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The Nijmegen Hyperon-Nucleon and Hyperon-Hyperon Interactions *

Th. A. Rijken
Institute for Theoretical Physics,
University of Nijmegen,
Nijmegen, The Netherlands
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Abstract

After a general introduction, where we position the the low-energy baryon-baryon interactions in the general framework of QCD, flavor SU(3), and chiral SU(3)⊗SU(3), we first review the Nijmegen interactions and the treatment of mesons, emphasizing the important role of the scalar-meson nonet. Then, we discuss the very recent new soft-core models: (i) one-boson-exchange model NSC97, and (ii) the extended-soft-core model. Stressed is the simultaneous description of all baryon-baryon channels. Results are discussed for YN and YY systems.

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I. INTRODUCTION

In the general physical framework of QCD, flavor SU(3), and chiral $SU(3)_L \otimes SU(3)_R$, a natural picture of a baryon is provided by the chiral-quark model (CQM) [1]. The CQM explains the successes of the (non-relativistic) quark model (QM) and, at the same time, the interaction between baryons using effective baryon-meson Lagrangians is embedded in a natural way within the context of the general framework mentioned above. The baryon consists of a core region, where the quarks reside, surrounded by the mesonic cloud. The coupling of mesons to quarks, dressed itself by mesons, in particular pions, is for instance very neatly expressed in the non-linear chiral model description of the baryon-baryon interactions. In Fig. 1, we have drawn two baryons that interact schematically.

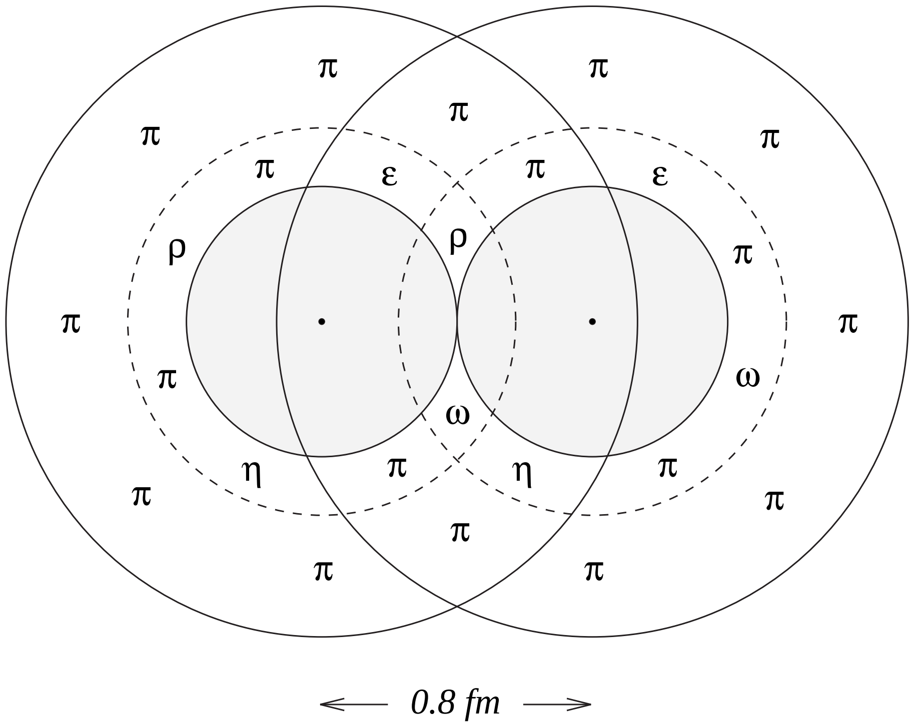

FIG. 1. Schematic presentation BB-system at distance $r = 0.8fm$

For high momentum transfer processes, i.e. high Q^2, the physics can be described directly by perturbative QCD and the quark-gluon density functions: the quark-gluon phase. For medium Q^2 there most naturally will be a mixed phase: quarks & gluons, and baryons & mesons. Finally, for low Q^2 the relevant degrees of freedom will be only baryons + mesons: the hadronic phase. For low and intermediate energies both the mixed and the hadronic phase is of relevance. So, we think that in the 'core region', besides quarks and gluons, mesons are also present. The latter are important in the quark-quark (QQ) interactions for intermediate and low Q^2. This in particularly for the description of phenomena that take place below $r \leq 1$ fm. For light nuclei and hypernuclei, both the long and the intermediate/short range interaction regions are important. However, for the heavier nuclei especially the intermediate and short range regions are important. For the heavier nuclei especially the intermediate and short range regions are vital, because the 'healing distance' is ≤ 1 fm.

The contents of this paper are as follows. In Section 2 we review the general approach of the Nijmegen group in constructing baryon-baryon interactions. In Section 3 we discuss the treatment of the pseudo-scalar, vector, and scalar mesons. This in particular with respect to flavor SU(3). In Section 4 the most recent soft-core model NSC97 [2] is discussed. This for both the YN and the YY channels. Also, some hypernuclei properties will be given. In Section 5 the latest developments of the extended-soft-core (ESC) models are reviewed. We report for the first time on preliminary results with the ESC models for YN and YY channels. Finally, in Section 6 we offer some conclusions and an outlook. Here, we comment on the prospects of the construction of realistic QQ forces.

II. NIJMEGEN BARYON-BARYON INTERACTIONS

The Nijmegen group has constructed OBE models for a realistic description of the nucleon-nucleon (NN) and hyperon-nucleon (YN) channels since 1972. After 1990, we started to construct models which also include two-meson exchange. This is in line with the approach advocated by our group in several publications, and for which we refer to the review [3]. In this talk, we will not give an extensive review of the models and applications but will focus on recent work and the prospects of future developments of the Nijmegen baryon-baryon (BB) interactions.

The OBE models can divided in *hard-core* (HC) and *soft-core* (SC) models. Of the first category are the well known model D [4] and model F [5]. They have been reviewed most extensively, in particular with respect to applications in YN and YY by Dover and Gal [6] and by Bando and Yamamoto [7]. The second category, the soft-core models, have been reviewed in [3, 8, 9]. They have an excellent fit to the NN data, and the YN data as well.

The potentials from the following nonets are included in the $NN + YN + YY$ models:

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

where the last nonet comes from pomeron and the $J = 0$ components of the tensor mesons.

