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HYPERON-NUCLEON INTERACTION AND MESON EXCHANGE

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We present first results of our general program which is to construct meson-exchange potentials for hadronic systems involving strange particles, i.e. for KN and AN. We proceed along the same guidelines which have been successfully applied in deriving the (latest version of the) Bonn NN potential, namely to keep the important recoil and nonlocal structure and to use a comprehensive set of diagrams without introducing any fictitious contribution. For KN we show that single vector-meson (ω, ρ) exchange already provides a fair description of the data except for the isospin-1 $P_{3/2}$ wave. This partial wave is remarkably improved by adding a specific higher-order process involving ΔK intermediate states. For the AN system we demonstrate the inadequacy of a nonrelativistic treatment of the AN interaction and point to the strong interplay between K and K^* -exchange in the tensor channel, which is even stronger than for π - and ρ -exchange in the NN system.

Quantum chromodynamics (QCD) is the fundamental theory of strong interactions. Therefore, the hadron-hadron interaction is completely determined by the underlying quark-gluon dynamics. However, partly due to our present lack of knowledge about the details of the confinement mechanism, we are far away from a quantitative understanding of the hadron-hadron force over the whole range in this way. Moreover, there is a good chance that such hadrons, i.e. nucleons, mesons and Δ -isobars, while being manifestations of the quark structure of matter, remain the relevant degrees of freedom for a wide range of nuclear physics phenomena. In that case, the overwhelming part of the force can be constructed in terms of meson-meson and meson-baryon vertices, which represent a natural and effective description of a complicated multi-quark reaction.

Recently, the Bonn group has finished the construction of a meson-exchange model of the NN interaction¹ which is solely based on suitable meson-nucleon-nucleon and meson-nucleon- Δ isobar vertices W_a . Antinucleons are left out from the beginning since it is known that the contribution of negative-energy states is quite small provided pseudovector coupling is used for the πNN vertex, which is suggested as an effective coupling (Weinberg-Lagrangian) starting from

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chiral invariance. The Hamiltonian $H = H_0 + W$ is treated in time-ordered (non-covariant) perturbation theory. This treatment corresponds to standard many-body theory and thus leads to a well-defined transition from the two- to the many-body problem. The resulting (energy-dependent) quasipotential V contains, in addition to single-meson exchange, explicit 2π -exchange contributions consistent with results obtained from dispersion theory (Paris potential²). Furthermore, it was essential to include corresponding $\pi\rho$ -exchange diagrams in order to obtain a quantitative fit to the NN data. It has been demonstrated (see ref. 1) that these contributions replace to a large extent the fictitious σ -exchange used in former ORE-models.

The extremely good reproduction of the empirical NN data with this model indicates the usefulness of the meson-exchange picture as an effective description for the low-energy NN interaction. In order to further check the validity of this picture the vertices (the parameters of which have been fixed by adjusting them to the two-body data) should now be used consistently in the evaluation of three-body forces, meson-exchange currents and other hadronic processes.

FIGURE 1
Vector-meson (ω, ρ)-exchange in KN scattering.

FIGURE 2
 Λ -baryon exchange in KN scattering.

Here we want to report on investigations of strange processes, i.e. KN and ΛN scattering, which we recently started at Jülich. We first turn our attention to K^+N scattering. Such an exotic channel is suited for the study of particle exchanges, in contrast to non-exotic processes like K^-N scattering where their effect is obscured by s-channel resonances. Basic single-particle exchange in KN are the vector-meson (ω, ρ) exchanges, see fig. 1. The exchange of pseudoscalar particles, especially of the pion, is not possible in this system. Therefore, the KN interaction is rather short-ranged. We also consider the exchange of a Λ -baryon, see fig. 2.

In addition to these exchanges, Davis, Cottingham and Alcock³ have included the exchange of a broad scalar, isoscalar σ -boson with a mass of 0.7 GeV and a width of 0.6 GeV. However, we are rather sceptical about this contribution since, in the NN system, such an exchange has to be considered to be to a large extent fictitious, mocking up explicit 2π (and $\pi\rho$, see ref. 1) contributions. Whether such an effective replacement is also possible in the KN problem has yet to be tested. In fact, as demonstrated below, it is precisely this σ -exchange which is responsible for the strong attraction in the isospin (I)-zero

FIGURE 3
Iterative time-orderings of a specific higher-order process in KN scattering with a ΔK intermediate state and involving σ -exchange.

