KfK 4706
Februar 1990

Neutron-Proton Scattering

P. Doll
Institut für Kernphysik

Kernforschungszentrum Karlsruhe

KERNFORSCHUNGSZENTRUM KARLSRUHE

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P. Doll

Kernforschungszentrum Karlsruhe GmbH, Karlsruhe

Kernforschungszentrum Karlsruhe GmbH
Postfach 3640, 7500 Karlsruhe 1

ISSN 0303-4003

ABSTRACT

Neutron-proton scattering as fundamental interaction process below and above hundred MeV is discussed. Quark model inspired interactions and phenomenological potential models are described. The seminar also indicates the experimental improvements for achieving new precise scattering data. Concluding remarks indicate the relevance of nucleon-nucleon scattering results to finite nuclei.

Invited talk presented at the XIII Nuclear Physics Symposium, Oaxtepec, Mexico, January 3 - 6, 1990.

NEUTRON-PROTON STREUUNG

Die Neutron-Proton Streuung wird für niedere und hohe Neutronenergien um 100 MeV als fundamentale Nukleon-Nukleon Wechselwirkung vorgestellt. Der Vortrag diskutiert die Bedeutung von Wechselwirkungsmodellen, die in diesem Energiebereich auf dem Quarkmodell beruhen. Auch phänomenologische Nukleon-Nukleon Potentiale werden vorgestellt. Abschließende Bemerkungen verweisen auf die Bedeutung der Nukleon-Nukleon Streudaten für das Verständnis der Struktur von Atomkernen.

Neutron-Proton Scattering

I. Introduction

There has been a great deal of progress in recent years in understanding the strong nucleon-nucleon (NN) interaction. The complexity of the strong NN interaction manifests itself in highly sophisticated potential models like the 'Paris' potential or the 'Bonn' potential, involving several meson species and multiple meson exchange to account for the observed low energy scattering data. The multiplicity of features already emphasizes that many degrees of freedom make up the strong NN interaction.

Definite features of the phenomenological (considering the nucleons as fundamental constituents) NN interaction follow from their transformation properties in ordinary space and spin spaces, as scalar, pseudoscalar, vector and tensor, and from symmetries with respect to charge, spatial reflexion (parity) and time-reversal. Many tests of these symmetries have been carried out, most sensitive when using the spin degree of freedom of the NN system, because of the stringent requirement of the Pauli principle for fermions for the orbital angular momentum L and the channel spin S and isospin T. The symmetries reduce drastically the number of degrees of freedom of the NN scattering matrix, characterized by the orbital angular momentum L and the total angular momentum $J = L+S$ in the notation ${}^{2S+1}L_J$, and the questions have to be investigated, on which underlying structures associated with the nucleon the symmetries are based on one side and how they carry over to nuclei on the other side. A very detailed knowledge of the free NN interaction is mandatory to understand their modification to the so-called effective NN interaction when investigating extended nucleon systems like nuclei or nuclear matter. For the free NN interaction on the experimental side, because of the high particle flux of charged particle accelerators very precise investigations have been carried out for proton-proton (p-p) scattering, and it was only during the last decade that secondary neutron beams - even polarized - of reasonable intensity supported an extensive neutron-proton (n-p) scattering program. A very detailed comparison of the (p-p) and (n-p) scattering observables allows to investigate the electromagnetic and charge independent contributions contained in both scattering systems.

II. Nucleon-nucleon interaction models

The present status of the fundamental theory of the strong NN interaction, based on QCD, is ambiguous; although QCD is widely believed to be correct and works fine in the perturbative regime, one of its key properties, viz. colour confinement, has not been proven rigorously. We are far from detailed calculations of the NN interaction properties based on QCD alone. In the case of simple systems, qqq for baryons and $q\bar{q}$ for mesons, the non-relativistic quark model [see e.g. Close[1]] and the MIT bag model[2] have met with great successes and failures. The MIT Bag model calculates in a static cavity, containing quark and gluon fields, static properties of light hadrons. These massless radiation fields are confined in a sphere under constant pressure, a key innovation of the model. Persuing this picture the adiabatic deformation of a bag containing six quarks into two colour singlet bags containing three each with quantum numbers of the neutron and proton has been calculated[3]. This model exhibits interesting features of the NN interaction.

The two-nucleon interaction energy at various fixed constraint separations is computed variationally. The interaction turns out to be repulsive for small separation mainly due to a repulsive magnetic colour interaction. The same interaction makes the Δ particle more massive than the nucleon. The terms which drive the attraction arise from electric colour interaction. The same term gives rise to the strong attraction between quark and antiquark. The baryon number density is shown in fig. 1 for three choices of 'elongation'. The development of concentrations of quarks in the two halves is well pronounced. In spite of the fact, that

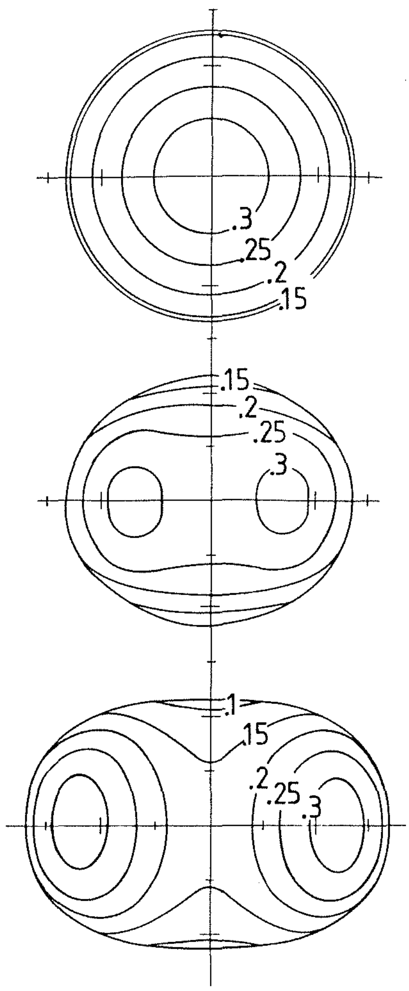

Fig. 1: Curves of equal baryon density (baryons/fm^3) in a cross section of the six-quark bag at various constraint separations (ref. 3)

the MIT Bag model provides a description of the non-spherical quark distribution, it cannot work for a complete separation into two nucleons. To incorporate the later phase hybrid models have to be employed.

