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Experimental Studies of Few-Nucleon Systems

St. Kistryn[a], B. Kłos[b], A. Kozela[c], P. Kulessa[c,d],
A. Łobejko[b], W. Parol[c], I. Skwira-Chalot[e], E. Stephan[b,*],
A. Szadziński[b], A. Wilczek[b], B. Włoch[c] and J. Zejma[a]

[a] *Institute of Physics, Jagiellonian University, 30-348 Kraków, Poland*
[b] *Institute of Physics, University of Silesia, 75 Pułku Piechoty 1, 41-500 Chorzów, Poland*
[c] *Institute of Nuclear Physics PAS, 31-342 Kraków, Poland*
[d] *on leave, present address: Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany*
[e] *Faculty of Physics, University of Warsaw, 02-093 Warsaw, Poland*

Doi: 10.12693/APhysPolA.139.319 *e-mail: elzbieta.stephan@us.edu.pl

Understanding nuclear interactions is the basis for describing nuclear systems, their structure and reactions. Studies of reactions in the simplest systems consisting of a few nucleons provide stringent tests for nuclear interaction models. The data collected by our group over the last 30 years are crucial for understanding the few-nucleon system dynamics. Measurements of observables (cross-section, vector and tensor analyzing powers) for the deuteron breakup in collision with a proton/deuteron were conducted at SIN/PSI (Switzerland), KVI (the Netherlands), FZ-Jülich (Germany) and CCB IFJ PAN Kraków (Poland), and provided data covering a wide range of the reaction phase-space. Main conclusions following from our research and its current status are presented.

topics: nuclear interactions, few-nucleon systems, three-nucleon force, polarization

1. Introduction

Studies of the bound states (e.g. ^{3}H, ^{3}He) and of the elastic proton–deuteron scattering indicated that three nucleon systems could not be precisely described by only pairwise interactions between nucleons. Deficiencies in the description of systems consisting of three and more nucleons are usually attributed to an additional part of dynamics, beyond the nucleon–nucleon (NN) interactions. The so-called three-nucleon force (3NF) is understood to be a consequence of internal degrees of freedom of the interacting nucleons. The 3NF arises in the meson-exchange picture as an intermediate excitation of a nucleon to a Δ isobar. Chiral effective field theory provides a systematic construction of nuclear forces in a fully consistent way. In this approach, the 3N forces appear naturally at a certain order [1, 2]. Calculations including 3NF describe correctly binding energies of light nuclei and a differential cross-section for proton–deuteron elastic scattering at intermediate energies (see [3] and references therein).

However, a residual difference (after including 3NF) between the measured and the calculated cross-sections for the elastic proton–deuteron scattering is observed at about 135 MeV and shows systematic increase with the beam energy. Similar effects are present in a cross-section for the neutron–deuteron scattering [4, 5]. There are also deficiencies in describing certain polarization observables in the proton–deuteron elastic scattering, indicating problems with the spin part of the existing models of 3NF.

Deuteron breakup reaction: $p + d \rightarrow p + p + n$ has three free nucleons in the final state, therefore their final momenta form a continuum of solutions. Particular kinematic configurations of the outgoing nucleons reveal various sensitivity to specific ingredients of the reaction dynamics. For this reason, and also due to a rich number of observables, the breakup reaction is a perfect candidate for testing nuclear interaction models. Since the dynamical effects to be traced are usually subtle, studies in the domain of few-nucleon systems require high statistical and systematic accuracies of the results.

The first precise measurements were performed just in selected kinematic configurations due to limitations of the electronic and data acquisition systems at that time. Even with such restrictions, they provided very important data to be confronted with calculations manifesting developments of the theoretical approaches. For example, the differential cross-section distribution for the so-called space star configuration at 65 MeV/nucleon [6] was compared with recent calculations in relativistic framework [7]. Progress in electronic and data acquisition systems enabled collecting of high data rates from many detector channels and, in consequence, led to a new generation of thorough studies of the deuteron breakup reaction with the use of large acceptance detection systems. Each such experiment provides several hundreds or thousands of data points per observable as a function of five independent variables, to be compared with the state-of-the-art theoretical calculations.

2. Experimental studies of deuteron breakup reaction

A comprehensive series of experiments to study the deuteron breakup was performed at KVI (Groningen, the Netherlands) with the use of SALAD [8] and BINA [9] detectors and at COSY (FZ-Jülich, Germany) with the Ge-Wall [10] and WASA [11] detectors. Differential cross-section of the deuteron–proton breakup reaction was measured in a wide range of energies between 50 and 200 MeV/nucleon, and in wide phase-space regions. In addition, the deuteron vector and tensor analyzing powers (at 50 and 65 MeV/nucleon) and proton analyzing powers (at 135 and 190 MeV/nucleon) were measured. All the observables were compared with the results of the state-of-the-art calculations, which led to several important findings. The milestones of these studies can be summarized as follows:

