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From J/ψ to LHCb pentaquarks

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The two exotic $P_c^+(4380)$ and $P_c^+(4450)$ discovered in 2015 by the LHCb Collaboration, together with the four resonances $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$, reported in 2016 by the same collaboration, are described in a constituent quark model which has been able to explain the properties of charmonium states from the J/ψ to the $X(3872)$. Using this model we found a $\bar{D}\Sigma_c^*$ bound state with $J^P = \frac{3}{2}^-$ that may be identified with the $P_c^+(4380)$. In the $\bar{D}^*\Sigma_c$ channel we found three possible candidates for the $P_c^+(4450)$ with $J^P = \frac{1}{2}^-$, $\frac{3}{2}^-$ and $\frac{3}{2}^+$ with almost degenerated energies. The $X(4140)$ resonance appears as a cusp in the $J/\psi\phi$ channel due to the near coincidence of the $D_s^\pm D_s^{*\pm}$ and $J/\psi\phi$ mass thresholds. The remaining three $X(4274)$, $X(4500)$ and $X(4700)$ resonances appear as conventional charmonium states with quantum numbers 3^3P_1, 4^3P_0 and 5^3P_0, respectively; and whose masses and widths are slightly modified due to their coupling with the corresponding closest meson-meson thresholds.

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1. Introduction

Since the mythical date of November 1974 when the J/ψ particle was discovered, two new dates have become important in Charm Physics, enriching the field with new and interesting structures. In 2003 Belle Collaboration discovered two new states, the $X(3872)$ and the $D_{s0}(2317)$, whereas CLEO Collaboration measured the properties of the $D_{s1}(2460)$. All these states can hardly be accommodated in the predictions of the naive (but successful) quark models. This year represents the beginning of the discovery of a series of states collectively called XYZ states whose description is a challenge for theorists.

In the last two years the discovery by the LHCb Collaboration of several new resonances provoked a lively discussion about their structures (see [1] for a review). Two resonances, $P_c^+(4380)$ and $P_c^+(4450)$, compatibles with a pentaquark state, were observed in 2015 in the J/ψ invariant mass spectrum of the $\Lambda_b^0 \to J/\psi K^- p$ process [2]. The values of the masses and widths from a fit using Breit-Wigner amplitudes are $M_{P_c(4380)} = (4380 \pm 8 \pm 29)$ MeV/c^2, $\Gamma_{P_c(4380)} = (205 \pm 18 \pm 86)$ MeV, $M_{P_c(4450)} = (4449.8 \pm 1.7 \pm 2.5)$ MeV/c^2 and $\Gamma_{P_c(4450)} = (39 \pm 5 \pm 19)$ MeV.

Thanks to the large signal yield, the roughly uniform efficiency and the relatively low background across the entire $J/\psi\phi$ mass range, the LHCb Collaboration [3, 4] observed in the $J/\psi\phi$ invariant mass of the $B^+ \to J/\psi\phi K^+$ decay the $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$ resonances. The quantum numbers of the $X(4140)$ and $X(4274)$ states are determined to be $J^{PC} = 1^{++}$ with statistical significance 5.7σ and 5.8σ, respectively. The $X(4500)$ and $X(4700)$ resonances have both $J^{PC} = 0^{++}$ with statistical significance 4.0σ and 4.5σ, respectively.

The $X(4140)$ was measured first by the CDF Collaboration [5], which in an unpublished update of their analysis [6] reported a second narrow peak near 4270 MeV. However, Belle and LHCb Collaborations do not found any signal of these resonances in two photon collision and B^+ decays respectively.

