



December 3, 2013

Molecular Structures in Hidden Charm Meson and Charmed Baryon Spectrum

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Using a constituent quark model we study the mass and decay channels of meson meson and meson baryon structures in the charm sector.

We show that the $X(3872)$ and $X(3940)$ resonances can be described as mixed charmonium-molecular states with $J^{PC} = 1^{++}$, whereas the $X(3915)$ and the $Y(3940)$ can be assigned to similar mixed states with $J^{PC} = 0^{++}$.

In the baryon spectrum we identify the $\Lambda_c^+(2940)$ as a D^*N molecule with $(I)J^P = (0)3/2^-$ and the recently reported $X_c(3250)$ as a $D^*\Delta$ resonance with $(I)J^P = (1)5/2^-$ or $(I)J^P = (2)3/2^-$.

PRESENTED AT

The 6th International Workshop on Charm Physics
(CHARM 2013)
Manchester, UK, 31 August – 4 September, 2013

1 Introduction

In the last several years many exotic hadronic states has been observed with unexpected properties that disfavor their interpretation as ordinary hadrons.

Most of these states appear near open flavor thresholds and therefore one can expect that loosely bound or resonant meson-meson or baryon-meson structures mix with the original $q\bar{q}$ or qqq structures to configure the physical states.

The $X(3872)$ was the first of this kind of states to be discovered. Its decays into $J/\psi\rho$ and $J/\psi\omega$ channels violate isospin and completely rules out a $c\bar{c}$ interpretation. Recently LHCb has fixed its quantum numbers [1]. Moreover other candidate to this quantum numbers appear in this mass region, namely the $X(3940)$, which was observed by Belle [2].

Two years after the discovery of the $X(3872)$, the $Y(3940)$ was observed by the Belle Collaboration [3]. Belle reported a mass of $M = 3943 \pm 11 \pm 13$ MeV and a width $\Gamma = 87 \pm 22 \pm 26$ MeV. A later measurement from BABAR [4] confirmed this resonance but with a mass value $M = 3919 \pm 3.8 \pm 2.04$ MeV. Later on, a new state, the $X(3915)$, has been reported by the Belle Collaboration in the $\gamma\gamma \rightarrow J/\psi\omega$ decay [5]. The measured mass is $M = 3914 \pm 3 \pm 2$ MeV and the width $\Gamma = 23 \pm 9$ MeV. The proximity of the masses could indicate that these states are connected to the same particle [6]. However there are evidences that the two states could be molecular states. The $Y(3940)$ has a lower limit for the decay $J/\psi\omega$ of $\Gamma > 1$ MeV, which is large for an OZI suppressed channel of conventional charmonium. On the other hand the product $\Gamma_{\gamma\gamma} \times B[X(3915) \rightarrow J/\psi\omega]$ is relatively large compared to charmonium predictions. Very recently, the quantum numbers of the $X(3915)$ were established as $J^\pi = 0^+$ [7].

These situations also appear in the baryon spectrum, where the $\Lambda_c^+(2940)$, observed by Babar [8] and later confirmed by Belle [9], is just 6 MeV/ c^2 below the D^*p threshold. Similarly the recently reported $X_c(3250)$ [10] state is close to the $D^*\Delta$ threshold.

In this work we propose a unified theoretical explanation of these states as meson meson or meson baryon molecular states in a constituent quark model that has been extensively used to describe the hadron phenomenology [11, 12].

The model is based on the assumption that the spontaneous chiral symmetry breaking generates the constituent mass. To compensate this mass term in the hamiltonian the Lagrangian must include Goldstone boson fields which mediates the interaction between quarks. The minimal realization of this mechanism include a pseudo scalar boson and an scalar one. In this model baryons (mesons) are described as clusters of three quark (one pair of quark and antiquark). This fact does not affect the heavy quark sector but is of paramount importance in the molecular picture because the only remaining interaction between the two molecular component, due to its color singlet nature, is the one driven by the Goldstone boson exchanges between the light

<i>Mass</i>	$c\bar{c}(2^3P_1)$	D^0D^{*0}	$D^\pm D^{*\mp}$	$J/\psi\rho$	$J/\psi\omega$
3871.5	8.00	86.61	4.58	0.53	0.29
3941.8	61.09	18.53	16.85	0.01	3.52

Table 1: Binding energy (in MeV) and channel probabilities (in %) for the $X(3872)$ and $X(3940)$ states.

quarks.