An other type of model applies the non-relativistic quark model to NN scattering, calculating in the framework of the quark cluster model[4] or in the quark compound bag model[5] the admixture of the six-quark bag in the deuteron. The one-gluon and one-pion exchange potential between quarks play a key role in the explanation of the short range repulsion between nucleons which is usually attributed to ω-meson exchange in the one-boson exchange model. Compared to the usual one-pion exchange model which considers the nucleons as point-like particles, part of the off-shell extrapolation of the pion-nucleon form-factor is explicitely elaborated. Quark antisymmetrization and non-orthogonality of the NN and quark compound bag wave functions represent a difficult consistency problem. Calculations carried out in the quark compound bag model support the statement that NN scattering data in a wide energy range can be described even without any one-boson exchange contribution (ref. 6). The $^3S_1$ and $^1S_0$ phase-shifts computed in the model agree with the experimental data within 10 %. The quark compound bag model exhibits eigenstates like dibaryon resonances and features comparable to the MIT bag model. Fig. 2 taken from ref. 6 is based on the quark compound bag model combined with the Nijmegen one-boson exchange potential and shows the parameter ε_1 describing the non-spherical S-D wave mixing, compared to values derived from scattering data. ε_1 is a measure of the tensor part of the NN interaction which is itself responsible for long range interaction in nuclei. It is intriguing to recognize the success of the quark models in describing the non-spherical quark distribution (see MIT Bag model) and the non-spherical part of the NN interaction. Measured observables which dominantly depend on the strength of the tensor interaction like the spin-spin correlation are presented later.

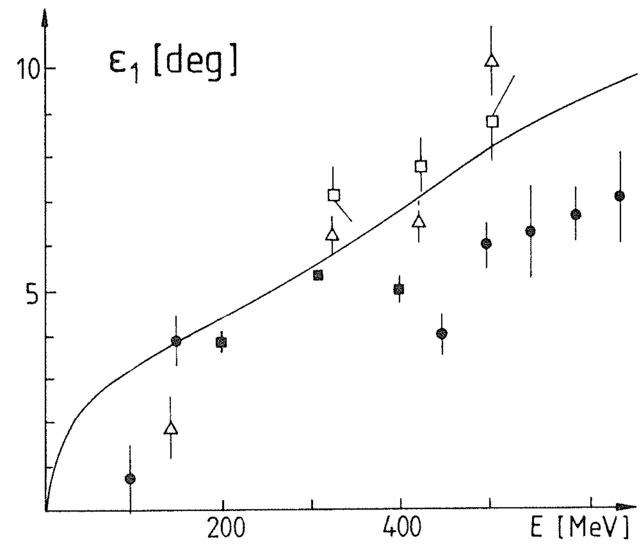

Fig. 2: Predicition of the quark compound bag model (ref. 6) for the S-D wave mixing parameter ε_1 compared to experimental results quoted in ref. 6. A more recent compilation of data is given in ref. 24. Data below 100 MeV are presented in fig. 12.

Since exclusively on quark and gluon-exchange based NN potentials are still far from providing satisfactory fits to all available NN data, continuing interest exists in the development and improvements of semiphenomenological NN potentials. From a practical point of view, comparison with the potential models is often made through the phase-shift analysis of experimental data. The phase-shift parameters δ are based on the partial wave expansion of the NN scattering matrix for fixed total angular momentum $J = L + S$ and in the notation $^{2S+1}L_J$. Semiphenomenological NN potentials, for example, the Bonn[7], Paris[8] and Nijmegen[9] are based on meson exchange theory. They employ effective meson-nucleon formfactors and coupling constants. The Bonn potential represents a comprehensive field-theoretical meson exchange model for the NN interaction at center-of-mass energies below pion production threshold. Higher order diagrams involving heavy meson exchange are included which prove crucial for a quantitative description of the low angular momentum phase-shifts. In the Paris potential the NN interaction is also derived from πN and ππ interactions including one-pion exchange and two-pion exchange. The short range part ($r < 0.8$ fm) of the interaction is parametrized by a constant soft core. At short distance the interaction considers the five components, central, spin-spin, tensor, spin-orbit and quadratic spin-orbit. Fig. 3 (ref. 8) shows the Paris potential description of the D-wave phase-shifts δ over a wide scattering energy range. The individual points stem from an analysis of experimental data resulting in D-wave phases as indicated in the figure 3. The picture nicely demonstrates the effect of the spin-orbit splitting in the n-p (isospin $T = 0$) channel $^3D_2$, $^3D_3$, $^3D_1$. While scattering of polarized nucleons at intermediate energies determine the ^3D spin-orbit coupling, those below hundred MeV determine the ^3P spin-orbit

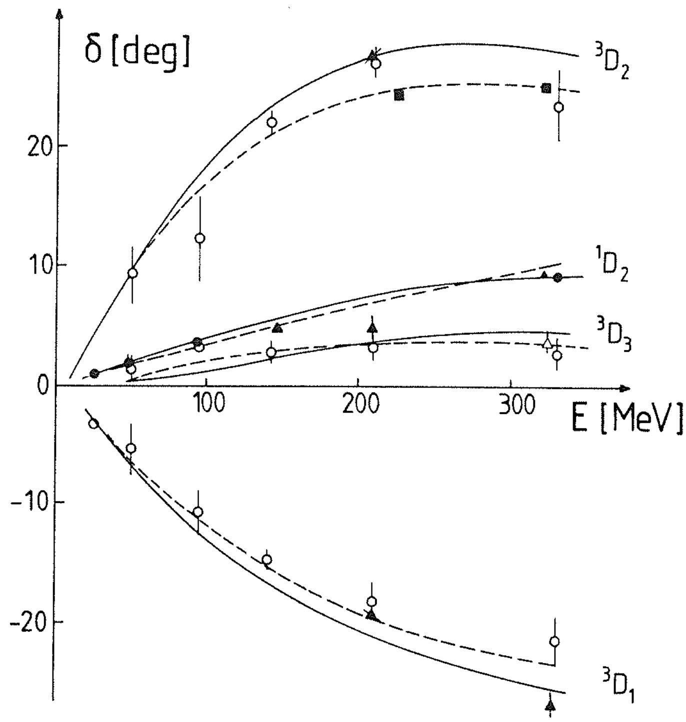

Fig. 3: The solid curves represent D-wave phase-shifts δ calculated with the Paris potential. For the dashed curves, circle, point and triangle data, see ref. 8.

coupling. Measured observables which dominantly depend on the strength of the spin-orbit interaction like the vector analyzing power are presented later.