Most of the XYZ resonances appear near open charm meson-meson thresholds and are explained as a coupled channel effect of $c\bar{c}$ structures with the meson-meson open channels. If the interaction is strong enough a new meson-meson (molecular) state appears besides the $c\bar{c}$ states, as in the case of the $X(3872)$ [7] but if the coupling is weak the only effect is the renormalization of the mass of the $c\bar{c}$ states, as in the case of the $D_{s0}(2317)$ [8]. Sometimes the meson-meson interaction is the responsible of forming the resonance state without the coupling to a $c\bar{c}$ state. As all the new resonances mentioned above appear near meson-meson or meson-baryon thresholds, we will explore the possibility of describing the new states within the same coupled channel scheme. To do that, we use the constituent quark model (CQM) presented in Ref. [9] and updated in Ref. [10] which has been extensively used to describe the hadron phenomenology. We use the same set of parameters of Ref. [10] without introducing any new one for the calculation. This is important, because the modification of the number or value of the parameters may modify arbitrarily the meson-meson or meson-baryon interaction and, thus, create artificially new states.

2. The model

The constituent quark model we use is based on the assumption that the light constituent mass appears due to the spontaneous chiral symmetry breaking of QCD at some momentum scale.

Regardless of the breaking mechanism, the simplest Lagrangian which describe this situation must contain chiral fields to compensate the mass term and can be expressed as [11]

$$\mathscr{L} = \overline{\psi}(i\not\partial - M(q^2)U^{\gamma_5})\,\psi \tag{2.1}$$

where $U^{\gamma_5} = \exp(i\pi^a\lambda^a\gamma_5/f_\pi)$, π^a denotes nine pseudoscalar fields $(\eta_{0,}\vec{\pi}, K_i, \eta_8)$ with i =1,...,4 and $M(q^2)$ is the constituent mass. This constituent quark mass, which vanishes at large momenta and is frozen at low momenta at a value around 300 MeV, can be explicitly obtained from the theory but its theoretical behavior can be simulated by parametrizing $M(q^2) = m_q F(q^2)$ where $m_q \simeq 300$ MeV, and

$$F(q^2) = \left[\frac{\Lambda^2}{\Lambda^2 + q^2}\right]^{\frac{1}{2}}. \tag{2.2}$$

The cut-off Λ fixes the chiral symmetry breaking scale.

The Goldstone boson field matrix U^{γ_5} can be expanded in terms of boson fields,

$$U^{\gamma_5} = 1 + \frac{i}{f_\pi}\gamma^5\lambda^a\pi^a - \frac{1}{2f_\pi^2}\pi^a\pi^a + \ldots \tag{2.3}$$

The first term of the expansion generates the constituent quark mass while the second gives rise to a one-boson exchange interaction between quarks. The main contribution of the third term comes from the two-pion exchange which has been simulated by means of a scalar exchange potential.

In the heavy quark sector chiral symmetry is explicitly broken and we do not need to introduce additional fields. However the chiral fields introduced above provide a natural way to incorporate the pion exchange interaction in the molecular dynamics.

The other two main properties of QCD (besides the chiral symmetry breaking) are confinement and asymptotic freedom. At present it is still unfeasible to analytically derive these properties from the QCD Lagrangian, hence we model the interaction with a phenomenological confinement and the one-gluon exchange potentials, the last one, following De Rujula [12], coming from the Lagrangian.

$$\mathscr{L}_{gqq} = i\sqrt{4\pi\alpha_s}\,\overline{\psi}\gamma_\mu G^\mu_c \lambda_c \psi\,, \tag{2.4}$$

where λ_c are the SU(3) color generators and G^μ_c the gluon field.

The confinement term, which prevents from having colored hadrons, can be physically interpreted in a picture where the quark and the antiquark are linked by a one-dimensional color flux-tube. The spontaneous creation of light-quark pairs may give rise at same scale to a breakup of the color flux-tube. This can be translated into a screened potential, in such a way that the potential saturates at the same interquark distance, such as

$$V_{CON}(\vec{r}_{ij}) = \{-a_c\,(1 - e^{-\mu_c r_{ij}}) + \Delta\}(\vec{\lambda^c}_i \cdot \vec{\lambda^c}_j) \tag{2.5}$$

where Δ is a global constant to fit the origin of energies. Explicit expressions for all these interactions are given in Ref. [9]. In the same reference all the parameters of the model are detailed, additionally adapted for the heavy meson spectra in Ref. [10].