The Nijmegen soft-core models are at present of two kinds: (i) the OBE models [10, 11] having NN and YN, and (ii) the ESC model [12, 13]. Recently, we have made YN and YY versions of the ESC model. The first preliminary global results will be discussed below. The ESC model is an extension of the OBE model having two-meson exchange and meson-pair exchange included. This is all in a similar context to the Nijmegen soft-core OBE models. That is, gaussian form factors, but no nucleon resonances. The latter are implicitly included via pair interactions by invoking duality arguments [13].

Another important class of models, for which already rather realistic NN versions have appeared recently, are the so-called chiral models. A variation on the ESC model using pair couplings from a chiral Lagrangian gave a very good description of the NN data for $T_{lab} \leq 320$ MeV, with no more free meson couplings than in OBE models [14]. This model, which is formulated in the context of chiral SU(3)$\otimes$SU(3) permits a straightforward extension to YN and YY. This in contrast to the work of Ordonnez et al. [15], which uses chiral perturbation theory, and for which the YN and YY extension is impossible.

The NN data have been accumulated and improved for about 50 years now. Below $T_{lab} = 350$ MeV, the data base contains about 4300 selected $pp + np$ data on cross sections and a variety of spin correlations. The experimental data on YN interactions (ΛN, ΣN, and ΞN) and the YY- YY interactions on the other hand are rather scarce. In our data base for YN, we use about 35 scattering data [16, 17, 18, 19, 20]. These scattering data are at very low energies and provide essentially only information on s-wave interactions. Furthermore, there is rather solid information that there are no YN bound states. Although the YN data are both few in number and have rather large errors compared to NN, it is our experience that it is nontrivial to fit the YN data *in conjunction* with NN while not allowing YN bound states.

In order to reach a realistic description of the NN and YN interactions simultaneously, we followed the following strategy: First, we construct a good NN interaction by making a fit to the NN data below $T_{lab} = 350$ MeV. Then, exploiting broken SU$_f$(3)-symmetry, we extend these interactions to YN, and make a fit to the YN data. In making this extension, we exploit the fact that YN systems are more sensitive to some parameters than NN, e.g. the $F/(F+D)$-ratio's and meson mixing angles. Also, we have to make certain 'short range' assumptions. In the HC models, the hard cores in YN are given freedom with respect to the hard-core parameters used in NN. Similarly in the SC models for the form factor cut-off masses. It appears to be possible to reach a very good description for YN using about 5 free parameters.

From the QCD viewpoint, SU$_f$(3)-symmetry is an accidental symmetry. It consists of transformations among the u, d, and s quarks. In the standard model the s quark belongs to a different family from the u and d quarks. Now, the gluons are flavor blind, and since the (constituent) masses of the quarks are not very different SU$_f$(3) is, although not a fundamental, a very useful broken symmetry. The basic difference $m_s \neq m_u \approx m_d$, defines the 'direction' of symmetry breaking, as is shown by the succesful Gell-Mann-Okubo scheme of mass breaking patterns in the meson and baryon SU$_f$(3) multiplets. Based on this one can also work out breaking of coupling constants. In the Nijmegen models, we usually assume that the coupling constants are not broken. In the most recent SC models [2], we introduced also breaking of the couplings. In the Nijmegen models, the kinematical breaking of SU$_f$(3) is included by using the physical masses of the mesons and baryons. So, the theoretical basis, using SU$_f$(3) symmetry for the extension of the NN interaction models to YN and YY, is rather solid. However, to implement rather strict rules is difficult in practice. For example, it turns out not to be trivial to have the proper amount of SU$_f$(3) breaking in the $\{27\}$ irrep in order to go to the $\Sigma^{\pm}p$ systems, such that no bound states are produced. Here, one has to introduce some ad hoc breaking in many models.

So far, there do not yet exist ΞN-scattering data. However, we have some information in the $S = -2$ sector, because of the observation of the ${}^{6}_{\Lambda\Lambda}He$ and ${}^{10}_{\Lambda\Lambda}Be$ hypernuclei. The contribution of the $\Lambda\Lambda$ interaction to the binding energy indicates a rather strong attractive $\Lambda\Lambda$ interaction. Models, successful in fitting $NN + YN$ will not necessarily be able to describe this $\Lambda\Lambda$ interaction, as we will discuus later on in this paper. Therefore, almost any information on e.g. ΞN scattering will be very useful for making our knowledge of the BB interactions complete.

III. MESONS, COUPLING CONSTANTS, FLAVOR SU(3)

A. The pseudo-scalar mesons $J^{PC} = 0^{-+}$

The coupling of the pseudo-scalar mesons to the $J^P = (1/2)^+$ baryons can be the ps coupling, $\mathcal{L}_{ps} = \sqrt{4\pi} g\bar{\psi} i\gamma_5 \psi \cdot \phi$, the pv coupling $\mathcal{L}_{pv} = \sqrt{4\pi}(f/m_\pi)\bar{\psi}\gamma_5\gamma_\mu\psi \cdot \partial^\mu\phi$, or a mixture of these couplings. When one assumes SU(3) for the pv coupling f, the Cabibbo theory of the weak interactions and the Goldberger-Treiman relation give $\alpha_{pv} = [F/(F+D)]_{pv} = 0.355(6)$. In the Nijmegen SC model, this value could be imposed while still keeping an excellent description of the YN data, including the accurate datum on the capture ratio at rest. This SC model has also a quite sizeable coupling to the baryons for the scalar ϵ. Nevertheless this OBE model is compatible with the soft-pion constraints on the $\pi\pi$ scattering lengths, because the potentially dangerous ϵ contribution is cancelled by an opposite pomeron-exchange contribution [3]. For details on e.g. the mixing we refer to [8].

B. The vector mesons $J^{PC} = 1^{--}$

An important ingredient of the BB force is the exchange of the vector meson nonet $(\rho, \phi, \omega, K^*)$. The details of our treatment of the vector mesons have been given again in [8]. We use ideal mixing between ω and ϕ. The $F/(F+D)$-ratio $\alpha_V^e = 1$ in all Nijmegen models. The magnetic α_V^m is not always the same. In the OBE models, the singlet-triplet strength in ΛN depends, besides on other things, especially on its value. See the results below for NSC97.