The exchange character of the nuclear force between two nucleons means physically that the proton does not always remain a proton, respectively the neutron, but changes its character and is sometimes a proton, sometimes a neutron. Therefore, it is impossible to formulate in a consistent way the coupling between the electromagnetic field and a system of nucleons which involves fixed heavy constituents like protons and neutrons, without considering exchange currents between the nucleons.

A very detailed reaction which especially tests the meson exchange contribution is the photodisintegration of the deuteron or according to time-reversal invariance the n-p radiative capture experiment. It was in n-p capture at pile energies where the first indication of meson exchange was given[17]. The main contribution to the total capture cross section comes from the transition from the nearly bound $^1S_0$ continuum state to the bound $^3S_1$ and $^3D_1$ states in the deuteron. The spin of one nucleon of the n-p pair has to be flipped via exchange of a meson and a M1 radiation is emitted. The destructive interference between the $^1S_0$ - $^3S_1$ and $^1S_0$ -$^3D_1$ transitions results in electrodisintegration of the deuteron in a deep minimum around the momentum transfer of $q^2 \simeq 12$ fm^{-2}. At this minimum the photon is almost exclusively coupled to the exchange meson. At lower energies the capture transition amplitude can be expressed in terms of electric and magnetic multipole amplitudes (E1, M1, E2, M2). Contributions of meson exchange currents (MEC) and intermediate Δ(1232) isobar excitations are mainly seen in the E1 and M1 amplitude[18] (see fig. 4). The major part of the contribution to the E1 amplitude is even inclu-

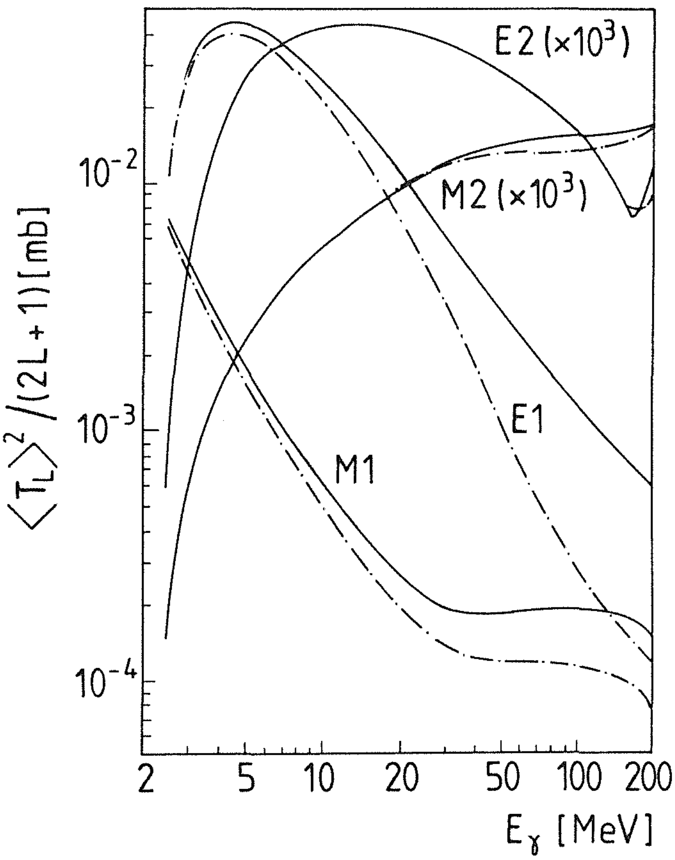

Fig. 4: Electric and magnetic dipole and quadrupole transition strengths as function of photon energy with (solid curves) and without (dashed-dotted curves) total meson exchange current contributions (ref. 18).

ded in the classical n-p dipol moment[19]. The impact of the tensor part of the long range NN interaction originating mainly from the one-pion exchange, can be seen in the forward-backward asymmetry of the differential capture cross section.

III. Neutron-proton scattering experiments

Several years ago, phase-shift analyses of n-p scattering data near 50 MeV revealed that, although the phase parameters δ were generally well determined, ambiguous and / or anomalous values were obtained for two important phase parameters. The $^3S_1$ - $^3D_1$ mixing parameter ε_1, which characterizes the non-spherical and long range part of the NN interaction, and the $^1P_1$ phase-shift parameter disagreed both with values expected from models and with any smooth interpolation of values from adjacent energies. In a phase-shift analysis, the best-fit values depend strongly on the quality of the data base: The total cross section, differential cross section and spin dependent observables. This unsatisfactory situation prompted us, to measure the n-p differential cross section $d\sigma/d\Omega(\theta)$, the vector analyzing power $A_y(\theta)$ and the spin-spin correlation parameter $A_{yy}(\theta)$, at our neutron beam facility[10] at the Karlsruhe cyclotron. High precision measurements of the backward angular shape of the differential cross section are shown in fig. 5. The new results[11] improve considerably the quality of the n-p data file in the energy range from 22 to 50 MeV. The 63.1 MeV data in fig. 5 are from the Davis group[12] and are included for comparison. The solid curves in fig. 5 are phase parameter fits. The starting values for the phase-shifts and their energy dependence were taken from the Paris potential. The higher partial waves (J > 4) were fixed. The $^1P_1$, $^3D_3$ and ε_1 parameters remained free during the whole procedure.

