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THE p(d,d′) REACTION AND THE σNN*(1440) COUPLING CONSTANT

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We make use of a NN $\to$ NN*(1440) transition potential derived from a quark model in a parameter-free way, to study the Roper excitation diagram contributing to the reaction p(d, d′). We also determine the πNN*(1440) and σNN*(1440) coupling constants.

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1. Introduction

The N*(1440) (Roper) is a broad resonance which couples strongly (60 −70%) to the πN channel and significantly (5−10%) to the σN channel [1]. It may therefore play an important role in nuclear dynamics as an intermediate state. Graphs involving the excitation of the N*(1440) appear in many different reactions from the p(α, α') to the heavy-ion collisions at relativistic energies [2−7].

Usually, the NN $\to$ NN*(1440) transition potential is taken as a straightforward generalization of some pieces of the NN interaction, scaling the coupling constants and incorporating resonance width effects. However, this procedure may have serious shortcomings, especially concerning the short-range part of the interaction [8].

Here we present some applications of a recently derived NN $\to$ NN*(1440) transition potential [9], obtained by means of the same quark-model approach previously used to study the NN system and transition potentials involving the Δ resonance [8, 10]. The main feature of the quark treatment is its universality in the sense that all baryon-baryon interactions are treated on an equal footing. Therefore, once the model parameters are fixed from NN data, there are no free parameters for any other case. A second important aspect is the appearance of quark exchanges between baryons, coming from quark antisymmetry. As quarks cannot be exchanged between two baryons if their wave functions do not overlap, the exchange contributions have necessarily short range.

After a brief description of the quark model based NN → NN*(1440) interaction (a complete discussion can be found in Ref. [9]), we focus our attention to the study of a reaction mediated by the excitation of the Roper resonance, the $\mathrm{p(d,d')}$ reaction, and on the derivation of the πNN*(1440) and σNN*(1440) coupling constants.

2. NN → NN*(1440) *transition potential*

In the Born-Oppenheimer approximation, the NN → NN*(1440) potential at interbaryon distance R is obtained by sandwiching the qq potential between NN and NN*(1440) states, written in terms of quarks, for all pairs formed by two quarks belonging to different baryons. In the model of Ref. [9], the qq potential contains a confining term taken to be linear (r_{ij}), the usual perturbative one-gluon-exchange (OGE) interaction containing Coulomb ($1/r_{ij}$), spin-spin ($\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j$) and tensor ($S_{ij}$) terms, and pion (OPE) and sigma (OSE) exchanges as a consequence of the breaking of chiral symmetry. The N*(1440) and N are given by $|\mathrm{N}^*(1440)\rangle = \left\{\sqrt{\frac{2}{3}}|[3](0\mathrm{s})^2(1\mathrm{s})\rangle - \sqrt{\frac{1}{3}}|[3](0\mathrm{s})(0\mathrm{p})^2\rangle\right\} \otimes [1^3]_\mathrm{c}$ and $|N\rangle = |[3](0s)^3\rangle \otimes [1^3]_\mathrm{c}$, where $[1^3]_\mathrm{c}$ is the completely antisymmetric color state, [3] is the completely symmetric spin-isospin state and $0s$, $1s$, and $0p$, stand for harmonic oscillator orbitals.

In Fig. 1, we show the potentials obtained for $L = 0$ ($^1S_0$ and $^3S_1$). The interaction is repulsive at short range ($0 < R$ (fm) < 0.6), attractive at intermediate range

