

Deuteron $NN^*(1440)$ components from a chiral quark model

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We present a nonrelativistic coupled-channel calculation of the deuteron structure including $\Delta\Delta$ and $NN^*(1440)$ channels, besides the standard NN S - and D -wave components. All the necessary building blocks to perform the calculation have been obtained from the same underlying quark model. The calculated $NN^*(1440)$ probabilities find support in the explanation given to different deuteron reactions.

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Since the discovery of nucleon structure, nucleon resonances have attracted considerable attention from theorists and experimentalists. An important effort was made to choose and design experiments that could probe the presence of resonance configurations in different nuclear systems. The basic idea lies in the observation that a small fraction of the nucleons will be internally excited and therefore present as virtual resonances in every nucleus. This may happen even at low energies due to the possibility of exciting internal nucleon degrees of freedom according to the process $NN \rightarrow NN^*$ (or $N^*N^*) \rightarrow NN$ involving intermediate N^* 's. As a consequence, the many nucleon wave function should be supplemented by configurations involving one or several nucleons in an excited baryon resonance state.

If the virtual N^* 's exist in bound nuclear states, one expects them to play an important role already in the bound two-nucleon system, the deuteron [1]. The most prominent low-lying even-parity nucleon resonances are the P_{33} , the $\Delta(1232)$, and the P_{11} , the $N^*(1440)$ or Roper resonance. The N^* 's contribute predominantly to the nucleon short-range correlations and enhance the high momentum components of the nuclear two-particle density. Being the deuteron isoscalar, the energetically lowest state $N\Delta$ is forbidden, and therefore the $\Delta\Delta$ and $NN^*(1440)$ components would be the relevant nonnucleonic configurations. The admixture probabilities of these *exotic* states are small due to the low nuclear density and the rather high resonance-nucleon mass difference. Nonetheless, they have been advocated long ago to understand elastic proton-deuteron backward scattering at energies above pion threshold [2] or the angular distribution of deuteron photodisintegration at energies above $E_\gamma = 100$ MeV [3]. Recent calculations have renewed the interest on these nonnucleonic components as they could be indirectly observed in several reactions as, for example, antiproton-deuteron annihilation [4], subthreshold antiproton production [5] or $pd \rightarrow dp$ processes [6]. Although the evidence for resonance configurations in the deuteron from such processes is indirect, is suggestive and encouraging.

The treatment of nucleon resonances in the nuclear wave function can be done in different ways. One possibility has consisted on keeping only nucleons (and no resonances) in the nuclear wave function and using effective operators. However, it would be surprising if such an *ad hoc* procedure would phenomenologically account for any detailed internal dynamics, because in the hard-core region two nucleons are likely to excite each other and thus mutually probe their

internal degrees of freedom. If one wants to turn the attention to the virtual contribution from these nucleon excited states, one has to include explicitly N^* transition potentials in a coupled channel calculation.

When performing a coupled channel calculation for the deuteron based on effective baryon-baryon potentials, a problem immediately arises. If one uses for the nucleon-nucleon (NN) channel an effective potential which is fitted to the NN scattering data, it will already include contributions from intermediate N^* 's, and thus one would obtain too much attraction at medium range. Therefore one has to modify the normal nucleon-nucleon potential and weaken the intermediate range attraction in order to account for the additional attraction from the explicit dispersion contribution to the potential with intermediate N^* 's. Such a procedure usually introduces an unwanted model dependence on the results obtained.

There are multiple examples in the literature of these types of calculations. Haapakoski and Saarela [7] studied $\Delta\Delta$ components on the deuteron changing in an *ad hoc* manner the intermediate range attraction of the central Reid soft-core potential until the deuteron binding energy was fit to the experimental value. The tensor force was not changed. Arenhövel, Danos, and Williams [8] studied $NN^*(1440)$ configurations using perturbation theory with the one-pion-exchange (OPE) potential and Hulthén NN deuteron wave functions. The singular nature of the potentials required a cutoff factor and the results were found to be rather sensitive to the cutoff chosen. Weber [9] and Nath and Weber [10] calculated NN^* components by means of an OPE potential in momentum space. The resulting probabilities were again found to be rather dependent on the high momentum suppression factor. Finally, Rost [11] performed a calculation where the existence of resonance components is taken into account by a modification of the intermediate attraction of the Reid hard-core potential. As a consequence, the study of nonnucleonic configurations in the deuteron based on standard meson-exchange NN potentials depends on two basic assumptions: on one hand, the hypothesis done to modify the intermediate range attraction of the NN interaction, on the other hand, the specific transition potential to the resonance configurations used.

