MENU 2007
11th International Conference
on Meson-Nucleon Physics and
the Structure of the Nucleon
September10-14, 2007
IKP, Forschungzentrum Jülich, Germany

THREE NUCLEON SYSTEM DYNAMICS STUDIED VIA D-P BREAKUP

St.Kistryn[⋆,1] , E.Stephan[%], N.Kalantar-Nayestanaki[#],

[⋆]Institute of Physics, Jagiellonian University, PL-30059 Kraków, Poland
[%]Institute of Physics, University of Silesia, PL-4007 Katowice, Poland
[#]Kernfysisch Versneller Instituut, NL-9747 Groningen, The Netherlands

Abstract

Three-nucleon ($3N$) system is the simplest non-trivial testing ground in which the quality of modern nucleon-nucleon (NN) interaction models can be probed quantitatively by means of rigorous technique of solving the Faddeev equations. It has been found that a proper description of the experimental data cannot be achieved with the use of NN forces alone. This indicates a necessity of including additional dynamics: subtle effects of suppressed degrees of freedom, introduced by means of genuine three-nucleon forces.

A large set of high precision, exclusive cross-section and analyzing power data for the ^{1}H($\vec{\mathrm{d}}$,pp)n breakup reaction at 130 MeV deuteron energy, obtained in a dedicated experiment at KVI Groningen, contribute significantly to constrain the physical assumptions underlying the theoretical models. Comparison of nearly 1800 cross-section data points with the predictions using nuclear interactions generated in various ways (semi-phenomenological meson exchanges, coupled barion channels approach, chiral perturbation theory), allowed to establish for the first time a clear evidence of importance of the $3N$ forces in the breakup process. Moreover, the results confirmed predictions of sizable influences of the Coulomb force in this reaction. Studies of the relativistic effects, another dynamical ingredient only recently introduced in the theoretical treatment of the breakup process, are under way.

1 Theoretical Foundations

Exploring the details of the nucleon-nucleon (NN) interaction is one of the most intensive activities of nuclear physics. An exact knowledge of all features of the two nucleon ($2N$) system dynamics would provide a natural basis for understanding of properties and interactions of nuclei. This optimistic

[1]E-mail address: stanislaw.kistryn@uj.edu.pl

presumption has to be verified by applying models of the NN interaction to describe 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 ($3N$) 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].

Models of NN forces describe the long range interaction part according to the meson-exchange picture (see Fig. 1), while the short range is based on phenomenology, adjusted by fitting a certain number of parameters to the NN scattering data. The most widely used in few-nucleon studies, so called realistic NN potentials are Argonne v_{18} (AV18), charge dependent (CD) Bonn, Nijmegen I and II (Nijm I, Nijm II). Their full equivalence with the phase shift analysis guarantees that all two-body aspects of the interaction are taken into account, what is reflected by the quality of the description which they provide for all pp and np observables below 350 MeV, expressed by a χ^2 per degree of freedom very close to 1.

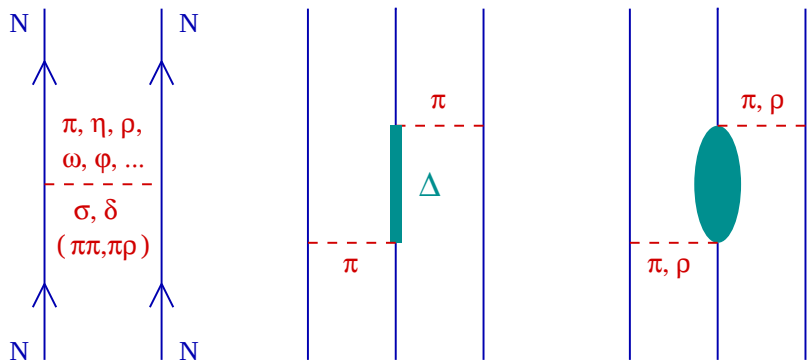

Figure 1: Schematic diagrams of the structure of the nucleon-nucleon interaction (left) and of the three-nucleon force (middle and right) in the meson exchange picture.

