Anti-charmed pentaquark $\Theta_c(3099)$ from QCD sum rules

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Abstract

We construct QCD sum rules for the anti-charmed pentaquark $\Theta_c(3099)$, recently reported at HERA. The sum rules are constructed similarly with the $\Theta^+(1540)$ sum rules using the anti-charmed analogue of the $\Theta^+$ interpolating field. The strange quark and quark-gluon mixed condensates, which were important in the $\Theta^+$ sum rules, are replaced by the gluon condensates whose contribution to the OPE is suppressed due to the heavy quark mass. Our result suggests that the parity of $\Theta_c$ is positive. We identify the difference from the $\Theta^+$ sum rule, which leads to the positive parity in this heavy-light pentaquark system. The obtained mass is similar to the experimental value.

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I. INTRODUCTION

The exotic $\Theta^+(1540)$ baryon, after its first discovery [1] and confirmations in subsequent experiments [2], has brought huge excitement in hadron physics. It is a narrow resonance containing 5 quarks, $uudd\bar{s}$, that has not been observed before. Though not confirmed, it is believed to be an isoscalar with spin $1/2$, forming a flavor $\bf{10}$. NA49 Collaboration [3] later reported the observation of the narrow resonance, $\Xi^{--}(1862)$, which could be another member of the same multiplet $\bf{10}$. The observation of the anti-charmed pentaquark $\Theta^0_c(3099)$ in the $D^*p$ invariance mass spectrum has been recently reported by H1 collaboration at HERA [4]. It is anti-charmed analogue of the $\Theta^+(1540)$ and has the quark content $uudd\bar{c}$. The pentaquark with one heavy anti-quark was first studied in Ref. [5] in a quark model. Then it has been studied in quark models [6] and Skyrme models [7, 8] and attracts recent interests [9] motivated by the current experimental activities. Thus, the pentaquarks are becoming a solid member in hadron spectroscopy and await a systematic compilation of their properties.

One interesting model for the pentaquark is the diquark-diquark-antiquark picture of Jaffe and Wilczek (JW) [10]. In this picture, $\Theta^+(1540)$ is composed by the constituent quarks, $ud\bar{u}d\bar{s}$. The two diquarks $ud\bar{u}d$ are identical and the boson symmetry restricts them to be in a relative $P$-wave. Thus, the two diquarks combined with an $S$-wave antiquark lead to even parity for $\Theta^+$. The positive parity is also supported by the triquark-diquark picture [11, 12], the soliton model prediction [13], the quark potential model calculations [14] and quenched lattice calculation [15]. However, dynamical calculations based on QCD sum rules [16] or lattice calculations of Refs. [17, 18] support the negative parity of $\Theta^+$. Therefore, the $\Theta^+$ parity is an important issue to be settled and should be determined eventually from reaction mechanisms. Indeed, various reactions have been suggested to determine the $\Theta^+$ parity. Several proposals are based on the order of magnitude of cross sections and polarization observables in the reactions including $\gamma N \to K\Theta^+$ [19, 21], $K^+p \to \pi^+K^+n$ [20], $\gamma n \to K^-K^+n$ [22], $p + p \to \Sigma + \Theta$ [23] and $\gamma N \to \bar{K}^*\Theta^+$ [24].

Among various QCD sum rule calculations for $\Theta^+$ [16, 25–27], the approach proposed by Sugiyama, Doi and Oka (SDO) [16] is particularly interesting. Here, the interpolating field for $\Theta^+$ is constructed by mostly following the JW picture except for the fact that all the quarks are placed locally. The same current has been used in the lattice calculation [17]. Since QCD sum rules deal with current quarks, one can certainly form two different diquarks (with opposite parity) from the $ud$ system and the boson symmetry no longer applies to the two-diquark system. Nevertheless, the two-diquark system still has odd parity as in the JW picture. The QCD sum rule of SDO has some interesting features. In the operator product expansion (OPE), each diquark propagates only to the diquark and the two diquarks with different parities do not mix each other. This feature is quite welcomed because the diquarks are expected to be a tightly bound system and hence they may not be easy to diffuse to the others in their propagations. The $\Theta^+$ properties in the SDO sum rule are mainly determined by the nonperturbative effects coming from the anti-strange quark. In particular, the negative parity, which is opposite to the JW prediction, is mainly driven by the quark-gluon mixed condensate, $\langle \bar{s}g_s\sigma \cdot Gs \rangle$, which is proportional to the average quark virtuality in the QCD vacuum. When the quark mass becomes heavier (like in the constituent quark picture), such a virtuality should become smaller and it may be possible to flip the parity.

