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Baryon-Baryon Interactions*

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Abstract

After a short survey of some topics of interest in the study of baryon-baryon scattering, the recent Nijmegen energy dependent partial wave analysis (PWA) of the nucleon-nucleon data is reviewed. In this PWA the energy range for both *pp* and *np* is now $0 < T_{lab} < 350$ MeV and a $\chi^2_{d.o.f.} = 1.08$ was reached. The implications for the pion-nucleon coupling constants are discussed. Comments are made with respect to recent discussions around this coupling constant in the literature. In the second part, we briefly sketch the picture of the baryon in several, more or less QCD-based, quark-models that have been rather prominent in the literature. Inspired by these pictures we constructed a new soft-core model for the nucleon-nucleon interaction and present the first results of this model in a χ^2-fit to the new multi-energy Nijmegen PWA. With this new model we succeeded in narrowing the gap between theory and experiment at low energies. For the energies $T_{lab} = 25 - 320$ MeV we reached a record low $\chi^2_{p.d.p.} = 1.16$. We finish the paper with some conclusions and an outlook describing the extension of the new model to baryon-baryon scattering.

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I. INTRODUCTION

A review of baryon-baryon scattering and the early work by the Nijmegen group has been given in [1]. Reviews of the recent work can be found in *e.g.* [2] and [3]. For the nucleon-nucleon work of other groups, like Bonn and Paris, we refer the reader to [4]. Although the items we discuss here are relevant, directly or indirectly, for all baryon-baryon channels, we focus in this paper mainly on the nucleon-nucleon channels. A shopping list of the items about which we want to learn more through the analysis of the experimental data and the study of theoretical models contains for example the following subjects:

1. Long-, intermediate-, and short-range mechanisms: *e.g.* single meson-echange $(\pi, \rho, ...)$, double meson-exchange $(\pi \otimes \pi, \pi \otimes \rho, ...)$, quark effects.

2. Relativistic effects: *e.g.* off-energy-shell effects, off-mass-shell effects.

3. Chiral-symmetry and soft-pion effects.

4. $SU(2, I)$- and $SU(3, F)$-symmetry of the coupling constants.

In this paper we concentrate on the first subject *i.e.* the mechanisms behind the nuclear force. Now, it is well known that the theoretical models do not explain the NN-data better than with a $\chi^2_{p.d.p.} \geq 1.8$. In this paper we describe a first attempt to investigate whether the new Nijmegen multi-energy partial wave analysis (PWA) [5] allows a better theoretical description of the data. This is done by an extension of the Nijmegen soft-core model [6].

The contents of this paper is as follows. In section 2 we report on the Nijmegen $pp + np$ multi-energy PWA. In section 3 we review briefly the situation around the pion-nucleon coupling constant. In section 4 we list the popular quark models and emphasize the synthesis of these quark models and the non-relativistic quark model in the general physical picture of a baryon as advocated by the chiral-quark model. In section 5 we introduce together with its first results, a new soft-core model, which we henceforth call the extended-soft-core (ESC) model. Finally, in section 6 we offer some conclusions and an outlook. Here we indicate how the ESC-model can be extended to all baryon-baryon channels.

II. MULTI-ENERGY PARTIAL-WAVE-ANALYSIS

After the multi-energy phase shift analysis of the pp data below 350 MeV [7], the Nijmegen group has recently finished a similar analysis for the pp and np data [5]. The $pp + np$ data base consists of 1787 pp-data and 2514 np-data. The principal method employed in this multi-energy PWA consists in a division of the internucleon distances r_{NN} into three regions:

(i) $r_{NN} \geq 2.0$ fm: the long-range region. Here the potential $V = V_L$ is dominated by the well known electromagnetic and one-pion-exchange potentials, $V_L \approx V_{EM} + V_{OPE}$. The residual potential comes from the spurs of the HBE, see next item.

(ii) $b \leq r_{NN} \leq 2.0$ fm ($b = 1.4$ fm): the intermediate-range region. Here the potential is taken to be a sum of the one-pion-exchange (OPE) and the heavy-boson exchanges (HBE) from the Nijmegen [6] soft-core potential, so $V = V_{EM} + V_{OPE} + V_{HBE}^{N}$. For the singlet waves the following modification proved to be advantageous: $V_{HBE}^{N} \rightarrow f_{med}^{s} V_{HBE}^{N}$, with $f_{med}^{s} = 1.8$.

