



December 2, 2013

$X(4260)$ as a Mixed Charmonium-Tetraquark State

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Using the QCD sum rule approach we study the $X(4260)$ state assuming that it can be described by a mixed charmonium-tetraquark current with $J^{PC} = 1^{--}$ quantum numbers. For the mixing angle around $\theta \simeq (53.0 \pm 0.5)^\circ$, we obtain a value for the mass which is in good agreement with the experimental mass of the $X(4260)$. For the decay width into the channel $X \rightarrow J/\psi\pi\pi$ we find the value $\Gamma_{X \rightarrow J/\psi\pi\pi} \simeq (4.1 \pm 0.6) \text{ MeV}$, which is much smaller than the total experimental width $\Gamma \simeq (108 \pm 12) \text{ MeV}$. However, considering the experimental upper limits for the decay of the $X(4260)$ into open charm, we conclude that we cannot rule out the possibility of describing this state as a mixed charmonium-tetraquark state

PRESENTED AT

The 6th International Workshop on Charm Physics

(CHARM 2013)

Manchester, UK, 31 August – 4 September, 2013

¹This work was supported by CNPq and FAPESP-Brazil.

1 Introduction

Recent results on charmonium spectroscopy carried out by BABAR and BELLE Collaborations revealed that many of the charmonium-like states observed in e^+e^- collisions do not fit into the usual scheme quarkonia interpretation, and have stimulated an extensive discussion about exotic hadron configurations. Among these states, the $X(4260)$ was first observed by BABAR Collaboration in the e^+e^- annihilation through initial state radiation [1], and it was confirmed by CLEO and BELLE Collaborations [2]. The $X(4260)$ was also observed in the $B^- \rightarrow X(4260)K^- \rightarrow J/\Psi\pi^+\pi^-K^-$ decay [3], and CLEO reported two additional decay channels: $J/\Psi\pi^0\pi^0$ and $J/\Psi K^+K^-$ [2]. One should notice that the $X(4260)$ mass is higher than the $D^{(*)}\bar{D}^{(*)}$ threshold, and if it was a normal $c\bar{c}$ charmonium state, it should decay mainly into this open-charm channel. However, this is not what was observed for this state [4, 5, 6]. Besides, the conventional $\Psi(3S)$, $\Psi(2D)$ and $\Psi(4S)$ $c\bar{c}$ states have been assigned to the well established $\Psi(4040)$, $\Psi(4160)$, and $\Psi(4415)$ mesons, respectively, and the prediction from quark models for the $\Psi(3D)$ state is 4.52 GeV. Therefore, the $X(4260)$ mass is not consistent with any of the 1^{--} $c\bar{c}$ states [7, 8, 9]. There are many theoretical interpretations for the $X(4260)$: tetraquark state [10], hadronic molecule of D_1D , D_0D^* [11], $\chi_{c1}\omega$ [12], $\chi_{c1}\rho$ [13], $J/\psi f_0(980)$ [14], a hybrid charmonium [15], a charm baryonium [16], etc. Within the available experimental information, none of these suggestions can be completely ruled out. However, there are some calculations, within the QCD sum rules (QCDSR) approach [8, 17], that can not explain the mass of the $X(4260)$ supposing it to be a tetraquark state [18], or a D_1D , D_0D^* hadronic molecule [18], or a $J/\psi f_0(980)$ molecular state [19].

In this work, we use again the QCDSR approach to evaluate both, mass and decay width, of the $X(4260)$ considering a new possibility for its structure: the mixing between two and four-quark states, which can be achieved with a mixed charmonium-tetraquark current in sum rules. For more details on this work please see the ref.[20].

