# RECONSTRUCTION OF THE NEUTRON MOMENTUM IN THE DEUTERON BREAKUP REACTION*

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Experiments devoted to studies of deuteron breakup reactions were carried out at KVI in Groningen with the use of the BINA detector. In this paper, a technique for direct neutron detection is presented. Time-of-flight information, signal amplitude and timing asymmetry measured at opposite sides of long scintillators were applied for direct neutron detection in kinematically complete three-body breakup experiments. The main motivation is to reach into phase-space regions, which have not been explored yet. The preliminary analysis of the $^2\mathrm{H}(p,pn)p$ and $^2\mathrm{H}(d,dn)p$ data measured at 160-MeV deuteron beam is presented.

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## 1. Introduction

Few-nucleon systems are basic laboratories for testing models of nucleon–nucleon interactions. The simplest cases, in which different theoretical models describing the system dynamics can be tested, are those composed of three ($3N$) and four ($4N$) nucleons. The differential cross sections of the deuteron breakup reactions are very sensitive to various aspects of the system dynamics, such as the Coulomb force effects or even more subtle effects due to the Three Nucleon Force (3NF). Exact solutions of the Faddeev equations with modern nuclear potential such as Tucson–Melbourn, Urbana IX, coupled-channel (CC) or alternative approach using Chiral Perturbation Theory (ChPT) are available. For verification and further developments of these models, systematic and precise data are needed.

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## 2. Experimental setup

BINA is an almost $4\pi$ detection system designed for few nucleon scattering experiments at intermediate energies. It is composed of two main parts, Forward Wall, covering angles (16°–40°) and Backward Ball (40°–165°). Backward Ball consists of 149 phoswich scintillators arranged in a fullerene-like symmetric shape. It plays a role of a scattering chamber as well as of a particle detector. Forward Wall is composed of a multi-wire proportional chamber (MWPC), 12 vertical thin scintillator 'stripes' ($\Delta E$) with the dimension of $0.2 \times 3.17 \times 86.8$ cm$^3$, and 10 horizontal thick scintillator 'slabs' ($E$) with the dimension of $9 \times 12 \times 220$ cm$^3$. Both the $\Delta E$ and the $E$ part of the detector are made of BICRON-408 plastic scintillator material. The scintillators form an array of virtual $\Delta E$–$E$ telescopes for particle identification. Detailed information about the detector can be found in Ref. [1]. The experiments were performed with the use of the deuteron beam at the energy of 160 MeV and liquid hydrogen and deuterium targets.

## 3. Reconstruction of neutron momentum

The BINA detector was designed to reconstruct charged particles produced in the final state of deuteron–deuteron and deuteron–proton scattering. A special approach has been developed in order to apply this detector for neutron detection. The thick $E$ scintillator has the highest sensitivity for neutron interaction, with an average efficiency for the neutron detection around 10% [2]. The rest of the Forward detector works as an active veto. Each thick $E$ bar was read out from both sides by photomultipliers (PMT). The signals from scintillators were used as start pulses in a Time-to-Digital Converters (TDC) working in a common-stop mode. A stop signal was produced by a properly delayed trigger signal. As a consequence, the times registered in PMTs on left- and right-hand sides ($t_{\mathrm{L}}$, $t_{\mathrm{R}}$) depend on the particle position along the scintillator, $x$,

$$\begin{aligned} t_{\mathrm{L}} &= t_{\mathrm{T}} + \frac{nx}{c} + t_{\mathrm{trig}}\,, \\ t_{\mathrm{R}} &= t_{\mathrm{T}} + \frac{n(L-x)}{c} + t_{\mathrm{trig}}\,, \end{aligned}$$

where $L$ is the length of the $E$ detector, $t_{\mathrm{T}}$ is the time of flight (TOF) of the particle from the reaction vertex.

The position along the $x$-axis can be calculated as the difference between the arrival time from both PMTs. The position along the $y$-axis is given by the position of the scintillator. In order to test the method, it has been applied to events with protons reconstructed in the final state. The left panel in Fig. 1 shows the correlation between the position coordinate of a proton derived from MWPC ($X_{\mathrm{C}}$) and the position reconstructed using the TDC information ($X_{\mathrm{T}}$). Resolution of the position reconstructed by the TDC method has been estimated to be around 3 cm (FWHM) as illustrated in the right panel of Fig. 1.

