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Recent Nijmegen Soft-core Hyperon-Nucleon and Hyperon-Hyperon Interactions*

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Abstract

We give a brief account of the results obtained with the most recently constructed Extended-Soft-Core (ESC) interactions. This ESC-model, henceforth called ESC00, describes nucleon-nucleon (NN), hyperon-nucleon (YN), and hyperon-hyperon (YY), in a unified manner using $SU_f(3)$-symmetry. The $SU_f(3)$-symmetry is only broken by using physical masses for both the baryons and the mesons. The coupling constants are fully $SU_f(3)$ symmetric. Compared to earlier versions of the Nijmegen interactions, we use in ESC00 for the first time two scalar-meson nonets for the YN- and YY-channels. The splitting of the traditional scalar nonet, used in the Nijmegen models, in two nonets is performed in such a way that the volume integrals of the potentials are unchanged. As usual in the Nijmegen approach, the basis is a fit to the NN-data using the Nijmegen PWA. In the version of the ESC00-model, used for YN and YY, for the energies $T_{lab} = 0 - 350$ MeV we reached the very low $\chi^2_{p.d.p.} = 1.15$. In distinction to more phenomenological models, the ESC-models allow a clearcut extension to YN and YY, using $SU_f(3)$-symmetry. In the YN-sector, we achieved a description which in several aspects is an improvement over the most recent soft-core OBE-models NSC97 [7]. The interaction in the $\Sigma N(^3S_1, I = 3/2)$-channel is now clearly repulsive, and the p-wave interactions in ΛN are such as to give attraction in the Hypernuclei and for Hyperonic matter. In the YY-sector, ESC00 has considerable attraction in the $^1S_0$ state for the $(\Lambda\Lambda, \Xi N, \Sigma\Sigma)$-system. This in contrast to the soft-core OBE-models.

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I. INTRODUCTION

In [1,2] we reported on an ESC-model for baryon-baryon scattering where many dynamical aspects of low energy QCD and Chiral-symmetry are accounted for. Here, the soft-core OBE-models of the Nijmegen group [3,4] are extended to include uncorrelated two-meson-exchange and, for the first time in baryon-baryon models, meson-pair exchanges. The latter were inspired by the pion-pair interactions discussed already in the fyfties, and contained in the Lagrangians of the non-linear σ-models of the sixties.

The latest soft-core OBE model NSC97 [7,8] has been reviewed in recent conference contributions [5,6]. A notable success of the NSC97-model is the achievement of solutions with good s-wave $\Lambda - N$ interaction. The NSC97e,f are favored because of their succes in describing the s-shell Λ-hypernuclei. It was found by Akaishi and co-workers [9] that NSC97f solves the ${}^{5}_{\Lambda}He$ overbinding problem [11]. Furthermore, Akaishi et al [10] also showed that the NSC97f solution fits the experimental Λ separation energies for the Λ-hypernuclei ${}^{3}_{\Lambda}H$, ${}^{A}_{\Lambda}He$ $(A = 4, 5, \ldots, 11)$.

The NSC97 solutions [7,8] provide the user with a variety of different s-wave interactions, from which an optimal can be selected in nuclear structure calculations. The optimal solution has to be sought in between NSC97e and NSC97f. However, the p-shell Hypernuclei studies seem to favor the NSC97a solution. The appearance of repulsive triplet-odd interactions in nuclear matter for the NSC97 solutions is rather unexpected, and rather doubtful e.g. in view of its consequences for p-shell hypernuclei as well as for neutron star matter. Also the ΛN-spin-orbit interaction seems to be too strong [13].

Furthermore, also the ΣN-sector is not fixed very well, since different Nijmegen models give rather different interactions in e.g. the ${}^{3}S_{1}(I = 3/2)$-wave. Dabrowski [12] analyzed the Lane part of the s.p. potential of the Σ in nuclear matter, using the YNG effective interactions [14]. It is argued the NSC97 solutions are incompatible with recent $(K^{-}, \pi^{\pm})$ experiments at BNL on the ${}^{9}Be$-target [15].

In the soft-core OBE models the important scalar-meson nonet are found to have meson-mixing conform the $Q\bar{Q}$-picture of the scalar-mesons with ideal mixing. It was noted that the upshot of this scalar-mixing is a rather weak attraction in the $\Lambda\Lambda$-channel. This seems not in agreement with the findings on the double-Λ hypernuclei.

