Meson exchange hyperon-nucleon interaction based on correlated $\pi\pi/K\bar{K}$ exchange

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Abstract. We present a new model for the hyperon-nucleon (ΛN, ΣN) interaction, derived within the meson exchange framework. The model incorporates the standard one-boson exchanges of the lowest pseudoscalar and vector meson multiplets with coupling constants fixed by $SU(6)$ flavor symmetry relations. As a new feature, the contribution in the scalar-isoscalar (σ) sector is derived from a microscopic model of correlated $\pi\pi$ and $K\bar{K}$ exchange. The same model is also used to constrain the interaction resulting from the vector-isovector (ρ) exchange channel. Additional short-ranged ingredients of the model in the scalar-isovector (a_0) and scalar-isospin-1/2 (κ) channels are likewise viewed as arising from meson-meson correlations but are treated phenomenologically. With this model a satisfactory reproduction of the available hyperon-nucleon data is achieved.

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1 Introduction

The hyperon-nucleon (YN) interaction is an ideal testing ground for studying the importance of $SU(3)$ flavor symmetry in hadronic systems. Existing meson exchange models of the YN force usually assume $SU(3)$ flavor symmetry for the hadronic coupling constants, and in some cases [1,2] even the $SU(6)$ symmetry of the quark model. The symmetry requirements provide relations between couplings of mesons of a given multiplet to the baryon current, which greatly reduce the number of free model parameters. Specifically, coupling constants at the strange vertices are connected to nucleon-nucleon-meson coupling constants, which in turn are constrained by the wealth of empirical information on NN scattering. Essentially all YN interaction models can reproduce the existing YN scattering data, so that at present the assumption of $SU(3)$ symmetry for the coupling constants cannot be ruled out by experiment.

One should note, however, that the various models differ dramatically in their treatment of the scalar-isoscalar meson sector, which describes the baryon-baryon interaction at intermediate ranges. For example, in the Nijmegen models [3–5] this interaction is generated by the exchange of a genuine scalar meson $SU(3)$ nonet. A genuine scalar meson $SU(3)$ nonet is also present in the so-called Ehime potential [6]. The Tübingen model [7], on the other hand, which is essentially a constituent quark model supplemented by π and σ exchange at intermediate and short ranges, treats the σ-meson as an $SU(3)$ singlet. Finally, in the quark models of Zhang *et al.* [8] and Fujiwara *et al.* [9] a scalar $SU(3)$ nonet is exchanged, though in this case between quarks and not between the baryons.

In the YN models of the Jülich group [1,2] the σ (with a mass of $\approx 550\,\mathrm{MeV}$) is viewed as arising from correlated $\pi\pi$ exchange. A rough estimate for the ratios of the σ-coupling strengths in the various channels can then be obtained from the relevant pion couplings. In practice, however, in the Jülich YN models, which start from the Bonn NN potential [10], the coupling constants of the fictitious σ-meson at the strange vertices ($\Lambda\Lambda\sigma$, $\Sigma\Sigma\sigma$) are free parameters —a rather unsatisfactory feature of the models.

These problems can be overcome by an explicit evaluation of correlated $\pi\pi$ exchange in the various baryon-baryon channels. A corresponding calculation was already performed for the NN case in ref. [11]. The starting point there was a field theoretic model for both the $N\bar{N} \to \pi\pi$ Born amplitudes and the $\pi\pi$ and $K\bar{K}$ elastic scattering [12]. With the help of unitarity and dispersion relations, the amplitude for the correlated $\pi\pi$ exchange in the NN interaction was computed, showing characteristic differences compared with the σ and ρ exchange in the (full) Bonn potential.

In a recent study [13] the Jülich group presented a microscopic derivation of correlated $\pi\pi$ exchange in various baryon-baryon (BB') channels with strangeness $S = 0, -1$

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and -2. The $K\bar{K}$ channel was treated on an equal footing with the $\pi\pi$ channel in order to reliably determine the influence of $K\bar{K}$ correlations in the relevant t-channels. In this approach one can replace the phenomenological σ and ρ exchanges in the Bonn NN [10] and Jülich YN [1] models by correlated processes, and eliminate undetermined parameters such as the $BB'\sigma$ coupling constants.

