

Few-nucleon scattering experiments at intermediate energies

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Observables in few-nucleon scattering processes are sensitive probes to study the two and many-body interactions between nucleons in nuclei. In the past decades, several facilities provided a large data base to study in detail the few-nucleon interactions below the pion-production threshold by exploiting polarized proton and deuteron beams and large-acceptance detectors. In this contribution, some recent results are discussed and interpreted by rigorous Faddeev calculations which are based upon modern potentials. Furthermore, the paper presents preliminary results from a pioneering and exclusive study of the four-nucleon scattering process at intermediate energies which was recently conducted at the KVI.

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1. Introduction

Understanding the exact nature of the nuclear force is one of the long-standing questions in nuclear physics. In 1935, Yukawa successfully described the pair-wise nucleon-nucleon (NN) interaction as an exchange of a boson [1]. Current NN models are mainly based on Yukawa's idea and provide an excellent description of the high-quality data base of proton-proton and neutron-proton scattering [2] and of the properties of the deuteron. However, for the simplest three-nucleon system, triton, three-body calculations employing NN forces clearly underestimate the experimental binding energies [3], demonstrating that NN forces are not sufficient to describe the three-nucleon system accurately. Some of the discrepancies between experimental data and calculations solely based on the NN interaction can be resolved by introducing an additional three-nucleon force (3NF). Most of the current models for the 3NF are based on a refined version of Fujita-Miyazawa's 3NF model [4], in which a 2π -exchange mechanism is incorporated by an intermediate Δ excitation of one of the nucleons [5, 6]. More recently, NN and three-nucleon potentials have become available which are derived from the basic symmetry properties of the fundamental theory of Quantum Chromodynamics (QCD) [7, 8]. These so-called chiral-perturbation (χ PT) driven models construct systematically a potential from a low-energy expansion of the most general Lagrangian with only the Goldstone bosons, e.g. pions, as exchange particles. The validity of the χ PT-driven models for the intermediate energies discussed in this paper remains, however, questionable and depends strongly on the convergence of results at higher terms in the momentum expansion.

2. Nucleon-deuteron elastic scattering

In the last decade, high-precision data at intermediate energies in elastic Nd and dN scattering [10, 11, 12, 9, 13, 15, 14, 16, 17, 18, 19, 20, 21, 23, 24, 26, 27, 28] for a large energy range together with rigorous Faddeev calculations [29] for the three-nucleon system have proven to be a sensitive tool to study the 3NP. In particular, a large sensitivity to 3NF effects exists in the minimum of the differential cross section [30, 31]. The results of a systematic study of the energy dependence of all available cross sections in elastic proton-deuteron scattering with respect to state-of-the-art calculations by the Hannover-Lisbon theory group are depicted in Fig. 1. The top panel shows the relative difference between the model predictions excluding the Δ -isobar contribution and data taken at a fixed center-of-mass angle of $\theta_{c.m.}=140^\circ$. The data points were extracted from a polynomial fit through each angular distribution. The error bars correspond to a quadratic sum of the statistical and systematic uncertainties of each measurement. Note that the discrepancies, reflecting the 3NF effects, increase drastically with incident energy and reach values of more than 100% at energies equal or larger than 200 MeV. The bottom panel in Fig. 1 shows a similar comparison between data and model predictions including the Δ -isobar as mediator of the 3NF effects. Clearly, a large part of the discrepancies is resolved. However, a smaller but significant deficiency remains which increases with energy to values of about 30% at an energy of 200 MeV.

3. Nucleon-deuteron break-up

Complementary to the elastic scattering experiments, three-nucleon studies have been performed exploiting the nucleon-deuteron break-up reaction. The phase space of the break-up chan-