In order to find the quark-antiquark bound states with this constituent quark model, we solve the Schrödinger equation using the Gaussian expansion method [13] (GEM), expanding the radial wave function in terms of basis functions

$$R_\alpha(r) = \sum_{n=1}^{n_{max}} c_n^\alpha \phi_{nl}^G(r), \tag{2.6}$$

where α refers to the channel quantum numbers and $\phi_{nl}^G(r)$ are Gaussian trial functions with ranges in geometric progression. This choice is useful for optimizing the ranges with a small number of free parameters [13]. In addition, the geometric progression is dense at short distances, so that it enables the description of the dynamics mediated by short range potentials.

The coefficients, c_n^α, and the eigenvalue, E, are determined from the Rayleigh-Ritz variational principle

$$\sum_{n=1}^{n_{max}} \left[(T_{n'n}^\alpha - E N_{n'n}^\alpha) c_n^\alpha + \sum_{\alpha'} V_{n'n}^{\alpha\alpha'} c_n^{\alpha'} = 0 \right], \tag{2.7}$$

where $T_{n'n}^\alpha$, $N_{n'n}^\alpha$ and $V_{n'n}^{\alpha\alpha'}$ are the matrix elements of the kinetic energy, the normalization and the potential, respectively. $T_{n'n}^\alpha$ and $N_{n'n}^\alpha$ are diagonal, whereas the mixing between different channels is given by $V_{n'n}^{\alpha\alpha'}$.

Following Ref. [14], in order to model the meson-baryon system we use a Gaussian form to describe the baryon wave function,

$$\psi(\vec{p}_i) = \prod_{i=1}^{3} \left[\frac{\alpha_i b^2}{\pi} \right]^{\frac{3}{4}} e^{-\frac{b^2 \alpha_i p_i^2}{2}}, \tag{2.8}$$

where we take the values $b = 0.518\, fm$ and $\alpha_i = 1$ for the nucleon wave function [14], and the scaling parameters α_i for different flavors are obtained using the prescription of Ref. [15].

To describe the coupling between two and four quark configuration, we assume now that the hadronic state can be described as

$$|\Psi\rangle = \sum_\alpha c_\alpha |\psi_\alpha\rangle + \sum_\beta \chi_\beta(P) |\phi_A \phi_B \beta\rangle, \tag{2.9}$$

where $|\psi_\alpha\rangle$ are $c\bar{c}$ eigenstates solution of the two-body problem, ϕ_A and ϕ_B are the two meson states with β quantum numbers, and $\chi_\beta(P)$ is the relative wave function between the two mesons.

Two- and four-quark configurations are coupled using the same transition operator that has allowed us to compute the above open-flavour strong decays. This is because the coupling between the quark-antiquark and meson-meson sectors requires also the creation of a light quark pair [16, 17]. We define the transition potential $h_{\beta\alpha}(P)$ within the ${}^3P_0$ model as [18]

$$\langle \phi_A \phi_B \beta | T | \psi_\alpha \rangle = P\, h_{\beta\alpha}(P)\, \delta^{(3)}(\vec{P}_{\rm cm}), \tag{2.10}$$

where P denotes the relative momentum of the two-meson state.

Using Eq. (2.9) and the transition potential in Eq. (2.10), we arrive to the coupled equations

$$c_\alpha M_\alpha + \sum_\beta \int h_{\alpha\beta}(P) \chi_\beta(P) P^2 dP = E c_\alpha\,, \tag{2.11}$$

Molecule	J^P	I	$Mass(MeV/c^2)$	Width $J/\psi p$	Width $\bar{D}^*\Lambda_c$
$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	$\frac{1}{2}$	4385.0	10.0	14.7
$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	$\frac{1}{2}$	4458.9	5.3	63.6
$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	$\frac{1}{2}$	4461.3	0.8	21.2
$\bar{D}^*\Sigma_c$	$\frac{3}{2}^+$	$\frac{1}{2}$	4462.7	0.2	6.3

Table 1: Masses of the different molecular states

$$\sum_\beta \int H_{\beta'\beta}(P',P)\chi_\beta(P)P^2dP + \sum_\alpha h_{\beta'\alpha}(P')c_\alpha = E\chi_{\beta'}(P'), \tag{2.12}$$

where M_α are the masses of the bare $c\bar{c}$ mesons and $H_{\beta'\beta}$ is the resonant group method (RGM) Hamiltonian for the two-meson states obtained from the $q\bar{q}$ interaction.

