

QCD sum rule study of the tensor $\Delta^0\Delta^0$ dibaryon state

M. Ahmadi¹, H. Mohseni¹, and K. Azizi^{1,2,*}

¹*Department of Physics, University of Tehran, North Karegar Avenue, Tehran 14395-547, Iran*

²*Department of Physics, Dogus University, Dudullu-Ümraniye, 34775 Istanbul, Türkiye*



(Received 16 August 2025; accepted 14 October 2025; published 3 November 2025)

We study the exotic $\Delta^0\Delta^0$ dibaryon state with quantum numbers $J^P = 2^+$ within the framework of QCD sum rules. A tensor interpolating current is constructed to determine the mass and residue of this state, including explicit calculations of contributions from quark, gluon, and mixed vacuum condensates up to dimension nine. The numerical analysis yields a mass of $m_{\Delta^0\Delta^0} = 2426^{+101}_{-108}$ MeV and a residue of $f_{\Delta^0\Delta^0} = (2.30^{+0.49}_{-0.45}) \times 10^{-4}$ GeV⁸. The predicted mass lies about 38 MeV below the $2m_{\Delta^0}$ threshold, which indicates the possible existence of a bound configuration. Consequently, the tensor $\Delta^0\Delta^0$ dibaryon may serve as a promising candidate for future experimental searches.

DOI: [10.1103/nfm8-q2hq](https://doi.org/10.1103/nfm8-q2hq)

I. INTRODUCTION

The investigation of multi-quark states within quantum chromodynamics (QCD) began shortly after the theory was established in the 1970s. A pioneering bag-model calculation from that period ignited interest in these exotic systems and motivated both experimental searches and alternative theoretical approaches. While conventional hadrons, such as mesons (quark-antiquark pairs) and baryons (three-quark states), were well understood within the quark model, the possibility of exotic hadrons, such as tetraquarks (four quarks) and pentaquarks (five quarks), attracted considerable theoretical attention [1]. Early theoretical models predicted the existence of multi-quark states, but experimental confirmation remained elusive for decades.

Significant progress occurred in the 2000s due to advancements in experimental techniques and particle accelerators. In 2003, the Belle Collaboration reported the discovery of the $X(3872)$, widely regarded as the first strong tetraquark candidate. This was followed by further discoveries, including the observation of pentaquark states by the LHCb experiment at CERN, where so-called “exotic” hidden-charm XYZ tetraquark and P_c pentaquark states were reported. These milestones marked a turning point in multi-quark research, opening new avenues for exploring QCD and deepening our understanding of hadron structure and the strong interactions that govern their behavior [2–7].

Dibaryons, as another important class of multi-quark hadrons, pose some of the most complex theoretical and experimental challenges in strong interaction physics. The deuteron, discovered in 1932 by Urey *et al.* [8], was the first identified dibaryon. Another intriguing example is the H dibaryon predicted by Jaffe [9], which continues to attract both experimental and theoretical interest. More recently, the $d^*(2380)$ resonance was observed in the total cross section at $\sqrt{s} = 2.37$ GeV with $\Gamma \approx 70$ MeV and quantum numbers $I(J^P) = 0(3^+)$, in double-pionic fusion reactions reported by the WASA-at-COSY Collaboration [10–14]. Following its observation, numerous studies have examined the $d^*(2380)$, including investigations of its total width [15], as well as analyses of its mass, binding energy, root-mean-square radius, and electromagnetic form factors in comparison with experimental data [16,17]. The $d^*(2380)$ has also been studied using QCD sum rules [18], where three Δ – Δ -like interpolating currents yielded a predicted mass $M_{d^*} = 2.4 \pm 0.2$ GeV, consistent with the WASA measurement. Further research has investigated its structure and decay properties using a chiral constituent quark model [19], evaluated the properties of its decuplet states [20], and explored its possible configurations as a hexaquark state [21].

Recent investigations have examined the influence of the $d^*(2380)$ hexaquark on the equation of state (EoS) of dense neutron star matter, exploring the implications of its existence for neutron star properties. These studies have shown that including the d^* state notably softens the EoS at high densities, thereby reducing the predicted maximum mass of neutron stars [22,23]. Motivated by the possibility of a stable hexaquark ($uuddss$) as a dark matter candidate, Ref. [24] investigated its compatibility with neutron star

*Contact author: kazem.azizi@ut.ac.ir

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

observations, focusing on constraints from maximum mass and tidal deformability.

In parallel, interest in dibaryons has been fueled by proposals to explore them as potential dark matter candidates [25–27]. Studies on the mass and stability of the H dibaryon, inspired by Jaffe’s original prediction [9], have been carried out using various particle physics models. The corrected MIT bag model yields $m_H = 2240$ MeV, placing it just above the $2m_\Lambda$ threshold [28], while a chiral model predicts a substantially lower value of 1130 MeV [29].

Various quark models have also been employed to study the $\Lambda\Lambda$ interaction and its binding energy [30–32]. QCD sum rule calculations give results consistent with Jaffe’s initial estimate, indicating a mass in the range 2.0–2.4 GeV [33]. Moreover, some experimental studies have reported positive signals to find a stable dibaryon state [34,35]. In particular, Ref. [35] reports data indicating the formation of a $\Delta\Delta$ system in the intermediate state, suggesting that the ABC effect is associated with the $(\pi\pi)_{I=L=0}$ channel. Using a simple string model, Ref. [36] found that the ground state of (q^6) remains stable against dissociation into two baryons and predicted a bound state very near the threshold for the $(q^3\bar{q}^3)$ case.

Further evidence for a bound H-dibaryon comes from lattice QCD simulations. A bound state with $I = 0$, $J = 0$, and quark content $uuddss$ was found at $m_\pi \sim 389$ MeV, with a binding energy of $16.6 \pm 2.1 \pm 4.6$ MeV, where the first uncertainty is statistical and the second systematic. With more measurements and improved analysis, the binding energy was refined to $B_H = 13.2 \pm 1.8 \pm 4.0$ MeV [37,38]. Using the baryon-baryon potential method described in Ref. [39], the HALQCD Collaboration performed simulations on three lattice volumes and at three quark masses, reporting a bound H-dibaryon with a binding energy of 30–40 MeV for pion masses between 673 and 1015 MeV [40]. Issues related to Lattice QCD were also investigated using chiral effective field theory at leading order for baryon–baryon interactions, focusing on the $\Xi\Xi$, $\Xi\Sigma$, and $\Xi\Lambda$ channels. This analysis revealed significant effects from SU(3) symmetry breaking, arising mainly from differences among the $\Lambda\Lambda$, $\Sigma\Sigma$, and ΞN thresholds. At physical masses, this breaking was found to reduce the H-dibaryon binding energy by as much as 60 MeV compared to the SU(3)-symmetric case [41].

The interaction between the nucleon (N) and the Omega baryon (Ω) was investigated in Ref. [42], where a bound state was identified with a binding energy of $18.9(5.0)_{-1.8}^{+12.1}$ MeV. Lattice QCD studies of the $\Omega\Omega$ dibaryon in the 1S_0 channel reported a binding energy of $B_{\Omega\Omega} = 1.6(6)_{-0.6}^{+0.7}$ MeV, indicating an overall attraction near the unitary regime [43]. Following this, analyses of two-particle momentum correlations for $\Omega\Omega$ and $p\Omega$ pairs in relativistic heavy-ion collisions predicted shallow bound states characterized by comparatively

large positive scattering lengths in the $J = 0$ $\Omega\Omega$ and $J = 2$ $p\Omega$ channels [44].

Using QCD sum rules, the exotic $\Omega\Omega$ dibaryons with $J^P = 0^+$ and 2^+ have been studied in a molecular picture. The predicted scalar state has a mass of (3.33 ± 0.22) GeV, suggesting a loosely bound system, while the tensor state at (3.24 ± 0.23) GeV may be more deeply bound [45]. The production of $p\Omega$ (5S_2) and $\Omega\Omega$ (1S_0) in central Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV was studied in Ref. [46], considering two possible structural scenarios: molecular states and compact six-quark states.