Thus, the extension to the charmed analogue $\Theta_c(3099)$ provides an interesting test for the
SDO sum rule and lattice calculations [17]. Here, the charm quark is quite heavy so that the constituent-quark picture may fit well and the JW prediction for the parity is expected to be reproduced from QCD. In fact, quenched lattice calculation finds the parity of $\Theta_c(3099)$ to be positive [28]. In the extension to the $\Theta_c(3099)$ sum rules, there are two important aspects, which make this sum rule different from the SDO sum rule. First of all, since the charm quark is too heavy to form quark condensate, it gives non-perturbative effects only by radiating gluons. The quark-gluon mixed condensate $\langle \bar{s}g_8 \sigma \cdot Gs \rangle$, which was the important contribution in the $\Theta^+$ sum rule, is replaced by gluonic operators in the heavy quark expansion that are normally suppressed. Secondly, the charm quark mass has to be kept finite in the OPE, which can be done by using the momentum space expression for the charm-quark propagator. This is different from the light-quark sum rule where the calculation is performed in the coordinate space and all the quark propagators are obtained based on the expansion with the small quark mass. Keeping these two aspects in mind, we construct QCD sum rules for $\Theta_c(3099)$ and see how they are different from the $\Theta^+(1540)$ sum rule.

This paper is organized as follows. In Section II, we introduce the interpolating field for $\Theta_c$ and show that it transforms properly under parity. Section III gives the phenomenological side and Section IV gives the OPE side. The QCD sum rules for $\Theta_c$ and their analysis are given in Section V.

II. INTERPOLATING FIELD FOR $\Theta_c$

In our sum rules, we use the following interpolating field for $\Theta_c$,

$$\Theta_c = \epsilon^{abk}(\epsilon^{aef}u^T_k C\gamma_5 d_f)(\epsilon^{bgh}u^T_g C d_h)\Gamma C\bar{c}^T_k .$$  

(1)

Here roman indices $a, b, \ldots$ are color indices, $C$ denotes charge conjugation, $T$ transpose. Note that we have introduced the $4 \times 4$ matrix $\Gamma$ in front of the antiquark, which is to be determined from parity consideration below. The $C\bar{c}^T$ satisfies the charge-conjugated Dirac equation and represents the anti-charm quark. The diquarks, $\epsilon^{aef}u^T_k C\gamma_5 d_f$ and $\epsilon^{bgh}u^T_g C d_h$, are isoscalar with spin 0. Due to the $\gamma_5$ difference, the two diquarks have opposite parities. To make a local interpolating field, all the quarks are defined at the same space-time.

To determine $\Gamma$, we consider the parity transformation of $\Theta_c$,

$$\Theta_c'(x') = \gamma_0 \Theta_c(x), \quad x' = (t, -x) .$$  

(2)

This parity transformation must be recovered when each quark (and the antiquark) in $\Theta_c$ transforms similarly, namely

$$q'(x') = \gamma_0 q(x), \quad (q = u, d, c) .$$  

(3)

This constraint in fact leads to the usual nucleon interpolating field [29] commonly used in nucleon QCD sum rules. Under this quark transformation, the two diquarks transform

$$u^T(x')C d'(x') = -u^T(x)C d(x) ,$$

$$u^T(x')C\gamma_5 d'(x') = u^T(x)C\gamma_5 d(x) .$$  

(4)

The anti-quark is transformed accordingly as

$$C\bar{c}^T(x') = -\gamma_0 C\bar{c}^T(x) .$$  

(5)
Substituting these into the interpolating field Eq. (1) and demanding the consistency with Eq. (2), we find \( \Gamma = 1 \). This type of interpolating field with \( c \to s \) has been used to investigate the properties of \( \Theta^+(1540) \) [15–17].

