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NEW RESULTS IN NUCLEON-NUCLEON SCATTERING

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Recent results on proton-proton elastic scattering at energies between 200 and 3000 MeV measured at the Indiana Cooler Ring, Saturne II and COSY/Jülich will be reviewed. The impact of these data on NN potentials and nuclear phase shifts is discussed.

1 Introduction

Much of our knowledge of the Nucleon-Nucleon (NN) force and low energy strong interactions stems from NN scattering experiments. The experimental database accumulated since the beginning of nuclear physics has allowed for the development of NN potential models and the representation of these data in terms of phase shifts. Information on the NN interaction is widely used in nuclear physics as an input for calculations in few and many body nuclear systems.

In the following I will restrict the scope of this report to proton proton elastic scattering, i.e. the isovector part of the NN interaction, where most of the recent data has been produced. However, a large amount of new neutron-proton scattering data from PSI has also become available, but will be covered in another contribution [1].

Proton-proton elastic scattering can be described by 5 complex amplitudes (see e.g. Ref. 2) which – taking into account an overall arbitrary phase – leaves nine real functions of energy and angle to determine from experiments. Thus, in addition to the unpolarized cross section at least 8 polarization observables (due to ambiguities usually more) must be measured. Since such a complete set of observables will be rarely available, the direct reconstruction of the scattering matrix is of limited use. It is unable to predict observables at other energies or angles, but because of its inherent model independence it is, however, a useful tool to cross check results of other approaches.

The most successful technique to parameterize the wealth of NN elastic scattering data has been a partial-wave analysis. Here, the phase shifts of the lowest partial waves are adjusted to fit the data, whereas the higher angular momentum phase shifts are taken from a model of long range part of the interaction, e.g. one-pion exchange. Thus, data taken at different angles *and* energies can be combined by assuming some smooth energy dependence of the phase shifts. Available phase shifts [3,4,5,6] are widely used as a representation of the experimental data base in comparison to models of the NN interaction.

At energies below or slightly above the pion production threshold, i.e. below 350MeV, where inelastic channels are nonexistent or weak, recent NN potentials [6,7,8,9,10,11] give an almost perfect fit to the experimental data, and phase shift analysis performed by different groups [3,5] give consistent results. In this region, new experiments must challenge the available predictions by extremely accurate data, preferentially on observables where the data base is still sparse. Here, the PINTEX collaboration [12] at the Indiana Cooler Ring has contributed new precise data.

With increasing energy NN data is less abundant, especially at energies above 1 GeV and for polarization observables. Many of the experiments in the 1-3 GeV region were carried out in the 1960s and 1970s and are often inconsistent with each other with respect to absolute normalization. The onset of inelastic channels and higher partial waves, however, increases the number of phase shift parameters (e.g. 121 in Ref. 13) to be determined from the data. Until recently, this prohibited the extraction of energy dependent phase shifts above 1.6 GeV and motivated experiments providing new precise and consistent data on many observables.

Experiments have also looked into the question of the possible existence of dibaryonic states which have been predicted by model calculations (e.g. Refs. 14,15) in different mass regions. They would be exhibited through interference with the nonresonant amplitudes as energy dependent structures in elastic scattering observables. However, despite extensive searches no firm evidence has been reported as yet.

At these high energies, there the inelasticities rule out the use of potential models and require coupled channels calculations, meson theoretical models are still in an early stage [16] and describe the data only qualitatively.

In the following new pp elastic scattering data from IUCF, SATURNE II and COSY will be discussed. These facilities have provided the bulk of new data with reference to an earlier review by H. Spinka [17].

The three experiments discussed here can be subdivided into two groups with respect to energy and experimental technique: At IUCF precision data of polarization observables were measured between 200 and 450 MeV, a region where potential models as well as phase shifts are believed to be very well known and can be put to a stringent test. The PINTEX collaboration uses a pure polarized hydrogen target internal to the Cooler Ring, combining by this novel technique extremely clean experimental conditions [18] with sufficient luminosity.