In Ref. [47], the ground state spectrum of two-flavor heavy quark baryons within the spin-singlet channel was investigated. Moreover, the relationship between the binding energy and the constituent quark masses was explored by varying quark masses across a range from strange to bottom quark masses. The S-wave $\Lambda\Lambda$ and $N\Xi$ systems were examined using lattice QCD [48], with results indicating that the $N\Xi$ interaction lies close to unitarity, whereas the $\Lambda\Lambda$ interaction at low energies does not support a bound state.

Theoretical studies on the N – Ω interaction have been presented in Refs. [49–52]. Additionally, Ref. [53] employed QCD sum rules and reported that an $N\Omega$ dibaryon bound state may exist in the $(^5S_2)$ channel, with a binding energy of approximately 21 MeV. The spectra of potential hidden-bottom and hidden-charm hexaquark states were investigated using the QCD sum rule framework [54]. This analysis suggests the possible existence of two baryonium states in the bottom-quark sector, with estimated masses of 11.84 ± 0.22 GeV for the $J^{PC} = 0^{++}$ state and 11.72 ± 0.26 GeV for the $J^{PC} = 1^{--}$ state.

In the heavy-flavor sector, studies of the mass spectra of molecular-type hexaquark states have indicated the possible existence of molecular configurations in the DD^* , $DD\bar{D}^*$, and $\Sigma_c\bar{D}^{(*)}$ systems, suggesting the emergence of numerous deuteronlike hexaquarks [55]. In Ref. [56], the study of doubly charmed H -like dibaryon $\Lambda_c\Lambda_c$ scattering from lattice QCD shows that the $\Lambda_c\Lambda_c$ system behaves as a typical scattering state with no bound state formation at the given quark mass. Furthermore, the investigation of doubly charmed hexaquark configurations was conducted within the diquark framework, employing both the constituent quark model and the quark-interchange approach. The analysis, based on key properties such as mass spectra, suggests the nonexistence of stable bound states. Nonetheless, the evaluated root-mean-square radii indicate that these hexaquark systems exhibit a notably compact configuration [57]. The possibility of the existence of dibaryon states composed of heavy baryons, such as $\Xi_c^*\Xi_c^*$ and $\Xi_c\Xi_c$, has been investigated [58–60]. In Ref. [60], calculations based on a variational method yield masses of 5.291 GeV for the $J^P = 0^+$ channel with total isospin $I = 1$, and 5.281 GeV for the $J^P = 1^+$ channel with $I = 0$. Fully heavy dibaryons represent a particularly

intriguing and debated topic. In Ref. [61], the authors explored the possibility of $bbbccc$ dibaryons and reported no bound states for either the $\Omega_{ccc}\Omega_{ccc}$ or $\Omega_{bbb}\Omega_{bbb}$ systems. Conversely, Ref. [62] indicated that the $\Omega_{ccc}\Omega_{ccc}$ system is weakly bound with a binding energy of 5.68(0.77) MeV, while Ref. [63] predicted a deeply bound $\Omega_{bbb}\Omega_{bbb}$ state, with a binding energy of 81^{+14}_{-16} MeV. More recently, Ref. [64] conducted a renewed analysis of the potential existence of $\Omega_{ccc}\Omega_{ccc}$ and $\Omega_{bbb}\Omega_{bbb}$ dibaryons using a constituent quark model. Their findings suggest that six charm or six bottom quarks can form bound states with quantum numbers $J^P = 0^+$, yielding binding energies of -0.71 MeV for the charm case and -1.98 MeV for the bottom case.

As outlined in the aforementioned studies, several theoretical frameworks have been utilized to investigate six-quark systems and dibaryons. These include QCD sum rules, lattice QCD, chiral perturbation theory, quark models, and effective field theories. Among these, the QCD sum rule approach has proven to be a powerful nonperturbative method, extensively applied to various hadronic phenomena, including hadron spectroscopy and decay processes. Within the QCD sum rule framework, suitable interpolating currents corresponding to the hadron of interest are constructed. These currents are employed to formulate two-point or three-point correlation functions, which are used to extract the hadron's mass and decay properties, respectively. By matching the operator product expansion (OPE) of the correlation function to its hadronic spectral representation, one derives sum rules that enable the determination of physical observables.

One of the key advantages of the QCD sum rule method is that it is firmly grounded in the fundamental QCD Lagrangian. The formalism is fully relativistic and free from arbitrary or purely phenomenological parameters, thereby ensuring a high degree of theoretical consistency and predictive reliability.

In the light quark sector, the mass and coupling constant of a scalar six-quark state composed of $uuddss$ quarks have been studied using the QCD sum rule approach to explore its viability as a dark matter candidate [65]. The possibility of a $\Delta^0\Delta^0$ dibaryon has also been investigated through various methods, such as the quark delocalization color screening model and the chiral quark model [66]. More recently, the scalar $\Delta^0\Delta^0$ state was studied using QCD sum rules [67], where the mass was estimated as $m_D = 2326^{+114}_{-126}$ MeV, and the decay constant was found to be approximately $f_D = (2.94^{+0.30}_{-0.34}) \times 10^{-4}$ GeV⁷. In the present work, we extend this line of investigation by calculating the mass and decay constant (residue) of a hypothetical $\Delta^0\Delta^0$ dibaryon in the tensor state with quantum numbers $J^P = 2^+$ using the QCD sum rule method.

II. METHODOLOGY

To investigate dibaryon systems within the framework of QCD sum rules, the $\Delta^0\Delta^0$ interpolating currents are constructed using the local Ioffe current representation of the Δ^0 baryon,

$$\eta_\mu = \frac{1}{\sqrt{3}} \epsilon^{abc} [2(d_a^T C \gamma_\mu u_b) d_c + (d_a^T C \gamma_\mu d_b) u_c], \quad (1)$$

where $C = i\gamma_2\gamma_0$ is the charge conjugation matrix, a, b, c denote color indices, γ_μ are Dirac gamma matrices, and T indicates the transpose operator.

Using this interpolating current, the $\Delta^0\Delta^0$ dibaryon with quantum numbers $J^P = 2^+$ is constructed as

$$J_{\mu\nu}^{\Delta^0\Delta^0} = \frac{1}{3} \epsilon^{abc} \epsilon^{def} [2(d_a^T C \gamma_\mu u^b) d^c + (d_a^T C \gamma_\mu d^b) u^c] \cdot C \gamma_5 \cdot [2d^dT (d^e C \gamma_\nu u^f) + u^dT (d^e C \gamma_\nu d^f)]. \quad (2)$$

To extract physical properties such as the mass and residue, we employ the two-point QCD sum rule method by analyzing the correlation function

$$\Pi_{\mu\nu\rho\sigma}(p^2) = i \int d^4x e^{ip \cdot x} \langle 0 | T \{ J_{\mu\nu}^{\Delta^0\Delta^0}(x) J_{\rho\sigma}^{\Delta^0\Delta^0\dagger}(0) \} | 0 \rangle, \quad (3)$$

where T is the time-order operator and $J_{\mu\nu(\rho\sigma)}^{\Delta^0\Delta^0}$ is the interpolating current for the tensor dibaryon state. In the framework of QCD sum rules, the correlation function is evaluated from two complementary perspectives. On the physical (phenomenological) side, the correlation function is modeled in terms of hadronic degrees of freedom in the timelike region, allowing for the extraction of physical parameters such as the mass and residue in different states. On the QCD (theoretical) side, the same correlation function is computed in the spacelike region using quark and gluon fields. This representation includes contributions from the QCD coupling constant, quark masses, and gluon condensates of various dimensions, capturing the nonperturbative aspects of the QCD vacuum. By equating the two sides through dispersion relations and invoking the quark-hadron duality assumption, one can extract the hadronic parameters in terms of QCD quantities. To enhance the reliability of the sum rule and suppress contributions from higher resonances and continuum states, Borel transformation and continuum subtraction procedures are employed. We commence by evaluating the hadronic (physical) representation of the correlation function through the insertion of appropriate complete sets of states, possessing the same quantum numbers as the interpolating current, into the corresponding positions. A complete set of intermediate hadronic states is inserted into the correlation function presented in Eq. (3). After performing the integration over x , the correlation function can be written as,

$$\Pi_{\mu\nu\rho\sigma}^{\text{Phys}}(p) = \frac{\langle 0|j_{\mu\nu}(0)|D(p)\rangle\langle D(p)|J_{\rho\sigma}(0)|0\rangle}{m_D^2 - p^2} + \dots, \quad (4)$$

where $\dots$ represents the higher states and continuum contributions. The matrix elements responsible for creating hadronic states from the vacuum can be parametrized in terms of the decay constant and the corresponding polarization tensor as follows:

$$\langle 0|J_{\mu\nu}^{\Delta^0\Delta^0}|D(p)\rangle = f_{\Delta^0\Delta^0}\varepsilon(p)_{\mu\nu}^\lambda + \dots \quad (5)$$

