could offer insight to check the validity of the constituent quark model beyond flavor thresholds. It would severely restrict the number of channels that may lodge meson-meson molecules. Out of the many states recently reported in charmonium and bottomonium spectroscopy, we do not really know how many will survive future

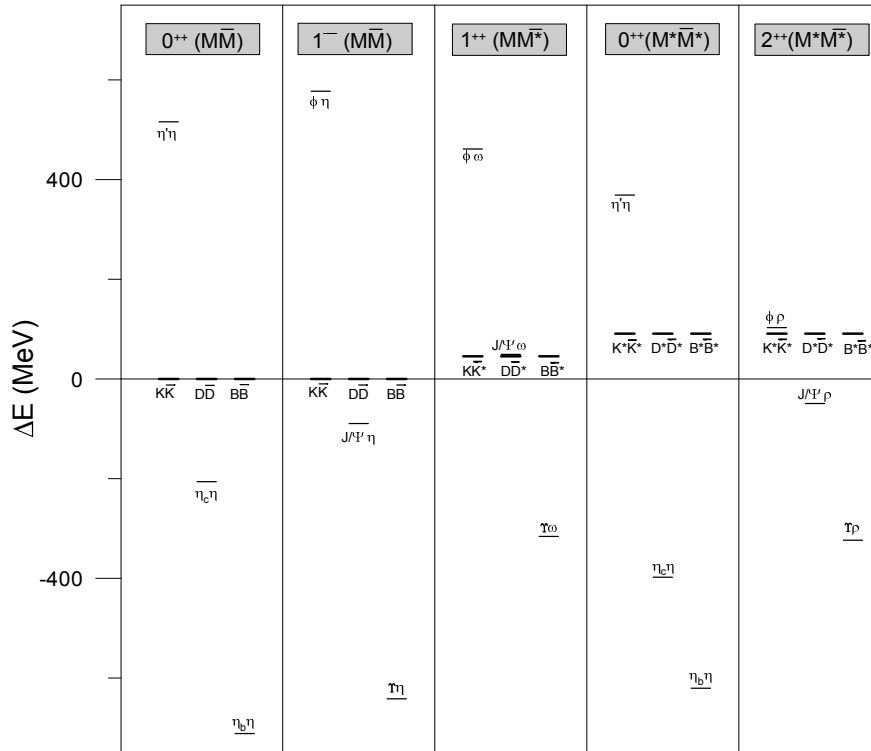


Fig. 1 Experimental thresholds of four-quark systems made of a heavy and a light quark and their corresponding antiquarks, $Qn\bar{Q}\bar{n}$ with $Q = s, c, \text{ or } b$, for several sets of quantum numbers, J^{PC} . We have set as our origin of energies the $K\bar{K}$, $D\bar{D}$ and $B\bar{B}$ masses for the hidden strange, charm and bottom sectors, respectively.

experimental screenings. We are still shocked by the θ^+ resonance, seen by so many experiments that later on did not find anything [14]. There is only one state that has been firmly established by different collaborations and whose properties seem to be hardly accommodated in the quark-antiquark scheme, this is the $X(3872)$ [7]. Regarding the zoo of other states that have been proposed, we have to stay tuned but also be cautious [11, 12]. Some members of this XYZ jungle are awaiting confirmation, seen only by one collaboration, like the intriguing charged state $Z(4430)$, seen by Belle but not by BABAR [15]. Other members of this jungle cannot be excluded to fit into the simple quark-antiquark scheme, like the $Z(3930)$ recently identified as the $\chi_{c2}(2P)$ charmonium state [16]. Other experimental signals seen only by a particular experiment, in some of the expected decay modes, or with low statistics, could just be the reflection of the opening of thresholds [13].

