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Experimental Studies of Nuclear Interactions in Few-Nucleon Systems

Abstract Systems of three nucleons (3N) can be treated as a testing ground for modern approaches to describe nuclear interactions. At intermediate energies, observables for 3N systems are sensitive to subtle effects of the dynamics beyond the pairwise nucleon–nucleon force, so-called 3N-force (3NF). For years the search for 3NF has been motivating precise measurements of observables of elastic nucleon–deuteron scattering and for the deuteron breakup reaction. Breakup of a deuteron in collision with a proton leads to the final state of three free nucleons, with variety of possible kinematic configurations, revealing locally enhanced sensitivity to particular aspects of the interaction dynamics, like 3NF, Coulomb force between protons, or relativistic effects. This feature makes the breakup reaction a very versatile tool for validation of the theoretical description. Reactions involving four nucleons pose immense challenges with regard to exact theoretical calculations for such systems. Nonetheless, they attract attention due to expected enhanced sensitivity to certain aspects of the nuclear dynamics, manifesting themselves in various channels and configurations. The most important results of recent experimental studies of 3N and 4N systems at intermediate energies are discussed. A brief survey of the ongoing projects is given.

1 Introduction

Understanding the structure and dynamics of nuclei as systems of interacting nucleons is one of the central goals of nuclear physics. Recently, the tremendous progress has taken place in the field of *ab initio* calculations applied to light and even medium mass nuclei, aiming at determination of their binding energies, radii, magnetic

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moments etc. Development of many-body techniques provides tools for such calculations, but the precise knowledge of basic interactions is a necessary starting point. The nucleon–nucleon potential is a leading part of the nuclear interaction and should be sufficient to describe basic properties of nuclei and main trends in observables. However, there are reasons for the additional dynamics called three-nucleon force (3NF) to play the role in any system consisting of more than 2 nucleons. The 3NF arises in the meson-exchange picture as an intermediate excitation of a nucleon to a Δ isobar. State-of-the-art models of 3NF's, like TM99 [1], Urbana IX [2], or Illinois [3], combined with the so-called realistic nucleon–nucleon (2N) potentials, constitute the basis for calculations of binding energies and scattering observables. Chiral Effective Field Theory provides a systematic construction of nuclear forces in a fully consistent way: the 3N forces appear naturally at a certain order [4,5].

The importance of 3NF contributions for a proper description of systems of more than two nucleons was first established in binding energies of few-nucleon states [6–9]. Ab-initio calculations show that contributions of 3NF's are important for correct description of shell structure of neutron-rich nuclei, stability close to the neutron drip line, saturation in nuclear matter (see e.g. [5,10,11]). The nuclear force used as an input of such calculations should be thoroughly tested on the basis of data measured for few-nucleon systems. Observables for three-nucleon systems, as a subject of accurate ab-initio calculations, represent an excellent testing ground for 2N + 3NF interactions, constructed in any of the ways mentioned above.

2 Experimental Studies of 3N Systems

Studies of 3N systems in nuclear reactions are mainly focused on measurements of observables for elastic nucleon–deuteron scattering and for breakup of deuteron in its collision with a nucleon. Developments of experimental techniques allowed recently to obtain large data sets representing the precision sufficient for tracing subtle effects, like the 3NF. Complete dynamical information on the process can be gained by determining a so-called complete set of observables. Therefore, in addition to differential cross section, the observables related to nuclear polarization are studied: vector and tensor analyzing powers, spin-correlation coefficients and polarization transfer coefficients.

Extensive discussions of the present status of understanding of the 3N system dynamics, based on the modern calculations and many precise and rich data sets, can be found in recent reviews [12–14]. Here, only a few chosen aspects are discussed, mostly related to systematic comparison of large data sets with the state-of-the-art calculations.