Here, $f_{\Delta^0\Delta^0}$ denotes the coupling constant, and $\varepsilon_{\mu\nu}$ is the polarization tensor associated with the spin-2 state. The polarization sum is given by

$$\sum_\lambda \varepsilon_{\mu\nu}^{(\lambda)} \varepsilon_{\rho\sigma}^{*(\lambda)} = \frac{1}{2}(T_{\mu\rho}T_{\nu\sigma} + T_{\mu\sigma}T_{\nu\rho}) - \frac{1}{3}T_{\mu\nu}T_{\rho\sigma}, \quad (6)$$

where

$$T_{\mu\nu} = -g_{\mu\nu} + \frac{p_\mu p_\nu}{p^2}. \quad (7)$$

Combining the above results and summing over polarization states via the corresponding completeness relation yields the physical representation of the correlation function in the following final form

$$\Pi_{\mu\nu\rho\sigma}^{\text{Phys}}(p) = \frac{f_{\Delta^0\Delta^0}^2}{m_D^2 - p^2} \left[\frac{1}{2}(g_{\mu\rho}g_{\nu\sigma} + g_{\mu\sigma}g_{\nu\rho}) \right] + \text{other structures} + \dots, \quad (8)$$

where the ellipses represent contributions from additional Lorentz structures, higher excited, and continuum states. The term proportional to $(g_{\mu\rho}g_{\nu\sigma} + g_{\mu\sigma}g_{\nu\rho})$ corresponds solely to the contribution from the spin-2 particle, while the remaining terms arise from the presence of spin-0 and spin-1 states as well.

In the next step of our analysis, we evaluate the correlator $\Pi_{\mu\nu\rho\sigma}(p)$ using OPE. For this purpose, we substitute the explicit form of the current $J_{\mu\nu}(x)$ into Eq. (3) and perform the necessary contractions of the quark fields via Wick's theorem to derive $\Pi_{\mu\nu\rho\sigma}^{\text{QCD}}(p)$. This leads to

$$\begin{aligned} \Pi_{\mu\nu\rho\sigma}^{\text{QCD}}(p) = & \frac{16}{9} \int d^4x e^{ip \cdot x} \times (\delta_{af}\delta_{be}\delta_{cd}\delta_{a'f'}\delta_{b'e'}\delta_{c'd'}\text{Tr}(S_{ad'}^d(x,0)\gamma^\rho\tilde{S}_{be'}^u(x,0)\gamma^\mu)\text{Tr}(S_{cc'}^d(x,0)\gamma^5\tilde{S}_{ff'}^d(x,0)\gamma^5) \\ & \times \text{Tr}(S_{da'}^d(x,0)\gamma^\sigma\tilde{S}_{eb'}^u(x,0)\gamma^\nu) \\ & - \delta_{ae}\delta_{bf}\delta_{cd}\delta_{a'f'}\delta_{b'e'}\delta_{c'd'}\text{Tr}(S_{ad'}^d(x,0)\gamma^\rho\tilde{S}_{be'}^u(x,0)\gamma^\mu)\text{Tr}(S_{cc'}^d(x,0)\gamma^5\tilde{S}_{ff'}^d(x,0)\gamma^5) \\ & \times \text{Tr}(S_{da'}^d(x,0)\gamma^\sigma\tilde{S}_{eb'}^u(x,0)\gamma^\nu) \\ & - \delta_{af}\delta_{bd}\delta_{ce}\delta_{a'f'}\delta_{b'e'}\delta_{c'd'}\text{Tr}(S_{ad'}^d(x,0)\gamma^\rho\tilde{S}_{be'}^u(x,0)\gamma^\mu)\text{Tr}(S_{cc'}^d(x,0)\gamma^5\tilde{S}_{ff'}^d(x,0)\gamma^5) \\ & \times \text{Tr}(S_{da'}^d(x,0)\gamma^\sigma\tilde{S}_{eb'}^u(x,0)\gamma^\nu) \\ & + \delta_{ad}\delta_{bf}\delta_{ce}\delta_{a'f'}\delta_{b'e'}\delta_{c'd'}\text{Tr}(S_{ad'}^d(x,0)\gamma^\rho\tilde{S}_{be'}^u(x,0)\gamma^\mu)\text{Tr}(S_{cc'}^d(x,0)\gamma^5\tilde{S}_{ff'}^d(x,0)\gamma^5) \\ & \times \text{Tr}(S_{da'}^d(x,0)\gamma^\sigma\tilde{S}_{eb'}^u(x,0)\gamma^\nu) \\ & + \delta_{ae}\delta_{bd}\delta_{cf}\delta_{a'f'}\delta_{b'e'}\delta_{c'd'}\text{Tr}(S_{ad'}^d(x,0)\gamma^\rho\tilde{S}_{be'}^u(x,0)\gamma^\mu)\text{Tr}(S_{cc'}^d(x,0)\gamma^5\tilde{S}_{ff'}^d(x,0)\gamma^5) \\ & \times \text{Tr}(S_{da'}^d(x,0)\gamma^\sigma\tilde{S}_{eb'}^u(x,0)\gamma^\nu) \\ & - \delta_{ad}\delta_{be}\delta_{cf}\delta_{a'f'}\delta_{b'e'}\delta_{c'd'}\text{Tr}(S_{ad'}^d(x,0)\gamma^\rho\tilde{S}_{be'}^u(x,0)\gamma^\mu)\text{Tr}(S_{cc'}^d(x,0)\gamma^5\tilde{S}_{ff'}^d(x,0)\gamma^5) \\ & \times \text{Tr}(S_{da'}^d(x,0)\gamma^\sigma\tilde{S}_{eb'}^u(x,0)\gamma^\nu) \\ & - \delta_{af}\delta_{be}\delta_{cd}\delta_{a'f'}\delta_{b'e'}\delta_{c'd'}\text{Tr}(S_{ad'}^d(x,0)\gamma^\rho\tilde{S}_{be'}^u(x,0)\gamma^\mu)\text{Tr}(S_{cc'}^d(x,0)\gamma^5\tilde{S}_{ff'}^d(x,0)\gamma^5) \\ & \times \text{Tr}(S_{da'}^d(x,0)\gamma^\sigma\tilde{S}_{eb'}^u(x,0)\gamma^\nu) \\ & + \delta_{ae}\delta_{bf}\delta_{cd}\delta_{a'f'}\delta_{b'e'}\delta_{c'd'}\text{Tr}(S_{ad'}^d(x,0)\gamma^\rho\tilde{S}_{be'}^u(x,0)\gamma^\mu)\text{Tr}(S_{cc'}^d(x,0)\gamma^5\tilde{S}_{ff'}^d(x,0)\gamma^5) \\ & \times \text{Tr}(S_{da'}^d(x,0)\gamma^\sigma\tilde{S}_{eb'}^u(x,0)\gamma^\nu) \\ & - \delta_{ad}\delta_{bf}\delta_{ce}\delta_{a'f'}\delta_{b'e'}\delta_{c'd'}\text{Tr}(S_{ad'}^d(x,0)\gamma^\rho\tilde{S}_{be'}^u(x,0)\gamma^\mu)\text{Tr}(S_{cc'}^d(x,0)\gamma^5\tilde{S}_{ff'}^d(x,0)\gamma^5) \\ & \times \text{Tr}(S_{da'}^d(x,0)\gamma^\sigma\tilde{S}_{eb'}^u(x,0)\gamma^\nu) \\ & + \delta_{af}\delta_{bd}\delta_{ce}\delta_{a'f'}\delta_{b'e'}\delta_{c'd'}\text{Tr}(S_{ad'}^d(x,0)\gamma^\rho\tilde{S}_{be'}^u(x,0)\gamma^\mu)\text{Tr}(S_{cc'}^d(x,0)\gamma^5\tilde{S}_{ff'}^d(x,0)\gamma^5) \\ & \times \text{Tr}(S_{da'}^d(x,0)\gamma^\sigma\tilde{S}_{eb'}^u(x,0)\gamma^\nu)) + 27638 \text{ similar terms.} \end{aligned} \quad (9)$$