2 The Two- and Four-quark Operator

In order to construct a mixed charmonium-tetraquark current, with $J^{PC} = 1^{--}$, we have to define the currents associated with the charmonium and the tetraquark states. For the charmonium part, we use the conventional charmonium vector current: $j_\mu^{\prime(2)} = \bar{c}_a\gamma_\mu c_a$, while the tetraquark part is interpolated by [18]

$$j_\mu^{(4)} = \frac{\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}} \left[(q_a^T C \gamma_5 c_b)(\bar{q}_d \gamma_\mu \gamma_5 C \bar{c}_e^T) + (q_a^T C \gamma_5 \gamma_\mu c_b)(\bar{q}_d \gamma_5 C \bar{c}_e^T) \right]. \quad (1)$$

As in Refs. [21, 22], we define the normalized two-quark current as

$$j_\mu^{(2)} = \frac{1}{\sqrt{2}} \langle \bar{q}q \rangle j_\mu^{\prime(2)}. \quad (2)$$

Then using these two currents we build the following mixed charmonium-tetraquark current for the $X(4260)$ state:

$$j_\mu(x) = \sin(\theta) j_\mu^{(4)}(x) + \cos(\theta) j_\mu^{(2)}(x) . \quad (3)$$

3 The Two-Point Correlation Function

To calculate the mass of a hadronic state using the QCDSR approach, the starting point is the two-point correlation function

$$\Pi_{\mu\nu}(q) = i \int d^4x e^{iq \cdot x} \langle 0 | T [j_\mu(x) j_\nu^\dagger(0)] | 0 \rangle = -\Pi_1(q^2) \left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2} \right) + \Pi_0(q^2) \frac{q_\mu q_\nu}{q^2}, \quad (4)$$

where $j_\mu(x)$ is given by Eq. (3). The functions $\Pi_1(q^2)$ and $\Pi_0(q^2)$ are two independent invariant functions related to spin-1 and spin-0 mesons, respectively. The two-point correlation function can be evaluated in two ways, according to the principle of duality: in the OPE side, we calculate it in terms of quarks and gluon fields using the Wilson's operator product expansion (OPE). In the phenomenological side, we insert a complete set of intermediate states with 1^{--} quantum numbers, and we parametrize the coupling of the vector state X with the current, defined in Eq. (3), through the coupling parametrization: $\langle 0 | j_\mu(x) | X \rangle = \lambda_X \epsilon_\mu$ where ϵ_μ is the polarization vector. Thus, we can write the phenomenological side of Eq. (4) as

$$\Pi_{\mu\nu}^{PHEN}(q) = \frac{\lambda_X^2}{M_X^2 - q^2} \left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2} \right) + \dots \quad (5)$$

where M_X is the mass of the X state and the dots represent the higher resonance contributions which will be parametrized, as usual, through introduction of the continuum threshold parameter s_0 [23]. The OPE side can be written in terms of a dispersion relation

$$\Pi^{OPE}(q^2) = \int_{4m_c^2}^{\infty} ds \frac{\rho^{OPE}(s)}{s - q^2}, \quad (6)$$

where $\rho^{OPE}(s)$ is the spectral density and can be obtained by: $\pi \rho^{OPE}(s) = \text{Im}[\Pi^{OPE}(s)]$. In this side, we work at leading order in α_s in the operators and we consider the contributions from the condensates up to dimension-8 in the OPE. After making a Borel transform in the equations (5) and (13), we are able to match both sides of the correlation function in order to extract the mass of the charmonium-tetraquark state.

3.1 Numerical Analysis

In Table 1, we list the numerical values of the quark masses and condensates that we have used in our sum rule analysis. The continuum threshold, $\sqrt{s_0}$, is a physical

Table 1: Quark masses and condensates values [19, 24, 25].

Parameters	Values
$m_c(m_c)$	(1.23 ± 0.05) GeV
$\langle \bar{q}q \rangle$	$-(0.23 \pm 0.03)^3$ GeV ³
$\langle \bar{q}g\sigma.Gq \rangle$	$m_0^2 \langle \bar{q}q \rangle$
m_0^2	(0.8 ± 0.1) GeV ²
$\langle g_s^2 G^2 \rangle$	(0.88 ± 0.25) GeV ⁴

parameter that should be related to the first excited state with the same quantum numbers. Since the spectrum of the mixed state, given by Eq.(3), is completely unknown we will fix the continuum threshold range starting with the smaller value which provides a valid Borel window. Using this criterion, we obtain s_0 in the range $4.6 \leq \sqrt{s_0} \leq 4.8$ GeV. Notice that reliable results from the sum rule approach only can be obtained establishing a valid Borel Window. This condition is satisfied imposing a good OPE convergence, the pole dominance over the continuum contribution and a good Borel stability. Then after we have determined the Borel window, we can calculate the ground state mass, which is shown, as a function of M_B^2 , in the Fig. 1.

