EXOTIC HADRONS AS FESHBACH RESONANCES*

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(Received June 9, 2014)

Since ten years ago a host of exotic resonances have challenged the usual quarkonium picture. A number of ideas have been put forward to explain these new states, but a comprehensive framework is still missing. We review the estimates for prompt production cross sections at hadron collider, and show that the interpretation of exotic states in terms of hadron molecules is not favored. We show a recently proposed model to solve this paradox and to explain the nature of above-threshold states in terms of Feshbach resonances.

DOI:10.5506/APhysPolBSupp.7.463
PACS numbers: 14.40.Rt, 13.25.Ft, 13.75.–n

1. Introduction

Heavy quarkonium sector is a laboratory where our understanding of QCD may be tested in a controlled framework. In the limit $m_Q \to \infty$ indeed, the non-perturbative gauge field dynamics can be described in terms of potential models or by effective theories like NRQCD. These tools have a remarkable predictive power about spectra, production cross sections and decay rates. However, in the last ten years B-factories have found a lot of unexpected resonances which do not fit conventional quarkonium interpretation. Because of their mysterious nature, they were called X, Y, Z. Several phenomenological pictures were proposed to describe these states, for instance meson molecules [1], compact tetraquarks [2], gluonic states [3] and hadroquarkonia [4] (for a review, see [5]). Despite a lot of theoretical efforts, a unified description is still missing.

* Presented at "Excited QCD 2014", Bjelašnica Mountain, Sarajevo, Bosnia and Herzegovina, February 2–8, 2014.

2. $X(3872)$ and the production paradox

Since the discovery of the $X(3872)$ resonance by Belle and BaBar [6], it was soon realized that this particle could not have been identified as a standard charmonium excitation. The proximity of the X mass to the threshold fits the prediction of a loosely bound molecule with a binding energy $E_\mathrm{b} = M_{X(3872)} - M_{D^0} - M_{D^{*0}} \simeq -0.14 \pm 0.22$ MeV, hence a size of ≈ 10 fm, much larger than the typical range of strong interaction [1]. The hypothesis is tempting because it accommodates isospin violation: since charged D^+D^{*-} threshold is 8 MeV higher than $D^0\bar{D}^{*0}$ threshold, the D^+D^{*-} component of the wave function is negligible, thus the isospin symmetry is broken. In [7], it was considered whether it is possible such a large, long-lived molecule to be formed within the hadrons ejected in a hadronic multi-TeV collision. For this purpose, they performed Monte Carlo simulations, and selected DD^* pairs[1] with relative 3-momentum $k_0 \lesssim \sqrt{2\mu E_\mathrm{b}} \sim 50$ MeV as molecular candidates. The answer was sharply negative, being the estimated MC cross section 300 times smaller than the experimental value. However, in [8], it was suggested that in loosely bound molecules Final State Interactions (FSI) (*i.e.* the rescattering of the components) are enhanced by quantum mechanic effects. The enhancement factor is evaluated by means of Watson Theorem, and is still not sufficient to reach the correct value, but the authors of [8] estimate that FSI allow the molecular components to have a relative momentum as large as $k_0 \sim 2m_\pi \sim 300$ MeV without splitting the state. The recourse to FSI was criticised in [9], by noting that a huge number of pions fly between the D and D^* mesons, thus invalidating the application of the Watson Theorem. The discussion remained open.

In [10], we proposed that the same pions which spoil the FSI mechanism could constitute a sort of "viscous medium", which makes the DD^* pairs to slow down by means of elastical scatters only, thus modifying their relative momentum k_0. As discussed in [7], indeed, the MC spectrum of DD^* pairs is an increasing function of k_0. When we turn on the interaction with pions, lower bins could be significantly refilled if even a small part of the many high-k_0 pairs was pushed to lower values. This would increase the number of molecule candidates, and the prompt production cross section as well.

The analysis in [10] was limited to samples of $p\bar{p} \to c\bar{c}$ events generated in Herwig and Pythia according to the Tevatron experimental setup (for details, see [7, 9, 10]). The interaction with pions makes the number of molecule candidates to increase by two orders of magnitude. However, the study of the full QCD events $p\bar{p} \to c\bar{c}, gg, gq, qq \ldots$ does not give the same striking results: even with five interactions with pions, the cross section does not increase more than $\mathcal{O}(10)$, see Fig. 1. Thus, even if we take into account the

[1] Hereafter by DD^* we understand $D^0\bar{D}^{*0} + \bar{D}^0 D^{*0}$.

interaction with the pions which spoil the FSI mechanism, we still are not able to reach the experimental value for the cross section.

