INVESTIGATION OF THREE NUCLEON FORCE EFFECTS IN DEUTERON–PROTON BREAKUP REACTION*

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Experiments devoted to study subtle ingredients of nuclear dynamics were carried out at KVI in Groningen with the use of the $^1\mathrm{H}(d,pp)n$ breakup reaction at the deuteron beam energy of 80 MeV/nucleon. The aim of the work is to determine the breakup cross sections and confront them with the set of modern calculations which model forces acting between nucleons. Elastic scattering process was also measured for the purpose of the cross section normalization. This paper presents preliminary results of the data analysis including geometry cross check, energy calibration, particles identification and sample distributions of the unnormalized breakup cross sections.

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1. Introduction

Investigation of the three-nucleon system dynamics provides understanding of effective nucleon–nucleon (NN) potential. Quantitatively, this can be done by comparing observables calculated with the use of the Faddeev equations with results of precise measurements. Modern realistic NN interaction models describe well systems composed of two nucleons, however they fail to reproduce data for three-nucleon ($3N$) systems. Only NN calculations combined with additional ingredients of the dynamics like three nucleon force ($3N$F) [1], Culomb force [2] or relativistic component [3] are able to give proper description of the data. The two- and three-nucleon interactions can be also modeled within the coupled-channel (CC) framework by an explicit treatment of the Δ-isobar excitation. Alternatively, contribution of NN and $3N$F to the dynamics may come from the Chiral Perturbation Theory. Here, the many-body interactions appear naturally at growing orders (non-vanishing $3N$F at next-to-next-to leading order). Previous experimental data [4–6] reveal quite seizable $3N$F and Coulomb effects, and confirmed its importance for understanding of the $3N$ system dynamics.

2. Experimental set-up

The experiment was performed with the use of the deuteron beam at the energy of 160 MeV provided by AGOR cyclotron at Kernfysisch Versneller Instituut in Groningen, The Netherlands. Charged products of elastic scattering and $^1\mathrm{H}(d,pp)n$ breakup reaction were detected by BINA (Big Instrument for Nuclear Analysis) [5]. The detection system was developed to investigate the few-body system dynamics in almost 4π geometry. The backward part of the system (BALL) is built of 2×149 plastic scintillators working in a phosphich mode. This part covers a range of polar angles between 40° and 165° and the full range of azimuthal angles. The front part (WALL) consists of the Multi Wire Proportional Chamber (MWPC) and two layers of plastic scintillators which form a ΔE–E system. The scintillator stripes of both layers were mounted orthogonally creating 120 hodoscopes. The WALL part is used for detection of particles with the polar angles from 13° to 40°. The MWPC provides resolution of 0.4° in polar and 0.6°–2.0° in azimuthal angles.

3. Analysis progress

Preliminary presorting was performed on the collected data. Parts of the data characterized with unstable beam current or problems in functioning of any system elements were carefully removed. The reaction channels were identified based on ΔE–E technique and sorted according to the relative

azimuthal angle $\phi_{12} = \phi_1 - \phi_2$ of the two coincident particles. This condition allowed for identification of the two reaction channels: elastic scattering ($\phi_{12} \sim 180°$) and breakup (particles which do not fulfill the restriction).

3.1. Elastic scattering

The elastic scattering is well suited for performing the detector calibration. To select this process, the particle identification was performed by setting gates on each ΔE–E spectrum (see Fig. 1). Then, the proton–deuteron

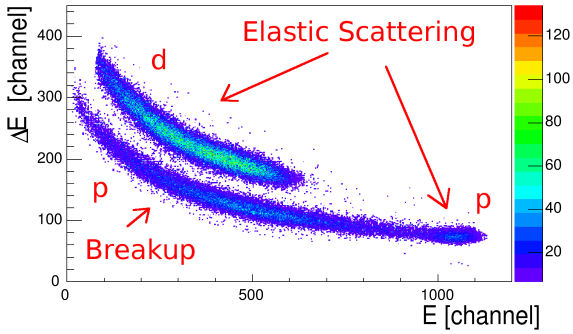

Fig. 1. Example of ΔE–E particle identification spectrum for the given telescope.

coincidences were chosen with the condition imposed on the relative differences of their azimuthal angles of $|\phi_1 - \phi_2| \sim 180°$. The angular relation obtained for events selected in this way is shown in Fig. 2. For the purpose of energy calibration, Geant4 simulation was performed and compared together with the data obtained in the dedicated measurements in which energy degraders of a few different thicknesses were used. Energies calculated in the

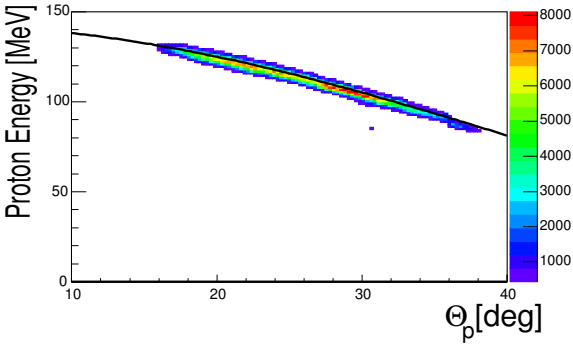

Fig. 2. Kinematical relation for the $^1\mathrm{H}(d,d)p$ elastic scattering at the beam energy of 160 MeV. The solid black line represents calculated relativistic kinematics.

