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$D^*\Delta$ molecular interpretation for the $X_c(3250)$

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ABSTRACT

Motivated by the newly observed structure at 3250 MeV/c^2 in the $\Sigma_c^{++}\pi^-\pi^-$ invariant mass spectrum by the BaBar Collaboration, we study the possible $D^*\Delta$ molecular structures in a constituent quark model. We found 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. However the only one which decays to $\Sigma_c\pi\pi$ has quantum numbers $I(J^P)=2(\frac{1}{2}^-)$ been our candidate for the $X_c(3250)$.

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 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.

Hadronic molecular states in this energy region have been studied in Ref. [5]. In both works resonances are generated dynamically in the unitary coupled channel approach with heavy quark symmetry. Several resonances in the 3250 MeV energy region have been found including many different coupled channels. However all the possible candidates are found with a very small width compare with the experimental width of the $X_c(3250)$. In Ref. [6] the combination of the heavy quark spin symmetry with the dynamics of local hidden gauge approach simplifies the approach rendering small or negligible most of the transitions between different channels.

In this Letter 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 constituent quark model initially designed for the description of the meson spectrum [7] with the new parametrization of Ref. [8]. This model has been applied successfully to the study of the hadron spectrum in the naive quark model [8,9] and the study of possible molecular structures of new meson states like the $X(3872)$ and other X, Y, Z states [10,11] and baryon states like the $\Lambda_c(2940)$ [12]. The model has been extensively described elsewhere [7,8] and therefore we will only summarize here its most relevant aspects.

Constituent quark models have a long history starting from the Isgur seminal work (see, for example, [13]) in which the potential between two massive quark (constituents) was modeled by a quadratic potential confinement plus a chromomagnetic interaction. In the eighties it was realized that the constituent mass is a consequence of the chiral symmetry breaking in the light quark sector at a momentum scale Λ_χ greater than the confinement scale Λ_{conf} [14]. In the region between the two scales, due to this breaking, the quark propagator gets modified and quarks acquire a dynamical momentum dependent mass [15]. The Lagrangian describing this scenario must contain chiral fields to compensate the mass term. The Goldstone bosons associated to the chiral fields lead to an additional interaction between light quarks. This fact does not affect the heavy quark sector but it is of paramount importance in the molecular picture because the only remaining

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Table 1
Quantum numbers, masses (in MeV/c^2), widths (in MeV) and maximum channel probability of the different $D^*\Delta$ resonances. $\Gamma_{D^*N\pi}$ show the result without phase space effects, while $\Gamma'_{D^*N\pi}$ include the correct momentum dependence of the Δ width.

J^P	I	Mass	$\Gamma_{\Sigma_c\rho}$	$\Gamma_{D\Delta}$	Γ_{D^*N}	Γ_{DN}	$\Gamma_{\Sigma_c\pi}$	$\Gamma_{D\pi\Delta}$	$\Gamma_{\Sigma_c\pi\pi}$	$\Gamma_{D^*N\pi}$	$\Gamma'_{D^*N\pi}$	P_{max} (Channel)
$\frac{1}{2}^-$	2	3232.7	0.018	0.005	0	0	24.9	0	2.60	111	78	99.71($^2S_{1/2}$)
$\frac{3}{2}^-$	2	3238.2	0.007	6.18	0	0	0	0.038	0	114	102	99.69($^4S_{3/2}$)
$\frac{5}{2}^-$	1	3226.1	0	0.003	1.23	0.64	0	0	1.2×10^{-6}	108	63	97.25($^6S_{5/2}$)

interaction between the two molecular components, due to its color singlet nature, is the one driven by the Goldstone boson exchanges between the light quarks.

The simplest Lagrangian which contains chiral fields to compensate the mass term can be expressed as

$$\mathcal{L} = \overline{\psi}\left(i\partial\!\!\!/ - M\left(q^2\right)U^{\gamma_5}\right)\psi \tag{1}$$

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 $i = 1, \ldots, 4$ 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 the parametrization $M(q^2) = m_q F(q^2)$ where $m_q \simeq 300$ MeV, and

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

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,

$$U^{\gamma_5} = 1 + \frac{i}{f_\pi}\gamma^5\lambda^a\pi^a - \frac{1}{2f_\pi^2}\pi^a\pi^a + \cdots. \tag{3}$$

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 this type of interaction does not act. However it constrains the model parameters through the light meson phenomenology and provides a natural way to incorporate the pion exchange interaction in the molecular dynamics.