Here, $\tilde{S}(x) = CS^T(x)C$ and $S^{u(d)}(x)$ are the u and d quarks' propagators, with color indices $a, b, \dots$. The color deltas ensure the correct color contractions in the traces. The next step in the QCD side involves employing the light-quark propagator in position space,

$$\begin{aligned} S_q^{ab}(x) = & i \frac{\not{x}}{2\pi^2 x^4} \delta_{ab} - \frac{m_q}{4\pi^2 x^2} \delta_{ab} - \frac{\langle \bar{q}q \rangle}{12} \left(1 - i \frac{m_q}{4} \not{x} \right) \delta_{ab} - \frac{x^2}{192} \langle \bar{q}g_s \sigma G q \rangle \left(1 - i \frac{m_q}{6} \not{x} \right) \delta_{ab} \\ & - \frac{ig_s G_{ab}^{\mu\nu}}{32\pi^2 x^2} [\not{x} \sigma_{\mu\nu} + \sigma_{\mu\nu} \not{x}] - \frac{\not{x} x^2 g_s^2 \langle \bar{q}q \rangle^2}{7776} \delta_{ab} - \frac{x^4 \langle \bar{q}q \rangle \langle g_s^2 G^2 \rangle}{27648} \delta_{ab} \\ & + \frac{m_q g_s}{32\pi^2} G_{ab}^{\mu\nu} \sigma_{\mu\nu} \left[\ln \left(\frac{-x^2 \Lambda^2}{4} \right) + 2\gamma_E \right] + \dots \end{aligned} \quad (10)$$

In these expressions, $q = u, d$, $\gamma_E \approx 0.577$ denotes the Euler-Mascheroni constant, Λ is a scale parameter, $G^2 \equiv G_{\mu\nu}^A G_{\mu\nu}^A$, $G_{\mu\nu}^{ab} \equiv G_{\mu\nu}^A t_{ab}^A$, $A = 1, 2, \dots, 8$, and $t^A = \lambda^A/2$, with λ^A being the Gell-Mann matrices. The terms in Eq. (10) include the perturbative part, represented by the first term corresponding to the free propagator of a light quark, emission of a single gluon and the nonperturbative contributions, which involve other gluonic effects such as the two-gluon condensate. For the two-gluon condensate, $\langle 0 | G_{\alpha\beta}^A(x) G_{\alpha'\beta'}^B(0) | 0 \rangle$, which leads to the four-dimension nonperturbative contribution, we consider the first term of the Taylor expansion for the gluon field at $x = 0$. We utilize [68],

$$\langle 0 | G_{\alpha\beta}^A(0) G_{\alpha'\beta'}^B(0) | 0 \rangle = \frac{\langle G^2 \rangle}{96} \delta^{AB} (g_{\alpha\alpha'} g_{\beta\beta'} - g_{\alpha\beta'} g_{\alpha'\beta}), \quad (11)$$

together with the SU(3) color identity,

$$t_{b'}^a t_{b'}^{a'} = \frac{1}{2} \left(\delta_{ab'} \delta_{a'b} - \frac{1}{3} \delta_{ab} \delta_{a'b'} \right). \quad (12)$$

In fact, the correlator $\Pi^{\text{Phys}}(p^2)$ can be rewritten using the dispersion relation,

$$\Pi^{\text{Phys}}(p^2) = \int_{M'^2}^{\infty} \frac{\rho^{\text{Phys}}(s)}{s - p^2} ds + \dots, \quad (13)$$

with $M' = (4m_d + 2m_u)$. The spectral density is

$$\rho^{\text{Phys}}(s) = f_{\Delta^0 \Delta^0}^2 \delta(s - m_{\Delta^0 \Delta^0}^2) + \rho^h(s) \theta(s - s_0), \quad (14)$$

where $\theta(z)$ is the step function and s_0 is the continuum threshold. Higher resonances and continuum contributions to $\rho^{\text{Phys}}(s)$ are represented through the unknown hadronic spectral density $\rho^h(s)$. It is evident that $\rho^{\text{Phys}}(s)$ yields the following expression:

$$\Pi^{\text{Phys}}(p^2) = \frac{f_{\Delta^0 \Delta^0}^2}{m_{\Delta^0 \Delta^0}^2 - p^2} + \int_{s_0}^{\infty} \frac{\rho^h(s)}{s - p^2} ds. \quad (15)$$

The theoretical calculation of $\Pi^{\text{OPE}}(p^2)$ is performed in the deep Euclidean region ($p^2 \ll 0$) via OPE. By analytically continuing $\Pi^{\text{OPE}}(p^2)$ to the Minkowski domain and taking its imaginary part, the two-point spectral density $\rho^{\text{OPE}}(s)$ is obtained, as presented below. In the deep Euclidean region ($p^2 \ll 0$), we perform the Borel transformation $\mathcal{B}$ to eliminate subtraction terms in the dispersion relation and to suppress the contributions from higher resonances and the continuum. Applying the Borel transform $\mathcal{B}$ in this domain yields,

$$\mathcal{B}\Pi^{\text{Phys}}(p^2) = f_{\Delta^0 \Delta^0}^2 e^{-m_{\Delta^0 \Delta^0}^2/M^2} + \int_{s_0}^{\infty} \rho^h(s) e^{-s/M^2} ds, \quad (16)$$

where M^2 denotes the Borel parameter and s_0 is the continuum threshold. To extract physical information from the correlation function, after applying the Borel transformation to both sides of the sum rule, the invariant amplitudes $\Pi^{\text{Phys}}(p^2)$ and $\Pi^{\text{QCD}}(p^2)$ are equated. Following this procedure, assuming hadron-parton duality, $\rho^h(s) \simeq \rho^{\text{QCD}}(s)$ in the duality region, we subtract the continuum part from the QCD side, yielding,

$$f_{\Delta^0 \Delta^0}^2 e^{-m_{\Delta^0 \Delta^0}^2/M^2} = \Pi^{\text{QCD}}(s_0, M^2), \quad (17)$$

where

$$\Pi^{\text{QCD}}(s_0, M^2) = \int_{M'^2}^{s_0} ds \rho(s) e^{-s/M^2}. \quad (18)$$

The spectral density $\rho(s)$ corresponds to the imaginary part of $\Pi^{\text{OPE}}(p^2)$ and is given by $\rho(s) = \frac{1}{\pi} \text{Im}[\Pi(s)]$. Under the assumptions $m_u \rightarrow 0$ and $m_d \rightarrow 0$, the explicit form of $\rho(s)$ reads,

$$\rho(s) = -\frac{47s^7}{6242697216000\pi^{10}} + \frac{527\langle G^2 \rangle s^5 g_s^2}{1651507200\pi^{10}} + \frac{s^4 \langle \bar{q}q \rangle^2 g_s^2}{376233984\pi^8} - \frac{1961s^4 \langle \bar{q}q \rangle^2}{209018880\pi^6} - \frac{331s^4 \langle \bar{q}q \rangle^2}{52254720\pi^6} \\ - \frac{41s^4 \langle \bar{q}q \rangle^2 g_s^2}{6449725440\pi^8} - \frac{23s^4 \langle \bar{q}q \rangle^2}{20901888\pi^6} + \frac{679s^3 \langle \bar{q}q \rangle^2 m_0^2}{7464960\pi^6} + \frac{13s^3 \langle \bar{q}q \rangle^2 m_0^2}{207360\pi^6} + \frac{17s^3 m_0^2 \langle \bar{q}q \rangle^2}{1492992\pi^6}. \quad (19)$$

