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Dynamics of three-nucleon systems studied in proton-induced deuteron breakup reaction.

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A series of experiments studying deuteron breakup in collision with proton was performed with the use of large acceptance detectors: SALAD and BINA at KVI Groningen and CCB PAS Krakow, GeWall and WASA at FZ-Juelich. Differential cross section and, in some cases, vector and tensor analyzing powers were measured over a significant part of the reaction phase space and a wide range of beam energies, from 50 to 200 MeV/nucleon. The collected data provided a basis for systematic comparison with the state-of-the-art theoretical calculations, demonstrating the importance of the three-nucleon force (3NF), and sensitivity of the breakup cross section to Coulomb interaction in the final state. There are many challenges in describing polarization observables and introducing 3NF does not necessarily resolve these discrepancies. A brief survey of the results is given, with emphasis on the energy dependence of particular effects or problems in description of the experimental data. Moreover, the prospectives of further studies of few-nucleon systems using BINA at CCB PAS Krakow are discussed.

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1. Introduction

Studies of scattering in few-nucleon systems are essential for understanding complexity of nuclear interactions and testing their theoretical description. The so-called realistic potentials of nucleon-nucleon interactions combined with three-nucleon force (3NF) models are widely used to describe nuclear interactions in systems consisting of at least three nucleons. Developments of calculations based on such a combination, including the long range Coulomb force [1–3] and/or performed in relativistic regime [4], have been crucial for comparing theoretical predictions with experimental data. Recently, chiral effective field theory (ChEFT) has been estabished as the most adequate approach to develop nuclear forces, providing a firm link to QCD through symmetries. Additional advantages of ChEFT include consistent treatment of two- and many-body forces, its perturbative nature and ability to determine the theoretical uncertainty. The uncertainties are usually identified with the truncation error due to the neglected higher orders of the chiral expansion, but the uncertainties of the so-called low-energy constants have also been discussed [5].

Fine-tuning of the 3N Hamiltonian parameters requires an extensive analysis of available elastic scattering and breakup data in nucleon-deuteron collisions. The short-range contact terms in the chiral 3NF enter the 3N Hamiltonian with unknown strengths, which must be fixed by fitting theoretical predictions to 3N data [6, 7]. The precise knowledge of these terms is highly significant in achieving a consistent description of nuclei and nuclear matter.

In the case of proton-deuteron elastic scattering, the data base is rich and includes analyzing powers, spin correlations, and polarization transfer coefficients (see [8] and references therein). The results show the importance of 3NF for correct description of certain observables, but also discrepancies suggesting a problem with the spin part of 3NF [9]. Deuteron breakup in collision with proton, leading to continuum of three-body final states, provides rich basis for studies of the 3N system, complementary to the elastic scattering. A series of experiments investigating the reaction of a deuteron breakup in collision with a proton was carried out with large acceptance detectors: SALAD and BINA at KVI Groningen and CCB PAS Krakow, GeWall and WASA at FZ-Juelich.

2. Differential cross section of the breakup reaction

Differential cross section of breakup reaction in $^2\mathrm{H}(p,pp)n$ and $^1\mathrm{H}(d,pp)n$ kinematics was measured in a significant part of the reaction phase space, across a wide range of beam energies, from 50 to 200 MeV/nucleon. Studies at the lowest energies in this range allow testing ChEFT calculations at a relatively low order, whereas the highest energies are of interest due to the predicted relativistic effects and the increasing contribution of the 3-nucleon force with energy. In each experiment, several hundred data points were obtained, according to the selected binning of emission angles and energies of two protons detected in coincidence in the output channel. The choice of the size of the energy and angular bins corresponded to the experimental resolutions and the required statistical precision of the result. In addition to analyzing the momentum of outgoing protons, the reaction kinematics can be reconstructed based on the momentum of the proton-neutron pair. So far, this strategy has been used to analyze the $^1\mathrm{H}(d,pn)p$ reaction at beam energy of 80 MeV/nucleon [10], thus extending the range of the phase space studied.