(iii) $r_{NN} \leq b$ fm: the short-range region. Here an energy dependent boundary condition is used in principle. In practice it appeared useful to use energy dependent square well potentials in the inner region. This is equivalent to

$$P\left(b; k^2\right) = P_{free}\left(b; k^2 - 2M_r V_S\right)$$

The parametrization of the energy dependence is as follows

$$V_{S,\beta}(k^2) = \frac{1}{2M_r} \sum_{n=0}^{N} a_{n,\beta}\ k^{2n}$$

independently for each wave $\beta = (L, S, J)$. Here, k denotes the relativistic cm momentum. For each wave only a couple of 'phase parameters' a_n's were needed to cover the energy interval $0 \leq T_{lab} \leq 350$ MeV unbiased. In total 21 phase parameters were used for *pp* and 18 for *np*.

With the parametrization of the potentials completed, the radial Schrödinger equation

$$\left(\frac{d^2}{dr^2} + k^2 - \frac{L^2}{r^2} - M_r V_\beta(r)\right) \chi_\beta(r) = 0$$

is solved and the phase shifts as a function of the parameters and the energy are obtained.

Very important ingredients of this PWA are:

a. The accurate treatment of the electromagnetic interactions:

$$V_{EM} = \tilde{V}_C\ +\ V_{MM}\ +\ V_{VP}$$

where $\tilde{V}_C$ is the improved Coulomb interaction, V_{MM} is the magnetic moment interaction, and V_{VP} is the vacuum polarization.

b. The OPE-amplitude is treated in Coulomb-distorted-wave Born-approximation. It appeared that a simple Coulomb barrier penetration factor was not sufficiently realistic. This CDWBA-treatment is very important in the determination of the pion-nucleon coupling constant.

c. The correction of the $I = 1$ *np*-waves for the $\pi^{\pm} - \pi^0$-mass difference.

As a result of this PWA a $\chi^2_{d.o.f} = 1.08$ was reached. For *pp*: $\chi^2 = 1787.0$, $N_{d.o.f} = 1613$ and for *np*: $\chi^2 = 2484.2$, $N_{d.o.f} = 2332$. In a combined $pp + np$ analysis one obtained $\chi^2 = 4263.8$, $N_{d.o.f} = 4301$. As an indication of the realistic energy dependence, it was found that extrapolation to the deuteron pole results in a predicted binding energy $B = 2.2247(35)$, whereas experimentally $B = 2.224575(9)$. As a result of this PWA very accurate $I = 0$ np phases are now available, the estimated errors are only slightly larger than those for the pp phases. The mixing parameter ϵ_1 is not small and reaches 4.57 ± 0.25 degrees at $T_{lab} = 350$ MeV.

The Nijmegen group has also constructed Reidlike phenomenological potential models [8], which fit the data equally well as the PWA, *i.e.* $\chi^2_{p.d.p} \approx 1.0$. These potentials make the results of this new PWA available for many applications in few body systems. As an example, we mention the very recent calculation of the triton using these Reidlike potentials [9]. It was found that these two-nucleon interactions predict the binding energy as $7.62-7.72$ MeV.

III. PION-NUCLEON COUPLING CONSTANT

The first accurate determination of the neutral pion-nucleon coupling constant was done by the Nijmegen group [10,7]. When this author presented the Nijmegen determination of this pion-nucleon coupling constant at the Vancouver conference in 1989 [11] it was suggested that also the charged pion-nucleon coupling constant should be determined with the same method. With the Nijmegen 1993 PWA [5] this has been done and also the charged pion-nucleon coupling turns out to be significantly lower than that found in the Karlsruhe 1980-analysis [12]. Meanwhile, also in a recent pion-nucleon partial wave analysis by the VPI&SU group a value consistent with the Nijmegen determination was found [13]. Moreover, a PWA of the combined pp and np data [14] and of the antinucleon-nucleon data revealed the same result [15]. In [16] the recent determinations of the πNN couplings are tabulated. Below in Table I we show Table I of ref. [16]. Here, DR refers to the use of dispersion relations, PWA to the usual phase shift or partial wave analysis. Soon after the publication of the Nijmegen π^0-coupling constant determination [10], it was heavily criticized in the literature. Notably, the claim was made, see for example [17], that the Nijmegen group had overlooked form factor effects. Still recently, it was suggested in the panel discussion of the Adelaide conference [18] that the value of the pion coupling constant found in the Nijmegen method depends on the shape of the form factor. This was dismissed in a Nijmegen paper on the several issues raised in the literature [16]. The main points made here are:

(i) The Nijmegen PWA is statistically impeccable. The criteria used in selecting the data base are unbiased and common practice under specialists on the NN phase shift analysis.

