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Precision studies of few-nucleon system dynamics

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Abstract

Modern nucleon-nucleon interaction models can be probed quantitatively in the three-nucleon (3*N*) environment by comparing predictions based on rigorous solutions of the Faddeev equations with the measured observables. Proper description of the experimental data can be achieved only if the models are supplemented with additional dynamical ingredients: subtle traces of suppressed degrees of freedom, effectively introduced by means of genuine three-nucleon forces and effects of the Coulomb force. As an example of precision studies of 3*N* system dynamics, new generation measurements of the $^{1}H(\vec{d},pp)n$ breakup reaction at 130 MeV are considered. Large sets of high accuracy, exclusive cross-section and analyzing power data acquired in these projects contribute significantly to constrain the physical assumptions underlying the theoretical interaction models. Comparisons of the cross-section data with the predictions using nuclear interactions generated in various ways, allowed to establish importance of including both, the 3*N* and the Coulomb forces to strongly improve description of the whole data set. Discrepancies observed in reproducing the analyzing power data hint at still persisting incompleteness of modeling the 3*N* system interaction dynamics.

Keywords: nuclear dynamics, breakup reaction, cross section, analyzing power, three-nucleon force
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1. Introduction

Precise knowledge of the nucleon-nucleon (*NN*) interaction is one of the most demanded pieces of information in the field of nuclear physics. Understanding the details of few-nucleon system dynamics is of crucial importance not only for the fundamental nuclear physics, but also for several fields of its application. They comprise, for instance, optimization of radiation shielding design for various installations, predicting performance of targets and guides of spallation neutron sources, evaluation of irradiation dose in nuclear medicine and biology, planning the future energy amplifiers and nuclear waste transmutation plants (accelerator-driven systems). The codes used in simulating the reactions rely on accurate modeling of two-nucleon (2*N*) and three-nucleon (3*N*) dynamics, and since this information enters at the very beginning of the calculations (fast, direct stage of the process in Intra-Nuclear Cascade or Quantum Molecular Dynamics), possible inaccuracies in the models can be easily a cause of severe flaws of the global predictions.

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In general, the desired exact understanding of all features of few-nucleon system dynamics would provide a natural basis for describing properties and interactions of nuclei. The $2N$ system has been intensively experimentally studied over last decades forming a solid data base, on which modern models of NN potentials have been founded. Thus, one tends to assume that the basic NN force is well under control. This optimistic presumption has to be verified by applying models of the NN interaction to reproduce properties of many-nucleon systems with increasing complexity. Obviously, the least complicated non-trivial environment is the one composed of three nucleons.

Dynamics of the three-nucleon system can be comprehensively studied by means of the nucleon-deuteron (Nd) breakup reaction. Its final state, constrained by only general conservation laws, provides a rich source of information to test the $3N$ Hamiltonian details. It is of particular importance when components of the models which account for subtle effects, like three-nucleon force (3NF) contributions to the potential energy of the $3N$ system, are under investigation. Nowadays precise predictions for observables in the $3N$ system can be obtained via exact solutions of the $3N$ Faddeev equations for any nucleon-nucleon interaction, even with the inclusion of a 3NF model [1, 2].

In few-nucleon studies the most widely used so called realistic NN potentials (RP) are Argonne v18 (AV18), charge dependent Bonn (CD Bonn) or Nijmegen I and II forces. Extension of that picture is provided by the baryon coupled-channel potential (CCP), in which one Δ-isobar degrees of freedom are allowed on top of purely nucleonic ones [3, 4, 5]. This framework is built around the modified CD Bonn potential, which in the following will be referred to as CDB+Δ. The most basic approach, however, stems from the effective field theory applied to the NN system. The resulting expansion scheme for nuclear systems is called chiral perturbation theory (ChPT). For the $3N$ system it is numerically developed in full at the next-to-next-to-leading (NNLO) order [6, 7, 8, 9]. All the above approaches can also be supplemented by model 3NF's. In the RP case semi-phenomenological 3NF's are used, most commonly the Tucson-Melbourne (TM99) or Urbana IX (UIX) models. In the CCP and ChPT frameworks this additional dynamics is generated naturally, together with the NN interactions. The predicted effects are, however, smaller than for the TM99 or UIX forces.

