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Hidden charm pentaquarks and tetraquark states

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We use the method of QCD sum rules to systematically study the mass spectrum of hidden-charm pentaquarks of spin $J = \frac{1}{2}/\frac{3}{2}/\frac{5}{2}$ and with the quark content $uudc\bar{c}$. Our results suggest that the $P_c(4380)$ and $P_c(4450)$ can be identified as hidden-charm pentaquark states having $J^P = 3/2^-$ and $5/2^+$, respectively.

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1. Introduction

Since the discovery of the $X(3872)$ in 2003 [1], dozens of charmonium-like XYZ states have been reported in recent years [2]. They are good candidates of tetraquark states, consisting of two quarks and two antiquarks. Two years ago in 2015, the LHCb Collaboration observed two hidden-charm pentaquark resonances, $P_c(4380)$ and $P_c(4450)$, in the $J/\psi p$ invariant mass spectrum [3]. They are good candidates of pentaquark states, consisting of four quarks and one antiquark. All the above states are exotic candidates, which can not be easily explained in the traditional quark model. They are of particular importance to understand the low energy behaviours of Quantum Chromodynamics (QCD).

There have been extensive theoretical studies on the existence of hidden-charm pentaquark states, and various theoretical methods and models have been applied to explain the nature of the $P_c(4380)$ and $P_c(4450)$, such as meson-baryon molecular states [4, 5, 6, 7], compact pentaquark states [8, 9], and kinematical effects related to the triangle singularity [10, 11], etc. We refer interested readers to reviews [12, 13, 14, 15, 16] for detailed discussions. We have also used the method of QCD sum rules [17, 18, 19] to study the mass spectrum of hidden-charm pentaquarks having spin $J = \frac{1}{2}/\frac{3}{2}/\frac{5}{2}$ and isospin $I = \frac{1}{2}$. In this paper we briefly introduce our method and results.

2. Local Pentaquark Currents

We have systematically constructed all the local hidden-charm pentaquark interpolating currents having spin $J = \frac{1}{2}/\frac{3}{2}/\frac{5}{2}$ and the quark contents $uudc\bar{c}$ in Refs. [20, 21, 22]. We briefly summarize the results here. There are three possible color configurations, $[\bar{c}_d c_d][\varepsilon^{abc} u_a u_b d_c]$, $[\bar{c}_d u_d][\varepsilon^{abc} c_a u_b d_c]$, and $[\bar{c}_d d_d][\varepsilon^{abc} c_a u_b u_c]$, where $a \cdots d$ are color indices, u, d, and c represent the up, down and charm quarks, respectively. These three configurations, as if they are local, can be related by the Fierz transformation and the color rearrangement:

$$\delta^{de}\varepsilon^{abc} = \delta^{da}\varepsilon^{ebc} + \delta^{db}\varepsilon^{aec} + \delta^{dc}\varepsilon^{abe} . \tag{2.1}$$

The first configuration, $[\bar{c}_d c_d][\varepsilon^{abc} u_a u_b d_c]$, can be easily constructed based on our studies on the internal structure of three-quark baryons [23]. However, the sum rules obtained using these currents are not useful. Considering that the $P_c(4380)$ and $P_c(4450)$ have masses significantly larger than the threshold of J/ψ and proton, but close to thresholds of D/D^* and $\Lambda_c/\Sigma_c/\Sigma_c^*$, we also construct currents belonging to the other two configurations, $[\bar{c}_d u_d][\varepsilon^{abc} c_a u_b d_c]$ and $[\bar{c}_d d_d][\varepsilon^{abc} c_a u_b u_c]$. Especially, we find the following two mixing currents:

$$\begin{aligned} J_{\mu,3/2-} &= \cos\theta_1 \times \xi_{36\mu} + \sin\theta_1 \times \psi_{9\mu} \qquad (2.2) \\ &= \cos\theta_1 \times [\varepsilon^{abc}(u_a^T C\gamma_\nu\gamma_5 d_b)\gamma_\nu\gamma_5 c_c][\bar{c}_d\gamma_\mu\gamma_5 u_d] \\ &\quad + \sin\theta_1 \times [\varepsilon^{abc}(u_a^T C\gamma_\nu u_b)\gamma_\nu\gamma_5 c_c][\bar{c}_d\gamma_\mu d_d] , \\ J_{\mu\nu,5/2+} &= \cos\theta_2 \times \xi_{15\mu\nu} + \sin\theta_2 \times \psi_{4\mu\nu} \qquad (2.3) \\ &= \cos\theta_2 \times [\varepsilon^{abc}(u_a^T C\gamma_\mu\gamma_5 d_b) c_c][\bar{c}_d\gamma_\nu u_d] \\ &\quad + \sin\theta_2 \times [\varepsilon^{abc}(u_a^T C\gamma_\mu u_b) c_c][\bar{c}_d\gamma_\nu\gamma_5 d_d] + \{\mu \leftrightarrow \nu\} . \end{aligned}$$

