PROCEEDINGS OF SCIENCE

Hadronic Molecules

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Possible molecular states in the hidden charm and bottom sector are discussed in a constituent quark model description. The $X(3872)$ resonance is described as a dynamically generated DD^* molecule coupled to a $c\bar{c}(2^3P_1)$ state, and its decay modes are calculated.
We also obtain in the D^*D^* $J^{PC} = 1^{--}$ channel a bound state that can be identified with the $Y(4008)$ charmonium state.

35th International Conference of High Energy Physics - ICHEP2010,
July 22-28, 2010
Paris France

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1. Introduction

Recently, the so-called XYZ mesons have challenged the description of the hadron spectroscopy. These new hadron resonances which cannot fit in a $q\bar{q}$ scheme have renewed the possibility of hadronic molecule interpretation.

In this work we present a model of heavy resonances dynamically generated by the coupling with the $q\bar{q}$ sector. The $X(3872)$ appear in the $J^{PC} = 1^{++}$ channel as a coupling of DD^* and $\chi_{c1}(2P)\,c\bar{c}$ state. No bound state is found if the coupling with the $c\bar{c}$ pair is neglected. This result allows us to understand simultaneously the isospin violation showed by the experimental data and the radiative decay rates.

No bound states are found in other channels but in the $D^*D^*\,J^{PC} = 1^{--}$ channel, which may coincide with the controversial $Y(4008)$ resonance. When extended to the bottom sector, we found the analog to the $X(3872)$ near the BB^* threshold.

2. The Model

To analyze these states we will follow the same method as in Ref. [1]. To improve the description of the $X(3872)$, we have included the $J/\psi\rho$ and the $J/\psi\omega$ channels through the rearrangement process [2], which are less important regarding the mass of the resonance, but necessary for the decays.

In a coupled channel model, the $X(3872)$ can decay radiatively either through the molecular component or the $c\bar{c}$ component. DD^* component can decay through annihilation of light quarks or via vector dominance through quark rearrangement [3]. Regarding the $c\bar{c}$ component, the partial width can be calculated through a E1 transitions between states $n^{2S+1}L_J$ and $n'^{2S'+1}L'_{J'}$.

The analysis of the strong decays $X \to \pi^+\pi^- J/\psi$ ($X \to \pi^+\pi^-\pi^0 J/\psi$) can be done in our formalism through the $\rho J/\psi$ ($\omega J/\psi$) wave function, including the ρ width in the energy propagator, which is not negligible.

3. Results

γ	E_{bind}	$c\bar{c}(2^3P_1)$	D^0D^{*0}	$D^\pm D^{*\mp}$	$J/\psi\rho$	$J/\psi\omega$	$\Gamma_{\pi^+\pi^-J/\psi}$	$\Gamma_{\pi^+\pi^-\pi^0J/\psi}$	R_1
0.231	−0.60	12.40	79.24	7.46	0.49	0.40	27.61	14.40	0.52
0.226	−0.25	8.00	86.61	4.58	0.53	0.29	24.18	10.64	0.44

Table 1: Binding energy (in MeV) and channel probabilities (in %) for the $X(3872)$ state for two values of the $^3P_0$ model γ parameter. Also, $X(3872) \to \pi^+\pi^- J/\psi$ and $X(3872) \to \pi^+\pi^-\pi^0 J/\psi$ decay widths (in KeV) and its ratio for the $X(3872)$ state for two different binding energies. The experimental values are $R_1 = \frac{X(3872)\to\pi^+\pi^-\pi^0 J/\psi}{X(3872)\to\pi^+\pi^- J/\psi} = 1.0 \pm 0.4 \pm 0.3(Belle),\, 0.8 \pm 0.3\,(BaBar)$.

We have performed a coupled channel calculation including the $c\bar{c}(2^3P_1)M = 3947.4$ MeV, the neutral and charged DD^* channels, and the $J/\psi\rho$ and $J/\psi\omega$ channels. Based on our first calculation [1], we have neglected the coupling with the $J^{PC} = 1^{++}, 1P$ because its negligible contribution to the $X(3872)$ binding energy. The calculation is parameter free since all the parameters are taken from the previous calculation [4].

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 have an idea of the sensitivity of the decay widths to the $X(3872)$ binding energy, we have fine-tuned the $^3P_0$ γ parameter to get the experimental mass range. In Table 1 we can see the results of this part of the calculation. Again in Table 1 we show the calculated width for the strong decays, which are not far from the experimental value.

Radiative decays results are shown in Table 2 for the $\gamma J/\psi$ channel and for the $\gamma\psi(2S)$ channel. The first aspect we notice is that the contribution of the molecular component to the decay width is very small. The ratios R_2^M and R_3^M are two orders of magnitude too small. These results clearly show that a pure molecule is unable to explain the data. If we include the $c\bar{c}$ component the widths are much bigger and the ratios are dominated by this contribution. We find a good agreement with the experimental ratio R_2 although for R_3 we obtain the correct order of magnitude but a value too low.