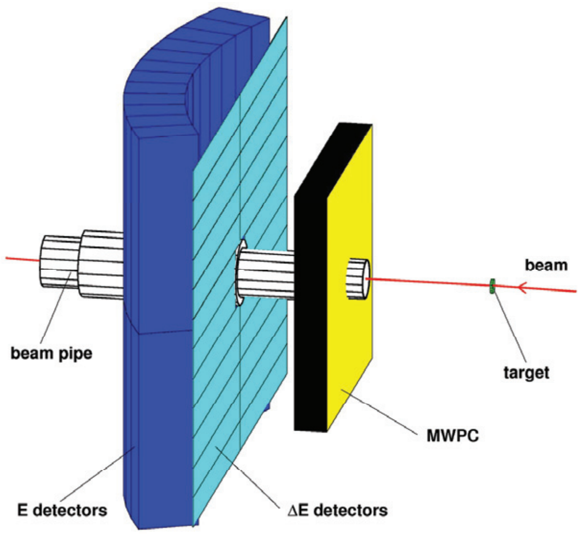
There are additional difficulties in interpretation of the experimental results by means of theoretical calculations. The most important feature, missed until recently, is the Coulomb interaction: The experiments are performed mainly for the deuteron-proton system while all calculations were strictly neglecting any long-range forces. Only in the last years a significant step forward has been made in including the Coulomb force effects for the breakup reaction. It was first attempted within the coupled-channels approach [10, 11] and recently applied also for the AV18+UIX potential [12]. Contrary to the former expectations, the influence of the Coulomb force on the breakup observables can be quite strong in certain kinematical regions.

2. New generation breakup experiments

To allow for conclusive comparisons between the experimental data and theoretical predictions large sets of data are required. Unfortunately, precise measurements of the breakup reaction are very demanding. The experimental coverage is concentrated at lower energies, below 30 MeV nucleon energy – see Refs. [2, 13] for references. In the recent years some revival of the activity can be noticed (see Ref. [14] for listing of papers), but again only few kinematical configurations are usually studied.

Our new approach to the breakup research in based on simultaneous measurements of large phase space regions by using high acceptance position-sensitive detection systems. Measurements of the ^{1}H($\vec{\mathrm{d}}$,pp)n reaction were carried out at KVI, Groningen, The Netherlands and FZ Jülich, Germany, at 130 MeV beam energy, providing worldwide first extensive sets of the breakup cross-section and analyzing power data, spanned on a systematic grid of kinematical variables.

Schematic views of the applied detection systems are shown in Fig. 1. The SALAD (Small Area, Large Acceptance Detector) system consists of three-plane multi-wire proportional chamber and a scintillation hodoscope. This last is build of two planes of segmented plastic scintillator detectors: 24 horizontal transmission detectors and 24 vertical stopping elements. The wire chamber is used to determine tracks of the charged reaction products, while the hodoscope provides energy information and is used for particle identification (proton vs. deuteron). The angular domain covered by the SALAD detector spans the polar angles θ between 13^o and 35^o and the whole range of the azimuthal angles φ. In the experiments polarized deuteron beams were used, in several polarization states (pure vector or tensor, mixed states, unpolarized). More detailed description of the experimental apparatus, procedures and of the



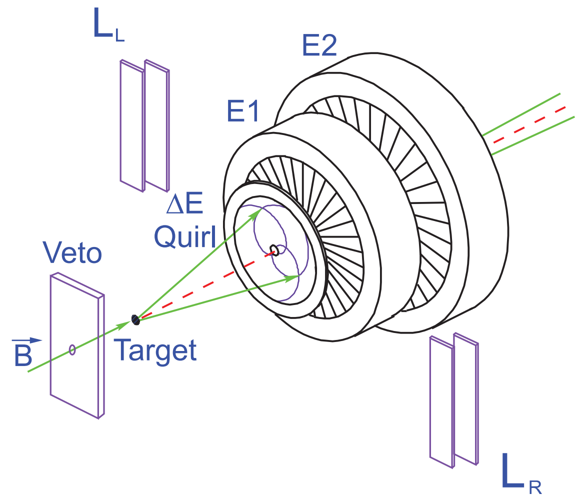


Figure 1: Schematic representation of the detection systems used in the first new-generation deuteron-proton breakup measurements at 130 MeV. *Left panel:* SALAD detector used at KVI Groningen. *Right panel:* GeWall detector used at FZ Jülich. The dimensions of both systems are very different and shown not to scale.