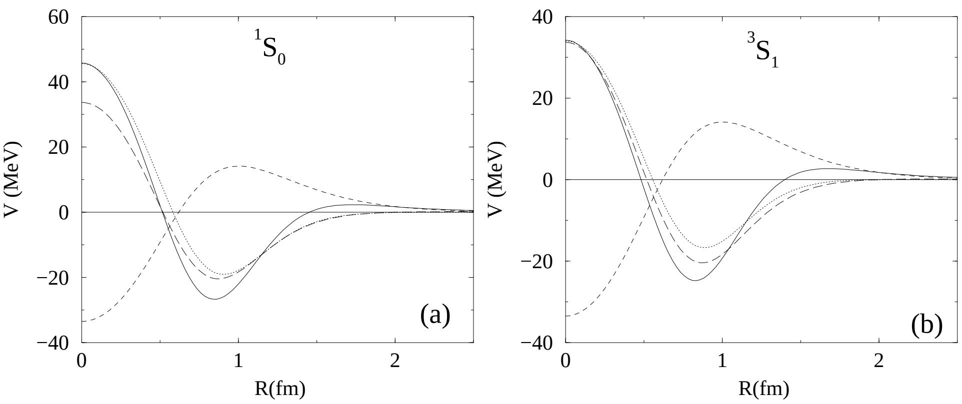

Fig. 1. NN → NN*(1440) *potential for (a) the* $^1S_0$ *partial wave, and (b) the* $^3S_1$ *partial wave. We have denoted by the long-dashed, dashed and dotted lines the central OPE, OSE and OGE contributions, respectively. By the solid line we plot the total potential.*

(0.6 < R (fm) < 1.4), and asymptotically repulsive. The last behavior is contrary to the naive expectation. This sign reversal is a direct consequence of the presence of a node in the N*(1440) wave function which implies a change of sign with respect to the N wave function. Certainly, it is possible to choose the opposite sign for the N*(1440) wave function with respect the N, and in this case the long-range part of the transition potential would become attractive, but there would also be an unexpected change from repulsion to attraction at short-range. This makes evident that the NN $\to$ NN*(1440) transition potential looks very different from the NN interaction, and that the simple scaling procedure does not seem to be appropriate to derive the interaction with a resonance.

3. *Roper excitation in* pd *scattering*

There are two experiments where the N*(1440) resonance contribution has been isolated by means of model-dependent theoretical methods. The first one is the p(α, α') reaction carried out in Saclay [11] already ten years ago. The data showed two peaks in the cross section, the most prominent one attributed to a Δ excitation in the projectile (DEP) [12], and the second one explained as a Roper excitation in the target (RET) [3]. The second experiment is the p(d, d$'$) reaction, that was studied making use of the same mechanisms [13]. These two reactions are particularly interesting because in both cases the projectile (d or α) has $T = 0$. This ensures that the N*(1440) reaction mechanism can only be driven by a scalar interaction.

Our purpose in this section is the study the target Roper excitation process in the p(d, d$'$) reaction making use of the quark model NN $\to$ NN*(1440) transition potential. We will consider the data where the Δ contribution has been subtracted [13] as our experimental data. The amplitude for the elementary process of N*(1440) production can be written in terms of the scalar transition potential $(V_0)_{\mathrm{NN}\to\mathrm{NN}^*}$ as [13]

$$|M|^2 = 12 F_{\mathrm{d}}^2 \left(\frac{f'}{m_\pi}\right)^2 |G^*|^2 \left|(V_0)_{\mathrm{NN}\to\mathrm{NN}^*}(q_{\mathrm{cm}})\right|^2 q_{\mathrm{cm}}^2 \,. \tag{1}$$

The function $F_{\mathrm{d}}(\boldsymbol{k})$ is the deuteron form factor

$$F_{\mathrm{d}}(\boldsymbol{k}) = \int \mathrm{d}\boldsymbol{r}\ \phi^*(\boldsymbol{r})\ \mathrm{e}^{\mathrm{i}\frac{1}{2}\boldsymbol{k}\cdot\boldsymbol{r}}\ \phi(\boldsymbol{r}) \tag{2}$$

where $\phi(\boldsymbol{r})$ is the deuteron S-wave function, and the momentum $\boldsymbol{k} = \boldsymbol{p}_{\mathrm{d}} - \boldsymbol{p}_{\mathrm{d}'}$ is taken in the initial deuteron rest frame. q_{cm} is the momentum transfer between the nucleons in the center of mass system and $f' \equiv f_{\pi\mathrm{NN}^*}$. G^* is the N*(1440) propagator as given in Ref. [13].

In order to perform the calculation, we need to extract the genuine scalar potential at all distances from the quark-model based NN $\to$ NN*(1440) interaction. Such potential presents a non-trivial structure at short distances due to the quark antisymmetrizer, which involves operators of the type $(1 + \boldsymbol{\sigma}_i\boldsymbol{\sigma}_j)$ and $(1 + \boldsymbol{\tau}_i\boldsymbol{\tau}_j)$.