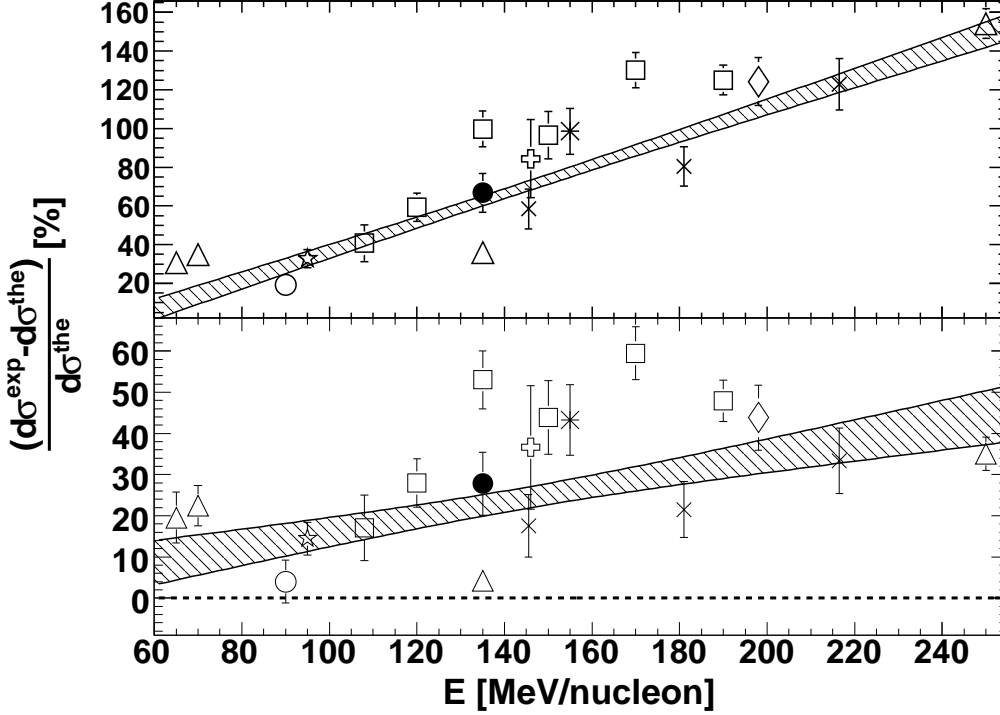


Figure 1: The relative difference between the calculations by the Hannover-Lisbon theory group and the measured cross sections for the elastic $p+d$ reaction as a function of beam energy for $\theta_{c.m.} = 140^\circ$. The top panel shows the differences with a calculation based on the CD-Bonn potential and the Coulomb interaction, whereas for the bottom panel an additional Δ isobar has been taken into account. Open squares are data from Ref. [11], open triangles are data from Refs. [13, 14, 26, 27], open circle is from [17], open star is from [19], crosses are from [20], star is from [18], open cross is from [16], diamond is from [21] and the filled circle is from [22]. The shaded band represents the result of a line fit through the data excluding the results obtained at KVI, RIKEN and RCNP. The width of the band corresponds to a 2σ error of the fit.

nel is much richer than that of the elastic scattering. The final state of the break-up reaction is described by five kinematical variables, as compared to just one for the elastic scattering case. Therefore, studies of the break-up reaction offer a way of much more detailed investigations of the nuclear forces, in particular of the role of 3NF effects. Predictions show that large 3NF effects can be expected at specific kinematical regions in the break-up reaction. Results of the cross sections and tensor analyzing powers have already been published for a deuteron-beam energy of 130 MeV on a liquid-hydrogen target [32, 33, 34]. These experiments were the first ones of its type which demonstrated the feasibility of a high-precision measurement of the break-up observables and they confirmed that sizable influences of 3NF and Coulomb effects are visible in the break-up cross sections at this energy. In the last years, more data at several beam energies and other observables have been collected to provide an extensive data base at intermediate energies.

Recent and interesting results have been obtained at KVI using a 4π detection system BINA, which provides a unique tool to study a large part of the phase space of the break-up reaction. Figure 2 presents some preliminary results of the vector analyzing powers in proton-deuteron break-

up for an incident proton beam of 190 MeV and for two symmetric kinematical configurations $(\theta_1, \theta_2) = (25^\circ, 25^\circ)$ and $(28^\circ, 28^\circ)$ for three different values of ϕ_{12} . Here, the angles θ_1 and θ_2 refer to the polar angles of the two final-state protons and ϕ_{12} to the relative azimuthal angle between these protons. The parameter S is directly related to the energies of the two final-state protons and is a measure of their energy correlation. The data are compared with calculations based on different models for the interaction dynamics as described in detail in the caption of the figure. For these configurations and observable, the effects of relativity and the Coulomb force are predicted to be small with respect to the effect of three-nucleon forces. At $\phi_{12} = 180^\circ$, the value of A_y is predicted to be completely determined by two-nucleon force effects with only a very small effect of 3NFs, which is supported by the experimental data. Note, however, that the effect of 3NFs increases with decreasing of the relative azimuthal angle ϕ_{12} , corresponding to a decrease in the relative energy between the two final-state protons. The observed discrepancies could point to a deficiency in the spin-isospin structure of the description of the many-nucleon forces in the present-day state-of-the-art calculations as discussed in Ref. [25].