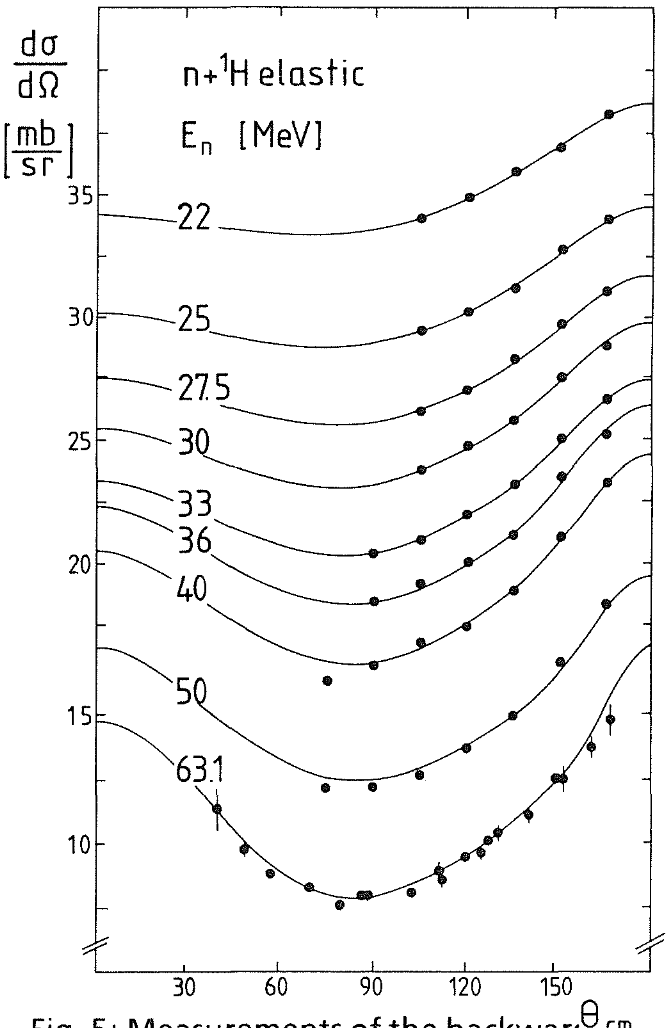

Fig. 5: Measurements of the backward angular shape of the differential cross section for neutron-proton scattering.

Correlations between the ^3P waves made it necessary to take the $^3P_1$ phase-shifts from the p-p (T = 1) system. Phase-shift analyses including all available n-p scattering data show reduced uncertainties, especially in the $^1P_1$ (T = 0) phase-shift parameter. The differential cross sections exhibit an increasing symmetry around 90° in the center-of-mass system with increasing energy, indicating the dominance of the $^1P_1$ interaction in the cross section observable. The energy dependence of the n-p scattering data in fig. 5 indicates that higher angular momenta are involved with increasing incident energy. The experiments employed a proton recoil detection technique as described e.g. in ref. 13.

In fig. 6 our data are compared with older measurements. Our results exhibit uncertainties which are a factor of 3 to 6 less than those of the previous data (open symbols) at slightly different incident energies. The very precise angular shape at backward angles seems to support the predictions from the Paris potential. The steeper shape of the data points than from the recent energy dependent (0 - 1.3 GeV) phase-shift analysis of Arndt[14] indicates to more negative $\delta(^1P_1)$ values than in the computer file of ref. 14.

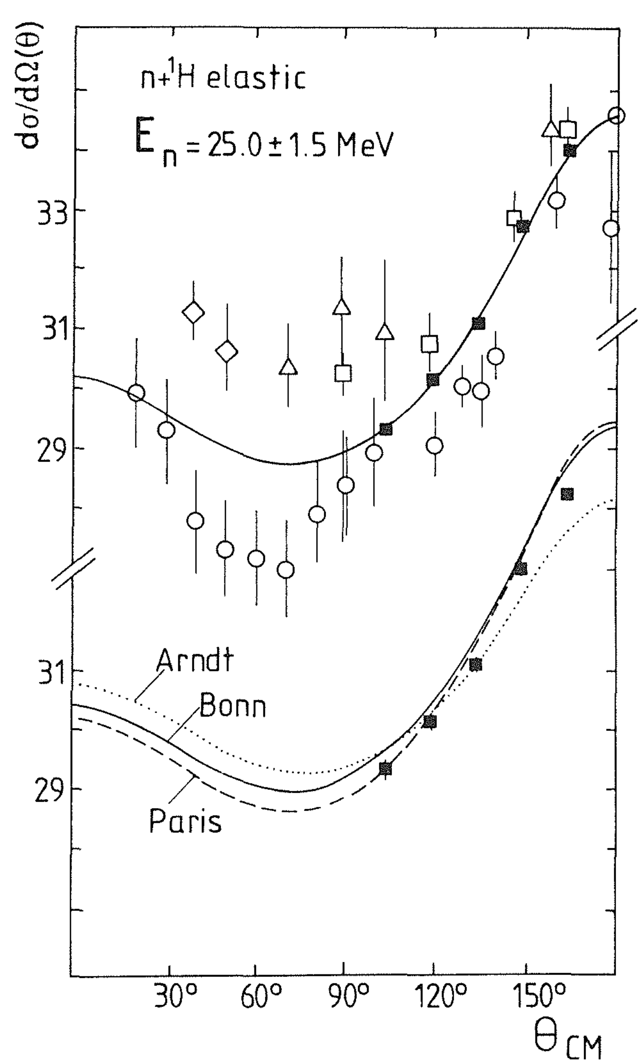

Fig. 6: Comparison of older and new precise differential cross section measurements dσ/dΩ [mb/sr] (upper part) and of three global predictions (lower part).

Polarization and analyzing power experiments in n-p scattering have been used in the past to investigate the validity of charge symmetry or time-reversal invariance in the strong NN interaction. On the assumption of conservation of parity and total angular momentum J, charge symmetry of the n-p interaction leads to the complete separation of the isoscalar (T = 0) and isovector (T = 1) parts of the NN scattering matrix. In the even (odd) partial waves, the isoscalar (T = 0) part contains spin triplet (singlet) and the isovector (T = 1) part spin singlet (triplet) terms only. Charge symmetry forbids transitions between the two parts of the scattering matrix and thus between the spin triplet (S = 1) and singlet (S = 0) states, e.g. $^3P_1 \leftrightarrow {}^1P_1$. The time-reversal invariance states that in elastic scattering the polarization of a spin-1/2 particle is equal to the analyzing power of the inverse scattering process, provided the target spin is non-zero. These symmetries were studied by means of polarization observables at low and high energies (see e.g. ref. 23). Charge independence breaking (CIB) is assumed to be observable in a detailed comparison of the n-p and p-p vector analyzing power.

