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Covalent hadronic molecules from QCD sum rules

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We examine Feynman diagrams corresponding to the $\bar{D}\Sigma_c$ hadronic molecular state, and propose a possible binding mechanism induced by shared light quarks. We study it using the method of QCD sum rules, and our results indicate this interaction to be attractive as long as the shared light quarks are totally antisymmetric.

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[*] Speaker

1. Introduction

Since the discovery of the $X(3872)$ in 2003 by the Belle Collaboration [1], many charmonium-like XYZ and hidden-charm P_c/P_{cs} states were discovered in the past two decades [2]. They are good candidates of tetraquark and pentaquark states, and their experimental and theoretical studies are significantly improving our understanding of Quantum Chromodynamics (QCD) at the low energy region [3–12]. Some of them can be interpreted as hadronic molecular states consisting of two conventional hadrons [13–15]. For example, the P_c states [16] are explained as $\bar{D}^{(*)}\Sigma_c^{(*)}$ hadronic molecular states in Refs. [17–22] bound by the one-meson-exchange interaction.

In this paper we propose another possible Feynman diagram between $\bar{D}$ and Σ_c induced by the light-quark-exchange interaction [23], as depicted in the left panel of Fig. 1. This diagram indicates that $\bar{D}$ and Σ_c are exchanging two light up/down quarks, which can induce some interaction between them, as depicted in the right panel of Fig. 1. Note that the two interactions, the one-meson-exchange interaction at the hadron level and the light-quark-exchange interaction at the quark-gluon level, can overlap with each other.

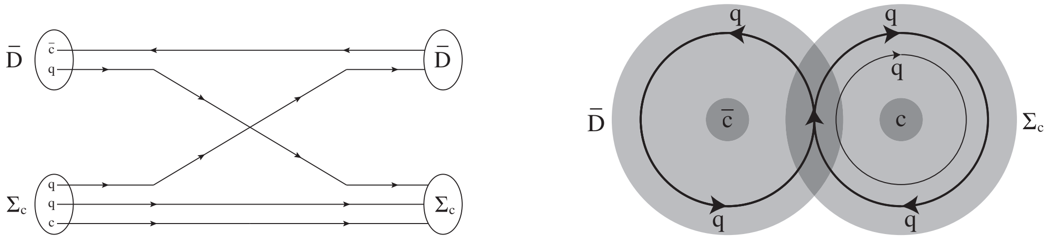

Figure 1: In the left panel we show the Feynman diagram between $\bar{D}$ and Σ_c corresponding to the light-quark-exchange interaction. In the right panel we show the possible binding mechanism induced by this interaction. Here q denotes a light up/down quark.

In this paper we shall systematically examine Feynman diagrams corresponding to the $\bar{D}\Sigma_c$ hadronic molecular state. We shall apply the method of QCD sum rules to investigate the light-quark-exchange interaction, and further propose a model-independent hypothesis: "*the light-quark-exchange interaction is attractive when the shared light quarks are totally antisymmetric*".

2. Correlation function of the $\bar{D}\Sigma_c$ hadronic molecule

In this section we investigate correlation functions of the $D^-\Sigma_c^{++}$, $\bar{D}^0\Sigma_c^+$, and $I = 1/2$ $\bar{D}\Sigma_c$ hadronic molecular states. Their corresponding interpolating currents are

$$\begin{aligned}
J^{D^-\Sigma_c^{++}}(x) &= [\bar{c}_d(x)\gamma_5 d_d(x)] \times \frac{1}{\sqrt{2}}[\epsilon^{abc} u_a^T(x)\mathbb{C}\gamma^\mu u_b(x)\gamma_\mu\gamma_5 c_c(x)]\,, \\
J^{\bar{D}^0\Sigma_c^{+}}(x) &= [\bar{c}_d(x)\gamma_5 u_d(x)] \times [\epsilon^{abc} u_a^T(x)\mathbb{C}\gamma^\mu d_b(x)\gamma_\mu\gamma_5 c_c(x)]\,, \\
J^{\bar{D}\Sigma_c}_{I=1/2}(x) &= \sqrt{\frac{1}{3}}J^{\bar{D}^0\Sigma_c^{+}}(x) - \sqrt{\frac{2}{3}}J^{D^-\Sigma_c^{++}}(x)\,.
\end{aligned} \tag{1}$$

