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The Nijmegen YN and YY Interaction*

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Abstract

We review briefly the Nijmegen YN and the YY interactions. In particular the SU(3)-parameters, the SU(3)-potentials, and short-range aspects of the hard core models D, F and the soft core model NSC are discussed. Furthermore, we give the predictions of the differential cross section and the Λ-spin observables D_{NN}, D_{SS}, D_{SL}, D_{LS}, and D_{LL} at $p_\Lambda = 600$ MeV/c for the models D, F and NSC.

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I. INTRODUCTION

The combined analysis of the baryon-baryon channels consists of two complementary activities. The first part of the study of the baryon-baryon interactions is the partial wave analysis of the scattering data. In case of the nucleon-nucleon systems extensive phase shift analyses are available. In case of the hyperon-nucleon systems, it is well known that the experimental data are too sparse to allow anything comparable to the partial wave analysis of the nucleon-nucleon data. So far, there are only the bubble chamber data of the sixties, the analysis of which is reviewed in *e.g.* [1]. The low energy YN-data are dominated by s-waves and there seem to be no bound states in any of the YN-channels. There is no information on the YY-channels, at least as scattering is concerned. The second part of the baryon-baryon study is the construction of baryon-baryon interactions based on the present viable theories of the strong interactions. As we restrict ourselves here to the low energy region the potential concept should be adequate to discuss the baryon-baryon interactions.

The aim of the baryon-baryon analysis, as far as the hadron dynamics is concerned, is to test SU(3)-symmetry, determinations of coupling constants, in particular the K and K^* couplings, and the $F/(F+D)$-ratio's. These items are determined chiefly by the intermediate and the long range part of the potentials. The mechanisms that play a role in the short range region are by no means clear yet. New physics could be expected to play a role in the short range part of the interaction. This will in particular affect s-wave scattering and so also from this angle the low energy YN and YY channels are interesting. For example the coupling of the mesons at short range could be different from what one naively would expect and quark-gluon- exchange (QGE) might play a role. The latter notwithstanding the fact that, at least in Born approximation, only low to moderate momentum transfers occur at low energies. A very important part of the experimental and theoretical research in this field will be the study of nuclei and hypernuclei. The succes of these activities will partly depend on the used baryon-baryon interaction which is often a necessary input. Therefore, it is clear that the construction of a realistic baryon-baryon potential will eventually be indispensable when one wants to unfold the detailed nuclear structure effects in a study of nuclei and hypernuclei.

The Nijmegen YN-potential hard core models HC-D [2] and HC-F [3] and the soft core model NSC [4], [5] have been designed to provide realistic baryon-baryon interactions. Starting from a good nucleon-nucleon model, using notably SU(3), YN-potentials have been constructed by fitting the YN-data using only a few free parameters. These models have been described and reviewed several times already, so we will not repeat this here. In the literature the NHC-models D and F have been analyzed and discussed by Dover and Gal [6] and by Bando and Yamamoto [7], especially the aspects relevant for hypernuclei. Dover and Feshbach have used model D in their study of the SU(3)-symmetry of the baryon-baryon interaction [8].

General theoretical aspects of the NSC-model have been discussed in our contribution to the Padua conference [9]. Here it is stressed that the NSC-model, apart from giving an excellent fit to the NN-data below 350 MeV, is in accordance with the low energy πN data, the soft-pion theorems, the regge phenomenology, and QCD. The NSC predictions for Λp-observables have been given at the PILAC workshop [10]. Here also a brief account is given of the form factors, coupling constants etc., and the potentials in each SU(3)-irrep. For more

mesons		{1}	{8}	$F/(F+D)$	angles
pseudoscalar	f	0.18455	0.27204	$\alpha_{PV} = 0.355^{\star)}$	$\theta_P = -23.00^0$
vector	g	2.52934	0.89147	$\alpha_V^e = 1.0$	$\theta_V = 37.50^0$
	f	0.97982	3.76255	$\alpha_V^m = 0.275^{\star)}$	
scalar	g	3.75548	1.27734	$\alpha_S = 1.28555$	$\theta_S = 40.895^{0\ \star)}$
diffractive	g	2.85507	0.44372	$\alpha_D = 1.02267$	$\psi_D = 15.50^{0\ \star)}$

TABLE I. Coupling constants, $F/(F+D)$-ratio's, mixing angles etc.

details we refer the reader to the original papers [4], [5].

