Possibility of $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$ as S -wave $D^{(*)}N$ molecular states

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In this talk, we give a brief review of our work studying the possibility of $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$ as S -wave $D^{(*)}N$ molecular states from QCD sum rules.

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1. Introduction

In 2005, Belle Collaboration observed an isotriplet of new states $\Sigma_c(2800)$,¹ the neutral one of which was confirmed by Babar Collaboration.² Moreover, Babar collaboration reported the observation of $\Lambda_c(2940)^+$,³ which was confirmed by Belle Collaboration.⁴

There have appeared two different ways to understand the inner structures of $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$. From a potential model prediction, their masses are close to theoretical values of Σ_c^* with $J^P = \frac{3}{2}^-$ or $\frac{5}{2}^-$ and Λ_c^* with $J^P = \frac{5}{2}^-$ or $\frac{3}{2}^+$, respectively.⁵ One way of studies grounds on the assignments of them as conventional charmed baryons.^{6–12} Another way bases on the assumption that they are some molecular candidates.^{13–19} In particular, Ortega *et al.* studied $\Lambda_c(2940)^+$ as a D^*N molecule with $J^P = \frac{3}{2}^-$ in a constituent quark model, and claimed obtaining a mass which agrees with the experimental data.²⁰

To investigate the possibility of $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$ as the S -wave DN state with $J^P = \frac{1}{2}^-$ and the S -wave D^*N state with $J^P = \frac{3}{2}^-$ respectively, we devoted to study them in Ref. 21 employing the method of QCD sum rules²² (for

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reviews see Ref. 23–27 and references therein; Particularly, many theorists began to study light pentaquark states in Refs. 28, 29 and heavy ones in Ref. 30).

2. $D^{(*)}N$ Molecular States in QCD Sum Rules

The basic point of QCD sum rules is to construct a proper interpolating current to represent the studied state. At present, molecular currents are built up with the color-singlet currents of composed hadrons to form hadron-hadron configurations of fields. One could find meson currents in Ref. 31 and nucleon ones in Ref. 32. Therefore, we build following forms of currents:

$$j = (\bar{q}^{c'} i\gamma_5 Q^{c'}) (\varepsilon_{abc} q_1^T C \gamma_\mu q_2^b \gamma_5 \gamma^\mu q_3^c), \quad (1)$$

for the S -wave DN or $\bar{B}N$ molecular state with $J^P = \frac{1}{2}^-$, and

$$j^\rho = (\bar{q}^{c'} \gamma^\rho Q^{c'}) (\varepsilon_{abc} q_1^T C \gamma_\mu q_2^b \gamma_5 \gamma^\mu q_3^c), \quad (2)$$

for the S -wave D^*N or $\bar{B}^*N$ molecular state with $J^P = \frac{3}{2}^-$. Here Q is heavy quark c or b , and q_1, q_2 , and q_3 denote light quarks u and/or d . The index T means matrix transposition, C is the charge conjugation matrix, with a, b, c and c' as color indices.

We derive QCD sum rules for molecular states with similar techniques as our previous works on heavy baryons³³ and molecular states.³⁴ Ultimately, one can gain mass sum rules²¹

$$M_H^2 = \frac{\int_{m_Q^2}^{s_0} ds \rho_1(s) s e^{-s/M^2} + d/d(-\frac{1}{M^2}) \hat{B} \Pi_1^{\text{cond}}}{\int_{m_Q^2}^{s_0} ds \rho_1(s) e^{-s/M^2} + \hat{B} \Pi_1^{\text{cond}}}, \quad (3)$$

where M_H is the mass of the hadronic resonance, s_0 is the threshold parameter, and M^2 indicates the Borel parameter. The spectral density $\rho_1(s)$ is given by the correlator's imaginary part. In its calculation, one works at leading order in α_s and considers condensates up to dimension 12. To keep the heavy-quark mass finite, one can use the momentum-space expression for the heavy-quark propagator.³¹ The light-quark part of the correlator can be calculated in the coordinate space employing the light-quark propagator, which is then Fourier-transformed to the momentum space in D dimension. The resulting light-quark part is combined with the heavy-quark part before it is dimensionally regularized at $D = 4$.

3. Numerical Results

Numerically, one could take input parameters as $m_c = 1.23 \pm 0.05$ GeV, $m_b = 4.24 \pm 0.06$ GeV, $\langle \bar{q}q \rangle = -(0.23 \pm 0.03)^3$ GeV³, $\langle g\bar{q}\sigma \cdot Gq \rangle = m_0^2 \langle \bar{q}q \rangle$, $m_0^2 = 0.8 \pm 0.1$ GeV², $\langle g^2 G^2 \rangle = 0.88$ GeV⁴, and $\langle g^3 G^3 \rangle = 0.045$ GeV⁶.²⁴ For the present case, it may have some difficulty to find a standard work window critically satisfying all the conventional rules, which has been discussed in detail for some other cases.^{35–38} By releasing the rigid OPE convergence criterion, one could choose some transition range as a compromise Borel window and arrive at $3.75 \pm 0.14 \pm 0.08$ GeV for the

S -wave DN state with $J^P = \frac{1}{2}^-$. To investigate the effect of different factorization of $\langle q\bar{q}q\bar{q} \rangle = \kappa \langle \bar{q}q \rangle \langle \bar{q}q \rangle$, we average three results for $\kappa = 1 \sim 3$ and arrive at the mass value 3.64 ± 0.33 GeV concisely for the S -wave DN state with $J^P = \frac{1}{2}^-$, which is somewhat higher than the experimental value of $\Sigma_c(2800)$ even considering the result's uncertainty. For the S -wave $\bar{B}N$ state with $J^P = \frac{1}{2}^-$, one can obtain the mass value 6.97 ± 0.34 GeV. Similarly, the final result is 3.73 ± 0.35 GeV for the S -wave D^*N state with $J^P = \frac{3}{2}^-$, which is greater than the experimental data of $\Lambda_c(2940)^+$ even taking into account the uncertainty. Therefore, it does not support the statement that $\Lambda_c(2940)^+$ could be the S -wave D^*N molecule with $J^P = \frac{3}{2}^-$. For the mass of S -wave $\bar{B}^*N$ state with $J^P = \frac{3}{2}^-$, one could gain 6.98 ± 0.34 GeV.

4. Summary

In summary, we have studied the possibility of $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$ as S -wave $D^{(*)}N$ states using QCD sum rules in Ref. 21. The final results are respectively greater than the experimental data of $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$, which could not support the statements that $\Sigma_c(2800)$ be the S -wave DN molecule with $J^P = \frac{1}{2}^-$ and $\Lambda_c(2940)^+$ be the S -wave D^*N molecule with $J^P = \frac{3}{2}^-$, respectively.

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