In this contribution we report results of a new YN model [14] that utilizes this microscopic model of correlated $\pi\pi$ and $K\bar{K}$ exchange to fix the contributions in the scalar-isoscalar (σ) and vector-isovector (ρ) channels. The model incorporates also the standard one-boson exchange contributions of the lowest pseudoscalar and vector meson multiplets with coupling constants determined by $SU(6)$ symmetry relations. Assuming the $SU(6)$ symmetry means that also the so-called $F/(F+D)$ ratios are fixed. In addition, there are further new ingredients as compared to the original Jülich YN model [1]. First of all, the contribution from the $a_0(980)$-meson is taken into account. Secondly, we consider the exchange of a strange scalar meson, the κ, with mass $\sim 1000\,\mathrm{MeV}$. Let us emphasize, however, that in analogy with the σ-meson these particles are likewise not viewed as being members of a scalar meson $SU(3)$ multiplet, but rather as representations of strong meson-meson correlations in the scalar-isospin-1/2 (πK) [12] and scalar-isovector ($\pi\eta$-$K\bar{K}$) [15] channels, respectively.

We want to mention that, recently, our group has persued also an alternative approach to the YN interaction, namely within the framework of the effective field theory [16,17]. In such a framework only the exchange of Goldstone bosons (pions, kaons, η) is taken into account explicitly, while all short-range physics is parametrized by contact terms. The results of a first calculation, performed in leading order in the power counting, look very promising as can be seen in ref. [16] and in this conference [17].

2 Potential from correlated $\pi\pi$ + $\mathrm{K\bar{K}}$ exchange

In this section we briefly describe the dynamical model [11, 13] for correlated two-pion and two-kaon exchange in the baryon-baryon interaction, both in the scalar-isoscalar (σ) and vector-isovector (ρ) channels. The contribution of correlated $\pi\pi$ and $K\bar{K}$ exchange is derived from the amplitudes for the transition of a baryon-antibaryon state ($B\bar{B}'$) to a $\pi\pi$ or $K\bar{K}$ state in the pseudophysical region by applying dispersion theory and unitarity. For the $B\bar{B}' \to \pi\pi$, $K\bar{K}$ amplitudes a microscopic model is constructed, which is based on the hadron exchange picture.

The Born terms include contributions from baryon exchange as well as ρ-pole diagrams (cf. ref. [15]). The correlations between the two pseudoscalar mesons are taken into account by means of a coupled-channel ($\pi\pi$, $K\bar{K}$) model [12,15] generated from s- and t-channel meson exchange Born terms. This model describes the empirical $\pi\pi$ phase shifts over a large energy range from threshold up to $1.3\,\mathrm{GeV}$. The parameters of the $B\bar{B}' \to \pi\pi$, $K\bar{K}$ model, which are interrelated through $SU(3)$ symmetry, are determined by fitting to the quasiempirical $N\bar{N}' \to \pi\pi$ amplitudes in the pseudophysical region, $t \leq 4m_\pi^2$ [13], obtained by analytic continuation of the empirical πN and $\pi\pi$ data.

From the $B\overline{B'} \to \pi\pi$ helicity amplitudes one can calculate the corresponding spectral functions (see ref. [13] for details), which are then inserted into dispersion integrals to obtain the (on-shell) baryon-baryon interaction in the σ (0^+) and ρ (1^-) channels:

$$V^{(0^+,1^-)}_{B_1',B_2';B_1,B_2}(t) \propto \int_{4m_\pi^2}^{\infty} \mathrm{d}t' \frac{\rho^{(0^+,1^-)}_{B_1',B_2';B_1,B_2}(t')}{t'-t}, \quad t<0\,. \quad (1)$$

Note that the spectral functions characterize both the strength and range of the interaction. For the exchange of an infinitely narrow meson the spectral function becomes a δ-function at the appropriate mass.

