DEUTERON–DEUTERON COLLISION AT 160 MeV

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(Received November 2, 2015)

The experiment was carried out using BINA detector at KVI in Groningen. For the first time, an extensive analysis of the data collected in back part of the detector is presented, where a clusterization method is utilized for angular and energy information. We also present differential cross sections for the ($dd \to dpn$) breakup reaction within dp quasi-free scattering limit and their comparison with first calculations based on Single Scattering Approximation (SSA) approach.

DOI:10.5506/APhysPolB.47.411

1. Introduction

Experimental studies of three-nucleon dynamics have been the focus of few-body research in recent decades. Among them, the nucleon–deuteron (Nd) scattering has been widely investigated. Experiments at KVI in Groningen, at KUTL/RIKEN/RCNP in Japan, and at IUCF in USA have provided large sets of high-precision data [1] (and references therein), not only for the cross sections but also for the polarization observables. Tremendous progress has been made to understand the $3N$ dynamics. With the new high-precision data, covering a large phase space, it has become possible to pin-down the effects as subtle as three-nucleon forces ($3NF$) [2, 3]. The experimental program at KVI has been carried out to extent those studies to the breakup reaction. It used initially the SALAD detector [4] later upgraded to the BINA detector setup [5], covering even larger phase space and with better detection capabilities. The experiments with SALAD and BINA alone filled up a large gap in the $3N$ database, not only Nd elastic scattering but also breakup reaction [1, 6]. The next step for the experimental program was to move forward in the sector of four-nucleon ($4N$) system, where the knowledge is scarce in both the theoretical as well as the experimental domains [7]. The $3N$F effect is expected to be enhanced in $4N$ system, that makes the study of $4N$ even more attractive.

2. Experiment

The BINA detector is a 4π apparatus designed for few-nucleon scattering experiments at intermediate energies. BINA is divided into two main parts, forward wall (θ: 13°–40°) and backward ball (θ: 40°–165°). The forward wall consists of (a) multi-wire proportional chamber (for reconstruction of angles of the scattered charged particles), (b) 24 vertical thin plastic scintillator 'stripes', and (c) 10 horizontal thick plastic scintillator 'slabs'. The plastic stripes and slabs form 240 ΔE–E telescopes for particle identification. The backward ball is nearly spherically symmetric, and made up of 149 triangular phoswich detector elements. These elements are arranged in such a way that the formed geometry of the ball resembles that of a soccer ball. The ball, at the same time, plays the role of the reaction chamber as well as the detector. The work presented here is based on the experiment performed at KVI in Groningen, the Netherlands, with the BINA detector, where an unpolarized beam of deuterons with an energy of 160 MeV was provided from AGOR cyclotron to impinge upon liquid hydrogen and liquid deuterium targets.

3. Data analysis and sample results

The most basic data analysis steps, in forward scattering (wall) region of BINA, such as particle identification, energy calibration and cross section evaluation were already described in our previous works [8, 11, 12]. For the data collected in the backward scattering (ball) region, the analysis task was difficult and challenging. This was mainly due to the lack of light tightness of the ball elements, which resulted in additional contributions from the neighboring elements to the registered signal, *i.e.* a particle was registered in the ball with more than one element responding. Contribution of such events was significant and could not be neglected.

Therefore, to reconstruct a particle emission angle and energy, a cluster instead of a single element was considered in the further analysis. In an ideal situation, where the ball elements would have been perfectly light-tight, the emission angles (θ, ϕ) of a detected charged particle in the i^{th} ball element would be taken at the centroid of that ball element, *i.e.* $\theta = \theta_i$ and $\phi = \phi_i$ — these are the angles before applying clusterization. A given cluster is characterized with its azimuthal ϕ_c and polar θ_c angles and its energy E_c. The ϕ_c and θ_c are calculated as weighted average of the angles of the cluster elements as follows:

$$\phi_c = \frac{\sum_{i=1}^{n} \phi_i E_i}{\sum_{i=1}^{n} E_i} \qquad \text{and} \qquad \theta_c = \frac{\sum_{i=1}^{n} \theta_i E_i}{\sum_{i=1}^{n} E_i}\,, \tag{1}$$

where n is the number of elements constituting a cluster and i refers to the i^{th} element in the cluster. The comparisons of the obtained emission angles, before and after the clusterization, are presented in Fig. 1 (azimuthal) and Fig. 2 (polar). The cluster method gives more realistic angular distribution for most of the events, filling the empty gaps.

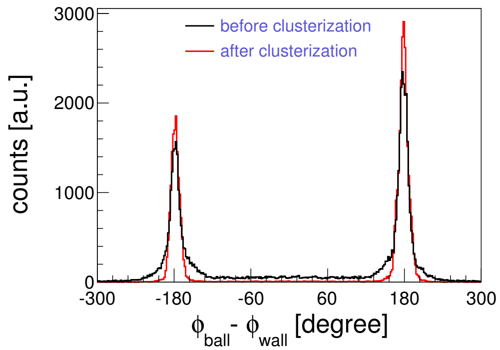

Fig. 1. The distribution of elastically scattered wall–ball coincident deuterons is presented as a function of their relative azimuthal angle. The peaks are centered around ±180° and the width of the peaks represents the angular resolution of the detector. Clusterization (the gray/red curve) led to an improvement in the angular resolution as compared to analysis performed without clusterization (the black curve).