data analysis methods can be found in Refs. [14, 15, 16]. The GeWall (Germanium Wall) detector is dedicated for registering charged reaction products at very small polar angles, between 4^o and 13^o, again with a full coverage of the azimuthal angles. It consists of three high-purity germanium detectors, first of which (Quirl) serves as the position sensitive transmission element, being divided on both sides into 200 sectors with the shapes of Archimedes spirals, bent in opposite directions. Overlaps of the front and rear side active segments allow to reconstruct tracks of the emitted protons or deuterons. The stopping detectors (Pizza's) are only weakly segmented, into 32 wedges each, to resolve position ambiguities for two-particle detection. In the measurements COSY beam was extracted to the target station only in two states: unpolarized and vector polarized. Detailed description of the GeWall application for the breakup measurement is given in Ref. [17].

3. Selected cross section results

The measurement of the $d-p$ breakup at 130 MeV at KVI provided the worldwide first extensive set of breakup cross-section data, spanned on a systematic grid of kinematical variables. Cross section values were extracted for about 80 kinematical configurations [14, 15, 16], defined by the polar angles of the two outgoing protons, θ_1,θ_2, and their relative azimuthal angle φ_{12}, and presented as functions of the arc-length variable S (equivalent to the kinetic energy of any of the two protons). The data, in total nearly 1800 experimental points, cover a substantial fraction of the phase-space and prove the importance of the 3NF effects for the breakup cross sections.

The role of additional dynamics in the breakup cross section is recapitulated in a global approach in Fig. 2. The relative difference of the experimental and theoretical cross sections, $(\sigma_{exp} - \sigma_{th})/\sigma_{exp}$ was determined and plotted as a function of E_{rel}, the kinetic energy of the relative motion of the two breakup protons. Combining the AV18 potential with the UIX 3NF (left panel) significantly improves the data description in almost the whole range of E_{rel} but the smallest relative energies, where it drives the predictions away from the data. Our previous analysis [14, 16], performed for TM99 3NF and CD Bonn NN potential, showed that by including the genuine 3NF the global χ^2 is reduced by about 40%.

In comparisons of our results we were faced with quite substantial disagreements at low values of E_{rel}. Only with the inclusion of the Coulomb force into the calculations in the coupled-channels approach they were mostly explained and removed [18]. A consistent theoretical treatment of the phenomenological 3NF and the Coulomb force has been achieved only very recently [12] and allows to scrutinize both these effects at the same level of accuracy. Middle panel of Fig. 2 shows the impact of the Coulomb force effects on our KVI cross section data. While at larger values

