

B. Kłos · I. Ciepał · B. Jamróz · G. Khatri · S. Kistryn  
A. Kozela · A. Magiera · W. Parol · I. Skwira-Chalot  
E. Stephan · The WASA-at-COSY Collaboration

# Systematic Study of Three-Nucleon Systems Dynamics in the Cross Section of the Deuteron–Proton Breakup Reaction

Received: 30 October 2013 / Accepted: 7 April 2014 / Published online: 6 May 2014  
© The Author(s) 2014. This article is published with open access at Springerlink.com

**Abstract** An experiment to investigate the  $^1\text{H}(\text{d}, pp)n$  breakup reaction using a deuteron beam of 340, 380 and 400 MeV and the WASA detector has been performed at the Cooler Synchrotron COSY–Jülich. The main goal was the detailed study of various aspects of few-nucleon dynamics in the medium energy region, with particular emphasis on relativistic effects and their interplay with three nucleon forces. These effects become more important with increasing available energy in the three nucleon system. Therefore the investigations at high energies are crucial to understand their nature. The almost  $4\pi$  geometry of the WASA detector gives an unique possibility to study various aspects of dynamics of processes in the three-nucleon reaction. Preliminary results obtained using the WASA detector are presented.

## 1 Introduction

Observables of deuteron–proton breakup reaction can be calculated using modern realistic nucleon–nucleon ( $NN$ ) interactions, combined with a suitable model of  $3N$  forces [1]. Moreover, the two- and three-nucleon interactions can be modeled within the coupled-channel framework of explicitly treating  $\Delta$ -isobar [2, 3]. Alternatively, the dynamics is treated within the Chiral Perturbation Theory (ChPT), so far at the next-to-next-to-leading order with all relevant  $NN$  and  $3N$  contributions taken into account [4]. The above listed calculations including different ingredients of nucleon–nucleon dynamics like the three nucleon force (3NF), the long-range Coulomb interaction or relativistic effects, predict their influence to reveal with different strength at different parts of the phase space. The cross section is very sensitive to all these effects. Previous measurements of the

---

This work has been supported by FFE funds of the Forschungszentrum Jülich; by the European Commission under the 7th Framework Programme through the “Research Infrastructures” action of the Capacities Programme (Call: FP7-INFRASTRUCTURES-2008-1), the Foundation for Polish Science—MPD program, co-financed by the European Union within the European Regional Development Fund, Małopolskie Centrum Przedsiębiorczości—Project Doctus—Małopolski fundusz stypendialny dla doktorantów, the Polish 2013–2015 science funds as research Project No. 2012/05/E/ST2/02313 and funding from Jagiellonian University within SET project—the project is co-financed by the European Union.

---

B. Kłos (✉) · B. Jamróz · E. Stephan  
Institute of Physics, University of Silesia, 40007 Katowice, Poland  
E-mail: barbara.klos@us.edu.pl

I. Ciepał · G. Khatri · S. Kistryn · A. Magiera · W. Parol  
Institute of Physics, Jagiellonian University, 30059 Kraków, Poland

A. Kozela  
Institute of Nuclear Physics PAN, 31342 Kraków, Poland

I. Skwira-Chalot  
Faculty of Physics, University of Warsaw, Warsaw, Poland

cross sections at different deuteron beam energies have demonstrated that an inclusion of  $3N$  and Coulomb forces in the theoretical calculations improves the description of the experimental data [5].

In recent years the relativistic treatment of the breakup reaction in  $3N$  system has been developed using the  $NN$  potential [6] and this approach has also been extended for calculations including  $3NF$  [7]. It was shown that in some particular regions of the breakup phase space, relativistic effects can increase or decrease the calculated breakup cross sections by up to 60%. At the same time the effects of  $3NF$  may change certain observables by a similar factor. The relativistic effects and their interplay with  $3NF$  become more important with increasing available energy in the three nucleon system. Therefore investigations at relatively high energies are important to confirm theoretical predictions for relativistic effects and to unambiguously fix a relevance of the  $3NF$  models.