Experimental data for ^{1}H$(d,pp)n$ reaction at 50 MeV/nucleon, collected with BINA at KVI [11] have been compared with theoretical calculations performed in two different approaches, the Coupled Channel framework by Deltuva (with CD-Bonn potential and explicit treatment of Δ-isobar) and ChEFT by the LENPIC Collaboration. So far, studies have been focused on asymmetric angular configurations, characterized with polar angles of protons $(\theta_1, \theta_2) = (25°, 15°)$ and $(20°, 15°)$. In these cases the predicted 3NF effects are small in both approaches, thus the energy is suitable for testing calculations based solely on the NN potentials. No significant differences have been observed between predictions of realistic potentials and ChEFT, and both approaches provided satisfactory description of the data at large relative azimuthal angles between protons φ_{12}. The comparisons strongly indicate that for certain kinematic configurations characterized by small φ_{12}, in the theoretical description the Coulomb force must be included, as a crucial for a proper data description. So far, this was realized only for the realistic potentials.

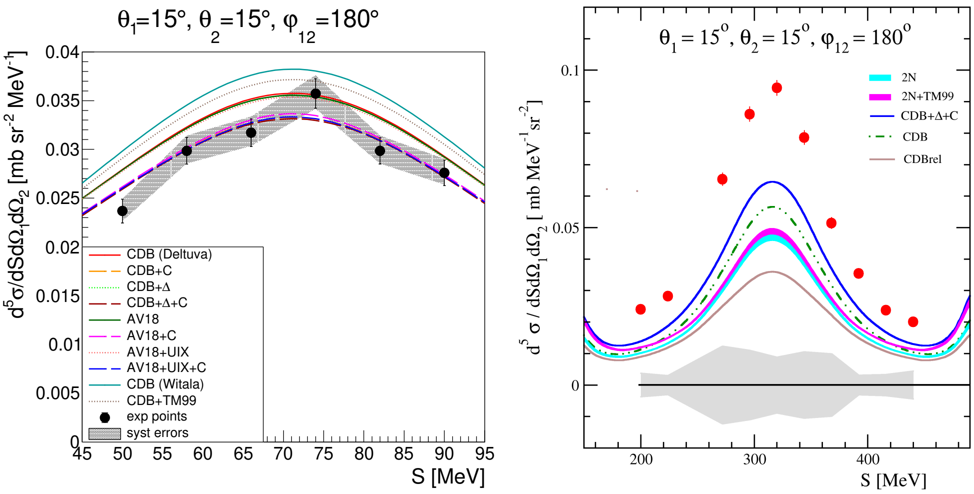

Figure 1: Examples of the differential cross section distributions in the function of the energy variable S (for definition see e.g. Ref. [14]) for selected experiments and angular configuration of $\theta_1 = 15°$, $\theta_2 = 15°$, $\varphi_{12} = 180°$ in the laboratory system. The data are compared to theoretical calculations by Deltuva and by Witała et al., listed in the legends; for more information see Refs.[14, 16]. (*Left panel*): the *pd* breakup reaction at 108 MeV, BINA@CCB experiment [16]. (*Right panel*): the *dp* breakup reaction at 170 MeV/nucleon, WASA@COSY experiment [14]; CDBrel means relativistic calculations of Witała et al. with CD-Bonn potential.

In contrast to observables for the elastic scattering, Coulomb interaction significantly modifies the differential cross section for the breakup reaction. This effect is particularly strong in kinematics close to the proton-proton Final State Interaction (FSI) configurations [12, 13]. Although large cross section modifications associated with repulsion between protons are observed even at beam energies as high as 170 MeV/nucleon [14], they are much more important at lower beam energies. Moreover, the Coulomb effect are sometimes spread over wide phase space regions, as it was observed in the BINA@CCB experiment studying the ^{2}H$(p,pp)n$ reaction at 108 MeV [15, 16], see an example in Fig.1, left panel. Hence, the inclusion of the Coulomb potential into the ChEFT calculations is crucial for studying breakup reactions in wide angular ranges.