- The influence of 3NF on the breakup cross-section has been demonstrated for the first time in the ^{2}H(p,pp)n reaction at the beam energy of 65 MeV/nucleon [12, 13]. Recently, this conclusion has been confirmed on the basis of a large data set collected at 80 MeV/nucleon [14].
- Contrary to the elastic scattering case, the breakup cross-section turned out to be sensitive to the Coulomb repulsion in the final reaction state [15, 16]. Since experimental data for the neutron–deuteron breakup are limited to low energies (see references in [3]), proper inclusion of the Coulomb force has been found indispensable, in particular in the region of final-state interaction configuration of the proton pair. Calculations comprising both the Coulomb interaction and 3NF [17] provided the most accurate description of the cross-section data over large phase-space regions at intermediate energies [14, 18–20].
- Polarization observables reveal very strong sensitivity to the interaction dynamics. On the basis of the collected data, problems in describing the deuteron tensor analyzing power of the ^{1}H(d,pp)n reaction at 65 MeV/nucleon [21, 22] and the proton analyzing powers of the ^{2}H(p,pp)n reaction at 135 and 190 MeV [23–25] were clearly demonstrated. Disagreements between data and theory appeared in certain kinematic configurations, and in some cases were even increased when 3NF was added. Conclusions from these studies supported earlier indications from the measurements of polarization observables for the proton–deuteron elastic scattering, demonstrating problems with the spin part of the existing 3NF models.
- Recently, measurements at 80 and 170 MeV/nucleon showed a rising with the energy discrepancy between the cross-section data and the state-of-the-art theoretical calculations [14, 18, 19]. It is not clear whether this discrepancy should be attributed to the deficiencies of the current 3NF models or to the relativistic effects.
- The data base for four-nucleon (4N) systems has been considerably enriched by measurements of observables for the ^{2}H(d,dp)n breakup reaction at the deuteron beam energy of 65 and 80 MeV/nucleon [26, 27]. Considering the lack of *ab initio* calculations for the 4N systems in the intermediate energy region, validity of single scattering approximation (SSA) [28] has been checked and generally confirmed for the cases of the cross-section and vector and tensor analyzing powers in the quasi-free scattering (QFS) region. The remaining discrepancies for the QFS cross-section might be attributed to the fact that the studied energy is probably too low to meet the SSA assumptions. In future, the collected data will provide a reference for forthcoming exact calculations, allowing for studies of the 3NF effects in the 4N systems.

3. Conclusions and outlook

As the above findings show, observables measured for the deuteron breakup in collision with a proton or deuteron provide very rich information on the reaction dynamics. At intermediate energies, depending on the kinematic configuration, the sensitivity of the cross-section to Coulomb interaction, 3NF and possibly also relativistic effects can be observed, see examples in Fig. 1. This feature poses a challenge to the theoretical description of the breakup reaction, but also opens up possibilities of thorough studies of the nuclear interactions.

Further progress in both theory and experiment is necessary to exploit in all details the full potential provided by the deuteron breakup reaction. The remaining problems in the differential cross-section and persistent problems with a precise description of polarization observables point to a necessity of employing a fully relativistic treatment of the breakup process (for the current status, see [7, 29])

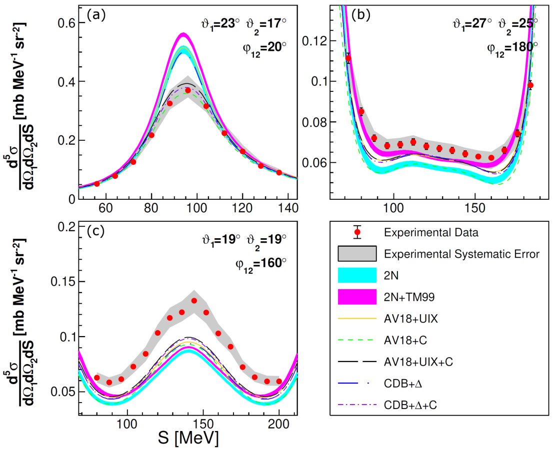

Fig. 1. Examples of cross-section distributions obtained for selected kinematic configurations (defined by proton emission angles specified in the parts) of the ^{1}H(d,pp)n reaction at 80 MeV/nucleon [14]: (a) configuration sensitive to the Coulomb interaction (best agreement with the AV18+C, AV18+UIX+C predictions), (b) configuration sensitive to 3NF (best agreement with the 2N+TM99 predictions), (c) configuration for which the existing calculations fail to describe the experimental data. For the definition of energy variable S and other details, see [14].

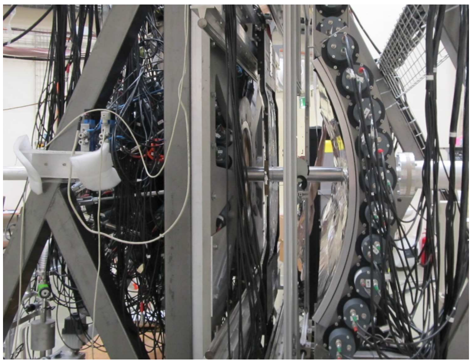

Fig. 2. BINA detector installed at the CCB beam line.

and ChEFT calculations at a high enough order. On the experimental side, there are still unexplored energy regions important for understanding the reaction dynamics. New possibilities of extending the studies to still broaden a phase-space region would be opened by facilitating precise enough neutron detection systems. The data collected with the BINA detector was used to test possibilities of reconstruction of neutron momenta, enabling the analysis of neutron–proton coincidences, see [30] for preliminary results.

Recently, the program of experimental studies of few-nucleon systems has been successfully introduced at the newly opened Cyclotron Center Bronowice (CCB) at the Institute of Nuclear Physics PAS in Krakow, Poland (see Fig. 2). Our group has initiated an experimental program of measurements of the differential cross-sections for the proton–deuteron elastic scattering at 108, 135, and 160 MeV and for the ^{2}H(p,pp)n breakup reaction at 108 and 160 MeV with the use of a BINA detector [31]. Further extensions to the program are expected to include neutron detection in a dedicated hodoscope and studies of systems composed of more than three nucleons.

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