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## Experimental Activities in Few-Body Physics

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**Abstract** Understanding the few-nucleon system remains one of the challenges in modern nuclear and hadron physics. 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 three-nucleon interactions below the pion-production threshold by exploiting polarized proton and deuteron beams and large-acceptance detectors. Only since recently, the four-nucleon scattering process at intermediate energies has been explored. In addition, there is a focus to collect data in the hyperon-nucleon sector, thereby providing access to understand the more general baryon-baryon interaction. In this contribution, some recent results in the few-nucleon sector are discussed together with some of the preliminary results from a pioneering and exclusive study of the four-nucleon scattering process. Furthermore, this paper discusses the experimental activities in the hyperon sector, in particular, the perspectives of the hyperon program of PANDA.

### 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  $2\pi$ -exchange mechanism is incorporated by an intermediate  $\Delta$  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 ( $\chi$ 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  $\chi$ PT-driven models for the intermediate energies remains, however, questionable and depends strongly on the convergence of results at higher terms in the momentum expansion.

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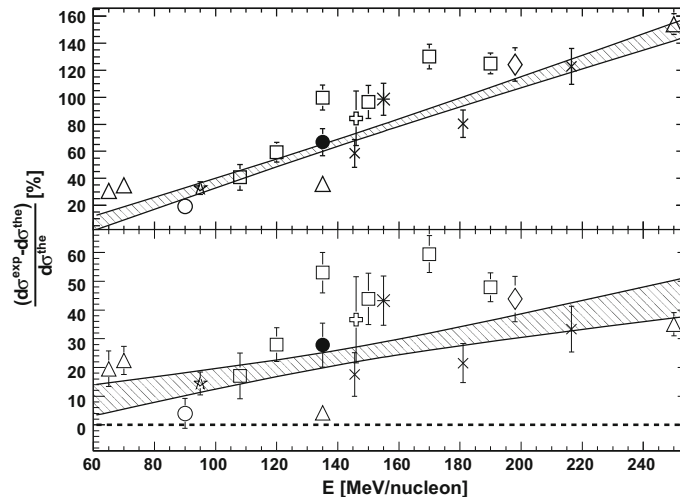
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## 2 Nucleon–Deuteron Scattering

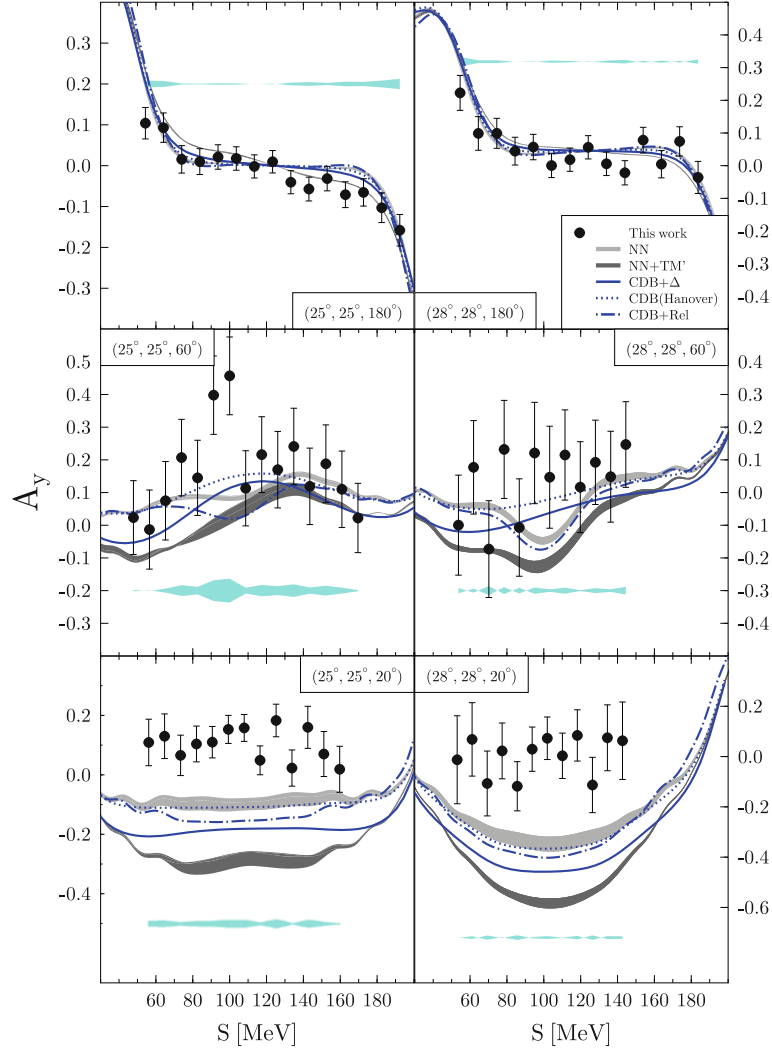
In the last decade, high-precision data at intermediate energies in elastic  $Nd$  and  $dN$  scattering [9–21, 23, 24, 26–28] for a large energy range together with rigorous Faddeev calculations [29] for the three-nucleon system have proven to be a sensitive tool to study the 3NF. In particular, a large 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  $\Delta$ -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  $\Delta$ -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.

