An open charm tetraquark candidate: note on $X_0(2900)$

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Motivated by the very recent observation of exotic $X_0(2900)$ in the process $B^+ \rightarrow D^+ D^- K^+$ by LHCb Collaboration, which could be an admirable open charm tetraquark state, we make an effort to study the possibility in QCD sum rules. In technique, four possible currents with $J^P = 0^+$ are investigated for the tetraquark candidate. The final mass values are calculated to be $2.77^{+0.19}_{-0.20}$ GeV for the axial-axial configuration and $2.75^{+0.18}_{-0.19}$ GeV for the scalar-scalar configuration, respectively. In view of the uncertainty of these results, they are both consistent with the $X_0(2900)$’s experimental data $2.8663 \pm 0.0065 \pm 0.0020$ GeV, which could support $X_0(2900)$ as a $0^+$ tetraquark state with open charm flavor.

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I. INTRODUCTION

Very newly, the LHCb Collaboration reported a model-dependent discovery of exotic structure with open charm in the $D^- K^+$ channel with a significance $\gg 5\sigma$ [1]. In particular for the spin-0 resonance $X_0(2900)$, its mass and width are measured to be $2.8663 \pm 0.0065 \pm 0.0020$ GeV and $57.2 \pm 12.2 \pm 4.1$ MeV, respectively. Considering the decay final states $D^- K^+$ of $X_0(2900)$, it could be proposed as a good candidate for an open charm tetraquark state [2].

In these years, many $X, Y, Z$ hadrons have attracted broad attentions and been listed as possible exotic states (for recent reviews see e.g. [3–5]). Triggered by the LHCb’s new experimental result on exotic $X_0(2900)$, we attempt to study whether it could be accommodated in an open charm tetraquark picture. To handle a genuine hadron state, one has to be confronted with the nonperturbative problem in QCD. As one credible way for evaluating the nonperturbative effects, the QCD sum rule method [6] is firmly established on QCD and has been widely applied to many hadronic systems [7–11]. For an example, the charm-strange $D_s^*(2317)$ was studied as a tetraquark state from QCD sum rules [12–17]. In this work, to uncover the underlying structure of $X_0(2900)$, we would perform the investigation on the possibility of $X_0(2900)$ as an open charm tetraquark state in QCD sum rules.

The rest of the paper is organized as follows. In Sec. II the possibility of $X_0(2900)$ as a tetraquark state is studied in QCD sum rules. The last part is a brief summary.

II. QCD SUM RULE ANALYSIS ON $X_0(2900)$ AS A $0^+$ TETRAQUARK STATE

In the QCD sum rule approach, a hadron is represented by the interpolating current. For a tetraquark state, the current can be constructed with a diquark-antidiquark configuration. Generally, one can write following currents for the $ud\bar{c}\bar{s}$ tetraquark state with $0^+$,

\[ j = \epsilon_{abg} \epsilon_{a'b'g'} (u^T_a C \gamma_5 d_b) (\bar{c}_{a'} \gamma_5 \bar{s}_{b'}^T) \]

for the scalar-scalar configuration,

\[ j = \epsilon_{abg} \epsilon_{a'b'g'} (u^T_a C d_b) (\bar{c}_{a'} C \bar{s}_{b'}^T) \]

for the pseudoscalar-pseudoscalar configuration,

\[ j = \epsilon_{abg} \epsilon_{a'b'g'} (u^T_a C \gamma_\mu d_b) (\bar{c}_{a'} \gamma^\mu \bar{s}_{b'}^T) \]
for the axial-vector-axial vector (abbreviated to axial-axial) configuration, and

\[ j_{\alpha i} = \epsilon_{\alpha i\beta}(u_a^T C \gamma_5 \gamma_\mu d_b)(\bar{c}_a \gamma^\mu \gamma_5 C \bar{s}_b^T) \]

for the vector-vector configuration. Here \( T \) indicates matrix transposition, \( C \) is the charge conjugation matrix, and the subscripts \( a, b, g, a', b' \) are color indices.