In making the chiral transformations local one incorporates the vector and axial mesons as the gauge-fields of this local symmetry, see e.g. [21]. A further interesting development has been to associate these gauge particles with a 'hidden' symmetry [22]. Writing $U = \exp[i\boldsymbol{\tau}\cdot\boldsymbol{\pi}(x)/f_\pi] = \xi_L^\dagger \xi_R$, the Lagrangian is invariant under the local gauge transformation $\xi_{L,R} \rightarrow h(x)\xi_{L,R}$, where $h \in$SU(2) and $h^\dagger h = 1$. In the large-N_c limit, one identifies the vector mesons with $V_\mu = \left(\partial_\mu \xi_L \xi_L^\dagger + \partial_\mu \xi_R \xi_R^\dagger\right)$. For $I = 1$, this gives on expanding the exponentials in U that $\boldsymbol{V}_\mu \approx \boldsymbol{\pi} \times \partial_\mu \boldsymbol{\pi} + \ldots$. Now it is interesting to note that when $\rho \sim \pi \times \partial_\mu \pi$ etc., the vector-octet coupling to the baryon-octet has $\alpha_V^e = [F/(F+D)]_V^e = 0.44$ instead of $\alpha_V^e = 1$ as required by 'universality' [23]. So, it will be interesting to see whether this identification really can be made in reality.

C. The Scalar Mesons $J^{PC} = 0^{++}$

The scalar mesons have since 1970 consituted an important role in the construction of the Nijmegen models. They are an essential ingredient both in the hard-core models D and F, as in all the soft-core models.

The scalar meson $\sigma(550)$ was introduced in 1960-1962 by Hoshizaki et al. [24] In the OBE models for NN, this scalar meson was necessary for providing sufficient intermediate-range central attraction and for the spin-orbit interaction required to describe the ^3P_J-splittings.

In 1971 it was realized that the exchange of the broad $\epsilon(760)$ could explain the role of the fictitious σ [25]. This broad $\epsilon(760)$ has been used in the Nijmegen OBE models. A recent analysis of the π-production in πN scattering with polarized nucleons claimed to have found unambiguous evidence for a broad isoscalar $J^{PC} = 0^{++}$ state under the ρ [26]. This was based on an amplitude analysis involving besides π-exchange also a_1-exchange in the production mechanism. In a similar analysis of data on $K^+n \to K^+\pi^-p$, evidence was found for an $I = 1/2, 0^+(887)$ strange scalar meson under the $K^*(892)$. In [27] this analysis is cited with reserve, asserting that the ϵ-parameters of [26] can not be correct because the $f_0(980)$ is neglected in the analysis. Also the Helsinki group finds now an ϵ-meson and other members of a scalar nonet [28].

Gilman and Harrari [29] showed that all Adler-Weisberger sum rules can be satisfied by saturation in the mesonic sector with the $\pi(140)$, $\epsilon(760)$, $\rho(760)$, and $a_1(1090)$. They found the ϵ, in [29] called σ, degenerate with the ρ and having a width of $\Gamma(\epsilon \to \pi\pi) = 570$MeV. Used in this work were the Regge high-energy behavior, SU(2)$\otimes$SU(2) chiral algebra of charges and pion dominance of the divergence of the axial-vector current. Similar phenomenology was derived by Weinberg requiring that the sum of the tree graphs for forward pion-scattering, generated by a chiral-invariant Lagrangian, should not grow faster at high energies than permitted by Regge behavior of the actual amplitudes [30, 31]. Therefore, it seems that chiral symmetry combined with Regge behavior requires a broad scalar ϵ degenerate with the ρ.

In the QM, the scalar mesons have been viewed as conventional ${}^3P_0$ $Q\bar{Q}$ states while other views are as crypto-exotic $Q^2\bar{Q}^2$ states [32] or glueball states. We will briefly review the assignments as $Q\bar{Q}$ and as $Q^2\bar{Q}^2$ states.

a. In the $Q\bar{Q}$ picture, one has for the unitary singlet and octet states, denoted respectively by ϵ_1 and ϵ_8,

$$\epsilon_1 = \left[u\bar{u} + d\bar{d} + s\bar{s}\right]/\sqrt{3}\ , \quad \epsilon_8 = \left[u\bar{u} + d\bar{d} - 2s\bar{s}\right]/\sqrt{6}\ .$$

In the following, we use the notation, by now more standard, $\epsilon(760) \equiv f_0'(760)$. The physical states are mixings of the pure SU(3) states and we write

$$f_0' = \cos\theta_s\epsilon_1 + \sin\theta_s\epsilon_8\ , \quad f_0 = -\sin\theta_s\epsilon_1 + \cos\theta_s\epsilon_8\ .$$

Then, for ideal mixing, $\tan\theta_s = 1/\sqrt{2}$ or $\theta_s = \theta_v \approx 35.3^0$, and we have

$$f_0' = \epsilon(760) = s\bar{s}\ , \quad f_0(980) = (u\bar{u} + d\bar{d})/\sqrt{2}\ .$$

b. In the $Q^2\bar{Q}^2$ picture [32] (see also [8]), one introduces diquarks Q^2 with $F = 3^*, C = 3^*$, and $S = 0$, where F, C, S denote respectively the flavor, color, and spin. Since $F = 3^*$, one denotes these diquark states by $\bar{Q}$. Then, the conjugated triplet $\bar{Q}$ has the contents: $\bar{S} = [ud]$, $\bar{U} = [sd]$, and $\bar{D} = [su]$, where $[ud]$ stands for the antisymmetric flavor wave function $ud - du$ and so on. The $Q\bar{Q}$ states form a scalar flavor nonet. In particular, Jaffe predicted the lowest mass state, which we assume here to be f_0', as $S\bar{S}$, with $I = 0$, $J^{PC} = 0^{++}$, and mass $M = 690$ MeV. In this scalar nonet, Jaffe predicted a degenerate pair of $I = 0$ and $I = 1$ state at $M = 1150$ MeV. These can be identified with the $f_0(980)$ and the $a_0(980)$. Explicitly, in the $Q^2\bar{Q}^2$ model, the quark content of the neutral states $f_0(760)$, $f_0(980)$, and $a_0(980)$ is

$$S\bar{S} = [\bar{u}\bar{d}][ud] \ \ , \ \ \left(U\bar{U} \pm D\bar{D}\right) = \left\{[\bar{s}\bar{d}][sd] \pm [\bar{s}\bar{u}][su]\right\}/\sqrt{2} \ .$$

The strange members of this nonet are combinations like $\kappa^+ \sim [ud][\bar{s}\bar{d}]$, etc. These are expected at about $M = 880$ MeV, just under the $K^*(892)$. Ideal mixing in the case of the $Q^2\bar{Q}^2$ states, means that

$$f_0' = \epsilon(760) = S\bar{S} \ , \ \ f_0(980) = (U\bar{U} + D\bar{D})/\sqrt{2} \ .$$

which in this case implies that $\tan\theta_s = -\sqrt{2}$, so that $\theta_s = \theta_v - 90^0 \approx -54.8^0$.