Precise measurements of proton–deuteron elastic scattering cross section were performed by several experimental groups at a number of proton and deuteron beam energies. Such a systematic study constitutes a solid basis for conclusions on importance of 3NFs in description of the cross section minimum. In spite of systematic differences between the data sets there is no doubt about the increasing role of the 3NF with beam energy. At beam energy of about 100 MeV/nucleon, certain deficiency of the calculations even with 3NF included is observed. The deficiency grows with beam energy and is not explained by the relativistic calculations.

Vector (proton and deuteron) and tensor (deuteron) analysing powers of deuteron–proton elastic scattering have also been measured in a wide range of energies with precision adequate for testing 3NF effects. Discrepancy between the predicted and measured tensor analyzing power T_{22}^{el} in the region of intermediate energies is one of examples illustrating the problem of describing the polarization observables with currently available 3NF models. The observable has been extensively measured at deuteron beam energies of 100, 130 and 140 MeV in experiments performed at several laboratories with the use of various techniques [15–18]. In Fig. 1 the net effects of 3NF are studied, i.e. the T_{22}^{el} values calculated with the CD-Bonn potential are subtracted both from the data and from the results of calculations including the TM99 3NF. At center-of-mass angles below 120° predicted effects of TM99 3NF depend significantly on energy, while the data are well described by the pure NN force predictions. At larger angles, predicted effects are significant, but almost independent of beam energy in this range. Behaviour of the data is very different: the distance of the data from the calculations with the pure NN force depends on the energy. The 3NF improves the description significantly in the case of measurement at 130 MeV, but comparison with other energies indicates an accidental character of the improvement. For the beam energy of 140 MeV the predicted effect of 3NF is not large enough to reproduce the data, and at 100 MeV the predicted influence of 3NF is too strong. It is apparent that unambiguous conclusions on the quality of data description are conditioned by precise experimental data covering large phase space and performed in a wide range of energies.

An extensive experimental program has been carried out at KVI to compare these findings with the results of measurements of the breakup reaction: the ^{1}H($\mathbf{d}$, pp)n and ^{2}H($\mathbf{p}$, pp)n reactions were studied at five beam
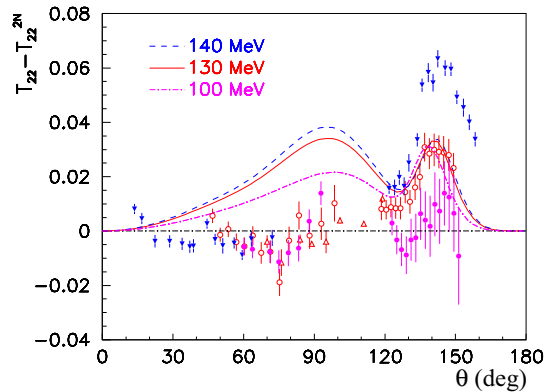
Fig. 1 Vector and tensor analyzing powers of the deuteron–proton elastic scattering: Net effect of 3NF for the T_{22}^{el} data (*full circles*—100 MeV, *open circles* and *triangles*—130 MeV, *full triangles*—140 MeV) compared to the predicted effect of TM99 3NF (lines as specified in the legend). Figure adopted from [18]. For more details see text

energies from 50 to 190 MeV/nucleon. The experiments comprised studies of differential cross sections and analyzing powers with the use of SALAD [19] and BINA [14] detection systems covering large parts of the phase space. An experiment probing the angular range that is particularly sensitive to the Coulomb interaction was conducted at FZ-Jülich at 65 MeV/nucleon [20] with the use of the GeWall detector. In the range of intermediate energies, the so-called axis observables were measured at 135 MeV/nucleon at IUCF [21] and, at the same energy, the complete set of observables (in a limited range of angles) was obtained in the experiment at RIKEN [22]. Recently, the new data sets were collected and are being analysed. Regarding differential cross sections, an experiment using the 4π WASA detector and deuteron beams of energies from 170 to 200 MeV/nucleon has recently been performed at the COSY ring of FZ-Jülich [23,24]. Investigations at lower (proton) beam energies between 108 and 160 MeV are currently being carried out with the use of the BINA detector at the newly opened Cyclotron Center Bronowice (Cracow, Poland) [25]. The studied range of energies can be very critical for understanding of 3N system dynamics: the predicted 3NF effects are already very significant, and the relativistic calculations gain in importance. On the other hand, it is the place where the 3NF starts to be less efficient in describing the elastic scattering cross section.