Beyond the chiral symmetry breaking scale one expects the dynamics to be governed by QCD perturbative effects. They are taken into account through the one gluon-exchange interaction derived from the Lagrangian

$$\mathcal{L}_{gqq} = i\sqrt{4\pi\alpha_s}\,\overline{\psi}\gamma_\mu G_c^\mu \lambda_c \psi, \tag{4}$$

where λ_c are the SU(3) color generators and G_c^μ the gluon field.

The other QCD nonperturbative effect corresponds to confinement, which prevents from having colored hadrons. Such a term can be physically interpreted in a picture in which 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 some 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 some interquark distance, using the expression

$$V_{CON}(\vec{r}_{ij}) = \left\{-a_c\left(1 - e^{-\mu_c r_{ij}}\right) + \Delta\right\}\left(\vec{\lambda^c}_i \cdot \vec{\lambda^c}_j\right) \tag{5}$$

where Δ is a global constant to fit the origin of energies. Explicit expressions for all these interactions are given in [8].

A similar chiral quark model including vector meson exchange has been applied to the study of hadron molecules in Ref. [16]. The inclusion of vector meson exchange reduces the contribution of gluon exchange which generates a different short range behavior between colorless objects in different sectors. In our case all the parameters of the model are consistently determined in the light and heavy quark sectors [8] and therefore we will be able to decide if a molecular configuration exists or not in a parameter free way.

Using the quark–quark interaction defined above, the bound state wave functions for the mesons which make up the molecule can be obtained solving the Schrödinger equation for a $q\bar{q}$ pair with the Gaussian Expansion Method [17]. For the baryon wave function we use a Gaussian form with a suitable parameter,

$$\psi(\vec{p}_i) = \prod_{i=1}^{3}\left[\frac{b^2}{\pi}\right]^{\frac{3}{4}} e^{-\frac{b^2 p_i^2}{2}} \tag{6}$$

where $b = 0.518$ fm is taken from Ref. [18]. In terms of Jacobi coordinates this wave function is expressed as

$$\psi = \left[\frac{b^2}{3\pi}\right]^{\frac{3}{4}} e^{-\frac{b^2 P^2}{6}} \phi_B(\vec{p}_{\xi_1}, \vec{p}_{\xi_2}) \tag{7}$$

where $\vec{P}$ is the baryon momentum and we remove the center of mass wave function. The $\vec{p}_{\xi_1}$ and $\vec{p}_{\xi_2}$ momenta correspond to the internal degrees of freedom. The internal spatial wave function used is written as

$$\phi_B(\vec{p}_{\xi_1}, \vec{p}_{\xi_2}) = \left[\frac{2b^2}{\pi}\right]^{\frac{3}{4}} e^{-b^2 p_{\xi_1}^2} \left[\frac{3b^2}{2\pi}\right]^{\frac{3}{4}} e^{-\frac{3}{4}b^2 p_{\xi_2}^2}. \tag{8}$$

The meson baryon interaction is derived using the Resonating Group Method (RGM). In our case it only includes the direct diagrams

$$V_D = \sum_{i\in A;\, j\in B} \int \Psi^\dagger_{\alpha_{A'}}(\vec{p}'_A)\Psi^\dagger_{\alpha_{B'}}(\vec{p}'_B) V^D_{ij}(\vec{P}', \vec{P})\Psi_{\alpha_A}(\vec{p}_A)\Psi_{\alpha_B}(\vec{p}_B). \tag{9}$$

With this potential, after partial wave projection, we solve the Lippmann–Schwinger equation for the T matrix

$$T(p', p; E) = V(p', p, E) - \int dq\, V(p', q, E)\frac{q^2}{q^2/(2\mu) - E - i0}T(q, p; E). \tag{10}$$

Finding the poles of the $T(p', p; E)$ matrix we will determine the mass of the possible molecule.

We present our results in Table 1. One can see that there are three possible $D^*\Delta$ states in the mass range of 3230 MeV/c^2. They are all $L = 0$ states.

All these states can decay through the $\Sigma_c^{++}\pi^-\pi^-$ channel by a similar mechanism to the initial single pion emission [19]. In terms of quarks degrees of freedom, the Δ resonance decays into a nucleon and a π^-. Once the pion is emitted the nucleon and the D^* meson interact interchanging the d and c quarks. As a result of the rearrangement process the pair $\Sigma_c^{++}\pi^-$ appears.

