Dynamics of 3N system at 100 MeV

Izabela Skwira-Chalot[1,*], *Nasser* Kalantar-Nayestanaki[2], *Stanisław* Kistryn[3], *Adam* Kozela[4], and *Elżbieta* Stephan[5]

[1]Faculty of Physics, University of Warsaw, Warsaw, Poland
[2]ESRIG, University of Groningen, AG Groningen, The Netherlands
[3]Institute of Physics, Jagiellonian University, Kraków, Poland
[4]Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland
[5]Institute of Physics, University of Silesia, Chorzów, Poland

Abstract. Differential cross section of the deuteron breakup reaction ^{1}H(d,pp)n exhibits sensitivity to interaction dynamics components like three-nucleon force and/or Coulomb force. This sensitivity facilitates comprehensive testing of theoretical potential models that describe interactions within three-nucleon systems. An analysis of experimental data of the breakup reaction, conducted at a beam energy of 100 MeV, has been performed. The presented cross section results for selected configurations agree well with calculations based on meson exchange model potentials and on state-of-the-art results within the Chiral Effective Field Theory framework.

1 Introduction

The deuteron breakup reaction, with its final state of three nucleons (3N), provides rich kinematic environment for testing various nuclear interaction models. It is widely acknowledged that simple two-nucleon (2N) potentials are not able to describe properties of systems made up of more than two nucleons [1, 2]. For such systems the dynamical effects like three-nucleon force (3NF) [3, 4] and Coulomb force [5] start playing an important role and must be included in theoretical calculations. The 3NF models, like Tucson Melbourn (TM99) [3] or Urbana IX (UIX) [4] are combined with NN potentials based on meson exchange model (CD Bonn [6], AV18 [7], Nijm I and Nijm II [8]) to calculate the 3N system observables [9]. The 3NF appears naturally in Chiral Effective Field Theory (χEFT) [10] at the next-to-next-to-leading order (N^{2}LO). In case of Coupled Channels (CC) framework the 3N interactions are modelled by explicit treatment of a single Δ-isobar degree of freedom [11].
In recent years significant efforts have been undertaken to incorporate all dynamical components into theoretical calculations. Currently calculations combining the 3NF and the long-range Coulomb interaction are accessible [5, 12] alongside relativistic calculations [13, 14]. Furthermore, in the realm of Chiral Effective Field Theory an enhanced version is under development [15–17], enabling state-of-the-art calculations for the breakup reaction [18, 19].

*e-mail: Izabela.Skwira@fuw.edu.pl

2 Experiment

The experiment was performed at KVI in Groningen. The deuteron beam accelerated to the energy of 100 MeV collided with a liquid hydrogen target. The Bina detector [20, 21], consisting of two components - forward Wall and backward Ball, was employed to register the reaction products. The Wall consisted of a three-plane Multi-Wire Proportional Chamber (MWPC) and a scintillator hodoscope, composed of 12 horizontal thin detectors (ΔE) and 10 vertical thick stopping detectors (E). This configuration covered laboratory polar angles (θ) between 12° and 35°, encompassing the full azimuthal angles for $\theta \leq 30°$. The Ball was composed of 149 phoswitch scintillators, extending the acceptance to laboratory polar angles up to 165° and the full range of azimuthal angles. Specifically for this experiment, the ΔE detector was removed to lower the energy threshold for the detection of particles.

3 Data selection

In this paper we present the results obtained by analyzing the data collected in the forward Wall. During the experiment, the breakup and the elastic scattering data have been registered simultaneously. All detected charged particles of a given event, proton-proton pairs from the breakup process and proton-deuteron pairs from the elastic scattering were identified using the time-of-flight technique. With the objective of determining the differential cross section for the breakup reaction, the data analysis focused on the proton-proton coincidences. The geometrical configuration ξ of a coincident proton-proton pair is characterized by their polar angles θ_1 and θ_2, and the relative azimuthal angle $\varphi_{12} = |\varphi_1 - \varphi_2|$. For each such geometry $\xi = (\theta_1, \theta_2, \varphi_{12})$, momentum and energy conservation introduce functional dependence between energies of the two protons, E_2 vs E_1. An example of such correlation observed for data points, together with a calculated kinematical curve is plotted in Fig. 1 (left panel). For each