Conclusions on the role of 3NF for the description of the cross section for the breakup reaction are to a large extent similar to the observations for the elastic scattering. The significance of 3NF for a correct description of the differential cross section has been confirmed [26,27]. The number of evidences on problems with correct description of analyzing powers was collected [21,22,28–30] even if (or when) 3NF is included into calculations. These facts confirm a problem with the description of spin observables in 3N systems.

Theoretical calculations show negligible sensitivity of elastic scattering to the Coulomb interaction [31] and to relativistic effects [32] over a wide range of energies. All the conclusions about the role of 3NF and quality of description of the elastics scattering data rely on the prediction of insignificance of the other effects. The breakup reaction cross section is sensitive to both of these effects and constitutes basis for tests of calculations including these dynamical ingredients. Coulomb effects turned out to be surprisingly large at specific kinematics [20,27,33] and correctly described by the calculations combining 3NF and Coulomb interactions [34], see also example in Fig. 2, left panel. There are indications on important role of the relativistic effects at energies as low as 65 MeV [35] particularly enhanced at specific kinematics, while at energy of 170 MeV/nucleon the predicted relativistic effects exceed 30% [36]. The first sample experimental results for one out of about 80 geometries analysed for the forward part of WASA detector is shown in Fig. 2, right panel. Statistical errors are dominated with uncertainty of the detection efficiency, determined on the basis of Monte Carlo simulation and will be significantly reduced in final results. A possible importance of the relativistic effects is indicated, but the full relativistic calculations including 3NFs [32] and studies of Coulomb effects are necessary for the final conclusions. Experimental studies of the breakup cross section are continued at energies between 100 and 160 MeV/nucleon [25], i.e. in the region of gradually rising 3NF and relativistic effects. Since the predicted effects of relativity and 3NF are acting either in the same or opposite direction, the studies in large phase space regions should allow for discrimination between these components.
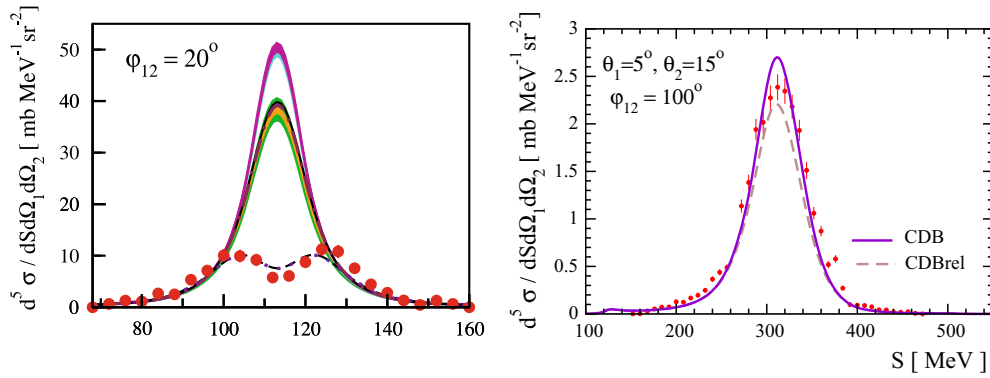
Fig. 2 Differential cross section of the breakup breakup reaction as a function of the energy variable—*S*-arc-length along two-proton kinematics. *Left panel* Sample angular configuration ($\theta_1 = 9°$, $\theta_2 = 9°$, $\phi_{12} = 20°$, beam energy 65 MeV/nucleon) strongly sensitive to Coulomb interaction; *dashed* and *dash-dotted lines* represent calculations with Coulomb force included, all *solid lines* and *bands* correspond to calculations for the nd system; figure adopted from [18]. *Right panel* Sample angular configuration ($\theta_1 = 5°$, $\theta_2 = 15°$, $\phi_{12} = 100°$, beam energy 170 MeV/nucleon) [24]; CDB, CDBrel—respectively non-relativistic and relativistic calculations with the CD-Bonn potential [36]
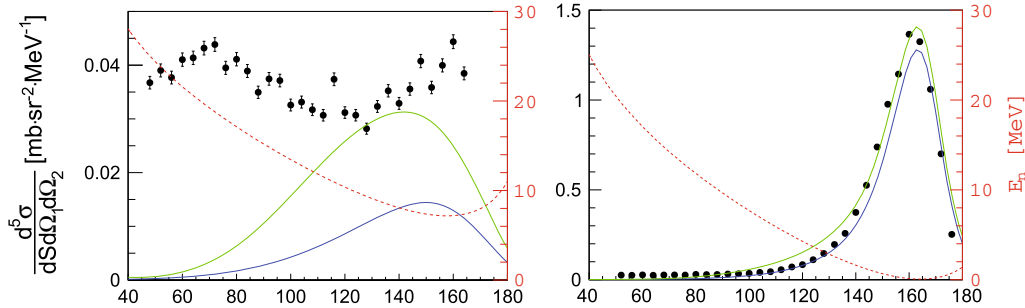
Fig. 3 Differential cross section of the *d-d* breakup reaction as a function of the energy variable *S*-arc-length along the proton–deuteron kinematics. Preliminary data obtained for two sample angular configurations characterised with $\theta_d = 26°$, $\theta_p = 22°$ are shown. The configurations differ in azimuthal angles: *left panel* non-coplanar configuration with $\phi_{dp} = 140°$, *right panel* coplanar configuration, with $\phi_{dp} = 180°$. The data are compared to calculations performed in the SSA regime [40]: *blue (dark gray) line*—1-term calculations, *green (light gray) line*—4-term calculations; the *dashed line* and the right-hand scale show neutron energy, calculated from the proton and deuteron momenta (colour figure online)