Table 2
Quantum numbers, masses (in MeV/c^2), widths (in MeV) and maximum channel probability of the different $\bar{B}^*\Delta$ resonances. $\Gamma_{\bar{B}^*N\pi}$ show the result without phase space effects, while $\Gamma'_{\bar{B}^*N\pi}$ include the correct momentum dependence of the Δ width.

J^P	I	Mass	$\Gamma_{\bar{B}\Delta}$	$\Gamma_{\bar{B}^*N}$	$\Gamma_{\bar{B}N}$	$\Gamma_{\Sigma_b\pi}$	$\Gamma_{\bar{B}\pi\Delta}$	$\Gamma_{\bar{B}^*N\pi}$	$\Gamma'_{\bar{B}^*N\pi}$	P_{max} (Channel)
$\frac{1}{2}^-$	2	6540.9	0.021	0	0	37.0	0	111	63	99.69($^2S_{1/2}$)
$\frac{3}{2}^-$	1	6554.7	12.47	0.22	0.019	0	0.076	115	109	97.10($^4S_{3/2}$)
$\frac{3}{2}^-$	2	6550.2	19.84	0	0	0	0	114	87	99.48($^4S_{3/2}$)
$\frac{5}{2}^-$	1	6531.9	0.001	0	0.90	0	0	108	49	96.76($^6S_{5/2}$)

Nevertheless this is not the main decay channel for the $D^*\Delta$ molecule. The width is dominated by the decay of the Δ into $N\pi$ being the main final state the $D^*N\pi$. Under the $D_0^*(2400)N$ hypothesis the resonance will decay to the $DN\pi$ channel. So the main decay channel of the state would give valuable information about the structure of the $X_c(3250)$ resonance. These are the channels where the experimentalists should look to confirm the nature of the $X_c(3250)$.

In Table 1 we give the partial widths for different decay channels. The width to the $D^*N\pi$ final state is obtained using the expression

$$\Gamma_{D^*N\pi} = \sum_\alpha \int_0^{k_{max}} dk\, k^2 \Gamma_\Delta(q) \left|\chi^\alpha_{D^*\Delta}(k)\right|^2, \tag{11}$$

where k is the relative momentum of the $D^*\Delta$ state and q the relative momentum of the πN system in its center of mass frame given by

$$q^2 = 2m_N\left(\sqrt{S_{\pi N}} - \sqrt{2m_N\sqrt{S_{\pi N}} - m_N^2 + m_\pi^2}\,\right) \tag{12}$$

with $S_{\pi N} = (\sqrt{M^2_{X_c}} - \sqrt{k^2 + m^2_{D^*}})^2 - k^2$ the invariant mass of the πN system. Here we take two different approximations. In the first one we use $\Gamma_\Delta(q) = \Gamma_\Delta = 115$ MeV which give the results $\Gamma_{D^*N\pi}$ in Table 1. In the second one we take into account phase space effects using $\Gamma_\Delta(q) = \Gamma_\Delta(\frac{q}{q_\Delta})^3$ where q_Δ is the momentum at the pole position of the Δ ($S_{\pi N} = M_\Delta$) and gives the results $\Gamma'_{D^*N\pi}$ in Table 1. As expected, the values obtained are in the order of the width of the Δ and are close to the experimental estimate of the width of the $X_c(3250)$.

As seen in Table 1 the only sizeable $\Sigma_c\pi\pi$ partial width correspond to the state $I(J^P) = 2(\frac{1}{2}^-)$ and therefore is the candidate for the $X_c(3250)$.

For completeness, we also include in Table 2 the bottom partners of these states.

As a summary we have calculated the possible molecular states of the $D^*\Delta$ system. We found three possible molecules whose mass fit with the experimental data for the $X_c(3250)$. The isospin of this resonance under our hypothesis could be 1 or 2, in contrast to possible 0 or 1 values if it was a $D_0^*(2400)N$ molecule. We propose the study of the $DN\pi$ and $D^*N\pi$ decay channels as a way to discriminate between the two molecular options. Among the three states found, the only one which decays to $\Sigma_c\pi\pi$ has quantum numbers $I(J^P) = 2(\frac{1}{2}^-)$ been this our candidate for the $X_c(3250)$.

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