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Recent Soft-core Baryon-Baryon Interactions*

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Abstract

We discuss recent results obtained with the Extended-Soft-Core (ESC) interactions for baryon-baryon (BB) scattering. The particular version of the ESC-model discussed in this paper, henceforth called ESC03, describes nucleon-nucleon (NN), hyperon-nucleon (YN), and hyperon-hyperon (YY), in a unified manner using (broken) $SU_f(3)$-symmetry. Novel ingredients are the inclusion of (i) the axial-vector meson potentials, (ii) a zero in the scalar-meson form-factors. These innovations, made it possible for the first time to keep the parameters of the model closely to the predictions of the $^3P_0$ quark-pair-creation model (QPC). This is the case for the meson-baryon coupling constants and $F/(F+D)$-ratio's as well. This implies that the number of free parameters in NN is reduced considerably and very much less than in the NN phase shift analysis. Also, the YN and YY results for this model are rather excellent.

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I. INTRODUCTION

The Nijmegen soft-core baryon-baryon models are based on the study of the NN-, YN-, and YY-interactions in particle physics, i.e. effective QCD theories like e.g. the quark-model(QM), involving only hadronic degrees of freedom. In this contribution the emphasis is on the underlying quark-physics, rather than on the best possible fit to the scattering data in terms of the χ^2. For that purpose we restricted the freedom of the parameters considerably, using information from the quark-model. This appeared feasible after we added two new ingredients to the ESC-model, which are (i) the inclusion of the axial-vector mesons, and (ii) the introduction of a zero in the scalar meson form factors.

In [1] we introduced the ESC-model for BB-scattering pointing out that many dynamical aspects of low energy QCD and chiral-symmetry are accounted for. In synopsis, an exposition of a modern theoretical basis for the soft-core approach for the baryon-baryon interactions has been given in [1, 2]. Starting from the Standard Model and integrating out the heavy flavors, one arrives at QCD for the u, d, s quarks. We follow the now fashionable scenario [3] that the QCD-vacuum becomes unstable for $Q^2 \leq \Lambda^2_{\chi SB} \approx 1$ GeV^2, causing spontaneous chiral symmetry breaking (χSB). The vacuum goes through a phase transition, generating constituent quark masses via $\langle 0|\bar{\psi}\psi|0\rangle \neq 0$ and reducing the gluon coupling α_s. Then, the pseudo-scalar mesons π, etc. being the corresponding Nambu-Goldstone bosons, it is natural to assume baryon dressing by pseudo-scalar mesons and also by other types of mesons. In this context, baryon-baryon interactions are described naturally by meson exchange, using form factors at the meson-baryon vertices. We restrict ourselves to low energy scattering and to the purely hadronic phase, which seems appropriate in view of the effective smallness of the quark-gluon coupling. Integrating out the (very) heavy mesons and baryons using the Wilsonian renormalization [4], we restrict ourselves to the lowest lying octet of baryons $(N, \Lambda, \Sigma, \Xi)$, and mesons with $M \leq 1.3$ GeV$/c^2$. This is the setting and general physical basis for the Nijmegen soft-core models.

In ESC, the soft-core OBE-models, see [5, 6] for references, are extended to include uncorrelated two-meson-exchange (TPS) and, for the first time in realistic baryon-baryon models, meson-pair exchanges (MPE). In [7] we discussed the results of the first versions of the Extended-Soft-Core (ESC) models for baryon-baryon. Here, we present results of the most recent version, where novel ingredients are introduced, which leads to a description of the nuclear and hyper-nuclear forces that is to large extend compatible with the predictions of the $^3P_0$ quark-pair-creation (QPC) Model [8, 9]. We take QPC-model predictions as a guidance, imposing as a constraint that the deviations of the parameters w.r.t. QPC are small. Since QPC scored considerable successes [10] in predicting e.g. meson and resonance decay couplings, it is reasonable to expect that if such constraints are possible then the predictions for YN and YY will be better, at least qualitatively. The feasibility of the QPC-model and the ESC-model presumably is due to the two innovations, mentioned above. In ESC03 both the NN-couplings, as well as the $F/(F+D)$-ratios are constraint by the QPC-model. For the first time e.g. the near equalities $g_\omega \approx g_\epsilon$ and $g_\rho \approx g_{a_0}$ are explained and realized in a good fit to the scattering data for NN and YN. For the results we focuss on NN, and mention very briefly some YN and YY features.