3 Results and discussion

As shown by Reuber *et al.* [13], the strength of the correlated $\pi\pi$ and $K\bar{K}$ in the σ channel exchange decreases as the strangeness of the baryon-baryon channels becomes more negative. For example, in the hyperon-nucleon systems (ΛN, ΣN) the scalar-isoscalar part of the correlated exchanges is about a factor of 2 weaker than in the NN channel, and, in particular, is also weaker than the phenomenological σ-meson exchange used in the original Jülich YN model [1]. Accordingly, we expect that the microscopic model with correlated $\pi\pi$ exchange will lead to a YN interaction which is less attractive.

Besides replacing the conventional σ and ρ exchanges by correlated $\pi\pi$ and $K\bar{K}$ exchange, there are in addition several new ingredients in the present YN model [14]. First of all, we now take into account contributions from $a_0(980)$ exchange. The a_0-meson is present in the original Bonn NN potential [10], and for consistency should also be included in the YN model. Secondly, we consider the exchange of a strange scalar meson, the κ, with mass $\sim 1000\,\mathrm{MeV}$. Let us emphasize, however, that both these particles are not viewed as being members of a scalar meson $SU(3)$ multiplet, but rather as representations of strong meson-meson correlations in the scalar-isovector ($\pi\eta$-$K\bar{K}$) [15] and scalar-isospin-1/2 (πK) channels, respectively. In principle, their contributions can also be evaluated along the lines of ref. [13], however, for simplicity in the present model they are effectively parameterized by one-boson exchange diagrams with the appropriate quantum numbers. In any case, these phenomenological pieces are of rather short range, and do not modify the long-range part of the YN interaction, which is determined solely by $SU(6)$ constraints (for the pseudoscalar and vector mesons) and by correlated $\pi\pi$ and $K\bar{K}$ exchange.

In fig. 1 we compare the integrated cross-sections for the new YN potential (solid curves) with the $YN \to Y'N$ scattering data as a function of the laboratory momentum, p_{lab}. The agreement between the predictions and the