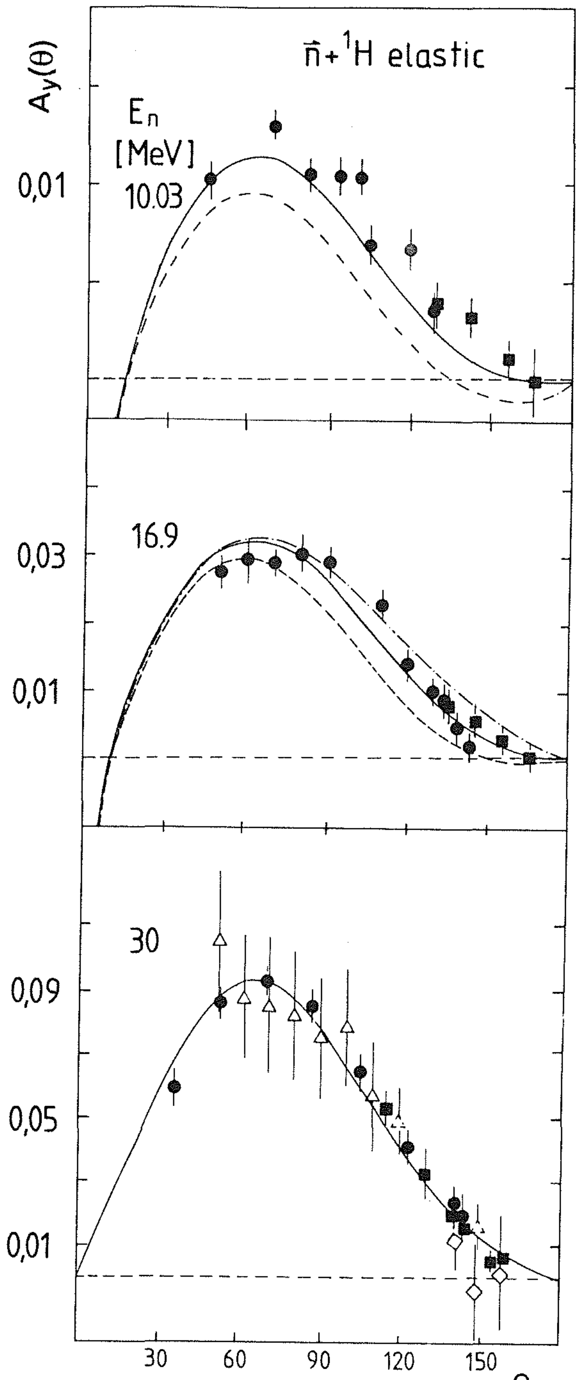

Fig. 7: Analyzing power in n-p scattering at three incident energies, and various model predictions (see text).

New precise measurements of the vector analyzing power for n-p scattering at low energies have been carried out recently. Fig.7 shows from the top to the bottom low energy data from the Wisconsin group[15], from the TUNL group[16] and from the Karlsruhe group. The precision measurements in this energy range were achieved by a series of technical improvements. At low energies the spin-orbit interaction is very small resulting in an analyzing power of about 1 %. With increasing neutron energy the analyzing power becomes about 9 % at 30 MeV. For the highest energy a comparison is done with older data around 30 MeV, demonstrating again the precision achieved especially at backward angles. At backward angles all groups detected recoil protons (indicated by squares). The solid curve is the prediction from the Paris potential for the 10.03 MeV and 16.9 MeV data and a fit for the 30 MeV data. The dashed curves are predictions from the Bonn potential. For the data at 16.9 MeV the authors show also Arndt's recent 0 - 1.3 GeV NN phase-shift analysis. The Wisconsin group states that the Bonn potential underestimates the P-wave spin-orbit splitting by 35 %. While the Bonn potential is also too low at 16.9 MeV, less difference between the Paris and Bonn potential is expected at higher energies, which is also demonstrated by the very similar $^3P_1$ phase parameters quoted in figure 12.

The n-p analyzing power measurement is also part of a program of the Basel group[21] which aims at an accurate determination of the NN tensor force. The tensor force, which is directly related to the $^3S_1$-$^3D_1$ mixing parameter ε_1, governs the binding energies and D-state probability of light nuclei and the binding of nuclear matter. The group reports[21] precise results of the analyzing power A_y at 68 MeV neutron energy in good agreement with the Paris potential.

For increasing energy the spin-spin part of the NN interaction should become increasingly important, mainly because of the vector identity $\vec{\sigma}_1 \cdot \vec{\sigma}_2 = 3 \cdot (\vec{\sigma}_1 \cdot \vec{q}) \cdot (\vec{\sigma}_2 \cdot \vec{q}) - S_{12}(\vec{q})$ where $S_{12}(\vec{q})$ is the tensor part of the NN interaction and $\vec{q}$ the momentum transfer during interaction. Since the tensor interaction mixes partial waves of the same parity, the $\vec{n}$-$\vec{p}$ spin-spin correlation observable A_{yy} (θ)should provide additional constraints on the $^3S_1$ - $^3D_1$ mixing parameter ε_1.

