Investigating the Structure of X(4140) in QCD

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Abstract. In this work, the masses of the ground states coupling to molecular or tetraquark currents with $J^{PC} = 0^{++}, 1^{++}, 2^{++}$ are studied to investigate the structure of X(4140) exotic meson observed at $J/\psi\phi$ invariant mass spectrum. We found that all currents predict ground states with masses of the same magnitude, which might be interpereted as the existance of at least three exotic structures with degenerate mass.

X(4140), an exotic meson, was experimentally observed by several collaborations in the invariant mass spectrum of $J/\psi\phi$ final states, and very recently its quantum numbers are announced to be $J^{PC} = 1^{++}$ by LHCb Collaboration[1–4]. However, the decay width of the state observed by LHCb is unexpectedly wider than the previous observations. Despite these observations, its structure has not been totally understood yet, as well as other exotic mesons. In the literature, its claimed that X(4140) might be a scalar, axial vector or a tensor meson, with positive charge conjugation, which might be a $D_s^*\bar{D}_s^*$ molecule or a tetraquark state [5–12].

In this work, we chose three molecule and three tetraquark currents, which can couple to X(4140), with $J^{PC} = 0^{++}, 1^{++}, 2^{++}$, and estimated the masses of the ground states coupling to these currents in the framework of QCD sum rules (QCDSR). In operator product expansion (OPE), we considered the terms including dimension eight, and we performed pole contribution tests carefully. According to our results, all of these currents couple to the ground states with degenerate masses which are in 10 MeV vicinity of X(4140). Therefore, by using QCDSR, it is not possible to conclude that X(4140) has a dominant molecular or tetraquark content. However, there may be three states degenerate in mass, with positive charge conjugation and different isospins.

In QCDSR, we consider the following two point correlation function

$$\Pi(q) = i\int d^4x e^{iq\cdot x}\langle 0|\mathcal{T}(J(x)J^{\dagger}(0))|0\rangle, \tag{1}$$

where $J(x)$ is the interpolating current. The following molecular currents

$$J(x) = \overline{s}^a(x)\gamma_\mu c^a(x)\,\overline{c}^b(x)\gamma^\mu s^b(x), \tag{2}$$

$$J_\mu(x) = \frac{(\overline{s}^a(x)\gamma_5 c^a(x)\,\overline{c}^b(x)\gamma_\mu s^b(x) - \overline{s}^a(x)\gamma^\mu c^a(x)\,\overline{c}^b(x)\gamma_5 s^b(x))}{\sqrt{2}}, \tag{3}$$

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$$J_{\mu\nu}(x) = \frac{(\overline{s}^a(x)\gamma_\mu c^a(x)\,\overline{c}^b(x)\gamma^\nu s^b(x) + \overline{s}^a(x)\gamma_\nu c^a(x)\,\overline{c}^b(x)\gamma^\mu s^b(x))}{\sqrt{2}}, \tag{4}$$

and the following tetraquark currents

$$J(x) = \varepsilon^{ijk}\varepsilon^{imn}(s^j(x)C\gamma_\mu c^k(x)\,\overline{s}^m(x)\gamma^\mu C\overline{c}^n(x)), \tag{5}$$

$$J_\mu(x) = \frac{\varepsilon^{ijk}\varepsilon^{imn}(s^j(x)C\gamma_5 c^k(x)\,\overline{s}^m(x)\gamma_\mu C\overline{c}^n(x) - s^j(x)C\gamma^\mu c^k(x)\,\overline{s}^m(x)\gamma_5 C\overline{c}^n(x))}{\sqrt{2}}, \tag{6}$$

$$J_{\mu\nu}(x) = \frac{\varepsilon^{ijk}\varepsilon^{imn}(s^j(x)C\gamma_\mu c^k(x)\,\overline{s}^m(x)\gamma^\nu C\overline{c}^n(x) + s^j(x)C\gamma_\nu c^k(x)\,\overline{s}^m(x)\gamma^\mu C\overline{c}^n(x))}{\sqrt{2}}, \tag{7}$$