(ii) Tests show that indeed the Nijmegen method determines the pole value of the pion-nucleon coupling constant.

(iii) Neither the shape nor reasonable values of the cut-off mass have any influence.

(iv) The presently available potential models are too bad to determine $f_{\pi NN}$ with an accuracy comparable to the Nijmegen NN phase shift analysis.

Group	Year	Method	$10^3 f^2_{pp\pi^0}$	$10^3 f^2_c$
Karlsruhe-Helsinki [12]	pre-1983	$\pi^\pm$ DR		79(1)
Nijmegen [7]	1987-1990	pp PWA	74.9(0.7)	
VPI&SU [13]	1990	$\pi^\pm p$ DR		73.5(1.5)
Nijmegen [14]	1991	combined NN PWA	75.1(0.6)	74.1(0.5)
Nijmegen [15]	1991	$\bar{p}p$ PWA		75.1(1.7)
Nijmegen [16]	1992	pp and np PWA	74.5(0.6)	74.8(0.3)

TABLE I. Recent πNN-coupling constant determinations.

IV. BARYON STRUCTURE, CHIRAL QUARK-MODELS

The quark-model picture of the baryons should be of some directional value in the deduction of a realistic model for baryon-baryon scattering. Interesting bag-models are the MIT [19], the Stony Brook [20], and the TRIUMF [21] models. A particularly interesting quark-model is the chiral-quark-model [22]. This model explains the successes of the non-relativistic quark-model (NRQM) and at the same time is closely connected with the description of hadron dynamics through interactions involving mesons and baryons using effective chiral lagrangians. The general idea is that the QCD-vacuum becomes unstable at $Q^2 \leq \Lambda^2_{\chi SB} \approx (1GeV)^2$. The vacuum goes through a phase transition, making for the quarks $\langle 0|\bar{\psi}\psi|0\rangle \neq 0$ and the gluon coupling α_S small. This generates the constituent quark masses and implies that the quarks move around in the core of a baryon essentially as being free, just as in the NRQM. Viewing (part of) the pion as the Goldstone boson, correlated with spontaneously broken chiral invariance, makes it natural that there is a soft-pion cloud around a constituent quark. High energy experiments indicate that the Pomeron couples to the quarks [23]. Then, a soft pion cloud around a constituent quark offers a natural explanation for the multi-peripheral component of the Pomeron. Also, the coupling of mesons to quarks dressed by a pion cloud is in accordance with the ideas that the non-linear sigma-model is relevant for the description of hadronic interactions [24]. We have drawn for a nucleon in Fig. 1 the picture that emerges from the bag-models and the chiral-quark-model, *i.e.* a quark-core surrounded by a meson cloud of pions and other mesons, Baryon-baryon

