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Investigation on the $\Omega(2012)$ from QCD sum rules

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We investigate the newly observed $\Omega(2012)$ using QCD sum rules. By constructing P-wave Ω currents with a covariant derivative and performing spin projection, we obtain spin-1/2 and spin 3/2 components. Using parity-projected sum rules, we extract the masses $M_{1/2^-} = 2.07^{+0.07}_{-0.07}$ GeV and $M_{3/2^-} = 2.05^{+0.09}_{-0.10}$ GeV, both consistent with experimental data. This suggests that $\Omega(2012)$ is a negative-parity P-wave excitation, though its spin remains undetermined and requires further analysis.

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PoS(HADRON2025)076

1. Inroduction

The $\Omega(2012)$ was first observed by Belle in 2018 via $\Upsilon(nS)$ decays [1], and later confirmed in $\Omega_c \to \pi^+\Omega(2012)^- \to \pi^+(\bar{K}\Xi)^-$ [2]. More recently, its observation was further supported by results from BESIII [3] and ALICE [4]. Its mass and width are [5]:

$$M = 2012.5 \pm 0.7 \pm 0.5 \text{ MeV}, \quad \Gamma = 6.4^{+2.5}_{-2.0} \text{ MeV}. \tag{1}$$

The conventional quark model interprets $\Omega(2012)$ as the first P-wave excitation of the Ω baryon with $J^P = 3/2^-$ [6–15]. This model predicts spin-orbit partners at $J^P = 1/2^-$ and $3/2^-$, and the $1/2^-$ state is expected to be broad. Alternatively, a molecular interpretation has been proposed due to $\Omega(2012)$'s proximity to the $\bar{K}\Xi^*(1530)$ threshold [16–26]. This approach suggests that only the $3/2^-$ state is favored, and predicts a sizable contribution to the three-body decay $\Omega(2012) \to \Xi\pi\bar{K}$ [16–19]. A hybrid model combining three-quark and molecular components has also been proposed [27].

Given the uncertainties in these interpretations, we explore $\Omega(2012)$ using QCD sum rules. Unlike previous studies using local three-quark currents [6, 7], we use a covariant derivative to enhance coupling to physical states especially to P-wave excitations, while in principle the currents may couple to both negative and positive parity states. We analyze the four possible spin-parity states $J^P = 1/2^\pm$ and $3/2^\pm$, and obtain the following masses for the negative parity states:

$$M_{1/2^-} = 2.07^{+0.07}_{-0.07} \text{ GeV}, \quad M_{3/2^-} = 2.05^{+0.09}_{-0.10} \text{ GeV}, \tag{2}$$

which agree well with experimental data. This suggest that $\Omega(2012)$ is likely a three-quark state.

The paper is structured as follows: In Sec. 2, we construct the P-wave currents. In Sec. 3, we present the QCD sum rule analysis. Numerical results are discussed in Sec. 4, and conclusions are drawn in Sec. 5.

2. P-wave Ω baryon currents

In this section we systematically construct the P-wave Ω baryon currents using three *strange* quark field $s_a(x)$, with $a = 1 \cdots 3$ the color index. Since the Ω baryon system that contains three identical *strange* quarks, it is not easy to differentiate the ρ-mode and λ-mode orbital excitations. Therefore, we can construct either the local P-wave Ω baryon currents containing either the ρ-mode or λ-mode orbital excitation, and we find it much easier to construct the currents of the ρ-mode, which contains the P-wave ss diquark field.

Phenomenologically, the P-wave ss diquark with the color representation $\bar{\mathbf{3}}_c$ can only have the total spin $s_{12} = 0$ and so the total angular momentum $j_{12} = 1$. Its corresponding diquark field is

$$\epsilon^{abc}[s_a^T C\gamma_5 \overleftrightarrow{D}_\mu s_b] = -2\epsilon^{abc}[(D_\mu s_a^T)C\gamma_5 s_b] \, . \tag{3}$$

We further adding another *strange* quark to obtain P-wave Ω baryon, whose total angular momentum is either $J = 1/2$ or $J = 3/2$. Their corresponding P-wave Ω baryon currents are

$$J = \epsilon^{abc} \, [(D_\mu s_a^T)C\gamma_5 s_b] \, \gamma^\mu s_c \, , \tag{4}$$

$$J_\mu = \epsilon^{abc} \, [(D^\nu s_a^T)C\gamma_5 s_b] \, (g_{\mu\nu} - \frac{1}{4}\gamma_\mu\gamma_\nu)s_c \, , \tag{5}$$

where $P_{\mu\nu} = g_{\mu\nu} - \frac{1}{4}\gamma_\mu\gamma_\nu$ is the spin-3/2 projection operator.

