

Narrow bound states of the DNN system

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Abstract We report on a recent calculation of the properties of the DNN system, a charmed meson with two nucleons. The system is analogous to the $\bar{K}NN$ system substituting a strange quark by a charm quark. Two different methods are used to evaluate the binding and width, the Fixed Center approximation to the Faddeev equations and a variational calculation. In both methods we find that the system is bound by about 200 MeV and the width is smaller than 40 MeV, a situation opposite to the one of the $\bar{K}NN$ system and which makes this state well suited for experimental observation.

Keywords Charm meson with nucleons · three body system · DNN

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1 Introduction

The $\bar{K}NN$ system has been the subject of much attention and recent papers converge to having bindings of about 20 MeV and large widths of about 80 MeV [1, 2, 3, 4, 5, 6]. A fraction of about 30 MeV of the width of the state of comes from absorption of the \bar{K} on the pair of nucleons, recently evaluated with precision in [7]. The large width can be intuitively understood since the $\bar{K}N$ merges into a $\Lambda(1405)$ that has a width of about 30 MeV, but since the $\Lambda(1405)$ can be formed with either nucleon, the width can be estimated of the order of 60 MeV, to which the absorption [7] must be added. It is no wonder that with a width much larger than the binding such state has not been found in spite of searches and claims (see discussion in [8, 9]).

The fate of the analogous DNN system could be quite different. Indeed, the analogous resonance, according to studies of the DN interaction with coupled channels [10, 11], is the $\Lambda_c(2595)$, which has a width of 2.6 MeV [12]. On the other hand, the binding of the DN system, that by analogy to the $\bar{K}N$ goes as the relativistic energy of the D , should also be bigger than in the case of the $\bar{K}N$ system. As a consequence we are led to have a state more bound and with a smaller width, which could be easily observable. In the study done in [13] this is what is observed looking into the problem from two perspectives: one is using the Fixed Center approximation to the Faddeev equations and the other one using a variational calculation. Both methods converge into a common answer providing a state around 3500 MeV with a width of about 30-40 MeV counting the absorption of the D by two nucleons.

2 The Fixed Center Approximation

In this approach we consider that the two nucleons form a cluster and that the D scatters with these nucleons without changing them from their ground state. This is fair when one has a bound D , which has no energy to excite the NN system. Under this assumption one has a set of coupled equations involving partition functions which for the D^0pp system sum the diagrams that we can see in Fig. 1.

These amplitudes fulfill a set of coupled equations

$$\begin{aligned} T_p &= t_p + t_p G_0 T_p + t_{ex} G_0 T_{ex}^{(p)} \\ T_{ex}^{(p)} &= t_0^{(p)} G_0 T_{ex}^{(n)} \\ T_{ex}^{(n)} &= t_{ex} + t_{ex} G_0 T_p + t_0^{(n)} G_0 T_{ex}^{(p)}, \end{aligned} \quad (1)$$

where the two-body amplitudes are given as $t_p = t_{D^0p, D^0p}$, $t_{ex} = t_{D^0p, D+n}$, $t_0^{(p)} = t_{D^0p, D^0p}$, and $t_0^{(n)} = t_{D+n, D+n}$. A set of similar, but easier equations, are obtained for scattering of the DNN in isospin $I = 3/2$ such that the proper $I = 1/2$ amplitude where the bound DNN state appears is given by

$$T^{(1/2)} = \frac{\frac{3}{2}t^{(0)} + \frac{1}{2}t^{(1)} + 2G_0 t^{(0)} t^{(1)}}{1 + \frac{1}{2}(t^{(1)} - t^{(0)})G_0 - G_0^2 t^{(0)} t^{(1)}},$$

where $t^{(0)}$, $t^{(1)}$ are the isospin $I = 0, 1$ DN amplitudes and G_0 is the D propagator folded by the NN form factor.