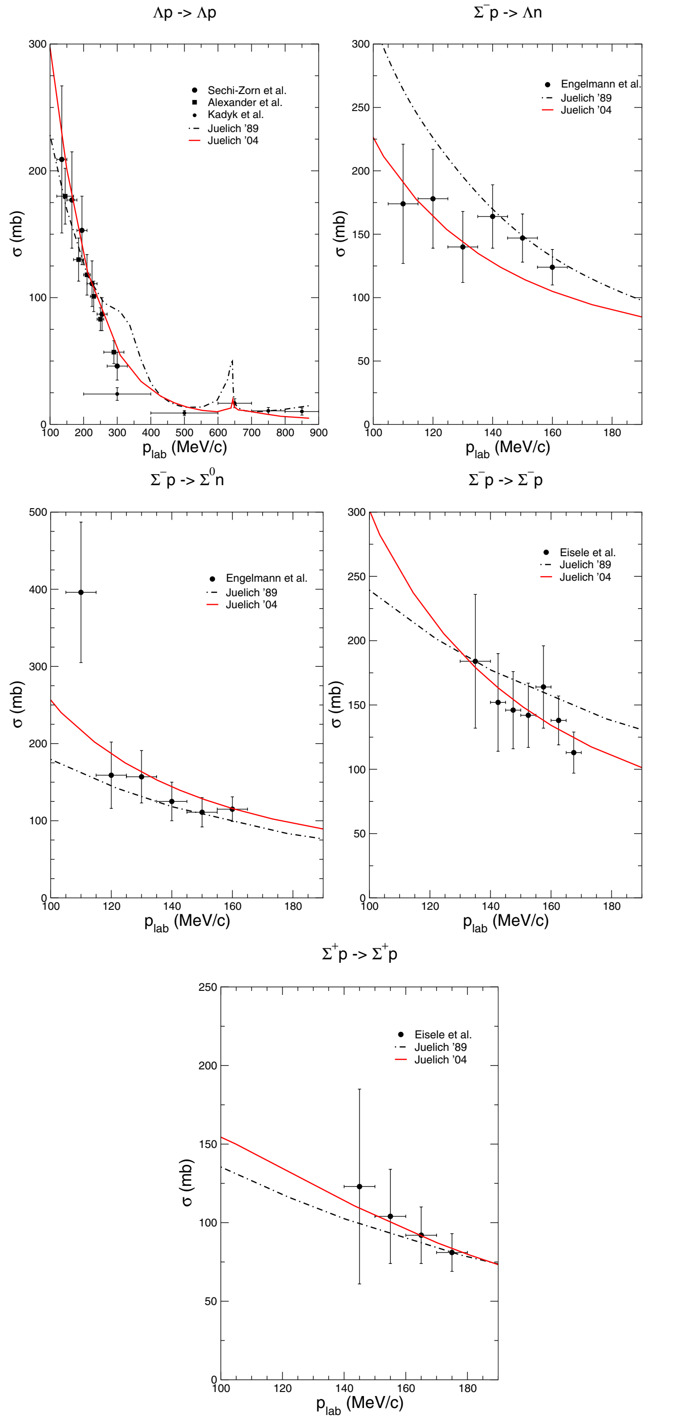

Fig. 1. Total cross-sections for YN scattering. The solid lines are results of the new YN model, based on correlated $\pi\pi$ and $K\bar{K}$ exchange, while the dash-dotted ones represent results of the original Jülich YN model A [1].

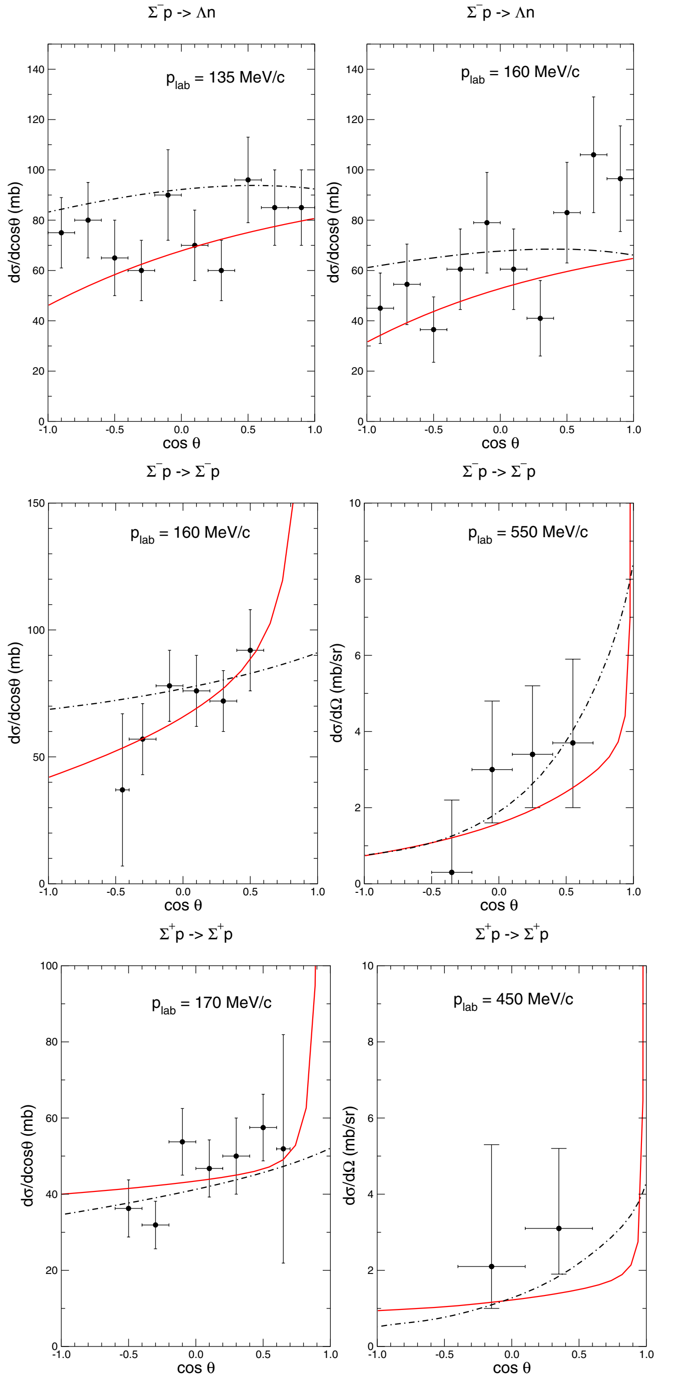

Fig. 2. Differential cross-sections for YN scattering. Same description of curves as in fig. 1.