Their sum rules can be used to well interpret the $P_c(4380)$ and $P_c(4450)$ as hidden-charm pentaquark states having $J^P = 3/2^-$ and $5/2^+$, respectively.

3. QCD sum rules analyses

In this section we use $J_{\mu,3/2-}$ and $J_{\mu\nu,5/2+}$ to perform QCD sum rule analyses. Again, we briefly introduce our method here, but refer to Refs. [20, 21, 22] for details. Firstly, we assume $J_{\mu,3/2-}$ and $J_{\mu\nu,5/2+}$ couple to physical states through

$$\langle 0|J_{\mu,3/2-}|X_{3/2-}\rangle = f_{X_{3/2-}} u_\mu(p)\,, \tag{3.1}$$

$$\langle 0|J_{\mu\nu,5/2+}|X_{5/2+}\rangle = f_{X_{5/2+}} u_{\mu\nu}(p)\,. \tag{3.2}$$

Their relevant two-point correlation functions can be written as

$$\begin{aligned}\Pi_{\mu\nu,3/2-}\left(q^2\right) &= i\int d^4x e^{iq\cdot x}\langle 0|T\left[J_{\mu,3/2-}(x)\bar{J}_{\nu,3/2-}(0)\right]|0\rangle \\ &= \left(\frac{q_\mu q_\nu}{q^2}-g_{\mu\nu}\right)(\not{q}+M_{X_{3/2-}})\Pi_{3/2-}\left(q^2\right)+\cdots\,,\end{aligned} \tag{3.3}$$

$$\begin{aligned}\Pi_{\mu\nu\rho\sigma,5/2+}\left(q^2\right) &= i\int d^4x e^{iq\cdot x}\langle 0|T\left[J_{\mu\nu,5/2+}(x)\bar{J}_{\rho\sigma,5/2+}(0)\right]|0\rangle \\ &= \left(g_{\mu\rho}g_{\nu\sigma}+g_{\mu\sigma}g_{\nu\rho}\right)(\not{q}+M_{X_{5/2+}})\Pi_{5/2+}\left(q^2\right)+\cdots\,,\end{aligned} \tag{3.4}$$

where $\cdots$ contains non-relevant spin components.

At the hadron level, we can use the dispersion relation to rewrite them as

$$\Pi(q^2)=\frac{1}{\pi}\int_{s_<}^{\infty}\frac{\mathrm{Im}\Pi(s)}{s-q^2-i\varepsilon}ds\,, \tag{3.5}$$

where $s_<$ is the physical threshold. We can evaluate its imaginary part by inserting intermediate hadron states $\sum_n |n\rangle\langle n|$, but adopting the usual parametrization of one-pole dominance for the ground state X together with a continuum contribution:

$$\begin{aligned}\rho(s)\equiv\frac{1}{\pi}\mathrm{Im}\Pi(s) &= \sum_n \delta(s-M_n^2)\langle 0|J|n\rangle\langle n|\bar{J}|0\rangle \\ &= f_X^2\delta(s-m_X^2)+\text{continuum}\,.\end{aligned} \tag{3.6}$$

At the quark and gluon level, we can calculate the two-point correlation functions (3.3–3.4) using the method of operator product expansion (OPE). After performing the Borel transform at both the hadron and quark-gluon levels, we can express the two-point correlation function as

$$\Pi^{(all)}(M_B^2)\equiv\mathscr{B}_{M_B^2}\Pi(p^2)=\int_{s_<}^{\infty}e^{-s/M_B^2}\rho(s)ds\,. \tag{3.7}$$

After assuming that the continuum contribution can be well approximated by the OPE spectral density above a threshold value s_0, we obtain the following sum rule relation

$$M_X^2(s_0,M_B) = \frac{\int_{s_<}^{s_0}e^{-s/M_B^2}\rho(s)sds}{\int_{s_<}^{s_0}e^{-s/M_B^2}\rho(s)ds}\,. \tag{3.8}$$