When combined with corresponding spin-isospin operators of each piece of the interaction, one obtains a general form $V^{(\mathrm{S,T})}_{\mathrm{NN}\to\mathrm{NN}^*} = V_0 + V_1(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2) + V_2\ (\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2) + V_3\ (\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)$, after projecting the quark spin-isospin degrees of freedom into nucleonic spin-isospin degrees of freedom [14]. From this projection, the functions V_i can be easily calculated [15]. In Fig. 2, we present the contribution to the p(d, d′) cross section coming from the different interactions at quark level.

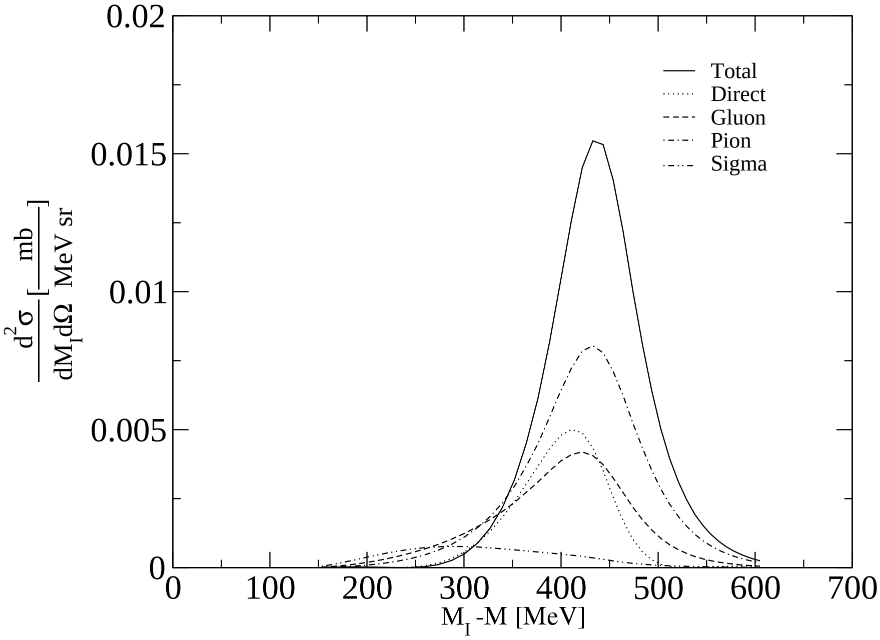

Fig. 2. Detailed contributions to the p(d, d′) *cross section coming from the different interactions at the quark level, neglecting the interference terms. We denote by direct the result obtained neglecting quark-exchange diagrams.* M_I *is the invariant mass of the target system.*

The most important ones are those from the scalar pieces generated from the pion and gluon exchange combined with quark exchanges. This shows that the process is driven by the short-range part of the interaction, where quark exchanges are relevant. In Fig. 3, we compare the result obtained using the quark-model derived NN → NN*(1440) potential to the experimental data. As can be seen, the cross section is underestimated, coming closer to data if one chooses a smaller value for the N*(1440) width ($\Gamma^* = 90$ MeV instead of $\Gamma^* = 300$ MeV as used in Ref. [13]). The bigger disagreement with the extracted data corresponds to the region where the error bars are larger, in other words, to the region where the uncertainties related to the theoretical method used to subtract the Δ contribution and interference term are important. The subtraction of the Δ contribution is proportional to the square of the $\pi N\Delta$ coupling constant. Its value is different in baryonic processes,