From the form of two-point correlator

\[ \Pi(q^2) = i \int d^4x e^{i q \cdot x} \langle 0 | T[j(x)j^\dagger(0)] | 0 \rangle, \]

it can be phenomenologically expressed as

\[ \Pi(q^2) = \frac{\lambda_H^2}{M_H^2 - q^2} + \frac{1}{\pi} \int_{s_0}^\infty \frac{\text{Im} \Pi_{\text{phen}}(s)}{s - q^2} ds, \]

where \( s_0 \) is the continuum threshold, \( M_H \) denotes the hadron’s mass, and \( \lambda_H \) is the hadron coupling constant \( \langle 0 | H | H \rangle = \lambda_H \). Theoretically, the \( \Pi(q^2) \) can be formalized as

\[ \Pi(q^2) = \int_{(m_c + m_s)^2}^{s_0} \frac{\rho(s)}{s - q^2} ds, \]

in which \( m_c \) is the charm mass, \( m_s \) is the strange mass, and the spectral density \( \rho(s) = \frac{1}{\pi} \text{Im} \Pi(s) \).

Matching the two expressions of \( \Pi(q^2) \), assuming quark-hadron duality, and applying a Borel transform, the sum rule can be

\[ \lambda_H^2 e^{-M_H^2/M^2} = \int_{(m_c + m_s)^2}^{s_0} \rho(s) e^{-s/M^2} ds, \]

with the Borel parameter \( M^2 \).

Eliminating \( \lambda_H \), one gains the hadron’s mass sum rule

\[ M_H = \sqrt{\left\{ \int_{(m_c + m_s)^2}^{s_0} \rho(s) e^{-s/M^2} ds \right\} / \left\{ \int_{(m_c + m_s)^2}^{s_0} \rho(s) ds \right\}}, \]

in which \( \rho(s) = \rho_{\text{pert}} + \rho^{(ss)} + \rho^{(g^2G^2)} + \rho^{(g\bar{s}sG_s)} + \rho^{(\bar{q}q)^2} + \rho^{(\bar{s}s)(g^2G^2)} \) that can be derived with similar techniques as Refs. 11, 13, 18. Concretely,

\[ \rho_{\text{pert}} = \frac{1}{3 \cdot 2^{10} \pi^6} \int_0^1 d\alpha \left( \frac{1 - \alpha}{\alpha} \right)^3 (as - m_c^2 + 4m_s m_c)(as - m_c^2)^3, \]

\[ \rho^{(ss)} = -\frac{(\bar{s}s)}{2^{10} \pi^6} \int_0^1 d\alpha \frac{1 - \alpha}{\alpha^2} [(1 - \alpha)m_c - \alpha m_s][(as - m_c^2)^2], \]

\[ \rho^{(g^2G^2)} = \frac{m_c(g^2G^2)}{3 \cdot 2^{12} \pi^6} \int_0^1 d\alpha \left( \frac{1 - \alpha}{\alpha} \right)^3 [(m_c - 3m_s)(as - m_c^2) + m_s m_c^2], \]

\[ \rho^{(g\bar{s}sG_s)} = \frac{(g\bar{s}s \cdot G_s)}{3 \cdot 2^{10} \pi^4} \int_0^1 d\alpha \left[ 3(1 - \alpha)m_c - \alpha m_s \rangle (as - m_c^2) \right], \]

\[ \rho^{(\bar{q}q)^2} = \frac{(\bar{q}q)^2}{3 \cdot 2^{12} \pi^2} \int_0^1 d\alpha \left( as - m_c^2 + m_s m_c \right), \]

\[ \rho^{(g^3G^3)} = -\frac{(g^3G^3)}{3 \cdot 2^{12} \pi^6} \int_0^1 d\alpha \left( \frac{1 - \alpha}{\alpha} \right)^3 (as - 3m_c^2 + 6m_s m_c), \]

\[ \rho^{(\bar{s}s)(g^2G^2)} = -\frac{m_c(\bar{s}s)(g^2G^2)}{3 \cdot 2^{12} \pi^4} \int_0^1 d\alpha \left[ 1 + 3 \left( \frac{1 - \alpha}{\alpha} \right)^2 \right], \]
for the scalar-scalar current,