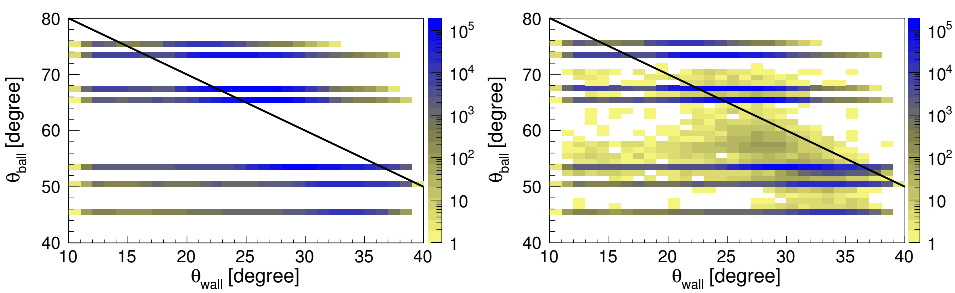

Fig. 2. A correlation between polar angles of wall (θ_{wall}) and ball (θ_{ball}) is presented for the wall–ball coincidence of the two elastically scattered deuterons. Left panel represents the case before applying the clusterization and the right — after.

In order to reconstruct the cluster energy, one needs to take into account a so-called attenuation factor α which refers to the light loss on the borders of the ball elements. Thus the cluster energy is calculated as follows:

$$E_{\rm c} = E_{\rm max} + \sum_{i=1}^{n-1} (1+\alpha) E_i \,, \tag{2}$$

where n and i have the same meaning as in Eq. (1) and the $E_{\rm max}$ is the energy deposited in a central cluster element where the particle is detected (deposits the largest part of its energy). The estimation of α was done by looking at cluster events where only two adjacent ball elements responded to the detection of an elastically scattered deuteron, since the deuteron energy was well-known (on the basis of the second deuteron angle measured in wall). Investigation performed for several sample elements showed that the α value is approximately 10%. The energy calibration, based on clusterization, was checked for the wall–ball coincident dd elastic scattering, see Fig. 3. Further details of the ball detector and the related data analysis can be found in [13]. Due to not high enough efficiency of ball, those data were used for checks of systematic effects only.

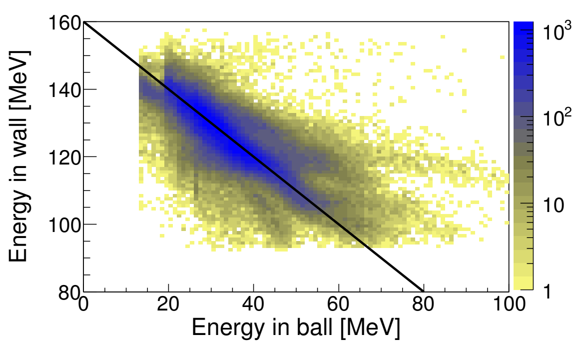

Fig. 3. The wall–ball energy correlation for the dd elastic scattering reaction. The black line refers to the calculated kinematics.

For the data collected in the forward wall region of BINA, in the first step, the unnormalized differential cross sections for the $dd \to dpn$ breakup reactions were obtained, as it was presented in Ref. [11]. They were subsequently normalized with the use of existing dd elastic scattering data from BBS experiment [15]. So far, we have obtained the cross sections for 147 kinematical configurations (about 4 500 data points) in the $dd \to dpn$ breakup reaction near to quasi-free scattering limit (neutron acting as a spectator). The data, when compared to the state-of-the-art calculations based on Single Scattering Approximation (SSA) [14], are well-described when the neutron energy is close to zero. We present here only sample cross section distributions, see Fig. 4. The normalization procedure and the full set of obtained cross section results can be found in [13].

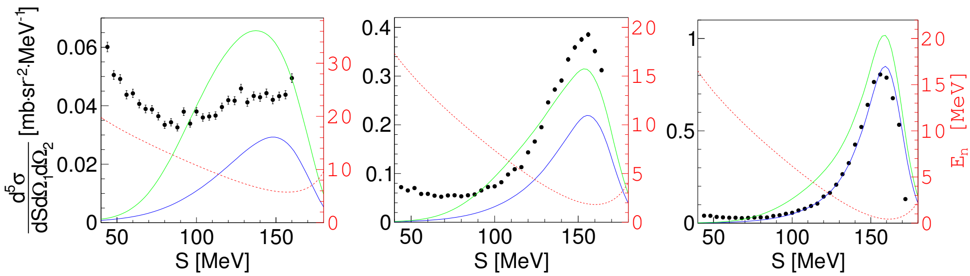

Fig. 4. Sample cross section distributions obtained for 3 geometries characterized by the same combination of polar angles: ($\theta_d = 22°$, $\theta_p = 20°$) and three different ϕ_{dp} values: 140° (left), 160° (center) and 180° (right). The solid lines are for theoretical prediction — dark gray/blue with 1-term calculations and gray/green with 4-term calculations. The dashed line and the right-hand scale (both in light gray/red color) present the dependence of the spectator neutron energy (E_n) along S-axis.

4. Conclusion and outlook

We presented a first attempt to precise data analysis of events registered in the ball part of the BINA detector. The obtained cross sections in QFS limit are fairly well-described when the spectator neutron energy is small enough. The precise experimental data, so obtained, in a wide phase-space region, can serve as valid tool for verification of rigorous theoretical calculations which have been and are being developed.

The author would like to thank Dr. A. Deltuva for providing the theoretical calculations. We also thank Prof. E. Stephenson and Dr. C. Bailey for allowing us to use their BBS results on elastic scattering for normalization purpose. We acknowledge support by the Foundation for Polish Science — MPD program, co-financed by the European Union within the European Regional Development Fund, the "Doctus" stipend by the Lesser Poland region for the Ph.D. students. This work was also supported by the Polish 2013–2016 science found as research Project 2012/05/E/ST2/02313, and by the European Commission within the Seventh Framework Programme through IA-ENSAR (contract No. RII3-CT-2010-262010).

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