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The Nijmegen hyperon-nucleon potentials*

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Abstract

The Nijmegen YN potential models are reviewed. Differences with the models constructed by the Jülich group are highlighted. A mini-review is given of the status of the scalar mesons and their relevance for the NN and YN interactions. Finally, the reactions $\overline{N}N \rightarrow \overline{Y}Y$ are discussed.

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I. INTRODUCTION

Realistic models for the hyperon-nucleon (YN) and hyperon-hyperon (YY) interaction are relevant to the study of flavor symmetry in strong interactions, the understanding of the properties of hypernuclei, multiquark states, neutron-star matter, and so on. The Nijmegen group has been constructing such models for many years now. In Table I one can find the different NN models and their YN counterparts: the hard-core models A to F, the soft-core (SC) model, and its recent 1993 NN update (not yet extended to the YN channels). With the exception of model A, which includes a TPE potential, they are all OBE models. From the χ^2-values listed it can be seen that the NN models have improved enormously over the years. The χ^2-values for the YN models have little meaning, since no new YN scattering data have become available since the sixties. YY scattering data are even non-existent. Still, theoretically the YN models have also improved.

The existing YN data are few and of low quality. (Additional constraints come from the hypernuclei [11]). There is essentially only information about the S waves. In building a YN model, therefore, one should use probably at most about 5 adjustable parameters. Flavor $SU(3)$ symmetry is a good starting point to reduce the number of parameters. It is clear, however, that $SU(3)$ is not a very good symmetry of the strong interactions (for a review see Ref. [12]). It is e.g. very much broken by the low pion mass. Unbroken $SU(3)$ would predict a $\{10^*\}$ of bound BB states, to which the deuteron belongs, and a $\{27\}$ of virtual bound states [13]. Realistically, one can only expect to see remnants of $SU(3)$. In the Nijmegen models, the kinematic breaking of $SU(3)$ is taken into account by using the correct masses of the mesons and baryons, but it is assumed that $SU(3)$ is still valid dynamically, i.e. $SU(3)$ is assumed for the coupling constants of the exchanged mesons. Of course, already in constructing the NN models $SU(3)$ has to be built in (although for NN itself it is not a strong constraint). For consistency, *complete* nonets must be included. Using only a few parameters, these NN models can then be extended to the YN channels. An additional advantage of this strategy is that predictions can be made for the YY and ΞN channels (which may be a good hunting ground for multiquark states [14–16]), since the interactions are (almost) fixed by $SU(3)$. $SU(3)$ for the coupling constants is very probably broken, but there are indications that this breaking is not enormous, so these predictions may actually be taken *somewhat* seriously.

It is sometimes stated that new YN data will easily discriminate between different models, such as the Nijmegen models D, F, and the SC model, and the YN models A and B constructed by the Jülich group [17]. To see that this is unlikely, one only has to look at the much better studied NN sector: realistic meson-exchange NN potentials, like the Paris model [18], the Nijmegen model [8], and the (full) Bonn model [19], are very different in terms of the physics input, but still, all three provide a more-or-less satisfactory description of the accurate and rich NN database. Similarly, disagreements with new YN data can probably be repaired by fine-tuning the parameters, relaxing some of the constraints, or making otherwise adjustments in the YN models. It is clear that *details* of the YN models are not severely tested by the existing experimental data. Issues like which terms of the potentials in an expansion of momentum should be kept or which type of form factor should be used, are probably irrelevant at present. For other more pronounced differences between the models, however, one can look for information elsewhere in strong-interaction physics.

An example is the treatment of the scalar mesons.

II. NIJMEGEN SOFT-CORE YN MODEL

Let us concentrate on the *SC* model and highlight some of the differences with the Jülich models. The *SC* model [8,9] is derived from Regge-pole theory [20]. At low energies the exchange of the lowest-lying trajectories in the complex-J plane reduces to the exchange of the conventional pseudoscalar, vector, and scalar mesons. Additional contributions come from the dominant $J = 0$ parts of the pomeron P and tensor-meson trajectories. The following complete nonets are included in the NN–YN model:

$$\begin{aligned} J^{PC} &= 0^{-+}: \ \pi; \eta, \eta'; K, \quad & J^{PC} &= 0^{++}: \ a_0; \varepsilon, f_0; K_0^*, \\ J^{PC} &= 1^{--}: \ \rho; \omega, \phi; K^*, \quad & J^{PC} &= 2^{++}: \ a_2; P \oplus f_2, f_2'; K_2^*. \end{aligned}$$