II. THE NIJMEGEN OBE-MODELS

The meson-baryon coupling constants are calculated via SU(3) , using the coupling constants of the NN-models as input. The assumption that SU(3) is not broken for the coupling constants has been affirmed recently in an analysis of the LEAR-data on $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ [11]. The determination of the pseudo-vector ΛNK coupling constant at the meson-pole gives $f^2_{\Lambda pK} = (71. \pm 7.) \times 10^{-3}$. Using the $g_{pp\pi^0}$ from the Nijmegen PSA [12] one finds $\alpha_{PV} = 0.34 \pm 0.04$. So there is no indication of a SU(3)-breaking of the pseudo-scalar meson coupling constants. Because it is the more theoretical model, we here mainly restrict ourselves to a discussion of the NSC-model.

1. YN-reactions (Y=1): (i) The $Q = +1$ channels $\Lambda p, \Sigma^+ n, \Sigma^0 p$; (ii) The $Q = 0$ channels $\Sigma^- p, \Sigma^0 n, \Lambda n$; (iii) The $Q = +2$ channel $\Sigma^+ p$. We have analysed the available low energy YN-data [13] for all YN-channels simultaneously. The used set of YN-data is for all Nijmegen YN-models the same. In fitting the YN-data, an excellent solution was found with nice values for α_{PV} and α_V^m, which appear qualitatively better than the Nijmegen hard-core potentials D and F. In Table I we give the singlet and octet coupling constants, mixing angles and $F/(F+D)$-ratio's. The values with a $\star)$ have been determined in the fit to the YN-data. The other parameters are either theoretical input or determined by the fitted parameters and the constraint from the NN-analysis.

For a more complete discussion of these results we refer to [5]. The value found for α_{PV} agrees very well with the determination in weak interactions (see [14]). The importance of a combined NN- and YN-analysis is that it takes into account the fact that α_{PV} enters in many coupling constants simultaneously (NNη_8, $\Sigma\Sigma\pi$, $\Lambda\Sigma\pi$, ΛNK, ΣNK, $\Lambda\Lambda\eta_8$, $\Sigma\Sigma\eta_8$) and therefore several measured cross sections and ratio's are sensitive to its value. Also, the value obtained for α_V^m is the same as that for relativistic SU(6) [15]. An important free parameter is the scalar mixing angle θ_S. Because we keep both $g_{\epsilon NN}$ and g_{S^*NN} fixed, in order not to disturb the NN-model, the nonet parameters g_1, α_S, θ_S are dependent and there is in fact only one free parameter left for the YN-fit. We have choosen this to be θ_S. We obtained $\theta_S \approx 40.9^0$, a value in between ideal mixing for the scalar $q^2\bar{q}^2$- and the scalar $q\bar{q}$-states. In the region where the data can be fitted successfully the $\Sigma^- p$ elastic and inelastic cross sections depend rather steeply on θ_S. The rather small value of the angle ψ_D means that the pomeron is dominantly an SU(3)-singlet as is also found in high energy scattering.

Comparing the couplings of the NSC-model with those of models D and F reveals: (i) the scalar meson couplings resemble those of model F, and (ii) the vector meson couplings resemble those of model D. This can be seen easily since in model D $\alpha_V^m = 0.334$, which is rather close to $\alpha_V^m = 0.275$, whereas in model F $\alpha_V^m = 0.588$. For the scalar mesons we have both in model F and the NSC-model a full nonet, whereas in model D only the ϵ-meson was included as a SU(3) singlet.

The potentials for all SU(3) irreps which occur in $\{8\} \otimes \{8\}$ are shown in Fig. 1. These are the potentials after the Green transformation (see [5]). They are taken from an extension of the YN-model to a model for the $Y = 0$ baryon-baryon coupled channels $\Lambda\Lambda$, ΞN, and $\Sigma\Sigma$ [16]. The given potentials are averages over the various channels. The dashed line potentials are quite similar to those obtained for the YN-channels (see [5]).

The hard-cores of models D and F were around 0.5 fm. Comparing with the SU(3) potentials of these models we found that for $r \geq 0.5$ fm: (i) the $\{27\}$, $\{10^*\}$, and the $\{8_s\}$ potentials are similar for the NSC-model and model F, (ii) the $\{8_a\}$ potentials are opposite for the NSC-model and model F. The differences between model D and F are mainly that they have opposite potentials in the $\{8_s\}$ and that the tail of model D in the $\{10\}$ is attractive.