3. $P_c^+(4380)$ and $P_c^+(4450)$ resonances

We consider the $\bar{D}^{(*)}\Sigma^{(*)}$ thresholds, which are the only ones where a sizable residual interaction can be expected, mainly due to pion exchanges.

In the mass region of the $P_c(4380)^+$ one can see in Table 1 that we obtain one $\bar{D}\Sigma_c^*$ state with $J^P = \frac{3}{2}^-$. Its mass is very close to the experimental one and should, in principle, be identified with $P_c(4380)^+$.

Referring to the channel $\bar{D}^*\Sigma_c$ we found three almost-degenerated states around M=4460 MeV/c^2 with $J^P = \frac{1}{2}^-$, $\frac{3}{2}^-$ and $\frac{3}{2}^+$. The existence of these three degenerated states may be the origin of the uncertainty in the experimental value of J^P. The energy of those states makes them natural candidates for the $P_c(4450)^+$. It is remarkable that the decay width through the $\bar{D}^*\Lambda_c$ channel is generally equal to or greater than the width via the $J/\psi p$ channel. This suggests that the $\bar{D}^*\Lambda_c$ channel is a suitable channel for studying the properties of these resonances. In particular, the width of the predicted $\bar{D}^*\Sigma_c$ resonance with $J^P = \frac{1}{2}^-$ is twelve times greater through the $\bar{D}^*\Lambda_c$ channel than through the $J/\psi p$ channel, being this decay a good check for the existence of the resonance.

Concerning the parity of the states, a molecular scenario is not the most convenient to obtain positive parity states because, being the $\bar{D}^{(*)}$ mesons and the $\Sigma_c^{(*)}$ baryons of opposite parity, the relative angular momentum should be at least $L = 1$ (P-wave) which will be above S-waves. This is reflected in the fact that the states with positive parity in Table 1 are those with smaller binding energies.

4. $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$ resonances

Table 2 shows the calculated naive quark-antiquark spectrum in the region of interest of the LHCb for the $J^{PC} = 0^{++}$ and 1^{++} channels. A tentative assignment of the theoretical states with the experimentally observed mesons at the LHCb experiment is also given. It can be seen that the naive quark model is able to reproduce all the new LHCb resonances except the $X(4140)$. The

State	J^{PC}	nL	Theory (MeV)	Experiment (MeV)
χ_{c0}	0^{++}	$3P$	4241.7	–
		$4P$	4497.2	$4506 \pm 11^{+12}_{-15}$
		$5P$	4697.6	$4704 \pm 10^{+14}_{-24}$
χ_{c1}	1^{++}	$3P$	4271.5	4273.3 ± 8.3
		$4P$	4520.8	–
		$5P$	4716.4	–

Table 2: Naive quark-antiquark spectrum in the region of interest of the LHCb [3, 4] for the 0^{++} and 1^{++} channels.

Mass	Width	$\mathscr{P}_{c\bar{c}}$	$\mathscr{P}_{D_sD_s^*}$	$\mathscr{P}_{D_s^*D_s^*}$	$\mathscr{P}_{J/\psi\phi}$
4242.4	25.9	48.7	43.5	5.0	2.7

Table 3: Mass, total width (in MeV), and $c\bar{c}$ component probabilities (in %) for the $X(4274)$ meson, obtained from the coupled channel calculation described in the text.

$X(4274)$, $X(4500)$ and $X(4700)$ appear as conventional charmonium states with quantum numbers 3^3P_1, 4^3P_0 and 5^3P_0, respectively.

A complete study of the decay width of these states has been performed in Ref [19] showing that the decay width of the $X(4274)$, $X(4500)$ and $X(4700)$ are, withing errors, in reasonable agreement with the data.