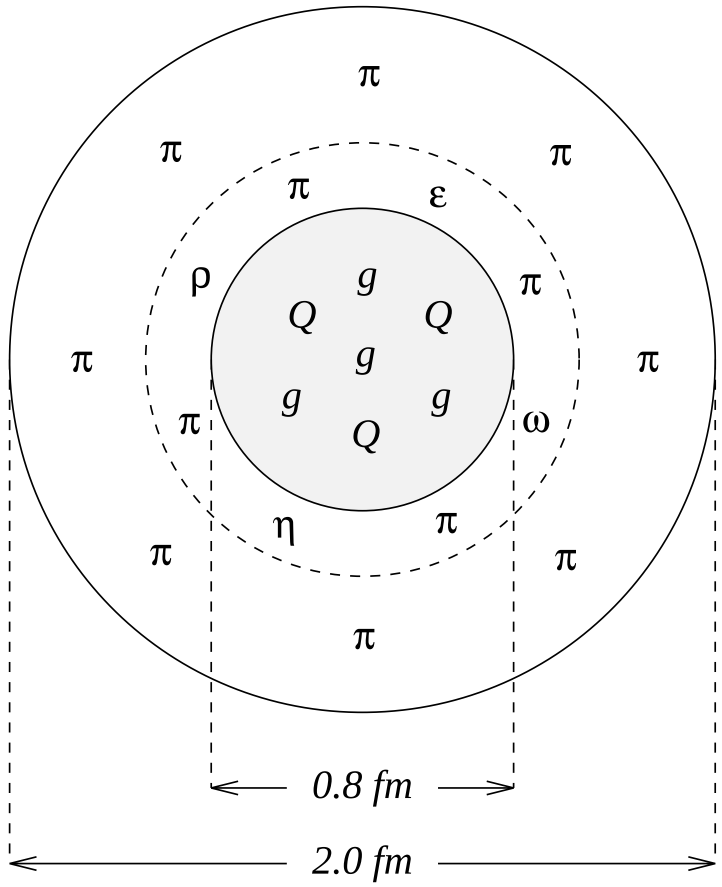

FIG. 1. Schematic model of the baryon structure

scattering is the quantum mechanical scattering of two of such systems. The chiral-quark-model in particular, provides a natural basis for an approach to baryon-baryon scattering using only mesonic degrees of freedom in the derivation of the baryon-baryon interactions. In the next paragraph we will describe such an attempt. We construct a new *NN*-model and make a fit to the 1993 multi-energy Nijmegen PWA.

V. EXTENDED SOFT-CORE MODEL

The potential of this new *NN*-model, henceforth referred to as the ESC-model, consists of the contributions of

(i) The OBE-potentials of [6], which apart from the low lying pseudo-scalar-, vector-, and scalar-mesons includes also contributions of the Pomeron. The latter represents the multi-peripheral (soft)pion exchanges and multi-gluon exchanges.

(ii) The 2π-potentials as given in [26]. These are two-pion-exchange potentials based on the pseudo-vector pion-nucleon coupling. We include only the so-called BW-graphs, *i.e.* we discard the TMO-graphs (see [26] for this nomenclature). This, because we think that the non-adiabatic expansions are not reliable. Therefore, we prefer to extend the present model later by including the non-adiabatic effects already in the OBE-potentials.

(iii) We extend the OBE-model of [6] further through the inclusion of phenomenological nucleon-nucleon-meson-meson vertices, henceforth referred to as 'pair interactions' or 'pair terms'. The vertices are listed in Table II.

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

TABLE II. Phenomenological Meson-Pair Interactions

The motivation for including these 'pair-vertices' is that similar interactions appear in chiral-lagrangians. They can be viewed upon as the result of the out integration of 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.* [25], 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 in essence described in [26]. The new type of graphs that have to be evaluated are those with one pair-vertex and with two pair-vertices.

Fitting this new model to the NN-data, using the 1993 Nijmegen single energy $pp+np$ phase shift analysis [5], leads to an excellent result. We reached for the energies in the range $25\leq T_{lab}\leq 320$ MeV, which comprises 3709 data, a $\chi^2_{p.d.p.}=1.16$ [27]. The (rationalized) coupling constants and form factor masses are given in Table III. Here, the f_η was not fitted but derived from f_π using $\alpha_{pv}=0.361$. We used for the σ a mass of $m_\sigma=500.4$ MeV, *i.e.* the lowest mass of the two-pole approximation used in [6]. The use of different form factors for $I_t=1$ and $I_t=0$ for vector and scalar exchange did not have much influence on the fit.

ps-pv		vector		scalar		pairs	
f_π	0.268	g_ρ	0.730	g_δ	1.299	$g_{(\pi\pi)_0}$	-0.160
f_η	0.069	f_ρ	3.299	g_ϵ	3.573	$g_{(\pi\pi)_1}$	-0.001
$f_{\eta'}$	0.271	g_ω	3.009	g_{A_2}	0.123	$f_{(\pi\pi)_1}$	-0.260
		f_ω	0.567	g_P	2.346	$g_{(\pi\rho)_0}$	0.073
Λ_{PV}	844.8	$\Lambda_{V,1}$	777.6	$\Lambda_{S,1}$	767.1	$g_{(\pi\rho)_1}$	0.506
		$\Lambda_{V,0}$	744.9	$\Lambda_{S,0}$	835.6	$g_{(\pi\omega)}$	-0.001
				m_P	309.1	$g_{(\pi\sigma)}$	-0.170
						$g_{(\sigma\sigma)}$	-0.302

TABLE III. Form factor masses, meson and meson-pair couplings.

The nuclear-bar phase shifts of the new NN-model are given in Table IV. In this table, the $I = 1$-phases are pp-phases and the $I = 0$-phases are np-phases. The χ^2 of the model w.r.t. the PWA-phases is denoted by $\Delta\chi^2$.