Let us start by discussing Fig. 1. In this figure we have plotted the experimental thresholds of four-quark systems made of a heavy and a light quark and their corresponding antiquarks for several sets of quantum numbers, J^{PC} , in three different flavor sectors: $Q = s$, hidden strange; $Q = c$, hidden charm; and $Q = b$, hidden bottom. In every flavor sector we represent the mass difference with respect

to the mass of $K\bar{K}$, $D\bar{D}$ and $B\bar{B}$, respectively. In a constituent quark model picture, the four-quark state $Qn\bar{Q}\bar{n}$ could either split into $(Q\bar{n}) - (n\bar{Q})$ or $(Q\bar{Q}) - (n\bar{n})$. One observes how the general trend for all quantum numbers is that the mass of the $(Q\bar{Q}) - (n\bar{n})$ two-meson system is larger than the mass of the $(Q\bar{n}) - (n\bar{Q})$ two-meson state for $Q = s$, but it is smaller for $Q = c$ or b . It is remarkable the case of $J^{PC} = 1^{++}$ for $Q = c$, where the $(Q\bar{Q}) - (n\bar{n})$ and the $(Q\bar{n}) - (n\bar{Q})$ two-meson states are almost degenerate. The reverse of the ordering of the masses of the $(Q\bar{Q}) - (n\bar{n})$ and $(Q\bar{n}) - (n\bar{Q})$ thresholds when increasing the mass of the heavy quark for all J^{PC} quantum numbers can be simply understood within the constituent quark model with a Cornell-like potential [11]. The binding of a coulombic system is proportional to the reduced mass of the interacting particles. Thus, for a two-meson threshold with a heavy-light light-heavy quark structure, the binding of any of the two mesons does not change much when increasing the mass of the heavy flavor, due to the reduced mass of each meson being close to the mass of the light quark. However, if the two-meson state presents a heavy-heavy light-light quark structure, the binding of the heavy-heavy meson increases with the mass of the heavy particle while that of the light-light meson remains constant, becoming this threshold lighter than the heavy-light light-heavy two-meson structure, as seen in Fig. 1.

Such a picture, together with the absence of long-range forces [17] in a charmonium-light two-meson system, may imply different consequences for the existence of molecules close to the meson-antimeson threshold. First, the possible existence of such molecules in the hidden-strange sector. If the $K\bar{K}$ interaction is attractive for some particular set of quantum numbers, this two-meson system may be stable because no other threshold appears below, the dissociation of the molecule being therefore forbidden (see the $Q = s$ states for any J^{PC} quantum numbers in Fig. 1). Such a possibility would become more probable for those quantum numbers where the quark model seems to work worst, those cases where one needs a P-wave in the simplest quark model structure, $q\bar{q}$, but can be obtained in S-wave from a four-quark system. In these cases, the mass of the four-quark system could be even below the predicted lowest quark-antiquark state. This is precisely the idea suggested by Weinstein and Isgur [18] as a plausible explanation of the proliferation of scalar mesons in the light quark sector. They concluded the $J^{PC} = 0^{++}$ and 1^{++} quantum numbers to be the best candidates to lodge a meson-antimeson molecule. These quantum numbers are P-wave in the quark model but S-wave in the four-quark picture and besides they are spin triplet, having therefore an attractive spin-spin interaction.

Second, the possibility of finding meson-antimeson molecules contributing to the meson spectrum becomes more and more difficult when increasing the mass of the heavy flavor, due to the lowering of the mass of the $(Q\bar{Q}) - (n\bar{n})$ threshold (see the $Q = c$ or b states for any J^{PC} quantum numbers in Fig. 1). This would make the system dissociate immediately. In such cases, the presence of attractive meson-antimeson thresholds would manifest in the scattering cross section but they will not lodge a physical resonance. These ideas favored the interpretation of several of the experimental signals in charmonium and bottomonium spectroscopy above flavor thresholds as originated from the opening of the threshold and not being resonances [13].

Thus, only a few channels may lodge molecular resonances. As discussed above, there is a remarkable exception to the general rule, the $(I)J^{PC} = (0)1^{++}$ quan-