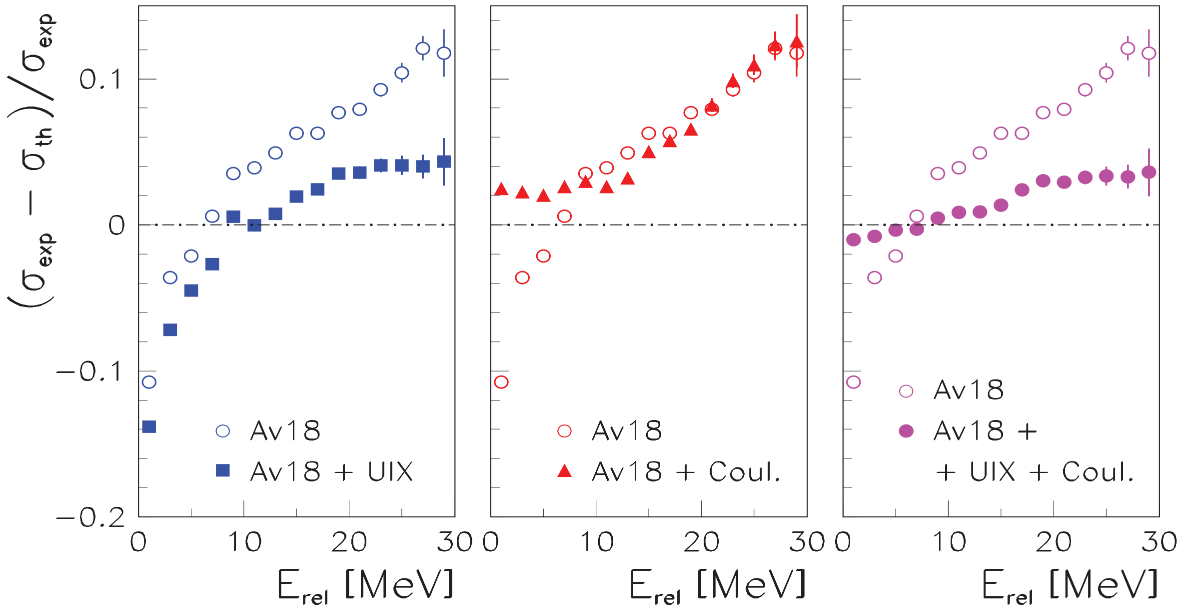


Figure 2: Relative discrepancies between the experimental KVI data and the theoretical predictions of the breakup cross sections as a function of the relative energy of the two breakup protons. *Left panel:* Action of UIX 3NF with respect to the pure *NN* AV18 potential. *Middle panel:* Action of the Coulomb force, when combined with the AV18 potential. *Right panel:* Combined action of the above two effects together.

of E_{rel} the influence of the long-range electromagnetic interaction is negligible, it strongly reduces the disagreements at small E_{rel}. The significance of the Coulomb effect could be established and its influence throughout the phase space could be traced only by using such a large set of the breakup data [18]. It has been also determined that even after including the Coulomb force there is still room for 3NF effects. The resulting total action of both dynamical ingredients supplementing the pure *NN* interaction can be seen in Fig. 2, right panel. One observes that at small E_{rel} values too strong action of the Coulomb force is compensated by 3NF effects, leading to a nearly perfect agreement between the data and the theoretical cross sections. The discrepancies remaining at large E_{rel} values hint at some still unresolved problems in our understanding of 3*N* system dynamics, e.g. non-complete model of 3NF.

The first calculations of the Coulomb force influences for the breakup reaction pointed to some quite spectacular effects for small emission angles of the two protons. Cross section is not only strongly suppressed but its distribution is distorted, with a local minimum enforced in the middle of the S-range. This behavior has been confirmed by a subset of KVI data, for configurations at the acceptance edge of the detection system [18]. These findings motivated the FZJ experiment in the forward-angle region, where the role of the Coulomb force was expected to be manifested even stronger. The cross section values have been analyzed at almost 2400 points (over 110 kinematical configurations), with the upper angular limit overlapping the acceptance of the KVI experiment (cf. Sect. 2). An excellent agreement between the two data sets is achieved [19, 20], although they stem from completely different measurements and normalization procedures. Examples of the breakup cross section distributions at six kinematical configurations, compared to various predictions, are shown in Fig. 3. Obviously, only the approaches which do include the Coulomb interaction are able to correctly reproduce the data. This statement is valid for the whole set of FZJ data, as demonstrated in Fig. 4. The square distance between the data and every of the 8 theoretical approaches is quantified in terms of χ^2 per data point, presented as a function of the relative energy of the two breakup protons (denoted in Fig. 4 as E_{12}). Clearly, for relative energies below about 5 MeV only the calculations including the Coulomb force lead to the smallest discrepancies with the data. This agreement can be considered as a proof of certain maturity of including the Coulomb force effects in the theoretical calculations. It is also worth noting that there are regions in the phase space where the net effect of the Coulomb force is very small ($E_{12} > 5$ MeV in Fig. 4, middle-bottom panel of Fig. 3). Those regions are best suited for searches of other, small dynamical effects.