III. PHENOMENOLOGICAL SIDE

QCD sum rules for the \( \Theta_c \) are constructed from the following correlation function,

\[
\Pi(q) = i \int d^4x e^{iq \cdot x} \langle 0|T(\Theta_c(x), \bar{\Theta}_c(0)|0) \rangle ,
\]

where Eq. (1) with \( \Gamma = 1 \) is used as the interpolating field. To construct the phenomenological side, we note that the \( \Theta_c \) interpolating field can couple to both parities [16, 30, 31]. For the positive parity state, the interpolating field couples through

\[
\langle 0|\Theta_c(x)|\Theta_c(p) : P = + \rangle = \lambda_+ U_\Theta(p) e^{-ip \cdot x} ,
\]

while for the negative parity, it couples through

\[
\langle 0|\Theta_c(x)|\Theta_c(p) : P = - \rangle = \lambda_- \gamma_5 U_\Theta(p) e^{-ip \cdot x} .
\]

Here, \( \lambda_\pm \) denotes the coupling strength between the interpolating field and the physical state with the specified parity. Using this, we obtain the phenomenological side of Eq. (6) separated into chiral even and odd parts,

\[
\Pi^{\text{phen}}(q) = -|\lambda_\pm|^2 \frac{\delta \pm m_\Theta}{q^2 - m_\Theta^2} + \cdots \equiv \Phi_q^{\text{phen}} + \Pi_1^{\text{phen}} ,
\]

where the plus (minus) sign in front of \( m_\Theta \) is for positive (negative) parity. The dots denote higher resonance contributions that should be parametrized according to QCD duality. It should be noted however that higher resonances with different parities contribute differently to the chiral-even and chiral odd parts [32]. Thus, \( \Phi_q^{\text{phen}} \) and \( \Pi_1^{\text{phen}} \) constitute separate sum rules.

The spectral density is given by

\[
\frac{1}{\pi} \text{Im}\Pi^{\text{phen}}(q) = \Phi_q |\lambda_\pm|^2 \delta(q^2 - m_\Theta^2) \pm m_\Theta |\lambda_\pm|^2 \delta(q^2 - m_\Theta^2) + \cdots .
\]

We notice that the chiral-odd part has opposite sign depending on the parity while the chiral even part has positive-definite coefficient. Thus, the chiral-odd part from the OPE side can determine the parity.

IV. OPE SIDE

In the OPE side, we calculate the five diagrams shown in Fig. 1. To keep the charm quark mass finite, we use the momentum-space expression for the charm quark propagators. For the light quark part of the correlation function, we calculate in the coordinate-space, which is then Fourier-transformed to the momentum space in \( D \)-dimension. The resulting light-quark part is combined with the charm-quark part before it is dimensionally regularized at \( D = 4 \).
FIG. 1: Schematic OPE diagrams representing the two diquarks and anti-charm quark propagating from 0 to \(x\). The solid lines denote quark (or anti-charm quark) propagators and the dashed lines are for gluon. The crosses in (c) denote the quark condensate. (a) is perturbative contribution where the diquarks and anti-charm quark just propagate through, (b) is gluon contribution coming from the diquarks, (c) is the \(\langle \bar{q}q \rangle^4\) contribution from the light quarks, and (d) and (e) are the gluon contributions from the charm quark.

