NUCLEAR FORCES WITHIN A CONSISTENT MESON-EXCHANGE MODEL

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Abstract

In this contribution we present a meson-exchange model for the NN-interaction which includes irreducible diagrams up to fourth order in a consistent way. These diagrams contain in particular an explicit determination of the 2π-exchange taking into account virtual Δ-excitation and direct $\pi\pi$-interaction. This part of the model agrees quantitatively with results obtained from dispersion theory which in turn are based on the analysis of πN- and $\pi\pi$-scattering data. A detailed interpretation of the lower partial wave phase-shifts of NN-scattering requires, however, (apart from the well-known OBE contributions) the introduction of additional irreducible diagrams containing also heavy boson exchange, in particular the combination of π and ρ. In the framework of this consistently extended meson model (it contains all terms up to an exchanged mass of 1 GeV) an accurate description of the NN--scattering data below 300 MeV laboratory energy as well as the deuteron data is achieved; the numerical results are definitely superior to well-known simplified boson exchange models, e.g. the one--boson exchange. Our enlarged viewpoint has also important consequences within the theory of nuclear matter due to our explicit determination of the 2π-exchange.

1. Introduction

Nowadays it seems to be generally accepted that the fundamental theory of strong interaction is, in fact, quantum chromodynamics (QCD). On that basis, the nucleon-nucleon (NN) interaction has to be considered as being in principle completely determined by quark and gluon exchanges. However, at the moment it appears by no means possible to give a fully satisfactory quantitative expression for the whole nuclear force in this way. So far, there are various promising attempts to describe the short range part of the NN-interaction[1)], whereas the medium and long range part which plays the major role within nuclear physics can presently not be understood from this viewpoint.

For this reason, we have - at least for the time being - to step back from the high-brow aim of a complete quantum-chromodynamical treatment of the NN-interaction. However, we can attempt to pursue our aim in the framework of a suitable approximation scheme which is based on QCD. Noticing first of all that the masses of all relevant hadrons are now in general understood within the framework of lattice QCD[2)], we may use them as parameters of the approximative concept. In very much the same way, we may further consider boson-nucleon vertices as a natural and effective description of a most complicated n-quark-reaction[3)]. Thus, we are lead to a boson-exchange model of nuclear forces which, however, is related to the fundamental theory of strong interaction. It differs from the old boson theory, which dates back to Yukawa[4)], in that it does not assume the mesons as fundamental fields. Within the framework of this new interpretation where the quantum fields are just used for a phenomenological description of the various bosons, it appears natural (and even compulsory) to introduce within the explicit expressions for the vertices characteristic form-factors (so far called regularization terms) which by now play the role of relevant physical parameters: They may be visualized as a consequence of the extension (in space) of the nucleons and might be - to some extent - related to the bag-radii (compare, however, the contribution of G. Miller in this volume). The use of cutoffs for the meson-nucleon vertices in our model appears natural from this new viewpoint and has its origin in the bag-structure of hadrons.

A consistent meson model taking into account all relevant exchange--diagrams has, up to date, never been accomplished. Most existing models are restricted to single meson exchanges and the more extended ones may include just the two-pion-exchange. It is, therefore, the aim of our work presented in this report to attempt a meson exchange model for the NN-interaction which is consistent inasmuch as it includes all diagrams up to an exchanged total meson-mass of $\simeq$ 1 GeV. This upper limit is reasonable because the cutoffs, which have to be applied according to our discussion in the last paragraph, are in the order of 1.0-1.5GeV. The necessity of this limitation appears as a direct consequence of the new (phenomenological) interpretation of boson--exchange. On the basis of such a model it now becomes possible to check reliably the extent to which this 'effective meson theory' of nuclear forces is valid and constitutes a realistic concept.

Apart from a really satisfactory description of all relevant phase--shifts of NN-scattering in the interval of 0-300 MeV (the effects on the various phases of the different exchange-terms, which according to our general rule have to be included, will be discussed in detail) this model leads at the same time to the interpretation of characteristic properties of nuclear matter: The 2π-exchange terms lead in a natural way to a characteristic density dependent quenching of the nuclear force within matter which is needed for a consistent and simultaneous description of light <u>and</u> heavy nuclei. Furthermore, the model offers the opportunity of taking into account the effect of virtual nuclear Δ-excitations within matter in a systematic way: This yields a natural explanation for the recent quark structure function measurements in iron[5).

2. Formalism

As in subsequent sections many diagrams will occur, we have to state once the rules of the game by which we evaluate them. We use the non--covariant or "old-fashioned" perturbation theory. It has been suggested to us by D. Schütte[6), and allows us to go, in a consistent way, from the two-body to the many-body problem. It further provides the possibility to take effects of mesonic variables in nuclear matter into account. The retardation in the propagator of non-covariant perturbation theory turns out to be essential for a realistic size and range of isobar contributions to the NN-interaction[7] and for the strength of the tensor force provided by pion-exchange. In non-covarian perturbation theory all possible time-orderings have to be taken into account separately. Therefore, the diagrams depicted in this report have to be considered as an abbreviated notation, just standing for all possible time-orderings. Anti-particle contributions in intermediate states are left out ("pair-suppression"[8]).

The Lagrangians of subsequent interactions are listed here in conventional notation (explanations can be found e.g. in ref. 7):

$$L_{ps} = \sqrt{4\pi} g_{ps} i\bar{\psi}\gamma_5\psi\varphi_{ps}$$

$$L_s = \sqrt{4\pi} g_s \bar{\psi}\psi\varphi_s$$

$$L_v = \sqrt{4\pi}\{g_v\bar{\psi}\gamma_\alpha\psi\varphi_v^\alpha + \frac{f_v}{4M}\bar{\psi}\sigma_{\mu\nu}\psi(\partial^\mu\varphi_v^\nu - \partial^\nu\varphi_v^\mu)\}$$

$$L_{N\Delta\pi} = \sqrt{4\pi}\frac{f_{N\Delta\pi}}{m_\pi}\bar{\psi}\vec{T}\psi_\mu\partial^\mu\vec{\varphi}_\pi + \text{h.c.}$$

$$L_{N\Delta\rho} = \sqrt{4\pi} i\frac{f_{N\Delta\rho}}{m_\rho}\bar{\psi}\gamma_5\gamma_\mu\vec{T}\psi_\nu(\partial^\mu\vec{\varphi}_\rho^\nu - \partial^\nu\vec{\varphi}_\rho^\mu) + \text{h.c.}$$

(In the 3 first lines the well-known isospin dependence is suppressed). The simplest contribution is the one-meson-exchange which is displayed in fig. 1; as those contributions are well-known, they will not be discussed further.

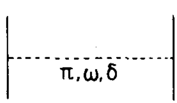


Fig. 1: One-meson-exchange contributions to the NN--interaction taken into account in this work.