The Karlsruhe group measured by means of a polarized TiH_2 target[20] the spin-spin correlation A_{yy} (θ) between 19 and 50 MeV. Fig. 8 shows our experimental results for A_{yy} (θ) together with older data for a neutron energy around 25 MeV. The dashed curve represents our own phase-shift analysis, the solid curve the prediction from the Paris potential[8], the dotted curve the results from the new Bonn potential[7]. The measurement of the spin-spin correlation parameter as a function of scattering angle represents a difficult piece of work and the sensitivity on the mixing parameter ε_1 is such that the error bars of our 25 MeV data (solid points in fig. 8) correspond to $\varepsilon_1 \pm 0.5°$. An independent determination of the mixing parameter ε_1 is aimed through the measurement of the longitudinal spin-spin correlation $A_{zz}(\theta)$ investigated by the Basel group[21]. Based on a general argument for a com-

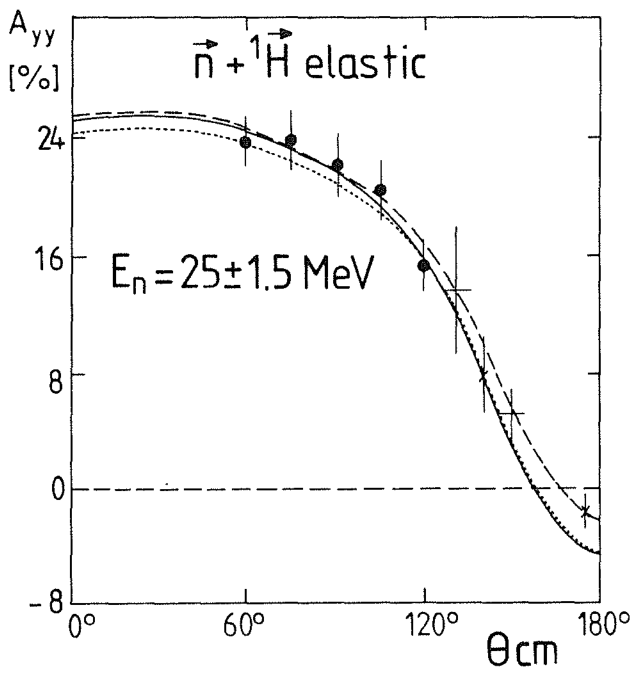

Fig. 8: Spin-spin correlation parameter A_{yy} as a function of scattering angle for elastic n-p scattering at 25 MeV.

plete description of the spin-spin dependence of the NN interaction it is necessary to study besides the longitudinal spin coupling (σ·q) also the transversal spin coupling (σ x q) to the momentum transfer. Both couplings are e.g. known to provide complementary information in electron scattering. A research group at PSI, Switzerland[22], continued recently to investigate the transversal and longitudinal spin dependence of the total cross section in n-p scattering. Figure 9 shows their preliminary result for $\Delta\sigma_L = \sigma(\leftrightarrows) - \sigma(\rightrightarrows)$, where the arrows indicate the spin orientation of the neutron and target proton, respectively. This observable is assumed to exhibit an even higher sensitivity to the tensor interaction strength ε_1. The negative cross section difference indicates that the spin triplet n-p (T = 0) scattering dominates at low energies. A comparison with the p-p (T = 1) scattering for the transversal and longitudinal total cross section indicates the spin singlet dominance there.

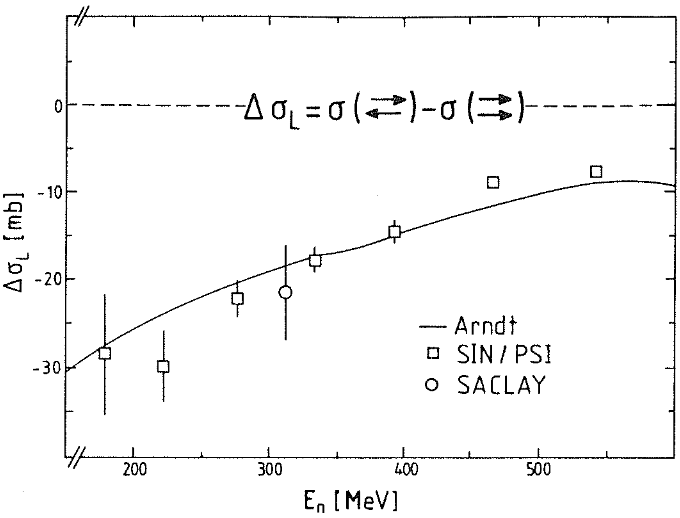

Fig. 9: Preliminary results on longitudinal cross section difference $\Delta\sigma_L$. The curve is a prediction from a global phase-shift analysis.

Having investigated the spin dependence of the strong NN interaction in elastic scattering one is inspired to ask the question to which extent spin forces are of strong nature or of electromagnetic origin. In electromagnetic field theory spin-spin interaction is ascribed to the interaction of two magnetic dipoles. Because of the meson exchange picture the charge distribution during n-p interaction represented by the nucleon currents is modified. Both aspects ask for the investigation of the electromagnetic radiation field associated with the n-p scattering process. For many years now, it has been clear that Partovi's impulse approximation calculation for radiative n-p capture[25] fails to reproduce the cross sections at extreme angles. The approximations which enter his non-relativistic treatment of deuteron photodisintegration and / or n-p capture below pion production threshold are the neglect of nucleon sub-structure, meson exchange currents (MEC), and multipoles higher than the octupole. Partovi used Hamada's potential for computation of the wave functions for the bound state of the deuteron and the n-p scattering states. The electromagnetic radiation stems from radial transitions $^3P_1$, $^3D_1 \rightarrow {}^3S_1$, (E1, E2) or from spin-flip transitions like $^1S_0 \rightarrow {}^3S_1$ (M1). The most dominant radiation between 10 and 70 MeV incident energy is of dipole character in accordance with the P-wave dominance in elastic scattering. With increasing energy the influence of the quadrupole radiation becomes larger.

Figure 10 shows experimental results for angular distributions of photons detected in n-p capture for neutron energies between 22 and 50 MeV from the Karlsruhe group and photodisintegration using 60 MeV gammas (see in ref. 26). The cross sections which are four orders of magnitude smaller than elastic scattering have been normalized to the total capture cross section. The angular shape of the data can be used to test the contributions of higher multipoles (E2, M2) (see fig. 4). These contributions shift the angular distribution towards larger angles away from symmetry around $\Theta_{cm} = 90°$. The forward-backward asymmetry which is defined in the center-of-mass system $[\sigma(55°) - \sigma(125°)] / [\sigma(55°) + \sigma(125°)]$ magnifies the contribution of higher partial waves. In fig. 10 the solid curves correspond to a Legendre fit, while the dashed curves are calculations[27] including meson exchange currents (MEC), relativistic corrections and Δ(1232) isobar contributions and the Paris potential for the n-p channel. For 115 MeV recent theoretical work[26] investigated especially the cross section in the forward direction, which is sensitive to the D-state probability of the deuteron, by using the one-boson exchange (coordinate-space) Bonn potential[7].