The program of this paper is as follows. In section 2 we further describe briefly the physics contents of the ESC03-model. In particular, indicate briefly how the ESC-model is extended to all baryon-baryon channels. In section 3 the NN-sector and the coupling constants are discussed. In section 4 some features for YN and YY are reviewed briefly.

II. ESC-MODEL FOR BARYON-BARYON

The potentials of the ESC-models have been reviewed e.g. in [7]. Here, we discuss them briefly, and in particularly the new features for ESC03:

(i) In addition to pseudo-scalar-, vector-, scalar-, and diffractive-potentials, we include for the first time the OBE-potentials from the axial-meson nonet $J^{PC} = 1^{++}$: $f_1(1285),\ a_1(1270),\ f_1(1420),\ K_1(1270)$.

(ii) In contrast to ESC00 [7] we included only the lowest-lying scalar nonet $J^{PC} = 0^{++}$: $\varepsilon(760),\ a_0(962),\ f_0(993),\ \kappa(900)$. Special for ESC03 is the introduction of a zero in the scalar-meson form factors at $k^2 = m_z^2$, where $m_z = 750$ MeV/c. This zero is natural in the QPC-model because of the p-wave overlap integrals, and has two important effects. First, it eliminates the strong inner attraction of the scalar mesons and helps to avoid deep bound states in e.g. $\Lambda N(^1S_0)$, which are present in the NSC97 [5] solutions. Second, it reduces the $g_{\epsilon NN}$-coupling, bringing it in line with the QPC-model predictions.

(iii) Like in ESC00, the TPSE-potentials as given in Ref. [11] are included. These are two-pseudo-scalar-exchange (PS-PS) potentials based on a combination of pseudo-vector (pv) and pseudo-scalar (ps) coupling to the baryon octet, described by a parameter a_{PV}. We note that we did not include uncorrelated two-meson-exchange potentials with vector- and scalar-mesons. Including these brings in a lot of exchanges with a mass > 1 GeV. Moreover, due to strong cancelations between the different diagrams for $I = 0$ mesons, these potentials are of moderate strength and can be covered largely by OBE and MPE.

(iv) As in ESC00, we included a (complete) set of phenomenological baryon-baryon-meson-meson vertices, henceforth refered to as 'meson-pair-exchange' (MPE). The vertices and resulting potentials are given in [1, 11] for NN. The motivation for the MPE is mainly dynamical. Additional motivation for including these MPE-potentials is that similar interactions are required in chiral Lagrangian's [12]. They can be viewed upon as the result of the out integration of the heavy-meson and resonance degrees of freedom. Also, in view of the fact that the Gaussian form-factors do not contain explicit two-meson cuts, e.g. the $\pi\pi$-cut in case of the ρ-meson etc., the latter can be accounted for by the MPE. In ESC03 we take only contributions from the MPE-interactions to first order in the pair couplings. Diagrams with two pair-couplings are very similar to taking into account the widths of the mesons in the OBE-potentials. Such effects are included for ϵ and ρ, where they are important. For heavier mesons, like a_1(1270 such effects are less important.

The extension of MPE to YN and YY is done by an $SU(3)$-classification of these pair-states, and the use of the proper $F/(F + D)$-ratio parameters for the baryon-baryon vertices, in analogy with those utilized for meson-baryon-baryon vertices. The included pairs are: $\{PP\}_{S_1}$, $\{PP\}_{S_8}$, $\{VP\}_{B_8}$, $\{PP\}_{V_8}$, $\{VP\}_{A_8}$, and $\{PS\}_{A_8}$. Here, P=pseudo-scalar, S=scalar, V=vector, and A,B=axial-vector, and S_1 stands for the symmetric unitary singlet combination etc. Typical example for each type S_1, S_8, B_8, V_8, A_8, and A_8 are respectively $(\pi\pi)_{I=0}$, $(\pi\eta)$, $(\pi\omega)$, $(\pi\pi)_{I=1}$, $(\pi\rho)_{I=1}$, $(\pi\sigma)$. In each case, the full $SU(3)$ structure is taken into account. To give an illustration, consider the MPE-interaction Hamiltonians for the cases $\{PP\}_{S_1}$ and $\{VP\}_{A_8}$:

$$\begin{aligned}
\mathcal{H}_{S_1PP} &= \frac{g_{S_1PP}}{\sqrt{3}} \Big\{ \boldsymbol{\pi}\cdot\boldsymbol{\pi} + 2K^\dagger K + \eta_8\eta_8 \Big\} \cdot \widetilde{\sigma} \\
\mathcal{H}_{V_8PP} &= g_{A_8PP} \Big\{ \frac{1}{2}\widetilde{\boldsymbol{\rho}}_\mu \cdot \boldsymbol{\pi}\times \overleftrightarrow{\partial^\mu}\boldsymbol{\pi} + \frac{i}{2}\widetilde{\boldsymbol{\rho}}_\mu\cdot(K^\dagger\boldsymbol{\tau}\overleftrightarrow{\partial^\mu}K) \\
&\quad + \frac{i}{2}\Big(\widetilde{K}^{*\dagger}_\mu\boldsymbol{\tau}(K\overleftrightarrow{\partial^\mu}\boldsymbol{\pi}) - h.c.\Big) + i\frac{\sqrt{3}}{2}\Big(\widetilde{K}^{*\dagger}_\mu\cdot \\
&\quad (K\cdot\overleftrightarrow{\partial^\mu}\eta_8) - h.c.\Big) + \frac{i}{2}\sqrt{3}\widetilde{\phi}_\mu(K^\dagger\overleftrightarrow{\partial^\mu}K) \Big\}
\end{aligned}$$

Here, $\widetilde{\sigma} = \bar{\psi}\psi$, $\widetilde{\boldsymbol{\rho}} = \bar{\psi}\gamma_\mu\boldsymbol{\tau}\psi$ etc., i.e. the baryon densities with the proper space-time properties.

III. NUCLEON-NUCLEON

As mentioned in e.g. [7], fitting this model to only the NN-data, using the 1993 Nijmegen single energy $pp + np$ phase shift analysis [13], leads to excellent results. Without the QPC-model constraints, fitting only the NN data, one reaches for the energies in the range $0 \leq T_{lab} \leq 350$ MeV, which contains 4233 data, typically a $\chi^2_{p.d.p.} = 1.11 - 1.15$. In a simultaneous fit of NN and YN we usually obtain an extra $\Delta\chi^2_{p.d.p.} \approx 0.10$. In ESC03 where we impose in addition the QPC-constraints rather strictly, we reached $\chi^2_{p.d.p.} = 1.35$. In Table III we show the fitted ESC03-parameters. The (rationalized) coupling constants and

pseudo-scalar		vector		scalar		pairs	
f_π	0.263	g_ρ	0.777	g_{a_0}	0.777	$g_{(\pi\pi)_0}$	-0.002
f_η	0.186	f_ρ	3.319	g_ϵ	3.214	$g_{(\pi\pi)_1}$	0.052
$f_{\eta'}$	0.160	g_ω	2.909	g_{A_2}	0.416	$f_{(\pi\pi)_1}$	0.034
		f_ω	-0.227	g_P	2.360	$g_{(\pi\eta)}$	-0.347
Λ_{P8}	853.2	Λ_{V8}	944.9	Λ_{S8}	775.2	$g_{(\pi\rho)_1}$	0.720
Λ_{P1}	1362.4	Λ_{V1}	803.8	Λ_{S1}	1191.1	$g_{(\pi\omega)}$	-0.110
a_{PV}	1.122			m_P	309.1	$g_{(\pi\sigma)}$	0.141

TABLE I: ESC03: Meson- and meson-pair-couplings, and form factor masses.

form factor masses are given in Table III. Here, the f_η was not fitted but derived from f_π using $\alpha_{pv} = 0.400$. The fitted α-parameters are: $\alpha_V^m = 0.448$, $\alpha_S = 0.852$. All other α parameters were fixed: $\alpha_{PV} = 0.40$, $\alpha_V^e = 1.0$, $\alpha_A = 0.368$, and $\alpha_D = 1.0$. The meson mixing used are the standard ones for the pseudo-scalar- and vector-mesons, see e.g. [5]. For the scalar mesons and the diffractive exchanges we used ideal mixing, and for the axial-mesons we took $\theta_A = 47.3^o$.