With increasing beam energy, the 3NF starts to play a significant role. The effects of 3NF were observed in cross section data for the ^{1}H$(d,pp)n$ breakup reaction collected at KVI at beam energies of 65 and 80 MeV/nucleon [17–19], with the use of SALAD and BINA detectors, respectively. For these two energies, calculations including both 3NF and Coulomb interactions provided a good description of the data sets over large phase space regions. There were also indications of problems in reproducing cross section distributions, limited to the small region of coplanar or nearly coplanar ($\varphi_{12} = 160°, 180°$) configurations at 80 MeV/nucleon, where all the predictions underestimated the data. This observation was confirmed in the WASA@COSY experiment at higher energy, of 170 MeV/nucleon [14], see Fig. 1, right panel. Moreover, similar effects were also observed in the BINA@KVI experiments at 135 MeV/nucleon and 190 MeV/nucleon [20, 21], where in certain coplanar configurations of the for ^{2}H$(p,pp)n$ reaction theories underestimate the cross section data. The observed discrepancies are not removed when relativistic effects are taken into account, at least in the calculations neglecting the 3NF (see Fig.1, right panel). It would be very interesting to compare these data with future relativistic calculations in the full version, i.e. including the 3NF, as well as to confront them with the results of ChEFT calculations in the required order.

Multidimensional information (5-fold differential cross section) and a variety of configurations in the breakup reaction continuum, revealing variable sensitivity to the dynamical effects, make this reaction a versatile ground for testing the theoretical predictions or fitting their parameters. On the other hand, this wealth of possibilities presents some difficulties in systematic analysis and in drawing general conclusions. To solve this problem, approaches that take into account invariant coordinates, for example, have been proposed [19, 22]. Such ongoing analyses will allow to sort out locally observed problems with theoretical description of the data and provide more coherent and systematic picture.

3. Polarization observables

Polarization observables reveal strong sensitivity to details of the nuclear potential. Availability of highly polarized proton and deuteron beams provided conditions for precise measurements of polarization observables in the 3N systems, especially of the vector and tensor analyzing powers. Deuteron breakup induced by a collision with proton is a perfect candidate for testing theoretical calculations due to a large number of independent polarization observables (a part of them vanish in the elastic scattering due to parity constrains) and continuum of its final-state. In a series of experiments at KVI, deuteron analyzing powers (at 50 and 65 MeV/ nucleon) and proton analyzing powers (at 135 and 190 MeV/nucleon) were measured in large phase space regions with the SALAD and BINA detectors. In the collected data, deficiencies in the theoretical description of deuteron tensor analyzing powers at 65 MeV/nucleon [19, 23] and proton analyzing powers at 135 and 190 MeV [24–26] were clearly demonstrated. In extreme cases, mainly in configurations with small φ_{12}, even the sign of the measured A_y was opposite to that predicted. Generally, in the *d-p* breakup reaction disagreements between data and theory appear in certain analyzing powers and kinematic configurations, and are sometimes even increased when the 3NF is included. It is very intriguing how the calculations within ChEFT currently being developed will describe the polarization observables in the 3N systems.

Compared to the elastic scattering, investigation of the breakup reaction at medium energies has so far covered a very small range of available polarization observables. Apart of mentioned