In a more fundamental approach the strong forces between the nucleons should be considered as interactions between their constituent quarks and treated by quantum chromodynamics (QCD). However, the NN interaction at low energies is intrinsically non-perturbative, causing that a direct QCD approach is not practical. The link between QCD and the NN interaction phenomenology is provided by effective field theories. Chiral perturbation theory (ChPT), the expansion scheme for the nuclear systems, has been first outlined by Weinberg [3]. Its application to the two nucleon system opened the way to construct an effective NN potential consistent with the (broken) chiral symmetry of QCD. The nuclear potential is expressed by an expansion in terms of $(Q/\Lambda_\chi)^\nu$, with Q describing generic nucleon momentum, Λ_χ representing the chiral symmetry breaking scale of about 1 GeV and ν giving the expansion order. Within the ChPT framework a complete description of the NN and $3N$ system has been established at the next-to-next-to-leading (NNLO) order [4–7]. Calculations for the NN system have been also performed at the next higher order, N^{3}LO ($\nu \leq 4$) [8, 9], what results in a description of the NN data as perfect as the traditional, phenomenological models. Alas, at this order no $3N$ contributions are included yet.

High quality models of the NN potentials, when applied to calculate observables in the $3N$ system, revealed discrepancies between the pure pairwise dynamics and the experimental results. They have been observed in binding energies of the few-nucleon systems and, most abundantly, in various observables of the Nd elastic scattering (for a detailed list of references see e.g. Ref. [10]). The most promising and widely investigated explanation of those disagreements is the presence of a genuine three-nucleon interactions. The realistic potentials are therefore supplemented by 3NF models, usually refined versions of the Fujita-Miyazawa force, in which one of the nucleons is excited into an intermediate Δ via a 2π-exchange with both remaining nucleons. The most popular version of such an interaction is the Urbana IX force. The Tucson-Melbourne (TM) 3NF extends this picture by allowing for additional processes contributing to the rescattering of the exchanged mesons on the intermediate excited nucleon. Schematically the structures of the 3NF models are depicted in Fig. 1. An alternative mechanism of generating a 3NF is based on the so-called explicit Δ-isobar excitation [11–13]. Calculations are performed in a coupled-channels approach in which the NN potential and effective 3NF is generated (together with other Δ-isobar induced effects) due to the explicit treatment of the degrees of freedom of a single Δ. Within the ChPT framework the 3NF appears naturally at NNLO and is handled on completely equal footing as graphs of the NN interaction. This leads to consistent NN and $3N$ forces and also strongly constrains the parameters of the 3NF.

Unfortunately, the comparisons of various elastic Nd scattering data with theoretical predictions lead to ambiguous conclusions. Sometimes inclusion of 3NF improves the agreement, but quite often (especially in the case of polarization observables) additional dynamics does not help, or even drives the predictions away from data. It is clear that the theoretical models need more constraints from the experimental data. It is therefore natural to extend the investigations of the $3N$ system to the Nd breakup reaction. The continuum of the final states, which has to be simultaneously described in its full richness by the assumed dynamical models of NN and $3N$ interactions, provides a lot of information to pin down the details of those theoretical models.

Additional difficulty in interpretation of the results are two features inherently present in the experimental data and until very recently missing in the theoretical formalisms. The first missing feature is the Coulomb interaction: the experiments are performed mainly for the deuteron-proton system while all calculations are strictly neglecting any long-range forces. Only in the last two years a significant step forward has been made in including the Coulomb force effects for the breakup reaction within the coupled-channels approach [14, 15]. Contrary to the former expectations, the influence of the Coulomb force on the breakup observables can be quite significant. Similarly, until last year all the calculations for the breakup reaction have been performed using a nonrelativistic framework and nonrelativistic kinematics. Pioneering study on incorporating relativity in the calculation of the breakup reaction [16] showed that the effects can be sizable, again in contrast to a parallel drawn from the Nd elastic scattering case.