In the following, using the shorthand

$$\Pi'(s_0, M^2) = \frac{d}{d(-1/M^2)} \Pi(s_0, M^2), \quad (20)$$

and after straightforward algebra, we obtain the mass and the residue

$$m_{\Delta^0 \Delta^0}^2 = \frac{\Pi'(s_0, M^2)}{\Pi(s_0, M^2)} = \frac{\int_{M^2}^{s_0} ds s \rho(s) e^{-s/M^2}}{\int_{M^2}^{s_0} ds \rho(s) e^{-s/M^2}}, \quad (21)$$

and

$$f_{\Delta^0 \Delta^0}^2 = e^{m_{\Delta^0 \Delta^0}^2/M^2} \Pi(s_0, M^2). \quad (22)$$

III. NUMERICAL ANALYSIS

For the numerical evaluation of the obtained expressions for the mass and residue of the $\Delta^0 \Delta^0$ dibaryon states with $J^P = 2^+$, a set of input parameters, including the gluon and quark condensates, is required. These parameters are listed in Table I.

At this point in the analysis, it is crucial to determine the appropriate working windows for the two auxiliary parameters involved in QCD sum rule calculations of physical observables, namely the Borel parameter M^2 and the continuum threshold s_0 . While these parameters are not physical in themselves, they are subject to specific constraints within the QCD sum rule framework and cannot be selected arbitrarily.

A key requirement is that physical quantities such as masses and residue should remain largely stable within certain ranges of M^2 and s_0 . Identifying these stability regions is essential for ensuring the reliability of the results, as it helps minimize theoretical uncertainties and validates the consistency of the QCD sum rule approach.

The parameters must be selected to ensure that the pole contribution (PC) dominates in the physical observables extracted via the sum rule method. Additionally, the stability of these results with respect to M^2 and the convergence of the OPE are critical constraints in the numerical analysis. These conditions can be quantitatively assessed by introducing the following expressions:

$$\text{PC} = \frac{\Pi(M^2, s_0)}{\Pi(M^2, \infty)}, \quad (23)$$

and

$$R(M^2) = \frac{\Pi^{\text{DimN}}(M^2, s_0)}{\Pi(M^2, s_0)}. \quad (24)$$

Here, we impose the following criteria: The upper bound of the Borel parameter M^2 is determined by ensuring that the pole contribution is considerably large compared to each of the higher excited states and continuum. In technical language, we require that the pole contribution be as maximum as possible in the exotic dibaryon channel: We set $\text{PC} \geq 0.2$. Moreover, the lower bound of M^2 is determined by the requirement of convergence of the OPE. This criterion implies that the perturbative contribution must dominate over the nonperturbative terms, and the effects of higher-dimensional operators should remain suppressed. To ensure this, we require that the combined contribution of the last three nonperturbative terms does not exceed 5% of the total (perturbative plus nonperturbative) contributions, i.e., $R(M^2) \leq 0.05$. Moreover, the chosen range for s_0 should lie significantly above the production threshold of two Δ^0 baryons, which is approximately $4m_{\Delta^0}^2 \simeq 6.07 \text{ GeV}^2$. The range of s_0 may be selected as the minimal value that ensures a stable and reliable Borel window. Alternatively, s_0 can be fixed by fulfilling additional constraints so as to maximize the PC. Note that for multiquark hadrons, or more precisely exotic states, the available information is often scarce. In such situations, s_0 can be estimated based on the aforementioned constraints.

We then choose the parameters $(2m_{\Delta^0 \Delta^0} + 0.2)^2 \text{ GeV}^2 \leq s_0 \leq (2m_{\Delta^0 \Delta^0} + 0.4)^2 \text{ GeV}^2$, which define an energetically feasible window for exciting the $\Delta^0 \Delta^0$ system to its first excited state. In addition, the Borel parameter is chosen as $8.0 \text{ GeV}^2 \leq M_B^2 \leq 10.0 \text{ GeV}^2$, which ensures the necessary conditions for a reliable QCD sum rule analysis.

Figures 1 and 2 present the mass and decay constant of the $\Delta^0 \Delta^0$ dibaryon as functions of M^2 and s_0 . Figure 1 (left panel) demonstrates that the mass remains relatively stable

TABLE I. Key input parameters and their values used in the analysis.

$\langle \bar{q}q \rangle$	$-(0.24 \pm 0.01)^3 \text{ GeV}^3$ [69]	m_0^2	$(0.8 \pm 0.1) \text{ GeV}^2$ [69]	$\langle \alpha_s G^2 \rangle$	$(0.012 \pm 0.004) \text{ GeV}^4$ [70]
$\langle \alpha_s \rangle$	(0.118 ± 0.005) [71]	$\langle g_s^2 \rangle$	$4\pi\alpha_s$		

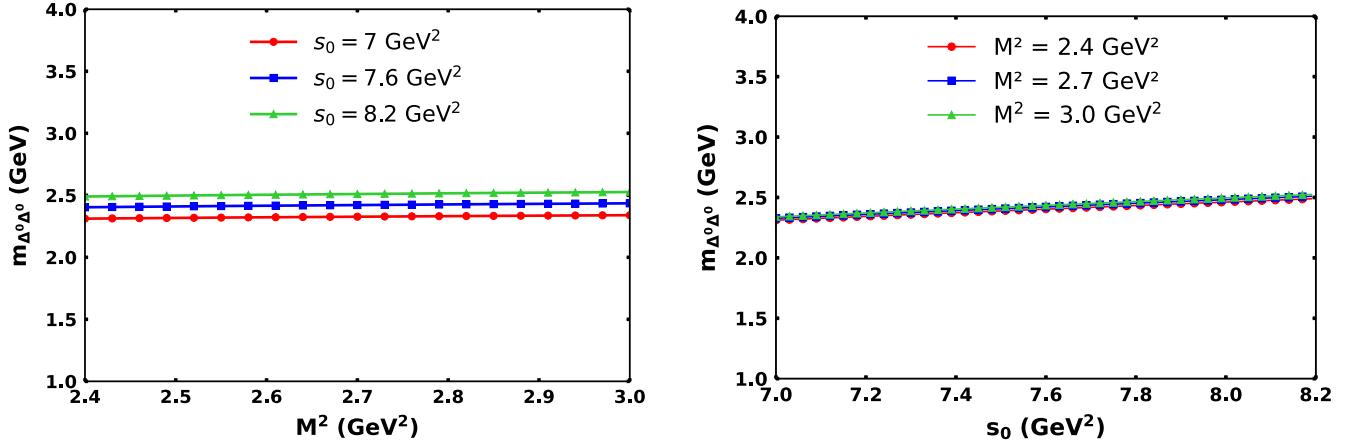


FIG. 1. Left panel shows the variation of the $\Delta^0\Delta^0$ dibaryon mass with respect to M^2 at fixed s_0 , while the right panel illustrates its dependence on s_0 at fixed M^2 .

across the chosen range of the Borel parameter M^2 and shows very good stability. In the right panel of Fig. 1, a mild dependence of the mass on the continuum threshold s_0 is observed. As shown in Fig. 2, though the residue shows a good stability with respect to the variations of M^2 in its working region, it indicates a residual sensitivity to variations in s_0 . As a result, the requirements of the method are satisfied.