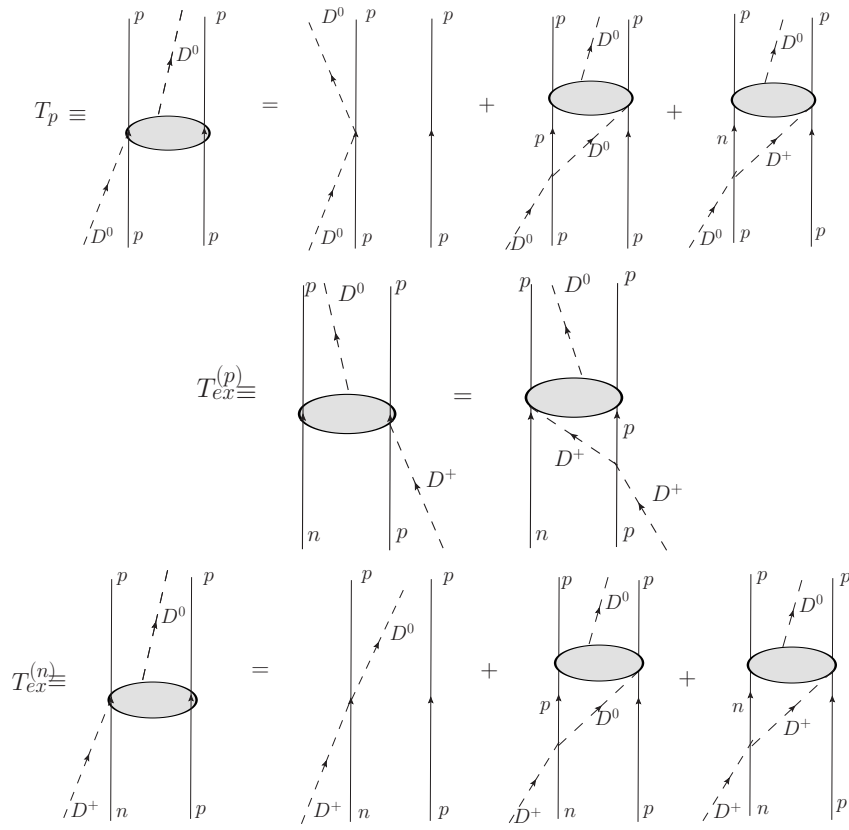


Fig. 1 Diagrammatic representations of the partition functions for the $D^0 pp \rightarrow D^0 pp$.

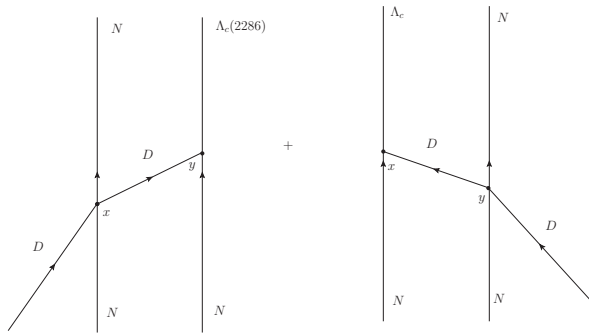


Fig. 2 Diagrammatic representation of the $D(NN)$ absorption.

$$G_0 = \int \frac{d^3q}{(2\pi)^3} F_{NN}(q) \frac{1}{q^{02} - \mathbf{q}^2 - m_D^2 + i\epsilon}, \quad (2)$$

The absorption of the D by two nucleons is based on the diagrams of Fig. 2, and they are included in a nonperturbative way where the elementary DN amplitudes are already modified to account by the possibility of the D being absorbed by a second nucleon.

The modulus squared amplitude for the DNN amplitude is shown in Fig. 3. We can see a clear peak around 3500 MeV with a width of about 20-30 MeV, which indicates the appearance of a state of the DNN system.

3 Variational calculation

Here we calculate the energy of the DNN system with a variational approach formulated for the $\bar{K}NN$ system in Refs. [1, 14]. As in the case of the FCA, we consider the DNN system with total isospin $I = 1/2$ and the total spin-parity $J^P = 0^-$. The trial wave function for the state is prepared with two components:

$$|\Psi^{J=0}\rangle = (\mathcal{N}^0)^{-1} [|\Phi_+^0\rangle + C^0|\Phi_-^0\rangle], \quad (3)$$

where \mathcal{N}^0 is a normalization constant and C^0 is a mixing coefficient. In the main component $|\Phi_+^0\rangle$, two nucleons are combined into spin $S_{NN} = 0$ and isospin $I_{NN} = 1$ so all the two-body subsystems can be in s wave. We also allow a mixture of the $|\Phi_-^0\rangle$ component where both spin and isospin are set to be zero, so the orbital angular momentum between two nucleons is odd.

We consider the following Hamiltonian in this study:

$$\hat{H} = \hat{T} + \hat{V}_{NN} + Re\hat{V}_{DN} - \hat{T}_{c.m.}, \quad (4)$$

where \hat{T} is the total kinetic energy, \hat{V}_{DN} is the DN potential term which is the sum of the contributions from two nucleons, and $\hat{T}_{c.m.}$ is the energy of the center-of-mass motion. For the NN potential \hat{V}_{NN} , we use three models: HN1R which is constructed from Hasegawa-Nagata No.1 potential [15], the Minnesota force [16], and the gaussian-fitted version of the Argonne v18 potential [17].

The DN potential in this approach is obtained by studying the DN scattering in the coupled channels of [11] and eliminating all except for the DN one with an effective potential such as to obtain the same scattering amplitude as with the coupled channels [18]. As in [11], we consider seven (eight) coupled channels in the isospin $I = 0$ ($I = 1$) sector, DN , $\pi\Sigma_c$, $\eta\Lambda_c$, $K\Sigma_c$, $K\Sigma'_c$, $D_s\Lambda$, and $\eta'\Lambda_c$ (DN , $\pi\Lambda_c$, $\pi\Sigma_c$, $\eta\Sigma_c$, $K\Sigma_c$, $K\Sigma'_c$, $D_s\Sigma$, and $\eta'\Sigma_c$).