E_{bind}(MeV)	$\Gamma^M_{J/\psi\gamma}$	R_2^M	$\Gamma^{c\bar{c}}_{J/\psi\gamma}$	$R_2^{c\bar{c}}$	R_2	$\Gamma^M_{\Psi(2S)\gamma}$	R_3^M	$\Gamma^{c\bar{c}}_{\Psi(2S)\gamma}$	$R_3^{c\bar{c}}$	R_3
-0.60	0.070	$2.5\,10^{-3}$	8.15	0.29	0.30	0.134	$4.8\,10^{-3}$	9.80	0.35	0.34
-0.25	0.056	$2.3\,10^{-3}$	5.25	0.22	0.22	0.101	$4.2\,10^{-3}$	6.31	0.26	0.26

Table 2: Radiative decay widths (in KeV) for the $X(3872) \to \gamma J/\psi$ channel for two different binding energies. $\Gamma^M\,(R^M)$ is the width(ratio) including only the contributions from the molecular part and $\Gamma^{c\bar{c}}\,(R^{c\bar{c}})$ from the $c\bar{c}$ component. $R_2 = \frac{\Gamma(X(3872)\to\gamma J/\psi)}{\Gamma(X(3872)\to\pi^+\pi^- J/\psi)}$ and $R_3 = \frac{\Gamma(X(3872)\to\gamma\psi(2S))}{\Gamma(X(3872)\to\pi^+\pi^- J/\psi)}$ are the full result. The experimental values available are $R_2 = 0.14\pm0.05\,(Belle)$, $0.33\pm0.12\,(BaBar)$ and $R_3 = 1.1\pm0.4$.

4. Hidden charm and bottom sectors

Besides the $X(3872)$, we performed a search for new molecules in the hidden charm sector. Apart from the $X(3872)$ we find no states but the controversial $Y(4008)$ as a D^*D^* molecule coupled to the 4^3S_1 $c\bar{c}$ state. This state was discovered along with the $X(4260)$ resonance at Belle, but still BaBar confirmation is needed. Its quantum numbers require the molecule to be in a relative P-wave state. We get a state with $64.5\,\%$ of D^*D^* molecule and $34.5\,\%$ of $4^3S_1\,c\bar{c}$. Also, the $\psi(4040)$ gets modified due to its proximity to the threshold acquiring a sizable D^*D^* component.

Concerning the hidden bottom sector, the reduction of the kinetic energy due to the mass of the b quark favors the creation of new clusters. We present the results in Table 3, showing the binding energy when a molecule is found. Among the new states predicted, we can remark the $X(3872)$ partner near the BB^* threshold. But there are many, specially the B^*B^* $J^{PC} = 2^{++}$ or BB_1 $J^{PC} = 1^{--}$ channels, with bigger binding energy.

It is interesting to remark that the coupling with $b\bar{b}$ is not always necessary, because in some sectors the relative position of the theoretical bottonium state and the threshold makes the potential to be repulsive. Only in the BB_1 threshold we appreciate that the coupling favors the creation of molecule structures. This mechanism reduces the number of possible molecules in the hidden bottom sector and also in the hidden charm sector.

Mesons	Threshold	J^{PC}	with $^3P_0$	without $^3P_0$
BB	$10558.56\,MeV$	0^{++}	–	$-0.02\,MeV$
BB^*	$10604.38\,MeV$	1^{++}	$-1.31\,MeV$	$-8.96\,MeV$
		1^{+-}	$-0.01\,MeV$	$-0.05\,MeV$
B^*B^*	$10650.20\,MeV$	1^{+-}	$-0.04\,MeV$	$-0.04\,MeV$
		2^{++}	$-4.02\,MeV$	$-9.26\,MeV$
$BB_1(^1P_1)$	$11002.5\,MeV$	1^{--}	$-5.2\,MeV$	–
$BB_1(^3P_1)$	$11002.5\,MeV$	1^{--}	$-4.61\,MeV$	$-0.002\,MeV$

Table 3: Hidden bottom sector molecular candidates. The parenthesis in BB_1 threshold references to the partial wave of the B_1 meson.

It is promising to find attraction in the 1^{--} channel where a tetraquark state (the $Y_b(10890)$) has been recently predicted [5].

5. Summary

We perform a search for possible molecule candidates in the hidden charm and bottom sector. The $X(3872)$ appears as a DD^* molecule generated by the coupling with the $c\bar{c}(2^3P_1)$, extending the calculation of Ref. [1] to include the $\rho J/\psi$ and $\omega J/\psi$ channels. We have also calculated the radiative and strong decays. The $c\bar{c}$ component is decisive to explain the radiative decays whereas the strong ratio is explained by the presence of charged DD^* components.

Among other XYZ states, our formalism allows us to explain the $Y(4008)$ meson as a D^*D^* molecule in the hidden charm sector. A search in the hidden bottom sector unveils a rich spectroscopy in an energy region to be explored.

Acknowledgments

This work has been partially funded by Ministerio de Ciencia y Tecnología under Contract No. FPA2007-65748, by Junta de Castilla y León GR12, by the European Community-Research Infrastructure Integrating Activity "Study of Strongly Interacting Matter" (HadronPhysics2 Grant No. 227431) and by the Spanish Ingenio-Consolider 2010 Program CPAN (CSD2007-00042).

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