To gain some insight into the nature of the $X(4140)$, that does not appear as a quark-antiquark state, and to see how the coupling with the open-flavour thresholds can modify the properties of the naive quark-antiquark states predicted above, we have performed a coupled-channel calculation including the $D_sD_s^*$, $D_s^*D_s^*$ and $J/\psi\phi$ ones for the $J^{PC} = 1^{++}$ sector. We found only one state with mass 4242.4 MeV and total decay width 25.9 MeV. This state is made by 48.7% of the $3P$ charmonium state and by 43.5% of the $D_sD_s^*$ component (see Tables 3 and 4). When coupling with thresholds, the modification in the mass is small. As we do not find any signal for the $X(4140)$, neither bound nor virtual, we analyze the line shape of the $J/\psi\phi$ channel as an attempt to explain the $X(4140)$ as a simple threshold cusp (see Ref [19] for the details).

Figure 1 compares our result with that reported by the LHCb Collaboration in the $B^+ \to J/\psi\phi K^+$ decays. The rapid increase observed in the data near the $J/\psi\phi$ threshold corresponds to a bump in the theoretical result just above such threshold. This cusp is too wide to be produced by a bound or virtual state below the $J/\psi\phi$ threshold.

Mass (MeV)	$\mathscr{P}_{c\bar{c}}$	$\mathscr{P}_{1P}$	$\mathscr{P}_{2P}$	$\mathscr{P}_{3P}$	$\mathscr{P}_{4P}$	$\mathscr{P}_{(n>4)P}$
4242.4	48.7	0.000	0.370	99.037	0.488	0.105

Table 4: Probabilities, in %, of nP $c\bar{c}$ components in the total wave function of the $X(4274)$ meson.

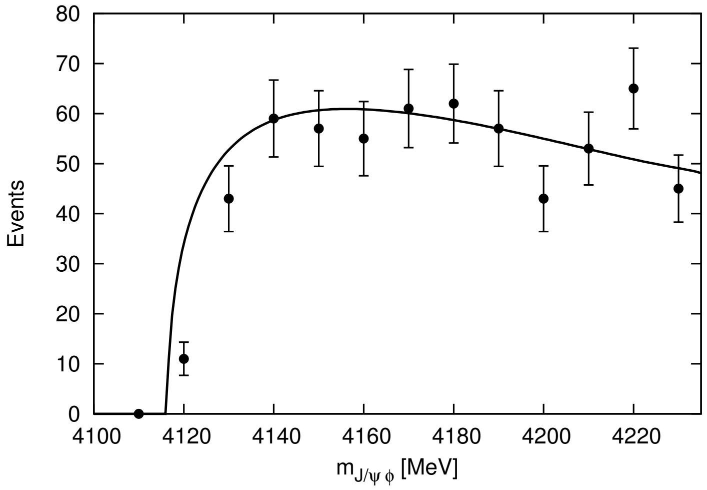

Figure 1: Line-shape prediction of the $J/\psi\phi$ channel. The curve shows the production of $J/\psi\phi$ pairs via direct generation from a point-like source plus the production via intermediate $c\bar{c}$ states. Note that the production constant has been fitted to the data (see Ref [19] for the details).

5. Summary

As a summary, our results confirm the fact that there are several states with a $\bar{D}^{(*)}\Sigma_c^{(*)}$ structure in the vicinity of the masses of the $P_c(4380)^+$ and $P_c(4450)^+$ pentaquark states reported by the LHCb.

Concerning the other resonances, three of them, namely $X(4274)$, $X(4500)$ and $X(4700)$, are consistent with bare quark-antiquark states with quantum numbers $J^{PC} = 1^{++}(3P)$, $J^{PC} = 0^{++}(4P)$ and $J^{PC} = 0^{++}(5P)$, respectively.

In the 1^{++} sector we do not find any pole in the mass region of the $X(4140)$, though. However, the scattering amplitude shows a bump just above the $J/\psi\phi$ threshold which reproduces the fast increase of the experimental data. Therefore, the structure showed by this data around 4140 MeV should be interpreted as a cusp due to the presence of the $D_sD_s^*$ threshold.

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