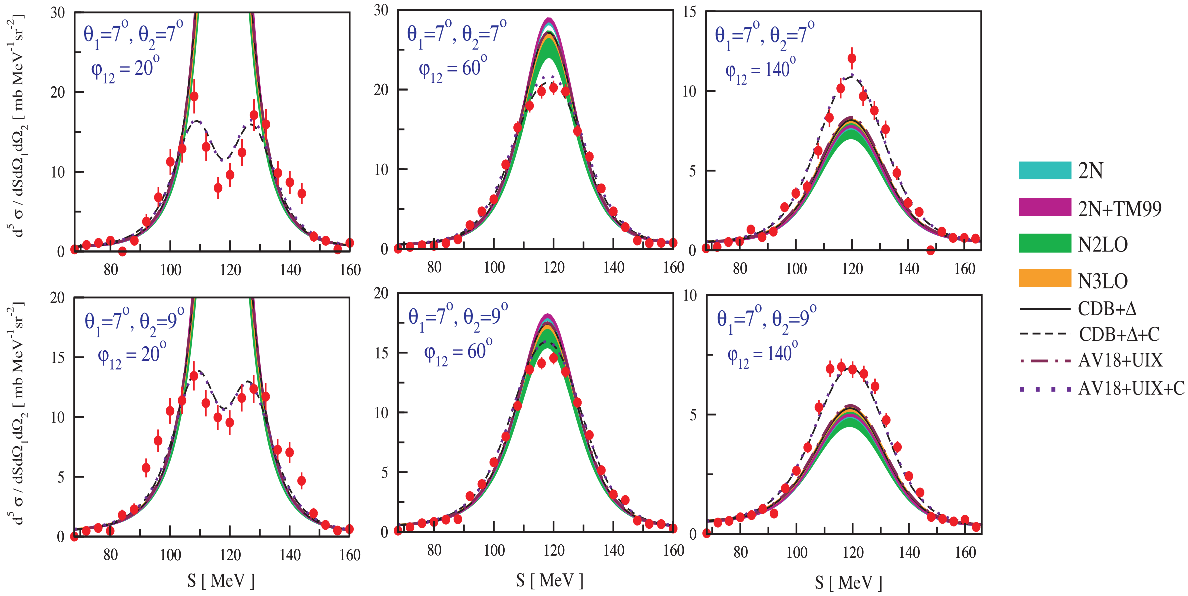


Figure 3: Examples of the breakup cross section distributions for six kinematical configurations (specified in the panels). Predictions obtained by various theoretical approaches are shown as bands and lines (see legend).

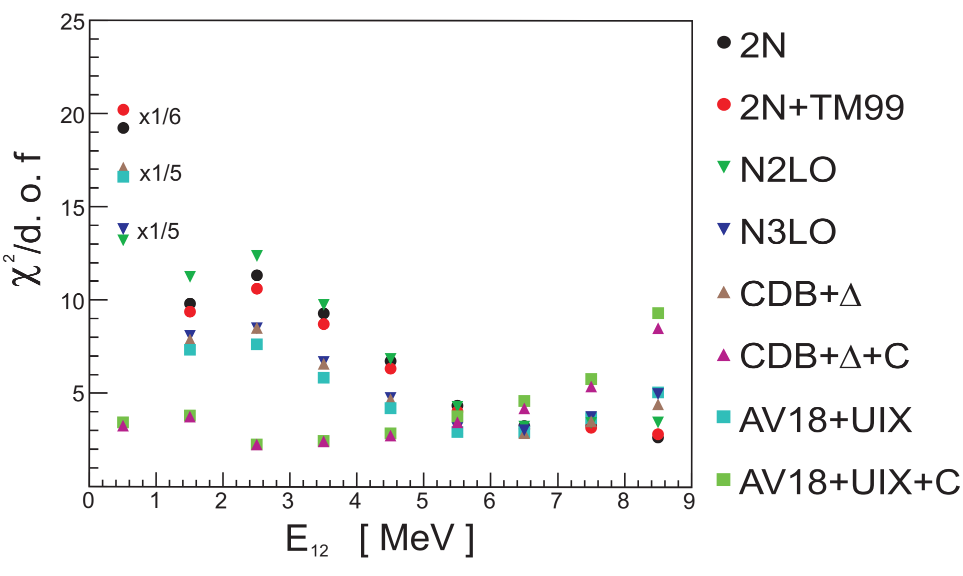


Figure 4: Quality of reproducing of the experimental FZJ breakup cross-section data by various theoretical predictions (see legend), as a function of the relative energy of the two breakup protons. Data description quality is quantified by chi-square per degree-of-freedom values, without a strict statistical meaning, rather as a relatively comparable parameter only.

4. Selected analyzing power results

Polarization observables provide still more insight into the details of few-nucleon system dynamics. Only with their use it is possible to probe quality of spin structure of the 3NF models. Therefore precise data in this sector are extremely valuable and longed-for, although their acquiring is still more demanding than for the cross section case.

