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# Nijmegen Model
# -recent theoretical developments-

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## I. INTRODUCTION

We present a new potential model for the low-energy baryon-baryon interaction, henceforth referred to as the extended-soft-core (ESC) model. The first results with the ESC-model were reported in [1]. The ESC model is an extension of the original one-boson-exchange (OBE) Nijmegen soft-core models [2, 3]. The particular characteristics of the ESC-model are as follows. The OBE potentials are due to the contribution of the $\pi$, $\eta$, $\eta'$, $\rho$, $\omega$, $\phi$, $a_0$, $\epsilon$, $f_0$, $a_2$, and Pomeron ($P$) Regge trajectories. The OBE-potentials are identical to those of [2, 3]. In the ESC-model we include in addition to these OBE potentials (i) two-pion-exchange (TPE) potentials, (ii) meson-pair-exchange (MPE) potentials, and (iii) two-meson-exchange (TME) potentials.

The TPE potentials are taken from [4], where the two-pion-exchange potential with Gaussian form factors is derived. In contrast to [1] we have now included both the BW- and the TMO-contributions, see [4] for the nomenclature, to the TPEP's and the TMEP's.

The MPE potentials involve the meson-pair baryon couplings. The latter are assumed to be saturated by (heavy) boson contributions. Here constraints from chiral-invariant Lagrangians, see for example [5, 6], are considered. We limit ourselves to the $\pi\pi$-, $\pi\rho$-, $\pi\omega$-, $\pi\sigma$-, and $\sigma\sigma$-pair vertices. (The $\sigma$ stands here for the contribution of the two-pole approximation of the broad $\epsilon$ meson.)

The TME potentials contains the contributions of the $\pi\otimes\rho$, $\pi\otimes\omega$, $\pi\otimes\epsilon$, $\sigma\otimes\sigma$, and $\pi\otimes P$ potentials. Like in the TPE case, also here we restrict ourselves to nucleons and mesons in the intermediate states. A strong motivation for the inclusion of these TME potentials is that in the pion-nucleon system the Born terms are important for a proper description of the pion-nucleon scattering lengths. The same can be expected to hold for the low-energy pion production of the $\rho$, $\omega$, etc. Also, having covered these contributions to the pion-meson exchange, one could reasonably expect that the meson-pair vertices are dominated by the heavy bosons. This makes these vertices accessible to a theoretical interpretation using couplings from chiral-symmetry models.

The form factor treatment is different from that in [2, 3]. We allow more freedom by using independent cut-off masses for the different mesons. We treat as free parameters the cut-off's for the $\pi$-, $\rho$-, $\omega$-, and the $\epsilon$-meson. For all other mesons we have put $\Lambda = 990$ MeV.

The interaction Lagrangians define in principle an effective relativistic theory. In the two-nucleon sector, the interaction kernel for the relativistic two-nucleon equation, is given by the two-nucleon irreducible Feynman diagrams. We apply the procedure of Salpeter [7] to the relativistic two-nucleon equation, i.e., we perform the integrals over the relative energies. In order to carry through this procedure, we employ the ansatz of Macke and Klein [8]. This leads to a three-dimensional momentum-space integral equation identical to that of Thompson [9]. The kernels for the potentials in momentum space correspond exactly to the "old-fashioned perturbation" diagrams. For example, in the case of the OBE kernels the off-energy-shell behavior is the same as, e.g., in [10], and contains the proper nonadiabatic effects. In this paper we will neglect these nonadiabatic effects, which means that we have the usual OBE potentials as in [2, 3].

## II. ESC MISCELLANEA

In [1] we introduced phenomenological nucleon meson-pair interactions to improve the fit to the nucleon-nucleon data. The meson-pair contributions account for the two-particle cuts. For example in the case of the $(\pi\pi)_1$-pair, the two-pion vertex correction to $\rho$-exchange implicitly included. Therefore, our choice of the gaussian form factor type is a very natural one. The inclusion of the pair-interactions strengthens the arguments for gaussian form factors which are coming from (i) the quark-model picture of the nucleons and (ii) the usual Regge residue parametrization.

We neglect the contributions from the negative-energy states of the nucleons. We assume that at low energies a strong "pair suppression" mechanism, i.e., suppression of the nucleon-antinucleon ($N\overline{N}$) pairs, is operative. In this context we refer to the compositeness and the large mass of the nucleons. This, of course, taking into account the fact that we are studying the low-energy regime. From relativity we know that pair suppression cannot be absolute. However, we mention that strong pair suppression is very plausible from the nonrelativistic quark-model (NRQM) point of view [11]. Also, in the chiral quark-model picture [12] it is rather unlikely that $N\overline{N}$ pairs play a role in the low-energy region. Now it turns out, see the results below, that the $(\pi\pi)_0$-pair-interactions of our model can not be considered as being remnants of the strong ($N\overline{N}$) pairs originating from the ps-type pion-nucleon coupling. Instead, the pair-vertices can be explained successfully in terms of (heavy) boson ($\rho$, $\sigma$, $A_1$, etc.) saturation (see below).