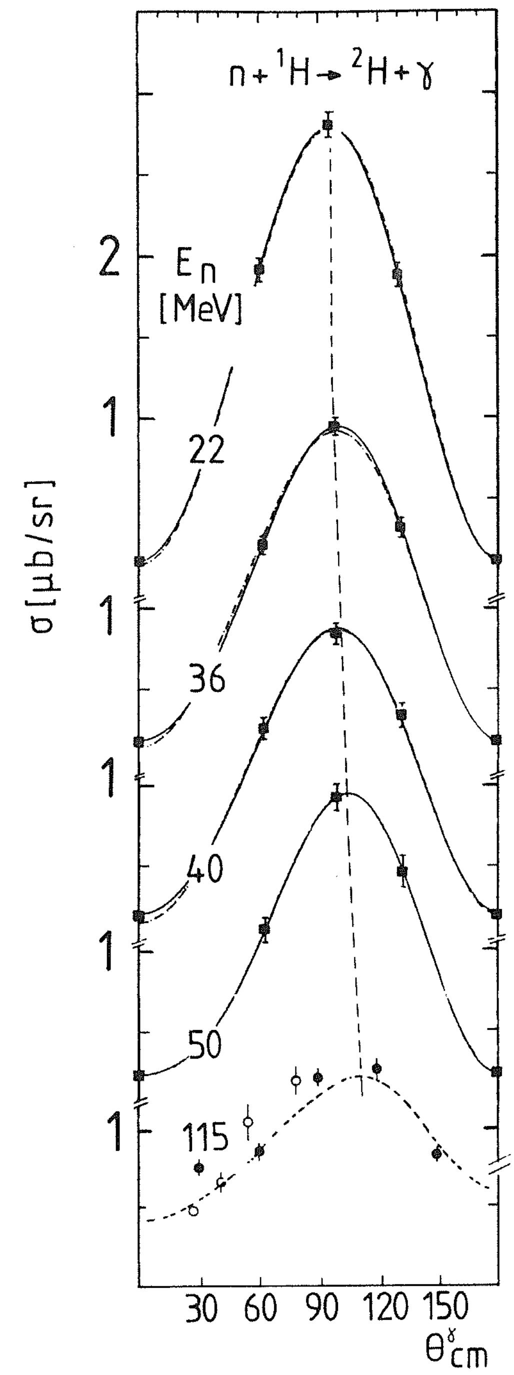

Fig. 10: Angular distribution of detected photons after n-p capture for various neutron energies. Solid curves are Legendre polynominal fits, dashed curves up to 40 MeV calculations from ref. 27 and for 115 MeV from ref. 26.

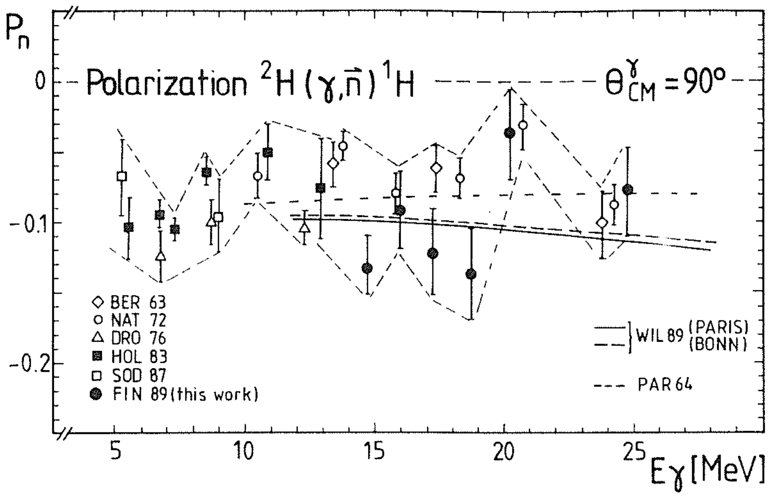

Fig. 11: Neutron polarization of the deuteron photodisintegration reaction as a function of the photon energy. A compilation of previous results is presented with new data (FIN89) and old (PAR64, ref.25) and recent (WIL89, ref.27) calculations

A number of groups have reported measurements[28)] of the neutron polarization after deuteron photodisintegration for photon energies between 6 and 14 MeV, and over this energy range the data tend to be somewhat less negative than classical impulse calculations[25)]. Since the neutron polarization at 90° arises mainly from E1-M1 interference terms involving M1 spin-flip transitions, the measurements will be sensitive to the presence of meson exchange currents. Calculations show that the inclusion of meson exchange currents (MEC) moves the theoretical curve to more negative values. Fig. 11 shows the result of our measurement (FIN89) detecting photons after capture of polarized neutrons by protons, along with previous measurements mostly measuring the polarization of outgoing neutrons after photodisintegration. Our results are much more negative, indicating the necessity of taking into account MEC-effect in this energy range even more than considered so far in extensive calculations[27)]. The scattering of the various experimental results is fairly wide, demonstrating the experimental difficulties of such complicated investigations. Where smaller error bars are quoted in previous experiments, data may have been taken in a more inclusive way. However, the grouping of data exhibits an interesting structure of the excitation function for the 90° analyzing power in n-p capture, which is not indicated by the theoretical calculations[25, 28)]. One may argue that some important ingredient may be missing in the calculations. These questions bear on the fundamental understanding of the NN interaction, on the consistent treatment of the pion exchange for both the long distance NN interaction and the electromagnetic interaction. The pseudoscalar (PS) and pseudovector (PV) couplings of a pion with a nucleon are only differentiated in the presence of an electromagnetic interaction. Most of the phenomenological NN potentials do not distinguish between PS and PV coupling.