In both experiments discussed here the elastic $d-p$ scattering has been measured simultaneously with the breakup reaction. In the case of polarization observables, the elastic scattering data were used to evaluate the beam polarization

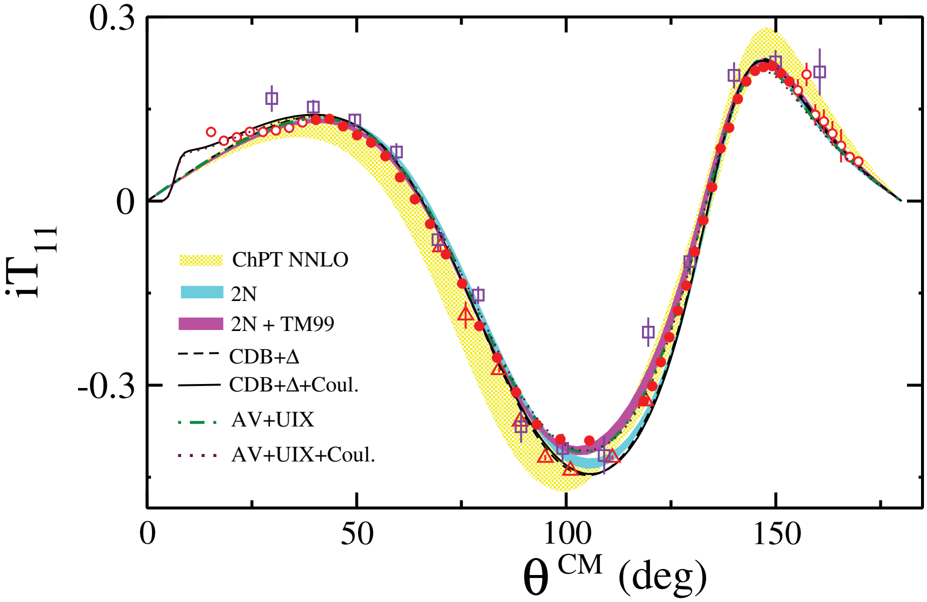


Figure 5: Angular distribution of vector analyzing power iT_{11} for the elastic $d-p$ scattering at 130 MeV. KVI data (dots) and FZJ data (circles) are compared to other available data sets and to various theoretical predictions (see legend).

at each used beam polarization state, but it occurred also possible to determine analyzing power values in a wide range of angles. Angular distributions of vector iT_{11} and tensor T_{20} and T_{22} analyzing powers have been obtained as valuable "by-products" [21]. The results for iT_{11} have been supplemented by the FZJ results in the regions of extreme (small and large) angles and are shown in Fig. 5. One can observe here a general success of predictions including 3NF, and (at very forward angles) the Coulomb force. High precision results of the tensor analyzing powers [21], however, lead to a conclusion (formulated also in earlier studies) that calculations provide quite a good description of the data, but none of them reproduces all the details of the experimental distributions. This strongly indicates that more refined models of 3NF are needed.

Polarization results for the $^1\mathrm{H}(\vec{\mathrm{d}},\mathrm{pp})\mathrm{n}$ breakup reaction encompass two vector, A_x, A_y, and three tensor, A_{xx}, A_{yy}, A_{xy}, analyzing powers (here given in their Cartesian representation). They have been evaluated at about 800 kinematical points for each observable and compared to predictions of various theoretical approaches [22, 23]. In our earlier study [24] we used an independent method to extract just a set of T_{20} values, which were later integrated and compared with appropriate results of the full analysis. Such tests of data consistency and proofs of validity of the applied analysis methods are of crucial importance for precise experiments. Another such test, based on parity restrictions imposed on the analyzing powers, is shown in Fig. 6. Space reflection symmetry requires that the analyzing power value extracted at a certain kinematical point $(\theta_1,\theta_2,\varphi_{12},S)$ and evaluated for the so-called "mirror" configuration point, characterized by the reversed value of the relative azimuthal angle φ_{12} ($\varphi_{12} \to -\varphi_{12}$) have to be either identical (for A_y, A_{xx} and A_{yy}) or differ in sign (for A_x and A_{xy}). It is therefore possible to construct parity-forbidden combinations of the analyzing powers, $O_r = A_r(\varphi_{12}) + (-1)^q \cdot A_r(-\varphi_{12})$, where $q = 1$ for $r \equiv y, xx, yy$ and $q = 0$ for $r \equiv x, xy$, which should be consistent with zero. Values of O_r for one selected angular configuration, presented as a function of S, are shown in right panels of Fig. 6. Their excellent consistency with zero demonstrates high quality of the evaluated analyzing power data.