Our OPE is given by

\[
\Pi^{\text{ope}}(q) = \Pi^{(a)} + \Pi^{(b)} + \Pi^{(c)} + \Pi^{(d)} + \Pi^{(e)}
\]

(11)

corresponding to each diagram in Fig. 1. The imaginary part of each diagram is calculated as

\[
\frac{1}{\pi} \text{Im}\Pi^{(a)}(q^2) = -\frac{1}{5 \cdot 5! \cdot 2^{12} \pi^8} \int_0^\Lambda du[\bar{q}(1-u) + m_c] \left(-uq^2 + \frac{m_c^2 u}{1-u}\right)^5,
\]

\[
\frac{1}{\pi} \text{Im}\Pi^{(b)}(q^2) = -\frac{1}{3! \cdot 3! \cdot 2^{10} \pi^6} \left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle \int_0^\Lambda du[\bar{q}(1-u) + m_c] \left(-uq^2 + \frac{m_c^2 u}{1-u}\right)^3,
\]

\[
\frac{1}{\pi} \text{Im}\Pi^{(c)}(q^2) = -\frac{1}{54} \langle \bar{q}q \rangle^4 (\bar{q} + m_c) \delta(q^2 - m_c^2),
\]

\[
\frac{1}{\pi} \text{Im}\Pi^{(d)}(q^2) = -\frac{1}{5! \cdot 3! \cdot 2^{10} \pi^6} \left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle \int_0^\Lambda du \left(\frac{u}{1-u}\right)^3 \times [3m_c^2 \bar{q}(1-u) + m_c(1-u)(3-5u)q^2 + 2um_c^3] \left(-uq^2 + \frac{m_c^2 u}{1-u}\right)^2,
\]

\[
\frac{1}{\pi} \text{Im}\Pi^{(e)}(q^2) = -\frac{\langle G^3 \rangle}{5! \cdot 4! \cdot 2^{13} \pi^8} \int_0^\Lambda du \left\{ \bar{q} \left[ q^2 \left(\frac{5u}{2} - 1\right) (1-u) - m_c^2 \left(\frac{3u}{2} + 7\right) \right] + 6m_c q^2 (2u - 1) - 2m_c^3 3u + \frac{1}{1-u} \right\} u \left(-uq^2 + \frac{m_c^2 u}{1-u}\right). \quad (12)
\]

where the upper limit of the integrations is given by \(\Lambda = 1 - m_c^2 / q^2\). The integrations can be done analytically but we skip the messy analytic expressions. For the charm-quark propagators with two and three gluons attached, we use the momentum-space expressions given in
Ref. [33]. In the $\Theta^+(1540)$ sum rule [16], $\langle s_g \sigma \cdot G_s \rangle$ was the important contribution. Since this condensate in the charm sector is replaced to $\langle G^3 \rangle$ in the heavy quark expansion [34], we include $\langle G^3 \rangle$ only from the heavy quark. The Wilson coefficients for light-quark condensates are found to vanish except for the $\langle \bar{q}q \rangle^4$ terms shown in Fig. 1(c). One can check that, for small $m_c$, our OPE reproduces the corresponding OPE in Ref. [16]. The first term yields corresponding terms in Ref. [16], when it is truncated up to $O(m_c^0)$. The second term in the limit $m_c \to 0$ gives the same gluon condensate as in Ref. [16]. The fourth term involves $\langle \alpha_s \pi G^2 \rangle$ in the limit $m_c \to 0$. When this part is converted to the quark condensate in the heavy quark expansion, we find precisely the same Wilson coefficient of quark condensate in Ref. [16]. Note that, similarly as in the phenomenological side, the OPE has a chiral odd and even part,

$$\Pi^{\text{ope}}(q) = \Pi_1^{\text{ope}}(q^2) + \#\Pi_q^{\text{ope}}(q^2).$$  \hspace{1cm} (13)