3. The 2π-exchange model

Our model for the 2π-exchange contribution to the NN-interaction is shown in fig. 2

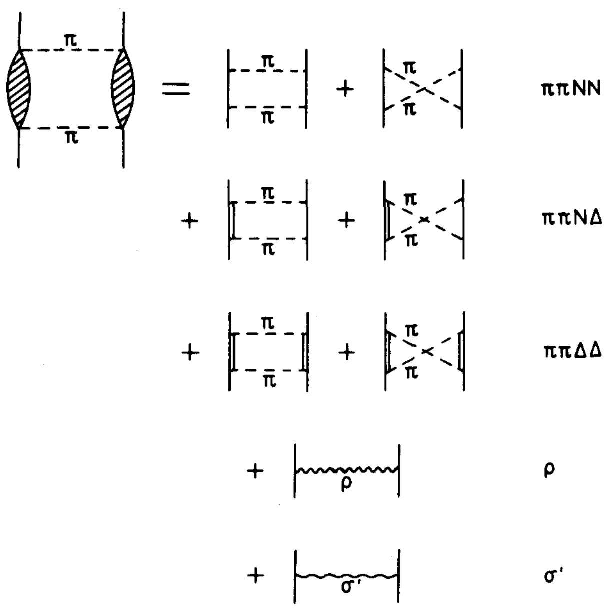


Fig. 2

Our model for the 2π-exchange contribution to the NN-interaction. A full line represents a nucleon and a double line a Δ(1232)-isobar. Further explanations are to be found in the text.

The various crossed box diagrams have to be taken into account as they are non-negligible[9)] and help to provide an iso-scalar character for the 2π-exchange contribution (at least in higher partial waves). An almost iso-scalar character is suggested by results from dispersion theory. The six upper diagrams of fig. 2 represent the uncorrelated 2π-exchange. However, there also exists a strong interaction between two pions: This gives rise to the well-known ρ-meson, if the two interacting pions are in a relative P-wave. On the other hand the relatively strong $\pi\pi$-S-wave interaction does not lead to a resonance. However, Durso et al.[10] have shown that the three diagrams on the left hand side of fig. 3 may well be approximated by the exchange of a scalar-isoscalar boson which we will denote by σ'. In the work quoted here the $\pi\pi$-S-wave interaction had first been determined from the empirical $\pi\pi$-S-wave phase-shifts of $\pi\pi$-scattering. σ' is thus introduced in a well-defined way in contrast to the σ used in former boson--exchange models.

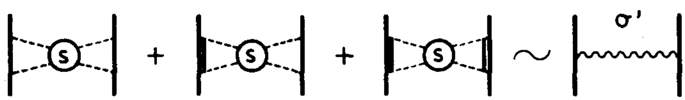


Fig. 3

Correlated 2π-exchange contributions considered in the work of Durso et al.[10]. The circled S symbolizes the $\pi\pi$-S-wave interaction adjusted to empirical $\pi\pi$-S-wave scattering. Further notation as in fig. 2.

The alternative way to derive the 2π-exchange contribution to the NN-interaction consists in the introduction of dispersion theory, in which empirical information of πN- and $\pi\pi$-scattering is used in order to evaluate the amplitude $N\bar{N} \to \pi\pi$[11]. We perform a quantitative comparison with the results from this latter approach. For this purpose we consider sufficiently high partial wave phase-shifts of NN-scattering, such that there is no cutoff-dependence. The contribution from our model in these higher partial waves is then uniquely determined by the πNN- and $\pi N\Delta$-coupling constant, the ρNN- and ωNN-coupling as well as the $\pi\pi$-S-wave contribution given by σ'. (All meson parameters used in this work are listed in section 6).

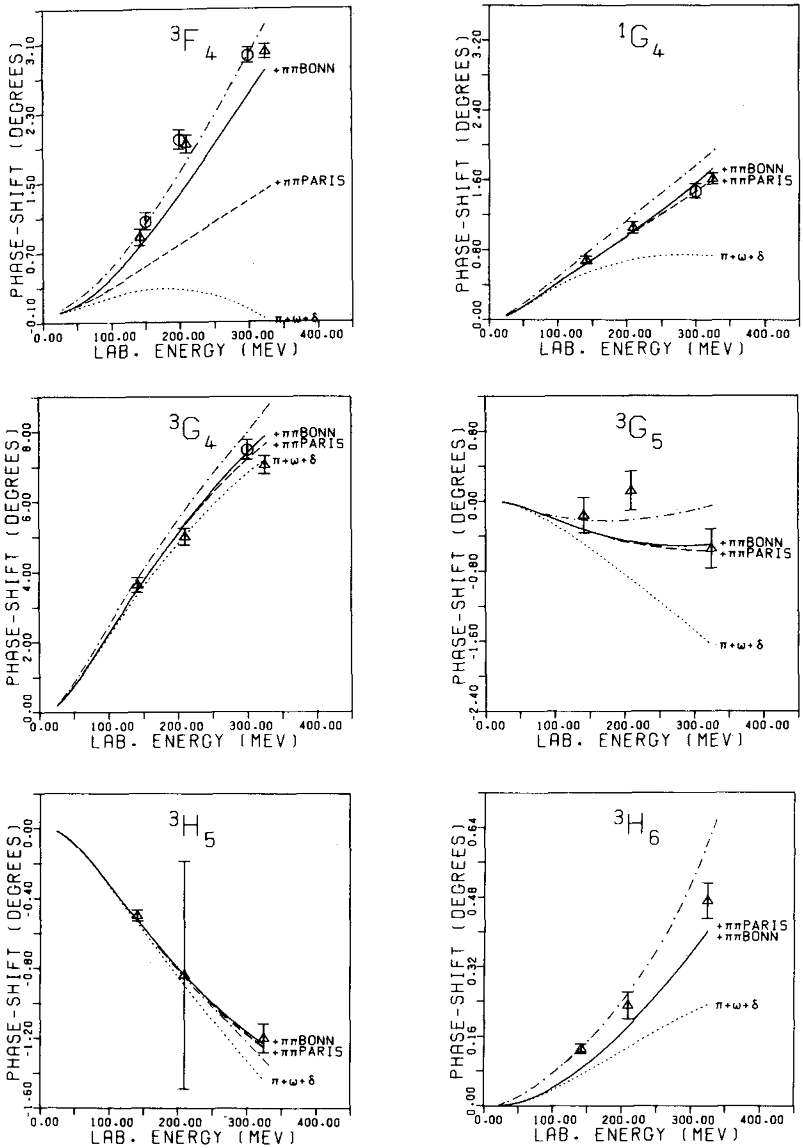


Fig. 4: Some higher partial wave phase-shifts of NN-scattering. The full line contains the contribution from our model for the 2π-exchange shown in fig. 2 (indicated by $+\pi\pi$ Bonn), the dashed line the dispersion-theoretic result taken from ref. 11 (indicated by $+\pi\pi$ Paris). In both curves the same one-π, -ω and -δ exchange, which is also displayed on its own in the dotted curve, is included. (The empirical data plotted are explained in the caption of fig. 11). The dash-dot curve denotes the result for the parametrized Paris-Potential which should be in quantitative agreement with the dashed curve. However, in e.g. $^3F_4$ and $^3H_6$ the original result for the 2π-exchange obtained by that group has obviously been changed by up to 100% to achieve a better agreement with the phase-shift data in some partial waves.