The numerical results were obtained by using a coordinate space version of the model. The OPEP treatment was adapted to the PWA by multiplying in momentum space the OPEP of [6] by $\sqrt{M/E(p)}$-factors for the initial and final state.

From Table IV one notices the great improvement of the new model over the OBE-model [6]. In particular this is obvious for the $^1P_1$-, the $^3D_2$-, and the $^3D_3$-waves. The $^3F_2$-wave however, is bending towards zero too quickly as a function of energy. Here the 2π-potential gives a repulsive tensor force. At this point the inclusion of $\pi\otimes\rho$-, $\pi\otimes\omega$-potentials in the future may be of help in particular. The values reported in Table III are very reasonable. The pion coupling was searched and $f^2_{NN\pi} = 0.072$, which is on the lower side of the determinations listed in Table I. We have $g^2_\rho = 0.53$ and $(f/g)_\rho = 4.52$, in reasonable agreement with VDM [29]. The agreement improves if we also take into account the contribution of the $\pi\pi$-pair terms (see remark below). The ω-, ϵ-, and pomeron- couplings are rather similar to those of [6].

Also the meson-pair couplings are accessible to a physical interpretation. The couplings $g_{(\pi\pi)_0}$ and $f_{(\pi\pi)_1}$ are not very small. This, notwithstanding the fact that the $I_t = 0$-channel is dominated by ϵ- and Pomeron-exchange, which tend to cancel each other largely. Similarly, because of the dominance of ρ-exchange in the $I_t = 1$-channel one would tend to expect small values for $g_{(\pi\pi)_1}$ and $f_{(\pi\pi)_1}$. However, the pion-pair contribution represents, among other things, the correction to the two-pole approximation used for the description of the broad ϵ and ρ meson, which is not negligible.
Also, with these πN-interactions all s- and p-wave pion-nucleon scattering lengths are accounted for very well (see also [2]). In particular, interpreting the $(\pi\pi)_0$-pair contribution as representing in fact the effect of the low mass tail of the broad ϵ-meson, one finds a contribution $\Delta a_{33} \approx 0.10$, which is needed together with the nucleon-pole contribution in order to give the experimental value.
For the $g_{(\pi\rho)_1}$- and $g_{(\pi\sigma)}$-coupling A_1-dominance would predict

$$|g_{(\pi\rho)_1}| = \left(\frac{m_\pi}{m_{A_1}}\right)^2 g_{A_1NN}(0) g_{A_1\rho\pi}(0) \approx 0.14$$

$$|g_{(\pi\sigma)}| = \left(\frac{m_\pi}{m_{A_1}}\right)^2 g_{A_1NN}(0) g_{A_1\sigma\pi}(0) \approx 0.10$$

In obtaining these estimates, we have used the predictions of the chiral-lagrangians in [30] and [31] for $g_{A_1\pi\rho}(m^2_{A_1})$ and $g_{A_1\pi\sigma}(m^2_{A_1})$. Extrapolation to zero momentum we have done by using a factor $\exp(-m^2_{A_1}/\mathcal{M}^2)$, where $\mathcal{M} = 1$ GeV. Additional input in this estimate is that $g_{A_1NN} \approx (m_\pi/m_{A_1}) f_{\pi NN} = 2.45$ [32] (see also [33]). Similarly, we find from the chiral-lagrangians the prediction, using σ-dominance, that roughly $g_{\sigma\sigma} \approx -0.50$, which is not far from -0.30 found in the fit. Likewise, assuming that $g_{(\pi\rho)_0}$ and $g_{(\pi\omega)}$ are dominated by respectively the H- and B_1-meson, we could estimate from the fitted values the couplings g_{HNN} and g_{B_1NN}. Of course, heavy boson dominance is not valid for all these pair couplings. If we would include also the $\pi \otimes \rho$-, $\pi \otimes \omega$- etc. potentials, then the residual interactions are more likely to be boson dominated. Therefore, the present results are preliminary.

VI. CONCLUSIONS AND OUTLOOK

The multi-energy Nijmegen PWA poses a nice new challenge to the theory of the low momentum transfer baryon-baryon interactions. The success of our ESC-model indicates that the better quality of the multi-energy Nijmegen PWA with respect to other phase shift analyses, indeed opens the door to a more thorough understanding of the low energy NN-data. To make progress in the problems concerning Few Body Physics, it is imperative that baryon-baryon interactions are used which are based on a very realistic description of nucleon-nucleon scattering. Conclusions about such parameters as the pion-nucleon coupling constant, the relativistic effects, the off-mass-shell effects etc. are otherwise liable to be fallacious.