These features of the soft-core OBE-model solutions have come out from the combination of model building based on the study of the YN-interactions in particle physics, effective QCD theories involving meson and/or quark-gluon degrees of freedom, and the study of nuclear structure. In order to make further progress this way, and to improve the dynamical BB-models based on meson-exchange, we continued our search for the best baryon-baryon interactions along the lines of the Nijmegen approach [16]. In ESC99 [17] we discussed the first version of the results on YN and YY. In this status report the most recent results are given and the changes compared to ESC99 are discussed. *It will appear that the ESC-model indeed can solve all problems, mentioned above.*

The contents of this paper is as follows. In section 2 we describe briefly the physics background of the ESC-models, indicate briefly how the ESC-model can be extended to all baryon-baryon channels, and report on the most recent results for nucleon-nucleon. In section 3 we give the first results for hyperon-nucleon, and in section 4 we discuss the results of the ESC-model for the for the $\Lambda - \Lambda$-interactions.

II. EXTENDED SOFT-CORE MODEL FOR BARYON-BARYON

The potential of this new ESC00-model contains the contributions of

(i) The OBE-potentials of [3,4,7], 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) Special for ESC00 is the use of two-scalar nonets. The scalar-meson potentials in NN are based on a single scalar-nonet, which is the same in all soft-core Nijmegen models. This nonet consists of: $\varepsilon(760)$, $a_0(962)$, $f_0(993)$, $\kappa(900)$. For the YN and YY we added in ESC00 a second scalar nonet with masses above $1GeV/c^2$: $\varepsilon(1370)$, $a_0(1450)$, $f_0(1580)$, $\kappa(1430)$. The particle physics background of these two scalar nonets can be found in the recent literature and the Particle Data Group tables [18].

(iii) The TPSE-potentials as given in Ref. [19,20]. These are two-pseudo-scalar-exchange potentials based on a combination of pseudo-vector and pseudo-scalar coupling to the baryon octet. 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. Then, also heavy pseudo-scalar-, heavy scalar-, axial-, and tensor-mesons should be included. This we postpone to the future.

(iv) We extend the OBE-models [3,4] further through the inclusion of phenomenological baryon-baryon-meson-meson vertices, henceforth referred to as 'meson-pair-exchange' (MPE). The vertices are given in [1,20].

The motivation for the MPE is mainly dynamical. In the MPE we included such exchanges, like e.g. $(\pi\rho)_1$, in order to account for quantum numbers not included in OBE. 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. Additional motivation for including these MPE-potentials is that similar interactions are required in chiral Lagrangians [21]. They can be viewed upon as the result of the out integration of the heavy-meson and resonance degrees of freedom. We are less radical than e.g. Weinberg [22], in that we do not integrate out the degrees of freedom of the mesons with masses below 1 GeV.

The $SU(3)$-extension of the ESC-model for NN to YN and YY is carried out by assigning the meson-pairs to the $SU(3)$-irreps. The proper $SU(3)$ combinations for respectively the singlet-, the octet-symmetric-, and octet-antisymmetric-irreps for the ps-ps-pairs can be found in the literature [23].

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. Then, also heavy pseudo-scalar-, heavy scalar-, axial-, and tensor-mesons should be included. This we pospone to the future.

Fitting this model to the NN-data, using the 1993 Nijmegen single energy $pp + np$ phase shift analysis [24], leads to an excellent result. We reached for the energies in the range

$0 \leq T_{lab} \leq 350$ MeV, which comprises 4233 data, a $\chi^2_{p.d.p.} = 1.15$. We remind the reader that other NN-models could reach typically $\chi^2_{p.d.p.} \approx 1.90$, and therefore the gain with the ESC-models is p.d.p no less than 0.75!

ps-pv		vector		scalar		pairs	
f_π	0.267	g_ρ	0.300	g_δ	1.123	$g_{(\pi\pi)_0}$	0.057
f_η	0.179	f_ρ	3.727	g_ϵ	4.158	$g_{(\pi\pi)_1}$	0.092
$f_{\eta'}$	0.176	g_ω	2.734	g_{A_2}	-0.364	$f_{(\pi\pi)_1}$	-0.214
		f_ω	0.088	g_P	2.924	$g_{(\pi\eta)}$	-0.093
Λ_{P8}	725.3	Λ_{V8}	739.5	Λ_{S8}	703.6	$g_{(\pi\rho)_1}$	0.930
Λ_{P1}	828.3	Λ_{V1}	721.9	Λ_{S1}	906.1	$g_{(\pi\omega)}$	-0.100
a_{PV}	0.443			m_P	309.1	$g_{(\pi\sigma)}$	-0.018
				g_{ϵ_2}	0.291	$g_{(P\pi)}$	0.237

TABLE I. ESC00: Form factor masses, meson and meson-pair couplings.