IV. Concluding remarks

The precision of the n-p scattering results presented in this work is in many respects comparable to that of p-p scattering data. Therefore, a phase-shift analysis of all reliable n-p scattering data in the energy range 16 - 50 MeV was performed. The phase parameters δ of the partial waves up to L ≦ 3 were allowed to vary. For higher partial wave the phase parameters were taken from the Paris potential. Phase parameters like $^1D_2$, $^3F_3$, $^3F_2$ and ε_2 which have been determined precisely in p-p scattering were given the values from Arndt's analysis[14)]. Recently the Nijmegen group[29)] did an independent phase-shift analysis of all n-p scattering data below 30 MeV. They find a large breaking of charge independence in the difference between the coupling constants $g^2{}_0$ and $g^2{}_c$ for neutral and charged pions, respectively. In a combined analysis, including also all p-p scattering data below 30 MeV, the effect of charge dependence is strikingly seen in the ^3P waves. Therefore, charge independence of the NN interaction is not only broken in the ^1S scattering but also in ^3P. E.g. the n-p $^3P_1$ phase-shifts are larger than the p-p $^3P_1$ parameters as demonstrated in the center part of fig. 12. The isospin violating potential in the $^3P_1$ - $^1P_1$ waves is assumed to be of the so-called class IV type (antisymmetric in isospin) while for the ^1S scattering to be of the class III (symmetric in isospin). Figure 12 shows for the $^1P_1$, $^3P_1$ and ε_1 phase parameters the predictions from the Paris potential[8)] and the Bonn potential[7)]. The solid curve in the ε_1 figure is the quark model prediction from fig. 2. Simple quark models

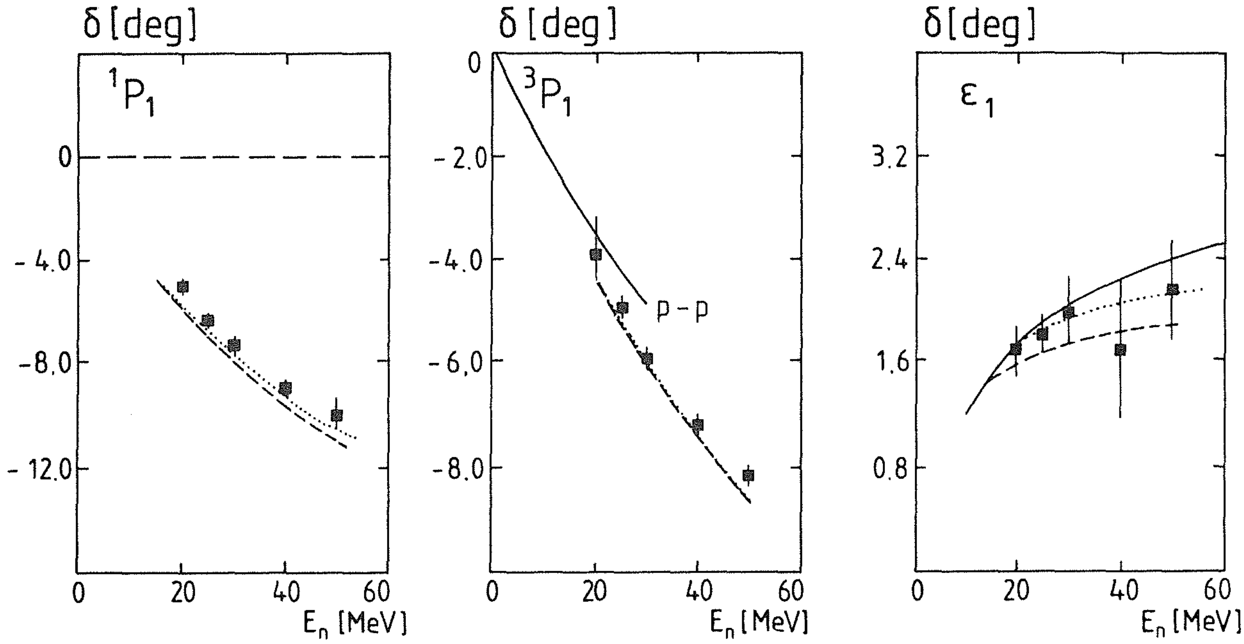

Fig. 12: Phase-shift parameters δ for elastic n-p scattering as function of the neutron energy, compared to the Paris (dashed) and the Bonn (dotted) potential.

have been used in the past[30] to estimate the effect of the up-and down-quark mass difference on an anomalous (i.e. only due to the strong interactions) isospin violating potential. Low energy p-p and n-p phase-shift differences are calculated and turn out to be of the order of a fraction of a degree as indicated in figure 12. Calculations have been extented to isospin violation in bound nuclei, like contributions to mirror nuclei binding energy differences. The Coloumb energy anomaly (Nolen-Schiffer effect) in heavier nuclei of about 80 keV indicates class III charge symmetry breaking of the NN interaction: The n-n interaction must be stronger than the p-p interaction.

With the knowledge about the two-nucleon system, especially the D-state probability strongly correlated with the mixing parameter ε_1, improved nuclear matter calculations can be performed. The discrepancies in the saturation densities for nuclei and nuclear matter can be almost completely traced back to differences in the amount of tensor force; namely the binding energy increases with decreasing tensor force. Therefore, the preference of the Bonn potential to be used for nuclear matter calculations is evident from the ε_1 part of figure 12 and also from findings at higher energies[24].

Finally the study of γ-ray emission in n-p scattering at energies typically involved in nuclear collision experiments using heavy ions, impinges on the question to which extent n-p bremsstrahlung can account for the high energy photon yields in a nuclear cascade model. Even if the pure bremsstrahlung model underpredicts the data by a large amount, the ignition process for the excitation of the giant dipole resonance may start from 'elementary' n-p capture.

The author would like to thank all colleagues mostly from the Karlsruhe group who contributed to this work.

F.P. Brady, V. Eberhard, G. Fink, T.D. Ford, L. Friedrich, J. Hansmeyer, W. Heeringa, E. Huttel, H.O. Klages, H. Krupp, H. Schieler, G. Schmalz, H. Skacel, F. Smend, G.D. Wicke, J. Wilczynski, Ch. Wölfl.

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