In the NSC-model we have for Λp clearly $|a_0| > |a_1|$, whereas in model D and F $a_0 \approx a_1$. This because of the strong $\Lambda\Sigma$-transition due to the large (repulsive) $\{8_a\}$-potential (see Fig. 1) as follows from $V_{\Lambda\Sigma}(^3S_1) = (V_{10^*} - V_{8_a})/2$. Also, it is the reason that the direct Λp interaction is rather weak in the triplet, because $V_{\Lambda\Lambda}(^3S_1) = (V_{10^*} + V_{8_a})/2$. This explains that in the $^3S_1$ there is a large contribution to the scattering length from the $\Lambda\Sigma$-transition. Turning off this transition we find for the scattering lengths $a_0 \to -2.27$ fm and $a_1 \to -0.19$ fm. This illustrates the weakness of the ΛN potential in the $^3S_1$ partial wave. This has important implications for the Λ-bindings energies in the hypernuclei as pointed out by Carlson and Gibson [20], and by Bando and Yamamoto [21].

2. YY-reactions (Y=0): (i) The $Q = +1$ channels $\Xi^0 p, \Sigma^+\Lambda, \Sigma^+\Sigma^0$; (ii) The $Q = 0$ channels $\Lambda\Lambda, \Xi^0 n, \Xi^- p, \Sigma^0\Lambda, \Sigma^0\Sigma^0, \Sigma^+\Sigma^-$; (iii) The $Q = -1$ channels $\Xi^- n, \Sigma^-\Lambda, \Sigma^0\Sigma^-$. The extension of the NN/YN-interaction to the YY-interaction is as far as the OBE-potentials are concerned straightforward. Since there are no scattering YY-data we can not fit any phenomenological parameters like the hard-core or cut-off's. To avoid the introduction of many new parameters we have tried to impose SU(3) restrictions also on the description of the short range region. Therefore we have constructed an alternative soft-core YN-model by assuming the NN cut-off $\Lambda = 964.52$ MeV for all channels and allowing for a modification of the inner region of the SU(3)-potentials by including potential wells when needed (SCW-model) [16]. Making a fit to the YN-data we got $\alpha_V^m = 0.449$ and $\theta_S = 40.2^0$. The Λp scattering length's became $a_0 = -2.97$ fm and $a_1 = -1.43$ fm. Contrary to the NSC-model the SCW-model predicts a resonance near the $\Sigma^+ n$ threshold in the Λp system, which however is due to the attractive well in the $\{8_a\}$ potential. Also there are $I = 0$ and $I = 1$ resonances in the $Y = 0$ channels in the SCW-model, again due to the attraction in the $\{8_a\}$-irrep. Since there is no sign of the $Y = 1$ companion of the deuteron in the $\{10^*\}$, we tend to consider this SCW-model as preliminary. The potentials for all SU(3) irreps which occur in $\{8\} \otimes \{8\}$ for the SCW-model are shown in Fig. 1 by the solid lines. In going to the YY-channels the inner region in the $\{1\}$-irrep can of course not be determined by the YN-fit and is therefore completely free. In the figure we have assumed that OBE gives

this potential. Then, the $^1S_0$ potential in the $\Lambda\Lambda$ channel is strongly repulsive in the inner region, with an attractive tail for $r > 1$ fm. This short range repulsion is caused by the $\{1\}$ potential and is also present in the ΞN and $\Lambda\Sigma$ channels. The effective range parameters are $a_0(\Lambda\Lambda) = -0.89$ fm and $r_0(\Lambda\Lambda) = 3.28$ fm. Of course, the existence of the H-dibaryon [17] is left open. Though no resonance or bound state is found in the $Y = 0, I = 0$ $^1S_0$-coupled channels with OBE-potentials, it can easily be accomodated for by introducing an attractive well in the $\{1\}$. The presence of strong QGE [18] could of course justify such a well.

Extensions of the Nijmegen HC-models to the $Y = 0$-sector has been discussed by Dover and Gal [6] and by Bando and Yamamoto [7] in relation to hypernuclei. Recently such an extension was used in a study of the newly observed double-Λ hypernuceus [19].