2 Experiment

Reliable breakup data sets, covering possibly large regions of the phase space, are urgently needed. Unfortunately, it still remains difficult to perform such measurements at the required level of precision. The experimental coverage is concentrated at lower energies, below 30 MeV nucleon energy – see Refs. [2, 17] for references. In the recent years some revival of the activity can be noticed (see Ref. [10] for listing of papers), but again only few kinematical configurations are usually studied. Consequently, the conclusions of the studies are still rather unclear - the details of missing dynamics are waiting to be revealed.

The project dedicated towards improving the status of the breakup database has been undertaken by the Polish-Dutch collaboration. The worldwide first extensive set of the breakup cross-section data, spanned on a systematic grid of kinematical variables, has been obtained in a dedicated measurement

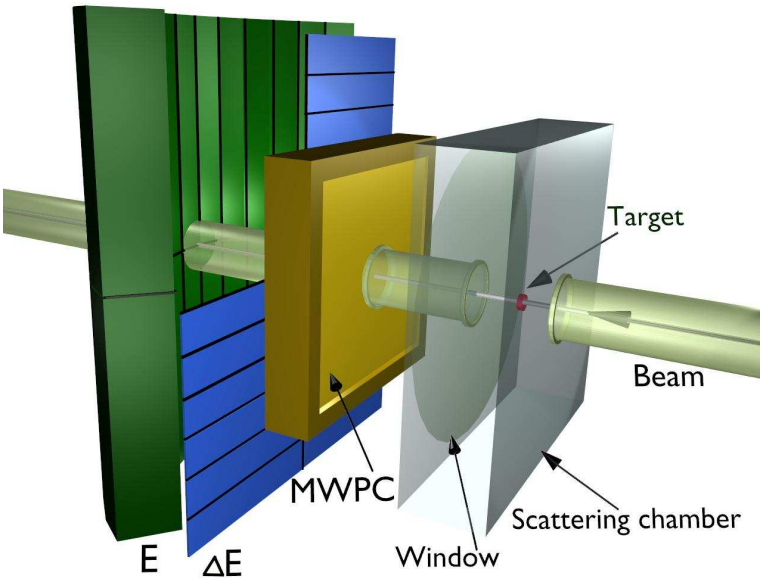

Figure 2: Schematic view of the detection system. Positions of the MWPC, the scintillation detectors and the scattering chamber with its exit window are shown and the central beam line is indicated. To allow some insight over the E detector wall 6 ΔE elements (one sector) are removed from the arrangement.

at 130 MeV of the deuteron beam. Along with the progress in a tedious data analysis the obtained results have been successively presented [18–20], amounting to a total of nearly 1800 cross-section data points. The analyzing power values are forthcoming, as well as the results for other energies [21–23].

The experimental data were acquired in measurements performed at the Kernfysisch Versneller Instituut (KVI), Groningen, The Netherlands. The deuteron beam with energy of 130 MeV was focused to a spot of approximately 2 mm diameter on a liquid hydrogen target of 4 mm thickness. The experimental setup consisted of a three-plane multi-wire proportional chamber (MWPC) and of two layers of a segmented scintillator hodoscope: horizontal transmission ΔE and vertical stopping E detectors. Each layer consisted of 24 elements, as shown in Fig. 2.

Position information from the MWPC was used for precise reconstruction of the particle emission angles, while the hodoscope allowed to identify the charged reaction products (protons vs . deuterons) and to determine their energies. Segmentation of the detector allowed to suppress accidental coincidences and to define on-line trigger conditions with the help of special programmable logic units.

The ΔE-E wall covered a substantial fraction of the phase-space: from about 10° to 35° for the polar angles θ and the full (2π) range of the azimuthal angles ϕ. Registered were coincidences of the charged reaction products: the two protons emitted from the breakup reaction or proton and deuteron from the elastic scattering. More details on the experimental setup and procedures, as well as on the data analysis are given in Refs. [18, 19].