\section{V. QCD SUM RULES AND ANALYSIS}

QCD sum rules for $\Theta_c$ are constructed by matching the two spectral densities in the Borel-weighted integral,

$$\int_{m_c^2}^{S_0} dq^2 e^{-q^2/M^2} \frac{1}{\pi} \text{Im}[\Pi_i^{\text{phen}}(q^2) - \Pi_i^{\text{ope}}(q^2)] = 0, \hspace{0.5cm} (i = 1, q),$$ \hspace{1cm} (14)

where $M^2$ is the Borel mass. Here, higher resonance contributions are subtracted according to the QCD duality assumption, which introduces the continuum threshold $S_0$. As the correlator contains the chiral odd and even part, we have two sum rules correspondingly,

$$|\lambda_\pm|^2 e^{-m_\pm^2/M^2} = \int_{m_c^2}^{S_0} dq^2 e^{-q^2/M^2} \frac{1}{\pi} \text{Im}[\Pi_q^{\text{ope}}(q^2)],$$ \hspace{1cm} (15)

$$\pm m_\Theta |\lambda_\pm|^2 e^{-m_\pm^2/M^2} = \int_{m_c^2}^{S_0} dq^2 e^{-q^2/M^2} \frac{1}{\pi} \text{Im}[\Pi_1^{\text{ope}}(q^2)].$$ \hspace{1cm} (16)

The second equation shows that the parity of $\Theta_c$ can be determined by the sign of its right-hand side (RHS). We use the following QCD parameters in our sum rules [35],

$$\langle \frac{\alpha_s}{\pi} G^2 \rangle = (0.33 \text{ GeV})^4, \hspace{0.5cm} \langle G^3 \rangle = 0.045 \text{ GeV}^6,$$

$$m_c = 1.26 \text{ GeV}, \hspace{0.5cm} \langle \bar{q}q \rangle = -(0.23 \text{ GeV})^3.$$ \hspace{1cm} (17)

The value for the quark condensate corresponds to $m_q = 7 \text{ MeV}$ ($q = u, d$) in the Gell-Mann–Oakes–Renner relation. The values for the quark and gluon condensates are rather standard in baryon or meson sum rules. For the charm quark mass, other values can be found in the literature, 1.1 GeV for its running mass and 1.5 GeV for the pole mass [36]. These fit the open charm mass $M_D$ in the sum rule of pseudoscalar correlator. Even a larger value is reported in Ref. [37]. Below, we will check the sensitivity of our result to this parameter as well as to the others.

In Fig. 2, we plot the RHS of Eqs. (15) and (16) with respect to the Borel mass for various continuum thresholds $\sqrt{S_0} = 3.2, 3.4$ and 3.6 GeV. As the left-hand side (LHS) of Eq. (15) is
positive definite, we check whether the RHS of Eq. (15) is consistently positive. Our result in Fig. 2(a) indeed shows that the RHS satisfies this constraint. In Fig. 2(b), we plot the RHS of the chiral-odd sum rule (16). Here, we see that the RHS is positive suggesting that the parity of $\Theta_c$ is positive. This positive parity agrees with the quenched lattice calculation [28].

The two observations do not change as we vary the continuum threshold from $\sqrt{S_0} = 3.2$ GeV to 3.6 GeV. The main contribution from the OPE is from the perturbative part [Fig. 1(a)] and the gluon condensate coming from the light quark [Fig. 1(b)]. The contribution from $\langle \bar{q}q \rangle$ and $\langle G^3 \rangle$ is found to be small and therefore the uncertainties in these parameters affect the result marginally. Other values for $m_c$ ranging from 1.1 GeV to 1.5 GeV are found to yield somewhat different curves but all of them have the same sign again supporting the positive parity.

Our result favoring the positive parity is consistent with the expectation from the constituent quark model picture with diquark correlations by Jaffe and Wilczek [10]. Namely, in the Jaffe-Wilczek picture, the two-diquark system has negative parity and, combining with the anticharm quark with intrinsic negative parity, the pentaquark has the positive parity in total. Note, in the SDO sum rule for $\Theta^+$ [16], this picture was not met by the large contribution from the quark-gluon mixed condensate, $\langle \bar{q}gs\cdot Gs \rangle$, which is proportional to the quark virtuality. This mixed condensate is now replaced by Fig. 1(e) through the heavy quark expansion, whose contribution to the OPE becomes marginal in our $\Theta_c$ sum rule. This constitutes the main mechanism for yielding positive parity in this heavy-light pentaquark system. Therefore, we have an interesting crossover from the strange sector to the charm sector in the pentaquark parity.