Also, the pair-interactions have an important role in the following sense. The contributions coming from intermediate states with nucleon resonances are not included explicitly. These effects are considered to be covered by the OBE potentials and in particularly by the MPE potentials in a dual sense [13, 14], for energies well below the resonance thresholds.

Since we assume that there are in principle no $N\overline{N}$ pairs, but we admit a rather strong contribution to the potentials from scalar-meson exchange, our model could be expected to be at variance with the soft-pion-theorems. Here the Pomeron contribution plays an important role. The $\epsilon - P$ cancellation is such that there is no real conflict with chiral symmetry, see [14]. We have argued in several places for the inclusion of the Pomeron in low-energy dynamics, see, e.g., [14]. As an explanation, both the two-gluon and the multi-peripheral picture as a representation of the Pomeron are appealing. As to the latter, multi-soft-pion and multi-meson effects can be expected to play a role, both in chiral Lagrangian models and QCD. High-energy experiments indicate that the Pomeron couples to the quarks [15]. This is an important feature in order to explain that the Pomeron-potential is repulsive [16].

## III. RESULTS NUCLEON-NUCLEON

The recent Nijmegen energy-dependent partial-wave analysis of the $NN$ data [17] is used in fitting the parameters of the model. In the analysis [17] the energy range for both $pp$ and $np$ is now $0 < T_{\rm lab} < 350$ MeV and a $\chi^2_{\rm d.o.f.} = 1.08$ was reached. We use in the fit the corresponding single-energy $\chi^2$ surfaces. With the new model we succeeded in reducing the gap between theory and experiment at low energies considerably. For the energies

$T_{\rm lab} = 0 - 350$ MeV we reached a record low $\chi^2$ per datum of 1.15 [18]. The parameters of a characteristic ESC-fit to the $NN$ data are given in table 1.
Note that in the table we give rationalized couplings, i.e. $f_\pi \equiv f_\pi/\sqrt{4\pi}$ , $g_{(\pi\pi)_0} \equiv g_{(\pi\pi)_0}/4\pi$ and the underlined entries are not searched but fixed parameters. Moreover, the given values correspond to the couplings at zero momentum transfer. The pion-nucleon coupling constant enters in many pieces of the ESC-potential. Therefore it is gratifying that the value of [17] gives indeed a minimum for the ESC-model. Furthermore, notice that we have a really soft OPE-potential. This could be understood as a coupling of the pion to the low mass tail of the broad $\epsilon$-meson. The $NN$-systems determine in particular the combination $(g+f)^2_\rho$, which enters the spin-spin and the tensor potentials. The ESC-model result is in between the VDM and the OBE-model [2] values. Finally, we note that the Pomeron- and $\epsilon$-couplings are comparable to those of [2].

## IV. EXTENSION TO HYPERON-NUCLEON

An important motivation for the development of the ESC-model has been the experience with the soft-core OBE-model in hypernuclei studies e.g. [19, 20]. In order to be able to extend a nucleon-nucleon model to the hyperon- and cascade-nucleon systems, the model must be very theoretical in order that not too many arbitrary parameters are to be fixed by the rather poor $YN$ data. As we show in table 2, the ESC-model is in this respect very promising.

Note that the values marked by $^*$ are theoretical input. For those marked by $^\dagger$ we note that the prediction from $\sigma$-saturation would imply resp. $-0.83$ and $-0.16$. In view of the $\sigma - P$ cancellation the values can be explained. (In a complete model, one should strictly include besides the $\pi\sigma$- and $\sigma\sigma$-pairs also $\pi P$-, $\sigma P$-, and $PP$-pairs.)

In view of the nice theoretical background, shown in the Table above, the extension of the ESC-model from nucleon-nucleon to hyperon-nucleon can be carried through using SU(3)-symmetry. For example, for the $(\rho\pi)_1$-pair interactions we have from $A_1$-saturation $g_{Y'Y(\rho\pi)_1} = \hat{g}_{Y'YA_1} g_{A_1\rho\pi}\ (m_\pi^2/m_{A_1}^2)$ , e.g.

$$g_{\Sigma\Lambda(\rho\pi)_1} = \hat{g}_{\Sigma\Lambda A_1} g_{A_1\rho\pi}\, \frac{m_\pi^2}{m_{A_1}^2} \ = \ (\hat{g}_{\Sigma\Lambda A_1}/\hat{g}_{NNA_1})\ g_{NN(\rho\pi)_1} \ = \frac{2}{\sqrt{3}}\,(1-\alpha_A)\, g_{NN(\rho\pi)_1}$$

The construction of the ESC-model for the Hyperon-Nucleon and the Cascade-Nucleon channels is in progress.