The meson meson and the meson baryon interactions are obtained using the Resonating Group method. The coupling between the $q\bar{q}$ and the four quarks configuration are performed using the 3P_0 model. A more detailed discussion of the model and its application to the states mentioned above can be found in [13].

2 Results for the charmonium sector

We have performed a calculation including the two quark $c\bar{c}(2^3P_1)$ together with the D^0D^{*0} , $D^\pm D^{*\mp}$, $J/\psi\rho$ and $J/\psi\omega$ channels. The coupling of the DD^* with the $J/\psi\rho$ and $J/\psi\omega$ channels is not enough to bind the molecule and it is mandatory to couple the $c\bar{c}$ pair to reach a molecular bound state. To introduce the isospin breaking in our calculation we will work in the charge basis instead of the isospin symmetric one, allowing the dynamics of the system to choose the weight of the different components. Isospin is explicitly broken using the experimental meson masses.

The different components for the $X(3872)$ and the $X(3940)$ are shown in Table 1.

The results for the experimental ratios $R_1 = \frac{\Gamma(X(3872) \rightarrow \pi^+\pi^-\pi^0 J/\psi)}{\Gamma(X(3872) \rightarrow \pi^+\pi^- J/\psi)} = 0.8 \pm 0.3$ and $R_2 = \frac{\Gamma(X(3872) \rightarrow \gamma\Psi(2S))}{\Gamma(X(3872) \rightarrow \gamma J/\psi)} \leq 2.1(90\%C.L.)$ are respectively 0.44 and 1.2 in agreement with the data.

As seen in Table 1, the $X(3940)$ has almost the same value of neutral and charged DD^* components. Therefore the isospin breaking has almost completely disappear and the resonance is basically $I = 0$. This justifies that the coupling with the $J/\psi\rho$ channel is almost negligible.

The $X(3872)$ decays basically through the DD^* component being the branching ratio for the different channels $\mathcal{B.R.}(X(3872) \rightarrow DD^*) = 0.89$, $\mathcal{B.R.}(X(3872) \rightarrow J/\psi\omega) = 0.1$, $\mathcal{B.R.}(X(3872) \rightarrow J/\psi\rho) = 3 \times 10^{-4}$. In this way the puzzle between this two states with the same quantum numbers seems to be solved in a satisfactory way.

We have performed the same calculation as before but for the $J^{PC} = 0^{++}$ sector. We include the 2^3P_0 $c\bar{c}$ channel together with the molecular channels $D\bar{D}(3736.05$ MeV), $J/\psi\omega(3879.56$ MeV), $D_s\bar{D}_s(3936.97$ MeV), $J/\psi\phi(4116.0$ MeV) where the channel thresholds are indicated between brackets. The results are shown in Table 2.

<i>state</i>	<i>Mass</i>	Γ	$c\bar{c}(2^3P_0)$	$D^0\bar{D}^0$	$J/\psi\omega$	$D_s\bar{D}_s$	$J/\psi\phi$
$X(3915)$	3896.5	4.10	34.22	46.67	9.42	9.67	0.03
$Y(3940)$	3970	189.3	57.27	35.32	0.15	5.72	1.54

Table 2: Mass and total width (in MeV) and channel probabilities (in %) for the $X(3915)$ and $Y(3940)$.

M (MeV)	$\mathcal{P}_{4S_{3/2}}$	$\mathcal{P}_{2D_{3/2}}$	$\mathcal{P}_{4D_{3/2}}$	$\mathcal{P}_{D^{*0}p}$	$\mathcal{P}_{D^{*+}n}$	$\mathcal{P}_{I=0}$	$\mathcal{P}_{I=1}$
2938,80	96,22	0,86	2,92	63,93	36,07	97,52	2,48

Table 3: Mass of the $\Lambda_c^+(2940)$ and contributions for the different channels.