To check further the reliability of our sum rules, we calculate the $\Theta_c$ mass and see if it
FIG. 3: The predicted $\Theta^+$ mass from chiral even sum rule (a) and chiral odd sum rule (b) determined as explained in the text. The notations are the same as Fig. 2.

agrees with the experimental value. The $\Theta^+$ mass is determined in two ways.

1. We take derivative of the chiral even sum rule (15) with respect to $1/M^2$ and divide the resulting equation by Eq. (15). As can be seen from Eq. (15), this step leads to $-m_\Theta^2$ in the LHS. The mass is then obtained by taking negative square root of the resulting RHS.

2. The same method as 1 applied to the chiral-odd sum rule, Eq. (16).

The results are shown in Fig. 3 for the two cases. At the continuum threshold $\sqrt{S_0} = 3.2$ GeV, both sum rules yield the $\Theta_c$ mass to be around 3.06 GeV and the result is practically independent of the Borel mass $M$. Changing the charm quark mass to a lower value of 1.1 GeV leads to $3.02$ GeV. For a much higher value of $m_c = 1.5$ GeV, we have $3.14$ GeV at the stable Borel region. So the extracted mass is slightly sensitive to the charm quark mass. The extracted mass is more sensitive to the continuum threshold. As we increase the continuum threshold, the result increases slightly also. At the large threshold of $\sqrt{S_0} = 3.6$ GeV, the predicted mass is around 3.4 GeV. Thus, our sum rules give the $\Theta_c$ mass that qualitatively agrees with the experimental value of 3.099 GeV.