III. SHORT-RANGE PHENOMENOLOGY

The general approach of the models HC-D, HC-F, and NSC is the same, as far as the type of the included potential forms, the treatment of the coupled channels and the kind of SU(3)-breaking. The latter is notably introduced via the use of the physical masses of the baryons and the mesons and by meson mixing. However, there is an essential difference w.r.t. the treatment of the short range region between the NHC-models and the NSC-model. Since the low energy YN-interactions are dominated by s-waves, we restrict ourselves here to the central and the spin-spin potentials. The hard-cores of models D and F were around 0.5 fm. Comparing with the SU(3) potentials of these models we found that for $r \geq 0.5$ fm: (i) the $\{27\}$, $\{10^*\}$, and the $\{8_s\}$ potentials are similar for the NSC-model and model F, (ii) the $\{8_a\}$ potentials are opposite for the NSC-model and model F. The differences between model D and F are mainly that they have opposite potentials in the $\{8_s\}$ and that the tail of model D in the $\{10\}$ is attractive. An important difference between the NHC-models and the NSC-model shows up *e.g.* in the $\{10\}$ for $^3S_1$ in Σ^+p. The strong attraction for $r \leq 0.5$ fm plays no role in the HC-models obviously, but restricts for example the α_S parameter in order to avoid bound states. In its turn the value of α_S has a large impact on *e.g.* the potential in the $\{8_a\}$.

The inner region ($r \leq 1$ fm) of the interactions is largely unknown at present. In models D and F hard cores are used to impose boundary conditions on the wave function at the hard core radii. This supposes implicitly that there is in all cases a strong repulsion at small distances. This repulsion in all channels cannot be explained by meson exchange and pomeron exchange. It is claimed that the strong QGE-models could provide such a repulsion, except for the $\{1\}$-irrep [18]. The advantage of the hard-core models is that the inner region does not put strong constraints on the OBE potentials. The drawback is that there will be a number of powerfull free parameters so that the information from the low energy YN-data w.r.t. for example $F/(F + D)$-ratio's may be considerably reduced.

The NSC-model tries to describe the short range region by using rather well known hadron physics only. OBE together with form factors is supposed to describe the low momentum transfer physics completely. In NN the NSC is very succesful in describing the data. Its extension to the YN-channels seems also rather successful in view of its nice SU(3) parameters. However, the special pecularities of OBE at short distances has definitely an impact on some qualitative features of the model. We mentioned above the strong $\Lambda N \to \Sigma N$-

conversion in the $^3S_1 -^3 D_1$ system and the weak direct ΛN-interaction in the $^3S_1$. As calculations by Carlson and Gibson [20] and by Yamamoto and Bando [21] have shown this might pose problems for the binding energies of the (light) hypernuclei.

Also, it is evident from Fig. 1 that OBE does not give repulsion at short distances for all channels. As seen from the figure for the NSC the clear exceptions are the irreps $\{10\}$ and $\{8_s\}$. Strong QGE predicts repulsion in most channels. The noticeable exception is the $\{1\}$-irrep, where in contrast to the NSC, a strong attraction is produced, which could make room for the existence of the H-particle.

IV. ΛP-OBSERVABLES

In Fig. 2 and Fig. 3 we show the predictions of the different Nijmegen models for the differential cross section and the Λ-spin observables $D = D_{NN}$, $R = D_{SS}$, $R' = D_{SL}$, $A = D_{LS}$, and $A' = D_{LL}$ (see *e.g.* [22]) for $p_\Lambda(\text{lab}) = 600$ MeV/c as a function of the cm-scattering angle. Included are the waves with $L \leq 2$. The differences between the model predictions are sufficiently big such that PILAC could easily discriminate between the models as shown in the design study [23]. A measurement of these observables would therefore rule out some of the theoretical models and in general be a big step forward in the understanding of the ΛN-interactions.

V. DISCUSSION AND CONCLUSION

The OBE-concept has been very fruitful in incorporating many of the major developments in hadron physics. Examples are the implementation of SU(3)-symmetry, (effective) description of the strong dynamics, physical interpretation of the regge pole concept etc. It is remarkable that the NSC OBE-model gives such beautiful SU(3) parameters. It will be most interesting to see whether this will stay when eventually new and improved YN-data are produced at *e.g.* KEK, KAON, PILAC, etc.

In order to improve our knowledge about the short range forces, better experimental information on the s-wave interaction in the YN and YY channels will be most important. In conjunction with that, a unified treatment of the low and high energy regions is very desirable. A representation of reggeons exists which has a simple relation to OBE at low energies, and which has been exploited in the NSC-model. (For a discussion and references, we refer to our Padua conference paper [9].) Using a model such as the NSC, insights gained from the regge phenomenology may be borrowed and tested experimentally at low energies. This will be profitable for both energy regimes.

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FIG. 1. Potentials for channels in definite SU(3)-irrep.

FIG. 2. $\sigma(\theta)$ in mb/sterad, $P(\theta)$, and $D(\theta)$ for $p_\Lambda(\mathrm{lab}) = 600$ MeV/c.

FIG. 3. Λ-spin observables R, R', A, and A' for $p_\Lambda(\mathrm{lab}) = 600$ MeV/c.