are chosen to investigate the structure of X(4140), where C is the charge conjugation matrix. In order to get the sum rules expression for the masses, the correlation function in Eq. 1 should be calculated twice, in terms of both hadronic and quark-gluon degrees of freedoms. In terms of physical states (hadrons), it can be expressed as

$$\Pi^{\mathrm{Phys}}(q) = \frac{\langle 0|J^{X_1}|X_1(q)\rangle\langle X_1(q)|J^{X_1\dagger}|0\rangle}{m_{X_1}^2 - q^2} + (.......)\,, \tag{8}$$

where M_{X_1} is the mass of the ground state coupling to the chosen current. The scalar (S), axial vector (AV) and tensor (T) matrix elements are defined as

$$\langle 0|J^X|X(q)\rangle = \lambda_{(S)}, \tag{9}$$
$$\langle 0|J^X_\mu|X(q)\rangle = \lambda_{(AV)}\varepsilon^{(\theta)}_\mu, \tag{10}$$
$$\langle 0|J^X_{\mu\nu}|X(q)\rangle = \lambda_{(T)}\varepsilon^{(\theta)}_{\mu\nu}, \tag{11}$$

where $\varepsilon^{(\theta)}_\mu$ and $\varepsilon^{(\theta)}_{\mu\nu}$ are vector and tensor polarizations. In terms of hadronic states, the correlators are obtained as

$$\Pi^{Phys}(q) = \frac{\lambda^2_{(S)}}{m_X^2 - q^2}\,, \tag{12}$$

$$\Pi^{Phys}_{\mu\nu}(q) = \frac{\lambda^2_{(AV)}}{m_X^2 - q^2} g_{\mu\nu} + \text{other structures} + ...\,, \tag{13}$$

$$\Pi^{Phys}_{\mu\nu,\alpha\beta}(q) = \frac{\lambda^2_{(T)}}{m_X^2 - q^2}\left\{\frac{1}{2}(g_{\mu\alpha}\,g_{\nu\beta} + g_{\mu\beta}\,g_{\nu\alpha})\right\} + \text{other structures} + ...\,, \tag{14}$$

where the structures of interest are shown.

In QCDSR, the same correlation functions are also calculated in terms of quark-gluon degrees of freedom with the help of the OPE. In OPE, we considered operators up to dimension eight and used the full quark propagators as

$$\begin{aligned} S_s^{ij}(x) &= i\frac{\not{x}}{2\pi^2 x^4}\delta_{ij} - \frac{m_s}{4\pi^2 x^2}\delta_{ij} - \frac{\langle \bar{s}s\rangle}{12}\Big[1 - i\frac{m_s}{4}\not{x}\Big]\delta_{ij} - \frac{x^2}{192}m_0^2\langle\bar{s}s\rangle\Big[1 - i\frac{m_s}{6}\not{x}\Big]\delta_{ij} \\ &- \frac{ig_sG_{ij}^{\alpha\beta}}{32\pi^2x^2}\Big(\not{x}\sigma^{\alpha\beta} + \sigma^{\alpha\beta}\not{x}\Big)\delta_{ij} - i\frac{x^2\not{x}g_s^2\langle\bar{s}s\rangle^2}{7776}\delta_{ij} - \frac{x^4\langle\bar{s}s\rangle\langle g_s^2GG\rangle}{27648} + ... , \end{aligned} \tag{15}$$

$$\begin{aligned} S_c^{ij}(x) &= i\int\frac{d^4ke^{-ik\cdot x}}{(2\pi)^4}\Big[\frac{\not{k}+m_c}{k^2-m_c^2}\delta_{ij} - \frac{g_sG_{ij}^{\alpha\beta}}{4}\frac{\sigma^{\alpha\beta}(\not{k}+m_c)+(\not{k}+m_c)\sigma^{\alpha\beta}}{(k^2-m_c^2)^2} \\ &+ \frac{g_s^2m_c}{12}\frac{k^2+m_c\not{k}}{(k^2-m_c^2)^4}G_{\alpha\beta}^AG^{A\alpha\beta}\delta_{ij} + \cdots\Big] \end{aligned} \tag{16}$$

