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EXPERIMENTAL STUDY OF THREE-NUCLEON DYNAMICS IN PROTON–DEUTERON BREAKUP REACTION*

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Proton–deuteron breakup reaction can serve as a tool to test state-of-the-art descriptions of nuclear interactions. At intermediate energies, below the threshold for pion production, comparison of the data with exact theoretical calculations is possible and subtle effects of the dynamics beyond the pairwise nucleon–nucleon interaction, namely the three-nucleon force (3NF), are significant. Beside 3NF, Coulomb interaction or relativistic effects are also important to precisely describe the differential cross section of the breakup reaction. The data analysis and preliminary results of the measurement of proton-induced deuteron breakup at the Cyclotron Center Bronowice, Institute of Nuclear Physics, Polish Academy of Sciences in Kraków are presented.

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1. Motivation

The understanding of nuclear interactions and the structure of nuclei is the focus of research in the domain of few-nucleon systems. Deuteron breakup in collision with a proton can serve as a tool for testing modern

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calculations describing nuclear interactions between three nucleons [1–3]. Recent progress in theory allowed for the first time to account for the most important, just after leading nucleon–nucleon interaction, parts of the involved dynamics. This includes three-nucleon force and Coulomb force effects, and calculations performed within a proper relativistic formalism [4–6].

The accurate theoretical calculations have to be confronted with a rich set of measurements. For this purpose, a series of experiments was carried out at KVI Groningen and FZ-Jülich to determine cross section and polarization observables of the $^1\mathrm{H}(d,pp)n$ and $^2\mathrm{H}(p,pp)n$ breakup reactions at intermediate energies [7–13]. The experimental data confirmed the importance of the 3NF and a huge influence of the Coulomb interaction between protons at certain kinematic configurations. However, some discrepancies persist, indicating that our present understanding of the problem is not yet perfect.

Continuation of the studies in a wide range of energies, at the regions of the maximum sensitivity for certain effects is necessary. For this purpose, the BINA (Big Instrument for Nuclear-polarization Analysis) detector setup has been installed at the Cyclotron Center Bronowice (CCB) in Kraków. The combination of the large phase space coverage of the BINA system and a wide range of accessible beam energies provides a unique possibility to study the dynamics of a three-nucleon system.

2. Experimental setup

The BINA detection system is designed to study the elastic and breakup reactions at intermediate energies. It allows to register coincidences of two charged particles in a nearly 4π solid angle, making it possible to study almost the full phase space of breakup and elastic reactions. The detector is composed of two main parts, the forward Wall and the backward Ball [14, 15], see Fig. 1.

The forward Wall consists of a three-plane multi-wire proportional chamber (MWPC) and telescopes formed by two layers of scintillator hodoscopes (vertically placed thin transmission-ΔE strips and horizontally placed thick stopping-E bars). The forward Wall allows to detect a charged particle scattered at a polar angle (θ) in the range of 10°–32° with a full azimuthal angle (Φ) coverage, and up to $\theta = 37°$ with partial azimuthal angle coverage (due to corners of the square-shaped active region of the MWPC). The Wall part has an excellent angular resolution of 0.5°. The backward angles (35°–160° in the LAB frame) are covered by the second detector group Ball, consisting of 149 "phoswitch"-type scintillation detectors measuring the particle energy and providing an approximate determination of the momentum direction. A liquid D_2 target is located inside the Ball detector which serves also as a vacuum chamber.