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 channel 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 [32–34]. 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  $4\pi$  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 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



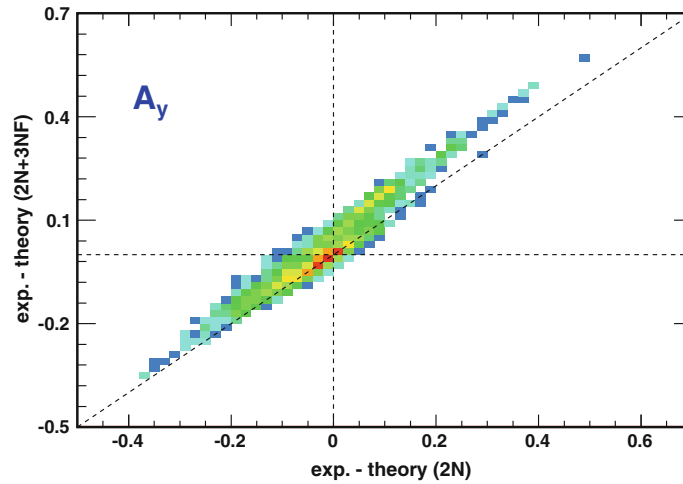
**Fig. 1** The relative difference between the calculations by the Hannover–Lisbon theory group and the measured cross sections for the elastic  $p + d$  reaction as a function of beam energy for  $\theta_{c.m.} = 140^\circ$ . The *top panel* shows the differences with a calculation based on the CD-Bonn potential and the Coulomb interaction, whereas for the *bottom panel* an additional  $\Delta$  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], *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  $2\sigma$  error of the fit



**Fig. 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  $\Delta$  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 ( $2\sigma$ )

values of  $\phi_{12}$ . Here, the angles  $\theta_1$  and  $\theta_2$  refer to the polar angles of the two final-state protons and  $\phi_{12}$  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  $\phi_{12}$ , 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].

A more global analysis is presently conducted in which the deficiencies with the state-of-the-art calculations are being systematically studied for all the available break-up data. These results will soon become available within a review article. For this paper, I present one of the preliminary outcomes of this analysis. In Fig. 3



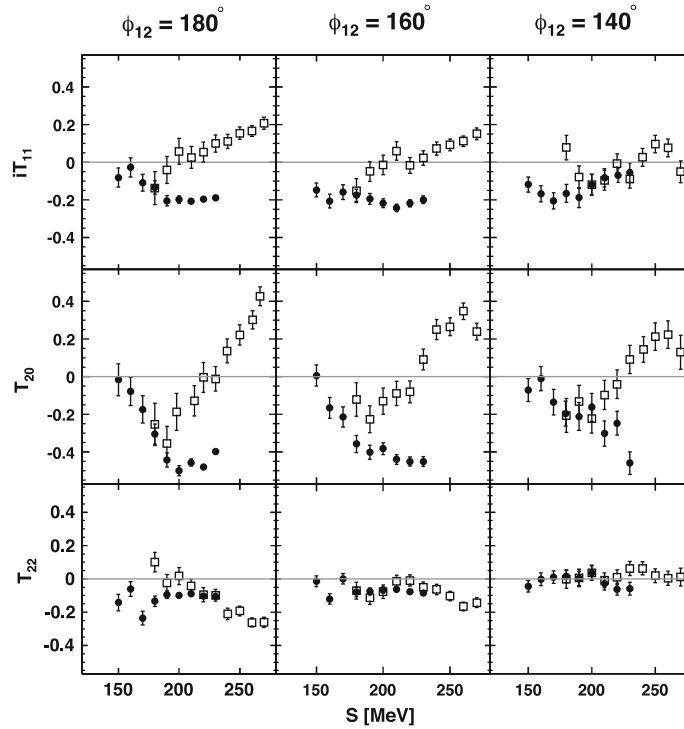
**Fig. 3** A global analysis of the proton–deuteron break-up data on the vector analyzing power,  $A_y$ , for two incident proton-beam energies of 135 and 190 MeV. The figure includes about 2500 data points for a large range in kinematics. The data are compared with predictions by the Hannover–Lisbon theory group. For a more detailed description, see text