$S_{1/2}$ wave at low energies, which is in conflict with any existing empirical analysis⁴. Therefore our general strategy will be to include the higher-order contributions (involving Δ resp. K^* intermediate states) explicitly and to avoid the use of σ -exchange as much as possible.

Until now we have concentrated on one specific contribution, shown in fig. 3. This process has not been studied in ref. 3 and gives a pronounced improvement in the description of the $I = 1$ $P_{3/2}$ wave.

The relevant Lagrangian densities are

$$\begin{aligned}\mathcal{L}_{NNv} &= g_{NNv} \bar{\psi}_N \gamma^\mu \psi_N \phi_{v,\mu} + \frac{f_{NNv}}{4M_N} \bar{\psi}_N \sigma^{\mu\nu} \psi_N [\partial_\mu \phi_{v,\nu} - \partial_\nu \phi_{v,\mu}] \\ \mathcal{L}_{KKv} &= \frac{ig_{KKv}}{2} [\phi_K^+ (\partial^\nu \phi_K) - (\partial^\nu \phi_K^+) \phi_K] \phi_{v,\nu} \\ \mathcal{L}_{NN\sigma} &= g_{NN\sigma} \bar{\psi}_N \psi_N \phi_\sigma \\ \mathcal{L}_{KK\sigma} &= g_{KK\sigma} M_K \phi_K^+ \phi_K \phi_\sigma \\ \mathcal{L}_{NAK} &= g_{NAK} \bar{\psi}_N i \gamma^5 \psi_A \phi_K + h.c. \\ \mathcal{L}_{\Delta N \rho} &= \frac{g_{\Delta N \rho}}{M_\rho} \bar{\psi}_\Delta i \gamma^5 \gamma^\mu \psi_N [\partial_\mu \phi_{\rho,\nu} - \partial_\nu \phi_{\rho,\mu}] + h.c.\end{aligned}\tag{1}$$

Here, v stands for ω, ρ . (In case of ρ -exchange, an appropriate isospin factor has to be added). With the help of these Lagrangians, the processes in figs. 1-3 can be evaluated in time-ordered perturbation theory, using the helicity formalism. (Details are given elsewhere⁵). The resulting expressions build up the quasipotential $V(z)$ and lead to the T-matrix by the unitarizing equation

$$T(z) = V(z) + V(z) \frac{1}{z - H_0 + i\epsilon} T(z)\tag{2}$$

which determines the scattering phase shifts as function of the lab momentum. In order to take the extended structure of hadrons into account each vertex has to be multiplied by a form factor, parametrized in the usual form

$$F_\alpha = \frac{\Lambda_\alpha^2 - M_\alpha^2}{\Lambda_\alpha^2 + \Lambda^2}\tag{3}$$

Here Λ is the momentum transfer; Λ_α is a parameter, the so-called cutoff-mass which has been adjusted to the empirical KN data.

The parameters used throughout this work are given in table 1 ($f_{NN\omega}$ has been set equal to zero). They are partly taken from experience in NN scattering

Coupling Constants	Λ_α
$\frac{g_{NN\omega}g_{KK\omega}}{4\pi} = 1.62$	$\Lambda_{NN\omega} = \Lambda_{KK\omega} = 2000$
$\frac{g_{NN\rho}g_{KK\rho}}{4\pi} = 0.54$	$\Lambda_{NN\rho} = \Lambda_{KK\rho} = 1750$
$\frac{f_{NN\rho}g_{KK\rho}}{4\pi} = 3.24$	
$\frac{g_{N\Lambda K}^2}{4\pi} = 17.31$	$\Lambda_{N\Lambda K} = 1500$
$\frac{g_{N\Delta\rho}g_{KK\rho}}{4\pi} = 3.56$	$\Lambda_{N\Delta\rho} = 2200$
$\frac{g_{NN\sigma}g_{KK\sigma}}{4\pi} = 1$	$\Lambda_{NN\sigma} = \Lambda_{KK\sigma} = 1500$

TABLE 1
Coupling constants and cutoff-masses Λ_α (in MeV) used throughout this work.