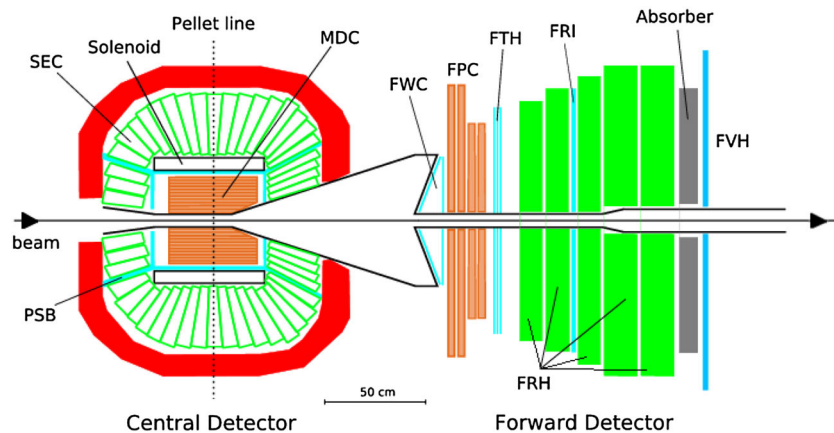
We proposed the measurement of differential cross section of the  ${}^1\text{H}(d, pp)n$  breakup reaction at energies of 340, 380 and 400 MeV. The investigations at this energy range will enable to study the evolution of the relativistic and  $3NF$  effects. This will put strong constraints on the theoretical calculations and will allow to improve the quality of the existing few-nucleon potential models. In this energy range only very scarce data for the breakup observables exist.

## 2 Experiment

The experiment using the  ${}^1\text{H}(d, pp)n$  breakup reaction at 340, 380 and 400 MeV deuteron beam energy has been performed in January 2013 at the Cooler Synchrotron COSY-Jülich with the WASA-at-COSY detector [8,9]. The WASA (Wide Angle Shower Apparatus) detector consists of four main components: Central Detector (CD), Forward Detector (FD), Pellet Target Device and the Scattering Chamber, covering almost full solid angle (see Fig. 1). Such a geometry of WASA gives an unique possibility to study various aspects of dynamics of the three nucleon system, which influence the differential cross section in different phase space regions.

A target supplier is placed on a top of the platform of the CD. It provides a narrow stream of frozen hydrogen or deuteron droplets of about  $20\ \mu\text{m}$  in diameter. The CD surrounds the interaction region and covers the region of the polar angles from  $20^\circ$  to  $169^\circ$ . It consists of four elements: Mini Drift Chamber (MDC), Plastic Scintillator Barrel (PSB), Scintillator Electromagnetic Calorimeter (SEC) and Super Conduction Solenoid (SCS). The FD covers the region of the polar angles from  $3^\circ$  to  $18^\circ$ . It consists of a set of plastic scintillators for identification of charged hadrons and track reconstruction: Forward Window Counter (FWC), Forward Proportional Chamber (FPC), Forward Trigger Hodoscope (FTH), Forward Range Hodoscope (FRH), Forward Range Interleaving Hodoscope (FRI) and Forward Veto Hodoscope (FVH).

In the experiment the trigger conditions allowed for identification of a single particle or two coincident particles. The following reaction channels were measured:  $dp$  elastic scattering and  $dp \rightarrow ppn$  breakup (the main two channels of  $dp$  reaction). The triggers were also prepared to register data for electromagnetic processes:  $dp \rightarrow {}^3\text{He} + \gamma$  and bremsstrahlung  $dp \rightarrow dp\gamma$  reaction. Their measurement and analysis are much



**Fig. 1** Schematic view of the detection system

more difficult due to low cross section values, however, they are also fundamental to our understanding of the nuclear dynamics [10, 11] and there are open questions concerning a mechanism of the bremsstrahlung process [12]. During the measurement the beam intensity was  $(1.3\text{--}1.4)\times 10^8$  deuterons in the flat top. The total input trigger rate was about 60 kHz, while the accepted trigger rate was about 30 kHz, so the dead time was about 50%. Our triggers were designed to include all possible classes of coincidences of two charged particles in order to avoid any bias in measurement of the breakup reaction. The luminosity was  $\sim 10^{29}/\text{s}/\text{cm}^2$  and we accumulated 20.1 TB data during 1.5 weeks of measurements.