The chiral-quark-model picture [22] makes it highly implausible that there will be large nucleon-antinucleon-pair effects in the low energy region (see also [34]). Incidentally, a model with large nucleon-antinucleon pair contributions should also include in the intermediate states pion-nucleon resonances up to 3 GeV, nucleon-hyperon-kaon intermediate states etc. Also, the presence of these pairs in nuclear Compton scattering is improbable. In fact, it is likely that the negative energy contributions of the constituents cancel out in the Thomson limit [35].

Multi-soft-pion and multi-meson effects on the other hand are expected, both in chiral-lagrangian models and QCD [24]. However, for reactions dominated by momentum transfers below 1 GeV, interactions based on gluon-exchange are presumably suppressed [22]. Therefore, models based on strong gluon-quark exchanges do not seem very realistic.

The proper theoretical framework for the phenomenological nucleon-nucleon meson-pair vertices seems the non-linear chiral $SU(2) \times SU(2)$- symmetry (for reference see *e.g.* [30]. Then, the extension from nucleon-nucleon to baryon-baryon can be tried by employing $SU(3) \times SU(3)$-symmetry (see *e.g.* [36]). This would introduce only a very restricted set of extra free parameters in for example hyperon-nucleon models.

The extension to higher nucleon-nucleon energies of the ESC-model requires the explicit treatment of the Δ_{33}-resonance degrees of freedom. This can be done immediately and will result in different meson-pair contributions. For low energy scattering this is unnecessary. This follows on the one hand from our successful fit to the low energy data by *e.g.* the new NN-model described above, and on the other hand this is explained to be possible to a certain degree of accuracy by duality (see the remarks in [2]).

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T_{lab}	25	50	100	150	215	320
♯ data	352	572	399	676	756	954
$\Delta\chi^2$	67	68	30	74	153	335
$^1S_0$	49.05	38.87	24.41	13.88	3.23	-9.91
$^3S_1$	79.99	62.21	42.91	30.77	19.44	6.36
ϵ_1	1.96	2.38	2.82	3.21	3.70	4.43
$^3P_0$	8.84	11.96	10.01	5.20	-1.46	-11.18
$^3P_1$	-4.85	-8.24	-13.22	-17.32	-21.94	-28.19
$^1P_1$	-6.19	-9.39	-13.87	-17.81	-22.57	-29.40
$^3P_2$	2.50	5.79	10.89	13.99	16.18	17.41
ϵ_2	-0.80	-1.70	-2.71	-3.01	-2.85	-2.10
$^3D_1$	-2.78	-6.39	-12.27	-16.71	-21.17	-26.56
$^3D_2$	3.67	8.91	17.37	22.48	25.44	25.54
$^1D_2$	0.69	1.69	3.83	5.86	7.96	9.75
$^3D_3$	0.05	0.31	1.34	2.53	3.77	4.70
ϵ_3	0.54	1.57	3.40	4.74	5.92	7.03
$^3F_2$	0.10	0.34	0.79	1.07	1.07	0.16
$^3F_3$	-0.22	-0.66	-1.47	-2.11	-2.82	-3.97
$^1F_3$	-0.41	-1.08	-2.09	-2.74	-3.39	-4.51
$^3F_4$	0.02	0.11	0.47	0.94	1.60	2.52
ϵ_4	-0.05	-0.19	-0.52	-0.82	-1.13	-1.49
$^3G_3$	-0.05	-0.25	-0.89	-1.66	-2.66	-4.12
$^3G_4$	0.17	0.70	2.09	3.49	5.15	7.33
$^1G_4$	0.04	0.15	0.41	0.67	1.03	1.63
$^3G_5$	-0.01	-0.05	-0.15	-0.23	-0.26	-0.17
ϵ_5	0.04	0.20	0.69	1.20	1.80	2.58
$^3H_4$	0.00	0.03	0.11	0.21	0.36	0.56
$^3H_5$	-0.01	-0.08	-0.29	-0.52	-0.77	-1.10
$^1H_5$	-0.03	-0.16	-0.51	-0.83	-1.15	-1.50
$^3H_6$	0.00	0.01	0.04	0.10	0.21	0.44
ϵ_6	-0.00	-0.03	-0.11	-0.22	-0.35	-0.54

TABLE IV. ESC nuclear-bar *pp* and *np* phase shifts in degrees.