For the pseudoscalar mesons, $SU(3)$ is assumed for the couplings in the pseudovector form. The $F/(F+D)$ ratio $\alpha_{\rm PV} = 0.355$ found is in perfect agreement with $\alpha_{\rm W}$ determined from the semileptonic weak decays of the baryon octet. The mixing angle is taken to be $\theta_{\rm P} = -23°$. The coupling constants found for η_1 and η_8 imply a violation of the OZI rule [8]. In the Bonn/Jülich models, the η and η' are not included. The justification [21] for this assumption comes from a dispersion-relation analysis of NN discrepancy functions [22], where there was little room for a *sizable* η coupling. The η, η' couplings in the Nijmegen models are therefore thought to be *"an artefact of the OBE-approximation (...) due to the neglect of the 3π continuum"* [21]. However, the η and η' couplings in the *SC* model are much smaller than in model D and F. Besides, one can not really justify ignoring η and η' by citing Ref. [22]. The situation is not so clear-cut as suggested in Ref. [21]. To start with, in Ref. [22] a too large $NN\pi$ coupling $f^2_{NN\pi} = 0.079$ was used[1]. (Rationalized coupling constants are used here.) Since OPE is so dominant, changing $f^2_{NN\pi}$ to the state-of-the-art value 0.0745 of Ref. [23] will certainly change the 3π-cut contribution to the discrepancy function [24]. Also, in Ref. [22] a large a_1 coupling was found, whereas the a_1 meson is included neither in the Bonn nor in the Nijmegen potential. Further, the treatment of the "3π continuum" can never be correct in the Bonn/Jülich models, since their ω coupling is way too large! Finally, and perhaps most importantly in the present context, although the couplings of η and η' to the nucleon are probably not very large, how about the hyperons? In Ref. [17] one can read the puzzling matter-of-fact statement that η and η' *"contribute negligible to the NN as well as to the YN interaction."* Let us take $\alpha_{\rm PV} = 0.355$ and $f^2_{NN\pi} = 0.0745$. Then one finds for the octet member: $f^2_{\Lambda\Lambda\eta_8} = f^2_{\Sigma\Sigma\eta_8} = 9.5 f^2_{NN\eta_8}$ and $f^2_{\Xi\Xi\eta_8} = 16.6 f^2_{NN\eta_8}$. So although the coupling of η, η' to nucleons may be small, their coupling to Λ, Σ, and even more so Ξ can still be significant, as is physically clear. Including the mixing between η_1 and η_8 one finds that η couples mostly to Σ and η' mostly to Λ (in the *SC* model). In view of the obvious bearing that the η and η' have on issues like the strangeness content of the

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[1] This was pointed out to me by Prof. de Swart.

nucleon, information on their couplings from the YN interaction is important. Nothing will be learned from simply leaving them out.

For the vector mesons, the $F/(F+D)$ ratio for the electric couplings is taken to be $\alpha_{\rm V}^{\rm e}=1$ (universal coupling of the ρ to the isospin current), while the fit gives the magnetic ratio as $\alpha_{\rm V}^{\rm m}=0.275$, in perfect agreement with nonstatic $SU(6)$. Ideal mixing is assumed. Again, the couplings of the ϕ meson to the hyperons is far from negligible. The ω electric coupling is $g^2_{NN\omega}=8.7$, in agreement with $g^2_{NN\omega}=8.1(1.5)$ found in the above mentioned dispersion-relation analysis [22]. The Bonn/Jülich models have $g^2_{NN\omega}=20$. Universal ρ coupling together with ideal mixing and the OZI rule predicts $g^2_{NN\omega}=9g^2_{NN\rho}\approx$ 4–7. In general, the couplings of the vector mesons found in the SC model are not too far from the predictions of the naive quark model [9], even more so than in model D and F [25].