We use the mixing current $J_{\mu,3/2-}$ defined in Eq. (2.2) to perform sum rule analyses. The detailed sum rule expression has been give in Ref. [22]. We find that the terms proportional to $\mathbf{1}\times g_{\mu\nu}$ are almost the same as those proportional to $\not{q}\times g_{\mu\nu}$, suggesting that the state coupled by $J_{\mu,3/2-}$ has the spin-parity $J^P=3/2^-$ [24]. Similarly, we use $J_{\mu\nu,5/2+}$ defined in Eq. (2.3) to perform sum rule analyses. These two sum rules will be used to perform numerical analyses in the next section.

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4. Numerical Analyses

In this section we use $J_{\mu,3/2-}$ and $J_{\mu\nu,5/2+}$ to perform numerical analyses. Various condensates inside their sum rules take the following values [2, 25, 26, 27, 28, 29, 30, 31]:

$$\begin{aligned} \langle\bar{q}q\rangle &= -(0.24\pm0.01)^3 \text{ GeV}^3 \,, \\ \langle g_s^2 GG\rangle &= (0.48\pm0.14) \text{ GeV}^4 \,, \\ \langle g_s\bar{q}\sigma Gq\rangle &= M_0^2 \times \langle\bar{q}q\rangle \,, \\ M_0^2 &= -0.8 \text{ GeV}^2 \,. \\ m_c &= 1.275\pm0.025 \text{ GeV} \,. \end{aligned} \tag{4.1}$$

There are altogether three free parameters: the mixing angles $\theta_{1/2}$, the Borel mass M_B, and the threshold value s_0. We use the following three criteria to constrain them:

1. To insure the convergence of the OPE series, we require the dimension eight to be less than 10%, which can be used to determine the lower limit of the Borel mass:

$$\text{CVG} \equiv \left| \frac{\Pi_{\langle\bar{q}q\rangle\langle g_s\bar{q}\sigma Gq\rangle}(\infty, M_B)}{\Pi(\infty, M_B)} \right| \leq 10\% \,. \tag{4.2}$$

2. To insure the one-pole parametrization to be valid, we require the pole contribution (PC) to be larger than or around 30%, which can be used to determine the upper limit of the Borel mass:

$$\text{PC}(s_0, M_B) \equiv \frac{\Pi(s_0, M_B)}{\Pi(\infty, M_B)} \gtrsim 30\% \,. \tag{4.3}$$

3. To obtain reliable mass predictions, we require that the s_0, M_B and $\theta_{1/2}$ dependence of the mass prediction be the weakest.

We use the sum rules for the current $J_{\mu,3/2-}$ as an example. Firstly, we fix $\theta_1 = -42^\circ$ and $s_0 = 23$ GeV^2, and find that: a) the OPE convergence improves with the increase of M_B, and the first criterion requires that $M_B^2 \geq 2.89$ GeV^2, and b) the PC decreases with the increase of M_B, and PC = 32% when $M_B^2 = 2.89$ GeV^2. Accordingly, we fix the Borel mass to be $M_B^2 = 2.89$ GeV^2 and choose 2.59 GeV$^2 < M_B^2 < 3.19$ GeV^2 as our working region. We show variations of M_X with respect to M_B in the left panel of Fig. 1, and find that the mass curves are quite stable inside this region.

To determine s_0, we show variations of M_X with respect to s_0 in the middle panel of Fig. 1 when fixing $\theta_1 = -42^\circ$. The s_0 dependence of the mass prediction is the weakest when s_0 is around 17 GeV^2, but the pole contribution at this point is too small (just 8%). We find that PC = 32% at $s_0 = 23$ GeV^2, where the M_B dependence is the weakest. Accordingly, we fix the threshold value to be $s_0 = 23$ GeV^2 and choose 21 GeV$^2 \leq s_0 \leq 25$ GeV^2 as our working region.

Finally, we change θ_1 and redo the above processes. We show variations of M_X with respect to θ_1 in the right panel of Fig. 1 when fixing $s_0 = 23$ GeV^2 and choosing M_B to satisfy the first criterion. We find that the θ_1 dependence of the mass prediction is weak when $\theta_1 \leq -40^\circ$. Accordingly, we fix the mixing angle θ_1 to be -42° and choose $\theta_1 = -42 \pm 5^\circ$ as our working region.