To extract the mass $m_{\Delta^0\Delta^0}$ and residue $f_{\Delta^0\Delta^0}$ of the $\Delta^0\Delta^0$ dibaryon with $J^P = 2^+$, we perform calculations using the range of values for the Borel parameter M^2 and the continuum threshold s_0 . The final values are obtained by averaging over the working intervals defined above. The results are as follows:

$$\begin{aligned} m_{\Delta^0\Delta^0} &= 2426_{-108}^{+101} \text{ MeV}, \\ f_{\Delta^0\Delta^0} &= (2.30_{-0.45}^{+0.49}) \times 10^{-4} \text{ GeV}^8. \end{aligned} \quad (25)$$

The uncertainties in the mass and decay residue arise from the variation between the extreme values of $m_{\Delta^0\Delta^0}$ and $f_{\Delta^0\Delta^0}$. The central mass value lies approximately 38 MeV below the $2m_{\Delta^0}$ threshold, indicating a possible bound molecular state of the scalar $\Delta^0\Delta^0$ dibaryon. Compared to the calculated $\Delta^0\Delta^0$ dibaryon in the $J^P = 0^+$ channel, where a mass of $m_{\Delta^0\Delta^0} = 2326_{-126}^{+114}$ MeV has been reported [67], the mass obtained in the $J^P = 2^+$ channel is higher by about 100 MeV, leading to a weaker binding. It is also worth noting that the $\Omega\Omega$ dibaryon, an exotic particle composed entirely of strange quarks, has been investigated in both the $J^P = 0^+$ and $J^P = 2^+$ channels [45]. In contrast to the $\Delta^0\Delta^0$ dibaryon, the predicted mass of the $\Omega\Omega$ state in the tensor channel is lower than that in the scalar channel, indicating a stronger binding for the tensor state.

It is important to emphasize that the present analysis excludes the influence of radiative corrections. Although the mass, extracted from the ratio of two sum rules, is

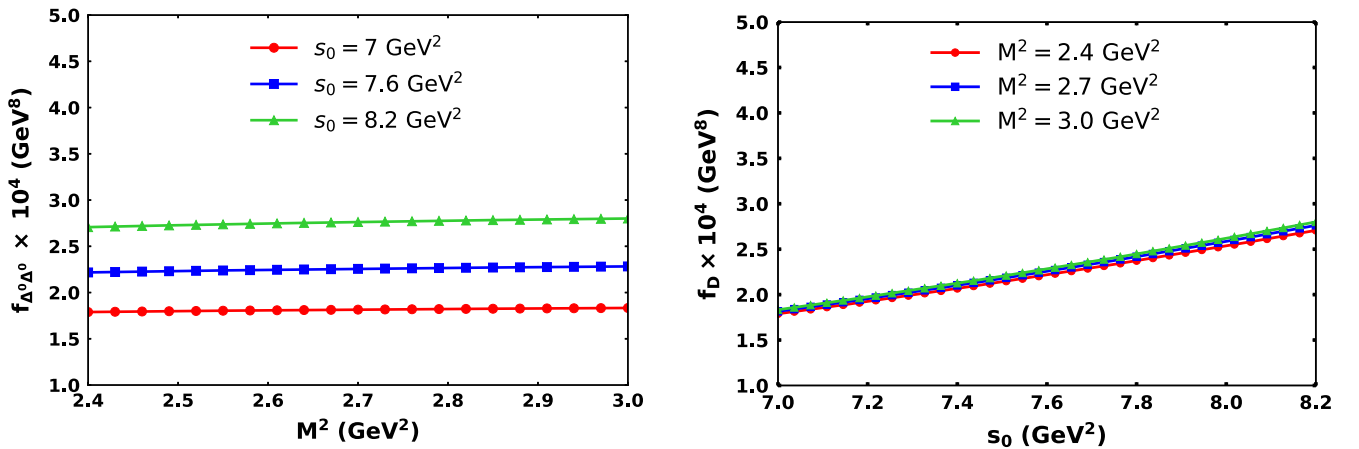


FIG. 2. Left panel shows the variation of the $\Delta^0\Delta^0$ dibaryon mass with respect to M^2 at fixed s_0 , while the right panel illustrates its dependence on s_0 at fixed M^2 .

relatively insensitive to such corrections, the residue calculated from an individual sum rule can exhibit considerable fluctuations. Furthermore, next-to-leading order (NLO) perturbative corrections to baryon sum rules have been reported as significant [72,73]. Similarly, while NLO α_s corrections to the perturbative component in the OPE for light tetraquark currents are sizable, their overall impact on the sum rules remains limited owing to the predominance of nonperturbative condensate contributions [74]. Furthermore, given that the analysis of the $\Delta^0\Delta^0$ dibaryon with $J^P = 2^+$ suggests the existence of a bound state, the estimation of its size can be interesting. Based on the definition of binding energy, the size of the $\Delta^0\Delta^0$ dibaryon can be determined using the following expression:

$$r \sim \frac{1}{\sqrt{2\mu B_E}} \quad (26)$$

where the binding energy is $B_E = 2m_{\Delta^0} - m_{\Delta^0\Delta^0}$. In this expression, r represents the distance between the components, while $\mu = \frac{m_1 m_2}{m_1 + m_2}$ corresponds to the reduced mass of the two-hadron system. The size of the tensor state is found to be approximately $r \simeq 0.90$ fm, nearly twice that of the $\Delta^0\Delta^0$ dibaryon in the $J^P = 0^+$ state. As is clear, both the tensor and scalar states remain below the confinement radius of 1 fm [75]. In the case of the tensor state, while it may suggest a molecular configuration, the radius indicates an overlap between two Δ^0 baryons, making the molecular description questionable. The obtained size suggests a compact hexaquark structure for this particle. However, calculating other properties of this state may help in achieving a better understanding of its internal configuration. In contrast to the $\Delta^0\Delta^0$ dibaryon, which represents a light-quark exotic dibaryon, it is of particular interest to estimate the radius of the $\Omega\Omega$ dibaryon mentioned above.

Based on the binding energy calculated in Ref. [45], and assuming the same quantum state as considered in our study, the resulting radii are found to be approximately $r \simeq 1.24$ fm for the $J^P = 0^+$ state and $r \simeq 0.97$ fm for the $J^P = 2^+$ state. These results indicate that the tensor state remains within the typical confinement radius.

IV. CONCLUDING NOTES

The investigation of newly observed exotic hadronic states constitutes a primary focus within contemporary hadron physics research. In this study, we explore tensor $\Delta^0\Delta^0$ dibaryon states with spin-parity $J^P = 2^+$ using the framework of QCD sum rules. We construct interpolating currents for the tensor $\Delta^0\Delta^0$ dibaryon, and calculate the corresponding spectral densities and two-point correlation functions, including contributions from condensates up to dimension nine. The numerical analysis indicates that the tensor current leads to stable mass sum rules. Based on this, we provide a reliable mass prediction for the tensor $\Delta^0\Delta^0$ dibaryon with $J^P = 2^+$, obtaining $m_{\Delta^0\Delta^0, 2^+} = 2426_{-108}^{+101}$ MeV. This result points to the possible existence of a bound state, with an estimated binding energy of approximately 38 MeV. The residue was determined to be $f_{\Delta^0\Delta^0} = (2.30_{-0.45}^{+0.49}) \times 10^{-4}$ GeV⁸. Additionally, we estimated the spatial size of the tensor $\Delta^0\Delta^0$ dibaryon to be approximately $r \simeq 0.90$ fm. The calculated binding energy suggests that the tensor $\Delta^0\Delta^0$ dibaryon is a potentially stable system. We hope that these findings will contribute to future theoretical investigations and experimental searches for dibaryon states.

DATA AVAILABILITY

No data were created or analyzed in this study.