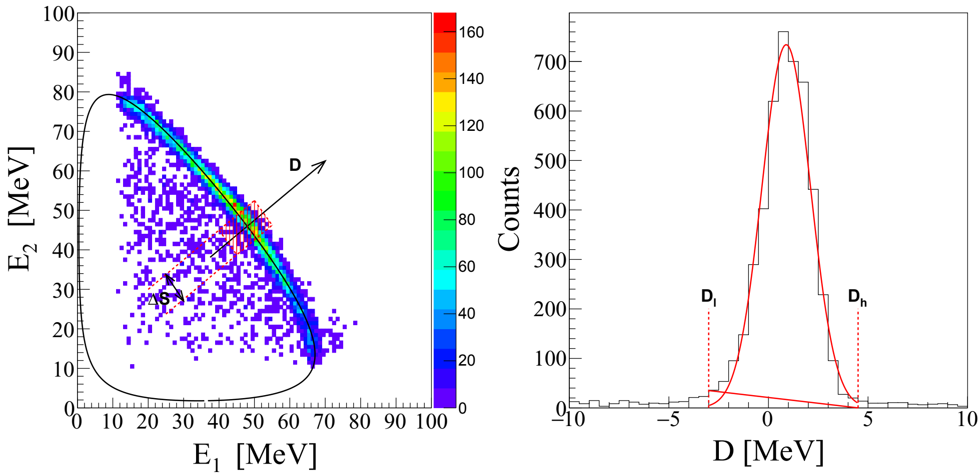

Figure 1. (Color online) *Left panel:* Kinematical spectrum, showing relation of the energies of the two coincident protons registered at $\theta_1 = 25° \pm 1°$, $\theta_2 = 15° \pm 1°$, $\varphi_{12} = 160° \pm 10°$. The solid line shows a three-body kinematical curve. ΔS bin and D variable are presented in a schematic way. *Right panel:* An example of D distribution of events belonging to one ΔS bin, with a Gaussian function fitted in the range $\pm 3\sigma$ from the fitted peak position (from D_l to D_h). (Figure from [22].)

event (point on the E_2-E_1 plane), its distance D from the kinematical curve, and the S-value, defined as arc-length along the kinematics with the starting point at the minimal E_2, were calculated. In the analysis, the angular integration limits for such kinematic spectra were chosen as $\Delta\theta_1 = \Delta\theta_2 = 2°$ and $\Delta\varphi_{12} = 20°$. The kinematic curve was divided along its length into slices of equal size of $\Delta S = 4$ MeV. For each ΔS bin, the corresponding D distribution (projection of the events on the central D axis) was plotted (see Fig. 1, right panel). The breakup events are grouped in a peak with a very low background, which is approximated as a linear function (red solid straight line in Fig. 1, right panel). To calculate the cross section at a central value of S for the given S-bin, the Gaussian function was fitted to the D distribution and the background was subtracted. A part of the background below the peak and the tail of the distribution are mainly due to protons undergoing hadronic interactions, and this loss was corrected on the basis of Monte Carlo simulations. In order to treat all kinematic configurations consistently, the integration limits of the D distribution were chosen at the values D_l and D_h (see Fig. 1, right panel) that correspond to -3σ and $+3\sigma$ distances from the maximum of the fitted peak. The obtained from the above procedure number of proton-proton coincidences, $N(\xi, S)$, was used to calculate the five-fold differential cross section according to the following formula:

$$\frac{d^5\sigma(\xi, S)}{d\Omega_1 d\Omega_2 dS} = \frac{N(\xi, S)}{L\epsilon(\xi, S)\Delta\Omega_1\Delta\Omega_2\Delta S}, \tag{1}$$

where: L is the luminosity integrated over the measurement time, obtained on the basis of the analysis of the elastic scattering data [22]. $\epsilon(\xi, S)$ is the total efficiency defined as a product of single particle detection efficiencies, and configurational efficiency which describes the influence of the geometrical acceptance and detector granularity on the detection probability of the two coincident protons in the BINA setup. $\Delta\Omega_1$ and $\Delta\Omega_2$ are the solid angles for the detection of the two protons, and ΔS is the bin size along the S arc-length.

4 Results and discussion

Differential cross section for the ^{1}H(d,pp)n breakup reaction at the deuteron beam energy of 100 MeV have been evaluated for 87 kinematical configurations within the detector acceptance. Examples of the cross section distributions for two kinematic configurations are presented in Fig. 2, for pairs of (θ_1, θ_2) angles chosen as (20°, 15°) and (25°, 25°). Estimation of systematic uncertainties is still preliminary.