PoS(HADRON2025)076

3. QCD sum rule analyses

In this section, we outline the QCD sum rules using the current defined in Eq. (5). As an example, the current J_μ with $J^P = 3/2^-$ couples to the physical state $|\Omega; 3/2^-\rangle$ via

$$\langle 0|J_\mu|\Omega; 3/2^-\rangle = f_- u_\mu(q), \tag{6}$$

where f_- is the coupling constant and $u_\mu(q)$ is the Rarita-Schwinger spinor. It also couples to the opposite parity state $|\Omega; 3/2^+\rangle$ as

$$\langle 0|J_\mu|\Omega; 3/2^+\rangle = f_+ \gamma_5 u_\mu(q). \tag{7}$$

We consider the two-point correlation function,

$$\Pi_{\mu\nu}(q^2) = i \int d^4x\, e^{iqx} \langle 0|T[J_\mu(x) J_\nu^\dagger(0)]|0\rangle, \tag{8}$$

which can be decomposed as

$$\Pi_{\mu\nu}(q^2) = \left(\frac{q_\mu q_\nu}{q^2} - g_{\mu\nu}\right) \Pi(q^2) + \cdots, \tag{9}$$

where the omitted terms correspond to spin-1/2 contributions and are neglected. The function $\Pi(q^2)$ satisfies a dispersion relation:

$$\Pi(q^2) = \int_{s_<}^{\infty} \frac{\rho(s)}{s - q^2 - i\varepsilon}\, ds, \tag{10}$$

with $\rho(s) = \mathrm{Im}\Pi(s)/\pi$ and $s_< = 9m_s^2$ as the OPE threshold.

At the hadronic level, inserting a complete set of intermediate states gives the spectral density:

$$\rho^{\rm phen}(s) = f_-^2(q + M_-)\delta(s - M_-^2) + f_+^2(q - M_+)\delta(s - M_+^2) \tag{11}$$

$$+\theta(s - s_0)\rho^{\rm cont}(s), \tag{12}$$

where $M_\mp$ are the masses of the negative and positive parity states, and s_0 is the continuum threshold. The corresponding correlation function becomes

$$\Pi^{\rm phen}(q^2) = f_-^2 \frac{q + M_-}{M_-^2 - q^2} + f_+^2 \frac{q - M_+}{M_+^2 - q^2}, \tag{13}$$

which can be decomposed as

$$\Pi^{\rm phen}(q^2) = \Pi_1^{\rm phen}(q^2)\, q + \Pi_0^{\rm phen}(q^2). \tag{14}$$

Defining spectral densities for each structure, we have

$$\rho_1^{\rm phen}(s) = f_-^2\delta(s - M_-^2) + f_+^2\delta(s - M_+^2), \tag{15}$$

$$\rho_0^{\rm phen}(s) = f_-^2 M_-\delta(s - M_-^2) - f_+^2 M_+\delta(s - M_+^2), \tag{16}$$

from which the parity-separated densities are

$$\rho_\mp^{\rm phen}(s) = \sqrt{s}\rho_1^{\rm phen}(s) \pm \rho_0^{\rm phen}(s). \tag{17}$$

On the QCD side, we calculate the same correlation function using the operator product expansion (OPE), which yields $\rho_1^{\text{OPE}}(s)$ and $\rho_0^{\text{OPE}}(s)$ corresponding to the above structures.

By matching the spectral densities at the hadronic and quark-gluon levels and applying a Borel transformation, we obtain the QCD sum rules:

$$\Pi_{\mp}(s_0, M_B) = 2M_{\mp} f_{\mp}^2 e^{-M_{\mp}^2/M_B^2} = \int_{s_<}^{s_0} (\sqrt{s}\rho_1^{\text{OPE}}(s) \pm \rho_0^{\text{OPE}}(s)) e^{-s/M_B^2} ds. \tag{18}$$

Here, the upper limit s_0 reflects the quark-hadron duality assumption, approximating the continuum with the OPE above the threshold.