The Saturne and COSY experiments focus on higher energies of 0.5 –

3 GeV. In this energy range a consistent and complete data base – especially regarding spin observables – is still needed. The experiments are complementary in their experimental approach and thus also in the observables measured.

The EDDA experiment is set up in the same spirit as the PINTEX experiment, using an internal polarized hydrogen target or an unpolarized CH_2 fiber target. It can access 5 observables: differential cross section, analyzing powers and spin correlation coefficients. It acquires excitation functions of these observables by taking data during synchrotron acceleration of the beam. This method facilitates a consistent normalization of the observables with respect to beam energy.

The NN program at Saturne has followed a different experimental approach. Installed at an external beamline the experiment uses a polarized solid state target or unpolarized CH_2 targets in conjunction with a two arm spectrometer arrangement. Since thick targets can be used, the luminosity of 10^{30}/s/cm^2 obtained is sufficient to do double scattering experiments, i.e. to analyze the polarization of one ejectile by a carbon analyzer. It can therefore access in addition observables like spin transfer coefficients, depolarization, and triple indexed observables.

To summarize, the two experiments covering the higher energy differ in their focus. The Saturne measurements excel in providing complete sets of observables at certain energies and angles, while the EDDA experiments stresses the consistent normalization of data taken at different energies.

2 The PINTEX Experiment at the Indiana Cooler Ring

At the IUCF Cooler Ring the PINTEX Collaboration [12] has pioneered experiments with polarized beams and internal polarized targets [19,20,21]. By injecting the polarized atomic hydrogen beam into a storage cell of 25 cm length and 10x10 mm^2 cross section a target thickness of $2{\cdot}10^{13}$ H/cm^2 is obtained. With beam currents of some 100 μA luminosity of typically $5{\cdot}10^{28}$/s/cm^2 were reached. The detector, shown in Fig. 1, detects both protons from elastic scattering in coincidence and covers c.m. scattering angles of $7° < \theta < 90°$.

Systematic errors were kept to a minimum by rapid reversal of the polarization direction. The polarized target could be oriented in any direction (±x,±y,±z in Fig. 1) by a weak guiding field and was changed every 2s. The orientation of the vertically polarized beam was reversed for every machine cycle of the Cooler Ring (6 minutes). This allows to determine four spin observables, the analyzing power and the spin correlation parameters A_y, A_{xx}, A_{yy}, and A_{xz}. Measurements were carried out at 8 proton beam energies between 200 and 450 MeV containing about 1400 new data points with typical

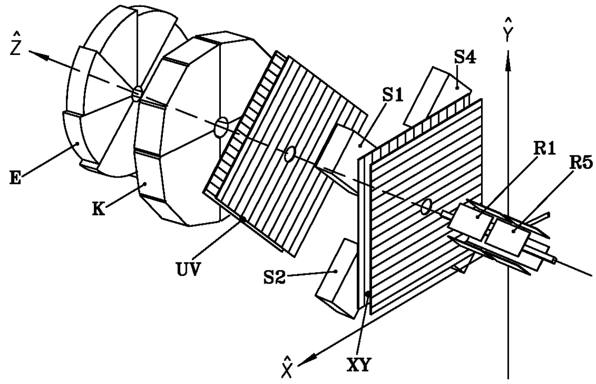

Figure 1: The PINTEX detector (not to scale): **S1-4, K, E**: plastic scintillation detectors, **XY, UV** wire chambers, **R1-8** silicon strip detector surrounding the storage cell centered at (x,y,z)=(0,0,0). Elastically scattered protons are detected either by a S-S or a R-(K or E) coincidence (adopted from [20]).