This implies that ideal mixing for the scalar mesons in the case of $Q^2\bar{Q}^2$ states is quite distinct from that for the $Q\bar{Q}$ states. To analyze some of the differences between the $Q\bar{Q}$ and the $Q^2\bar{Q}^2$ assignments for the BB channels, we remind the reader that in our strategy, we keep the NN channel fixed. Considering the mixing, one obtains for $g_{\epsilon NN}$ and $g_{f_0 NN}$ in terms of the flavor singlet and octet couplings

$$g_{\epsilon NN} \ = \ \cos\theta_s g_1 + \sin\theta_s g_8 \ , \ \ g_{f_0 NN} = -\sin\theta_s g_1 + \cos\theta_s g_8 \ ,$$

where $g_1 = g_{\epsilon_1 NN}$, and $g_8 = g_{\epsilon_8 NN} = (4\alpha_s - 1)g_{a_0}/\sqrt{3}$. Now, $g_{a_0 NN}$, $g_{\epsilon NN}$, and $g_{f_0 NN}$ are fitted in NN. Then, the only freedom left for the YN and the YY systems is in the variation of the scalar mixing angle θ_s in such a way that the scalar $F/(F+D)$ ratio is restricted by [5, 11]:

$$g_8 \equiv \frac{(4\alpha_s - 1)}{\sqrt{3}} g_{a_0 NN} = \sin\theta_s g_{\epsilon NN} - \cos\theta_s g_{f_0 NN} \ ,$$

from which it is clear that $\alpha_s = \alpha_s(\theta_s)$, i.e. fixing the mixing angle fixes also the $F/(F+D)$ ratio. This relation implies roughly that for positive values of θ_s the $\alpha_s > 0$ and for negative values $\alpha_s < 0$. For the ideal mixing in the $Q\bar{Q}$ case $\alpha_s \approx +1.0$ and for ideal mixing in the $Q^2\bar{Q}^2$ case $\alpha_s \approx -1.0$. This difference between the $Q\bar{Q}$ and the $Q^2\bar{Q}^2$ assignment is quite important for the YN and the YY systems. Now, of course one should allow for the possibility that the actual physical states, $\epsilon(760)$ and $f_0(980)$, are mixtures of the $Q\bar{Q}$ and the $Q^2\bar{Q}^2$ states. We expect that $\theta_s > 0$ if the $Q\bar{Q}$ component dominates, whereas $\theta_s < 0$ when the $Q^2\bar{Q}^2$ component dominates.

In Fig. 2, we show the strength of the scalar-exchange central potential, in arbitrary units, for the diagonal matrix elements in YN. Here, we assumed equal masses for the members of the scalar nonet. Considering the contribution from the scalar nonet, we note the following. In the $\Sigma^+ p(^3S_1)$ channel, the scalar nonet contribution is attractive in the $Q\bar{Q}$ case, whereas in the $Q^2\bar{Q}^2$ case it is repulsive. In the $\Lambda\Lambda(^3S_1)$ channel, the scalar nonet contribution is much stronger for $Q^2\bar{Q}^2$ domination than for $Q\bar{Q}$ domination. Note, that for the spin-singlet the interaction in ΛN is quite similar to that in ΣN, due to the dominance of the $\{27\}$ irrep. Similarly, in Fig. 3 (see later) for the $\Xi N(^1S_0, I=0)$ and the $\Xi N(^3S_1, I=1)$ states.

So far, the OBE soft-core models all have $\theta_s > 30^0$, which indeed implies that the $\Lambda\Lambda$ and the ΞN potentials are rather weakly attractive in the intermediate range. They therefore

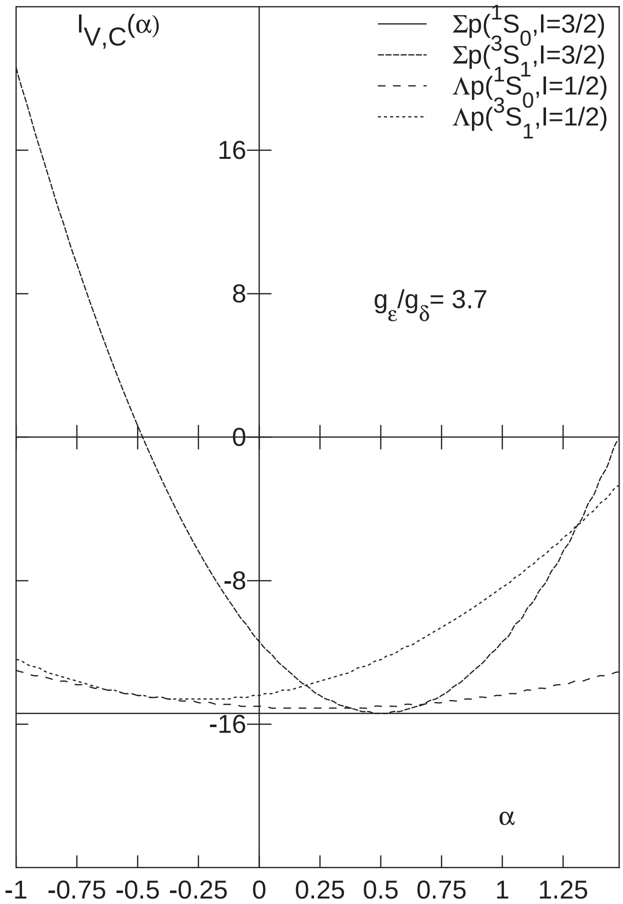

FIG. 2. Volume integral scalar-exchange central YN potentials

cannot produce sufficient attraction to account for the binding emergies of the experimentally found double-Λ hypernuclei, e.g. $^{10}_{\Lambda\Lambda}$Be [33].