## V. CONCLUSION AND OUTLOOK

The ESC-model provides an excellent fit to the $NN$ data. Moreover the introduced pair-couplings, which were originally introduced primarily with only a phenomenological justification [1], turned out to be fully interpretable theoretically. The successful interpretation of the pair-couplings using heavy meson saturation makes the ESC-model ideal for the extension to Hyperon-Nucleon and Cascade-Nucleon systems.

Moreover, from the dual picture of strong interactions [13] we can argue that the ESC-model is essentially also a complete dynamical model. At low energies, the effect of the meson-nucleon resonances is implicitly included in the pair-interactions.

The development of ESC-models for the Hyperon- and Cascade-Nucleon channels is under way. These models will give a rather complete and a quantitative description of high quality as far as the hadronic degrees of freedom are concerned. Effects of explicit quark and gluonic degrees of freedom are not contained in the ESC-model and it will be very interesting to see what the eventual shortcomings of such a purely hadronic model will be.

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# TABLES

| ps-pv | | vector | | scalar | | pairs | |
|---|---|---|---|---|---|---|---|
| $f_\pi$ | 0.267 | $g_\rho$ | 0.405 | $g_\delta$ | 1.778 | $g_{(\pi\pi)_0}$ | 0.141 |
| $f_\eta$ | 0.069 | $f_\rho$ | 3.111 | $g_\epsilon$ | 4.740 | $g_{(\pi\pi)_1}$ | 0.023 |
| $f_{\eta'}$ | 0.184 | $g_\omega$ | 3.358 | $g_{A_2}$ | 0.0 | $f_{(\pi\pi)_1}$ | 0.018 |
| | | $f_\omega$ | 0.893 | $g_P$ | 2.712 | $g_{(\pi\rho)_0}$ | -.063 |
| $\Lambda_{P_8}$ | 628.1 | $\Lambda_{V_8}$ | 826.4 | $\Lambda_{S_8}$ | 990.0 | $g_{(\pi\rho)_1}$ | -.417 |
| $\Lambda_{P_1}$ | 990.0 | $\Lambda_{V_1}$ | 1080 | $\Lambda_{S_1}$ | 939.9 | $g_{(\pi\omega)}$ | 0.046 |
| | | | | $m_P$ | 309.0 | $g_{(\pi\sigma)}$ | -0.328 |
| | | | | | | $g_{(\sigma\sigma)}$ | 0.095 |

TABLE I. Coupling constants, cut-off's, and pair couplings.

| $J^{PC}$ | $(M_1M_2)_I$ | Boson | Prediction | Fit |
|---|---|---|---|---|
| $0^{++}$ | $(\pi\pi)_0$ | $\sigma(760), P$ | $g_{(\pi\pi)_0} = 0.00^\dagger$ | 0.14 |
| $1^{--}$ | $(\pi\pi)_1$ | $\rho(760)$ | $g_{(\pi\pi)_1} = 0.02$ | $0.02^*$ |
| | | | $f_{(\pi\pi)_1} = 0.18$ | $0.18^*$ |
| $1^{++}$ | $(\pi\rho)_1$ | $A_1(1270)$ | $g_{(\pi\rho)_1} = -.42$ | $-.42^*$ |
| | $(\pi\sigma)_1$ | $A_1(1270)$ | $g_{(\pi\sigma)} = -.16$ | $-.33$ |
| $1^{+-}$ | $(\pi\rho)_0$ | $H(1190)$ | $g_{(\pi\rho)_0} =$ - - | $-.06$ |
| | $(\pi\omega)$ | $B(1235)$ | $g_{(\pi\omega)} =$ - - | 0.05 |
| $0^{++}$ | $(\sigma\sigma)$ | $\sigma(760), P$ | $g_{(\sigma\sigma)} = 0.00^\dagger$ | 0.10 |
| | $(\pi\eta)$ | $\delta(980)$ | $g_{(\pi\eta)} = -.02$ | $-.02^*$ |
| | $(\pi\eta')$ | $\delta(980)$ | $g_{(\pi\eta')} = 0.00$ | $0.00^*$ |

TABLE II. MPE-couplings: Predictions and Fit