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The $X_c(3250)$ as a $D^*\Delta$ molecule

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A new structure at 3.25 GeV/c^2 has been recently reported by the BaBar collaboration which has received the name of $X_c(3250)$. A preliminary fit to this structure gives a mass M=3245 $\pm$ 20 MeV/c^2 and a width $\Gamma = 108 \pm 60$ MeV/c^2. A molecular interpretation as a $D_0^*(2400)N$ bound state has been proposed since the threshold for this channel is close to the nominal mass. However the width of the $D_0^*(2400)$ seems to be too large to explain the width of the $X_c(3250)$. As the $D^*\Delta$ threshold is also close to the nominal mass of the state, we investigate the possibility to be a $D^*\Delta$ bound state. We find three possible molecules with $I(J^P)$ quantum numbers $2(\frac{1}{2}^-)$, $2(\frac{3}{2}^-)$ and $1(\frac{5}{2}^-)$ which are compatible with the measured mass and width.

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1. Introduction

A new structure at 3.25 GeV/c^2 has been recently reported by the BaBar collaboration in the $\Sigma_c^{++}\pi^-\pi^-$ invariant mass spectrum [1] which has received the name of $X_c(3250)$. A preliminary Breit-Wigner plus background fit to this structure gives a mass $M = 3245 \pm 20$ MeV/c^2 and a width $\Gamma = 108 \pm 60$ MeV/c^2 [2].

Soon after the experimental observation He *et al.* [3] suggested that the $X_c(3250)$ could be a $D_0^*(2400)N$ molecular state. This hypothesis has been tested in a QCD sum rule calculation by Zhang [4]. The conclusion of this work is that the conventional OPE convergence should be released to obtain a state with a mass of 3.18 GeV/c^2. Therefore only weak conclusions can be drawn regarding the explanation of the $X_c(3250)$ as a $D_0^*(2400)N$ molecular state in this framework. One reason to suspect why this description may fail is that the $D_0^*(2400)$ resonance is too broad ($\Gamma = 267$ MeV) which makes difficult to justify an experimental width of the order of 100 MeV.

In this work we propose an alternative description of the $X_c(3250)$ as a $D^*\Delta$ molecule. In this case, the threshold is located at 3240 MeV/c^2 so the $X_c(3250)$ state is almost at threshold. Furthermore the width of the Δ fits better with the experimental result.

We will use a similar framework that has been used to study many different hadron molecules. One typical example is the $X(3872)$ which can decay into $J/\psi\rho$ and so completely rules out a $c\bar{c}$ interpretation. In Ref. [5] we performed a study of this state as a possible DD^* molecule coupled to $c\bar{c}$ states within the framework of the CQM of Ref. [6], finding an overall good description of some measured properties. Other XYZ states have been studied in Ref. [7]. This model also describe the deuteron as a NN bound state[8] and predicts a $\Delta\Delta$ bound state[9] with the quantum numbers proposed by the WASA-at-COSY collaboration[10].

In the baryon sector the $\Lambda_c(2940)$ has been proposed as a possible D^*N molecule [11] within the same model.

2. The Chiral Quark Model

We will use the CQM of Refs. [6, 12]. In these references all the details of the model can be found and here we only summarize the most important aspects.

One of the most important features of QCD at low energies is the spontaneous breaking of chiral symmetry. The model uses the most simple Lagrangian that describes this effect which can be written as

$$\mathscr{M} = \bar{\Psi}(i\gamma^\mu\partial_\mu - MU^{\gamma_5})\Psi \tag{2.1}$$

where $U^{\gamma_5} = e^{i\pi^a\lambda^a\gamma_5/f_\pi} \sim 1 + \frac{1}{f_\pi}\gamma_5\lambda^a\pi^a - \frac{1}{2f_\pi^2}\pi^a\pi^a$ with π^a the pseudo-Goldstone meson octet. This effect generates the constituent quark mass for light quarks and the interaction between quarks through Goldstone bosons.