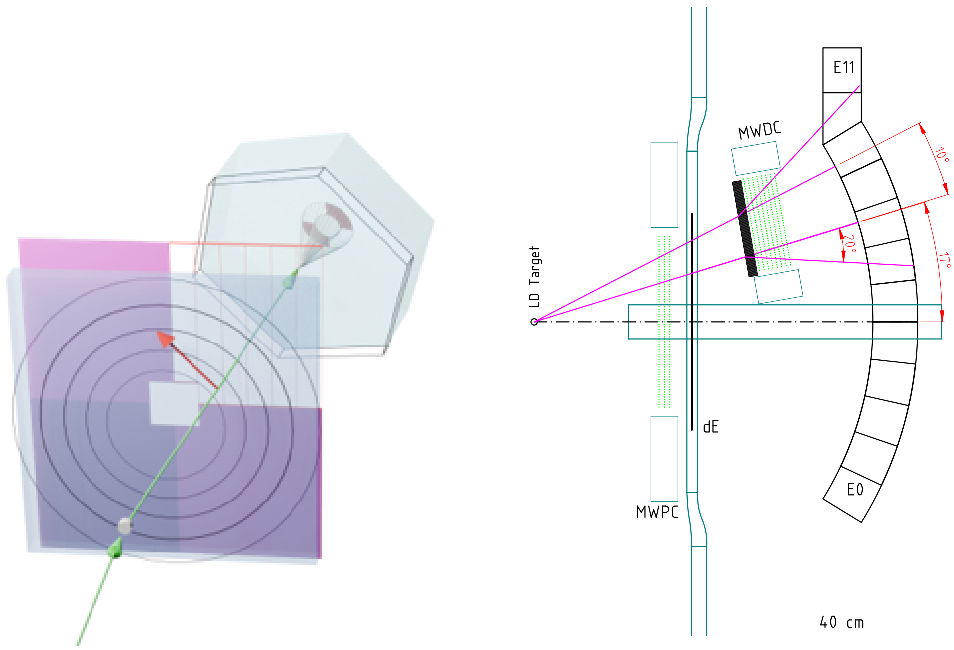

Figure 2: Schematic view of BINA Wall equipped in its upper-right sector with the proposed proton polarimeter, consisting of a graphite scatterer and MWDC. (*Left panel*): Perspective view showing placement of the hexagonal polarimeter with respect to MWPC and ΔE detectors. (*Right panel*): Schematic cross-section through the polarimeter with examples of tracks of protons scattered on graphite at the limits of the polarimeter acceptance. Position of the polarimeter along the beam axis (distance from the target and inclination angle with respect to the beam axis) defines its acceptance and angular resolution, therefore it will be determined on the basis of theoretical predictions and dedicated simulations.

above analyzing powers, there were measurements of axial polarization observables performed at IUCF at the beam energy of 135 MeV/nucleon [27]. One single measurement of the polarization transfer coefficients and induced polarization, P^y, in the $^1\mathrm{H}(d,pp)n$ reaction was conducted at RIKEN at the beam energy of 135 MeV/nucleon [28]. This experiment provided precise data for 7 independent observables in kinematic configurations close to the so-called *pn* Final State Interaction (FSI) configuration.

The new project to measure induced polarization P^y and, ultimately, also P^x, in a number of configurations of the $^2\mathrm{H}(p,\vec{p}p)n$ breakup reaction at beam energy of 160 MeV, using the BINA detector, has been proposed to be carried out at CCB Krakow. Contrary to the elastic scattering, the breakup reaction is not time-reversal symmetric, meaning the induced polarization is not equivalent to any analyzing power and must be measured directly. In coplanar configurations of the two protons, defined by a relative azimuthal angle φ_{12} of 180° (in-plane configurations of the 3-body final state) only one component, P^y, is present. In other cases, another transversal component, P^x, is allowed. The studies at 135 MeV/nucleon in the region of FSI configuration, where a proton and a neutron are emitted with very similar momenta, showed a sensitivity of the induced polarization to details of the interaction dynamics [28].

In the new project it is planned to measure the polarization of one of the two protons originating from the breakup reaction, with the use of a dedicated polarimeter installed within the Wall part of the BINA detector, see Fig. 2. The project is focused on detecting two protons emitted forward, within the acceptance of the so-called BINA Wall. Events of interest to determine the induced proton polarization will be selected by the following conditions: the proton of higher energy, at least 80 MeV, is emitted towards the polarimeter, scattered on graphite analyzer and precisely tracked by multiwire drift chamber, while the proton of lower energy is registered in the part of Wall which is free of polarimeter. In this way, the energy of the second proton will not be altered and the corresponding energy threshold will be low, at approximately 20 MeV.

4. Summary

The inclusion of the 3N force significantly improved the description of the scattering cross section in systems of three nucleons in the intermediate energy range. For the breakup reaction, it turned out to be necessary to take into account the Coulomb repulsion between protons in the exit channel. A rich and systematic (in beam energy) set of differential cross section data collected for the breakup reaction provides a very versatile testing ground for the state-of-the art calculations. As the beam energy increases, in some regions of phase space the description through realistic potentials with 3NF forces and Coulomb interactions included is not fully satisfactory. It would be very interesting to confront the data for the breakup reaction with the ChEFT calculations as they become available with consistently derived NN and 3N forces in the required order. Up to now, such a comparison has only been possible for the data taken at 50 MeV/nucleon, where the 3NF plays rather marginal role.

The study of polarization observables represents a qualitative extension of the cross section studies, due to their sensitivity to details of the interaction dynamics. Precise description of the proton and deuteron analysing powers poses certain challenge for the theoretical models. Here, too, high expectations are placed on the ChEFT calculations. Reaching for more observables, such as proton polarization induced in the breakup reaction, will give a more comprehensive picture of the process and will provide the data for even more rigorous tests of the theoretical predictions.

Acknowledgments

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