Fig. 4 demonstrates a close agreement of our 2π-exchange contribution with the dispersion-theoretical result as well as the empirical NN--phase-shifts. This double agreement confirms that we have chosen a physically reasonable model. At the same time this proves the consistency of our basic assumptions. In addition, our method has the advantage to permit an explicit determination of the virtual Δ-admixture which plays a decisive role in the theory of nuclear matter. In fact, nuclear binding is to an overwhelming part due to this admixture and the ππ-S-state interaction represented here by σ'. After having checked our model for the 2π-exchange successfully in higher partial waves, we proceed now to states of lower angular momentum. We show first the various contributions of the 2π-exchange diagrams in a lower partial wave phase-shift compared to a higher one in fig. 5.

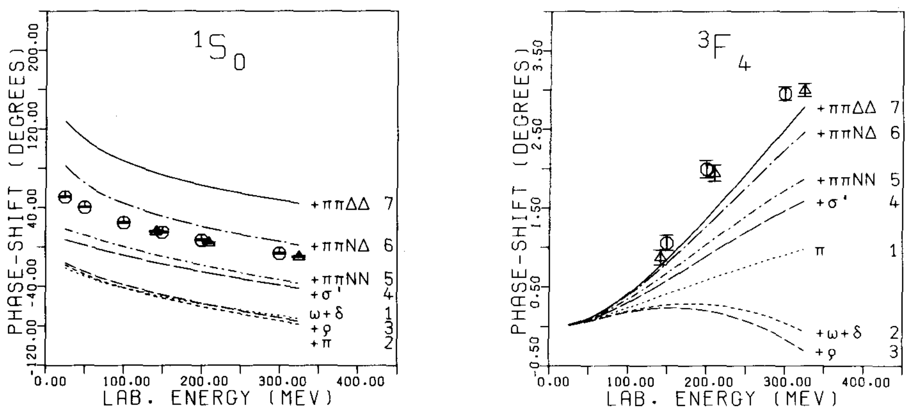


Fig. 5

$^1S_0$ and $^3F_4$ partial wave phase-shifts displaying the individual contributions to the 2π-exchange, which are added up successively in the denoted order (numbers at the left hand side). The short notation for the various contributions is defined in fig. 2.

What can be seen in the $^1S_0$-state is typical for all lower partial waves: The 2π-exchange is too attractive, i.e. the curve Nr. 7 is too high (in contrast to the behaviour in higher phases like $^3F_4$). As the contributions are sensitive to the cutoff regularization of the πNN- and πNΔ-vertex in low partial waves, one may argue that the over-

-attraction might be due to a wrong choice of the cutoff-mass. Therefore, we demonstrate in fig. 6 the cutoff-dependence of the whole 2π--exchange contributions.

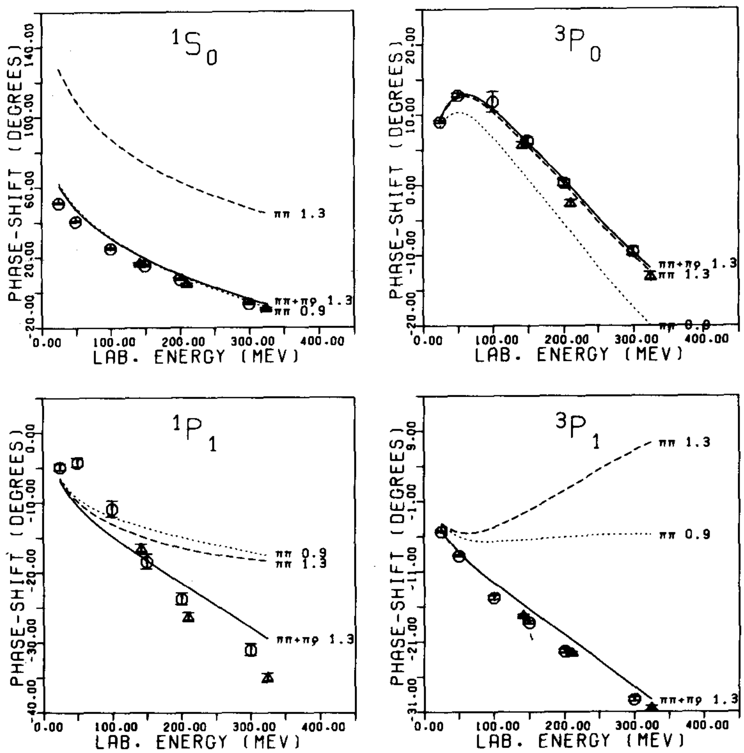


Fig. 6

2π-exchange contributions to the phase-shifts of four different low partial waves with two different choices of the cutoff-mass, Λ_π, regularizing the pion-vertex, namely Λ_π = 1.3 GeV (denoted in fig. 6 by ππ 1.3) and Λ_π = 0.9 GeV (ππ 0.9). For the former case the effect of the additional πρ-contribution (compare section 4) is also demonstrated (ππ+πρ 1.3). In addition all curves contain the one-meson -exchange of π, ω and δ.

It is seen from fig. 6 that e.g. a simultaneous fit of the $^1P_1$ and the $^3P_1$-phase-shift can never be achieved, as a stronger cutoff lowers the $^3P_1$ and raises the $^1P_1$, although both phase-shifts had to be lowered for a closer agreement with the empirical phase-shift data. Also a consistent fit of ^1S_o and $^3P_1$ is obviously impossible: When the ^1S_o-phase-shift is correct (namely for Λ_π = 0.9 GeV), the $^3P_1$ is still considerably too high.

The conclusion states that a model consisting of one-meson- and 2π-exchange only is unable to describe the empirical NN-data if the concept of regularizing the vertices by cutoffs is applied in a consistent way.

4. The $\pi\rho$-contribution

The failure in low partial waves of the model developed so far is no reason to give up. Various meson-exchange contributions, which have to be taken into account according to our consistency rule developed in the introduction, have been neglected so far. As we already realized on the one-meson-exchange level, π and ρ play the role of counterparts. It seems therefore reasonable to include next the two boson-exchange diagrams of π and ρ expecting them to counterbalance $\pi\pi$-contributions.