data [18] is clearly excellent in all channels. Also shown are the predictions from the original Jülich YN model A [1] (dash-dotted curves). The main qualitative differences between the two models appear in the $\Lambda p \to \Lambda p$ channel, for which the Jülich model [1] (with standard σ and ρ exchange) predicts a broad shoulder at $p_{lab} \approx 350\,\mathrm{MeV/c}$. This structure, which is not supported by the available experimental evidence, is due to a bound state in the $^1S_0$ partial wave of the ΣN channel. But also quantitatively the new model provides a better description of the data in the various YN channels as compared to the original Jülich model.

Differential YN cross-sections [18,19] are presented in fig. 2. These observables have not been taken into account in the fitting process and therefore the corresponding results are genuine predictions of the model. Evidently, the available data are rather well reproduced by our new YN

Table 1. YN scattering lengths in the $^1S_0$ (a_s) and $^3S_1$ (a_t) partial waves derived from our new model (J04) together with the corresponding results of the Jülich model A [1].

Channel	Model	a_s (fm)	a_t (fm)
ΛN	J04	−2.56	−1.66
	A [1]	−1.56	−1.59
$\Sigma N(I = 1/2)$	J04	$0.90 - i0.13$	$-3.83 - i3.01$
	A [1]	$1.42 - i0.08$	$2.47 - i3.74$
$\Sigma N(I = 3/2)$	J04	−4.71	0.29
	A [1]	−2.26	−0.76

model. In comparison to the results of the original Jülich model one can say that the angular dependence in the $\Sigma^- p$ channel is now much better described and it seems to be more in line with the trend of the angular dependence exhibited by the data in the $\Sigma^- p \to \Lambda n$ channel too. Note that the large difference between the model predictions in very forward direction in some reaction channels is only due to the Coulomb interaction, which was not taken into account in the original Jülich model.

Results for the scattering lengths are compiled in table 1. One can see that the scattering lengths in the $^3S_1$ ΛN partial wave (a_t) are of similar magnitude for the old and new YN models, but in the $^1S_0$ state (a_s) the new model yields a significantly larger value. The stronger $^1S_0$ component of the new model is reflected in the larger Λp cross-section near threshold, cf. fig. 1. The scattering lengths for ΣN with $I = 1/2$ are complex because this channel is coupled to the ΛN system. In the singlet case the scattering lengths are comparable for the two models whereas in the triplet case they even have opposite signs. We want to emphasize, however, that in both models the latter partial wave is attractive. But in the original Jülich model the attraction is so strong that there is a near-threshold quasibound state in the ΣN channel that causes the real part of a_t to be positive, cf. the discussion in ref. [14]. In the ΣN channel with $I = 3/2$ the singlet scattering length of the new model is about twice as large as the one of the original Jülich model. Note that a comparably large singlet scattering length is also predicted by all of the YN models presented in ref. [3]. The scattering lengths for the $^3S_1$ are small in both cases, but of opposite sign. Now, however, it is indeed so that our new YN model is repulsive in this partial wave whereas the old model is attractive.

Finally, let us mention that the new YN model provides sufficient attraction in order to support a bound hypertriton state [20]. This was not the case with the (static version of the) old Jülich YN model [2], cf. ref. [21]. The resulting binding energy for $^3_\Lambda$He is -2.270 MeV, which is close to the experimental value of $-2.354(50)$ MeV. It will be interesting to see the performance of the new YN interaction model in applications to heavier hypernuclei. In any case, preliminary results for the four-baryon sector indicate that, like other YN potentials in the literature, our new model too cannot resolve the long-standing differences between theory and experiment with regard to the Λ separation energies [22].

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