-
- [1] M. Gell-Mann, A schematic model of baryons and mesons, *Phys. Lett.* **8**, 214 (1964).
 - [2] S. K. Choi *et al.* (Belle Collaboration), Observation of a narrow charmonium-like state in exclusive $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ decays, *Phys. Rev. Lett.* **91**, 262001 (2003).
 - [3] E. S. Swanson, The new heavy mesons: A status report, *Phys. Rep.* **429**, 243 (2006).
 - [4] R. Aaij *et al.* (LHCb Collaboration), Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \rightarrow J/\psi K^- p$ decays, *Phys. Rev. Lett.* **115**, 072001 (2015).
 - [5] H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, The hidden-charm pentaquark and tetraquark states, *Phys. Rep.* **639**, 1 (2016).
 - [6] R. F. Lebed, R. E. Mitchell, and E. S. Swanson, Heavy-quark QCD exotica, *Prog. Part. Nucl. Phys.* **93**, 143 (2017).
 - [7] S. L. Olsen, T. Skwarnicki, and D. Zieminska, Nonstandard heavy mesons and baryons: Experimental evidence, *Rev. Mod. Phys.* **90**, 015003 (2018).
 - [8] H. C. Urey, F. G. Brickwedde, and G. M. Murphy, A hydrogen isotope of mass 2, *Phys. Rev.* **39**, 164 (1932).
 - [9] R. L. Jaffe, Perhaps a stable dihyperon, *Phys. Rev. Lett.* **38**, 195 (1977).
 - [10] P. Adlarson *et al.* (WASA-at-COSY Collaboration), ABC effect in basic double-pionic fusion—observation of a new resonance?, *Phys. Rev. Lett.* **106**, 242302 (2011).

- [11] P. Adlarson *et al.* (WASA-at-COSY Collaboration), Isospin decomposition of the basic double-pionic fusion in the region of the ABC effect, *Phys. Lett. B* **721**, 229 (2013).
- [12] A. Gal and H. Garcilazo, Three-body calculation of the $\Delta\Delta$ dibaryon candidate D(03) at 2.37 GeV, *Phys. Rev. Lett.* **111**, 172301 (2013).
- [13] P. Adlarson *et al.* (WASA-at-COSY Collaboration), Evidence for a new resonance from polarized neutron-proton scattering, *Phys. Rev. Lett.* **112**, 202301 (2014).
- [14] P. Adlarson *et al.* (WASA-at-COSY Collaboration), Measurement of the $np \rightarrow np\pi^0\pi^0$ reaction in search for the recently observed $d^*(2380)$ resonance, *Phys. Lett. B* **743**, 325 (2015).
- [15] Y. Dong, P. Shen, F. Huang, and Z. Zhang, Theoretical study of the $d^*(2380) \rightarrow d\pi\pi$ decay width, *Phys. Rev. C* **91**, 064002 (2015).
- [16] Y. Dong, P. Shen, F. Huang, and Z. Zhang, Study of $d^*(2380)$ resonance in a chiral constituent quark model, *Int. J. Mod. Phys. A* **33**, 1830031 (2018).
- [17] Y. Dong, P. Shen, F. Huang, and Z. Zhang, The properties of $d^*(2380)$ in a hexaquark scenario, *J. Phys. Soc. Jpn. Conf. Proc.* **26**, 022016 (2019).
- [18] H. X. Chen, E. L. Cui, W. Chen, T. G. Steele, and S. L. Zhu, QCD sum rule study of the $d^*(2380)$, *Phys. Rev. C* **91**, 025204 (2015).
- [19] F. Huang, Y. B. Dong, P. N. Shen, and Z. Y. Zhang, Understanding $d^*(2380)$ in a chiral quark model, *EPJ Web Conf.* **199**, 02017 (2019).
- [20] M. Bashkanov, G. Clash, M. Mocu, M. Nicol, and D. P. Watts, Decay properties of the $d^*(2380)$ hexaquark multiplet, [arXiv:2012.11449](https://arxiv.org/abs/2012.11449).
- [21] H. Kim, K. S. Kim, and M. Oka, Hexaquark picture for $d^*(2380)$, *Phys. Rev. D* **102**, 074023 (2020).
- [22] M. O. Celi, M. Bashkanov, M. Mariani, M. G. Orsaria, A. Pastore, I. F. Ranea-Sandoval, and F. Weber, Destabilization of high-mass neutron stars by the emergence of d^* -hexaquarks, *Phys. Rev. D* **109**, 023004 (2024).
- [23] M. O. Celi, M. Mariani, R. Kumar, M. Bashkanov, M. G. Orsaria, A. Pastore, I. F. Ranea-Sandoval, and V. Dexheimer, Exploring the role of d^* hexaquarks on quark deconfinement and hybrid stars, *Phys. Rev. D* **112**, 023027 (2025).
- [24] M. Shahrabaf, D. Blaschke, S. Typel, G. R. Farrar, and D. E. Alvarez-Castillo, Sexaquark dilemma in neutron stars and its solution by quark deconfinement, *Phys. Rev. D* **105**, 103005 (2022).
- [25] G. R. Farrar and G. Zaharijas, Nuclear and nucleon transitions of the H dibaryon, *Phys. Rev. D* **70**, 014008 (2004).
- [26] G. R. Farrar, Stable sexaquark, [arXiv:1708.08951](https://arxiv.org/abs/1708.08951).
- [27] G. R. Farrar, A precision test of the nature of dark matter and a probe of the QCD phase transition, [arXiv:1805.03723](https://arxiv.org/abs/1805.03723).
- [28] A. Halprin and A. K. Kerman, Lepton bags, *Phys. Rev. D* **26**, 2532 (1982).
- [29] S. A. Yost and C. R. Nappi, The mass of the H dibaryon in a chiral model, *Phys. Rev. D* **32**, 816 (1985).
- [30] M. Oka, K. Shimizu, and K. Yazaki, Hyperon—nucleon and hyperon-hyperon interaction in a quark model, *Nucl. Phys. A* **464**, 700 (1987).
- [31] U. Straub, Z. Y. Zhang, K. Brauer, A. Faessler, and S. B. Khadkikar, Binding energy of the dihyperon in the quark cluster model, *Phys. Lett. B* **200**, 241 (1988).
- [32] Y. Koike, K. Shimizu, and K. Yazaki, Study of hyperon—nucleon and hyperon-hyperon interaction in the flipflop model, *Nucl. Phys. A* **513**, 653 (1990).
- [33] N. Kodama, M. Oka, and T. Hatsuda, H dibaryon in the QCD sum rule, *Nucl. Phys. A* **580**, 445 (1994).
- [34] A. S. Khrykin, V. F. Boreiko, Y. G. Budyashov, S. B. Gerasimov, N. V. Khomutov, Y. G. Sobolev, and V. P. Zorin, Search for NN decoupled dibaryons using the process $p\bar{p}\gamma\gamma X$ below the pion production threshold, *Phys. Rev. C* **64**, 034002 (2001).
- [35] M. Bashkanov, C. Bargholtz, M. Berlowski, D. Bogoslawsky, H. Calen, H. Clement, L. Demiroers, E. Doroshkevich, D. Duniec, C. Ekstrom *et al.*, Double-pionic fusion of nuclear systems and the ABC effect: Approaching a puzzle by exclusive and kinematically complete measurements, *Phys. Rev. Lett.* **102**, 052301 (2009).
- [36] J. Vijande, A. Valcarce, and J. M. Richard, Stability of hexaquarks in the string limit of confinement, *Phys. Rev. D* **85**, 014019 (2012).
- [37] S. R. Beane *et al.* (NPLQCD Collaboration), Evidence for a bound H-dibaryon from lattice QCD, *Phys. Rev. Lett.* **106**, 162001 (2011).
- [38] S. R. Beane *et al.* (NPLQCD Collaboration), The deuteron and exotic two-body bound states from lattice QCD, *Phys. Rev. D* **85**, 054511 (2012).
- [39] N. Ishii, S. Aoki, and T. Hatsuda, The nuclear force from lattice QCD, *Phys. Rev. Lett.* **99**, 022001 (2007).
- [40] T. Inoue (HAL QCD Collaboration), Bound H-dibaryon from full QCD simulations on the lattice, *Proc. Sci. LATTICE2011* (2011) 124 [[arXiv:1111.5098](https://arxiv.org/abs/1111.5098)].
- [41] J. Haidenbauer and U. G. Meissner, Exotic bound states of two baryons in light of chiral effective field theory, *Nucl. Phys. A* **881**, 44 (2012).
- [42] F. Etminan, H. Nemura, S. Aoki, T. Doi, T. Hatsuda, Y. Ikeda, T. Inoue, N. Ishii, K. Murano, and K. Sasaki (HAL QCD Collaboration), Spin-2 $N\Omega$ dibaryon from lattice QCD, *Nucl. Phys. A* **928**, 89 (2014).
- [43] S. Gongyo, K. Sasaki, S. Aoki, T. Doi, T. Hatsuda, Y. Ikeda, T. Inoue, T. Iritani, N. Ishii, T. Miyamoto *et al.*, Most strange dibaryon from lattice QCD, *Phys. Rev. Lett.* **120**, 212001 (2018).
- [44] K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, Y. Kamiya, and A. Ohnishi, Probing $\Omega\Omega$ and $p\Omega$ dibaryons with femtoscopic correlations in relativistic heavy-ion collisions, *Phys. Rev. C* **101**, 015201 (2020).
- [45] X. H. Chen, Q. N. Wang, W. Chen, and H. X. Chen, Exotic $\Omega\Omega$ dibaryon states in a molecular picture, *Chin. Phys. C* **45**, 041002 (2021).
- [46] J. Pu, K. J. Sun, C. W. Ma, and L. W. Chen, Probing the internal structures of $p\Omega$ and $\Omega\Omega$ with their production at the Large Hadron Collider, *Phys. Rev. C* **110**, 024908 (2024).
- [47] P. M. Junnarkar and N. Mathur, Spectrum of two-flavored spin-zero heavy dibaryons in lattice QCD, *Phys. Rev. D* **111**, 1 (2025).
- [48] K. Sasaki *et al.* (HAL QCD Collaboration), $\Lambda\Lambda$ and $N\Xi$ interactions from lattice QCD near the physical point, *Nucl. Phys. A* **998**, 121737 (2020).