The treatment of the scalar mesons is one of the major differences between the Bonn/Jülich and Nijmegen approaches. *No* scalar mesons are included in the Jülich models, except for a fictitious "$\sigma(550)$" that parametrizes correlated TPE. As a consequence, the $NN\sigma$, $\Lambda\Lambda\sigma$, and $\Sigma\Sigma\sigma$ couplings can be adjusted more-or-less independently. In the SC model, on the other hand, a complete nonet of scalar mesons is included and the couplings are constrained by $SU(3)$. The mixing angle is found to be $\theta_{\rm S}=41^\circ$, not so far from the value 35° predicted in the $q^2\overline{q}^2$ picture. Although Ref. [17] seems to suggest that the SC model also includes a low-mass "σ" meson, this is not the case. It *does* include, however, a *broad* $\varepsilon(760)$, that cannot be found in the Tables of the Particle Data Group, and which, when treated properly, would give a potential of TPE range (as would the ρ). In the next section, the case will be made, once more, for a low-lying scalar nonet, and in particular the $\varepsilon(760)$ hidden under the $\rho^0(770)$ and the $K_0^*(887)$ hidden under the $K^*(892)$.

The pomeron is an essential ingredient in Regge-pole theory. In QCD, the physical nature of pomeron exchange is understood as color-singlet two- or multigluon exchange [26–28]. In the SC potential it provides a significant contribution to the short-range repulsion[2], as a result of which a realistic value for the ω coupling constant is obtained. Due to the inclusion of the pomeron, the coupling constants of the SC potential are consistent [29] with the soft-pion theorems for the πN S-wave scattering lengths [30].

The SC YN model contains 6 free parameters (not counting $\alpha_{\rm PV}$ and $\alpha_{\rm V}^{\rm m}$): 4 cut-offs in the exponential form factors, the mixing angle $\theta_{\rm S}$ for the scalar mesons, and an angle $\psi_{\rm D}$ that dials the mixing between the pomeron (an $SU(3)$ singlet, which is a mixture of the "bare" pomeron and the $SU(3)$ singlet $f_{2,1}$) and the $SU(3)$ octet $f_{2,8}$. Due to the strong theoretical constraints, there is really very little freedom in the SC model. In fact, it is very hard to avoid meaningless resonances when going to the YY and ΞN channels [31].

The Jülich model A includes π, ρ, ω, "$\sigma(550)$," K, and K^* exchange. Model B includes also 4th-order diagrams involving π, ρ, "$\sigma(550)$," K, and K^* exchange (but not ω) plus

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[2] During the theory session, the question was raised by Prof. Yazaki how a scalar-like pomeron exchange can be repulsive. The answer (Th. Rijken, private communication) appears to be that in the derivation from Regge-pole theory pomeron exchange automatically gives repulsion. In the Low-Nussinov two-gluon–exchange model it can also be understood: the adiabatic terms of the potential happen to cancel and the first non-adiabatic corrections turn out to be repulsive.

$\Delta(1232)$ and $Y^*(1385)$ contributions. (The sizable crossed-box diagrams are not included, however) The *SC* potential contains no 4th-order terms in the potential. One of the main reasons is that it is far from trivial to include these if one wants to apply $SU(3)$ in the same manner as in the OBE models, i.e. with the exchange of complete nonets. Even as we speak, however, Th. Rijken is biting the bullet to construct an NN model that includes two-meson exchanges consistently and is thus extendable to the YN channels.

III. THE SCALAR MESONS

The scalar mesons have always been a controversial topic. In early OBE models for the NN interaction there was a clear need for an isoscalar scalar "σ" meson with an effective mass of about 550 MeV [32–34]. While no such low-mass particle exists, there was some evidence in production experiments for a broad structure $\varepsilon(760)$ under the ρ^0, often explained away as a strong $\pi\pi$ final-state interaction. Later it was pointed out [35–37] that such a wide ($\Gamma \approx 640$ MeV) $\varepsilon(760)$ simulates the narrow-"σ" exchange in OBE models.

The situation in phase-shift analyses of $\pi\pi$ scattering data, obtained from reactions as $\pi N \rightarrow \pi\pi N$, has for a long time been confusing and not conclusive [38]. In these analyses the assumption has always been that only π exchange is relevant, while a_1 exchange can be neglected. Very recently, however, the situation has been much clarified [39]. Data on $\pi N \uparrow\rightarrow \pi^+\pi^- N$ using a polarized target provide unambiguous evidence for a broad $I = 0$ $0^{++}(750)$ state, when a proper amplitude analysis is done, including also a_1 exchange. In a similar amplitude analysis of data on $K^+ n \uparrow\rightarrow K^+\pi^- p$ [40] evidence is found for $I = 1/2$ $0^+(887)$ strange scalar mesons under the $K^*(892)$.