4. Exclusive deuteron-deuteron break-up

The 3NF effects are in general small in the three-nucleon system. A complementary approach is to look into systems for which the 3NF effects are significantly enhanced in magnitude. For this, it was proposed to study the four-nucleon system. The experimental data base in the four-nucleon system is presently poor in comparison with the three-nucleon system. Most of the available data were taken at very low energies, in particular below the three-body break-up threshold of 2.2 MeV. Also, theoretical developments are evolving rapidly at low energies [36, 37, 38, 39], but lag behind at higher energies. The experimental data base at intermediate energies is very limited [40, 41, 42]. This situation calls for extensive four-nucleon studies at intermediate energies.

Recently, comprehensive measurements of cross sections and spin observables in various $d+d$ scattering processes at 65 MeV/nucleon, namely the elastic and three-body break-up channels, were performed at KVI using the BINA detector. With the corresponding results, the four-nucleon scattering data base at intermediate energies is significantly enriched. Figure 3 depicts some of the preliminary results of the deuteron-deuteron three-body break-up reaction, $d+d \rightarrow d+p+n$, which were obtained via the unambiguous detection of a proton in coincident with a deuteron in the final state. For the first time, a systematic and exclusive study of the three-body break-up reaction in deuteron-deuteron scattering at intermediate energies was shown to be feasible and provided precision results in the four-nucleon sector as well.

5. Conclusions

In the past decades, our understanding of the nuclear forces has drastically improved. These developments can be attributed to the enormous progress made in theory and in experiment. In particular, in the three-nucleon sector, the theoretical descriptions are ab-initio, based on high quality potentials, and (partly) able to include effects like Coulomb and relativity. Also, the experimental techniques have significantly improved in the course of time and have provided a huge data base with high-precision data and covering a huge part of the phase space. The four-nucleon data base

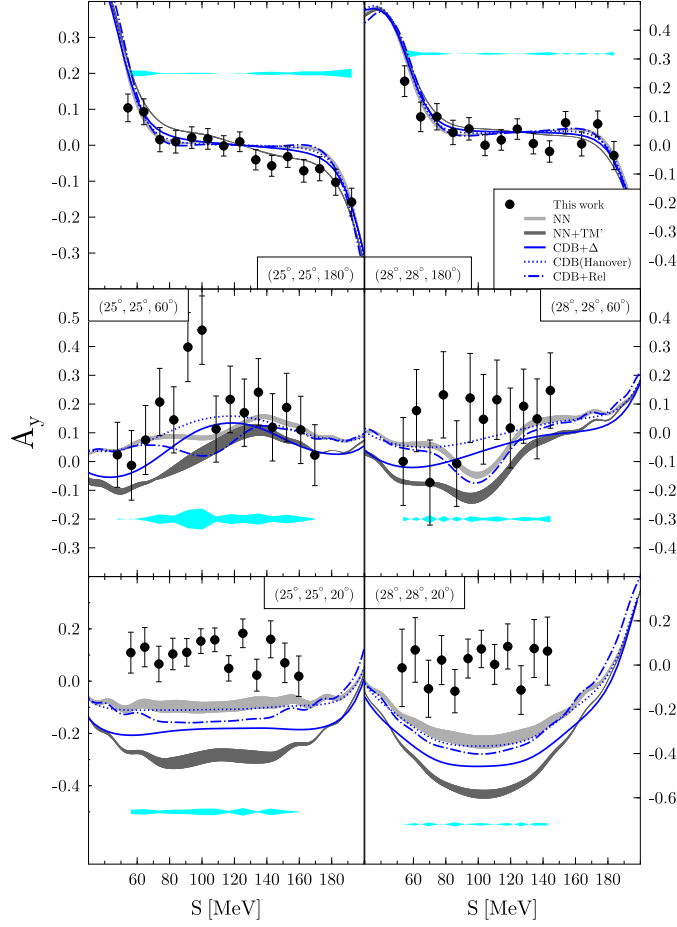


Figure 2: A comparison between the results of the analyzing power measurements for a few selected break-up configurations with various theoretical predictions. The light gray bands are composed of various modern two-nucleon (NN) force calculations, namely CD-Bonn, NijmI, NijmII, and AV18. The dark gray bands correspond to results of the calculations with the same NN forces including the TM' (3N) potential. The lines represent the predictions of calculations by the Hannover-Lisbon group based on the CD-Bonn potential (dotted) and CD-Bonn potential extended with a virtual Δ excitation (solid blue). The blue dash-dotted lines are derived from calculations by the Bochum-Cracow collaboration based on the CD-Bonn potential including relativistic effects [35]. The errors are statistical and the cyan band in each panel represents the systematic uncertainties (2σ).

at intermediate energies is growing significantly, thereby providing potentially new insights and a testing ground for our present understanding of the many-body force effects.