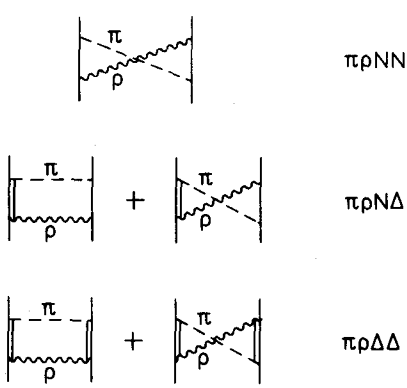


Fig. 7: $\pi\rho$-contributions to the NN-interaction considered in this work.

Fig. 7 displays the contributions to be considered in analogy to the diagrams of uncorrelated 2π-exchange. (The diagrams shown represent the contributions to the kernel in the Lippmann-Schwinger-type equation).

(The correlated 3π-exchange is represented by the ω which we took already into account on the one-boson-exchange level). The typical and large contributions are displayed in detail in fig. 8 for two examples.

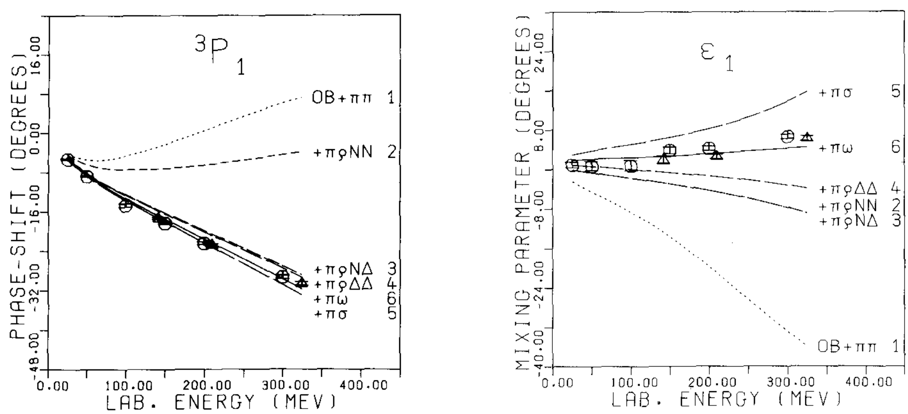


Fig. 8

Individual πρ as well as πσ and πω contributions in the $^3P_1$-phase-shift and the ε_1-mixing parameter. The individual contributions are added up successively according to the numbers given at the end of the curve labels. The abbreviated notation for the contributions is explained in fig. 7 and 10. (The curves 5 and 6 which correspond to additional 2 boson-exchanges are discussed in section 5).

The global effect of all $\pi\rho$-diagrams in other low partial waves have already been demonstrated in fig. 6 curve "$\pi\pi+\pi\rho$ 1.3" in comparison to curve "$\pi\pi$ 1.3". Clearly, the $\pi\rho$-contributions are absolutely needed for a quantitative description of low partial waves if a realistic model for the 2π-exchange is applied.

The fact that the $\pi\rho$-contributions are of relevance had been pointed out already in the work of Durso et al.[14]. In this work, however, the $\pi\rho$-contribution was suggested as an instrument to reduce the ω-coupling, which is always rather large in OBE-models if compared to the SU(3) prediction. Our findings are that this suggestion is not realistic for two reasons: First, the $\pi\rho$-contribution sometimes varies tremendously from state to state (compare e.g. the contribution in ^3P_o and $^3P_1$ of fig. 6) which is not the case with the ω; second, the over-attraction of the 2π-exchange in low partial waves is such that in addition to a rather large ω-coupling further repulsion is needed. Therefore, the effect of the $\pi\rho$-contribution is to function as a counterpart of the 2π-exchange contribution and not to partially provide the short range repulsion of the NN-interaction which anyhow should be about equally strong in all partial waves.

At this stage of the development of our model it is instructive to ask the question, what the fictitious scalar isoscalar σ-boson of the former one-boson-exchange (OBE) model[15] stood for. The old belief that it replaced the sum of all correlated and uncorrelated irreducible 2π-exchange contributions is true only for high partial waves (where the $\pi\rho$-contributions are negligible because of their short-range); in low partial waves the 2π-exchange contribution appears by no means to be isoscalar, whereas after its smoothening out by the $\pi\rho$-exchanges an approximation by a one-σ-exchange appears possible, as demonstrated in fig. 9.

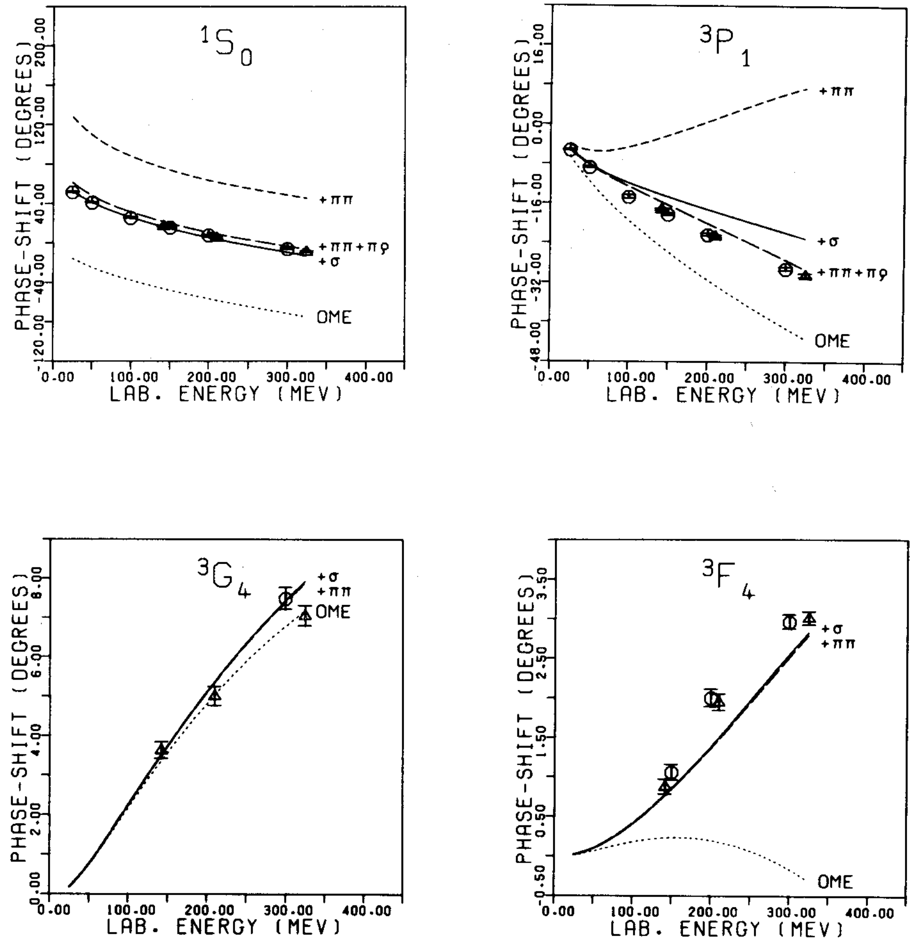


Fig. 9.