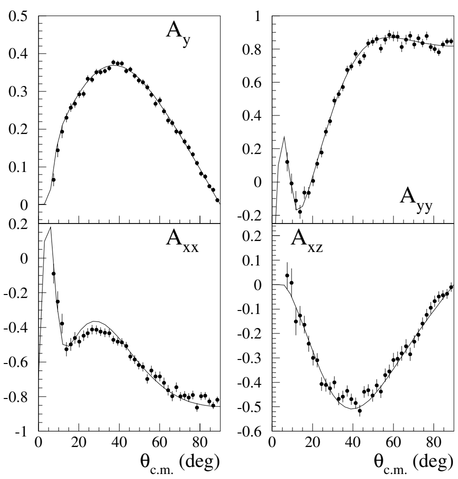

Figure 2: Results of the PINTEX experiment [20] for analyzing power A_y and spin correlation coefficients A_{xx}, A_{yy}, and A_{xz} at T_p=250 MeV. The solid line is the result of a recent phase shift analysis [3,4] (solution SM97) not including this data.

errors of 0.01. The data at 250 MeV is shown in Fig. 2 as an example. Calibration of the beam and target polarization were achieved with respect to Ref. 22 with an accuracy of 1% by applying a newly developed method [23] of transporting this polarization standard to higher energies.

In this energy range almost no data was available on the four observables measured by this experiment. Its precision therefore puts the predictions of potential models and available phase shift solutions to a test. In Refs. 20 and 21 the authors compare the new data to established NN potentials, like the Bonn, Paris and updated Argonne potential and find good agreement. The same holds for a comparison to phase shifts [3,5] published in the last years. The progress made in the past decade is highlighted by the observation that potentials or phase shifts agree best when their free parameters have been adjusted recently.

3 The Nucleon-Nucleon Program at Saturne II

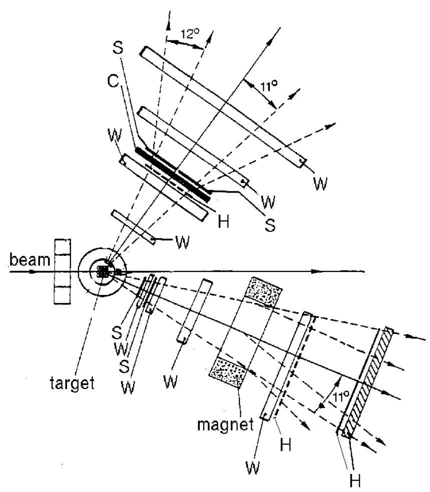

Figure 3: Sketch of the detector setup of the Saturne II NN program: both spectrometer arms are equipped with wire chambers (W), scintillator counters (S), and scintillator hodoscopes (H). One in addition with a carbon analyzer (C) and the other with a magnet for particle identification (adopted from [24]).

The NN-program [25] at Saturne II has been going on for two decades and was recently discontinued due to the shutdown of Saturne II. It has produced the majority of pp and np elastic scattering data at energies above 1 GeV. The experimental setup [26,27,28], sketched in Fig. 3, consists of a polarized solid state target of frozen spin type and a rotateable two arm spectrometer. The disadvantage of not using a pure hydrogen target and the impossibility of rapid reversal of the target spin is counterbalanced by the high luminosity of typically $5 \cdot 10^{30}/\mathrm{cm}^2/\mathrm{s}$ obtained with a thick target in combination with the Saturne II polarized beam of 10^8 protons/spill. This allows to access the polarization of one ejectile by scattering off a carbon analyzer (C in Fig. 3) and to measure as the only experiment discussed here, spin transfer, depolarization and triple indexed [2] spin observables.

The NN-program has produced about 5400 data points in pp elastic scattering on 20 different observables, about 1000 of those involve double scattering to detect the polarization of the recoil protons. For a compilation see Ref. 29 Some data are shown in a different contribution to these proceedings [30] where they are discussed with respect to an unexpected energy dependence in spin singlet amplitudes.