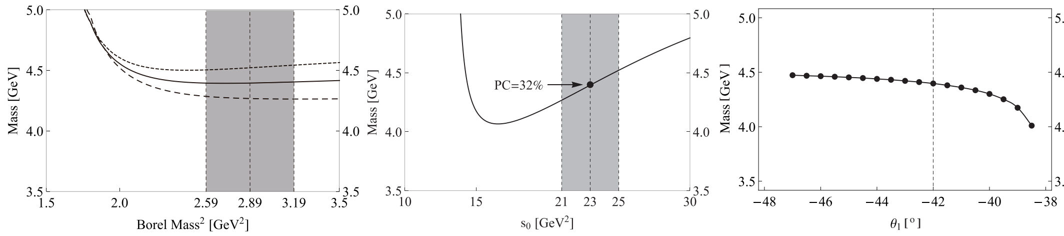

Figure 1: Variations of $M_{3/2^-}$ with respect to the Borel mass M_B (left), the threshold value s_0 (middle) and the mixing angle θ_1 (right), calculated using the current $J_{\mu,3/2-}$ of $J^P = 3/2^-$.

Altogether, the working regions are found to be 21 GeV$^2 \leq s_0 \leq 25$ GeV^2, 2.59 GeV$^2 < M_B^2 <$ 3.19 GeV^2, and $-47^\circ < \theta_1 < -37^\circ$, where we obtain the following numerical results:

$$\begin{aligned} M_{3/2^-} &= 4.40^{+0.17}_{-0.22}\ \text{GeV}\,, \\ f_{3/2^-} &= (6.5^{+3.2}_{-2.9}) \times 10^{-4}\ \text{GeV}^6\,. \end{aligned} \tag{4.4}$$

Here the mass uncertainty is due to the mixing angle θ_1, the Borel mass M_B, the threshold value s_0, the charm quark mass m_c, and various condensates. This mass value is consistent with the experimental mass of the $P_c(4380)$, and supports it to be a hidden-charm pentaquark having $J^P = 3/2^-$.

Similarly, we use the current $J_{\mu\nu,5/2+}$ of $J^P = 5/2^+$ to perform numerical analyses, and obtain the following numerical results:

$$\begin{aligned} M_{5/2^+} &= 4.50^{+0.26}_{-0.24}\ \text{GeV}\,, \\ f_{5/2^+} &= (5.5^{+3.4}_{-2.4}) \times 10^{-4}\ \text{GeV}^6\,, \end{aligned} \tag{4.5}$$

This mass value is consistent with the experimental mass of the $P_c(4450)$, and supports it to be a hidden-charm pentaquark having $J^P = 5/2^+$.

5. Summary and discussions

In this paper we use the method of QCD sum rules to study the hidden-charm pentaquark states $P_c(4380)$ and $P_c(4450)$. After systematically constructing all the local hidden-charm pentaquark interpolating currents of spin $J = \frac{1}{2}/\frac{3}{2}/\frac{5}{2}$ and with the quark contents $uudc\bar{c}$, we find two mixing currents, $J_{\mu,3/2-}$ of $J^P = 3/2^-$ and $J_{\mu\nu,5/2+}$ of $J^P = 5/2^+$. We use them to perform QCD sum rule analyses and obtain

$$\begin{aligned} M_{3/2^-} &= 4.40^{+0.16}_{-0.23}\ \text{GeV}\,, \\ M_{5/2^+} &= 4.50^{+0.26}_{-0.23}\ \text{GeV}\,. \end{aligned}$$

These values are consistent with the experimental masses of the $P_c(4380)$ and $P_c(4450)$, suggesting that the $P_c(4380)$ and $P_c(4450)$ can be well interpreted as hidden-charm pentaquark states having $J^P = 3/2^-$ and $5/2^+$, respectively.

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We have also investigated their bottom partners, the hidden-bottom pentaquark states ($b\bar{b}uud$) of $J^P = 3/2^-$ and $J^P = 5/2^+$. We use the method of QCD sum rules to evaluate their masses to be

$$
\begin{aligned}
M_{P_b(3/2^-)} &= 10.83^{+0.26}_{-0.29}\ \text{GeV}\,, \\
M_{P_b(5/2^+)} &= 10.85^{+0.24}_{-0.27}\ \text{GeV}\,,
\end{aligned} \tag{5.1}
$$

and propose to search for them in future LHCb and BelleII experiments.

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