The approximation of the 2π-exchange plus πρ-exchange by a fictitious σ-boson (g_σ^2 = 11.12, m_σ = 575 MeV) in two high and two low partial waves. The dotted curve contains all iterated one-meson-exchange (OME) contributions (i.e. π,ω,δ,ρ). The other contributions, displayed with an obvious notation, are added on top of the OME. In higher partial waves the πρ-contribution is left out because it is negligible.

5. Further irreducible contributions of fourth order

Guided by our rule that we are going to consider all diagrams up to an exchanged mass of 1 GeV which seems sensible as the cutoffs applied in our model are of the order 1.0-1.5GeV we have to take into account further diagrams. One irreducible contribution of that kind will certainly be the $\pi\omega$-contribution (fig. 10). However, from the last section we know that the antagonist structure of the one-boson--exchanges may continue in higher irreducible meson-exchanges. The counterpart to the ω is the intermediate-range attraction, which in our explicit meson-exchange model is provided by the 2π-exchange, damped, however, in an essential way by the $\pi\rho$-diagrams. Therefore, we have to consider a $\pi\sigma$-contribution as well (fig. 10). The σ stands for the sum of all $\pi\pi$- and $\pi\rho$-diagrams as explained in the last section. (The σ-approximation is used by us only in this higher diagram).

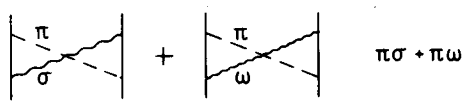


Fig. 10

$\pi\sigma$- and $\pi\omega$-contributions to the NN-interaction included in our model.

These two contributions almost completely cancel each other in most partial waves, except for the ε_1-mixing parameter where we observe a sizeable increase (see fig. 8), and it is for this reason why a rather low cutoff-mass for the pion-nucleon vertex could be chosen, namely 1.3 GeV, to be compared to 1.5 GeV in usual meson-exchange models. In this way more consistency between the cutoffs of the πNN- and $\pi N\Delta$--vertices could be achieved; the latter has a cutoff-mass of 1.2 GeV in our model.

Table 1

Meson parameters applied in the present model and from other sources.

vertex	meson-mass, m_α (MeV)	$g_\alpha^2(t=-m_\alpha^2)$	$g_\alpha^2(t=0)$; (f/g)	coupling constant from other sources or comments	cutoff-mass Λ_α (GeV)	n_α
NN π	138.03	14.4	14.08	14.28±0.18 πN-scattering, ref. 16	1.3	1
				14.52±0.40 $\bar{p}p$ forward dispersion relation, ref. 17		
				NN-phase-shift analyses: 14.25 ref. 18 (Bugg) 14.5 ref. 19 (Arndt)		
ρ	769.	0.75	0.41; (6.1)	0.55±0.06 (6.1±0.6) fit to $N\bar{N}\to\pi\pi$ partial waves, ref. 20	1.5	1
ω	782.6	20.	10.6	12.0 ref. 21 8.1±1.5 ref. 22	1.5	1
δ	983.	2.93	1.69	-	2.0	1
σ'	600.	9.0	5.33	$\pi\pi$-S-wave interaction, compare ref. 10	1.25	1
NΔ π	138.03	0.224	0.218	quark model with g_π^2 = 14.4 : 0.224	1.2	1
ρ	769.	15.51	4.58	quark model with g_ρ^2 = 0.55 : 13.4	1.5	2

$g_\alpha(t) := g_0 \left\{ \frac{\Lambda_\alpha^2 - m_\alpha^2}{\Lambda_\alpha^2 + t} \right\}^{n_\alpha}$; nucleon mass: 938.926 MeV;
mass of Δ-isobar: 1232. MeV.

Table 2

Deuteron and low energy parameters predicted by our model (theory) and by experiment (experiment).

	Theory	Experiment
Deuteron:		
binding energy, E_B (MeV)	2.22469	2.224644±0.000046 ref. 23
D-state probability, P_D (%)	4.27	5±2
quadrupole-moment, Q_D (fm^2)	0.281	0.2860 ± 0.0015 ref. 24
asymptotic S-state, A_S	0.9043	0.8846 ± 0.0008 ref. 25
asymptotic D/S-state, η	0.0267	0.0271 ± 0.0004 ref. 25
root-mean-square radius (fm)	2.0026	1.9635 ± 0.0045 ref. 26
ΔΔ-probability (%)	0.5	
np low energy scattering:		
singlet: a_s (fm)	-23.745	-23.748 ± 0.010
r_s (fm)	2.755	2.75 ± 0.05
triplet: a_t (fm)	5.424	5.424 ± 0.004 ref. 27
r_t (fm)	1.760	1.759 ± 0.005

In the theoretical results quoted here the nucleonic wave function of the deuteron has been normalized to unity for simplicity. In a more refined consideration of the deuteron, Δ- and mesonic components should be separated out. They would, on the one hand, reduce the normalization of the nucleonic wave function and by that the theoretical result of most deuteron quantities cited, but, on the other hand, add meson-current contributions which will at least partly compensate the former effect. This will be discussed in detail in a future paper.

6. The meson parameters and the quantitative description of the NN data

In table 1 we give the meson-parameters used throughout this work and compare them to other sources. A rather close agreement can be observed. The description of the low energy scattering and the deuteron data is excellent as can be seen from table 2. The fit of the phase-shifts of NN-scattering are shown in fig. 11, where also a comparison of our theoretical results with those from energy-independent (error-bars) and energy-dependent (dashed curve) phase-shift analysis is performed. Further, results from a typical OBE model are also given in fig. 11 (dotted curve) demonstrating the considerable improvements of our extended meson-exchange model compared to the simplified approach (watch especially the $^1P_1$, $^3P_1$ and $^3D_2$ phase-shifts). Apart from the phase-shifts the so-called observables of NN-scattering were directly computed for the present model: They also show a superior agreement to experiment[28].

7. Nuclear Matter

Though we have not yet applied the present extended model to nuclear matter, we may estimate the main qualitative results from the experience with former models including iterative isobar-diagrams[7,29]. Pauli- and dispersion effects, which in a natural way occur in a model for the NN-interaction with explicit diagrams of the fourth order, will reduce the overbinding, commonly found in nuclear matter calculations, especially when a nuclear force with a realistically weak tensor force is applied. These medium effects have proven to be essential for nuclear saturation, and cannot be taken into account by simple potential models for the nuclear force. The density-dependence of the effects improve the relation between the binding energy of light and heavy nuclei. Moreover, isobar excitations of the nucleons in nuclear matter are a natural feature of our model. We expect the probability to be in the order of former calculations[29] which was found to be about 10%. This may be a possible explanation for recent structure function measurements in iron by the EMC-group[5].