3 Experimental Studies of 4N Systems

Even though the investigations of three-nucleon systems are far from being complete, another step in the direction of increasing complexity of the system is taken: studies of reactions with four nucleons. Variety of entrance and exit channels, various total isospin states etc. pose challenges to theoretical calculations, but may also enhance sensitivity to certain aspects of the nuclear dynamics, manifested in various channels and configurations. Considering the ratio of three- to two-nucleon configurations, increased influence of the 3NF is expected in the four-nucleon system as compared to the three-nucleon system.

Exact numerical calculations for four-nucleon systems at intermediate energies are still a long-term aim. However, a considerable development has taken place recently. For elastic scattering and transfer reactions converged solutions for all two-body reactions up to 30 MeV beam energy are available [37–39]. At energies of about 100 MeV/nucleon calculations based on Single Scattering Approximation (SSA) has been performed for the deuteron-deuteron elastic scattering and breakup cross sections [40].

The database for four-nucleon systems at intermediate energies is gradually created. The differential cross section of elastic scattering was measured at deuteron energies of 241 [41] and 135 MeV [42]. The breakup reaction cross section was measured in a wide phase space regions at 135 [43] and 160 MeV [44]. The comparison of quasi-free scattering (QFS) in the $^2H(d, pd)n$ breakup (with neutron as a spectator) with the elastic *dp* scattering has beem performed, leading to interesting conclusions concerning analysing powers [43]. Recently, the data have been compared to SSA calculations. Preliminary results for the breakup cross section at 160 MeV [44] show good agreement with the SSA calculations in configurations close to QFS and, as expected, deterioration of the agreement for non-coplanar configurations, see example in Fig.3. Generally, the

description given by SSA calculation is good at low neutron energy, which is consistent with the assumption of a target neutron acting as a spectator.