\[
\rho_{\text{pert}}^{(ss)} = \frac{1}{3 \cdot 2^{10} \pi^6} \int \frac{1}{\Lambda} \, d\alpha \left( 1 - \frac{\alpha}{\Lambda} \right)^3 \left( (3s - m_c^2 - 4m_s m_c)(\alpha - m_c^2)^3, 
\right.
\]

\[
\rho^{(ss)} = \frac{\langle ss \rangle}{2^6 \pi^4} \int \frac{1}{\Lambda} \, d\alpha \frac{1 - \alpha}{\alpha^2} \left( (1 - \alpha)m_c + 2m_s m_c \right)(\alpha - m_c^2),
\]

\[
\rho^{(\bar{q}q \cdot G)} = -\frac{m_c \langle g^2 G \rangle}{3 \cdot 2^{12} \pi^6} \int \frac{1}{\Lambda} \, d\alpha \left( 1 - \frac{\alpha}{\Lambda} \right)^3 \left( (m_c + 3m_s)(\alpha - m_c^2) - m_s m_c^2 \right),
\]

\[
\rho^{(\bar{q}q)} = \left( \frac{\langle ss \rangle \langle g^2 G \rangle}{2^6 \pi^4} \right) \int \frac{1}{\Lambda} \, d\alpha \left[ 1 + 3 \left( \frac{1 - \alpha}{\alpha} \right)^2 \right],
\]

for the pseudoscalar-pseudoscalar current,

\[
\rho_{\text{pert}}^{(ss)} = \frac{1}{3 \cdot 2^{8} \pi^6} \int \frac{1}{\Lambda} \, d\alpha \left( 1 - \frac{\alpha}{\Lambda} \right)^3 \left( (3s - m_c^2 + 2m_s m_c)(\alpha - m_c^2)^3, 
\right.
\]

\[
\rho^{(ss)} = -\frac{\langle ss \rangle}{2^2 \pi^4} \int \frac{1}{\Lambda} \, d\alpha \frac{1 - \alpha}{\alpha^2} \left( (1 - \alpha)m_c - 2m_s m_c \right)(\alpha - m_c^2),
\]

\[
\rho^{(g^2 G)} = -\frac{m_c \langle g^2 G \rangle}{3 \cdot 2^{12} \pi^6} \int \frac{1}{\Lambda} \, d\alpha \left( 1 - \frac{\alpha}{\Lambda} \right)^3 \left( (2m_c - 3m_s)(\alpha - m_c^2) + m_s m_c^2 \right),
\]

\[
\rho^{(\bar{q}q \cdot G)} = -\frac{\langle g^3 G \rangle}{3 \cdot 2^{25} \pi^4} \int \frac{1}{\Lambda} \, d\alpha \left( 1 - \frac{\alpha}{\Lambda} \right)^3 \left( (\alpha - m_c^2 + 3m_s m_c \right),
\]

\[
\rho^{(\bar{q}q)} = -\left( \frac{\langle ss \rangle \langle g^2 G \rangle}{2^6 \pi^4} \right) \int \frac{1}{\Lambda} \, d\alpha \left[ 1 + 3 \left( \frac{1 - \alpha}{\alpha} \right)^2 \right],
\]

for the axial-axial current, and

\[
\rho_{\text{pert}}^{(ss)} = \frac{1}{3 \cdot 2^{10} \pi^6} \int \frac{1}{\Lambda} \, d\alpha \left( 1 - \frac{\alpha}{\Lambda} \right)^3 \left( (3s - m_c^2 - 2m_s m_c)(\alpha - m_c^2)^3, 
\right.
\]

\[
\rho^{(ss)} = \left( \frac{\langle ss \rangle}{2^6 \pi^4} \right) \int \frac{1}{\Lambda} \, d\alpha \frac{1 - \alpha}{\alpha^2} \left( (1 - \alpha)m_c + 2m_s m_c \right)(\alpha - m_c^2),
\]

