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ΔΔ ABC partner in the $N\bar{D}$ system

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Abstract. We perform a study of the $N\bar{D}$ interaction within a chiral constituent quark model. This model has been completely tight in the description of the NN interaction and the baryon and meson spectra, therefore provides a parameter–free framework from where to address the problem of the charm -1 two hadron systems. We predict the existence of a unique bound state, $\Delta\bar{D}^*$ with $(T, S) = (1, 5/2)$, that would appear in the scattering of $\bar{D}$ mesons on nucleons as a D wave state. This resonance resembles our findings in the $\Delta\Delta$ system, that offered a plausible explanation to the cross section of double–pionic fusion reactions through the so–called ABC effect.

The study of the chiral symmetry restoration in a hot and/or dense medium, the suppression of the J/Ψ production in heavy ion collisions, or the possible existence of exotic nuclei with heavy flavors are a few examples of problems where the correct understanding of the interaction between nucleons and $\bar{D}$ mesons is necessary. Indeed, the FAIR facility at GSI will soon allow to study the $N\bar{D}$ interactions inside nuclear matter [1]. However, before one can extract information from the incoming experiments, a good description of the same problem in free space has to be achieved. At this point one has to admit that there is a complete lack of experimental information at low energies. Therefore the conclusions extracted from generalizations of models that have been successful in the light–flavor sector may be helpful.

We approach the study of the $N\bar{D}$ system ($N\bar{D}$, $N\bar{D}^*$, $\Delta\bar{D}$, $\Delta\bar{D}^*$) from a chiral constituent quark model (CCQM) [2, 3], which successfully described the NN interaction and the meson spectra in all flavors, with the hope that our predictions may be supported by the next generation of experiments to be done at $\bar{P}$ANDA.

In the CCQM, the wave function of a baryon–meson $B_i M_j$ system can be written as:

$$\Psi^{LST}_{B_i M_j}(\vec{R}) = \mathcal{A}\left[B_i\left(123; -\frac{\vec{R}}{2}\right) M_j\left(4\bar{5}; +\frac{\vec{R}}{2}\right)\right]^{LST}, \tag{1}$$

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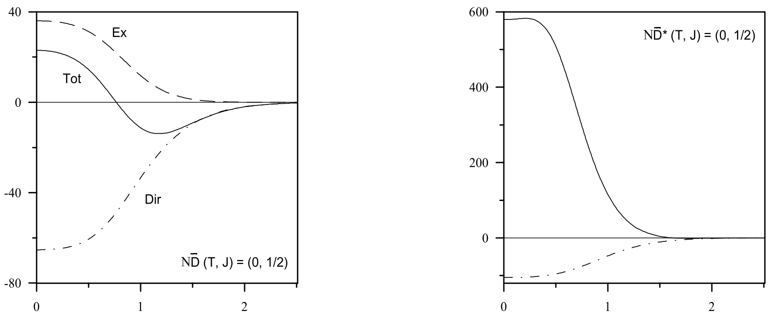

Figure 1. Interacting potential showing Pauli effects in the $(T, J) = (0, 1/2)$ channel: $N\bar{D}$ (left panel) and $N\bar{D}^*$ (right panel). Solid line stands for the total potential. See text for details.

being $\mathcal{A}$ the antisymmetrization operator that exchanges pairs of identical quarks. In the limit where a baryon and a meson overlap, the normalization of their wave function can be written as:

$$\mathcal{N}_{B_i M_j}^{L=0ST}[R \to 0] \longrightarrow 4\pi \left\{1 - \frac{R^2}{8}\left(\frac{4}{b^2} + \frac{1}{b_c^2}\right)\right\} \left\{[1 - C(S,T)] + \frac{1}{6}\left(\frac{R^2}{8b_c^2}\right)^2 \left[\gamma^2 - C(S,T)\right] + \ldots\right\}, \tag{2}$$

where $\gamma = f(b, b_c)$ and $C(S, T)$ is a spin–flavor coefficient. Thus, depending on the value of C one may find interesting features. When C is close to 1 there is a large suppression (Pauli suppression) of the norm for $R \to 0$. In the limit of C=1, Pauli blocking appears as the norm goes to zero. In the $N\bar{D}$ system there is one channel showing this feature: $\Delta\bar{D}^*$ with (T, S) = (2, 5/2), due to lacking degrees of freedom to accomodate the light quarks present on this configuration.