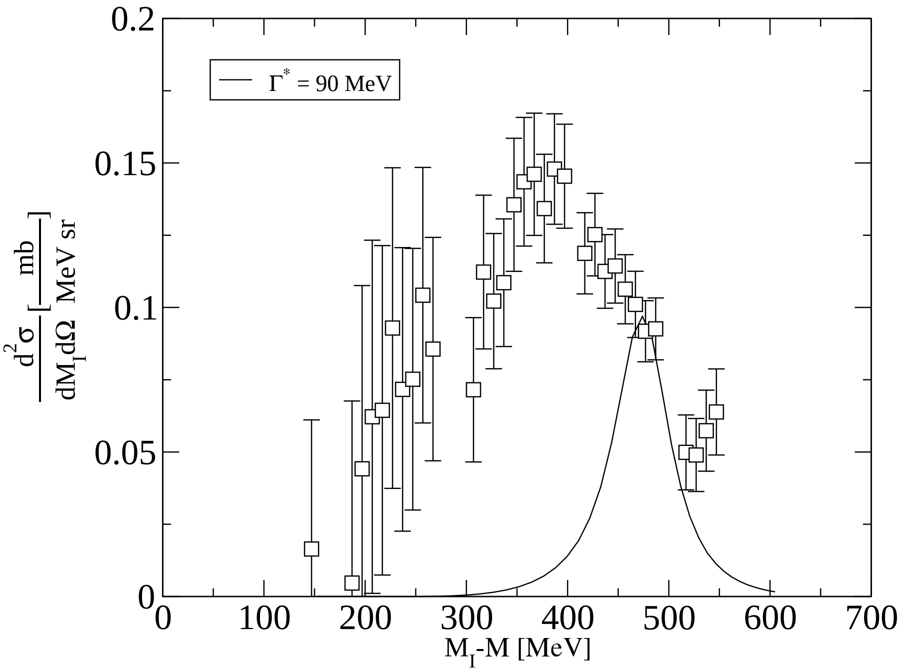

Fig. 3. Quark model result for the RET process contributing to the $\mathrm{p(d, d')}$ *reaction.* M_I *is the invariant mass of the target system. Experimental data correspond to* T_d = *2.3* GeV *and* θ^L = *1.1 deg. They were obtained in Ref. [13] by means of a theoretical subtraction of the* Δ *contribution.*

$f^2_{\pi N\Delta}/4\pi = 0.35$, than the one used in our model, $f^2_{\pi N\Delta}/4\pi = 0.22$ [16], because it includes tensor coupling between the $^1S_0$ NN and the $^5D_0$ NΔ partial waves. As a consequence, the baryonic calculation of the Δ contribution could be underestimating the region above the peak overestimating in this way the N*(1440) contribution. The way to wipe out those uncertainties would be to calculate the Δ contribution together with the interference term making use of quark-model potentials.

4. πNN*(1440) *and* σNN*(1440) *coupling constants*

The usual way to determine the meson-NN coupling constants is through the fitting of NN scattering data with phenomenological meson exchange models, or using a microscopic model of the decay vertex (like, for example, a pair creation model) that fits the meson-NN decay width. However, as NN*(1440) scattering data do not exist, and we do not have a clear picture of the structure of the σ meson, one has to resort to another procedure to determine the meson-NN*(1440) coupling constants.

Taken into account that the quark transition potential obtained can be written at all distances in terms of baryonic degrees of freedom [16], one way to obtain the coupling constants is to parametrize the asymptotic central interactions as

$$V^{\rm OPE}_{\rm NN\to NN^*(1440)}(R) = \frac{1}{3}\,\frac{g_{\pi\rm NN}}{\sqrt{4\pi}}\,\frac{g_{\pi\rm NN^*(1440)}}{\sqrt{4\pi}}\,\frac{m_\pi}{2M_{\rm N}} \times \frac{m_\pi}{2(2M_r)}\,\frac{\Lambda^2}{\Lambda^2-m_\pi^2}\,[(\boldsymbol{\sigma}_{\rm N}.\boldsymbol{\sigma}_{\rm N})(\boldsymbol{\tau}_{\rm N}.\boldsymbol{\tau}_{\rm N})]\,\frac{{\rm e}^{-m_\pi R}}{R} \tag{3}$$

and

$$V^{\rm OSE}_{\rm NN\to NN^*(1440)}(R) = -\,\frac{g_{\sigma\rm NN}}{\sqrt{4\pi}}\,\frac{g_{\sigma\rm NN^*(1440)}}{\sqrt{4\pi}}\,\frac{\Lambda^2}{\Lambda^2-m_\sigma^2}\,\frac{{\rm e}^{-m_\sigma R}}{R}\,. \tag{4}$$

By comparing these baryonic potentials with the asymptotic behavior of the ones previously calculated from the quark model, we can extract the πNN*(1440) and σNN*(1440) coupling constants in terms of the elementary πqq coupling constant and the one-baryon model dependent structure.