In Fig. 2 the results of the theoretical calculations are presented as solid lines. Black lines represent theoretical calculations with the CD Bonn potential only [23]. Red and green lines represent the calculations within the coupled-channels approach [23] with the CDB + Δ potential, without and with the Coulomb force included (CDB + Δ + C), respectively. The blue lines represent state-of-the-art calculations within the Chiral Effective Field Theory [19]. The dark blue lines show predictions obtained with 2N potentials based on the semilocal momentum-space regularized (SMS) chiral potentials at N^4LO^+, while light blue ones represent results based on the SMS N^4LO^+ 2NF supplemented by the N^2LO 3NF (in both cases the cutoff value of $\Lambda = 450$ MeV was used). The distributions shown in Fig. 2 point at an overall feature - the obtained experimental breakup cross sections in most cases appear to be in a good agreement with the theoretical calculations. Generally, the predicted 3NF effects are negligible and both meson exchange model and χEFT potentials provide almost indistinguishable results. For kinematic configurations in which the two protons move close to each other and thus the Coulomb force influence is expected (see panels with $\varphi_{12} = 40°$) we observe a good agreement of our results only with theory that includes 3NF and Coulomb force simultaneously (CDB + Δ + C). All the other calculations, neglecting the Coulomb repulsion between protons, clearly overestimate the data.

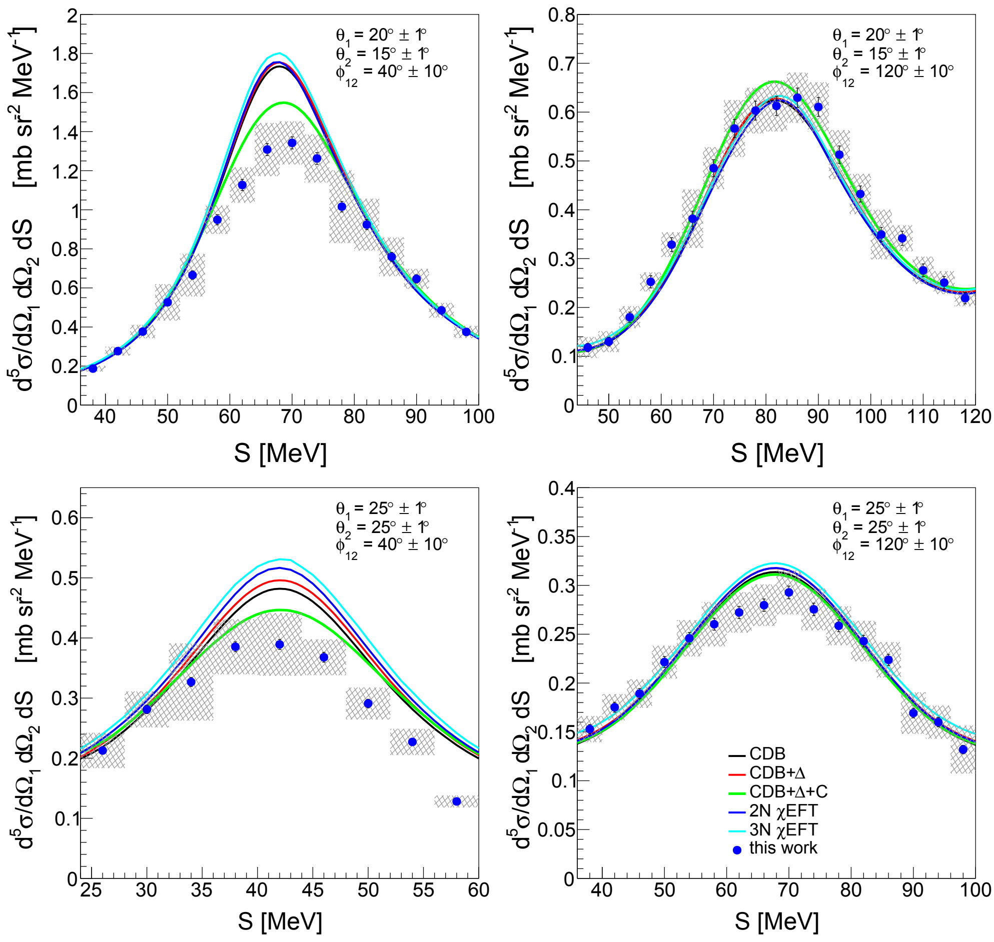

Figure 2. (Color online) Examples of the differential cross section distributions of the ^{1}H(d,pp)n breakup reaction as a functions of the S value (blue points). The error bars represent statistical uncertainties only. The grey rectangles show preliminary estimation of systematic uncertainties. The lines represent the results of the theoretical calculations (see text).