We find a narrow state which can be identified with the $X(3915)$. This resonance is basically a mixture of $c\bar{c}$ and $D\bar{D}$ molecular components. Moreover a second wide resonance appears at $M = 3970$ MeV. This resonance can be the old $Y(3940)$, today disappeared from the PDG. Its dominant component is the $c\bar{c}(2^3P_0)$ although the contribution of the molecular $D\bar{D}$ is also significant. This structure provide a possible explanation for the unusual decay mode $J/\psi\omega$ through the rescattering $0^{++} \rightarrow D\bar{D} \rightarrow J/\psi\omega$.

3 The $\Lambda_c^+(2940)$ and the $X_c(3250)$

To explain the $\Lambda_c^+(2940)$ we have studied the possible molecular sytructures of the ND^* system. We found a molecular state with $J^P = \frac{3}{2}^-$ quantum numbers at a mass of 2938,68 MeV/ c^2 . One can see from Table 3 that the molecule is basically a $4S_{3/2}$ D^*N state with a small mixture of $D_{3/2}$ states.

The different components in the charge basis show that the $\Lambda_c^+(2940)$ is a $D^{*0}p$ molecule with a sizable $D^{*+}n$ component. Looking to the isospin one realizes that the state is almost a pure $I = 0$ state as required by the experimental data. The results

Decay channel	$Width$ (MeV)	decay channel	$Width$ (keV)
$\Lambda_c^+ \rightarrow D^0p$	9.42	$\Lambda_c^+ \rightarrow \Sigma_c^{++}\pi^-$	29.7
$\Lambda_c^+ \rightarrow D^+n$	10.74	$\Lambda_c^+ \rightarrow \Sigma_c^+\pi^0$	25.2
		$\Lambda_c^+ \rightarrow \Sigma_c^0\pi^+$	21.1
$\Gamma(total)$	20.2	$\Gamma(experimental)$	17_{-6}^{+8}

Table 4: Widths of the $\Lambda_c^+(2940)$ for different decay channels.

J^P	I	$Mass(Mev/c^2)$	$P_{max}(Channel)$
$\frac{1}{2}^-$	2	3232,7	99,71($^2S_{1/2}$)
$\frac{3}{2}^-$	2	3238,2	99,69($^4S_{3/2}$)
$\frac{5}{2}^-$	1	3226,1	97,25($^6S_{5/2}$)

Table 5: Quantum numbers and masses of the different $D^*\Delta$ resonances

for the different decay widths are shown in Table 4. The widths of the D^0p and D^+n decay channels are of the order of the experimental width whereas the contributions of the $\Sigma\pi$ channels are negligible. The predicted total width also agree with the experimental data.

Finally, in the $D^*\Delta$ sector, there are three possible states in the mass range of 3230 MeV/ c^2 (see Table 5). They are basically $L = 0$ resonances.

All these states can decay through the $\Sigma_c^{++}\pi^-\pi^-$ channel by rearrangement. Nevertheless this is not the main decay channel for the $D^*\Delta$ molecule because it should be easier to decay through the $D^*N\pi$ channel. This is the channel where the experimentalist should look to confirm the structure of the $X_c(3250)$.

4 Summary

As a summary, we have found that molecular structures may play an important role in the description of the meson and baryon spectra. In particular the $X(3872)$, $X(3940)$, $X(3915)$ and $Y(3940)$ can be describes as DD^* resonances coupled to $q\bar{q}$ states. Without changing any parameter we found a D^*N molecule in the $J^P = \frac{3}{2}^-$ channel and $I = 0$ with a mass and total width that agrees with the experimental data for the $\Lambda_c^+(2940)$ baryon. Finally we found that the recently reported $X_c(3250)$ can be explained as a $D^*\Delta$ molecule.

ACKNOWLEDGEMENTS

This work has been partially funded by Ministerio de Ciencia y Tecnología under Contract No. FPA2010-21750-C02-02, by the European Community-Research Infrastructure Integrating Activity “Study of Strongly Interacting Matter” (Hadron-Physics3 Grant no. 283286) and by the Spanish Ingenio-Consolider 2010 Program CPAN (CSD2007-00042).

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