for s and c quarks respectively. Applying the steps of traditional QCDSR analysis, the sum rules for the masses are found as

$$m_{X(4140)}^2 = \frac{\int_{(m_s+m_c)^2}^{s_0} ds\, s\,\rho^{\mathrm{OPE}}(s)e^{-s/M^2}}{\int_{(m_s+m_c)^2}^{s_0} ds\rho^{\mathrm{OPE}}(s)e^{-s/M^2}}, \tag{17}$$

where s_0 is the continuum threshold, M^2 is the Borel mass and $\rho^{\mathrm{OPE}} = \mathrm{Im}[\Pi^{\mathrm{OPE}}/\pi]$ is the spectral density.

To obtain the numerical values of the masses, the working regions of s_0 and M^2 are determined as

$$4.0\ \mathrm{GeV}^2 \le M^2 \le 6.0\ \mathrm{GeV}^2 \qquad \text{and} \qquad 19.7\ \mathrm{GeV}^2 \le s_0 \le 21.5\ \mathrm{GeV}^2,$$

where the effects of continuum, higher resonances and condensates with higher dimensions satisfy the requirements of QCDSR. Other input parameters such as quark masses and the values of the condensates are taken from [13]. We present our results for the masses in Table 1, in comparison with the previous results estimated by QCDSR calculations and also by experiments. The obtained results are stable with respect to the variations of s_0 and M^2 within the aforementioned working regions.

The mass estimated by the scalar molecular current (Eq. 2) is in agreement with the results of the previous works interpreting X(4140) as a scalar $D_s^*\bar{D}_s^*$ molecule. Both molecular and tetraquark axial vector currents (Eq. 3 and 6) are also in good agreement with the recent measurement of LHCb. However, the masses obtained by all currents (Eq. 2-7) are almost degenerate, which does not allow us to claim that X(4140) is showing quantum properties of a specific current among those we investigated. This result might be a sign for the existence of scalar and tensor partners of axial vector X(4140) observed by LHCb. In the literature, such scenario was introduced for X(3872) and its possible partners[14].

In conclusion, we presented a QCD sum rules analysis of the two point correlation function for possible $D_s^*\bar{D}_s^*$ molecule and tetraquark currents with $J^{PC} = 0^{++}, 1^{++}$ and 2^{++}. According to our results, the mass of the axial vector structure observed by LHCb is obtained correctly by both molecular and tetraquark axial vector currents. In addition, we obtained similar masses for the states that couple to molecular and tetraquark currents with $J^{PC} = 0^{++}$ and 2^{++}. From a QCD sum rule point of view, we conclude that possible partners of an axial vector X(4140) should also be considered. Consequently, X(4140) should be investigated more, by studying its decays, and by other approaches as well.

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Table 1. Table of the masses calculated in this work, and their comparison with literature.

	This Work (GeV)	Literature (GeV)	Experiments (MeV)
0^{++} Molecular	4.16 ± 0.07	4.14 ± 0.09 [5] 4.13 ± 0.10 [6, 7] 4.48 ± 0.17 [8] 4.43 ± 0.16 [9] 4.14 ± 0.08 [10]	
1^{++} Molecular	4.15 ± 0.06		
2^{++} Molecular	4.15 ± 0.05		
0^{++} Tetraquark	4.16 ± 0.06	3.98 ± 0.08 [11]	
1^{++} Tetraquark	4.15 ± 0.06	3.95 ± 0.09 [12]	
2^{++} Tetraquark	4.18 ± 0.09	4.13 ± 0.08 [11]	
CDF [2, 3]			$M_X = 4143.4^{+2.9}_{-3.0} \pm 0.6$
CMS [4]			$M_X = 4148.0 \pm 2.4 \pm 6.3$
LHCb [1]			$M_X = 4146.5 \pm 4.5^{4.6}_{-2.8}$
Average [1]			$M_X = 4146.9 \pm 2.3$

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