During the last decade an important effort has been devoted to the qualitative and quantitative understanding of the nucleon-nucleon interaction based on quark degrees of freedom. The first attempts of the early 1980s based on the one-

gluon-exchange (OGE) force [12,13] evolved to the so-called hybrid quark models [14–16]. The original OGE was supplemented by Goldstone-boson exchanges at the level of quarks and, thus, fully quark-model based NN potentials were obtained. The OGE provided the first explanation of the repulsive core of the NN interaction. Although it is known that quark antisymmetry on the Goldstone-boson exchanges induces the same effect [17], the OGE still results crucial to regularize the short-range part of the Goldstone-boson exchange tensor force. The pseudoscalar-boson exchange tensor coupling is fundamental to reproduce the NN phase shifts, and, finally, the scalar-boson exchange provides the necessary medium-range attraction. The two-baryon problem based on quark-quark interactions is solved by means of the resonating group method (RGM) in a coupled-channel scheme considering usually NN , $\Delta\Delta$, and hidden color-hidden color components. The importance of particular configurations, like $N\Delta$, to describe the low orbital angular momentum partial waves has been recently demonstrated [18]. Such calculations present the great advantage that any baryon-baryon interaction can be determined, once the NN potential has been fixed, in a completely parameter-free way. Therefore the quark-model framework provides an adequate scheme to study nonnucleonic configurations on the deuteron without the aforementioned uncertainties appearing in meson-exchange models.

In the present work we want to focus on the influence of the most important nonnucleonic channels on the deuteron properties. In order to have a consistent calculation we will make use of baryonic potentials constructed from the same underlying quark-quark interaction potential so that no parameters are fitted independently for the different channels. The quark-model parameters have been previously determined to describe the deuteron binding energy and S -wave NN phase shifts with enough accuracy so that conclusions on the role played by the different channels, and thus, by the $N^*(1440)$ resonance or Δ can be inferred.

Within the quark model framework, this problem has already been partially undertaken using different approximations. The possible effects of a bigger Hilbert space were considered in Ref. [19] through the formation of six-quark bags at short distances. Reference [14] proposed an alternative formulation in terms of quark-shell configurations, later on projected onto physical channels. Reference [20] proposed an indirect calculation where the nonnucleonic configurations were not explicitly considered for the calculation of the two-body system. As a consequence, these methods rely again on several hypotheses that could hide physical conclusions. In Ref. [21] the influence of N and Δ resonances on the NN interaction has been studied. The most significant contribution was obtained from channels involving N and Δ ground states, although a quantitative calculation of the nonnucleonic configurations was not performed.

Among the various constituent quark models already available in the literature, to have a reliable prediction for the nonnucleonic components of the deuteron one should require an accurate description of the bound state and, at the same time, the 3S_1 and 3D_1 NN scattering partial waves. For consistency one should also require coherent results for the other

TABLE I. Quark-model parameters.

m_q (MeV)	313
b (fm)	0.518
α_s	0.498
α_{ch}	0.0258
m_σ (fm $^{-1}$)	3.538
m_π (fm $^{-1}$)	0.70
Λ (fm $^{-1}$)	4.30

NN S wave, the 1S_0 . The model of Refs. [15,22] fulfills the above requirements. The present study has been done by means of a Lippmann-Schwinger formulation of the RGM equations in momentum space [22].

In our calculation Eq. (20) of Ref. [22] has been generalized to a coupled channel scheme. It implies a modification of Eq. (24) of Ref. [22] with additional terms which contain the different $NN \rightarrow NN^*$ couplings. The calculation of the transition potential has been simplified using the Born-Oppenheimer approximation. We have carefully checked the quality of our approximation in order to guarantee that our results will not be influenced. It can be seen that the on-shell properties for the low angular momentum partial waves obtained by means of the Born-Oppenheimer method are of the same quality (within 5% for energies below 250 MeV) as those obtained, using the same quark model Hamiltonian, but making use of the RGM [23].

The potential yields a fairly good reproduction of the experimental data up to laboratory energies of 250 MeV. In Table I we quote the quark model parameters that have been taken from Ref. [22]. As can be seen, a fine tuning has been done in order to consider the other nonnucleonic configurations. Let us finally mention that the quark-quark interaction used reproduces the even-parity baryon spectrum [N , $N^*(1440)$, $\Delta(1232)$, $\Delta(1600)$,...] in an exact Faddeev calculation [24].

Within the above described framework we have calculated the deuteron binding energy and wave function making emphasis in a simultaneous description of the NN scattering phase shifts. For the bound state problem, Eq. (20) of Ref. [22] can be discretized in momentum space and written as

$$\sum_j (H_{ij} - E \delta_{ij}) \Psi_j = 0, \quad (1)$$

where we have used a simplified notation and the indices i and j run not only for all the discretization points but also for the different channels included in the calculation. The non-trivial solutions are given by the zeros of the Fredholm determinant

$$|H_{ij} - E \delta_{ij}| = 0, \quad (2)$$

being the values of E that satisfy the previous equation the energy of the bound states. Once the energies have been found the wave function can be easily calculated solving the linear problem of Eq. (1).

We show in Table II the different configurations and partial waves included in our calculation. In Table III we present

TABLE II. Different channels and partial waves considered in our calculation. We give in the second column the energy difference (MeV) with respect to the NN system.