\[
\rho^{(g^2 G)} = -\frac{m_c \langle g^2 G \rangle}{3 \cdot 2^{12} \pi^6} \int \frac{1}{\Lambda} \, d\alpha \left( 1 - \frac{\alpha}{\Lambda} \right)^3 \left( (2m_c + 3m_s)(\alpha - m_c^2) - m_s m_c^2 \right),
\]

\[
\rho^{(\bar{q}q \cdot G)} = -\frac{\langle g^3 G \rangle}{3 \cdot 2^{25} \pi^4} \int \frac{1}{\Lambda} \, d\alpha \left( 1 - \frac{\alpha}{\Lambda} \right)^3 \left( (\alpha - m_c^2 + 2m_s m_c \right),
\]

\[
\rho^{(\bar{q}q)} = -\left( \frac{\langle ss \rangle \langle g^2 G \rangle}{2^6 \pi^4} \right) \int \frac{1}{\Lambda} \, d\alpha \left[ 1 + 3 \left( \frac{1 - \alpha}{\alpha} \right)^2 \right],
\]
for the vector-vector current. Here $\langle \bar{q}q \rangle$ generally denotes the light $\langle \bar{u}u \rangle$ or $\langle \bar{d}d \rangle$ quark condensate, and the integration limit is defined as $\Lambda = m_c^2/s$.

To extract the mass value $M_H$ for the tetraquark state, one could perform the numerical analysis of sum rule (4). The quark masses are taken as $m_c = 1.27 \pm 0.02$ GeV and $m_s = 93^{+13}_{-5}$ MeV [19]. Other input parameters are $\langle \bar{q}q \rangle = -(0.24 \pm 0.01)^3$ GeV$^3$, $\langle \bar{s}s \rangle = m_0^3 \langle \bar{q}q \rangle$, $\langle g_s \sigma \cdot Gs \rangle = m_0^2 \langle \bar{s}s \rangle$, $m_0^2 = 0.8 \pm 0.1$ GeV$^2$, $\langle y^2G^2 \rangle = 0.88 \pm 0.25$ GeV$^4$, and $\langle y^3G^3 \rangle = 0.58 \pm 0.18$ GeV$^6$ [6,8]. In accordance with a standard procedure, both the OPE convergence and the pole dominance should be examined to choose work windows for the threshold $\sqrt{s_0}$ and the Borel parameter $M^2$.

Taking the axial-axial case as an concrete example, the various relative OPE contributions are compared as a function of $M^2$ in FIG. 1. There three main condensate contributions, i.e. the two-quark condensate, the mixed condensate, and the four-quark condensate, could cancel each other out to some extent, and most of other high dimension condensates are very small. Thus, the perturbative term could play an important role on the total OPE contribution while taking $M^2 \geq 1.8$ GeV$^2$. In phenomenology, FIG. 2 shows the comparison between pole and continuum contribution of sum rule (4) for $\sqrt{s_0} = 3.4$ GeV, which reveals that the relative pole contribution is approximate to be 50% at $M^2 = 2.2$ GeV$^2$ and decreases with $M^2$. Similarly, the upper bounds of $M^2$ are $M^2 = 2.1$ GeV$^2$ for $\sqrt{s_0} = 3.3$ GeV and $M^2 = 2.3$ GeV$^2$ for $\sqrt{s_0} = 3.5$ GeV. Hence, for the axial-axial case, Borel windows are taken as $1.8 \sim 2.1$ GeV$^2$ for $\sqrt{s_0} = 3.3$ GeV, $1.8 \sim 2.2$ GeV$^2$ for $\sqrt{s_0} = 3.4$ GeV, and $1.8 \sim 2.3$ GeV$^2$ for $\sqrt{s_0} = 3.5$ GeV. In FIG. 3, the mass $M_H$ as a function of $M^2$ from sum rule (6) is shown for the axial-axial case, and $M_H$ is calculated to be $2.77 \pm 0.14$ GeV in the chosen work windows. Further, taking into account the uncertainty from the variation of quark masses and condensates, one gets $2.77 \pm 0.14^{+0.05}_{-0.06}$ GeV (the first error due to the variation of $\sqrt{s_0}$ and $M^2$, and the second one rooting in the variation of QCD parameters) or concisely $2.77^{+0.19}_{-0.20}$ GeV for the axial-axial case.