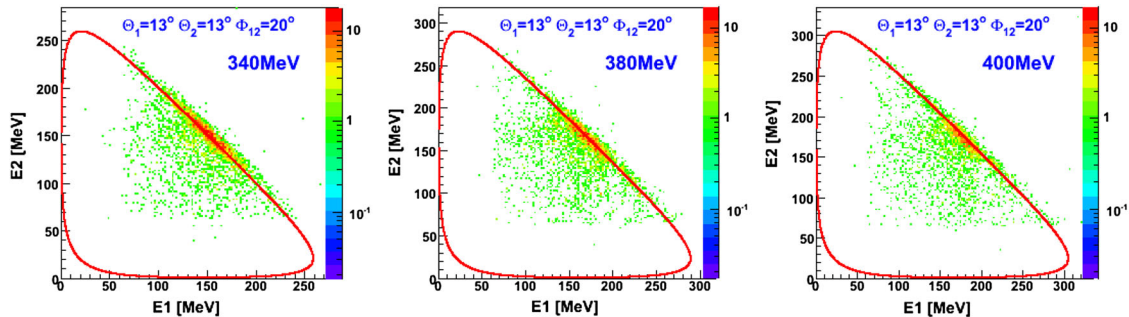
### 3 Data Analysis

The first step of data analysis consists of selecting particles of interest i.e. two protons from the breakup process and deuteron–proton pairs from elastic scattering channel. Identification of protons and deuterons in Forward Detector is performed with the use of the  $\Delta E$ - $E$  technique. In the whole range of energies, a clear separation between loci of protons and deuterons is observed in the Forward Detector. Almost all deuterons from elastic dp scattering are stopped in the fourth plane of the Forward Range Hodoscope (FRH).

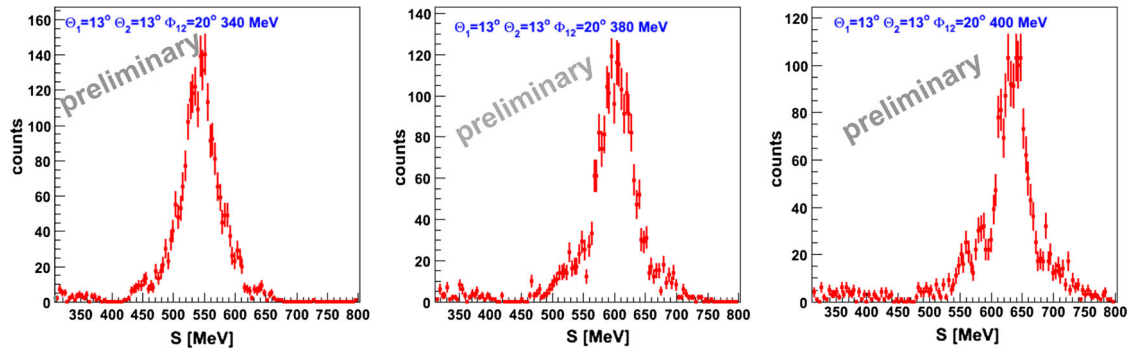
After the selection of the proton–proton coincidences and having performed the energy calibration, any kinematical configuration of the breakup reaction within the angular acceptance of the detection system can be analyzed. The configuration was defined by the emission angles of the two outgoing protons: two polar angles  $\theta_1$  and  $\theta_2$  and the relative azimuthal angle  $\phi_{12}$  (reconstructed from FPC in Forward Detector and MDC in Central Detector). The position sensitive detection system allows to determine polar angles with precision better than  $1^\circ$ . The data were integrated with in angular ranges of  $\theta$  ( $\pm 1^\circ$ ) and  $\phi$  ( $\pm 5^\circ$ ). These ranges are larger as compared to angular resolution of the detectors and, therefore, no significant systematic uncertainty is related to the determination of solid angles. The reconstruction of angles is verified on the basis of kinematics of the elastic scattering. The statistical accuracy of the cross section  $\frac{d\sigma^5}{d\Omega_1 d\Omega_2 dS}$  data point was estimated to be about 1%.