The masses and couplings are then extracted as

$$M_{\mp}^2(s_0, M_B) = \frac{\int_{s_<}^{s_0} (\sqrt{s}\rho_1^{\text{OPE}}(s) \pm \rho_0^{\text{OPE}}(s))\, s\, e^{-s/M_B^2} ds}{\int_{s_<}^{s_0} (\sqrt{s}\rho_1^{\text{OPE}}(s) \pm \rho_0^{\text{OPE}}(s))\, e^{-s/M_B^2} ds}, \tag{19}$$

$$f_{\mp}^2(s_0, M_B) = \frac{\int_{s_<}^{s_0} (\sqrt{s}\rho_1^{\text{OPE}}(s) \pm \rho_0^{\text{OPE}}(s))\, e^{-s/M_B^2} ds \times e^{M_{\mp}^2/M_B^2}}{2M_{\mp}}. \tag{20}$$

4. Numerical analysis

In this section, we present our numerical results. We begin with the $J^P = 3/2^-$ state. According to Eq. (19), the extracted mass depends on the Borel mass M_B and threshold s_0. To determine their optimal ranges, we apply three standard criteria: (a) good OPE convergence, (b) sufficient pole contribution, and (c) stability of the mass with respect to M_B and s_0.

To ensure OPE convergence, we impose:

$$\text{CVG}_A = \left|\frac{\Pi_-^{\text{D}=11+10+9+8}}{\Pi_-(\infty, M_B^2)}\right| \leq 5\%, \tag{21}$$

$$\text{CVG}_B = \left|\frac{\Pi_-^{\text{D}=7+6}}{\Pi_-(\infty, M_B^2)}\right| \leq 10\%, \tag{22}$$

$$\text{CVG}_C = \left|\frac{\Pi_-^{\text{D}=5+4}}{\Pi_-(\infty, M_B^2)}\right| \leq 20\%. \tag{23}$$

the criterion CVG_C sets the lower bound $M_B^2 \geq 1.54$ GeV^2, with the others automatically satisfied.

For the pole contribution, we require:

$$\text{PC} = \left|\frac{\Pi_-(s_0, M_B^2)}{\Pi_-(\infty, M_B^2)}\right| \geq 40\%, \tag{24}$$

which leads to an upper bound $M_B^2 \leq 1.76$ GeV^2 for $s_0 = 6.0$ GeV^2. We also find that s_0 must be above a minimum $s_0^{\text{min}} = 5.3$ GeV^2. Thus, the Borel window is determined as 1.54 GeV$^2 \leq M_B^2 \leq$ 1.76 GeV^2 for 5.3 GeV$^2 \leq s_0 \leq$ 6.7 GeV^2. The resulting mass and coupling are:

$$M_{3/2^-} = 2.05^{+0.09}_{-0.10} \text{ GeV}, \tag{25}$$

$$f_{3/2^-} = 0.037^{+0.007}_{-0.007} \text{ GeV}^3. \tag{26}$$

Uncertainties stem from M_B, s_0, and the condensates .

Table 1: Masses and coupling constants extracted from the currents J in Eq. (4) and J_μ in Eq. (5).

Current	state	Mass[GeV]	Coupling constant[GeV^3]
J	$\|\Omega; 1/2^+\rangle$	$3.05^{+0.21}_{-0.15}$	$0.168^{+0.045}_{-0.040}$
	$\|\Omega; 1/2^-\rangle$	$2.07^{+0.07}_{-0.07}$	$0.079^{+0.011}_{-0.011}$
J_μ	$\|\Omega; 3/2^+\rangle$	$3.13^{+0.27}_{-0.18}$	$0.074^{+0.015}_{-0.009}$
	$\|\Omega; 3/2^-\rangle$	$2.05^{+0.09}_{-0.10}$	$0.037^{+0.007}_{-0.007}$