In Table 1 we show some of the properties of the state found for different NN potentials. As seen in the Table, the DNN system in the $J = 0$ channel is bound below the Λ_c^*N threshold ($B \sim 209$ MeV) for all the NN potentials employed. A large kinetic energy of the deeply bound system is overcome by the strong attraction of the DN potential, while the NN potential adds a small correction. Comparing the results with three different nuclear forces, we find that the binding energy is smaller when the NN potential has a harder repulsive core.

Although we will not discuss it here, we also find in [13] a state with $J = 1$ but less bound and more uncertain than the $J = 0$ that we have exposed.

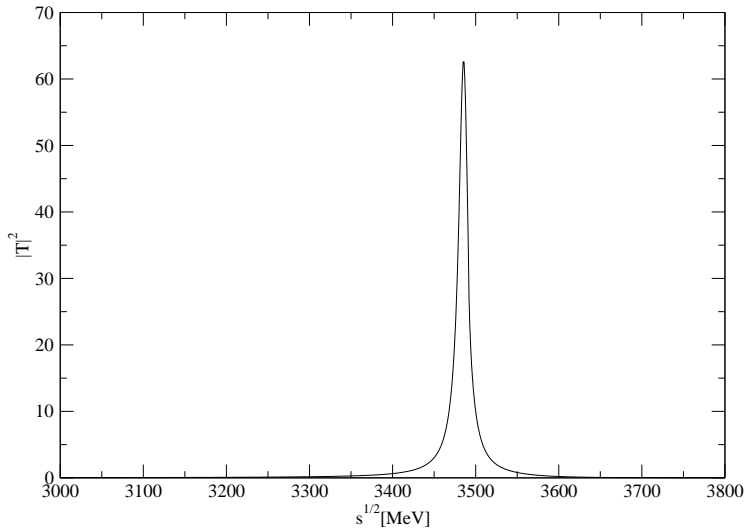


Fig. 3 Modulus squared of the three-body scattering amplitude for $I = 1/2$ and $J = 0$ including absorption with reduced NN radius.

Table 1 Results of the energy compositions in the variational calculation for the ground state of the DNN system with total isospin $I = 1/2$ (range parameter $a_s = 0.4$ fm). Terms “bound” and “unbound” are defined with respect to the Λ_c^*N threshold. All the numbers are given in MeV.

| | HN1R | | Minnesota | | Av18 | |
|----------------------|---------|---------|-----------|---------|---------|---------|
| | $J = 1$ | $J = 0$ | $J = 0$ | $J = 0$ | $J = 0$ | $J = 0$ |
| | unbound | bound | bound | bound | bound | bound |
| B | 208 | 225 | 251 | 209 | | |
| M_B | 3537 | 3520 | 3494 | 3536 | | |
| $\Gamma_{\pi Y_c N}$ | - | 26 | 38 | 22 | | |
| E_{kin} | 338 | 352 | 438 | 335 | | |
| $V(NN)$ | 0 | -2 | 19 | -5 | | |
| $V(DN)$ | -546 | -575 | -708 | -540 | | |
| T_{nuc} | 113 | 126 | 162 | 117 | | |
| E_{NN} | 113 | 124 | 181 | 113 | | |
| $P(Odd)$ | 75.0 % | 14.4 % | 7.4 % | 18.9 % | | |

4 Possible experiments to produce the DNN state

As a suggestion to observe experimentally this state we can think of the $\bar{p} \ ^3He \rightarrow \bar{D}^0 D^0 pn \rightarrow \bar{D}^0 [DNN]$ reaction, which could be done by FAIR at GSI. With a \bar{p} beam of $15 \text{ GeV}/c$ there is plenty of energy available for this reaction and the momentum mismatch of the D^0 with the spectator nucleons of the 3He can be relatively small. Estimations made in [13] indicate that one would expect several thousand events per day for the background of the proposed reaction. A narrow peak could be visible on top of this background corresponding to the DNN bound state formation.

Another possibility is the high-energy π induced reaction. An analogous reaction is $\pi^- d \rightarrow D^- D^+ np \rightarrow D^- [DNN]$ where the relevant elementary process is $\pi^- N \rightarrow$

D^+D^-N . Since the DN pair in the DNN system is strongly clustering as the A_c^* , the reaction $\pi^-d \rightarrow D^-A_c^*n \rightarrow D^-[DNN]$ is also another candidate. The elementary reaction $\pi^-p \rightarrow D^-A_c^*$ is relevant in this case. Such reactions may be realized in the high-momentum beamline project at J-PARC.

5 Conclusions

We have studied the DNN system with $I = 1/2$ using two independent methods: the Fixed Center Approximation to the Faddeev equations and a variational method, and have found that the system is bound and rather stable, with a width of about 20-40 MeV. We obtained a clear signal of the quasi-bound state for the total spin $J = 0$ channel around 3500 MeV.

The small width of the DNN quasi-bound state is advantageous for the experimental identification. The search for the DNN quasi-bound state can be done by \bar{p} induced reaction at FAIR, π^- induced reaction at J-PARC, and relativistic heavy ion collisions at RHIC and LHC.

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