In the quark model, several mechanisms give rise to scalar ($J^P = 0^+$) mesons. The simplest model is the ${}^3P_0$ $q\overline{q}$ states. Then there are the glueball states and the cryptoexotic $q^2\overline{q}^2$ states [41]. A physical scalar meson will in general be a mixture of $q\overline{q}$, $q^2\overline{q}^2$, and glueball components. The $q\overline{q}$ states are expected [42] near the other ${}^3P$ $q\overline{q}$ mesons around 1250 MeV. Glueballs are also not very likely to exist below 1000 MeV [43]. For the $q^2\overline{q}^2$ states, however, one [41] does predict a low-lying nonet of scalar mesons. The physical reason is the same as what (hopefully) draws the H-dibaryon below the $\Lambda\Lambda$ threshold: attractive color-magnetic forces. The lowest state, with only nonstrange quarks, has $I = 0$ and decays "OZI-superallowed" into $\pi\pi$. It can be identified with the $\varepsilon(760)$ under the $\rho^0(770)$. This nonet contains also a nearly degenerate set of $I = 0$ and $I = 1$ cryptoexotic scalar mesons (like the $\rho(770)$ and $\omega(782)$) with an $\overline{s}s$ pair. These are easily identified as the $f_0(975)$ and $a_0(983)$ mesons, previously called $S^*(975)$ and $\delta(983)$ respectively, with their relatively large branching ratios into $\overline{K}K$ in the absence of significant phase space. The $\varepsilon(760)$ and $f_0(975)$ are "magically mixed." The nonet is completed by a set of broad $I = 1/2$ strange mesons $K_0^*(887)$ seen [44] under the $K^*(892)$. Ironically, at about the same time this attractive and simple scheme was proposed [41], the ε was killed off by the Particle Data Group.

Additional arguments for low-lying scalar mesons come from a completely independent approach by Weinberg. He observed that although chiral $SU(2) \otimes SU(2)$ symmetry is dynamically broken, it still has algebraic consequences [45]. With m_π and m_ρ as input and a few very plausible additional assumptions (which involve the pomeron!), one derives in this scheme that π, ε, and the helicity-zero states of ρ and a_1 belong to one chiral multiplet, and one predicts among other things that $\Gamma_\rho \approx m_\rho^3/96\pi f_\pi^2$ ($f_\pi \approx 95$ MeV), $m_\varepsilon = m_\rho$ and $\Gamma_\varepsilon \approx 9\Gamma_\rho/2$. In other words: *chiral symmetry requires a broad scalar* ε *degenerate with the* ρ. An easy generalization shows that in the limit of $SU(3)\otimes SU(3)$ one will find also strange scalar and vector mesons degenerate with the ρ and ε. It is not so easy, however, to include $SU(3)$ breaking, but it is conceivable that the strange scalar K_0^* will remain approximately degenerate with the $K^*(892)$, as in the Jaffe picture. It would be interesting to see what the experimental situation really is with respect to this K_0^* meson, since it is clearly very broad into πK, and would thus play a role in the YN interaction similar to $\varepsilon(760)$ in the NN case. In the SC model the K_0^* is assumed to have a mass of 1 GeV but no width is included.

In spite of these theoretical speculations, it will probably take more experimental evidence for the $\varepsilon(760)$ and $K_0^*(887)$ to convince the Particle Data Group to resurrect these mesons.

The confusing situation regarding the scalar mesons is reflected in the nonets picked in the Nijmegen potentials. Model A contained no scalar mesons; in model B and D only ε was included as a unitary singlet; model F had the "wrong" octet members with masses around 1250 MeV; models C, E, and the SC model included (what we now believe to be) the "correct" (low-lying) nonet.

