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# 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

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

where the two-body amplitudes are given as $t_p = t_{D^0p,D^0p}$, $t_{ex} = t_{D^0p,D^+n}$, $t_0^{(p)} = t_{D^+p,D^+p}$, 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.

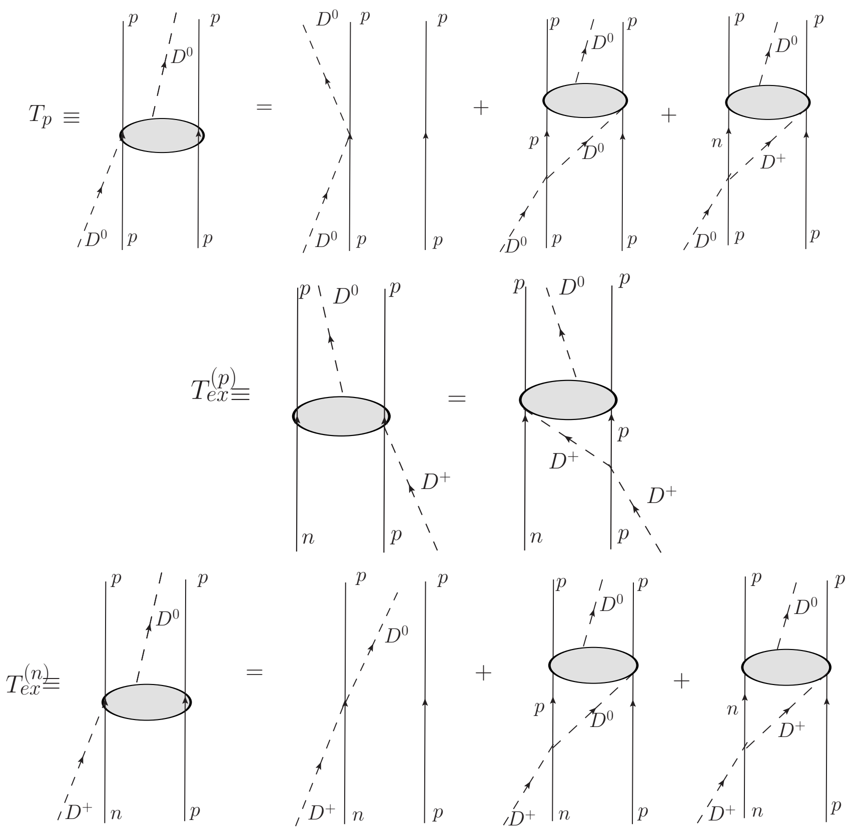


**Fig. 1** Diagrammatic representations of the partition functions for the $D^0pp \to D^0pp$.

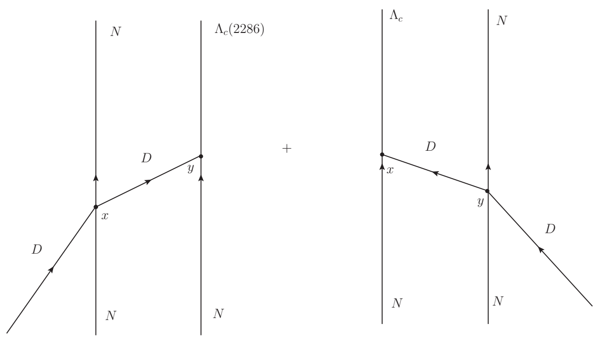


**Fig. 2** Diagrammatic representation of the $D(NN)$ absorption.

$$G_0 = \int \frac{d^3q}{(2\pi)^3} F_{NN}(q) \frac{1}{{q^0}^2 - \mathbf{q}^2 - m_D^2 + i\epsilon}, \tag{2}$$

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:

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

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:

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

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, $DN$, $\pi\Sigma_c$, $\eta\Lambda_c$, $K\Xi_c$, $K\Xi_c'$, $D_s\Lambda$, and $\eta'\Lambda_c$ ($DN$, $\pi\Lambda_c$, $\pi\Sigma_c$, $\eta\Sigma_c$, $K\Xi_c$, $K\Xi_c'$, $D_s\Sigma$, 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 $\Lambda_c^* N$ 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.

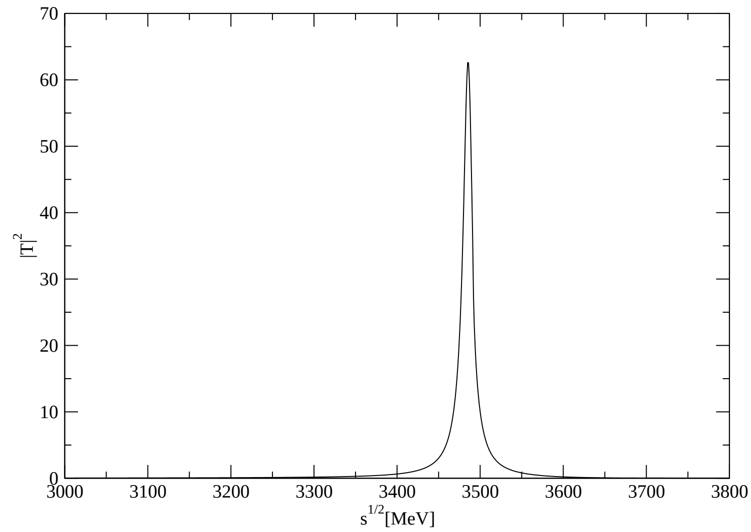


**Fig. 3** Modulus squared of the three-body scattering amplitude for $I = 1/2$ and $J = 0$ including absorption with reduced $NN$ radius.

**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 $\Lambda_c^* N$ threshold. All the numbers are given in MeV.

| | HN1R | | Minnesota | Av18 |
|---|---|---|---|---|
| | $J = 1$ | $J = 0$ | $J = 0$ | $J = 0$ |
| | unbound | 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 $\bar{p}\,^3He \to \bar{D}^0 D^0 pn \to \bar{D}^0[DNN]$ reaction, which could be done by FAIR at GSI. With a $\bar{p}$ beam of 15 $GeV/c$ there is plenty of energy available for this reaction and the momentum mismatch of the $D^0$ with the spectator nucleons of the $^3$He 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 $\pi$ induced reaction. An analogous reaction is $\pi^- d \to D^- D^+ np \to D^-[DNN]$ where the relevant elementary process is $\pi^- N \to$

$D^+D^-N$. Since the $DN$ pair in the $DNN$ system is strongly clustering as the $\Lambda_c^*$, the reaction $\pi^- d \to D^- \Lambda_c^* n \to D^-[DNN]$ is also another candidate. The elementary reaction $\pi^- p \to D^- \Lambda_c^*$ 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, $\pi^-$ induced reaction at J-PARC, and relativistic heavy ion collisions at RHIC and LHC.

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