The two–body interactions are obtained in the CCQM [2, 3], where hadrons are described as clusters made of constituent quarks, whose mass is coming from the spontaneous chiral symmetry breaking. Perturbative effects are described by the OGE interaction [4], whereas nonperturbative effects are related to the exchange of Goldstone bosons, $V_\chi(\vec{r}_{ij}) = V_{\rm OSE}(\vec{r}_{ij}) + V_{\rm OPE}(\vec{r}_{ij})$, being OSE and OPE scalar and pseudoscalar exchange potentials. The interaction reads:

$$V_{q_i q_j}(\vec{r}_{ij}) = \begin{cases} \left[q_i q_j = nn\right] \Rightarrow V_{\rm CON}(\vec{r}_{ij}) + V_{\rm OGE}(\vec{r}_{ij}) + V_\chi(\vec{r}_{ij}) \\ \left[q_i q_j = cn\right] \Rightarrow V_{\rm CON}(\vec{r}_{ij}) + V_{\rm OGE}(\vec{r}_{ij}) \end{cases}, \tag{3}$$

where the tags n and c stand for light and heavy quarks, respectively. Chiral symmetry is explicitly broken for heavy quarks and therefore no V_χ acts on them. In our case, the presence of a heavy antiquark makes the interaction quite simple as it cannot be exchanged by the antisymmetrizer operator. Once the qq and $q\bar{q}$ interactions are known, the meson–baryon interaction is obtained through a Born–Oppenheimer formalism.

The interactions coming from direct and exchange diagrams of Ref. [5] have been separated, as seen in Fig. 1 (left). The difference between the total and the direct potential is due to quark–exchange effects. The direct contribution is always attractive and can be identified with a baryonic–like potential, but the character of the exchange piece may vary. For instance one can find a repulsive exchange contribution in $N\bar{D}$ $(T, J) = (0, 1/2)$ or an attractive one in $\Delta\bar{D}^*$ $(T, J) = (1, 5/2)$. Therefore dynamical quark exchange features play a major role in the $N\bar{D}$ system, having observable consequences.

Several channels experiment Pauli features and therefore become strongly repulsive at short distances. This is the case of $N\bar{D}^*(T, J) = (0, 1/2)$, where the norm is suppressed because the value of $C(S, T) = 2/3$ is close to 1, as can be seen in the right panel of Fig. 1. Quark antisymmetry effects are evident in this figure, as the dashed-dotted line corresponds to a direct or hadronic potential and the solid line to the total interaction. Therefore hadronic models can in no way show the consequences of the Pauli

Table 1. Baryon-meson channels in the coupled (T, J) basis. The tag inside parentheses stands for the character of the interaction, being R and A repulsive and attractive. Correspondingly, W and S mean weakly and strongly.

	$T=0$		$T=1$		$T=2$	
$J=1/2$	$N\bar{D}-N\bar{D}^*$	(R)	$N\bar{D}-N\bar{D}^*-\Delta\bar{D}^*$	(R)	$\Delta\bar{D}^*$	(WR)
$J=3/2$	$N\bar{D}^*$	(WA)	$N\bar{D}^*-\Delta\bar{D}-\Delta\bar{D}^*$	(WR)	$\Delta\bar{D}-\Delta\bar{D}^*$	(A)
$J=5/2$			$\Delta\bar{D}^*$	(A)	$\Delta\bar{D}^*$	(SR)

effects in the $N\bar{D}$ system. Analogously, the left panel of Fig. 2 shows the $\Delta\bar{D}^*(T, J) = (2, 5/2)$ channel, where Pauli blocking takes place. The norm goes to zero, absolutely forbidding the overlapping of the two hadrons for $R = 0$. All the contributions become very strong at short distances and the resulting potential is strongly repulsive.

These two–body baryon–meson interactions were used to solve the Lippmann–Schwinger equation for negative energies using the Fredholm determinant. This method allows to obtain predictions for energies of bound states and gives information about the character of the partial wave being studied. The meson–baryon system considered is $B_i M_j$, being $B_i = N$ or Δ and $M_j = \bar{D}$ or $\bar{D}^*$, in an S–wave that interacts through a potential V that contains a tensor force. Then, in general, there is a coupling to the $B_i M_j$ D–wave, but our $B_i M_j$ system may also couple to different baryon–meson states having the same (T, J) quantum numbers. The baryon–meson channels, coupled in the isospin–spin basis, are shown in Table 1. So, if different baryon–meson channels are labelled by A_i, the Lippmann–Schwinger equation for the scattering of a baryon–meson system becomes:

$$t^{\ell_\alpha s_\alpha,\ell_\beta s_\beta}_{\alpha\beta;TJ}(p_\alpha, p_\beta; E) = V^{\ell_\alpha s_\alpha,\ell_\beta s_\beta}_{\alpha\beta;TJ}(p_\alpha, p_\beta) + \sum_{\gamma=A_1,A_2,\cdots}\sum_{\ell_\gamma=0,2}\int_0^\infty p_\gamma^2 dp_\gamma V^{\ell_\alpha s_\alpha,\ell_\gamma s_\gamma}_{\alpha\gamma;TJ}(p_\alpha, p_\gamma)$$

$$\times G_\gamma(E; p_\gamma) t^{\ell_\gamma s_\gamma,\ell_\beta s_\beta}_{\gamma\beta;TJ}(p_\gamma, p_\beta; E),\ \alpha,\beta = A_1, A_2, \cdots, \quad (4)$$

where t is the two-body scattering amplitude, T, J, and E are the isospin, total angular momentum and energy of the system, $\ell_\alpha s_\alpha$, $\ell_\gamma s_\gamma$, and $\ell_\beta s_\beta$ are the initial, intermediate, and final orbital angular momentum and spin, respectively, and p_γ is the relative momentum of the two-body system γ.