We can reproduce the experimental mass of the $X(4260)$, $M_X = 4250 \pm 9$ MeV, setting the value of the mixing angle as

$$\theta = (53.0 \pm 0.5)^0, \quad (7)$$

altogether with the variations of other parameters as indicated in Table I, and considering the continuum threshold in the range $\sqrt{s_0} = 4.70 \pm 0.10$ GeV. Thus, we can also estimate the meson-current coupling parameter. Using the same values of the s_0 , θ and the Borel Window used for the mass calculation, we get:

$$\lambda_X = (2.00 \pm 0.23) \times 10^{-2} \text{ GeV}^5. \quad (8)$$

4 The $X(4260)$ Decay Modes

The QCDSR technique can also be used to evaluate the coupling constants and form factors for a given vertex. Indeed, the authors in Ref.[26] determined the form factors and coupling constants for many hadronic vertices containing charmed mesons, by using the QCD sum rules method.

First, we evaluate the coupling constant associated with the vertex $X J/\psi \sigma$ to estimate the decay width of the process $X \rightarrow J/\psi \pi\pi$. We assume that the two pions in the final state come from the σ meson. In order to determine this coupling constant, we must calculate the three-point function defined as

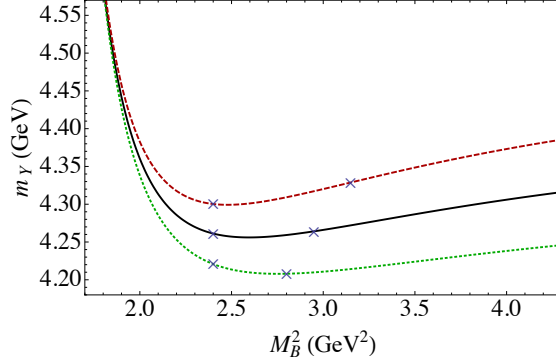


Figure 1: The mass as a function of the sum rule parameter M_B^2 for $\sqrt{s_0} = 4.60$ GeV (dotted line), $\sqrt{s_0} = 4.70$ GeV (solid line), $\sqrt{s_0} = 4.80$ GeV (long-dashed line). The crosses indicate the valid Borel Window.

$$\Pi_{\mu\nu}(p, p', q) = \int d^4x d^4y e^{ip'\cdot x} e^{iq\cdot y} \langle 0|T\{j_\mu^\psi(x)j_\nu^\sigma(y)j_\nu^{X\dagger}(0)\}|0\rangle \quad (9)$$

with $p = p' + q$. The respective interpolating fields are given by the currents of J/ψ , σ and $X(4260)$ states. For the σ meson current we use: $j^\sigma = \frac{1}{\sqrt{2}}(\bar{u}_a u_a + \bar{d}_a d_a)$.

The three-point correlation function can also be described in terms of hadronic degrees of freedom (Phenomenological side) as well as in terms of quarks and gluons fields (OPE side). In order to evaluate the phenomenological side of the sum rule we insert, in Eq.(9), intermediate states for X , J/ψ and σ . Using the definitions:

$$\langle 0|j_\mu^\psi|J/\psi(p')\rangle = M_\psi f_\psi \epsilon_\mu(p'), \quad \langle 0|j^\sigma|\sigma(q)\rangle = A_\sigma, \quad \langle X(p)|j_\nu^X|0\rangle = \lambda_X \epsilon_\nu^*(p),$$

we obtain the following relation:

$$\Pi_{\mu\nu}^{PHEN}(p, p', q) = \frac{\lambda_X M_\psi f_\psi A_\sigma g_{X\psi\sigma}(q^2)}{(p^2 - M_X^2)(p'^2 - M_\psi^2)(q^2 - M_\sigma^2)} \left[(p' \cdot p) g_{\mu\nu} - p'_\nu q_\mu - p'_\nu p'_\mu \right] + \dots, \quad (10)$$

where the dots stand for the contribution of all possible excited states. The form factor, $g_{X\psi\sigma}(q^2)$, is defined by the generalization of the on-shell mass matrix element, $\langle J/\psi\sigma|X\rangle$, for an off-shell σ meson:

$$\langle J/\psi\sigma|X\rangle = g_{X\psi\sigma}(q^2) \left[p' \cdot p \epsilon^*(p') \cdot \epsilon(p) - p' \cdot \epsilon(p) p \cdot \epsilon^*(p') \right], \quad (11)$$

which can be extracted from the effective Lagrangian that describes the coupling between two vector mesons and one scalar meson: $\mathcal{L} = i g_{X\psi\sigma} V_{\alpha\beta} A^{\alpha\beta} \sigma$, where $V_{\alpha\beta} = \partial_\alpha X_\beta - \partial_\beta X_\alpha$ and $A^{\alpha\beta} = \partial^\alpha \psi^\beta - \partial^\beta \psi^\alpha$, are the tensor fields of the X and ψ fields respectively. In the OPE side, we work at leading order in α_s and we consider the condensates up to dimension-5. Taking the limit $p^2 = p'^2 = -P^2$ and doing the Borel

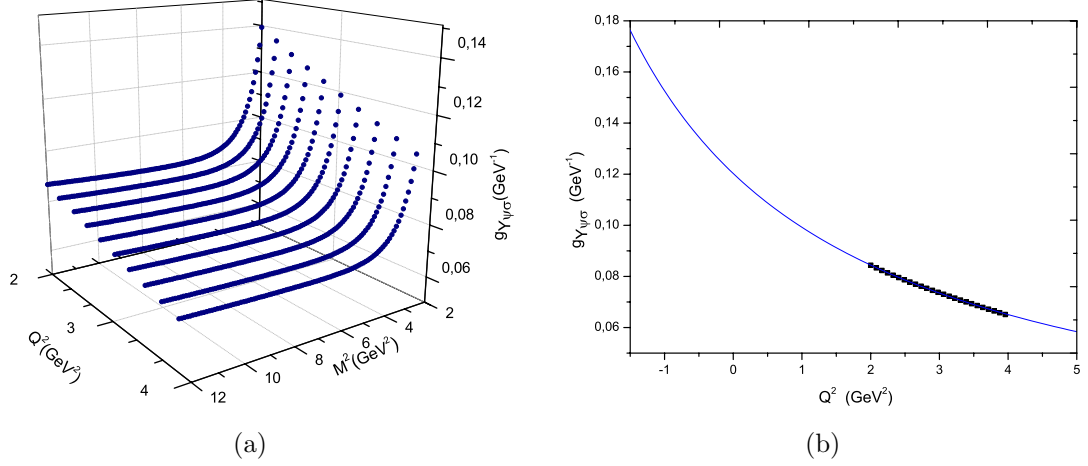


Figure 2: **a)** $g_{X\psi\sigma}(Q^2)$ values obtained by varying both Q^2 and M^2 . **b)** QCDSR results for $g_{X\psi\sigma}(Q^2)$, as a function of Q^2 , for $\sqrt{s_0} = 4.76$ GeV (squares). The solid line gives the parametrization of the QCDSR results through Eq. (14).

