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$\Delta\Delta$ vs $N\bar{D}$: a test-bench for the ABC effect

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Basic features common to all phenomenological models of hadron structure lead to the prediction of dibaryon resonances independent of more detailed features of the dynamics. In particular, an $(I)J^P = (0)3^+$ $\Delta\Delta$ resonance used to explain the double pionic fusion through the so–called ABC effect. Within the same framework we report a resonance with the same basic features in the $N\bar{D}^*$ system that could be pursued in the future program at $\bar{P}$ANDA.

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In Ref. [1] the $N\bar{D}$ interaction was analyzed within a chiral constituent quark model (CCQM). Due to the lack of experimental data at low energies for the free space interaction, the generalization of a model that describes the NN interaction and the meson spectrum in all flavor sectors may be a reliable framework from where to obtain parameter-free predictions in the charm sector.

In the constituent quark model [2], hadrons are described as clusters of three interacting massive quarks, where the mass comes from the spontaneous breaking of the original chiral symmetry of the QCD Lagrangian. Perturbative effects of QCD are taken into account through a well–known one–gluon–exchange potential (OGE), initially derived in Ref. [3]. Nonperturbative effects due to spontaneous chiral symmetry breaking occur at some momentum scale, at which light quarks interact by exchanging 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. A linear confinement piece is also included. Therefore, the total interaction reads:

$$V_{q_iq_j}(\vec{r}_{ij}) = \begin{cases} [q_iq_j = nn] \Rightarrow V_{\rm CON}(\vec{r}_{ij}) + V_{\rm OGE}(\vec{r}_{ij}) + V_\chi(\vec{r}_{ij}) \\ [q_iq_j = cn] \Rightarrow V_{\rm CON}(\vec{r}_{ij}) + V_{\rm OGE}(\vec{r}_{ij}) \end{cases} , \tag{1}$$

where the tags n and c stand for light and heavy quarks, respectively. As chiral symmetry is explicitly broken for heavy quarks, the chiral potential does not act on cn combinations. Within this model, a nice description of both the baryon (N and Δ) and meson spectra ($\bar{D}$ and $\bar{D}^*$) [2] was obtained. The parameters of the model were tuned all in previous works so predictive power is expected. They are listed in Ref. [1]. We employ a Born–Oppenheimer formalism to construct the two–hadron wave function out of the qq and $q\bar{q}$ interactions. In the two–body interactions, large differences are found between the contributions with and without quark exchanges for some particular channels. They are due to Pauli effects. If we consider the limit of the norm of a baryon–meson wave function when the hadrons overlap ($R \to 0$):

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

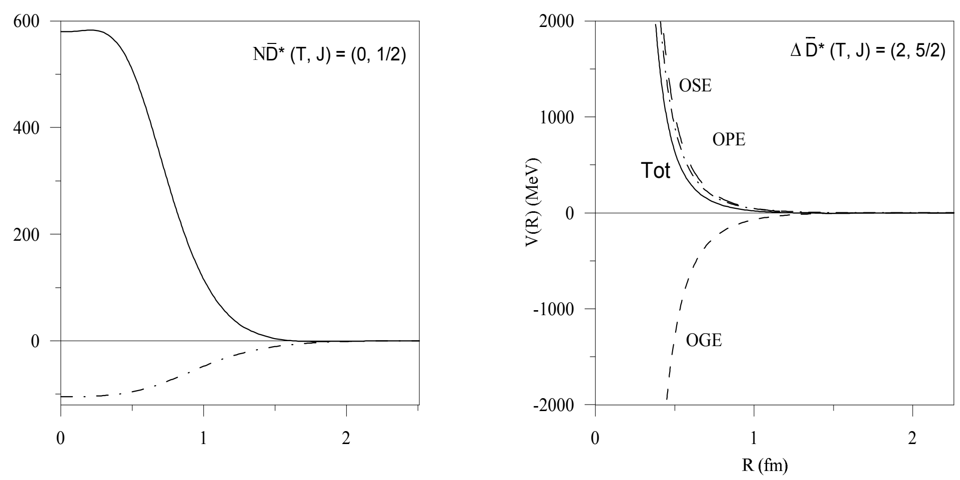

Figure 1: Interacting potential in two different channels showing Pauli effects: $N\bar{D}^*$ $(T,J) = (0,1/2)$ (left panel) and $\Delta\bar{D}^*$ $(T,J) = (2,5/2)$ (right panel). See text for details.