In spite of the progress made in experimental and theoretical techniques to study the many-nucleon system, there are still various open questions which urgently need to be addressed. A large part of these questions point to our present understanding of 3NF effects. This paper discusses some results of few-nucleon scattering experiments taken at intermediate energies. Although, the overall comparison between data and theory improve significantly by taking into account 3NF effects, there are still various channels, phase spaces, and observables which show huge discrepancies.

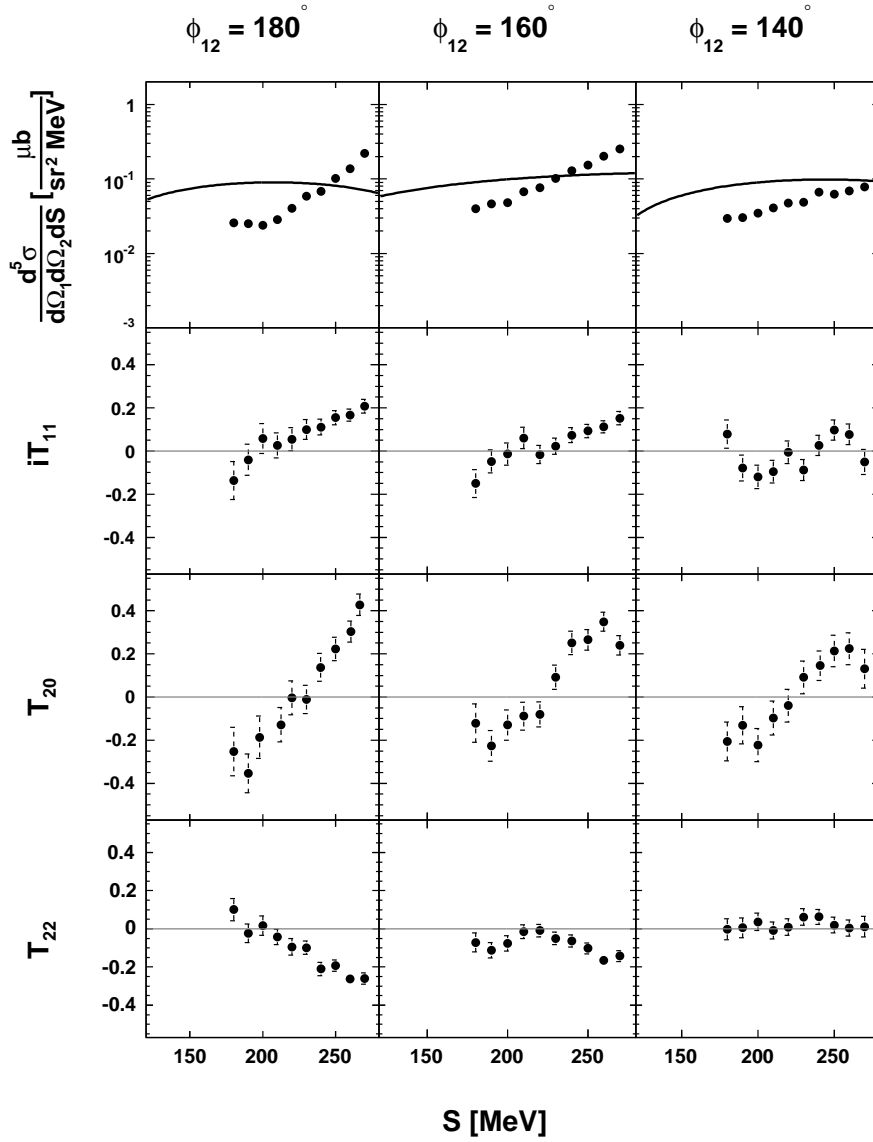


Figure 3: The cross sections, vector-, and tensor-analyzing powers at $(\theta_d, \theta_p) = (15^\circ, 15^\circ)$ as a function of S for different azimuthal opening angles. The solid curves in the top panels correspond to phase-space distributions. They have arbitrary normalization with respect to the data. The gray lines in other panels show the zero level of the analyzing powers. Only statistical uncertainties are indicated.

Therefore, the existing data base for few-nucleon scattering observables provide an ideal basis to develop a better understanding of three-nucleon force effects in few-nucleon interactions.

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