Geant4 code were compared with signals from the detector for the given polar angle and the given hodoscope. Second step was to retrieve the initial kinetic energies of the nucleons, what was done with the use of the simulations as well. The relation between proton energy at the reaction point and the energy in the detector is presented in Fig. 3. The elastic events were also used for the geometry cross check and correction of beam-shift from the target center, allowing better reconstruction of the momenta of detected charged particles.

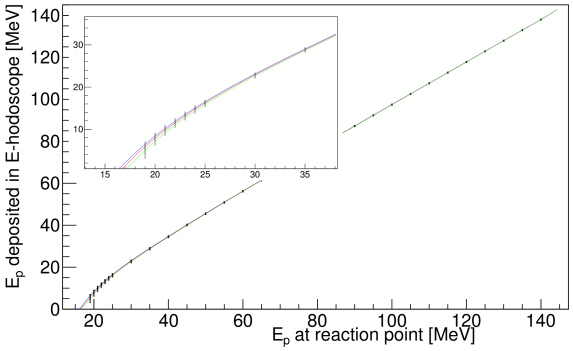

Fig. 3. Relation between energy deposited in the thick E-detector and kinetic energy at the reaction point.

3.2. Breakup channel

The aim of the experiment is to obtain differential cross sections for the breakup reaction for various angular configurations defined by polar angles of the two protons (θ_1, θ_2) and their relative azimuthal angle ϕ_{12}. Kinematical spectra (kinetic energy of the first proton *vs.* kinetic energy of the coincident one) E_1 *vs.* E_2 for different breakup geometries were obtained (see Fig. 4). Events were projected onto the theoretical kinematical curve corresponding to the point-like, central geometry and counted for the given S value (arc-length along the kinematical curve).

A number of the breakup coincidences was obtained as a function of the S and it corresponds to the unnormalized cross sections. The data needs to be corrected for efficiency of the detection system and normalized to the elastic events to obtain absolute values of the cross sections. This work is still in progress and so far shape of the obtained distributions can be qualitatively compared with the theoretical predictions, see Fig. 5.

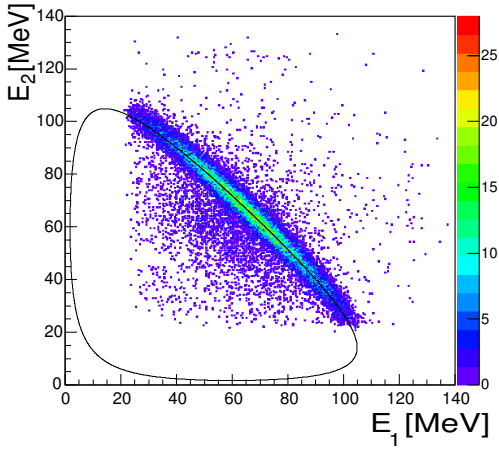

Fig. 4. E_1 *vs.* E_2 kinematical relation for the two registered protons in the chosen angular configuration ($\theta_1 = \theta_2 = 20°$, $\phi_{12} = 80°$). Solid line represents theoretical kinematical relation for the central geometry.

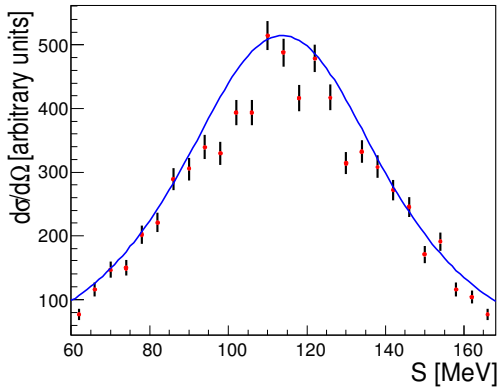

Fig. 5. Example of the unnormalized differential cross section for the chosen angular configuration ($\theta_1 = \theta_2 = 20°$, $\phi_{12} = 80°$) of the two breakup protons. Theoretical predictions of CDBON+TM99 are also presented as the solid line.

4. Summary and outlook

The obtained precise experimental data in a wide phase space region can serve as a valid tool for verification of rigorous theoretical calculations which have been and are being developed. Collecting of such data will be continue. In the near future, series of experiments using the proton beam of energy in the range from 70 MeV to 230 MeV and BINA detector will be performed in the Cyclotron Center Bronowice in Kraków.

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