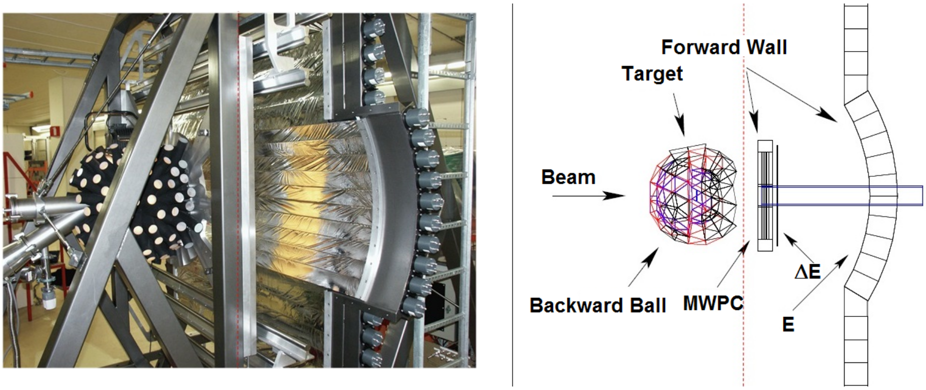

Fig. 1. A side view of BINA. The left panel shows a photograph of BINA side-view and the right one presents a schematic drawing of the forward Wall and the backward Ball.

3. Preliminary results

The first data have been collected for elastic scattering and the *pd* breakup reaction at three proton beam energies: 108, 135 and 160 MeV. Preliminary analysis was performed with the aim of checking consistency of the data collected in the Wall part. The efficiency of MWPC is about 90%. The particle identification (PID) is based on the ΔE–E technique. The events of interest are the coincidences of two charged particles, *i.e.* proton pairs from the breakup process and proton–deuteron from the elastic scattering. This allows us to identify protons and deuterons. Sample PID spectrum, obtained for one combination of overlapping elements of the ΔE and E detectors, is presented in Fig. 2, left. Three groups of events are well visible: a long branch of protons coming from the breakup reaction, a spot of elastically-scattered protons located in the region of the highest energy deposited (in the E detector) and a spot of deuterons coming from the elastic scattering. Proton–proton coincidences analyzed for sample angular configurations reveal correct kinematic dependencies of breakup reaction, see Fig. 2, right.

The energy calibration of the E detectors was carried out on the basis of special runs with proton beam of various energies (70, 83, 97, 108 and 120 MeV) scattered off an Al target. The data were compared to a Monte Carlo simulation performed using Geant4. The registered events are defined by the side ($s =$ right/left), the E detector number ($N = 0, 1, \ldots, 9$) and the polar angle $\theta \pm 1°$. In order to supress the effect of light attenuation along the bar, a combination $\sqrt{c1\,c2}$ of the ADC conversions, $c1$ and $c2$, related to the readout of photomultiplier tubes on both ends of the E detector bar, is used. The distribution of elastically scattered protons is analyzed by fitting

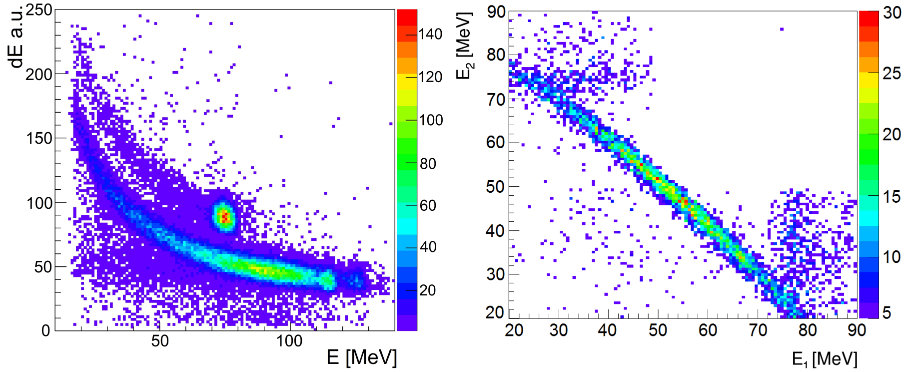

Fig. 2. Left panel: Sample particle identification spectrum obtained for one combination of thin ΔE and thick E scintillators for the beam energy of 135 MeV. Good separation of protons (lower band and spot) and deuterons (upper spot) is visible. Right panel: Kinematical spectrum (correlation of proton energies) obtained for breakup events collected at beam energy of 108 MeV for one selected angular configuration of the two protons $\theta_1 = 29^\circ, \theta_2 = 27^\circ, \Phi_{12} = 180^\circ$.

a Gaussian function for each combination of s, N, θ. A sample calibration curve obtained for detector $E2$ for both sides (right and left) and emission angle ($\theta = 16^\circ \pm 1^\circ$) is presented in Fig. 3.