5 Conclusions

The ^{1}H(d,pp)n reaction was tested experimentally at the deuteron beam energy of 100 MeV. The final state of the breakup reaction features three free nucleons, out of which in our experiment two protons were detected by the BINA detector, and used to determine the five-fold differential cross-section distributions for 87 angular configurations in the forward polar angles region. In this work a general scheme of the breakup events analysis and a small sample of the results are presented. Our experimental cross sections have been compared with theoretical predictions performed in two different approaches, CC framework by A. Deltuva and chiral EFT by the LENPIC Collaboration. The comparisons strongly confirm that for kinematic configurations characterized by small relative azimuthal angles between the two protons, in the theoretical description the Coulomb force must be included, as a key ingredient of the dynamics of the 3N system. For angular configurations characterized by larger relative proton momenta, experimental cross section is in as good agreement with calculations based on pure NN potentials (CD Bonn, SMS N^4LO^+) as with the ones supplemented by 3NF (CD Bonn + Δ, SMS N^4LO^+ + N^2LO). This means that in the studied region of the phase space, at a relatively low beam energy of 50 MeV/nucleon, the three-nucleon force effects in the breakup cross section are negligible. These conclusions are confirmed by a quantitative analysis based on two deviation factors χ^2_{red} and A [24].

References

[1] Viviani M., A variational approach to three- and four-nucleon systems, Nucl. Phys. A 631, 111 (1998)
[2] Nogga A., Kamada H. and Glockle W., Modern nuclear force predictions for the α particle, Phys. Rev. Lett. 85, 944 (2000)
[3] Coon S.A. and Han H.K., Reworking the Tucson-Melbourne three-nucleon potential, Few-Body Syst. 30, 131 (2001)
[4] Pudliner B.S., Pandharipande V.R., Carlson J. and Wiringa R.B., Quantum Monte Carlo calculations for A≤6 nuclei, Phys. Rev. Lett. 74, 4397 (1995)
[5] Deltuva A., Fonseca A.C. and Sauer P.U., New calculation schemes for proton-deuteron scattering including the Coulomb interaction, Phys. Rev. C 73, 057001 (2006)
[6] Machleidt R., High-precision, charge-dependent Bonn nucleon-nucleon potential, Phys. Rev. C 63, 024001 (2001)
[7] Wiringa R.B., Stoks V.G.J. and Schiavilla R., Accurate nucleon-nucleon potential with charge-independence breaking, Phys. Rev. C 51, 38 (1995)
[8] Stoks V.G.J., et al., Construction of high-quality NN potential models, Phys. Rev. C 49, 2950 (1994)
[9] Witała H., et al., Cross Section Minima in Elastic *Nd* Scattering: Possible Evidence for Three-Nucleon Force Effects, Phys. Rev. Lett. 81, 1183 (1998)
[10] Epelbaum E., et al., Three-nucleon forces from chiral effective field theory, Phys. Rev. C 66, 064001 (2002)
[11] Deltuva A., Machleidt R. and Sauer P.U., Realistic two-baryon potential coupling two-nucleon and nucleon-D-isobar states: Fit and applications to three-nucleon system, Phys. Rev. C 68, 024005 (2003)
[12] Deltuva A., Momentum-space calculation of proton-deuteron scattering including Coulomb and irreducible three-nucleon forces, Phys. Rev. C 80, 064002 (2009)
[13] Witała H., et al., Relativistic effects in neutron-deuteron elastic scattering, Phys. Rev. C 71, 054001 (2005)
[14] Witała H., et al., Three-nucleon force in relativistic three-nucleon Faddeev calculations, Phys. Rev. C 83, 044001 (2011)
[15] Machleidt R. and Samaruca F., Chiral EFT based nuclear forces: achievements and challenges, Phys. Scr. 91, 083007 (2016)
[16] Reinert P., et al., Semilocal momentum-space regularized chiral two-nucleon potentials up to fifth order, Eur. Phys. J. A 54, 86 (2018)
[17] Reinert P., et al., Precision determination of pion-nucleon coupling constants using effective field theory, Phys. Rev. Lett. 126, 092501 (2021)
[18] Skibiński R., et al.,The nucleon-induced deuteron breakup process as a laboratory for chiral dynamics, Front. Phys. 11, 1084040 (2023)
[19] Skibiński R. and Chahar V., private communication.

[20] Ramazani-Moghaddam-Arani A., et al., Elastic proton-deuteron scattering at intermediate energies, Phys. Rev. C 78, 014006 (2008)

[21] Kistryn St. and Stephan E., Deutron-proton breakup at medium energies, J. Phys. G: Nucl. Part. Phys. 40, 063101 (2013)

[22] Skwira-Chalot I., et al., Studies of deuteron-proton collisions at 100 MeV, Few-Body Syst. 62, 92 (2021)

[23] Deltuva A., private communication.

[24] Sharma S.K., et al., Ranking and validation of spallation models for isotopic production cross sections of heavy residua, Eur. Phys. J. A53, 150 (2017)