3 Cross Section Results

The main purpose of the here discussed part of the project was a *systematic* study of the quality with which the breakup cross sections can be reproduced by theoretical predictions. The investigation spans a significant fraction of the breakup reaction phase space, with the attainable geometries defined by the experimental conditions. In the attempted systematic approach of scanning the phase space, the cross-section data are presented on a regular grid of polar and azimuthal angles with a constant step in the arclength variable S. Polar angles of the two protons θ_1 and θ_2 are changed between 15° and 30° with the step of 5° (with an additional set for $\theta_1 = \theta_2 = 13°$) and their relative azimuthal angle ϕ_{12} is taken in the range from 40° to 180°, with the step of 20°. For each combination of the central values θ_1, θ_2 and ϕ_{12} the experimental data were integrated within the limits of ± 1° for the polar angles and of ± 5° for the relative azimuthal angle. The bin size along the kinematic curve S was 4 MeV. Such limits allowed to reach sufficient statistical accuracy while keeping the angle and energy integration effects to a minimum, not affecting the comparison with the theoretical predictions.

The cross-section results for all 80 kinematical configurations of the ^{1}H(d,pp)n breakup reaction were compared with three sets of theoretical predictions: the realistic potential approach without and with TM 3NF, the ChPT predictions and the calculations performed within the coupled-channels formalism. The detailed discussion concentrated on the influence of three-nucleon forces is given in Refs. [10, 18, 19]. A summary is shown in Fig. 3 in form of a global comparison, as the ratio of χ^2_{2N} to χ^2_{2N+3N} in order to magnify the influence of the 3NF effects. The χ^2 values are calculated for all data points with respect to various theoretical predictions, without and with inclusion of 3NF effects. One finds that the consistency between the predictions of the CD Bonn potential and the data is improved by adding the TM 3NF in configurations with relatively large ϕ_{12} angles (ratio above 1). On the other hand, for $\phi_{12} < 120°$ including the 3NF into the calculations drives the results away from the data. This behavior is qualitatively confirmed by the coupled-channels calculations, however the amplitude of the changes

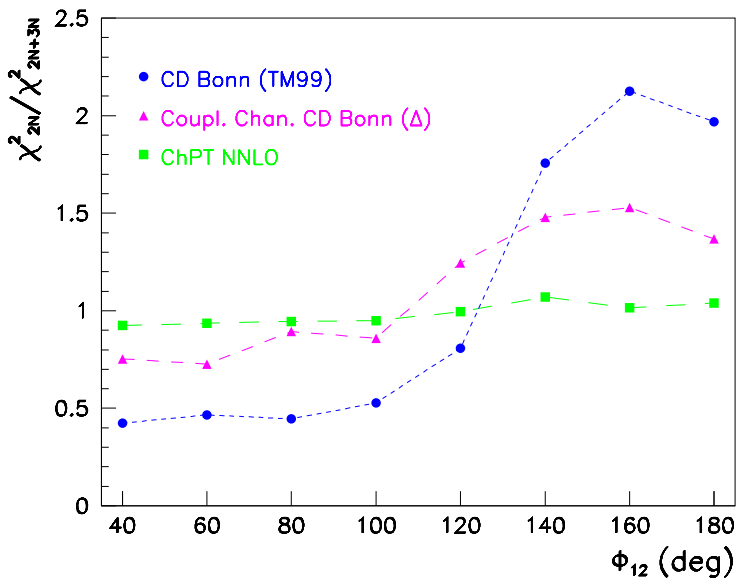

Figure 3: Ratios of χ^2 values for calculations without and with the 3NF contributions. The cross-section data with the experimental absolute normalization were used in computing the χ^2_{2N} and χ^2_{2N+3N} values for groups of kinematical configurations with the same ϕ_{12} angle. The results of data comparison with the calculations with realistic potentials, within the coupled-channels and ChPT approaches are shown by dots, triangles and squares, respectively. Lines connecting the points are to guide the eye only.

induced by including the Δ-isobar excitation contributions is smaller. For the ChPT calculations essentially no effect is present, the ratio stays close to 1 for all values of ϕ_{12}, what is due to large theoretical uncertainties of the ChPT predictions at NNLO. We were able to conclude, that inclusion of 3NF (in the realistic potential approach) leads to a global better description of the data, quantified by a decrease of the χ^2 value by about 40%.