YN and ΞN studies will certainly give very valuable new information on the possible role of the scalar mesons and insight into how chiral symmetry is manifested in nature.

D. The pomeron $J^{PC} = 0^{++}$ and the heavy mesons $J^{PC} = 1^{+-}$ etc.

In the Low-Nussinov two-gluon model [34] it was once proposed [36] to distribute the two-gluon coupling over the quarks of a hadron, the so-called 'subtractive-pomeron'. Then, one would expect at low energies an attractive, van der Waals type of force. This is in conflict with the results from Regge phenomenology [39]. However, it became apparent experimentally in the study of the $pp \to (\Lambda\phi K^+)p$ and $pp \to (\Lambda\bar{\Lambda}p)p$ reactions at $\sqrt{s} = 63$ GeV [35] that the pomeron couples dominantly to individual quarks. This leads to the so-called 'additive-pomeron'. The dominance of the one-quark coupling can be understood as due to the fact that in the case of a coupling to two quarks the loop momentum involved in such a coupling has to pass through at least one baryon. Thus, the baryon wave function is involved, which leads to a suppression of a^2/R^2, where a and R are respectively the quark and the baryon radius [37]. Now, it is interesting to know whether this is also true at lower energies. In the Low-Nussinov model one can argue that the pomeron-quark coupling leads to a repulsive gaussian potential [8], which has been used in the SC models. The importance of the pomeron in OBE models being compatible with chiral symmetry has been pointed out in [3].

So far, the axial and the tensor mesons, have hardly been explored in models of baryon-baryon interactions for low energies. The axial mesons are very important in connection with chiral symmetry and play an important role in sum rules [38]. The tensor mesons are very important at higher energies, lying on a dominant Regge trajectory, exchange-degenerate with the vector mesons. There is no problem in incorporating these heavy mesons in the Nijmegen work. Recently, we included these mesons, using the estimates based on the Regge hierarchy from [39]. With regard to the general features, no qualitative changes in the description of the NN and YN channels were observed.

IV. SOFT-CORE OBE-MODELS

Recently [2], we started the construction of SC models where the form factors depend on the $SU_f(3)$ assignment of the mesons, and not globally depending on the $SU_f(3)$ structure of the BB channel. The latter was done for the NSC89 model. In principle, we introduce form factor masses Λ_8 and Λ_1 for the $\{8\}$ and $\{1\}$ members of each meson nonet, respectively. In the application to YN and YY, we allow for $SU_f(3)$-breaking, by using different cut-offs for the strange mesons K, K^*, and κ. In Table I, we list the parameters for the d-version of the NSC97 model. They are quite similar to those for the NSC89 model, cf. [11]. An excellent fit to the NN channels was obtained: $\chi^2_{p.d.p} = 1.55$.

TABLE I. NSC97d-model: Coupling constants etc., $m_\kappa = 1362.9$

mesons		{1}	{8}	F/(F + D)	angles
pseudoscalar	f	0.18474	0.27286	$\alpha_{PV} = 0.355^{\star)}$	$\theta_P = -23.00^0$
vector	g	2.56998	0.83689	$\alpha_V^e = 1.0^{\star)}$	$\theta_V = 37.50^{0\star)}$
	f	1.33512	3.53174	$\alpha_V^m = 0.355$	
scalar	g	3.89900	1.39511	$\alpha_S = 1.041$	$\theta_S = 41.02^0$
diffractive	g	2.75990	0.00822	$\alpha_D = 1.0^{\star)}$	$\psi_D = 0.0^{0\star)}$

For the same model NSC97d, we list in Table II the fitted form factor masses (cut-offs), and the $SU_f(3)$ breaking parameters for the coupling constants $\Delta g(Y_8)$. The scheme for flavor symmetry breaking of the coupling constant follows from the $^3P_0$ mechanism [40] for the meson-baryon-baryon coupling. We assume that $\gamma_u = \gamma_d \neq \gamma_s$. Here, the γ's denote the $^3P_0$ pair-creation constants. Details will be given in [2].

In Table III, we give several results obtained with the NSC97 models. We also include for comparison, similar results for model D and F, and of the previous SC model, NSC89.

The results in Table III are given as a function of α_V^m. One sees that the singlet-triplet strength of the ΛN interaction depends smoothly on α_V^m. In the rightmost column, it is shown that all NSC97 models have an excellent fit to YN. All results, given for U_Λ, U_Σ, and

TABLE II. Form factor masses, $SU(3)$-breaking couplings.

mesons	Λ_1	Λ_8	Λ_{YNK}	$\Delta g(Y_8)$
pseudoscalar	872.1	1254.6	1281.6	1.2624
vector	949.3	895.1	1225.6	1.1478
scalar	989.0	548.7	935.75	1.0396

TABLE III. NSC97a-e: ΛN-Scattering length's, χ^2 YN-data, etc.

	α_V^m	a_s	a_t	U_Λ	U_Σ	Γ_Σ	χ^2
(a)	0.4447	-0.79	-2.29	-24.3	-20.4	13.7	18.3
(b)	0.4047	-1.15	-2.24	-27.5	-18.2	14.4	19.2
(c)	0.3647	-1.47	-2.00	-23.9	-14.0	16.3	16.6
(d)	0.3547	-1.99	-1.88	-28.4	-7.3	14.0	16.1
(e)	0.3447	-2.26	-1.80	-26.2	-7.5	15.0	16.2
NSC89	0.275	-2.73	-1.48	-30.8	-27.1	26.9	15.8
D	0.334	-1.77	-2.06	-40.1	-29.3	10.3	19.4
F	0.588	-2.18	-1.93	-30.8	+5.8	9.6	27.1

Γ_Σ were calculated using the Bando-Yamamoto YNG interactions constructed for the NSC97 models [41]. The Λ well depth $U_\Lambda = -28$ MeV, obtained from analyses of the (π^+, K^+) and (K^-, π^-) cross sections on nuclear targets [43] is well fit, in particular, by NSC97d. (We note that the NSC89 model gives $U_\Lambda = -30.8$, in contrast to what is reported in [42]). Also interesting is that for the NSC97 models, Γ_Σ is much smaller than is the case for the NSC89 model. This is more consistent with the recently confirmed ${}^4_\Sigma He$ hypernucleus [44], which has a conversion width $\Gamma \approx 7$ MeV. This rather small Σ-conversion width has been explained by Harada et al. [45], using the SAP interactions derived using model D. Results for the NSC97 potentials with regard to the Carlson-Gibson [46] computation of the ${}^3_\Lambda$He, ${}^4_\Lambda$He, and ${}^5_\Lambda$He hypernuclei are not availaible yet. The same is true for the Miyagawa-Gloeckle [47] computation of the hypertriton ${}^3_\Lambda$H, whose binding was reproduced exactly by the NSC89 model.