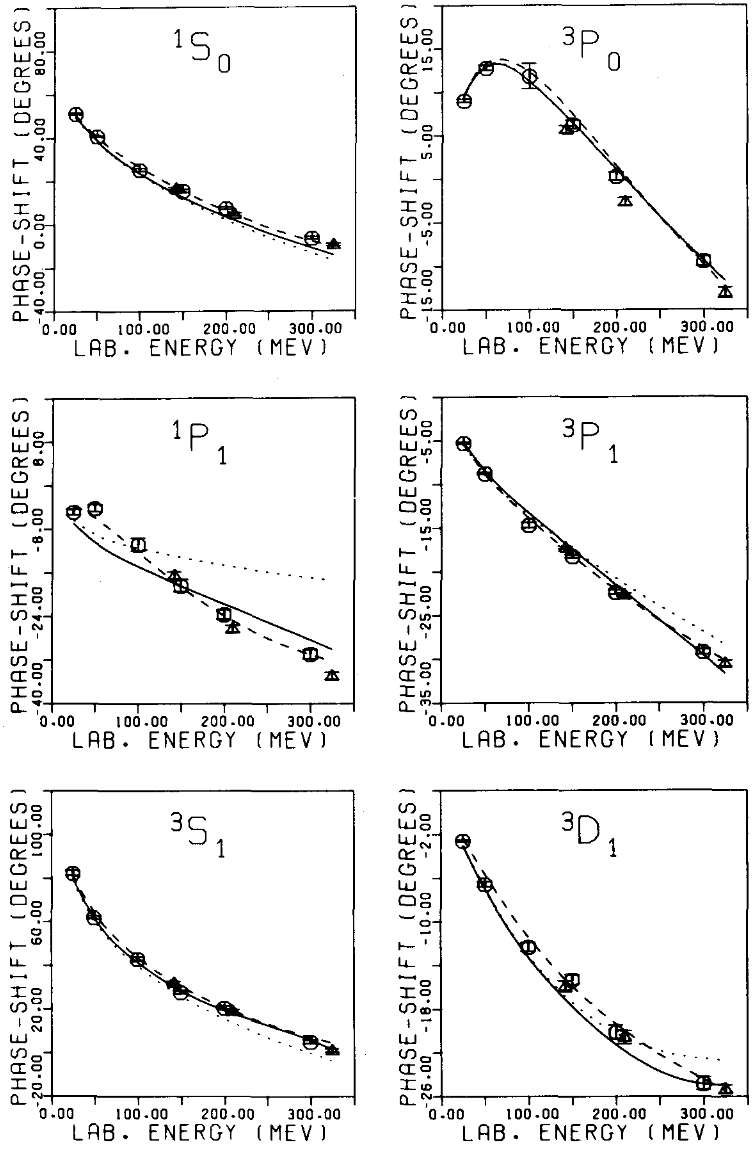


Fig. 11: Partial-wave phase-shifts of NN-scattering. The full line represents the results from our model. The dotted line refers to a typical OBEP. The energy-dependent phase-shift analysis of Arndt et. al.[19] is displayed in the dashed curve; energy-independent analyses are given from the latter group (octagon) and from Bugg and coworkers[18] (triangle).

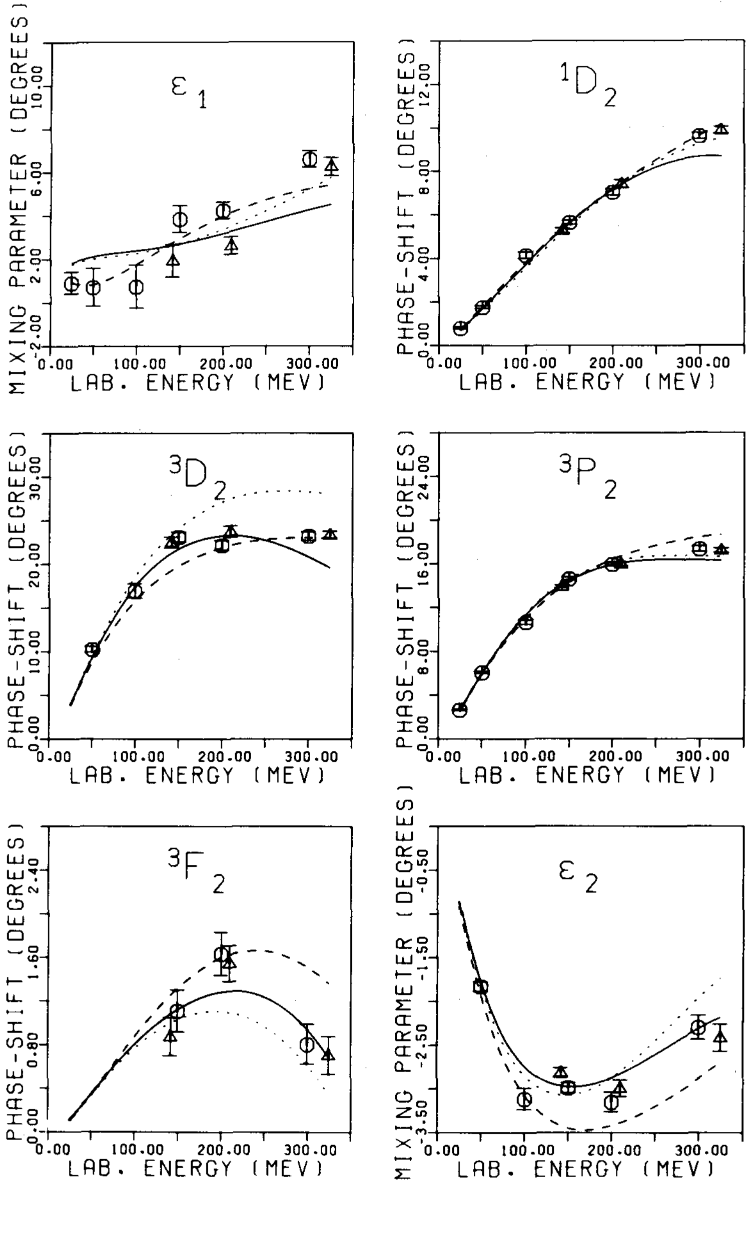
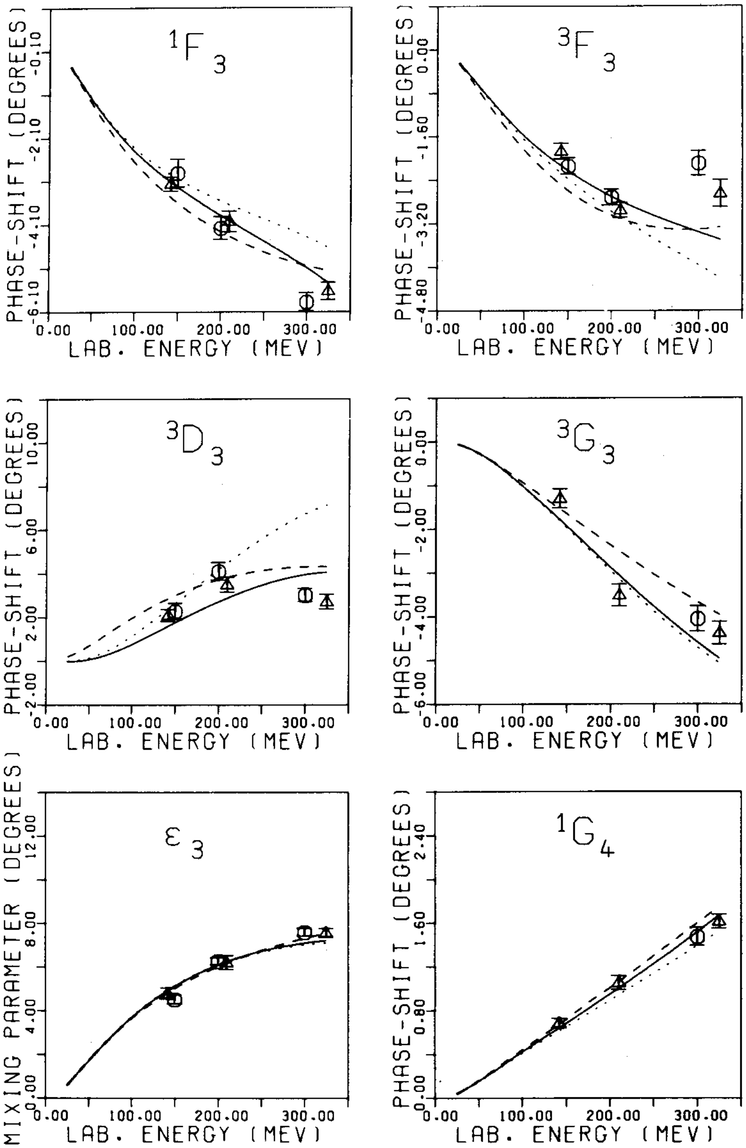