Global analysis of the analyzing power results leads to a slightly disappointing conclusion that the sensitivity of these observables to the details of the $3N$ system dynamics is rather week. It is demonstrated in Fig. 7, in which the quality of description of each analyzing power is quantified in terms of χ^2 per data point for seven theoretical approaches. Generally all calculations seem to be quite successful in reproducing the data, especially for the vector analyzing powers. There are, however, certain hints of problems in the sector of tensor analyzing powers. In particular, the calculations with realistic potentials and TM99 3NF are giving the worst agreement with the data, drastically in

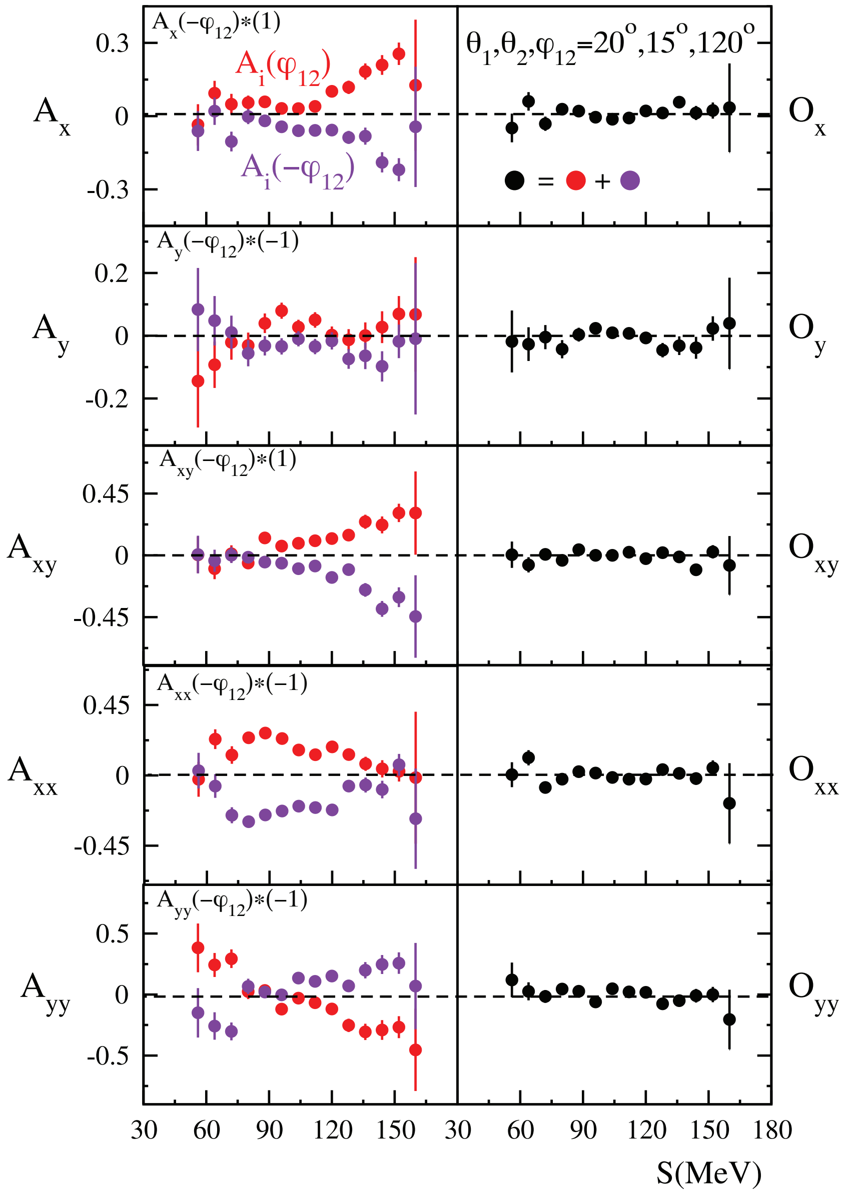


Figure 6: Data consistency check by means of comparing the parity-forbidden combinations of the analyzing power values. *Left panels*: Distributions of the analyzing powers at the selected kinematical configuration (red dots) and the anti-symmetrized values (appropriate multiplier factor given in each panel) of the analyzing powers for the "mirror" configuration (violet dots). *Right panels*: Resulting distributions of the sums of the anti-symmetrized values from left panels.