(e.g. $f_{NN\rho}/g_{NN\rho} = 6$), partly from symmetry relations, and partly adjusted to the data. Note that σ -exchange is only used for comparison.

The resulting K^+N scattering phase shifts are shown in fig. 4 as function of the kaon lab momentum, in various partial wave states $L_{1,2J}$. Perhaps surprisingly, single vector-meson exchange provides already a qualitative description

FIGURE 4

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FIGURE 4

K^+N scattering phase shifts as function of the kaon lab momentum in various partial wave states $L_{I,2J}$. The solid line is obtained with a potential model given by the diagrams in figs. 1-3. (The box diagrams in fig. 3 provide a vanishing contribution in isospin-zero states). Therefore the dash-dot and solid curves are identical in this case. The dotted line originates from ω -exchange only whereas the dash-dot curve contains all diagrams of figs. 1 and 2. By adding σ -exchange to those diagrams the dashed curve is obtained. The error bars are taken from the empirical phase shift analysis of Hashimoto⁶.

of the empirical situation, apart from the P_{13} wave. (The contribution of Λ -baryon exchange is negligibly small). Note the strong effect of ρ -exchange, which is especially pronounced in isospin-zero states (due to the additional factor of (-3)). Furthermore, it is to a large extent of spin-orbit type, due to the relatively strong tensor coupling. This is clearly seen from the figures by comparing corresponding states with $L = J \pm 1/2$. In those states, ρ -exchange goes into the opposite direction, being larger in the $L = J - 1/2$ state, which is precisely due to the fact that the eigenvalue of $\underline{L} \cdot \underline{g}$ is $1/2 L$ for $J = L + 1/2$ but $-1/2(L+1)$ for $J = L - 1/2$.

How can the P_{13} wave be improved without destroying the already fair agreement in the other partial waves? Obviously what is needed is a contribution which (i) acts only in isospin-1 states, (ii) is mainly of spin-orbit type (in order to have a small effect in S-states), (iii) is rather short-ranged (in order to be small in states with higher angular momentum). These requirements are uniquely fulfilled by the box-diagrams of fig. 3 (proposed to be studied already in ref. 4): The ΔK state can only be reached from $I=1$ KN states and ρ -exchange provides a short-ranged contribution, mainly of spin-orbit type. The results in fig. 4 show that our expectations are indeed confirmed: The diagrams

of fig. 3 yield a strong improvement in the P_{13} state, but change the other partial waves only in a minor way. On the other hand, if one tries to improve P_{13} by adding scalar-isoscalar σ -exchange, this has obviously disastrous consequences for the S-states in both isospin channels.

	1	2	exp ⁴
$a_{S_{1/2}}^{I=1}$	-0.224	0.096	-0.28; -0.33
$a_{S_{1/2}}^{I=0}$	0.008	0.568	-0.11; 0.18

TABLE 2
 K^+N S-wave scattering lengths (in fm) obtained (1) from the potential model given by figs. 1-3, (2) by replacing the box diagrams of fig. 3 by single σ -exchange are compared with upper and lower limits of empirical results taken from ref. 4.

This fact likewise shows up in the S-wave scattering lengths shown in table 2: Whereas the results obtained with the model containing the box diagrams roughly agree with the empirical situation, the inclusion of σ -exchange provides numbers which are far off the empirical values. Consequently we feel that a corresponding discrepancy in the $I=0$, $S_{1/2}$ wave present in ref. 3 is not due to a failure of the meson-exchange picture in general, but due to the inclusion of strong σ -exchange, which to our feeling is overestimated and should to considerable extent be replaced by higher-order diagrams involving not only π but also NK^* and ΔK^* intermediate states. The study of such diagrams (including inelasticities which have been neglected so far) will be the subject of a forthcoming paper.

