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**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

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Abstract An experiment to investigate the $^1\mathrm{H}(\mathbf{d},\, pp)n$ 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 4π 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 Δ-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

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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 $^1H(d, pp)n$ 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}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 μm in diameter. The CD surrounds the interaction region and covers the region of the polar angles from 20° to 169°. 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° to 18°. 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 Hodoscop (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 $dp \to ppn$ breakup (the main two channels of dp reaction). The triggers were also prepared to register data for electromagnetic processes: $dp \to {}^3\text{He} + \gamma$ and bremsstrahlung $dp \to dp\gamma$ reaction. Their measurement and analysis are much

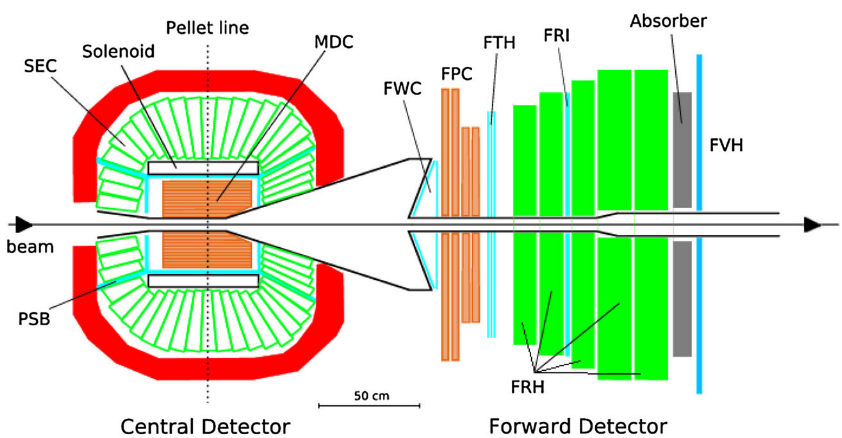

Fig. 1 Schematic view of the detection system

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 $(1.3–1.4)\times 10^8$ 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 $\sim 10^{29}/\mathrm{s}/\mathrm{cm}^2$ 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 ΔE-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 θ_1 and θ_2 and the relative azimuthal angle ϕ_{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°. The data were integrated with in angular ranges of θ (±1°) and ϕ (±5°). 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 ±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 substraction 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}H($\mathbf{d}$, pp)n breakup reaction.

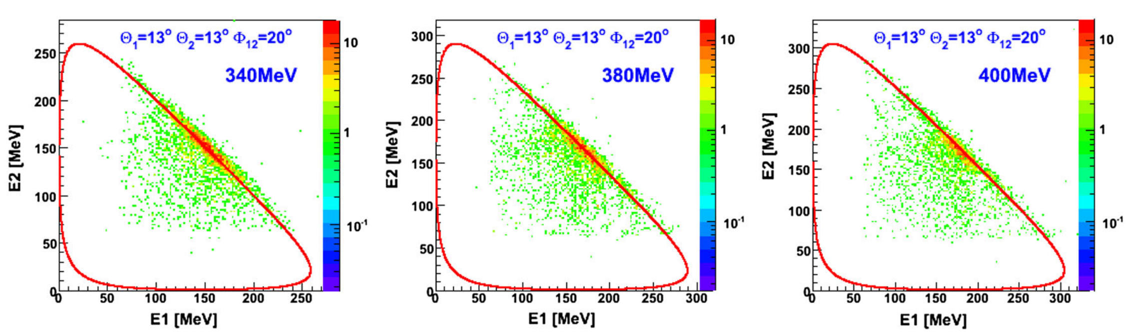

Fig. 2 E_1-E_2 coincidence spectra of the two protons registered at one kinematical configuration ($\theta_1 = 13° \pm 1°$, $\theta_2 = 13° \pm 1°$, and $\phi_{12} = 20° \pm 5°$) in measurements at three beam energies. The *solid line* shows a three-body kinematical curve, calculated for the central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

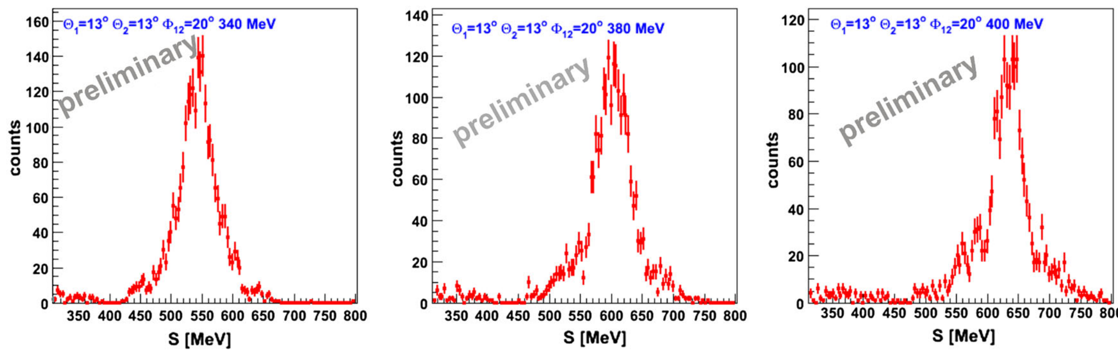

Fig. 3 An example of the preliminary non-normalized rate of breakup events obtained for the chosen kinematical configuration ($\theta_1 = 13° \pm 1°$, $\theta_2 = 13° \pm 1°$, and $\phi_{12} = 20° \pm 5°$) at three different deuteron beam energies. Data are presented as a function of the S value (arc-length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

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