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NDD^* three-body molecular states

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We start from the assumption that the $\Lambda_c(2940)$ and $\Lambda_c(2910)$ correspond mostly to D^*N bound states with $J^P = 1/2^-$ and $3/2^-$, respectively. Then, adding a D meson as a third particle, and assuming that the DN and DD^* interactions are mainly dominated by the $\Lambda_c(2765)$ and $T_{cc}(3875)$ resonances, we look for the possible binding of the D^*DN three body system within the framework of the Fixed Center Approximation. We find one state for each spin channel with a binding of about 60 MeV with respect to the $\Lambda_c(2940)D$ and $\Lambda_c(2910)D$ thresholds and a width of about 90 MeV. As an alternative picture we also study the system as a cluster of DN and a D^* meson interacting on the cluster, and find similar results. The observation of these $J^P = 1/2^+$, $3/2^+$ states would provide new and valuable information concerning the DN and D^*N interaction, a topic of current interest.

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1. Introduction

The study of three-body bound states has been gaining significant attention recently, and in particular those systems containing one nucleon and two mesons. In Ref. [1] it was shown that the $ND\bar{D}$ system is bound, which is only natural given the strong $D\bar{D}$ interaction and the attractive nature of the DN interaction. A notable recent discovery was the observation of the T_{cc} state, first reported in Ref. [2]. This prompted investigations into whether the DND^* system could also be bound, with a study conducted in Ref. [3] using the Gaussian expansion method. This work constructs potentials for the DN, D^*N, and DD^* interactions based on the one-boson exchange model, using the Gaussian expansion method [4] to explore the binding of the DND^* system. The study finds that bound state solutions exist for $I(J^P) = 1/2(1/2^+)$ and $1/2(3/2^+)$, although the binding energies are highly sensitive to the cutoff values and other model parameters, and the widths of the states cannot be evaluated.

In the present work, we approach this problem from a different angle, employing the fixed center approximation (FCA) to the Faddeev equations as our framework. While this method is less precise in theory, it benefits from empirical input that constrains the results and simultaneously provides estimates for the widths of the states.

2. Formalism

In this section we briefly discuss the FCA formalism. We assume the presence of a D^*N cluster, corresponding to either the $\Lambda_c(2940)$ or $\Lambda_c(2910)$, with an external D meson interacting with the components of this cluster. Then, we consider all possible rescattering processes where the external D meson initially collides with the nucleon into the partition function T_1, and those where it first interacts with the D^* meson into T_2. The coupled equations for the system can then be written as:

$$\left.\begin{aligned} T_1 &= t_1 + t_1 G_0 T_2 \\ T_2 &= t_2 + t_2 G_0 T_1 \end{aligned}\right\} \quad T = T_1 + T_2, \tag{1}$$

where t_1 and t_2 are the scattering amplitudes for the interaction of D with N and D^*, respectively, and G_0 is the D propagator modulated by the wave function of the D^*N system.

$$G_0 = \int \frac{d^3q}{(2\pi)^3} F(q) \frac{1}{q^{02} - \vec{q}^{\,2} - M_D^2 + i\epsilon}. \tag{2}$$

In the previous expressions q^0 is the energy of the D in the rest frame of ND^*, and $F(q)$ is the form factor of the ND^* state which is given by

$$F\,(q) = \frac{1}{\mathcal{N}} \int_{\substack{|\vec{p}| \le q_{\max} \\ |\vec{q}-\vec{p}| \le q_{\max}}} \frac{d^3p}{(2\pi)^3} \frac{1}{M_{ND^*} - E_N(\vec{p}) - \omega_{D^*}(\vec{p})} \frac{1}{M_{ND^*} - E_N(\vec{p}-\vec{q}) - \omega_{D^*}(\vec{p}-\vec{q})}, \tag{3}$$

with M_{ND^*} the mass of the $\Lambda_c(2940)$ or the $\Lambda_c(2940)$, $E_N(\vec{p})$ and $\omega_{D^*}(\vec{p})$ the N and D^* energies, and $\mathcal{N} = F(0)$ is a normalization factor. In Eq. (3), we introduce a cutoff $q_{\max}$, which serves as the regulator for the loops to obtain the pole in the D^*N interaction, and we take it to be $q_{\max} = 600$ MeV. Additional details on the formalism can be found in Ref. [5], in particular normalization factors, as well as isospin and spin considerations.