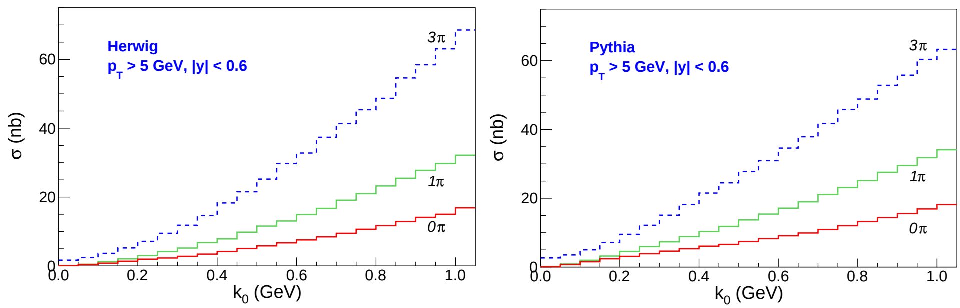

Fig. 1. Enhancement of $X(3872)$ cross section due to the interaction with n pions, with Herwig (left panel) and Pythia (right panel).

Finally, we wish to remark that we could apply the same framework to antideuteron production at the LHC. If the deuteron cross section happens to be much smaller than the $X(3872)$ at high p_T, considering both hadron molecules would be unlikely. This could seem the case if we use ALICE deuteron preliminary data [11], use Herwig to extrapolate the behavior at high p_T, and compare with CMS $X(3872)$ measurements [12], see Fig. 2. This result is not significative (data are not efficiency-corrected, the MC curve depends strongly on the hadronization mechanism), however it clearly indicates that new data by LHC for antideuteron production cross sections could give an interesting contribution to the discussion.

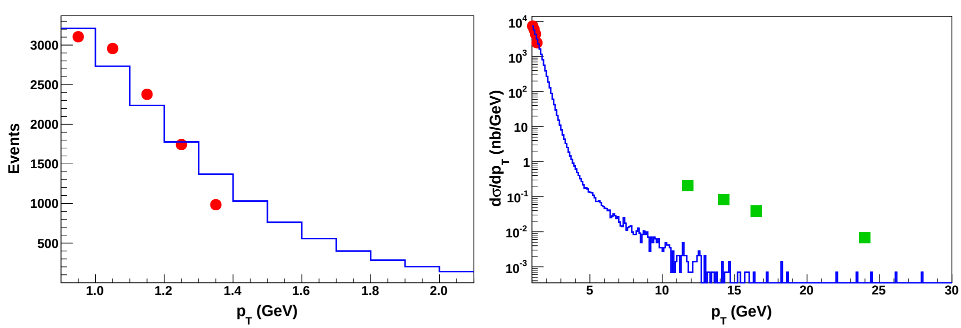

Fig. 2. Antideuteron events produced in pp at $\sqrt{s} = 7$ TeV. We generate 10^9 events with Herwig, with partonic cuts $p_T^{\text{part}} > 2$ GeV and $|y^{\text{part}}| < 6$. Antideuteron candidates have $|\eta| < 0.9$ and $k_0 < 300$ MeV. The MC curve (solid/blue) is rescaled in order to match ALICE data (gray/red circles) [11]. We report CMS $X(3872)$ data (gray/green squares) [12].

3. Feshbach molecules

We have shown that prompt production cross section of $X(3872)$ can hardly be reconciled with a pure molecular nature. Moreover, all quantitative evaluations of molecular spectra put the states at- or below-threshold, but many of the charged exotic states are above-threshold, which is not compatible with the classical definition of bound state. To explain this, we proposed in Ref. [13] a tentative description using the formalism of low-energy Feshbach resonances [14], an important tool in investigations of the basic atomic physics of cold atoms. We assume that the $X(3872)$ and Z_cs resonances are 4-quark compact states with flavor content $c\bar{c}q\bar{q}$. The color structure is free to rearrange in two ways: *(i)* a hadrocharmonium-like configuration [4], with color structure $(c\bar{c})\,(q_1\bar{q}_2)$, *(ii)* an open charm-like configuration, with color structure $(c\bar{q}_1)\,(q_2\bar{c})$. The mass eigenstate is a superposition of these two configurations: both interpolating operators have the same global quantum number, and mix under renormalization because of strong dynamics. Each configuration can indeed evolve into the other one, so they cannot be considered one at a time: we are dealing with a compact object, whose quark color quantum numbers are not separately conserved during time evolution. This state is not a simple bound state of mesons, so we escape the issue of molecule production cross section. We can describe this state in a 2-coupled channels formalism. We call P and Q respectively the open charm subspace and the hadrocharmonium (closed) subspace.