In the QPC-model [9] the NN-couplings can be written in the following form

$$f_{BBM}(\mp) = \gamma_M \left(\frac{4\pi}{9}\right)^{1/4} X_M\left(I_M, L_M, S_M, J_M\right)\ F_M^{(\mp)}$$

where (i) γ_M is the (running) pair-creation constant, (ii) X_M are the recoupling coefficients, which depend on the meson quantum numbers, and (iii) $F_M^{\mp}$ are the quark-wave function overlap integrals for the $Q\bar{Q}(L = 0,1)$-mesons in terms of the nucleon and meson radii, respectively R_B and R_M. For $\rho \to e^+e^-$ the current-field-identity (CFI) and the Van Royen-Weisskopf relation [14] give for the $\rho\pi\pi$ coupling

$$f_\rho = \frac{m_\rho^{3/2}}{\sqrt{2}|\psi_\rho(0)|} \Leftrightarrow \gamma\left(\frac{2}{3\pi}\right)^{1/2} \frac{m_\rho^{3/2}}{|\psi_\rho(0)|}\ ,$$

where the last expression on the r.h.s. is the QPC-model form of this coupling [9]. Identification leads to the prediction: $\gamma_M = \frac{1}{2}\sqrt{3\pi} = 1.535$. Taking $R_B = 0.8 fm$ and $R_M = 0.56 fm$, we obtain the predictions shown in Table III. From Table III one notices a couple of rela-

Meson	$r_M[fm]$	X_M	γ_M	$^3P_0$	ESC03
$\rho(770)$	0.56	$1/2$	1.53	$g = 0.78$	0.78
$\omega(783)$	0.56	$3/2$	1.53	$g = 2.40$	2.91
$a_0(962)$	0.56	$\sqrt{3}/2$	1.53	$g = 0.79$	0.78
$\epsilon(760)$	0.56	$3\sqrt{3}/2$	1.53	$g = 2.11$	3.21
$a_1(1270)$	0.56	$3\sqrt{3}/2$	1.53	$g = 2.73$	2.86

TABLE II: ESC03 Couplings and $^3P_0$-Model Relations.

tions in the $^3P_0$-model: $g_\omega \approx 3g_\rho$, $g_\epsilon \approx 3g_{a_0}$, $g_{a_0} \approx g_\rho$, and $g_\epsilon \approx\ g_\omega$. The axial coupling satisfies $f_{NNa_1} \approx (m_{a_1}/m_\pi)f_{NN\pi}$, which is the Schwinger relation [15]. In the last column of Table III we show the fitted NN-couplings for the vector-, scalar-, and axial-couplings. One sees that all couplings in ESC03 are pretty much in line with the QPC-predictions. However, one must realize that the QPC-predictions are naive in the sense that in principle these couplings have to be renormalized by taking into account mesonic vertex dressing. Also, one expects that the mesons have different $Q\bar{Q}$-radii. Nevertheless, it is remarkable that the ESC03 couplings can be choosen close to QPC-predictions. Relaxing a bit on e.g. the ρ and a_0 couplings etc. one can easily reach $\chi^2_{p.d.p} \approx 1.25$. Also, the $\alpha = F/(F+D)$-ratios are predicted by the QPC-model, and these are $\alpha_{PV} = \alpha_A = 0.4$, $\alpha_V^e = \alpha_S = 1.0$. The α-parameters used in the fit are close to these values, see Table IV below.