To summarize, we have constructed QCD sum rules for the recently discovered anti-charmed pentaquark $\Theta_c(3099)$. The charm quark mass is kept finite in the OPE while for the light quark propagators we use the coordinate space expressions obtained from the expansion in the small quark mass. Our sum rules suggest that the parity of $\Theta_c$ is positive, which is opposite to that of $\Theta^+(1540)$ determined from QCD sum rules. The obtained mass is qualitatively consistent with the experimental value of the H1 Collaboration.
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[1] LEPS Collaboration, T. Nakano et al., Phys. Rev. Lett. 91 (2003) 012002.
[2] S. Stepanyan et al. [CLAS Collaboration], Phys. Rev. Lett. 91 (2003) 252001; J. Barth et al. [SAPHIR Collaboration], Phys. Lett. B 572 (2003) 127; V. V. Barmin et al. [DIANA Collaboration], Phys. Atom. Nucl. 66 (2003) 1715 [Yad. Fiz. 66 (2003) 1763]; V. Kubarovsky, S. Stepanyan [CLAS Collaboration], AIP Conf. Proc. 698 (2004) 543; A. E. Asratyan, A. G. Dolgolenko, M. A. Kubantsev, hep-ex/0309042; V. Kubarovsky et al. [CLAS Collaboration], Phys. Rev. Lett. 92 (2004) 032001; A. Airapetian, et al. [HERMES Collaboration], Phys. Lett. B 585 (2004) 213; S. Armstrong, B. Mellado and S. L. Wu, hep-ph/0312344; A. Aleev, et al. [SVD Collaboration], hep-ex/0401024.
[3] C. Alt et al. [NA49 Collaboration], Phys. Rev. Lett. 92 (2004) 042003.
[4] A. Aktas et al. [H1 Collaboration], hep-ex/0403017.
[5] C. Gignoux, B. Silvestre-Brac, J. M. Richard, Phys. Lett. B 193 (1987) 323; H. J. Lipkin, Phys. Lett. B 195 (1987) 484.
[6] Fl. Stancu, Phys. Rev. D 58 (1998) 111501; M. Genovese, J.-M. Richard, Fl. Stancu, S. Pepin, Phys. Lett. B 425 (1998) 171.
[7] D. O. Riska, N. N. Scoccola, Phys. Lett. B 299 (1993) 338.
[8] Y. Oh, B.-Y. Park, D.-P. Min, Phys. Lett. B 331 (1994) 362; Phys. Rev. D 50 (1994) 3350; Y. Oh, B.-Y. Park, Phys. Rev. D 51 (1995) 5016.
[9] K. Cheung, hep-ph/0308176; T. E. Browder, I. R. Klebanov, D. R. Marlow, Phys. Lett. B 587 (2004) 62; I. W. Stewart, M. E. Wessling, M. B. Wise, hep-ph/0402076; M. A. Nowak, M. Praszalowicz, M. Sadzikowski, J. Wasiltuk, hep-ph/0403184; H. Y. Cheng, C. K. Chua, C. W. Hwang, hep-ph/0403232.
[10] R. L. Jaffe and F. Wilczek, Phys. Rev. Lett. 91 (2003) 232003.
[11] M. Karliner, H. J. Lipkin, hep-ph/0307243.
[12] N. I. Kochelev, H. J. Lee, V. Vento, hep-ph/0404065.
[13] D. Diakonov, V. Petrov, M. Polyakov, Z. Phys. A 359 (1997) 305.
[14] C. E. Carlson, C. D. Carone, H. J. Kwee, V. Nazaryan, Phys. Lett. B 579 (2004) 52.
[15] T. W. Chiü, T. H. Hsieh, hep-ph/0403020.
[16] J. Sugiyama, T. Doi, M. Oka, Phys. Lett. B 581 (2004) 167.
[17] S. Sasaki, hep-lat/0310014.
[18] F. Csikor, Z. Fodor, S. D. Katz, T. G. Kovacs, JHEP 0311 (2003) 070.
[19] Y. Oh, H. Kim, S. H. Lee, Phys. Rev. D 69 (2004) 014009.
[20] T. Hyodo, A. Hosaka, E. Oset, Phys. Lett. B 579 (2004) 290.
[21] Q. Zhao, Phys. Rev. D 69 (2004) 053009; K. Nakayama, W. G. Love, hep-ph/0404011.
[22] K. Nakayama, K. Tsushima, Phys. Lett. B 583 (2004) 269.
[23] A. W. Thomas, K. Hicks, A. Hosaka, Prog. Theor. Phys. 111 (2004) 291; C. Hanhart et al., hep-ph/0312236; S. I. Nam, A. Hosaka, H. C. Kim, hep-ph/0401074.
[24] Y. Oh, H. Kim, S. H. Lee, hep-ph/0312229.
[25] S. L. Zhu, Phys. Rev. Lett. 91 (2003) 232002.
[26] R. D. Matheus, F. S. Navarra, M. Nielsen, R. Rodrigues da Silva, S. H. Lee, Phys. Lett. B 578 (2004) 323.
[27] M. Eidemuller, hep-ph/0404126.
[28] T. W. Chiu, T. H. Hsieh, hep-ph/0404007.
[29] D. K. Griegel, Nucleon Propagation In Nuclear Matter: A QCD Sum Rule Approach, Ph.D Thesis, University of Maryland, 1991.
[30] D. Jido, N. Kodama, M. Oka, Phys. Rev. D 54 (1996) 4532.
[31] F. X. Lee, X. Y. Liu, Phys. Rev. D 66 (2002) 014014.
[32] X. M. Jin, J. Tang, Phys. Rev. D 56 (1997) 515.
[33] L. J. Reinders, H. Rubinstein, S. Yazaki, Phys. Rept. 127 (1985) 1.
[34] E. Bagan, J. I. Latorre, P. Pascual, Z. Phys. C 32 (1986) 43.
[35] M. A. Shifman, A. I. Vainshtein, V. I. Zakharov, Nucl. Phys. B 147 (1979) 385.
[36] S. Narison, Phys. Lett. B 520 (2001) 115.
[37] M. Eidemuller, Phys. Rev. D 67 (2003) 113002.