We have also started to investigate the ΛN system, in an analogous framework. There exist already a series of papers by the Nijmegen group⁷ dealing with hyperon-nucleon scattering. They are however based on OBE-potentials given in coordinate space, which can only be derived after serious approximations have been made, see below. In contrast, our procedure is to keep the original momentum-space expressions for the interaction. Moreover, the use of time-ordered perturbation theory provides a tractable three-dimensional formalism together with a reliable description of meson retardation effects, which have been shown to be of utmost importance in the NN system, see ref. 1. In contrast, common 3-dimensional reductions of the Bethe-Salpeter equation, like e.g. the Blankenbecler-Sugar choice taken in ref. 7, provide a wrong descrip-

tion of meson retardation effects and thus lead to an unrealistically large size of higher-order contributions. Specifically, the structure of the propagator in time-ordered perturbation theory due to lowest-order exchange is given by, see fig. 5:

FIGURE 5
Lowest-order exchange in time-ordered perturbation theory.

$$g(Z) = \frac{1}{2\omega} \left(\frac{1}{Z - E_1 - E_2 - \omega} + \frac{1}{Z - E_1' - E_2' - \omega} \right) \quad (4)$$

Here Z is the starting energy. The result is essentially obtained by subtracting the energies involved in the intermediate state (dash-dot line in fig. 5) from the starting energy. Neglecting the recoil effects, i.e. putting $Z = E_1 + E_2$ resp. $E_1' + E_2'$, we obtain the conventional, static propagator $\omega^{-2} = 1/(\underline{k}^2 + m_\alpha^2)$ where $\underline{k}$ is the momentum-transfer and m_α the mass of the exchanged meson. The inclusion of recoil effects suppresses higher-order iterations of the processes of fig. 5, since large intermediate momenta are involved. This is explicitly seen, for the example of the higher-order process in

FIGURE 6
Higher-order box diagram contributing to AN scattering.

fig. 6, in fig. 7: Here we show the potential $V(q', q, Z)$ due to this process, in the 1S_0 partial wave, for $Z = 2E_q$ and $q = 250$ MeV, with and without inclusion of recoil effect. Obviously, the recoil effects are non-negligible suppressing the contribution by about 20 to 30 %.

FIGURE 7
Potential $V(q', q, Z)$ due to the process in fig. 6, in the $1S_0$ partial wave, for $Z = 2E_q$ and $q = 250$ MeV, as function of q' . The solid line includes the retardation effects whereas they are omitted in the dash-dot curve.

Furthermore, the potentials of ref. 7 are based on a nonrelativistic expansion of the meson-hyperon vertices in order to allow for an analytic Fourier transformation into coordinate space. As in NN^8 , this approximation has sizable effects also for the ΛN system and should thus be avoided. As an example, we present in fig. 9a the potential in the $1S_0$ partial wave based on the exchange graphs of fig. 8; fig. 9b shows the corresponding phase shifts, obtained by solving the unitarizing equation for the scattering amplitude. The results clearly demonstrate the inadequacy of the nonrelativistic approximation.

FIGURE 8
Strangeness-exchange processes in the ΛN system.

FIGURE 9

a) Potential $V(q',q,Z)$ due to the process in fig. 8, in the $1S_0$ partial wave, for $Z = 2E_q$ and $q = 250$ MeV, as function of q' . The solid line denotes the unapproximated result whereas, for the dash-dot curve, retardation effects have been omitted in the propagators. For the dashed curve, the nonrelativistic approximation at the vertices has been applied in addition. b) The corresponding result for the AN phase shift.

FIGURE 10
Tensor potential a) based on K, K^* -exchange in the AN system. b) derived from π, ρ -exchange in the NN system.

Finally, we want to report on an interesting observation concerning the strength of the tensor force in the AN system, which is mainly built up by the diagrams of fig. 8. As fig. 10a demonstrates, there is an extremely strong cancellation between the contributions of K and K^* -exchange leading to a very

small tensor force in the relevant momentum region. This interplay between K and K^* -exchange is analogous to π - and ρ -exchange in the NN system, see fig. 10b. In fact, due to the larger mass of the kaon compared with the pion mass, the cancellation is much more complete in the ΛN system. Consequently, the role of the tensor force in building up the binding energy of a Λ particle in nuclear matter should be very small.

More details concerning our results for the ΛN system can be found elsewhere⁹.

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