In the $S = -2$ systems, the experimental information is limited to the ground states of ${}^6_{\Lambda\Lambda}$He, ${}^{10}_{\Lambda\Lambda}$Be, and ${}^{13}_{\Lambda\Lambda}$B from which it is inferred that $\Delta B_{\Lambda\Lambda} = 4 - 5$MeV corresponding to a rather strong $\Lambda\Lambda$-interaction. The estimate for the ${}^1S_0$ $\Lambda\Lambda$-matrix element in ${}^6_{\Lambda\Lambda}$He for model D [4] is $\Delta B_{\Lambda\Lambda} = 4$ MeV, in agreement with the experimental observation. Model F [5] gives a repulsive $\Lambda\Lambda$ interaction, in contradiction to the data. For more details we refer to [48].

Now, the characteristic feature of model D is that instead of a scalar nonet, there is only a scalar singlet. This makes the scalar central attraction BB-channel independent, and so equally strong as in NN. However, in the SC models, constructed sofar, we have nearly ideal-mixing for $Q\bar{Q}$ states, which implies that

$$|V_{\Lambda\Lambda}(0^+)| < |V_{\Lambda N}(0^+)| < |V_{NN}(0^+)|$$

which leads to much weaker attractive potentials than in the case of model D in the $\Lambda\Lambda, \Xi N$ systems. For example, estimates for the $\Lambda\Lambda({}^1S_0)$ scattering length, based on $\Delta B_{\Lambda\Lambda}$ quoted above, is $a_{\Lambda\Lambda}(^1S_0) \approx -2.0$ fm [49]. In the NSC89 and NSC97 models we obtain $a_{\Lambda\Lambda}(^1S_0) \approx -0.2$ fm. As can be seen from Fig. 3, which shows the scalar-nonet I_V as a function of α_s, the only way to produce stronger $\Lambda\Lambda$ forces is to go to smaller θ_s and ipso facto a smaller α_s. However, when we tried this for the SC-OBE models, we produced a $\Lambda N(^1S_0)$ bound state. In the next section, we discuss these matters for the ESC model.

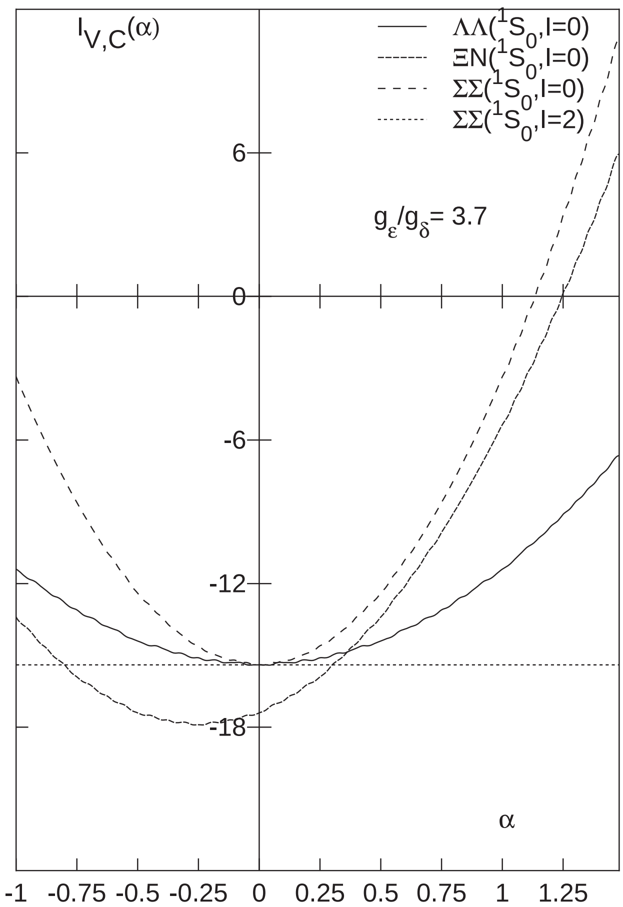

FIG. 3. Volume integral for scalar-exchange central YY potentials

V. EXTENDED SOFT-CORE MODELS

The potential of the extended-soft-core (ESC) model contains,

(i) The soft-core OBE potentials of [10, 11], which are reviewed above,

(ii) The soft-core two-meson exchanges: pseudo-scalar-pseudo-scalar, pseudo-scalar-vector, pseudo-scalar-scalar, and pseudo-scalar-diffractive potentials [13]. This for all members of the pseudo-scalar, vector, scalar, and diffractive nonets. Here, we included both the so-called BW graphs and TMO graphs (see [50] for the nomenclature).

(iii) The soft-core meson-pair exchanges, $\pi\otimes\pi$, $\pi\otimes\rho$, $\pi\otimes\omega$, $\pi\otimes\epsilon$, $\pi\otimes P$, etc. Here again, all members of the considered meson nonets are included. The phenomenological baryon-baryon-meson-meson vertices, henceforth referred to as 'pair interactions' or 'pair terms' are

$$
\begin{aligned}
J^{PC}=0^{++} \quad &: \quad \mathcal{H}_S = \left(\bar\psi'\psi'\right)\left\{g_{(\pi\pi)_0}\left(\underline{\pi}\cdot\underline{\pi}\right)+g_{\sigma\sigma}\sigma^2\right\}/m_\pi \\
J^{PC}=1^{--} \quad &: \quad \mathcal{H}_V = \left[g_{(\pi\pi)_1}\bar\psi'\gamma_\mu\underline{\tau}\psi' - \frac{f_{(\pi\pi)_1}}{2M}\bar\psi'\sigma_{\mu\nu}\underline{\tau}\psi'\partial^\nu\right]\left(\underline{\pi}\times\partial^\mu\underline{\pi}\right)/m_\pi^2 \\
J^{PC}=1^{++} \quad &: \quad \mathcal{H}_A = g_{(\pi\rho)_1}\left(\bar\psi'\gamma_\mu\gamma_5\underline{\tau}\psi'\right)\left(\underline{\pi}\times\underline{\rho}^\mu\right)/m_\pi \\
&\quad\ \ \mathcal{H}_P = g_{(\pi\sigma)}\left(\bar\psi'\gamma_\mu\gamma_5\underline{\tau}\psi'\right)\left(\sigma\partial^\mu\underline{\pi}-\underline{\pi}\partial^\mu\sigma\right)/m_\pi^2
\end{aligned}
$$