ε 1
MIXING PARAMETER (DEGREES)
LAB. ENERGY (MEV)
1D 2
PHASE-SHIFT (DEGREES)
LAB. ENERGY (MEV)
3D 2
PHASE-SHIFT (DEGREES)
LAB. ENERGY (MEV)
3P 2
PHASE-SHIFT (DEGREES)
LAB. ENERGY (MEV)
3F 2
PHASE-SHIFT (DEGREES)
LAB. ENERGY (MEV)
ε 2
MIXING PARAMETER (DEGREES)
LAB. ENERGY (MEV)

Fig. 11, cont'd



1F3
PHASE-SHIFT (DEGREES)
-0.10
-2.10
-4.10
-6.10
0.00
100.00
200.00
300.00
LAB. ENERGY (MEV)
3F3
PHASE-SHIFT (DEGREES)
0.00
-1.60
-3.20
-4.80
0.00
100.00
200.00
300.00
LAB. ENERGY (MEV)
3D3
PHASE-SHIFT (DEGREES)
10.00
6.00
2.00
-2.00
0.00
100.00
200.00
300.00
LAB. ENERGY (MEV)
3G3
PHASE-SHIFT (DEGREES)
0.00
-2.00
-4.00
-6.00
0.00
100.00
200.00
300.00
LAB. ENERGY (MEV)
ε3
MIXING PARAMETER (DEGREES)
12.00
8.00
4.00
0.00
0.00
100.00
200.00
300.00
LAB. ENERGY (MEV)
1G4
PHASE-SHIFT (DEGREES)
2.40
1.60
0.80
0.00
0.00
100.00
200.00
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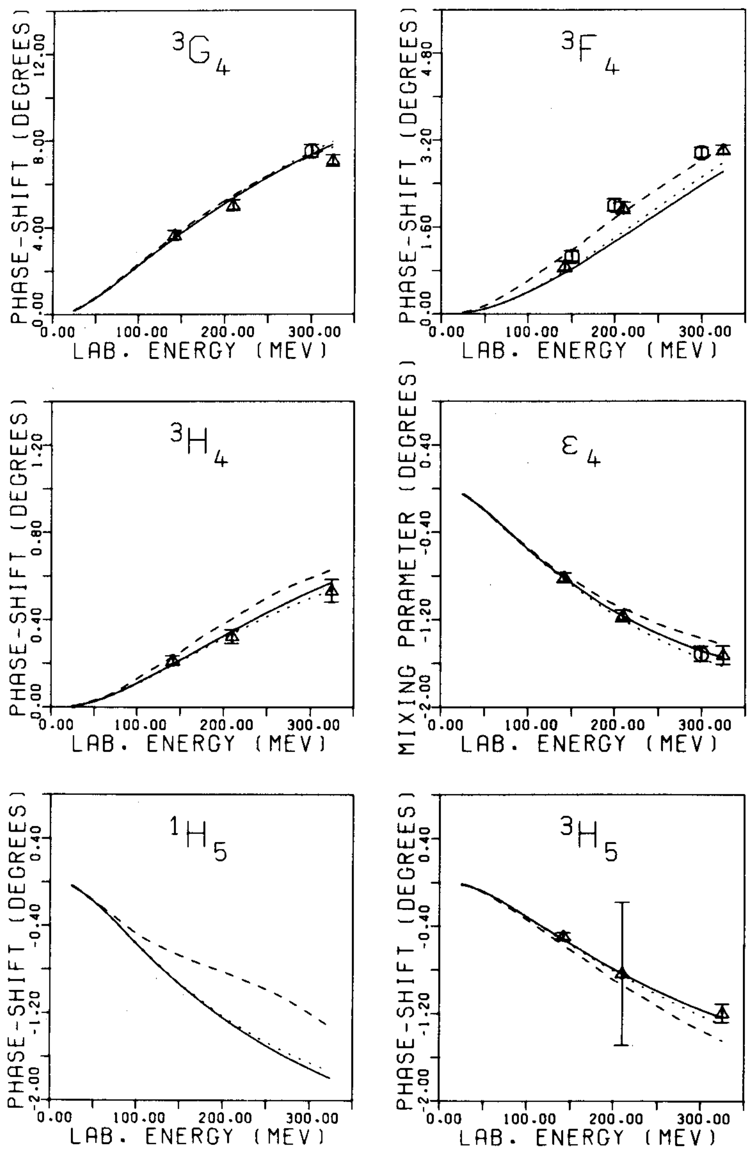
LAB. ENERGY (MEV)