In comparisons of our results we were faced with quite substantial disagreements at low polar angles. Only with the inclusion of the Coulomb force into the calculations in the coupled-channels approach they were mostly explained and removed - see Fig. 4. Only with such a large set of the breakup data significance of the Coulomb effects could have been proved and their behavior traced over the phase space. More details on this topic are given in Refs. [10,20]. It has been also established that even after including Coulomb effects, there is still room for 3NF effects. Final conclusion, however, will be possible only when calculations treating simultaneously all the effects will become available.

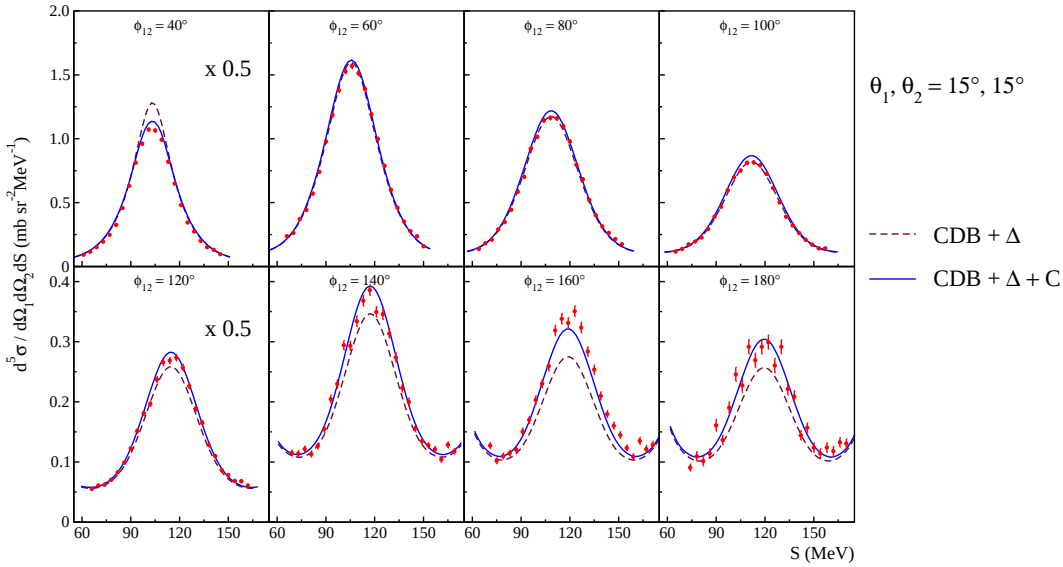

Figure 4: Differential cross sections of the deuteron-proton breakup at 130 MeV deuteron energy, plotted as a function of the arc length S along the kinematical curve. The data are shown for 8 kinematical configurations characterized by the proton polar angles $\theta_1 = \theta_2 = 15°$ and various relative azimuthal angles ϕ_{12}, as indicated in the individual panels. Experimental data are compared to the results of calculations with the coupled-channels CD Bonn + Δ potential, without (dashed lines) and with (solid lines) inclusion of the Coulomb interaction. The data and calculations in the leftmost panels are normalized to the common vertical axis by the indicated factor.

4 Conclusions

The described project is the first extensive and systematic study, covering a large fraction of the breakup phase space. Global comparisons of the whole cross section data set with various theoretical predictions show that the present day models of the $3N$ system dynamics reproduce the majority of the data with satisfactory precision. In many cases in which the predicted effects due to genuine 3NF are non-negligible, their inclusion tends to improve the agreement with the data. However, thanks to the applied experimental technique of covering a significant fraction of the breakup phase space with a highly symmetric detection system, it has been shown that there are also systematic regularities in discrepancies of the measured cross sections and the predictions of all the theoretical approaches. These established disagreements are to a large extent explained by including Coulomb effects into the calculations. This is an important step towards a precise and complete

description of the breakup observables, which should eventually include all aspects of the medium-energy reaction mechanism.