The motivation for including these 'pair vertices' is that similar interactions appear in chiral Lagrangians. They can be viewed upon as the result of integrating out the heavy-meson and resonance degrees of freedom. Moreover, they also represent two-meson exchange potentials. We are less radical than Weinberg, see e.g. [51], in that we do not integrate out the degrees of freedom of the mesons with masses below 1 GeV. The techniques to derive the explicit expressions for the potentials corresponding to the meson-pair exchange potentials with soft (i.e. gaussian) form factors, is described in [50, 13].

In fitting this new model to the NN data, using the 1993 Nijmegen single-energy $pp+np$ phase shift analysis [52], excellent results were obtained for the ESC models. In [12], we reached a record low χ^2 with this approach. There, we used the adiabatic approximation, and moreover did not include the TMO graphs. Including the latter and all non-adiabatic and vertex corrections up to $1/M$, we got $\chi^2\approx 1.20-1.40$ [13, 14]. This for energies in the range $0\leq T_{lab}\leq 320$ MeV, which comprises 4301 data. At present, these applications of the ESC model have been in configuration space. In the near future, we will also perform NN fits in momentum space. In particular, we hope to improve the high-energy behavior of the model.

The meson-pair couplings are accessible to a physical analysis, and are not therefore arbitrary free parameters. There are two options to constrain these pair couplings. The first is by using chiral Lagrangians. Such an approach has been worked out in [14]. The second is by assuming *(heavy) meson-domination* (HMDM) [12]. That is, we assume that the pair vertices can be calculated assuming (heavy) meson saturation. For example, the $(\pi\pi)_1$ vertex is dominated by the ρ pole. We then make the approximation that the ρ propagator can be taken as $1/m_\rho^2$, which should be reasonable for low momentum transfer. Making these assumption we can readily extend the ESC model from NN to YN, YY, etc. Consider, for example, the $(\pi\rho)_1$ and the $(\pi\sigma)$ pair interactions. For the $g_{(\pi\rho)_1}$ and $g_{(\pi\sigma)}$ coupling, A_1 dominance would predict

$$
\begin{aligned}
|g_{(\pi\rho)_1}| &= \left(\frac{m_\pi}{m_{A_1}}\right)^2 g_{A_1NN}(0)g_{A_1\rho\pi}(0)\approx 0.14 \\
|g_{(\pi\sigma)}| &= \left(\frac{m_\pi}{m_{A_1}}\right)^2 g_{A_1NN}(0)g_{A_1\sigma\pi}(0)\approx 0.10
\end{aligned}
$$

In obtaining these estimates, we have used the predictions of the chiral Lagrangians in [30] and [53] for $g_{A_1\pi\rho}(m_{A_1}^2)$ and $g_{A_1\pi\sigma}(m_{A_1}^2)$. We have made the extrapolation to zero momentum by using a factor $\exp(-m_{A_1}^2/\mathcal{M}^2)$, where $\mathcal{M} = 1$ GeV. Additional input in this estimate is that $g_{A_1NN} \approx (m_\pi/m_{A_1}) f_{\pi NN} = 2.45$ [54]. Similarly, we find from the chiral Lagrangians the prediction, using σ dominance, that roughly $g_{\sigma\sigma} \approx 0.60$. Ref. [14], on the other hand, predicts $g_{(\pi\rho)_1} = 0.384$ and $g_{(\pi\sigma)} = 0$. In practice, we treat the pair couplings as free parameters in the fit to the NN data. (An exception is the chiral model of [14]). Comparison of the fitted couplings with model values, obtained as described above, gives an indication how realistic this approach is.

The extension to YN and YY is straightforward. For example

$$g_{Y'Y(\rho\pi)_1} = \hat{g}_{Y'YA_1} g_{A_1\rho\pi} \left(m_\pi^2/m_{A_1}^2\right),$$

which leads to, for example,

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

The application of the ESC model to YN and YY has only been started very recently. Here, we report on the first very preliminary results. To use the ESC model in the Nijmegen scheme of model building, we first had to update our ESC models for NN in order to make them fully consistent with SU$_f(3)$. For example, double-K exchange has to be included. Doing this, we sofar obtained a good NN fit with $\chi^2_{p.d.p} \approx 1.6$. Then, in going to YN we allowed as free parameters: θ_s, Δg_{pv}, Δg_v, Δg_s, and m_κ. Moreover, we allowed the form factor cut-off's of the strange mesons to deviate from the values for $\{8\}$ exchange, as determined in NN.

Notice, we do not yet attempt to reach at a definite and fully investigated model having e.g. a minimal number of free parameters. We want to find out in the first place, whether the ESC model allows for YN and, in particular, YY interactions that are qualitatively different from those possible for OBE models.

The fit for the YN scattering data is rather satisfactory. We found $\chi^2 = 24$ for the 35 data. For example, the capture ratio at rest $r_R = 0.463$ comes out right on top of the precisely known experimental value $r_R = 0.468 \pm .010$. Most remarkable is that the scalar mixing angle for this ESC model comes out as $\theta_s = -35.4^0$, and the corresponding $\alpha_s = -0.316$. This, implies that for YY we expect much stronger $\Lambda\Lambda$ and ΞN attractive potentials than in the case of the soft-core OBE models, like NSC97 which we discussed above. However, less satisfactory are the Λp low-energy parameters. We have for $\Lambda p(^1S_0)$ and $\Lambda(^3S_1)$ respectively $a_s = -4.47$ fm and $a_t = -1.41$ fm. This is probably not satisfactory for the spin structure of the Λ hypernuclei. Yamamoto and Bando [55] found the spin-singlet interaction in the NSC89 too strong. Clearly we still have to do some retuning of the parameters before an acceptable model for YN has been reached.