4 The EDDA Experiment at COSY

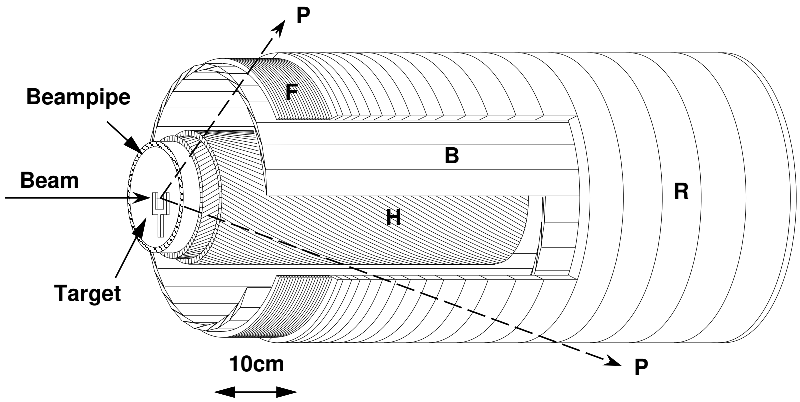

Figure 4: The EDDA detector (not to scale): **Target** fiber (CH_2), later a polarized atomic hydrogen beam; beampipe (2mm Al in the solid angle covered); **B** scintillator bars; **R** scintillator semi-rings; **F** semi-rings from scintillating fibers. **H** scintillating fiber helix detector.

The aim of the EDDA[31] experiment at the Cooler Synchrotron COSY at Jülich/Germany is to provide excitation functions of differential cross section, analyzing powers and spin correlation coefficients in the energy range 300-2500 MeV and a wide angular range. Here, scattering events off an internal target are detected *during the synchrotron acceleration* of the beam, such that a low-statistics excitation function is acquired within a machine cycle,

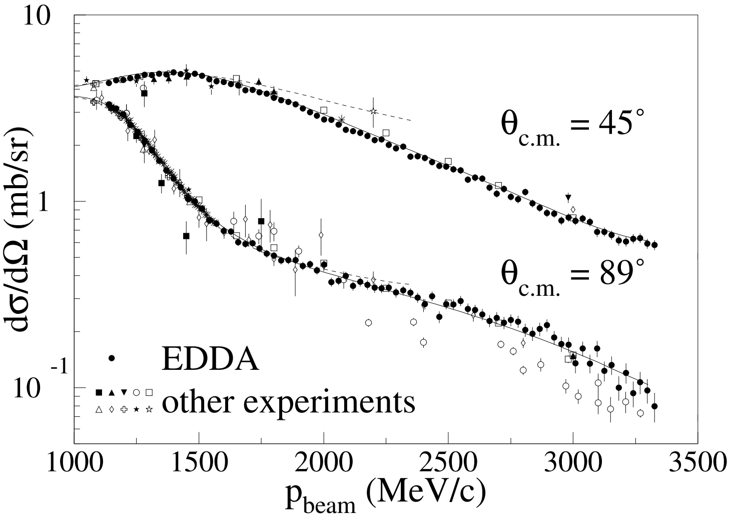

Figure 5: Excitation functions of the pp differential cross section [32] measured by the EDDA experiments at some selected angles. The lines are explained in the text.

i.e. within a few seconds. Statistical accuracy is achieved by accumulating over many such cycles. The advantage of this technique is that scattering at different energies are measured consistently, independent of long term drifts in luminosity or polarization monitors. This was first demonstrated at Saturne in a measurement of the differential cross section at 90° by Garcon et al. [33].

The EDDA detector (cf. Fig. 4) is a cylindrical scintillator hodoscope surrounding the beam pipe downstream of the target position. The two protons are detected in coincidence in two detector layers, where the point of incidence is measured. This allows for a reconstruction of the scattering vertex and an angular resolution of better than 1° in the center-of-mass. The angular range covered in the c.m. is 35° to 90°.

A measurement of the differential cross section was carried out by using thin 5x4μm^2 CH_2 fiber targets. The background due to scattering of carbon nuclei was measured with a pure carbon fiber target and subtracted statistically. The relative luminosity - i.e. the change of luminosity with beam energy - was monitored by two different methods: the current of the secondary electrons emitted of the fiber was measured by a sensitive amperemeter and the yield of δ-electrons detected at 40° by PIN-diodes. Both monitors gave consistent results within 2.5% error. Absolute normalization was achieved with reference to a precision measurement at LAMPF [34]. The results have been published [32] and excitation function at two angles, in comparison to previously available data, are shown in Fig. 5. The cross section manifest a smooth dependence on energy. Within the statistical accuracy of typically 5% no evidence of structures are seen, as they could arise from possibly existing dibaryonic resonances coupling to the elastic channel.