IV. THE REACTIONS $\overline{\mathrm{N}}\mathrm{N} \to \overline{\mathrm{Y}}\mathrm{Y}$

Important for the study of the YN interaction are also the reactions $\overline{N}N \to \overline{Y}Y$. High-quality data for $\overline{p}p \to \overline{\Lambda}\Lambda$ have been obtained by the PS185 collaboration at the Low-Energy Antiproton Ring (LEAR) at CERN [46]. Some data are already available for $\overline{p}p \to \overline{\Lambda}\Sigma, \overline{\Sigma}\Lambda$ [47], and also the charged-Σ channels will follow. A particularly nice feature of these reactions is that they are "self-analyzing": due to the (electro)weak decay of the hyperons spin-observables can be measured without the need for secondary scattering. In $\overline{p}p \to \overline{\Lambda}\Lambda \to \overline{p}\pi^+p\pi^-$, for instance, PS185 detects all four charged decay products. The hyperon polarization and spin correlations can then be reconstructed. The fast electromagnetic decay $\Sigma^0 \to \Lambda$ can be taken into account, so that Σ^0 and Λ production can be separated. In case of charged-Σ production, only two of the four decay products are charged, but now the Σ's themselves leave tracks. Another nice feature of the PS185 experiment is that the quality of the LEAR antiproton beam is such that its momentum can be tuned very close to the $\overline{Y}Y$ thresholds, where only a few partial waves contribute significantly.

The reactions $\overline{N}N \to \overline{Y}Y$ have been studied by many groups, both in a meson-exchange and quark picture. Coupled-channels calculations including all the $\overline{Y}Y$ channels, $\overline{\Lambda}\Lambda$, $\overline{\Lambda}\Sigma$, $\overline{\Sigma}\Lambda$, and $\overline{\Sigma}\Sigma$, have been done by the Nijmegen group using the YN models D [48] and the SC model [49,50], and by the Jülich group [51,52]. DWBA approaches to $\overline{p}p \to \overline{\Lambda}\Lambda$ can be found in Refs. [53–55], examples of quark models in Refs. [56,57]. In Ref. [49] a partial-wave analysis was performed of the $\overline{p}p \to \overline{\Lambda}\Lambda$ data close to the threshold at 1435 MeV/c. For a data set of 142 observables, $\chi^2_{\mathrm{min}}/N_{\mathrm{obs}} = 1.03$ was obtained. It was shown that the transitions with $\ell(\overline{\Lambda}\Lambda) = \ell(\overline{p}p) - 2$, in particular ${}^3D_1 \to {}^3S_1$, ${}^3F_2 \to {}^3P_2$, and ${}^3G_3 \to {}^3D_3$, dominate this reaction. Scattering in the singlet states is negligible to an extent that one can speak of a dynamical selection rule. In a meson-exchange picture all this can easily be explained as a consequence of the strong coherent tensor force from $K(494)$ and $K^*(892)$ exchange, together with wave-function overlap between initial and final state for these transitions [49,50]. In this rather model-independent approach, where only the (charge-conjugated) long-range SC potential is used, the ΛNK coupling constant could be determined at the kaon pole. The result was $f^2_{\Lambda NK} = 0.071(7)$, where the error is statistical. As a systematic check also the kaon mass was determined, which gave $m_K = 480(60)$ MeV. The accuracy of these numbers will be improved by a analysis of all the data on $\overline{p}p \to \overline{\Lambda}\Lambda$ up to about 2 GeV/c. A similar analysis of upcoming data on $\overline{\Lambda}\Sigma$, $\overline{\Sigma}\Lambda$, and $\overline{\Sigma}\Sigma$ will lead to a determination of the ΣNK coupling and thus a test of $SU(3)$ and the $SU(3)$ Goldberger-Treiman relations.

Since the analysis of Ref. [49] has shown beyond doubt that a one-kaon–exchange mechanism is indeed present in $\overline{p}p \to \overline{\Lambda}\Lambda$, it is hard to see how naive quark models can provide a realistic description for these reactions. In particular, it seems difficult to get a strong enough tensor force without kaon exchange. A "hybrid" model, where the long-range interaction is still given by meson exchange but some quark-gluon description is attempted for the short-range dynamics, would probably be more fruitful. For the YN reactions, Oka and collaborators have made very interesting progress along these lines [58], using the quark cluster model [59]. Another interesting alternative approach for $\overline{N}N \to \overline{Y}Y$ is the diquark model of Ref. [60], which has the advantage that it can also be used at higher momenta than 2 GeV/c.

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TABLES

TABLE I. The different potential models for NN and YN scattering developed by the Nijmegen group.

	NN		YN	
Model	χ^2/data	Ref.	χ^2/data	Ref.
A	large	[1]	0.71	[1]
B	5.9	[2]	0.68	[2]
C	4	[3]	0.62	[3]
D	2.4	[4]	0.65	[5]
E	2.22	[6]	0.61	[6]
F	2.17	[7]	0.89	[7]
SC	2.09	[8]	0.58	[9]
$SC93$	1.90	[10]	—	—