The (rationalized) coupling constants and form factor masses are given in Table II. Here, the f_η was not fitted but derived from f_π using $\alpha_{pv} = 0.355$. In Table II g_{ϵ_2} is the NN-coupling of the heavy $\epsilon(1370)$, a member of the 2nd scalar-nonet, mentioned above. *We stress that the ESC-model does not have large (unphysical) cut-off masses in the form-factors.* The value found for $a_{PV} \approx 0.5$, which means that the off-shell terms in the PS-PS potential are very small. We notice that the ESC-model gives a great improvement with respect to the OBE-model [3]. In particular it appeared that the $^1P_1$-, the $^3D_2$-, and the $^3D_3$-waves have much improved.

III. HYPERON-NUCLEON

In the NSC97-model [7], the form factors depend on the $SU_f(3)$-assignment of the mesons. In principle we introduce form factor masses 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 $K = 605.5$ MeV. *In contrast to NSC97 the coupling constants obey strict $SU(3)$-symmetry.*

Special for ESC00 is the use of two-scalar nonets. The members of these are listed above. There are two views on these nonets. The first is that they are $Q^2\bar{Q}^2$-states respectively $Q\bar{Q}$-states [25]. The second is that these nonets originate from $Q\bar{Q}$-states coupled to meson-meson states [18]. It appeared that in order to accomodate for the $\kappa(900)$ exchange we had to weaken the g_8-coupling from the NN-fit. This was achieved in ESC00 by a distribution of the strength over a low-lying and a heavy scalar nonet. In addition to the parameters given in Table II,we fitted the $\alpha = F/(F+D)$ ratio's for MPE's. These are $\alpha^e_{pr,V} = 0.98, \alpha^m_{pr,V} = 0.74, \alpha_{pr,S} = 0.45, \alpha_{pr,A} = -0.17$. The fitting for the Nijmegen set of 35 YN-scattering data

mesons		{1}	{8}	$F/(F+D)$	angles
pseudoscalar	f	0.23361	0.26686	$\alpha_{PV} = 0.400^{\star)}$	$\theta_P = -23.00°$
vector	g	3.04667	0.30022	$\alpha_V^e = 1.0$	$\theta_V = 37.50°$
	f	-0.90856	3.04667	$\alpha_V^m = 0.404^{\star)}$	
scalar 1	g	3.91927	0.90408	$\alpha_S = -0.505$	$\theta_S = -19.75°$ $^{\star)}$
scalar 2	g	0.26632	1.00311	$\alpha_S = 0.336$	$\theta_S = -68.49°$ $^{\star)}$
diffractive	g	2.92400	0.3641	$\alpha_D = 0.25$	$\psi_D = 0.0°$ $^{\star)}$

TABLE II. ES00: Form factor masses, meson and meson-pair couplings.

resulted in $\chi^2 = 22.9$. In this fit, the 12 Λp X-sections have $\chi^2(\Lambda p) = 6.9$, the 18 $\Sigma^- p$ X-sections $\chi^2(\Sigma^- p \to \Sigma^- p, \Sigma^0 n, \Lambda n) = 15.5$, and the 4 X-sections for $\Sigma^+ p$ have $\chi^2(\Sigma^+ p) = 0.5$. The capture ratio at rest was fitted to be $r_R = 0.472$, which close to its experimental value.

In Table III the $\Sigma^+ p$-phases are listed. We notice that the ESC00 ΣN-interactions are such that the ${}^3S_1(I = 3/2)$-interaction is quite repulsive. This is in accordance with Dabrowski's finding [12]. Here the MPE potential is very important for this result. For Λp the fit results in the low energy parameters

$$a_s = -2.109 \text{ fm} \quad r_s = 3.143 \text{ fm}\,; a_t = -1.491 \text{ fm} \quad r_t = 2.490 \text{ fm}\,.$$

$p_{\Sigma^+}(MeV/c)$	200	400	600	800	1000
$T_{\rm lab}(MeV)$	16.7	65.5	142.8	244.0	364.5
${}^1S_0$	28.13	16.46	-0.23	-16.30	-30.80
${}^3S_1$	-15.60	-32.41	-49.03	-64.24	-77.44
ϵ_1	-1.94	-5.29	-7.15	-7.76	-7.73
${}^3P_0$	6.00	13.44	9.80	1.12	-8.51
${}^1P_1$	2.30	6.52	7.07	3.72	-1.45
${}^3P_1$	-3.05	-8.87	-14.07	-18.61	-22.25
${}^3P_2$	1.19	6.67	11.78	13.24	11.99
ϵ_2	-0.39	-2.01	-3.14	-3.11	-2.27
${}^3D_1$	0.32	1.46	0.98	-2.58	-8.59
${}^1D_2$	0.32	1.92	4.15	5.10	3.21
${}^3D_2$	-0.48	-2.73	-6.03	-10.75	-16.89
${}^3D_3$	0.04	0.53	0.80	-0.84	-4.88

TABLE III. ESC00 nuclear-bar $\Sigma^+ p$ phases in degrees

Like in ESC99, from Table IV the p-wave interactions seem to be improved compared to NSC97. By using $\alpha_{PV} = 0.3505$ we obtained another solution having larger positive $^3P_2$-phases, leading to more p-wave attraction than in the solution shown here. The p-waves for ESC00 are similar to those of ESC99. Here, in nuclear matter the p-waves are attractive [26].