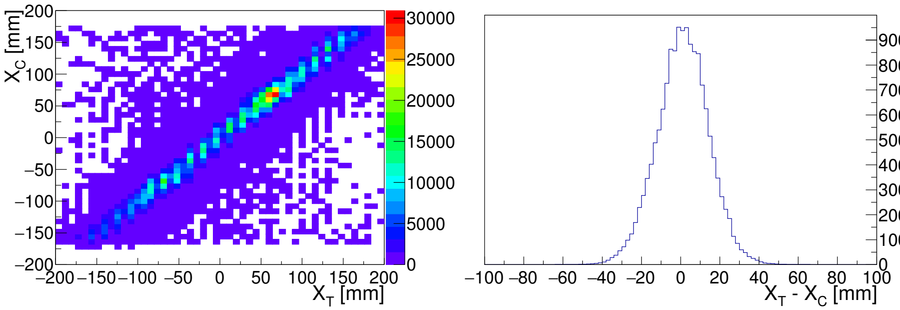


Fig. 1. Left panel: the $x$-coordinate reconstructed from the time information ($X_{\mathrm{T}}$) plotted *versus* the $x$-coordinate obtained from MWPC ($X_{\mathrm{C}}$). Right panel: histogram of the differences ($X_{\mathrm{T}}$–$X_{\mathrm{C}}$).

The second method of reconstruction of the particle position along the scintillator relies on the asymmetry of signal magnitudes, measured by left and right photomultipliers. It is well-known that assuming linear light attenuation, the logarithm of the ratio between these magnitudes depends linearly on the position along the scintillator. In our approach, this dependence has not been assumed and the position calibration has been obtained using the position information from MWPC. The quality of position reconstruction given by this method is shown in Fig. 2. Both methods, ADC- and TDC-based, provide independent measurements, and combined together with proper weights could result in a better position reconstruction for events where no information from MWPC is available.

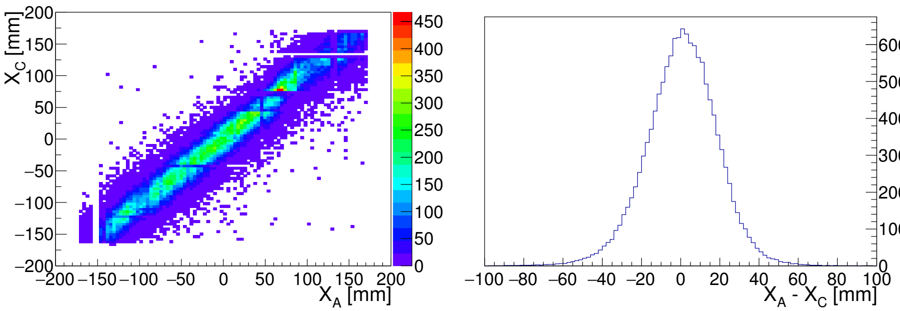


Fig. 2. The same as in Fig. 1, but instead of time asymmetry, the difference between signal amplitudes measured in the left and right PMT has been used for the $x$-coordinate reconstruction.

Taking the sum of $t_{\mathrm{L}}$ and $t_{\mathrm{R}}$ removes the dependence on the hit position and allows calculating time of flight for a given particle. Using this information, the energy of the particle can be directly calculated. Figure 3 illustrates the resolution of the energy reconstruction for protons with the use of TOF. To find a neutron TOF, at least one charged particle must be registered in the Wall detector in order to calculate the time of the interaction vertex. Having the neutron position and its energy, one can reconstruct its momentum.

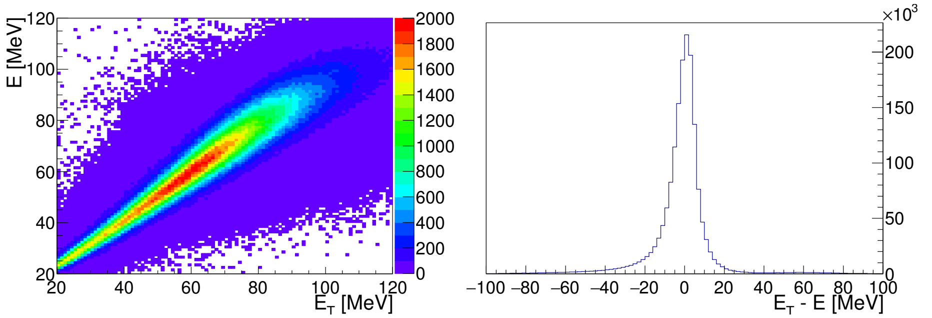


Fig. 3. The same as in Fig. 1, but for energy reconstructed from the timing and delivered by standard method based on the pulse height calibration.

## 4. Results

By selecting events with a good candidate for a detected neutron and an accompanying charged particle (proton in the case of *dp* and deuteron for *dd* scattering), one can check kinematical consistency of the reaction. For a 3-body reaction, usually the relation between the energies of the two registered particles is plotted for a kinematical configuration defined by fixed polar angles ($\theta_1$, $\theta_2$) and the relative azimuthal angle ($\Delta\phi_{12}$) between momenta of these particles. Sample geometrical configurations are presented in Fig. 4. Size of the $\theta$ and $\phi_{12}$ bins are $\Delta\theta = 5°$, $\Delta\phi_{12} = 10°$, respectively. The quality of the neutron momentum reconstruction can also be inferred from the reconstructed missing mass of the proton–neutron and deuteron–neutron system (for *dp* and *dd* reactions, respectively). As can clearly be seen in Fig. 5, in both cases, the missing mass distribution is peaked, as expected, around the proton's mass.