Their correlation functions in the coordinate space can be separated into:

$$\begin{aligned}
\Pi^{D^-\Sigma_c^{++}}(x) &= \Pi_0^{\bar{D}\Sigma_c}(x) + \Pi_G^{\bar{D}\Sigma_c}(x)\,, \\
\Pi^{\bar{D}^0\Sigma_c^{+}}(x) &= \Pi_0^{\bar{D}\Sigma_c}(x) + \Pi_G^{\bar{D}\Sigma_c}(x) - \Pi_Q^{\bar{D}\Sigma_c}(x)\,, \\
\Pi_{I=1/2}^{\bar{D}\Sigma_c}(x) &= \Pi_0^{\bar{D}\Sigma_c}(x) + \Pi_G^{\bar{D}\Sigma_c}(x) + \Pi_Q^{\bar{D}\Sigma_c}(x)\,,
\end{aligned} \tag{2}$$

where $\Pi_0^{\bar{D}\Sigma_c}(x) = \Pi^{\bar{D}}(x) \times \Pi^{\Sigma_c}(x)$ is the leading term contributed by non-correlated $\bar{D}$ and Σ_c; $\Pi_G^{\bar{D}\Sigma_c}(x)$ describes the double-gluon-exchange interaction between $\bar{D}$ and Σ_c, which is not taken into account in the present study; $\Pi_Q^{\bar{D}\Sigma_c}(x)$ describes the light-quark-exchange interaction between $\bar{D}$ and Σ_c.

3. QCD sum rule study of the $\bar{D}\Sigma_c$ hadronic molecule

In this section we apply the method of QCD sum rules to investigate the light-quark-exchange interaction $\Pi_Q(x)$, and study its contributions to the $D^-\Sigma_c^{++}$, $\bar{D}^0\Sigma_c^{+}$, and $I = 1/2$ $\bar{D}\Sigma_c$ hadronic molecular states.

Given $X \equiv |\bar{D}\Sigma_c\rangle$ to be a molecular state, its mass M_X can be expanded as

$$M_X = M_{\bar{D}} + M_{\Sigma_c} + \Delta M \equiv M_0 + \Delta M\,, \tag{3}$$

so that we can expand its correlation function at the hadron level as

$$\Pi(q^2) = \frac{f_X^2}{M_X^2 - q^2} + \cdots \approx \frac{f_X^2}{M_0^2 - q^2} - \frac{2M_0 f_X^2}{\left(M_0^2 - q^2\right)^2}\Delta M + \cdots\,. \tag{4}$$

The former is contributed by non-correlated $\bar{D}$ and Σ_c, and the latter is contributed by their interactions. After comparing Eq. (4) to Eq. (2), we perform the Borel transformation at both hadron and quark-gluon levels to obtain:

$$f_X^2 e^{-M_0^2/M_B^2} = \Pi_0(M_B^2, s_0) = \int_{s_<}^{s_0} e^{-s/M_B^2}\rho_0(s)ds\,, \tag{5}$$

$$-\frac{2M_0 f_X^2}{M_B^2}\Delta M e^{-M_0^2/M_B^2} = \Pi_Q(M_B^2, s_0) = \int_{s_<}^{s_0} e^{-s/M_B^2}\rho_Q(s)ds\,, \tag{6}$$

which can be used to further derive

$$-\frac{2M_0}{M_B^2}\Delta M = \frac{\Pi_Q(M_B^2, s_0)}{\Pi_0(M_B^2, s_0)} = \frac{\int_{s_<}^{s_0} e^{-s/M_B^2}\rho_Q(s)ds}{\int_{s_<}^{s_0} e^{-s/M_B^2}\rho_0(s)ds}\,. \tag{7}$$

4. Discussions on the parameter ΔM

The parameter ΔM is actually not the binding energy, because we are using local currents in QCD sum rule analyses. We can relate it to some potential $V(r)$ between $\bar{D}$ and Σ_c, satisfying $V(r = 0) = \Delta M$ and $V(r \to \infty) \to 0$. We systematically investigate the light-quark-exchange interaction $\Pi_Q(x)$, and study its contributions to the $D^-\Sigma_c^{++}$, $\bar{D}^0\Sigma_c^+$, and $I = 1/2$ $\bar{D}\Sigma_c$ hadronic molecular states. Their mass corrections are evaluated to be:

$$\begin{aligned} \Delta M^{D^-\Sigma_c^{++}} &= 0\,, \\ \Delta M^{\bar{D}^0\Sigma_c^+} &= 95\text{ MeV}\,, \\ \Delta M^{\bar{D}\Sigma_c}_{I=1/2} &= -95\text{ MeV}\,. \end{aligned} \tag{8}$$

Accordingly, our results suggest that there can be the $\bar{D}\Sigma_c$ covalent molecule of $I = 1/2$. Its binding mechanism induced by shared light quarks is similar to the covalent bond in the chemical molecule induced by shared electrons, so we call such hadronic molecule the "covalent hadronic molecule".

Recalling that the two shared electrons must spin in opposite directions when forming a chemical covalent bond, our QCD sum rule results indicate a similar hypothesis: "*the light-quark-exchange interaction is attractive when the shared light quarks are totally antisymmetric*".

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