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3. Results

In Fig. 1, we present the results for $|T|^2$ assuming that $\Lambda_c(2940)$ is a $J^P = 1/2^-$ state and $\Lambda_c(2910)$ is $3/2^-$. We find two states: one with $J^P = 1/2^+$ and another with $3/2^+$. Relative to the thresholds at 2940 MeV + M_D and 2910 MeV + M_D, these states are bound by approximately 70 and 50 MeV, respectively. The peaks in $|T|^2$ have associated widths corresponding to that of the three-body system, with the widths calculated to be around 90 MeV.

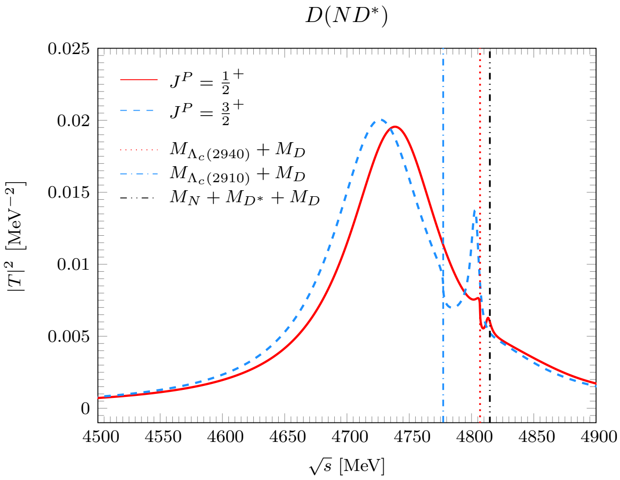

Figure 1: $|T|^2$ as a function of the total energy of the three-body system, $\sqrt{s}$, for $q_{\max} = 600$ MeV, assuming the ND^* cluster is bound into the $\Lambda_c(2940)$ and $\Lambda_c(2910)$ for spins $1/2$ and $3/2$, respectively.

Both peaks on Fig. 1 primarily reflect the structure of t_1 (the DN amplitude), while the terms involving t_2 have a minimal effect. This is expected, as t_2 is much weaker than t_1. Indeed, the $\Lambda_c(2765)$ is bound by about 40 MeV, while T_{cc} is only bound by 360 keV, indicating that the DN interaction is significantly stronger than the DD^* interaction. In this scenario, we can imagine the nucleon acting as the "glue" to which both the D and D^* particles attach.

The narrow peak observed in the $J^P = 3/2^+$ case, between the thresholds, originates from the T_{cc} amplitude. Other structures near the thresholds can be identified as threshold effects and could represent less bound states of the system. Similar structures also appear in the $D^*D^*D^*$ and could be related with the Efimov effect discussed in Ref. [6].

Table 1: Masses and width of the bound states DND^* in MeV, assuming two different configurations.

$D(ND^*)$			$D^*(ND)$		
J^P	mass [MeV]	width [MeV]	J^P	mass [MeV]	width [MeV]
$1/2^+$	4738.6	91.4	$1/2^+$	4760.6	23.9
$3/2^+$	4726.5	93.3	$3/2^+$	4706.8	98.3

As an alternative scenario, we also consider the possibility that the ND system forms the cluster, bound as $\Lambda_c(2765)$, with an external D^* interacting with it. Table 1 contains a comparison between the results assuming this new picture and the previous results shown in Fig. 1. The difference between them can be taken as an estimate for the systematic uncertainties of the FCA approach.

4. Conclusions

We have conducted a study on the possible bound states of the DND^* system, using the FCA to evaluate the three-body scattering matrix. This method requires selecting a bound two-body cluster, for which we choose the ND^* system, and then allow a third particle, the D meson, to interact with the components of the cluster. Alternatively, we consider the ND system as the cluster, with the D^* meson scattering off it. In both scenarios, we find bound states with $J^P = 1/2^+$ and $3/2^+$ near the $\Lambda_c(2765)D$ or $\Lambda_c(2765)D^*$ thresholds, showing similar qualitative results. While we lean towards the $D(ND^*)$ configuration, the variations in mass between the two scenarios can be seen as an estimate of the uncertainties in our approach. Nonetheless, we conclude that the existence of these bound states is inevitable given the reasonable assumptions made about the D^*N and DN interactions. Observing such states would provide valuable insight into these interactions, helping to clarify the nature of the DN and D^*N bound states.

Acknowledgments

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