Application of this model to YY looks rather promising in that attraction similar to model D is expected for $\Lambda\Lambda$ and ΞN.

VI. DISCUSSION AND OUTLOOK

We first review some remarks that have been made, pertinent to the Nijmegen interactions, in the recent literature based on computations and information from hypernuclear studies on the central, the spin-spin, and the spin-orbit YN interactions:

a. **central**: The Λ well depth U_Λ is determined as $U_\Lambda = 27 - 28$ MeV from analyses of the (π^+, K^+) and (π^-, K^-) cross sections on nuclear targets with $A = 3 - 89$ [43]. The Nijmegen SC gives $U_\Lambda = 30.8$ MeV in [55] and $U_\Lambda = 32.3$ MeV in [56]. Also, it has been shown [48, 57] that the Λ single-particle energies agreed for the models, mentioned above, quite well with the BNL-AGS and the KEK data as a function of the mass number A.

b. **spin-spin**: The spin splittings of the levels for several hypernuclei have been analyzed recently extensively by Yamamoto et al. [48] using the YNG-type G-matrix [55] using the Nijmegen [4, 11] potentials. Recent experimental developments from (π^+, K^+) reactions with the KEK-SKS spectrometer [58, 59] and the BNL-AGS [60] have provided detailed information on the fine structure within several hypernuclei. The results for the theoretical interactions show significant deviations from each other and from the data. From the overall picture one can not discriminate definitely between the different potentials. Therefore, as new experiments are planned, in particular those using hypernuclear γ-ray spectrometers [61] with the germanium detectors (E287 experiment at KEK) and the Toroidal spectrometer, there are good prospects for progress in this sector. In view of these developments, one can envisage that the ΛN spin-spin interaction will be established rather well in the coming years. For more recent work see [63].

c. **spin-orbit**: The CERN-PS experiment on $^{16}\mathrm{O}(K^-, \pi^-)^{16}_{\Lambda}\mathrm{O}$ [64] and the BNL-AGS experiment on $^{13}\mathrm{C}(K^-, \pi^-)^{13}_{\Lambda}\mathrm{C}$ [65] lead to $V_{SO}(\Lambda N)/V_{SO}(NN) = 0.05 \pm 0.05$ [66], which is claimed to be smaller than the OBE models give. On the other hand, study of the heavier hypernuclei in the reactions $^{139}\mathrm{La}(\pi^+, K^+)^{139}_{\Lambda}\mathrm{La}$ and $^{89}\mathrm{Y}(\pi^+, K^+)^{89}_{\Lambda}\mathrm{Y}$ suggest larger spin-orbit forces in the ΛN interaction [44, 57]. However, these systems may show interesting many-body effects, which could influence the effective spin-orbit interaction. Of course, this could also be the case for the reactions on carbon and oxygen. Further experimental and theoretical activity concerning the spin-orbit interaction seems very promising to yield valuable information.

   However, it must be pointed out that the Nijmegen SC model satisfies the QM relations quite closely [11]: $g_{\Sigma\Sigma\omega} \approx g_{\Lambda\Lambda\omega} \approx \frac{2}{3} g_{NN\omega}$, and $g_{\Sigma\Sigma\phi} \approx g_{\Lambda\Lambda\phi}$, and $g_{NN\phi} \approx 0$, this in contrast to the Nijmegen models D and F. Also, the scalar mesons satisfy similar relations reasonably well (see also the discussion in [9]). Now, the SC model fits the NN P waves very accurately, and also for the triplet P-wave potentials we have $V_{\Lambda N} = (9V_{27} + V_{8s})/10$, i.e. very similar to the NN, which is purely V_{27}.

   Also, information on the ΛN spin-orbit interaction can be expected from Λ-nucleus scattering [67]. Here it is emphasized that a small spin-orbit interaction can be expected if $(f + g)_{\Lambda\Lambda\omega} = 0$. In the SC-model there is indeed a tendency to suppress this quantity. It will be interesting to see whether such a constraint on the ω couplings is confirmed by the experiments.

   The spin-orbit interaction has also given a puzzle in the quark-model. Namely, the P-wave baryons were hard to describe by the theory if one kept the full Fermi-Breit spin-orbit interaction from gluon exchange [68]. For the literature since 1980, see

Valcarce et al. [69]. Here one finds an indication that meson-exchange between quarks $(\pi, \epsilon, \rho, \omega,$ etc.) is a possible solution. This, as suggested before in this paper, is a most natural course. Another possibility is that the inclusion of the decay channels will be a way out of this problem [70].

An important recent development is the tendency to consider besides gluon exchange also meson exchange between quarks [73, 74]. This was stimulated by the problems encountered when one tried to explain the P-wave baryons using the Fermi-Breit interaction due to OGE [68] (see also [75]). In the case of constituent quarks there is no compelling reason to ignore meson exchange ($J^{PC} = 0^{-+}, 1^{--}, 0^{++}, 1^{++}$, etc.) between quarks. This brings us to the issue of the realistic QQ interactions. We envisage for low and intermediate energies, as well as for high energy processes up to moderate momentum transfer, that meson-exchange will play its natural role in the QQ interactions, besides of course the pure QCD interactions based on gluonic exchanges: i.e. the quark-gluon and the hadronic phase are both present in the QQ dynamics relevant to our field. If one accepts this view, then the SC interactions can be translated to the QQ level. One could e.g. fold the meson exchange between quarks using the gaussian $3Q$ wave functions of the baryons.

In view of the issues, mentioned above, an important purpose of the baryon-baryon studies, both in free space, (hyper)nuclei, and nuclear matter, is to bridge the gap between the observations of hadronic phenomena and the quark world. To contribute further in this area, we have to develop very strict, realistic, and precise theoretical models for the baryon-baryon interactions, a long term goal of the Nijmegen group. In this connection, the future of a Kaon factory, as foreseen in the JHF project, is extremely promising for the obvious reasons: (i) high-statistics experiments on YN interactions in free space, (ii) mass production of hypernuclei, and (iii) both low-, intermediate-, and high-energy data.

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