transform to $P^2 \rightarrow M^2$, we get the following expression in the structure $p'_\nu q_\mu$:

$$\frac{\lambda_X A_\sigma M_\psi f_\psi g_{X\psi\sigma}(Q^2)}{(M_X^2 - M_\psi^2)(Q^2 + M_\sigma^2)} \left(e^{-M_\psi^2/M^2} - e^{-M_X^2/M^2} \right) + B(Q^2) e^{-s_0/M^2} = \Pi^{OPE}(M^2, Q^2), \quad (12)$$

where $Q^2 = -q^2$, and $B(Q^2)$ gives the contribution to the pole-continuum transitions [22, 27, 28, 29]. The M_ψ and f_ψ are the mass and decay constant of the J/ψ meson and M_σ is the mass of the σ meson. Their values are given by: $M_\psi = 3.1$ GeV, $f_\psi = 0.405$ GeV [30], and $M_\sigma = 0.478$ GeV [31]. The parameters λ_X and A_σ represent the couplings of the X and σ states with the respective currents. The value of λ_X is given by Eq. (8), while A_σ was calculated in Ref. [32] and its numerical value is $A_\sigma = 0.197$ GeV². Finally, the $\Pi^{OPE}(M^2, Q^2)$ function is given by

$$\Pi^{OPE}(M^2, Q^2) = \frac{\sin(\theta)}{48\sqrt{2}\pi^2} \int_0^1 d\alpha e^{-\frac{m_c^2/M^2}{\alpha(1-\alpha)}} \left[\frac{m_c \langle \bar{q}g\sigma.Gq \rangle}{Q^2} \left(\frac{1-2\alpha(1-\alpha)}{\alpha(1-\alpha)} \right) - \frac{\langle g_s^2 G^2 \rangle}{2^5 \pi^4} \right]. \quad (13)$$

In the sum rule of the three-point correlator we are interested in determine a region in the Borel mass where the form factor is independent of M^2 . In Fig. 2a), we plot the $g_{X\psi\sigma}(Q^2)$ as a function of both M^2 and Q^2 . Notice that in the region $7.0 \leq M^2 \leq 10.0$ GeV², the form factor is stable, as a function of M^2 , for all values of Q^2 . In Fig. 2b), we plot the Q^2 dependence of $g_{X\psi\sigma}(Q^2)$, obtained for $M^2 = 8.0$ GeV². Therefore, in order to calculate the coupling constant, we must estimate the value of the form factor at the meson pole: $Q^2 = -M_\sigma^2$. For this purpose, we need to extrapolate

the form factor to the region of Q^2 where the sum rule method is not applicable. Such extrapolation can be done by parametrizing the $g_{X\psi\sigma}(Q^2)$ form factor using a monopole form:

$$g_{X\psi\sigma}(Q^2) = \frac{g_1}{g_2 + Q^2}. \quad (14)$$

Using this monopolar fit to the data indicated by the squares in Fig. 2b), we found the following parameters: $g_1 = (0.58 \pm 0.04)$ GeV and $g_2 = (4.71 \pm 0.06)$ GeV². The solid line in Fig. 2b) shows that the parametrization given by Eq. (14) fits quite well the data for $g_{X\psi\sigma}(Q^2)$. Finally, the coupling constant $g_{X\psi\sigma}$ is given by:

$$g_{X\psi\sigma} = g_{X\psi\sigma}(-M_\sigma^2) = (0.13 \pm 0.01) \text{ GeV}^{-1}. \quad (15)$$

The main source of uncertainty comes from the variations of s_0 and θ . The decay width for the process $X(4260) \rightarrow J/\psi\sigma \rightarrow J/\psi\pi\pi$ in the narrow width approximation is given by

$$\frac{d}{ds} \Gamma_{X \rightarrow J/\psi \pi\pi} = \frac{|\mathcal{M}|^2}{8\pi M_X^2} \left(\frac{M_X^2 - M_\psi^2 + s}{2M_X^2} \right) \frac{\Gamma_\sigma(s) M_\sigma}{\pi} \frac{p(s)}{(s - M_\sigma^2)^2 + (M_\sigma \Gamma_\sigma(s))^2}, \quad (16)$$

with $p(s)$ given by $p(s) = \frac{\sqrt{\lambda(M_X^2, M_\psi^2, s)}}{2M_X}$, where $\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2ac - 2bc$, and $\Gamma_\sigma(s)$ is the s-dependent width of an off-shell σ meson [31]:

$$\Gamma_\sigma(s) = \Gamma_{0\sigma} \sqrt{\frac{\lambda(s, M_\pi^2, M_\pi^2)}{\lambda(M_X^2, M_\pi^2, M_\pi^2)} \frac{M_X^2}{s}}, \quad (17)$$

where $\Gamma_{0\sigma}$ is the experimental value for the decay of the σ meson into two pions. Its value is $\Gamma_{0\sigma} = (0.324 \pm 0.042 \pm 0.021)$ GeV [31]. The invariant amplitude squared can be obtained from the matrix element in Eq. (11). We get:

$$|\mathcal{M}|^2 = \frac{g_{X\psi\sigma}^2(s)}{3} \left[M_X^2 M_\psi^2 + \frac{1}{2} (M_X^2 + M_\psi^2 - s)^2 \right] \quad (18)$$

Therefore, the decay width for the process $X(4260) \rightarrow J/\psi \pi\pi$ is given by

$$\Gamma_{X \rightarrow J/\psi \pi\pi} = \frac{M_\sigma}{16\pi^2 M_X^4} \int_{4M_\pi^2}^{(M_X - M_\psi)^2} ds |\mathcal{M}|^2 \Gamma_\sigma(s) p(s) \frac{(M_X^2 - M_\psi^2 + s)}{(s - M_\sigma^2)^2 + (M_\sigma \Gamma_\sigma(s))^2}. \quad (19)$$

Hence, taking variations on s_0 and θ in the same intervals given above, we obtain from Eqs. (15)-(19) the following value for the decay width

$$\Gamma_{X \rightarrow J/\psi \pi\pi}^\sigma = (1.0 \pm 0.4) \text{ MeV} . \quad (20)$$

Doing the same analysis presented before, but now considering some adjustments [20] for each channel, we can proceed to estimate the decay widths related to other

processes like $X \rightarrow J/\psi f_0(980) \rightarrow J/\psi \pi\pi$ and $X \rightarrow J/\psi f_0(980) \rightarrow J/\psi KK$. Hence, we find [20]

$$\Gamma_{X \rightarrow J/\psi \pi\pi}^{f_0} = (3.1 \pm 0.2) \text{ MeV} , \quad (21)$$

$$\Gamma_{X \rightarrow J/\psi KK}^{f_0} = (1.3 \pm 0.4) \text{ MeV} . \quad (22)$$

Our estimation for the total width is given by $\Gamma_{tot} \simeq 5.4 \pm 1.0 \text{ MeV}$, which is much smaller than the experimental data $\Gamma_{exp} = 108 \pm 12 \text{ MeV}$.

5 Summary and Conclusions

In summary, we have used the QCDSR approach to study the two-point and three-point functions of the $X(4260)$ state, by considering a mixed charmonium-tetraquark current. A very good agreement with the experimental value of the $X(4260)$ mass is achieved for the mixing angle around $\theta \simeq (53.0 \pm 0.5)^0$. To evaluate the width of the decay $X(4260) \rightarrow J/\psi \pi\pi$, we work with the three-point function. First, we assume that the two pions in the final state come from the σ and $f_0(980)$ scalar mesons. We also consider the process $X(4260) \rightarrow J/\psi KK$ with the $f_0(980)$ as an intermediate state. The obtained value for width is $\Gamma_X \simeq (5.4 \pm 1.0) \text{ MeV}$, which is much smaller than the experimental data: $\Gamma_{exp} \simeq (108 \pm 12) \text{ MeV}$. Possibly the main decay channel of the $X(4260)$ should be into D mesons, mostly due to the presence of charmonium in its internal structure. These channels could increase the value estimated for Γ_X . Therefore, our findings indicate that an exotic hadronic structure for the $X(4260)$ cannot be ruled out. Indeed, a mixed charmonium-tetraquark state is a good candidate for explaining the mass and the decay channels observed experimentally.

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