The $[\Lambda^2/(\Lambda^2-m_i^2)]$ vertex factor in Eqs. (3) and (4) comes from the vertex form factor chosen at momentum space at the quark level, $[\Lambda^2/(\Lambda^2+\boldsymbol{q}^{\,2})]^{1/2}$, where chiral symmetry requires the same form for pion and sigma. Then it is clear that the extraction from any model of the meson-baryon-baryon coupling constants depends on this choice. We shall say, they depend on the coupling scheme.

To get $g_{\pi\rm NN^*(1440)}/\sqrt{4\pi}$, we take our results for the $^1S_0$ one-pion exchange potential, and we fit its asymptotic behavior (in the range $R: 5 \to 9$ fm) to Eq. (3). We obtain

$$\frac{g_{\pi\rm NN}}{\sqrt{4\pi}}\,\frac{g_{\pi\rm NN^*(1440)}}{\sqrt{4\pi}}\,\frac{\Lambda^2}{\Lambda^2-m_\pi^2} = -\,3.73\,, \tag{5}$$

i.e., $g_{\pi\rm NN^*(1440)}/\sqrt{4\pi} = -0.94$. As explained above, only the absolute value of this coupling constant is well defined. In Ref. [17] a different sign with respect to our coupling constant is obtained what is a direct consequence of the different global sign chosen for the N*(1440) wave function. The coupling scheme dependence can be explicitly eliminated if we compare $g_{\pi\rm NN^*(1440)}$ with $g_{\pi\rm NN}$ extracted from the NN $\to$ NN potential within the same quark model approximation. Thus we get

$$\left|\frac{g_{\pi\rm NN^*(1440)}}{g_{\pi\rm NN}}\right| = 0.25\,. \tag{6}$$

This ratio is similar to that obtained in Ref. [17] and a factor 1.5 smaller than the one obtained from the analysis of the partial decay width. Nonetheless, one can find in the literature values for $f_{\pi\rm NN^*(1440)}$ ranging between 0.27−0.47 coming from different experimental analyses with uncertainties associated to the fitting of parameters [1, 3, 17].

By proceeding in the same way for the OSE potential, we obtain

$$\left|\frac{g_{\sigma\rm NN^*(1440)}}{g_{\sigma\rm NN}}\right| = 0.47\,. \tag{7}$$

Our result agrees quite well with the only experimental available result, obtained in Ref. [18], 0.48. Furthermore, we can give a very definitive prediction of the magnitude and sign of the ratio of the two ratios,

$$\frac{g_{\pi \mathrm{NN}^*(1440)}}{g_{\pi \mathrm{NN}}} = 0.53\, \frac{g_{\sigma \mathrm{NN}^*(1440)}}{g_{\sigma \mathrm{NN}}}\,, \tag{8}$$

which is an exportable prediction of our model.

5. *Conclusion*

We have carried out a test of a quark-model based NN $\rightarrow$ NN*(1440) potential derived from an universal qq interaction. The consideration of the long-range tail of the potential as compared to the baryonic parametrization allows the extraction of the πNN*(1440) and σNN*(1440) coupling constants. On the other hand the consideration of the physical mechanisms involved in the reactions $\mathrm{p}(\alpha, \alpha')$ and $\mathrm{p}(\mathrm{d}, \mathrm{d}')$, in particular the RET, allows to test the scalar short-range part of the interaction. The results we get are quite encouraging in spite of the lack of a full quark model calculation. To pursue this could open a new way to search for effects of the microscopic structure in the mentioned processes.

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REAKCIJA p(d, d′) I KONSTANTA VEZANJA σNN*(1440)

Primjenjujemo prijelazni potencijal NN $\to$ NN*(1440), izveden iz kvarkovskog modela bez parametara, radi proučavanja doprinosa Roperovog dijagrama uzbude reakciji p(d, d′). Također određujemo konstante vezanja πNN*(1440) i σNN*(1440).