Fig. 11, cont'd



3G4
PHASE-SHIFT (DEGREES)
LAB. ENERGY (MEV)
3F4
3H4
ε4
MIXING PARAMETER (DEGREES)
1H5
3H5
0.00
100.00
200.00
300.00

Fig. 11, cont'd

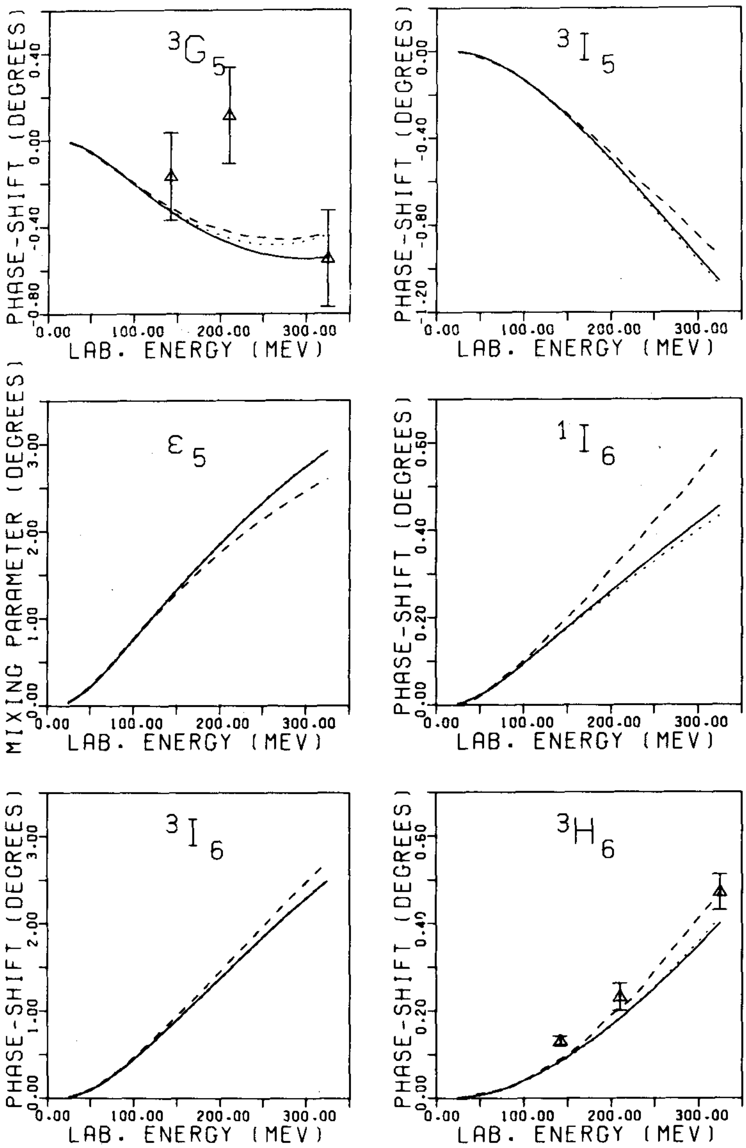

$^3G_5$
$^3I_5$
ε_5
$^1I_6$
$^3I_6$
$^3H_6$
PHASE-SHIFT (DEGREES)
MIXING PARAMETER (DEGREES)
LAB. ENERGY (MEV)
0.00
100.00
200.00
300.00

Fig. 11, cont'd

Summary and conclusions

For the NN-interaction we consider meson-exchange as the possibly adequate approximation scheme describing effectively the complicated underlying multi-quark processes. Based on that principle idea we construct a meson-exchange model for the NN-interaction which includes irreducible diagrams up to fourth order. From the quark-bag structure of hadrons it is evident that for the meson-baryon vertices a form--factor is needed. Quantitative consideration within our model lead us to a value for the cutoff mass of such a form-factor of 1.2 to 1.5 GeV. We conclude from this fact that for a consistent meson-exchange model it is necessary to take into account diagrams with a total mass of the exchanged mesons up to ≃ 1 GeV, i.e. up to almost the cutoff region.

Part of our model represents an explicit determination of the 2π--exchange contribution including virtual Δ-excitation and the direct $\pi\pi$-interaction. A quantitative check shows a remarkable agreement of our model with results from dispersion theory which are based on the analysis of πN- and $\pi\pi$-scattering data. With the same part of our model we also achieve a rather satisfactory description of higher partial waves of NN-scattering.

For lower partial waves it turns out that the 2π-exchange is by far too attractive in order to account for the empirical data. However, according to the rules for a consistent model which we stated above further diagrams including heavy boson exchange have to be considered anyhow. Following this line we find that the irreducible diagrams of π- and ρ-exchange (containing also virtual Δ-excitation) add a strong repulsion in low partial waves, and by that compensating the over--attraction of the 2π-exchange in exactly that way which is needed for a quantitative interpretation of low partial waves.

We take further irreducible diagrams of $\pi\sigma$- and $\pi\omega$-exchange into account (where the σ represents the sum of all $\pi\pi$- and $\pi\rho$-diagrams in an approximate way), observing a cancellation to a large extent in most partial waves between these two groups of fourth order diagrams. As a remarkable exception, however, the ε_1-mixing parameter is considerably increased, as the contribution to the tensor force provided by the $\pi\rho$-diagram is strongly dominant over the analogous but opposite contribution from $\pi\omega$. This net increase of the tensor force allows us to use a lower value for the cutoff mass of the πNN-vertex than in old and simplified boson-exchange models. In that way the physically necessary close agreement between the form-factor for the πNN- and the πNΔ-vertex is achieved. In all older boson models with virtual Δ-excitation the vertex-functions for the two different pion vertices used to differ tremendously.

Summarizing we may state that the overall description of the two nucleon data by our complete model is excellent. The predictions for the phase--shifts of NN-scattering and the observables up to 300 MeV laboratory energy is most satisfactory. Remarkable improvements are to be seen especially in the $^1P_1$-, $^3P_1$- and $^3D_2$-phase-shifts. The empirical low energy data, i.e. scattering length and effective range, are reproduced exactly. With the latter quantities there have always been problems within boson models in the past.

Our extended model for the NN-interaction leads to considerable alterations of the usual nuclear matter theory which uses simple potential models for the nuclear force. Due to the different treatment of intermediate states in a many-body surrounding compared to the free case, characteristic modifications occur when our model for the NN-interaction is inserted into nuclear matter. These well-known Pauli- and dispersion--effects cause a density-dependent quenching of the nuclear force. This additional repulsion which results from our model in a natural way is desperately needed for a quantitative explanation of the binding energy in nuclear matter which is usually too large in conventional potential models, especially when higher orders in the hole-line expansion are included. Due to the density-dependence of the quoted effects our nuclear matter results further improve the relation in the binding energy of light and heavy nuclei. In addition, our findings about the Δ-excitation in nuclear matter provides a possible explanation of the recent quark structure function measurements in nuclei[5)]: The Δ-admixture is found in the order to 10 - 15% in rough agreement with the analysis of Szwed[5)].

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