$p_\Lambda(MeV/c)$	100	200	300	400	500	600	633.4
$T_{\rm lab}(MeV)$	4.5	17.8	39.6	69.5	106.9	151.1	167.3
$^1S_0$	22.45	28.94	27.01	22.44	17.79	14.98	15.79
$^3S_1$	17.43	26.65	30.65	34.29	42.48	69.67	-68.12
ϵ_1	0.10	0.45	0.68	0.20	-2.03	-10.14	19.80
$^3P_0$	0.08	0.49	0.91	0.54	-1.09	-3.83	-4.86
$^1P_1$	-0.08	-0.56	-1.65	-3.40	-5.64	-7.98	-8.62
$^3P_1$	-0.04	-0.36	-1.21	-2.67	-4.63	-6.83	-7.50
$^3P_2$	0.09	0.58	1.44	2.26	2.66	2.52	2.37
ϵ_2	0.00	-0.01	-0.10	-0.32	-0.65	-1.06	-1.24
$^3D_1$	0.00	0.01	0.09	0.36	1.10	3.32	2.70
$^1D_2$	0.00	0.06	0.37	1.14	2.28	3.36	3.62
$^3D_2$	0.00	0.07	0.34	0.87	1.53	1.98	2.03
$^3D_3$	0.00	0.02	0.13	0.33	0.49	0.39	0.26

TABLE IV. ESC00 nuclear-bar Λp phases in degrees

IV. HYPERON-HYPERON

In the $S = -2$-systems, the limited experimental information of the ground states of the double $\Lambda\Lambda$-hypernuclei, e.g. $^{6}_{\Lambda\Lambda}He$, and $^{10}_{\Lambda\Lambda}Be$, indicates that the $\Lambda\Lambda$-interaction is rather attractive. For example, estimates for the $\Lambda\Lambda(^1S_0)$ scattering length, obtained in different studies are as follows. Reported values for a_s are: -2.0 [27], $-(4-8)$ [28], and -12.9 [29]. As mentioned before [7], the soft-core OBE-models have difficulty to produce strong attraction in $\Lambda\Lambda$. In the ESC-models this situation is very different. There is now attraction from both TPSPS and MPE, but also from OBE. In ESC00 we roughly have a situation, similar to that suggested by Dover [30], where

$$|V_{NN}| \geq |V_{\Lambda\Lambda}| > |V_{\Lambda N}| \ ,$$

but *realized with purely mesonic forces*. This is in contrast to the soft-core OBE-models. The reason is that the mixing for the scalar mesons has changed. In ESC00 is $\theta_S = -19.75^o$, which is in between ideal mixing for $Q\bar{Q}$ and $Q^2\bar{Q}^2$. In particular, the interaction in the $SU(3)$-irrep $\{1\}$ is now attractive, in contrast to the soft-core OBE-models. In total the attraction in the $I = 0$ system $^1S_0(\Lambda\Lambda, \Xi N, \Sigma\Sigma)$ is too strong and produces a bound-state.

We note that the $\Sigma\Sigma$-threshold is about 320 MeV above the $\Lambda\Lambda$-threshold in the Lab-system, which is rather distant. Suppression of the $\Lambda\Lambda \to \Xi N, \Sigma\Sigma$-couplings eliminates the bound-state. Then, $a_{\Lambda\Lambda}(^1S_0) = -2.4$ fm and $r_{\Lambda\Lambda}(^1S_0) = 2.9$ fm. Another possibility is that off-energy-shell effects can eliminate the bound-state. Becuase we use energy independent potentials, they are defined in principle at the $\Lambda\Lambda$-threshold. Then, taking into account the energy dependence leads to e.g. extra contributions to the non-local ϕ-function, some suppression of the $\Lambda\Lambda \to \Sigma\Sigma$- and $\Sigma\Sigma \to \Sigma\Sigma$-potentials. It appeared that these effects are sufficient to eliminate the bound-state. The result is in this case $a_{\Lambda\Lambda}(^1S_0) = -10.6$ fm and $r_{\Lambda\Lambda}(^1S_0) = 2.7$ fm. Clearly, this needs further investigation.

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