![FIG. 1: The relative contributions of various condensates as a function of $M^2$ in sum rule (4) for $\sqrt{s_0} = 3.4$ GeV for the axial-axial case.](image)

In the very similar procedure, the Borel windows for the scalar-scalar case are taken as $1.9 \sim 2.2$ GeV$^2$ for $\sqrt{s_0} = 3.3$ GeV, $1.9 \sim 2.3$ GeV$^2$ for $\sqrt{s_0} = 3.4$ GeV, and $1.9 \sim 2.4$ GeV$^2$ for $\sqrt{s_0} = 3.5$ GeV. Its mass $M_H$ dependence on $M^2$ from sum rule (4) is shown in FIG. 4 for the axial-axial case, and $M_H$ is computed to be $2.75 \pm 0.13$ GeV in the work windows. Moreover, one gets $2.75 \pm 0.13^{+0.05}_{-0.06}$ GeV or concisely $2.75^{+0.18}_{-0.19}$ GeV for the scalar-scalar case.

After analyzing the pseudoscalar-pseudoscalar and the vector-vector cases in the same way, one notes that their OPE convergence is so unsatisfactory and their corresponding Borel curves are quite unstable that one cannot find proper work windows to get reliable hadronic masses. Comparing with the experimental data, the final results for the axial-axial and the scalar-scalar cases both agree with the measured mass of
FIG. 2: The phenomenological contribution in sum rule (1) for $\sqrt{s_0} = 3.4$ GeV for the axial-axial case. The solid line is the relative pole contribution (the pole contribution divided by the total, pole plus continuum contribution) as a function of $M^2$ and the dashed line is the relative continuum contribution.

FIG. 3: The mass of $0^+$ tetraquark state with the axial-axial configuration as a function of $M^2$ from sum rule (5). The ranges of $M^2$ are $1.8 \sim 2.1$ GeV$^2$ for $\sqrt{s_0} = 3.3$ GeV, $1.8 \sim 2.2$ GeV$^2$ for $\sqrt{s_0} = 3.4$ GeV, and $1.8 \sim 2.3$ GeV$^2$ for $\sqrt{s_0} = 3.5$ GeV.

FIG. 4: The mass of $0^+$ tetraquark state with the scalar-scalar configuration as a function of $M^2$ from sum rule (5). The ranges of $M^2$ are $1.9 \sim 2.2$ GeV$^2$ for $\sqrt{s_0} = 3.3$ GeV, $1.9 \sim 2.3$ GeV$^2$ for $\sqrt{s_0} = 3.4$ GeV, and $1.9 \sim 2.4$ GeV$^2$ for $\sqrt{s_0} = 3.5$ GeV.
$X_0(2900)$ viewing the uncertainty. It could support $X_0(2900)$ as a $0^+$ tetraquark state with the axial-axial or the scalar-scalar configuration.

### III. SUMMARY

Invigorated by the very new observation of $X_0(2900)$ by LHCb Collaboration, we explore the possibility of $X_0(2900)$ as an open charm tetraquark state with $0^+$ by QCD sum rules. In the end, we gain the final result for the scalar-scalar case is $2.75^{+0.18}_{-0.19}$ GeV, and the one $2.77^{+0.19}_{-0.20}$ GeV for the axial-axial case. Considering the uncertainty of these results, they are both in agreement with the experimental value of $X_0(2900)$, which that $X_0(2900)$ be a $0^+$ tetraquark state with open charm flavor, which is . It supports that $X_0(2900)$ could be interpreted as a $0^+$ tetraquark state, whose configuration could be either the axial-axial or the scalar-scalar. In the future, further experimental observations and theoretical efforts may shed more light on the internal structure of $X_0(2900)$.

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