Another crucial non-perturbative effect of low energy QCD is confinement. This fact prevents hadrons to be in colored states and we used a linear screened confinement.

QCD perturbative effects are included with the coupling between quarks and gluons given by

$$\mathscr{L}_{gqq} = i\sqrt{4\pi\alpha_s}\bar{\Psi}\gamma_\mu G_c^\mu \lambda^c \Psi \tag{2.2}$$

which gives rise to the one gluon exchange interaction.

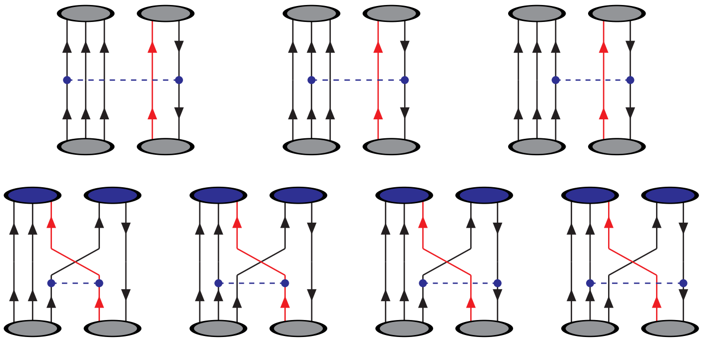

Figure 1: Diagrams that contribute to the meson-baryon interaction (first row) and to rearrangement processes (second row).

J^P	I	state	Mass (MeV/c^2)	E_b(MeV)	P_{max}(Channel)
$\frac{1}{2}^-$	2	$D^*\Delta$	3233	-6.47	$99.71(^2S_{1/2})$
$\frac{3}{2}^-$	1	$D\Delta$	3097	-0.88	$99.13(^4S_{3/2})$
$\frac{3}{2}^-$	2	$D^*\Delta$	3238	-0.98	$99.69(^2S_{1/2})$
$\frac{5}{2}^-$	1	$D^*\Delta$	3226	-13.12	$97.25(^6S_{5/2})$

Table 1: Possible $D^{(*)}\Delta$ states found within the model. The mass, binding energy and maximum partial wave probability are given.

3. The meson-baryon interaction

The meson-baryon interaction is obtained using the Resonating Group Method. No antisymmetry effects are present and the interaction is given by

$$V_D = \sum_{i\in A;j\in B} \int \Psi^\dagger_{\alpha_{A'}}(\vec{p}\,'_A)\Psi^\dagger_{\alpha_{B'}}(\vec{p}\,'_B)V_{ij}(\vec{P}\,',\vec{P})\Psi_{\alpha_A}(\vec{p}_A)\Psi_{\alpha_B}(\vec{p}_B) \tag{3.1}$$

where V_D is the Direct RGM kernel and $\Psi_{\alpha_C}(\vec{p}_C)$ are the internal wave functions of a C baryon or heavy meson with α_C quantum numbers. The diagrams contributing to V_D are shown in the first row of Fig.1.

However processes in which a quark is exchanged between the meson and the nucleon (rearrangement processes) are possible and give rise to different decay modes. The contributing diagrams are represented in the second row of Fig.1.

4. Results

First we have performed a calculation looking for possible $D_0^*(2400)N$ bound state and we have not found any in the sectors with quantum numbers J^P $(\frac{1}{2}^+)$, $(\frac{1}{2}^-)$ and $(\frac{3}{2}^-)$. We then calculated possible $D^{(*)}\Delta$ molecular states and their bottom partners. The results are summarized in Tables 1 and 2. In the charm sector we find one $D\Delta$ state and three $D^*\Delta$, being one of these last three states our candidate for the $X_c(3250)$. All of them have a bottom partner and we find one additional state in the $\bar{B}\Delta$ and $\bar{B}^*\Delta$ sectors.