IV. HYPERON-NUCLEON AND HYPERON-HYPERON

The form factor scheme employed in the ESC-models is the same as in the NSC97-model [5], see also [7]. We assign Λ_8 and Λ_1 for each meson-nonet, for respectively the $\{8\}$- and $\{1\}$-members. In the application to YN and YY we allow for $SU_f(3)$-breaking, by using different cut-off's for the $K = 853.2$ MeV.

Another important element is that we have used flavor-symmetry breaking of the coupling constants (FSB), like in NSC97. The scheme of this breaking is worked out according to the QPC-model, but a little different as in NSC97. The need for this breaking can be viewed a necessity in order to have some freedom to fit YN, making the imposition of the quark-model relations possible. FSB is described by distinguishing between the pair creation constants for the non-strange and the strange quarks, i.e. $\gamma_u = \gamma_d \neq \gamma_s$. In ESC03 we have fitted $\gamma_s/\gamma_{u,d} = 0.792$, and used this breaking for all OBE-couplings. The pair-couplings are taken $SU(3)$-symmetric.

mesons		{1}	{8}	$F/(F+D)$	mixing-angles
pseudo-scalar	f	0.220	0.262	$\alpha_{PV} = 0.400^{\star)}$	$\theta_P = -23.00^0$
vector	g	2.537	0.778	$\alpha_V^e = 1.0$	$\theta_V = 37.50^0$
	f	-0.972	3.319	$\alpha_V^m = 0.45^{\star)}$	
scalar	g	2.996	0.777	$\alpha_S = 0.85$	$\theta_S = 37.5^{0\ \star)}$
axial	g	1.593	2.858	$\alpha_A = 0.37$	$\theta_S = 47.30^{0\ \star)}$
diffractive	g	2.235	0.416	$\alpha_D = 1.0$	$\psi_D = 23.21^{0\ \star)}$

TABLE III: ESC03: Meson coupling parameters.

In addition to the parameters given in Table IV, we fixed the $\alpha = F/(F+D)$ ratio's for MPE's. These are $\alpha^e_{pr,V} = 1.0, \alpha^m_{pr,V} = 0.275, \alpha_{pr,S} = 1.0, \alpha_{pr,A} = 0.40$. The fitting for the Nijmegen set of 35 YN-scattering data resulted in $\chi^2 = 43.3$. In this fit, the 12 Λp X-sections have $\chi^2(\Lambda p) = 6.7$, the 18 $\Sigma^- p$ X-sections $\chi^2(\Sigma^- p \to \Sigma^- p, \Sigma^0 n, \Lambda n) = 32.2$, and the 4 X-sections for $\Sigma^+ p$ have $\chi^2(\Sigma^+ p) = 0.5$. The capture ratio at rest was fitted to be $r_R = 0.45$, which close to its experimental value 0.468 ± 0.01

Notice that the ESC03 ΣN-interactions are such that for free scattering the $^3S_1(I = 3/2)$-interaction is quite attractive. This is not in accordance with Dabrowski's finding [16]. One way out of this problem is the possibility of three-body forces (TBF), e.g. from our pair-interactions, giving a substantial effective two-body repulsion in this channel.

As for the YY-systems ESC03 succesfully describes the $\Lambda\Lambda(^1S_0)$-interaction. In contrast to the believe for many years, the NAGARA-event [17] gives $\Delta B_{\Lambda\Lambda}(^{6}_{\Lambda\Lambda}He) = 1.01 \pm 0.20^{+0.18}_{-0.11}$, showing that the strength of the $\Lambda\Lambda(^1S_0)$-interaction is rather weak, and more in line of the predictions of the soft-core OBE-models [18]. This means a revolution in the $S = -2$-sector as compared to the situation at the time of HYP2000 [7]. As in NSC97 in ESC03 we have again $Q\bar{Q}$-ideal-mixing for the scalar mesons, which in view of the NAGARA-event seems to be favored by nature. The calculated values of $\Delta B_{\Lambda\Lambda}(^{6}_{\Lambda\Lambda}He)$ with the G-matrix interactions, including the $\Lambda\Lambda - \Xi N, \Sigma\Sigma$-couplings, are 0.6 MeV for NSC97f, and 1.2 MeV for ESC03 [19]. A really striking positive result for the ESC-model.

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