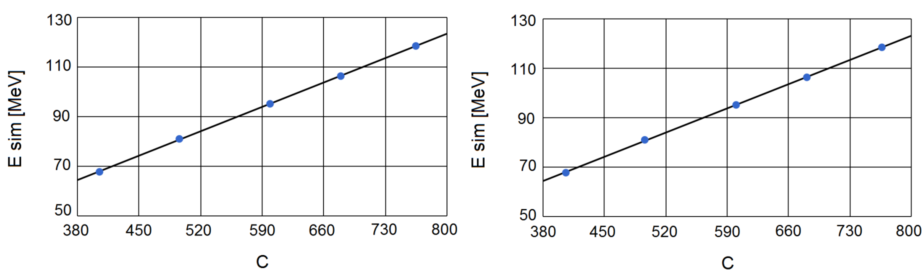

Fig. 3. Sample calibration curves obtained for the detector $E2$ for the right-hand side (right panel) and left-hand side (left panel) with respect to the beam direction and for a selected proton emission angle $\theta = 16^\circ \pm 1^\circ$. On the horizontal axis, $\sqrt{c1\,c2}$ is defined as a C. Statistical uncertainties are smaller than the size of the points.

The analysis of integrated luminosity is ongoing. Without the absolute normalization, the shapes of the cross-section distribution as a function of the S variable corresponding to the energy measured along the breakup kinematics [14] were studied for several angular configurations. In Fig. 4, a comparison of arbitrarily normalized data with calculations is presented.

In this configuration, the predicted effect of 3NF is insignificant. The calculations based on the CD-Bonn potential including the 3NF (CDB+Δ, CDB+TM99) and without 3NF (CDB) are very close to each other. The observed small difference of the widths between the calculations and the measurement will be verified in the further analysis.

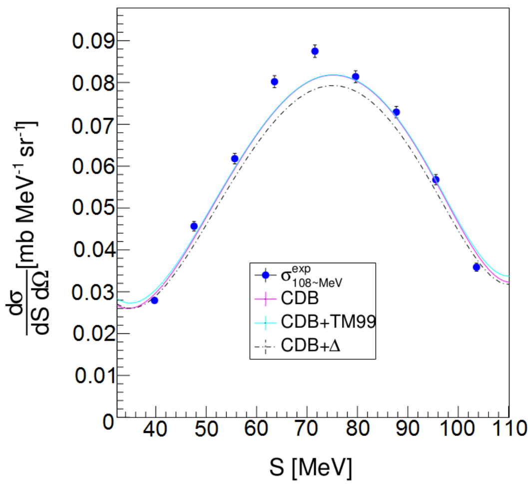

Fig. 4. Preliminary differential cross section for a sample kinematic configuration: $\theta_1 = 29°, \theta_2 = 27°, \Phi_{12} = 180°$ at the beam energy of 108 MeV. The measured data are compared with the calculations: H. Witała (CDB, CDB+TM99), A. Deltuva (CDB+Δ). Normalization of data points is arbitrary.

4. Summary and outlook

A very preliminary analysis of the data taken with the BINA detector at CCB demonstrates a proper and efficient functioning of the forward part of this detector. The aim of the further analysis is to obtain the differential cross section of the breakup reaction at 108 MeV as a function of kinematic variables. The absolute normalization relies on the elastic scattering data measured in parallel to the breakup reaction and the known elastic scattering cross section [16].

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