4 Summary

Due to recent progress in experimental techniques, the database for the 3- and 4-nucleon system studies at intermediate energies has been significantly enriched. Continuum of breakup states is studied in experiments employing detection systems covering large parts of the phase space, what makes the analysis of observables as a function of kinematic variables feasible. New data sets will be collected in the near future for such systems, complementing the basis for tests of the state-of-the-art and forthcoming theoretical calculations, helping to understand details of the few-nucleon system dynamics.

References

1. S.A. Coon, H.K. Han, Reworking the Tucson-Melbourne three-nucleon potential. Few-Body Syst. **30**, 131 (2001)
2. B.S. Pudliner, V.R. Pandharipande, J. Carlson, S.C. Pieper, R.B. Wiringa, Quantum Monte Carlo calculations of nuclei with A$\leq$7. Phys. Rev. C **56**, 1720 (1997)
3. S.C. Pieper, V.R. Pandharipande, R.B. Wiringa, J. Carlson, Phys. Rev. C **64**, 014001 (2001)
4. E. Epelbaum, H.W. Hammer, U.G. Meiner, Rev. Mod. Phys. **81**, 1773 (2009)
5. R. Machleidt, F. Samaruca, Chiral EFT based nuclear forces: achievements and challenges. Phys. Scr. **91**, 083007 (2016)
6. M. Viviani, A variational approach to three- and four-nucleon systems. Nucl. Phys. A **631**, 111c (1998)
7. A. Nogga, H. Kamada, W. Glöckle, Modern nuclear force predictions for the alpha particle. Phys. Rev. Lett. **85**, 944 (2000)
8. S.C. Pieper, R.B. Wiringa, Quantum Monte Carlo calculations of light nuclei. Ann. Rev. Nucl. Part. Sci. **51**, 53 (2001)
9. P. Navratil, V.G. Gueorguiev, J.P. Vary, W.E. Ormand, A. Nogga, Structure of A = 10–13 nuclei with two- plus three-nucleon interactions from chiral effective field theory. Phys. Rev. Lett. **99**, 042501 (2007)
10. J. Carlson et al., Quantum Monte Carlo methods for nuclear physics. Rev. Mod. Phys. **87**, 1067 (2015)
11. G. Hagen, M. Hjorth-Jensen, G.R. Jansen, T. Papenbrock, Emergent properties of nuclei from ab initio coupled-cluster calculations. Phys. Scr. **91**, 063006 (2016)
12. K. Sagara, Experimental investigations of discrepancies in three-nucleon reactions. Few Body Syst. **48**, 59 (2010)
13. N. Kalantar-Nayestanaki, E. Epelbaum, J.G. Meschendorp, A. Nogga, Signatures of three-nucleon interactions in few-nucleon systems. Rep. Prog. Phys. **75**, 016301 (2012)
14. St Kistryn, E. Stephan, Deuteron–proton breakup at medium energies. J. Phys. G Nucl. Part. Phys. **40**, 063101 (2013)
15. K. Sekiguchi et al., Polarization transfer measurement for ^{1}H(d, p)^{2}H elastic scattering at 135 MeV/nucleon and three-nucleon force effects. Phys. Rev. C **70**, 014001 (2004)
16. H. Mardanpour et al., Precision measurement of vector and tensor analyzing powers in elastic deuteron–proton scattering. Eur. Phys. J. **31**, 383 (2007)
17. E. Stephan et al., Vector and tensor analyzing powers of elastic deuteron–proton scattering at 130 MeV deuteron beam energy. Phys. Rev. C **76**, 057001 (2007)
18. St Kistryn, E. Stephan, Polarization observables in few-nucleon scattering. Int. J. Mod. Phys. Conf. Ser **40**, 1660072 (2016)
19. N. Kalantar-Nayestanaki et al., A small-angle large-acceptance detection system for hadrons. Nucl. Instr. Meth. A **444**, 591 (2000)
20. I. Ciepał et al., Investigation of the deuteron breakup on proton target in the forward angular region at 130 MeV. Few-Body Syst. **56**, 665 (2015)
21. H.O. Meyer et al., Axial observables in dp breakup and the three-nucleon force. Phys. Rev. Lett. **93**, 112502 (2004)
22. K. Sekiguchi et al., Three-nucleon force effects in the ^{1}H(d, pp)n reaction at 135 MeV/nucleon. Phys. Rev. C **79**, 054008 (2009)
23. B. Kłos et al., Systematic studies of the three-nucleon system dynamics in the cross section of the deuteron–proton breakup reaction. Few Body Syst. **55**, 721 (2014)
24. B. Klos et al., Experimental study of three-nucleon dynamics in the dp breakup collisions using the WASA Detector. Few Body Syst. **58** (2017). doi:10.1007/s00601-016-1206-x
25. A. Kozela et al., Systematic study of three-nucleon system dynamics in deuteron-proton breakup reaction. To be published in Few-Body Syst., Topical collection: the 23rd European Conference on Few-Body Problems in Physics
26. St Kistryn et al., Evidence of three-nucleon force effects from 130 MeV deuteron proton breakup cross section measurement. Phys. Rev. C **68**, 054004 (2003)
27. St Kistryn et al., Systematic study of three-nucleon force effects in the cross section of the deuteron–proton breakup at 130 MeV. Phys. Rev. C **72**, 044006 (2005)
28. E. Stephan et al., Vector and tensor analyzing powers in deuteron–proton breakup at 130 MeV. Phys. Rev. C **82**, 014003 (2010)