We can think of the open charm configuration as a molecular-like state, made up of two open-charm mesons interacting with a non-binding potential. We also assume that the hadrocharmonium system admits bound states giving rise to a discrete spectrum of levels. The real spectrum is unknown, but we can roughly expect these levels to be in correspondence of the sum of the masses of hadrocharmonium 'constituents'. The coupling between the P and Q subspaces, described by some H_{QP} Hamiltonian term, appears in the expression of the scattering length

$$a \simeq a_P + C \sum_n \frac{|\langle \Psi_n | H_{QP} | \Psi_{\rm th}\rangle|^2}{E_{\rm th} - E_n} \simeq a_{NR} - C \frac{|\langle \Psi_{\rm res} | H_{QP} | \Psi_{\rm th}\rangle|^2}{\nu}\,.$$

If a level in the closed subspace is above the threshold of the continuum spectrum and close to it, the correspondent term dominates the sum, giving rise to an attractive interaction and favoring the formation of a metastable resonance at the hadrocharmonium level, that is called Feshbach resonance (Fig. 3). The effect is enhanced the smaller the difference in energy $E - E_{\rm th} = \nu$, E being the bound level and $E_{\rm th}$ the open-charm threshold. The Feshbach phenomenon is therefore the formation of a resonance in the 'scattering' between different internal tetraquark states.

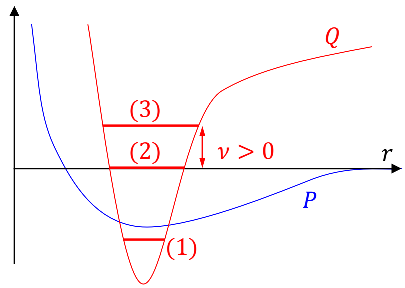

Fig. 3. P and Q are the open and closed channels respectively. (1) Charged $X(3872)$ partners suppression, (2) X case (3), Z_c case.

Going back to the $X(3872)$, the relative hadrocharmonium state would be made by a $c\bar{c}$ pair with $J^{\rm PC} = 1^{--}$ and a light component with $I^{\rm G}J^{\rm PC} = 1^{+}1^{--}$, held together by hadronic Van der Waals-like forces. This $J/\psi\,\rho^0$ level would have a mass of 3872 MeV. Since also the open charm threshold is at 3872 MeV, the detuning is compatible with zero and the scattering length is huge, whence the $X(3872)$ is so narrow. On the other hand, the charged threshold $D^+\,\bar{D}^{*0}$ is at $\approx$ 3876 MeV, whereas the $J/\psi\,\rho^+$ level is still at 3872 MeV. The level happens to slip below threshold, the scattering length a becomes positive and the interaction repulsive. This breaks isospin and explains why there are not $X(3872)^+$ states decaying into $J/\psi\,\pi^+\pi^0$. The decay width of a Feshbach resonance is $\Gamma = A\sqrt{\nu}$. We report in Table I the results extended to Z_cs and Z_b exotic resonances. It is remarkable that the value $A \sim 10$ MeV$^{1/2}$ happens to be compatible for all reported states.

TABLE I

Exotic states in term of Feshbach resonances. The width is related to the detuning by $\Gamma = A\sqrt{\nu}$, with $A \sim 10$ MeV$^{1/2}$.

State	Hadro-$q\bar{q}$	Open c/b	Γ [MeV]	ν [MeV]
$X(3872)$	$J/\psi\,\rho^0$	$D^0\bar{D}^{*0}$	0	0
$Z_c(3900)$	$\psi(3770)\,\pi$	$D^+\bar{D}^{*0}$	46 ± 22	23 ± 6
$Z_c'(4020)$	$h_c(2P)\,\pi_{P\text{-wave}}$	$D^{*+}\bar{D}^{*0}$	24.8 ± 9.5	9 ± 4.5
$Z_c'(4025)$	$h_c(2P)\,\pi_{P\text{-wave}}$	$D^{*+}\bar{D}^{*0}$	7.9 ± 3.7	5.6 ± 2.8
$Z_b(10610)$	$\chi_{b0}(1P)\,\rho_{P\text{-wave}}$	$B^+\bar{B}^{*0}$	18.4 ± 2.4	3 ± 2
$Z_b'(10650)$	$\chi_{b0}(1P)\,\rho_{P\text{-wave}}$	$B^{*+}\bar{B}^{*0}$	11.5 ± 2.2	1.8 ± 1.5

Finally, LHCb very recently confirmed a $Z^+(4430)$ with quantum numbers $I^{\rm G}J^{\rm P} = 1^+1^+$ [15]. This state is very far from any open charm threshold with correspondent quantum numbers, but is well described in terms of tetraquarks [16]. This adds an unexpected contribution to the discussion, and more studies on the topic are needed.

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