the case of A_{xy}. This observation has been confirmed in a more detailed inspection of the χ^2 values as function of E_{rel} [22, 23]. A_{xy} is well described by pure *NN* interactions, while inclusion of TM99 3NF worsens the agreement, practically in the whole range of relative energies with exception of the highest one. In the case of A_{xx} and A_{yy} the largest discrepancy between the data and all calculations is present for the lowest values of E_{rel}. The problem with description of A_{xx} at low energies is even increased when the Coulomb interaction is included in the calculations. For the vector analyzing power no particular tendencies can be observed and a good description of the data by all theories is confirmed. The influences of 3NF and Coulomb force on vector analyzing powers are practically negligible in the whole studied region. These last conclusions have been confirmed also by the data from the FZJ experiment [17].

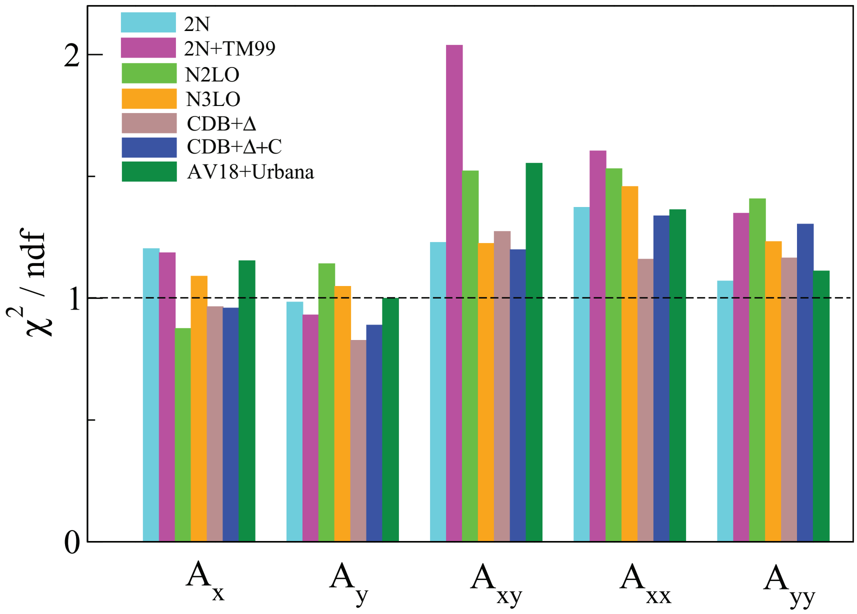


Figure 7: Global comparison of the KVI analyzing power data with various theoretical predictions (see legend). Data description quality is quantified by chi-square per degree-of-freedom values, without a strict statistical meaning, rather as a relatively comparable parameter only. Figure adopted from Ref. [22].

Even in the region of small angles, where for cross sections Coulomb effects were huge, the vector analyzing powers reveal no significant sensitivity to neither Coulomb force nor 3NF. However, it has been established that the quality of reproducing the analyzing power values is quite different - the χ^2 values for A_y are twice as large as for the A_x case. Such effect has been found also in the follow-up experiment at 100 MeV [23], up to now only partially evaluated.

5. Summary

Studies of the ^{1}H($\vec{\mathrm{d}}$,pp)n breakup reaction at 130 MeV have opened a new era of few-nucleon studies with precision experiments exploring large space-phase regions. Cross-section and analyzing-power data from this project are shedding light on the role of various aspects of the 3N system dynamics. After the pioneering experiments, further cross-section data sets are being acquired at several beam energies [23, 25, 26]. They present a general success of the modern calculations in describing the data, however, possibly complete theoretical treatments, including all important ingredients (3NF, Coulomb interaction, relativistic effects), as well as developments in ChPT are very important for better understanding of the few-nucleon system dynamics.

The cross-section data are supplemented with equally large sets of various analyzing powers and measurements of even higher-order polarization observables (see e.g. Refs. [22, 23, 27, 28]). Certain discrepancies observed in those observables are hints of problems in the spin (and perhaps isospin) part of the current models of 3NF. More experiments to study 3N system dynamics are planned at several laboratories. First attempts to proceed to the next step – continuation of the few-body system studies in the four-body environment, have already been started [29, 30].

Acknowledgments

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