29. M. Eslami-Kalantari et al., Proton–deuteron break-up measurements with BINA at 135 MeV. Mod. Phys. Lett. A **24**, 839 (2009)
30. H. Mardanpour et al., Spin-isospin selectivity in three-nucleon forces. Phys. Lett. B **687**, 14 (2010)
31. A. Deltuva, A.C. Fonseca, P.U. Sauer, Momentum-space treatment of the Coulomb interaction in three-nucleon reactions with two protons. Phys. Rev. C **71**, 054005 (2005)
32. H. Witała et al., Three-nucleon force in relativistic three-nucleon Faddeev calculations. Phys. Rev. C **83**, 044001 (2011)
33. St Kistryn et al., Evidence of the Coulomb-force effects in the cross-sections of the deuteron-proton breakup at 130 MeV. Phys. Lett. B **641**, 23–27 (2006)
34. A. Deltuva, Momentum-space calculation of proton–deuteron scattering including Coulomb and irreducible three-nucleon forces. Phys. Rev. C **80**, 064002 (2009)
35. H. Witała, J. Golak, R. Skibiński, Selectivity of the nucleon-induced deuteron breakup and relativistic effects. Phys. Lett. B **634**, 374 (2006)
36. H. Witała, Private Communication
37. A. Deltuva, A.C. Fonseca, Calculation of multichannel reactions in the four-nucleon system above breakup threshold. Phys. Rev. Lett. **113**, 102502 (2015)
38. A. Deltuva, A.C. Fonseca, Deuterondeuteron scattering above four-nucleon breakup threshold. Phys. Lett. B **742**, 285 (2015)
39. G. Lazauskas, Modern nuclear force predictions for n-3H scattering above the three- and four-nucleon breakup thresholds. Phys. Rev. C **91**, 044001(R) (2015)
40. A. Deltuva, A.C. Fonseca, Three-cluster breakup in deuteron-deuteron collisions: single scattering approximation. Phys. Rev. C **93**, 044001 (2016)
41. A.M. Micherdzinska et al., Deuteron–deuteron elastic scattering at 231.8 MeV. Phys. Rev. C **75**, 054001 (2007)
42. A. Ramazani-Moghaddam-Arani et al., Three-body break-up in deuteron–deuteron scattering at 65 MeV/nucleon. Phys. Rev. C **83**, 024002 (2011)
43. A. Ramazani-Moghaddam-Arani et al., Spin observables in the three-body break-up process near the quasi-free limit in deuteron–deuteron scattering. Phys. Lett. B **725**, 282 (2013)
44. G. Khatri, Investigation of Deuteron Disintegration. PhD Thesis, Jagiellonian University, Kraków (2015)