- [49] K. Morita, A. Ohnishi, F. Etminan, and T. Hatsuda, Probing multistrange dibaryons with proton-omega correlations in high-energy heavy ion collisions, *Phys. Rev. C* **94**, 031901 (2016); **100**, 069902(E) (2019).
- [50] J. Haidenbauer, S. Petschauer, N. Kaiser, U. G. Meißner, and W. Weise, Scattering of decuplet baryons in chiral effective field theory, *Eur. Phys. J. C* **77**, 760 (2017).
- [51] H. Garcilazo and A. Valcarce, Ωd bound state, *Phys. Rev. C* **98**, 024002 (2018).
- [52] T. Iritani *et al.* (HAL QCD Collaboration), $N\Omega$ dibaryon from lattice QCD near the physical point, *Phys. Lett. B* **792**, 284 (2019).
- [53] X. H. Chen, Q. N. Wang, W. Chen, and H. X. Chen, Mass spectra of $N\Omega$ dibaryons in the 3S_1 and 5S_2 channels, *Phys. Rev. D* **103**, 094011 (2021).
- [54] B. D. Wan, L. Tang, and C. F. Qiao, Hidden-bottom and -charm hexaquark states in QCD sum rules, *Eur. Phys. J. C* **80**, 121 (2020).
- [55] B. Wang, K. Chen, L. Meng, and S. L. Zhu, Spectrum of molecular hexaquarks, *Phys. Rev. D* **110**, 014038 (2024).
- [56] Y. Geng, L. Liu, P. Sun, J. J. Wu, H. Xing, Z. Yan, and R. Zhu, Doubly charmed H -like dibaryon $\Lambda_c\Lambda_c$ scattering from lattice QCD, *Proc. Sci. LATTICE2024* (2025) 307.
- [57] H. T. An, S. Q. Luo, and X. Liu, Doubly-charmed hexaquarks in the diquark picture, *Phys. Rev. D* **112**, 054041 (2025).
- [58] N. Lee, Z. G. Luo, X. L. Chen, and S. L. Zhu, Possible deuteron-like molecular states composed of heavy baryons, *Phys. Rev. D* **84**, 014031 (2011).
- [59] N. Shiri, N. Tazimi, and M. Monemzadeh, Bound state solutions of the Schrödinger equation for dibaryons via asymptotic iteration method, [arXiv:2305.02716](https://arxiv.org/abs/2305.02716).
- [60] Z. Shah, D. Rathaud, and A. K. Rai, Masses of dibaryonic $\Xi_c^*\Xi_c^*$ states, *Proc. Sci. HQL2023* (2024) 080.
- [61] J. M. Richard, A. Valcarce, and J. Vijande, Very heavy flavored dibaryons, *Phys. Rev. Lett.* **124**, 212001 (2020).
- [62] Y. Lyu, H. Tong, T. Sugiura, S. Aoki, T. Doi, T. Hatsuda, J. Meng, and T. Miyamoto, Optimized two-baryon operators in lattice QCD, *Phys. Rev. D* **105**, 074512 (2022).
- [63] N. Mathur, M. Padmanath, and D. Chakraborty, Strongly bound dibaryon with maximal beauty flavor from lattice QCD, *Phys. Rev. Lett.* **130**, 111901 (2023).
- [64] P. Martín-Higueras, D. R. Entem, P. G. Ortega, J. Segovia, and F. Fernández, Study of the $\Omega_{cccc}\Omega_{ccc}$ and $\Omega_{bbbb}\Omega_{bbb}$ dibaryons in a constituent quark model, *Phys. Rev. D* **111**, 054002 (2025).
- [65] K. Azizi, S. S. Agaev, and H. Sundu, The scalar hexaquark $uuddss$: A candidate to dark matter?, *J. Phys. G* **47**, 095001 (2020).
- [66] H. Huang, J. Ping, and F. Wang, Dynamical calculation of the $\Delta\Delta$ dibaryon candidates, *Phys. Rev. C* **89**, 034001 (2014).
- [67] H. Mutuk and K. Azizi, Investigation of $\Delta 0\Delta 0$ dibaryon in QCD, *Phys. Rev. D* **105**, 094021 (2022).
- [68] B. Barsbay, K. Azizi, and H. Sundu, Heavy-light hybrid mesons with different spin-parities, *Eur. Phys. J. C* **82**, 1086 (2022); **82**, 1138(E) (2022).
- [69] V. M. Belyaev and B. L. Ioffe, Determination of baryon and baryonic resonance masses from QCD sum rules. 1. Non-strange baryons, *Sov. Phys. JETP* **56**, 493 (1982).
- [70] V. M. Belyaev and B. L. Ioffe, Determination of the baryon mass and baryon resonances from the quantum-chromodynamics sum rule. Strange baryons, *Sov. Phys. JETP* **57**, 716 (1983).
- [71] H. Furstenuau, Scaling violation and fragmentation functions in e^+e^- annihilation, Report No. CERN-PPE-94-155, CERN, Geneva, 1994.
- [72] N. V. Krasnikov, A. A. Pivovarov, and N. N. Tavkhelidze, The use of finite energy sum rules for the description of the hadronic properties of QCD, *Z. Phys. C* **19**, 301 (1983).
- [73] S. Groote, J. G. Körner, and A. A. Pivovarov, $O(\alpha_s)$ corrections to the correlator of finite mass baryon currents, *Phys. Rev. D* **61**, 071501 (2000).
- [74] S. Groote, J. G. Körner, and D. Niinepuu, Perturbative $O(\alpha_s)$ corrections to the correlation functions of light tetraquark currents, *Phys. Rev. D* **90**, 054028 (2014).
- [75] F. K. Guo, C. Hanhart, U. G. Meißner, Q. Wang, Q. Zhao, and B. S. Zou, Hadronic molecules, *Rev. Mod. Phys.* **90**, 015004 (2018); **94**, 029901(E) (2022).