a summary plot is depicted for all the available vector-analyzing data points in proton-deuteron break-up for two incident proton energies, namely 135 and 190 MeV. The figure depicts the deviations with respect to calculations from the Hannover–Lisbon theory group. The y-axis represents the deviation with a calculation based upon the CD-Bonn potential and excluding the effect of the 3NF, whereas the x-axis represents the deviation with the same calculation including 3NF effects. Here, the  $\Delta$  resonance within a coupled-channel framework mimics the 3NF effects. The calculation takes into account the effect of the Coulomb force. The color intensity on the z-axis represents the number of kinematical configurations, e.g. data points, that fall into the corresponding bin. Note that a large amount of data points are close to the origin. For those cases, the calculations predict a negligible 3NF effect and the data agrees well with the model predictions. In the ideal case, one hopes that all the data would lie on the horizontal line, implying that the 3NF effects are correctly incorporated in the model. Data that fall on the diagonal line away from the origin would imply that the calculations predict only a small 3NF effect, whereas the data are incompatible with this assumption. The horizontal line indicates the worse case scenario, e.g. the inclusion of a 3NF effect makes the discrepancy with the experimental data larger. Strikingly, a large fraction of the break-up data fall within the diagonal and vertical line, indicating that our present understanding of 3NF effects is not under control for this channel and observable.

### 3 The Next Generation Few-Body Experiments

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 [36–39], but lag behind at higher energies. The experimental data base at intermediate energies is very limited [40–42]. 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 4 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.



**Fig. 4** The vector- and tensor-analyzing powers at  $(\theta_d, \theta_p) = (15^\circ, 15^\circ)$  (*open squares*) and  $(\theta_d, \theta_p) = (25^\circ, 25^\circ)$  (*filled circles*) as a function of  $S$  for different azimuthal opening angles. Only statistical uncertainties are indicated. The total systematic uncertainty is estimated to be  $\sim 7.5\%$

Although the experimental database in the two- and three-nucleon system is very extensive, data on hyperon-nucleon and hyperon-hyperon interactions are very scarce. Fundamentally, however, an experimental (in combination with a theoretical) study of the interaction between strange-rich baryons is of highly interest for the few-body community, since it will allow to understand in more detail the general interactions between baryons. Most of the data on hyperon-nucleon scattering stems from bubble chamber studies from the 60s and 70s. Theoretically, major progress has been made for these systems. For example, effective field theoretical predictions are underway [43]. Clearly, the experimental progress is presently lacking behind.

The most promising experimental studies will come from various hypernuclear experiments conducted worldwide. Various single  $\Lambda$ -hypernuclei have been discovered already by using beams of kaons, pions, or virtual photons to convert a nucleon to a hyperon inside the nucleus and by exploiting the missing-mass technique. Combined with gamma detection, precision spectroscopy studies can be performed to reveal the details of the hyper-nucleon interaction.

A study of the hyperon-hyperon interaction becomes possible via spectroscopy studies of  $\Lambda\Lambda$  hypernuclei. The existence of these exotic hypernuclei has been established decades ago, already in 1966 [44]. So far, only a few  $\Lambda\Lambda$  hypernuclei has been discovered, which leads to an enormous discovery potential for future experiments. The PANDA (antiProton ANnihilations at DArmstadt) experiment at the future FAIR facility in Darmstadt, Germany, will provide an excellent tool to study  $\Lambda\Lambda$  hypernuclei with great precision. The key is to make use of a beam of antiprotons which allows to produce  $\Xi^-$  particles with a relatively large cross section. The  $\Xi^-$  particles are slowed down and captured in a second target nucleus where they can convert eventually into two  $\Lambda$  particles with the emission of a 28 MeV photon. The  $\Lambda\Lambda$  hypernuclei are sub-sequentially identified and studied via gamma spectroscopy (using a half sphere of Germanium detectors) and via the weak decay products of the hyperons. The feasibility of such experiment has been proven and reported in Ref. [45]. The hypernuclear study will be an integral part of a much broader physics program by the PANDA collaboration. A detailed description of the complete physics program of PANDA can be found in Ref. [45].

## 4 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 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. 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.

From an experimental point-of-view, the future “few-body” challenge would lie in providing accurate data in the hyperon-nucleon and hyperon–hyperon sector. With this, the hope is to enrich the study of the nucleon–nucleon force towards the more general baryon–baryon interaction. Future experiments, such as PANDA, show good perspectives in this direction.

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