The existence of bound states in the solution of the Lippmann–Schwinger equation would imply the existence of exotic states with charm -1. Such states could be identified in future experiments at the FAIR facility.

Pauli principle at the quark level has strong consequences in the dynamics of the baryon–meson system, since all channels exhibiting Pauli features, either suppression or blocking, present repulsive character. They are $(T, J) = (2, 5/2)$, $(0, 1/2)$, and $(1, 1/2)$, see Table 1. On the other side, among the nine spin–isospin baryon–meson channels, only two of them are attractive: $(T, J) = (2, 3/2)$, $(1, 5/2)$. In the latter case there is no channel–coupling as the $\Delta\bar{D}^*$ is the only channel coupled to these quantum numbers, and it hosts the only bound state of the system, with a binding energy of 3.87 MeV.

The importance of quark antisymmetrization dynamics is not a new effect found here, but the same was observed when studying the $\Delta\Delta$ system within this model [6]. In that case, an S–wave resonance with maximum spin was predicted. Experimental evidence of such resonance was found in the NN scattering data, in the $^3D_3$ partial wave, therefore as a D–wave resonance in the NN scattering [7]. This prediction has been recently used as a possible explanation of the measured cross section of the double–pionic fusion of nuclear systems through the so–called Abashian–Booth–Crowe (ABC) effect [8]. The creation of an intermediate resonant $\Delta\Delta$ state as the one predicted in Ref. [6] ($(T)J^P = (0)3^+$ and M =2.37 GeV) allowed to describe the cross section of the double-pionic fusion reaction $pn \to d\pi^0\pi^0$.

In a similar manner, the bound state we have found in the present study, $\Delta\bar{D}^*$ $(T, J) = (1, 5/2)$, would show up in the scattering of $\bar{D}$ mesons on nucleons as a D wave resonance. One of the goals

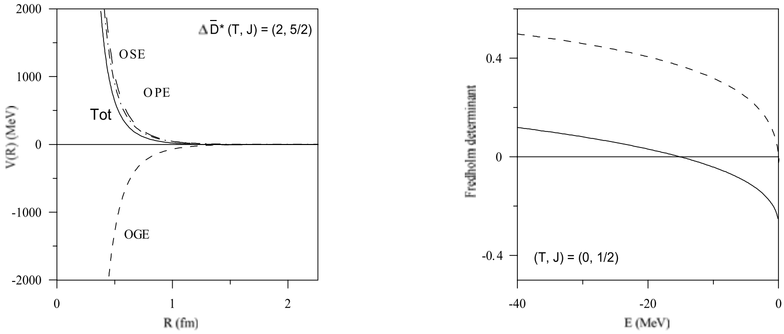

Figure 2. Direct and exchange contributions to the $N\bar{D}(T,J) = (0,1/2)$ interaction (left panel) and Fredholm determinant obtained from the direct potentials (right panel).

of the $\bar{P}$ANDA Collaboration is precisely to study the interaction between D mesons and nucleons, therefore our prediction may be taken as a challenge to be tested at future experiments.

In order to make clear the importance of the quark antisymmetrization effects, let us have a look at Refs. [9, 10], where the $N\bar{D}$ systems were analyzed in a hadronic model using lagrangians that satisfy heavy quark symmetry and chiral symmetry. There, the $(T)J^P = (0)1/2^-$ state was the most attractive channel, having a bound state of around 1.4 MeV. We have redone our coupled–channel calculation by using the direct potentials that arise in our model when including just the direct diagrams. These direct potentials correspond to a purely baryonic interaction, as no quark exchanges are taken into account. Two physical systems, $N\bar{D}$ and $N\bar{D}^*$, are coupled to $(T,J) = (0,1/2)$. The direct contribution in both is shown in dashed–dotted line in both panels of Fig. 1. In both plots the magnitude of the exchange effects can be easily appreciated. As shown in Table 1, the coupled–channel calculation for the $(T)J^P = (0)1/2^-$ channel shows that it is repulsive. However when considering a hadronic potential by performing the coupled–channel calculation with the direct potentials only, the result is shown in Fig. 2 (right). The dashed line shows the calculation for the single channel problem $N\bar{D}$ and the solid line indicates the coupled–channel problem $N\bar{D} - N\bar{D}^*$. In both cases we would find attraction, in agreement with the results of Refs. [9, 10].

Therefore, the existence of a unique bound state in the $N\bar{D}$ system with quantum numbers $(T,J) = (1,5/2)$ is a sharp prediction of our model, which is based on quark–exchange dynamics, since in hadronic models there are several channels presenting attraction. We hope that such a prediction may be tested in the near future thanks to the experimental program of the $\bar{P}$ANDA Collaboration at FAIR.

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