The EDDA data allowed the VPI group to extend their phase shift analysis to higher energies. The dashed(solid) lines in Fig. 5 show the VPI solutions SM94 [13] (SM97 [3]) prior to (after) inclusion of the EDDA data. The impact of the new data especially at forward angles and higher energies is evinced.

In 1997 a polarized atomic hydrogen beam target [35] was installed. With an unpolarized COSY beam with typically $3 \cdot 10^{10}$ protons stored in the beam, the luminosity of $\approx 10^{28}$ obtained in a crossing beam experiment, i.e. without a storage cell, is sufficient. The target polarization was oriented by a weak guiding field and was flipped after every machine cycle of about 15 s duration. In contrast to the differential cross section measurement the thin internal atomic beam allows for data acquisition both during beam acceleration and deceleration. The bulk of the data has been accumulated and is currently being analyzed. In conjunction with a polarized proton beam the experiment plans to measure the spin correlation parameters A_{xx}, A_{yy}, and A_{xz} in the near future.

5 Discussion

As shown in Section 2, the IUCF data have confirmed that both phase shifts as potential models are in perfect agreement with experiments at low energies. The situation is less clear for energies above 1 GeV and will be examined in the following.

5.1 Status of Phase Shift Analysis

Above the pion production threshold the phase shifts are complex to accommodate the arising inelasticities. This doubles the number of parameters to be fitted, and introduces some model dependence in the assumptions on the inelasticities of higher partial waves not adjusted in the fit.

There are two groups which have produced phase shifts for the energy region where recent published data from Saclay and COSY have increased the data base considerably. The VPI group around D. Arndt [3,4] has extracted energy dependent phase shifts up to 2.5 GeV beam energy, and the Saclay-Geneva Group [36] at several fixed energies between 1.8 and 2.7 GeV. The treatment of inelasiticies and higher partial waves in these two analyses is a little different, and the PSA results are therefore somewhat model dependent. Bystricky, Lechanoine-LeLuc and Lehar [36] have compared the PSA solutions and find large differences in the phase shifts for some partial waves.

5.2 Direct Reconstruction of Amplitudes

The direct reconstruction of the scattering matrix bears no model dependance and should be able to confirm one or the other phase shift solution. This has been done successfully at lower energies (for a review see Ref. 37).

The Saclay-Geneva Group [36] has also attempted a direct reconstruction of the scattering matrix at 4 energies between 1.8 and 2.7 GeV based mainly on recent polarization data from Saturne and the differential cross section data from COSY. Unfortunately, in most cases they find two solutions which fit the data equally well. A comparison to the amplitudes calculated from the VPI and Saclay-Geneva phase shifts shows that each is favored by one of the two competing solutions for the amplitudes. Thus, the direct reconstruction of the scattering matrix does not confirm any of the available phase shifts, so that both should be taken as approximations yet to be improved.

6 Conclusion

The new data on analyzing powers and spin correlation coefficients from the PINTEX collaboration at IUCF have confirmed that modern NN potentials as well as recent phase shift solutions give a very good description of the experimental data below 450 MeV, provided their free parameters have recently been adjusted to the experimental data base.

At higher energies - say above 1.2 GeV - the inclusion of the new data from Saclay and COSY, has led to phase shift solutions extending up to the 2.5 GeV region. It was shown, however, that - although providing a decent description of the available data base - the phase shifts cannot be considered as very precise. Since the NN-program at Saturne has been discontinued, the EDDA experiment will be the primary source of new experimental data in the near future. This data will be needed to remedy the ambiguities apparent both in the direct reconstruction of the amplitudes and the extraction of reliable phase shifts. Here, analyzing power data are currently being analyzed and spin correlation parameters are planned to be measured starting 1999.

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