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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)

being $\gamma = f(b,b_c)$ and $C(S,T)$ a spin–flavor coefficient, it is clear that quark antisymmetry effects appear in those channels where $C \sim 1$, because the norm gets suppressed. For $C=1$, the norm goes to zero when $R \to 0$, what is called Pauli blocking [4]. $C(S,T)$ is a spin–isospin coefficient that depends on the total spin and isospin of the baryon–meson system. Appreciable Pauli features are found for $N\bar{D}^*$ with $(T,J)=(0,1/2)$ and $\Delta\bar{D}^*$ with $(T,J)=(2,5/2)$, as they have, respectively, $C=2/3$ and $C=1$. The situation is illustrated in Fig. 1. Left panel shows the direct contribution in dashed-dotted line against the total $(0,1/2)$ (direct+exchange) potential in solid line. The effect of quark antisymmetrization is easily appreciated by comparing both lines. The direct potential can be considered as a genuine baryonic potential. While direct contributions are long ranged, quark exchange diagrams govern the short–range part of the interaction. Right panel of Fig. 1 shows the different pieces of the potential that contribute to the interaction with quantum numbers $(2,5/2)$. In this channel, as $C(S,T)=1$, the norm is completely suppressed and therefore all contributions are very strong at short distances, building up an extremely repulsive interaction.

The Pauli blocking just found is not an unprecedented feature of the $N\bar{D}$ system. Although there are no Pauli blocked channels in the NN system, it also appears in $N\Delta$ for $(S,T)=(1,1)$ and $(2,2)$. This blocking is reflected into a strong short–range repulsion that can be checked experimentally by looking at the πd elastic scattering [5]. In the $\Delta\Delta$ case, blocking is found at $(S,T)=(2,3)$ and $(3,2)$, both with $L=0$ and also for $(3,3)$ with $L=1$, which is a distinctive feature of the $\Delta\Delta$ interaction.

The 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 under consideration is B_iM_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_iM_j D–wave, but our B_iM_j system may also couple to different baryon–meson systems 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 labeled by A_i, the Lippmann–Schwinger equation for the scattering of a baryon–meson system becomes:

$$t^{\ell_\alpha s_\alpha,\ell_\beta s_\beta}_{\alpha\beta;TJ}(p_\alpha,p_\beta;E) = V^{\ell_\alpha s_\alpha,\ell_\beta s_\beta}_{\alpha\beta;TJ}(p_\alpha,p_\beta) + \sum_{\gamma=A_1,A_2,\cdots}\sum_{\ell_\gamma=0,2}\int_0^\infty p_\gamma^2 dp_\gamma V^{\ell_\alpha s_\alpha,\ell_\gamma s_\gamma}_{\alpha\gamma;TJ}(p_\alpha,p_\gamma) \times G_\gamma(E;p_\gamma) t^{\ell_\gamma s_\gamma,\ell_\beta s_\beta}_{\gamma\beta;TJ}(p_\gamma,p_\beta;E) \;,\; \alpha,\beta = A_1,A_2,\cdots \,, \quad (3)$$

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. At Table 1 we also compile the character of the interactions at all possible spin–isospin channels. One can see how the channels with $C \simeq 1$ exhibit repulsion. In other words, the Pauli principle at the level of quarks has observable consequences in the dynamics of the $N\bar{D}$ system. Two attractive channels were found, those with $(T,J) = (2,3/2)$ and $(1,5/2)$, being this latter the most attractive. It corresponds to a unique physical system $\Delta\bar{D}^*$, and presents a bound state with a binding energy of 3.87 MeV.