NN	3S_1 - 3D_1	0.0
$NN^*(1440)$	3S_1 - 3D_1	501.0
$\Delta\Delta$	3S_1 - 3D_1 - 7D_1 - 7G_1	586.0

the results obtained for the nonnucleonic probabilities and the static properties of the deuteron. In all cases the deuteron binding energy is correctly reproduced, being $E_d = -2.2246$ MeV. We have shown the results of a calculation including only NN components, including NN and $\Delta\Delta$ configurations and finally the full calculation including also $NN^*(1440)$ configurations. Among the allowed configurations, the $NN^*(1440)$ has not been usually included in the deuteron calculations due to the great uncertainty associated to the coupling constant and cutoff parameters [8,11]. The first result we would like to emphasize is the fact that the probability of $NN^*(1440)$ channels are smaller than the $\Delta\Delta$ ones. They do not show much influence on the static properties of the deuteron as it seems to be case for the deuteron form factors [25]. However, these small components find support in the explanation given in the literature to some deuteron reactions [4–6]. Subthreshold antiproton production in $d-p$ and $d-d$ reactions [5], $pd \rightarrow dp$ reactions [6], or antiproton-deuteron annihilation at rest [4] are compatible with small percentage of $NN^*(1440)$ in the deuteron wave function.

The prediction we obtain for the $NN^*(1440)$ probabilities, a larger component of the ${}^3D_1[NN^*(1440)]$ partial wave than the ${}^3S_1[NN^*(1440)]$ partial wave, agrees with the ordering obtained by other calculations present in the literature [11,21]. This can be understood if one takes into account that the tensor coupling, which is the main responsible for the presence of nonnucleonic components on the deuteron wave function, is much stronger for the ${}^3S_1(NN) \rightarrow {}^3D_1[NN^*(1440)]$ transition than for the ${}^3D_1(NN) \rightarrow {}^3S_1[NN^*(1440)]$ one, enhancing in this way the D -wave influence with respect to the S -wave component. Regarding the absolute value of the probabilities, our results are a factor 10 smaller than those reported on Ref. [11], where an estimation of 0.17% for the $NN^*(1440)$ configuration was obtained (0.06% for the 3S_1 and 0.11% for the 3D_1 partial wave). The dependence of this result on the hypothesis made and the deviation from the results we obtain could be understood in the following way. The deuteron is calculated using the Reid hard-core potential. When including $NN^*(1440)$ components, the channel coupling induces an attractive in-

teraction on the NN system, that needs to be subtracted out. Such a subtraction was done by reducing the intermediate range attraction of the central part of the Reid hard-core potential without modifying the tensor part, as was done in Ref. [7] to calculate the probability of $\Delta\Delta$ components. As a consequence, in these type of calculations the strength of the tensor coupling to the $NN^*(1440)$ state can be enhanced by decreasing the intermediate range attraction in the NN channel. The balance between these two sources of attraction cannot be disentangled in a clearcut way. This is a similar problem to the one arising in the ${}^1S_0(NN)$ partial wave when the coupling to the $N\Delta$ system was included [26]. The same attractive effect could be obtained by a central potential or a tensor coupling to a state with higher mass, being necessary other observables to discriminate between the two processes [26]. This seems to be the reason of the much bigger probability for the $NN^*(1440)$ components in Ref. [11], that on the other hand showed a great dependence on the choice of the NN phenomenological potential. In Ref. [21], although the contribution of resonance configurations has been included to study the nucleon-nucleon system, there are no numerical predictions to compare with.

There are other estimations on the literature. The results of Ref. [8] are only of qualitative interest. The pathological behavior of the transition potential to resonance states was regularized by a cutoff factor that made the potential too weak at small distances. In Ref. [20] they study the effective numbers for different resonance configurations on the deuteron making use of baryon wave functions obtained from the diagonalization of a quark-quark interaction containing gluon and pion exchange in a harmonic oscillator basis including up to $2\hbar\omega$ excitations, and deuteron wave functions obtained from the Paris potential or a different quark model approach. They obtain an upper limit of 1% for $\Delta\Delta$ components and 0.1% for $NN^*(1440)$ in agreement with the order of magnitude and ordering of our results.

To summarize, we have studied the resonance structure of the deuteron using quark-model based interactions. The $NN^*(1440)$ baryon resonance probabilities in the deuteron, being smaller than the $\Delta\Delta$ ones, are in agreement with indirect estimations obtained from the analysis of processes like subthreshold antiproton production on $d-p$ collisions or $pd \rightarrow dp$ reactions.

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TABLE III. Deuteron wave function (%).

NN		$NN^*(1440)$		$\Delta\Delta$				r_m (fm)	A_S (fm $^{-1/2}$)	η
3S_1	3D_1	3S_1	3D_1	3S_1	3D_1	7D_1	7G_1			
95.3780	4.6220							1.976	0.8895	0.0251
95.1989	4.5606			0.1064	0.0035	0.1243	0.0063	1.985	0.8941	0.0250
95.1885	4.5377	0.0022	0.0148	0.1224	0.0036	0.1245	0.0063	1.985	0.8941	0.0250

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