The kinematical spectra  $E_1$  versus  $E_2$  are shown in Fig. 2. Events for configurations of interest are projected onto the kinematical curve corresponding to the point-like, central geometry. Events within a distance of  $\pm 2$  MeV from the  $E_1$ - $E_2$  kinematical curve were taken into account. The rate of events is obtained as a function of the arc-length  $S$  measured along the kinematic curve (Fig. 3). So far, the preliminary method of background subtraction was applied. In the final analysis, the background of accidental coincidences will be approximated by linear function between the two limits of integration for small slices along the kinematical curve. The events below this function will be subtracted. In the next steps the rates have to be normalized using rates of dp elastic scattering events, the known scattering cross-section [13], and the detector efficiency.

The data analysis is in progress with the aim to determine the differential cross sections for the the deuteron breakup process in the  $d + p$  system at energies of 340, 380 and 400 MeV. The data will be compared to the relativistic theoretical calculations as soon as they become available for the  $^1\text{H}(\mathbf{d}, pp)n$  breakup reaction.



**Fig. 2**  $E_1$ - $E_2$  coincidence spectra of the two protons registered at one kinematical configuration ( $\theta_1 = 13^\circ \pm 1^\circ$ ,  $\theta_2 = 13^\circ \pm 1^\circ$ , and  $\phi_{12} = 20^\circ \pm 5^\circ$ ) in measurements at three beam energies. The *solid line* shows a three-body kinematical curve, calculated for the central values of the experimental angular ranges. The energy thresholds for the identification of protons in the Forward Detector is about 50 MeV



**Fig. 3** An example of the preliminary non-normalized rate of breakup events obtained for the chosen kinematical configuration ( $\theta_1 = 13^\circ \pm 1^\circ$ ,  $\theta_2 = 13^\circ \pm 1^\circ$ , and  $\phi_{12} = 20^\circ \pm 5^\circ$ ) at three different deuteron beam energies. Data are presented as a function of the  $S$  value (arc-length along the kinematics with the starting point at the  $E_2$  minimum, see Fig. 2)

**Open Access** This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and the source are credited.

## References

1. Glöckle, W., Witała, H., Hüber, D., Kamada, H., Golak, J.: The three-nucleon continuum: achievements, challenges and applications. *Phys. Rep.* **274**, 107 (1996)
2. Deltuva, A., Chmielewski, K., Sauer, P.U.: Nucleon–deuteron scattering with  $\Delta$ -isobar excitation: Chebyshev expansion of two bayrontransition matrix. *Phys. Rev. C* **67**, 034001 (2003)
3. Deltuva, A., Machleidt, R., Sauer, P.U.: Realistic two-bayron potential coupling two-nucleon and nucleon- $\Delta$ -isobar states: fit and applications to three-nucleon system. *Phys. Rev. C* **68**, 024005 (2003)
4. Epelbaum, E.: Few-nucleon forces and systems in chiral effective field theory. *Rep. Prog. Nucl. Phys.* **57**, 645–741 (2006)
5. Kistryn, S., Stephan, E.: Deuteron–proton breakup at medium energies. *J. Phys. G: Nucl. Part. Phys.* **40**, 063101 (2013)
6. Witała, H., Skibinski, R., Golak, J.: Relativistic effects in exclusive neutron–deuteron breakup. *Eur. Phys. J. A* **30**, 369 (2006)
7. Witała, H., et al.: Three-nucleon force in relativistic three-nucleon Faddeev calculations. *Phys. Rev. C* **83**, 044001 (2011)
8. Bargholtz, Chr., et al.: The WASA detector facility at CELSIUS. *Nucl. Instrum. Methods Phys. Res. A* **594**, 339–350 (2008)
9. Adam, H.H., et al.: arXiv:nucl-ex/0411038
10. Skibinski, R., et al.: Search for three-nucleon force effects in two-body photodisintegration of  $^3\text{He}$  ( $^3\text{H}$ ) and in the time reversed proton–deuteron radiative capture process. *Phys. Rev. C* **67**, 054001 (2003)
11. Bacca, S.: Electromagnetic reactions and few-nucleon dynamics. arXiv:1308.5219v1 (2013)
12. Greiff, J., et al.: Quasifree bremsstrahlung in the  $dp \rightarrow dp\gamma$  reaction above the pion production threshold. *Phys. Rev. C* **65**, 034009 (2002)
13. Ermisch, K., et al.: Systematic investigation of the elastic proton–deuteron cross section-at intermidate energies. *Phys. Rev. C* **68**, 051001(R) (2003)