J^P	I	state	Mass (MeV/c^2)	E_b(MeV)	P_{max}(Channel)
$\frac{1}{2}^-$	2	$\bar{B}^*\Delta$	6541	-14.21	$99.69(^2S_{1/2})$
$\frac{3}{2}^-$	1	$\bar{B}\Delta$	6499	-10.72	$88.14(^4S_{3/2})$
$\frac{3}{2}^-$	2	$\bar{B}\Delta$	6506	-3.67	$94.72(^4S_{3/2})$
$\frac{3}{2}^-$	1	$\bar{B}^*\Delta$	6555	-0.39	$97.10(^4S_{3/2})$
$\frac{3}{2}^-$	2	$\bar{B}^*\Delta$	6550	-4.85	$99.48(^4S_{3/2})$
$\frac{5}{2}^-$	1	$\bar{B}^*\Delta$	6532	-23.16	$96.76(^6S_{5/2})$

Table 2: Possible $\bar{B}^{(*)}\Delta$ states found within the model. The mass, binding energy and maximum partial wave probability are given.

J^P	I		$\Gamma_{D\Delta}$	Γ_{D^*N}	Γ_{DN}	$\Gamma_{D\pi\Delta}$	$\Gamma_{D^*N\pi}$	$\Gamma_{DN\pi}$
$\frac{1}{2}^-$	2	$D^*\Delta$	0.005	0	0	0	111	0
$\frac{3}{2}^-$	1	$D\Delta$	0	1.31	0.001	0	0.049	113
$\frac{3}{2}^-$	2	$D^*\Delta$	6.18	0	0	0.038	114	0
$\frac{5}{2}^-$	1	$D^*\Delta$	0.003	1.23	0.64	0	108	0

Table 3: Widths (in MeV) for different decay channels of the possible $D^{(*)}\Delta$ states found.

J^P	I		$\Gamma_{\bar{B}\Delta}$	$\Gamma_{\bar{B}^*N}$	$\Gamma_{\bar{B}N}$	$\Gamma_{\bar{B}\pi\Delta}$	$\Gamma_{\bar{B}^*N\pi}$	$\Gamma_{\bar{B}N\pi}$
$\frac{1}{2}^-$	2	$\bar{B}^*\Delta$	0.021	0	0	0	111	0
$\frac{3}{2}^-$	1	$\bar{B}\Delta$	0	3.91	0.02	0	0	98
$\frac{3}{2}^-$	2	$\bar{B}\Delta$	0	0	0	0	0	108
$\frac{3}{2}^-$	1	$\bar{B}^*\Delta$	12.47	0.224	0.019	0.076	115	0
$\frac{3}{2}^-$	2	$\bar{B}^*\Delta$	19.84	0	0	0	114	0
$\frac{5}{2}^-$	1	$\bar{B}^*\Delta$	0.001	0	0.90	0	108	0

Table 4: Widths (in MeV) for different decay channels of the possible $\bar{B}^{(*)}\Delta$ states found.

We have also analyzed different decay channels of the states found. Those are given in Tables 3 and 4. As seen in the tables the width of the states is dominated by the Δ decay into $N\pi$, been the main decay channel for $D^{(*)}\Delta$ ($\bar{B}^{(*)}\Delta$) the $D^{(*)}N\pi$ ($\bar{B}^{(*)}N\pi$) channel.

As seen in Table 1 the ΔD^* hypothesis implies a negative parity of the state against a positive parity in the $D^*(2400)N$ hypothesis. In the second case $I = 1$ is implied while in the first case $I = 2$ is also possible. The main decay channel would be $D^*N\pi$ in the first case and $DN\pi$ in the second case. These differences will allow to distinguish between the two hypothesis. Also in both cases a bottom partner should appear, however in the first case the mass would be around 100 MeV/c^2 lower that in the second case and will have a value in the order of 6.5 GeV/c^2.

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