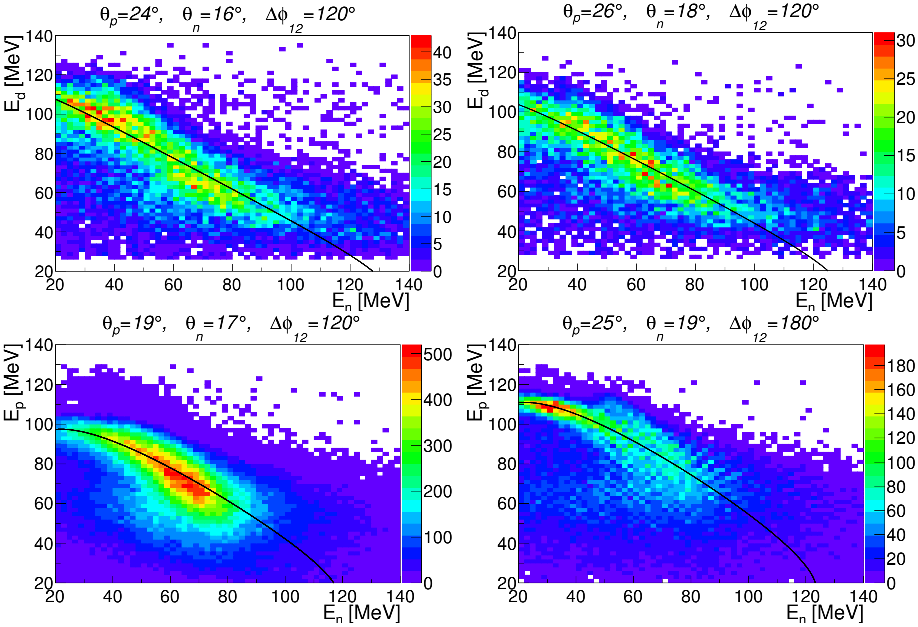


Fig. 4. Three-body breakup kinematics for some selected angular configurations defined in the panels. The results for ${}^{2}\mathrm{H}(d,dn)p$ reactions and ${}^{2}\mathrm{H}(p,pn)p$ reactions are shown in the top and bottom panels, respectively. The proton or deuteron energy is on the vertical, neutron energy on horizontal axis. The solid lines represent the theoretical kinematics calculated for the point-like geometry.

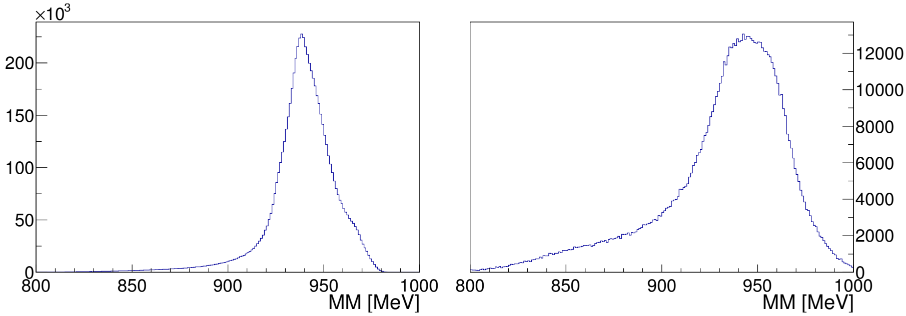


Fig. 5. The missing mass (MM) spectra; the left panel shows MM for the $p$–$n$ system, the right one for the $d$–$n$ system. Both distributions are peaked, as expected, around the proton's mass.

## 5. Conclusion

A set of useful tools and a technique for reconstruction of neutron momenta was developed utilizing complete time and amplitude information from the thick $E$ scintillator. The method will allow for the direct studies of the Coulomb force effects by comparing cross sections of the $^2\mathrm{H}(d,dn)p$ and $^2\mathrm{H}(d,dp)n$ reactions at the same kinematical conditions. Moreover, the charge symmetry breaking can be studied as suggested in Ref. [3].

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REFERENCES

[1] E. Stephan *et al.*, *Int. J. Mod. Phys. A* **24**, 515 (2009).

[2] J. Kuboś, B.Sc. Thesis, AGH UST Kraków, 2014.

[3] C.R. Howell *et al.*, *Phys. Rev. C* **48**, 2855 (1993).