tum numbers in the charmonium sector. In this case the $(c\bar{n}) - (n\bar{c})$ ($D\bar{D}^*$) and $(c\bar{c}) - (n\bar{n})$ ($J/\Psi\omega$) thresholds are almost degenerate, and the attractive $D\bar{D}^*$ interaction together with the cooperative effect of the almost degenerate two-meson thresholds give rise to the widely discussed $X(3872)$ [19]. In spite of the general idea that the stability of a system made of quarks comes favored by increasing the mass of the heavy flavor, it becomes more complicated when several vectors in color space contribute to generate a color singlet, as it is the case of four-quark systems [20]. The reason is that, as explained above, the mass of one of the thresholds, $(Q\bar{Q}) - (n\bar{n})$, diminishes rapidly when the heavy quark mass increases (see Fig. 1), making therefore the meson-antimeson system, $(Q\bar{n}) - (n\bar{Q})$, unstable. This simple reasoning of coupled-channel calculations was illustrated in Ref. [21]. It is the coupling to the almost degenerate $J/\Psi\omega$ channel the responsible for having a bound state just below the $D\bar{D}^*$ threshold. Such an explanation comes reinforced by the recent observation of the decay $X(3872) \rightarrow J/\Psi\omega$ [22]. When the mass of the heavy quark is augmented from charm to bottom, the $B\bar{B}^*$ becomes more attractive due to the decreasing of the kinetic energy and having essentially the same interaction. However, the coupling to the lower channel, $\Upsilon\omega$, destroys any possibility of having a bound state. Thus, based on the constituent quark model ideas, one should not expect a twin of the $X(3872)$ in bottomonium spectroscopy like those pointed out in hadronic models based on the traditional meson theory of the nuclear forces or resorting to heavy quark symmetry arguments [17]. Finally, the coupling to channels containing the light pion destroys the degeneracy between meson-antimeson and charmonium-light two-meson thresholds, an important mechanism for binding four-quark states in the $I = 0$ sector. This excludes, for example, the existence of charged partners of the $X(3872)$, as explained in Ref. [19]. Only one S-wave channel, the $J^{PC} = 2^{++}$, where the coupling to the charmonium-pion two-meson system is prohibited, may be candidate for lodging a resonance close above the $D^*\bar{D}^*$.

The proliferation of resonances above flavor thresholds could rely on our poor knowledge of confinement. Refs. [23] have analyzed the stability of $Qn\bar{Q}\bar{n}$ and $QQ\bar{n}\bar{n}$ systems by considering only a multiquark confining interaction in an attempt to discern whether confining interactions not factorizable as two-body potentials would influence the stability of four-quark states. The ground state of systems made of two quarks and two antiquarks of equal masses was found to be below the dissociation threshold. Whereas for the cryptoexotic $Qn\bar{Q}\bar{n}$ the binding decreases with increasing mass ratio m_Q/m_n , for the flavor exotic $QQ\bar{n}\bar{n}$ the effect of mass symmetry breaking is opposite.

The discussion on the last paragraph drives us to a brief comment on exotic states $QQ\bar{n}\bar{n}$. In this case the situation is rather different to the nonexotic $Qn\bar{Q}\bar{n}$ system, because the possible dissociation thresholds do not contain states made of a heavy quark and a heavy antiquark, whose binding would increase linearly with the mass of the heavy flavor. Thus, stability will be favored by increasing the mass of the heavy flavor, being much more probable in the bottom sector than in the strange one [24]. The search of such exotic states is a hot experimental subject for the incoming years in different experimental facilities [25].

Summarizing, recent experimental data on charmonium spectroscopy have suggested the existence of a large number of states above charmed meson thresholds. They have been baptized as X 's, Y 's, and Z 's, due to their unusual properties not easily explained in terms of simple quark-antiquark pairs. Such proliferation of

states has pointed out to the existence of meson-antimeson molecules. In a quark-model picture we have justified how such molecules may contribute to the light meson spectroscopy. In particular, they could explain the existence of non quark-antiquark states for quantum numbers that can be obtained from four-quarks in an S-wave but need orbital angular momentum from a quark-antiquark pair. When increasing the mass of the heavy flavor, the possibility of having meson-antimeson resonances decreases with the mass of the heavy quark. Only in some particular cases the cooperative effect of nearby two-meson channels with an attractive meson-antimeson interaction may produce resonances in the charmonium sector, the $X(3872)$ being the example par excellence. Increasing the mass of the heavy quark destroys the possibility of a twin state in the bottom sector, against the predictions of hadronic models based on the traditional meson theory of the nuclear forces or heavy quark symmetry. Improved confinement interactions considering many-body forces go against the stability of non-exotic four-quark states in the energy region close to the flavor thresholds. Finally, in the exotic sector, due to the nonexistence of thresholds made of two heavy quarks, the stability of two-meson states would increase with the mass of the heavy quark.

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