5. Summary

In this paper, we investigated the recently observed Ω(2012) using QCD sum rules. We constructed P-wave Ω currents with a covariant derivative and performed spin projections to obtain spin-1/2 and 3/2 states. By applying parity-projected sum rules, we systematically analyzed the four spin-parity channels $1/2^\pm$ and $3/2^\pm$, and extracted their masses and couplings. The results are summarized in Table 1. In particular, we obtained:

$$M_{1/2^-} = 2.07^{+0.07}_{-0.07}\ \text{GeV}, \tag{27}$$

$$M_{3/2^-} = 2.05^{+0.09}_{-0.10}\ \text{GeV}. \tag{28}$$

Both values are consistent with the observed Ω(2012), suggesting it is a P-wave excited Ω baryon with three strange quarks. However, due to the closeness of these masses, we cannot determine its spin. Investigation of decay properties is needed to fix the spin, which will be a future study.

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References

[1] J. Yelton *et al.* [Belle], Phys. Rev. Lett. **121**, no.5, 052003 (2018).

[2] Y. Li *et al.* [Belle], Phys. Rev. D **104** (2021) no.5, 052005.

[3] M. Ablikim *et al.* [BESIII], Phys. Rev. Lett. **134** (2025) no.13, 131903

[4] S. Acharya *et al.* [ALICE], [arXiv:2502.18063 [hep-ex]].

[5] [Belle], [arXiv:2207.03090 [hep-ex]].

[6] T. M. Aliev, K. Azizi, Y. Sarac and H. Sundu, Phys. Rev. D **98** (2018) no.1, 014031.

[7] T. M. Aliev, K. Azizi, Y. Sarac and H. Sundu, Eur. Phys. J. C **78** (2018) no.11, 894.

[8] M. V. Polyakov, H. D. Son, B. D. Sun and A. Tandogan, Phys. Lett. B **792** (2019), 315-319.

[9] Z. Y. Wang, L. C. Gui, Q. F. Lü, L. Y. Xiao and X. H. Zhong, Phys. Rev. D **98** (2018) no.11, 114023.

[10] L. Y. Xiao and X. H. Zhong, Phys. Rev. D **98** (2018) no.3, 034004.

[11] M. S. Liu, K. L. Wang, Q. F. Lü and X. H. Zhong, Phys. Rev. D **101** (2020) no.1, 016002.

[12] A. J. Arifi, D. Suenaga, A. Hosaka and Y. Oh, Phys. Rev. D **105** (2022) no.9, 094006.

[13] C. Menapara and A. K. Rai, Chin. Phys. C **46** (2022) no.10, 103102.

[14] K. L. Wang, Q. F. Lü, J. J. Xie and X. H. Zhong, Phys. Rev. D **107** (2023) no.3, 034015.

[15] H. H. Zhong, R. H. Ni, M. Y. Chen, X. H. Zhong and J. J. Xie, Chin. Phys. C **47** (2023) no.6, 063104.

[16] Y. H. Lin and B. S. Zou, Phys. Rev. D **98** (2018) no.5, 056013.

[17] M. P. Valderrama, Phys. Rev. D **98** (2018) no.5, 054009.

[18] R. Pavao and E. Oset, Eur. Phys. J. C **78** (2018) no.10, 857.

[19] Y. Huang, M. Z. Liu, J. X. Lu, J. J. Xie and L. S. Geng, Phys. Rev. D **98** (2018) no.7, 076012.

[20] T. Gutsche and V. E. Lyubovitskij, J. Phys. G **48** (2020) no.2, 025001.

[21] N. Ikeno, G. Toledo and E. Oset, Phys. Rev. D **101** (2020) no.9, 094016.

[22] C. H. Zeng, J. X. Lu, E. Wang, J. J. Xie and L. S. Geng, Phys. Rev. D **102** (2020) no.7, 076009.

[23] J. X. Lu, C. H. Zeng, E. Wang, J. J. Xie and L. S. Geng, Eur. Phys. J. C **80** (2020) no.5, 361.

[24] X. Liu, H. Huang, J. Ping and D. Chen, Phys. Rev. C **103** (2021) no.2, 025202.

[25] N. Ikeno, W. H. Liang, G. Toledo and E. Oset, Phys. Rev. D **106** (2022) no.3, 034022.

[26] X. Hu and J. Ping, Phys. Rev. D **106** (2022) no.5, 054028.

[27] Q. F. Lü, H. Nagahiro and A. Hosaka, Phys. Rev. D **107** (2023) no.1, 014025.