The situation is similar to the one encountered when studying the $\Delta\Delta$ interaction. There, four bound states compatible with the NN system (J,T) were found, as shown in Table 2, corresponding in order of decreasing binding energy to the channels $(J,T) = (1,0),(0,1),(2,1)$ and $(3,0)$. Such states appear in the spectrum of the NN system. The most bound, $(J,T) = (1,0)$ corresponds to the deuteron. The $(J,T) = (0,1)$ is the $^1S_0$ virtual bound state and the $(2,1)$ state is the $^1D_2$ resonance lying at 2.17 GeV [6]. Note that the $^3F_3\, NN$ resonance has no counterpart in Table 2 because only even parity states were computed and $^3F_3$ is odd. Thus, the $(J,T) = (3,0)$ state which is also bound in the $\Delta\Delta$ system would correspond to a new NN resonance that is predicted in our framework. It is interesting that some hint of a $(3,0)$ resonance can already be seen in the analyses of the NN data of Ref. [7], as it appears in Fig. 2. The (J,T) = $(3,0)$ channel corresponds in the case of the NN system to the $^3D_3$ partial wave. The most distinctive feature of a resonance is that as the energy increases the real part of the amplitude changes sign going from positive to negative while the imaginary part becomes large, so that the amplitude describes a counterclockwise loop in the Argand diagram. The energy at which this change of sign occurs corresponds to the mass of the resonance. We show in Fig. 1 the real and imaginary parts of the $^3D_3$ amplitude obtained from the single-energy analysis of Ref. [7]. As one can see a resonance-like behavior seems to be present at about 700 and 1100 MeV. These kinetic energies correspond to invariant masses of 2.2 and 2.37 GeV so that in either case the ordering of the state agrees with that predicted by Table 2. As mentioned before, the $\Delta\Delta$ bound state in the channel (J,T) = (3,0) has been predicted also by other models [8, 9, 10], and a method to search experimentally for this state has also been proposed [11].

This prediction has been used as a possible explanation of the measured cross section of the

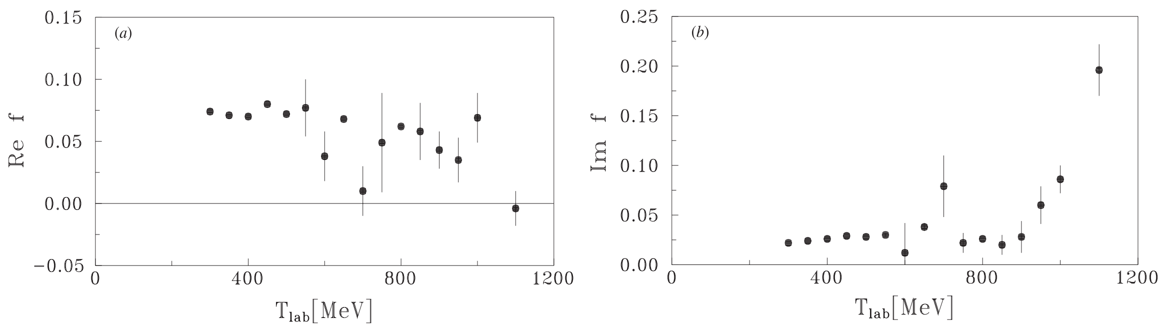

Figure 2: (*a*) Real and (*b*) imaginary parts of the single–energy solutions for the $^3D_3$ NN partial wave taken from Ref. [7]

Table 2: Binding energies (in MeV) of the $\Delta\Delta$ states with total angular momentum j and isospin i

(J,T)	(0,1)	(0,3)	(1,0)	(1,2)	(2,1)	(2,3)	(3,0)	(3,2)
B	108.4	0.4	138.5	5.7	30.5	Unbound	29.9	Unbound

double–pionic fusion of nuclear systems through the so–called Abashian–Booth–Crowe (ABC) effect [12]. The formation of an intermediate $\Delta\Delta$ resonance with the isospin, spin, parity and mass found in Ref. [13] ($(T)J^P = (0)3^+$ 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 way, the bound state found in the $(T,J) = (1,5/2)\,\Delta\bar{D}^*$ channel would appear in the scattering of $\bar{D}$ mesons on nucleons as a D–wave resonance, which could in principle be measured in the near future. There are proposals for experiments by the $\bar{P}$ANDA Collaboration [14] to produce D mesons by annihilating antiprotons on the deuteron. They are based on recent estimations of the cross section for the production of $D\bar{D}$ pairs in proton-antiproton collisions [15]. The predicted $\Delta\bar{D}^*$ state has quantum numbers $(T)J^P = (1)5/2^-$ and is a sharp prediction of quark–exchange dynamics because in a hadronic model the attraction appears in different channels.

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