The theoretical predictions show that the effects of the Coulomb force, relativity and of the 3N interaction affect the breakup observables in different ways and with varying strength when inspecting the full reaction phase space. Such selectivity makes possible tracing the details of certain effects in regions where the others are proved to have relatively small influences. This is e.g. true for studies of the $3N$ forces - even if the Coulomb effects in the breakup cross sections are large, there are regions in which their influence is much smaller than the expected effects of the additional nuclear dynamics. With even larger experimental coverage of the breakup phase space with respect to several observables and for various beam energies, the eventually established pattern of discrepancies between the data and the calculations might help to improve the understanding of the full dynamics of the $3N$ system.

Acknowledgments

This report is given on behalf of the whole Collaboration working on the described project. Indispensable contributions from all experimentalists and theoreticians are sincerely acknowledged, as well as the help of KVI technical staff. Financial support for the project has been provided in parts by several Polish, Dutch and European Institutions. The presenting author expresses thanks to the MENU 2007 Organizers for invitation and support.

References

[1] W. Glöckle, *The Quantum Mechanical Few-Body Problem*, (Springer-Verlag, Berlin Heidelberg, 1983, ISBN 3-540-12587-6).

[2] W. Glöckle *et al.*, *Phys. Rep.* **274**, 107 (1996).

[3] S. Weinberg, *Physica A* **96**, 327 (1979); *Phys. Lett.* **B295**, 114 (1992).

[4] E. Epelbaum *et al.*, *Phys. Rev. C* **66**, 064001 (2002).

[5] D. R. Entem and R. Machleidt, *Phys. Lett. B* **524**, 93 (2002).

[6] E. Epelbaum, W. Glöckle, and U.-G. Meißner, *Eur. Phys. J. A* **19**, 125 (2004); *ibid.* **19**, 401 (2004).

[7] E. Epelbaum, *Rep. Prog. Nucl. Phys.* **57**, 654 (2006).

[8] D. R. Entem and R. Machleidt, *Phys. Rev. C* **66**, 014002 (2002); *ibid.* **68**, 041001(R) (2003).

[9] E. Epelbaum, W. Glöckle, and U.-G. Meißner, *Nucl. Phys.* **A747**, 362 (2005).

[10] St. Kistryn, *Three-Nucleon Force Effects in the Deuteron-Proton Breakup Reaction*, (habilitation thesis, DjaF Kraków 2005, ISBN 83-86774-42-8).

[11] K. Chmielewski *et al.*, *Phys. Rev. C* **67**, 014002 (2003).

[12] A. Deltuva, K. Chmielewski, and P. U. Sauer, *Phys. Rev. C* **67**, 034001 (2003).

[13] A. Deltuva, R. Machleidt, and P. U. Sauer, *Phys. Rev. C* **68**, 024005 (2003).

[14] A. Deltuva, A. C. Fonseca, and P. U. Sauer, *Phys. Rev. Lett.* **95**, 092301 (2005); *Phys. Rev. C* **72**, 054004 (2005).

[15] A. Deltuva, A. C. Fonseca, and P. U. Sauer, *Phys. Rev. C* **73**, 057001 (2006).

[16] H. Witała, J. Golak, and R. Skibiński, *Phys. Lett. B* **634** 374 (2006).

[17] J. Kuroś-Żołnierczuk *et. al.*, *Phys. Rev. C* **66**, 024004 (2002).

[18] St. Kistryn *et al.*, *Phys. Rev. C* **68**, 054004 (2003).

[19] St. Kistryn *et al.*, *Phys. Rev. C* **72**, 044006 (2005).

[20] St. Kistryn *et al.*, *Phys. Lett. B* **641**, 23 (2006).

[21] A. Biegun *et al.*, *Acta Phys. Pol. B* **37**, 213 (2006).

[22] H. Mardanpour *et al.*, *Nucl. Phys.* **A790**, 426c (2007).

[23] R. Sworst *et al.*, to appear in *Phys. Lett. B*.