**Title:** Simulation of Star configurations in the BINA detector

**Author:** Albert Szadziński, Andrzej Wilczek, Elżbieta Stephan, B. Włoch, N. Kalantar-Nayestanakic, St. Kistryn, Barbara Kłos, Angelina Łobejko i in.

**Citation style:** Szadziński Albert, Wilczek Andrzej, Stephan Elżbieta, Włoch B., Kalantar-Nayestanakic N., Kistryn St., Kłos Barbara, Łobejko Angelina i in. (2020). Simulation of Star configurations in the BINA detector. “Acta Physica Polonica B” (Vol. 51, No 3 (2020), s. 763-768), doi 10.5506/APhysPolB.51.763

# SIMULATION OF STAR CONFIGURATIONS IN THE BINA DETECTOR*

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

[a]Institute of Physics, University of Silesia, 41-500 Chorzów, Poland
[b]Institute of Nuclear Physics Polish Academy of Sciences, 31-342 Kraków, Poland
[c]KVI-CART, University of Groningen, 9747 AA Groningen, The Netherlands
[d]Institute of Physics, Jagiellonian University, 30-348 Kraków, Poland
[e]Forschungszentrum Jülich IKP, 52425 Jülich, Germany
[f]Faculty of Physics, University of Warsaw, 02-093 Warszawa, Poland

*(Received January 14, 2020)*

Star Anomaly is one of the most intriguing and unsolved discrepancies between theoretical calculations and experimental data observed in the domain of few-nucleon systems at low energies. Previous and upcoming measurements of the breakup reaction with the use of the BINA detector enable systematic studies of the Star configurations at intermediate energies. A dedicated simulation was developed to study feasibility of registering such events with the required accuracy and to support the future data analysis. An additional rotation angle $\beta$ has been introduced to parametrise the Star configurations. First results concerning the acceptance of certain segments of BINA for registering the Star configurations are presented.

DOI:10.5506/APhysPolB.51.763

## 1. Introduction

Studies of few-body systems are a key to understanding nuclear interactions and properties of nuclei. Models of nucleon–nucleon interactions based on meson-exchange theories have proven insufficient to correctly describe the dynamics of the simplest few-nucleon systems ($A > 2$) [1]. Theoretical and experimental investigations showed that, in order to correctly describe nuclear interactions, an additional ingredient, 3NF (three-nucleon force),

* Presented at the XXXVI Mazurian Lakes Conference on Physics, Piaski, Poland, September 1–7, 2019.

is necessary. Nowadays, 3NF can be either introduced by advanced models, such as for example TM99 [2] or Urbana IX [3], or as an effective force emerging naturally together with the nucleon–nucleon interactions. The latter solution is applied in the Coupled-Channel (CC) [4] method by adding a $\Delta$-isobar degree of freedom. Another, and more fundamental approach, is based on the Chiral Effective Field Theory [5], where the contribution of 3NF arises naturally at a certain order of calculations. Recently, the Coulomb interactions and relativistic effects have also been introduced into the theoretical framework and it turned out that they played an important role in the description of few-body systems. In spite of many successful developments in description of observables for three-nucleon systems, there are still unexplained effects, even at low energies, for example in polarization-dependent observables ($A_y$ Puzzle) and in cross section for the Space Star.

### *1.1. Space Star Anomaly*

The Space Star Anomaly was for the first time observed in a *nd* breakup reaction at 13 MeV, where the measured cross section was 30% above the theoretical predictions [6]. Interestingly, another experiment to study the *pd* breakup reaction at the same energy showed a discrepancy of 15%, with the theory overestimating the experimental results [7]. The Space Star configuration corresponds to the final state of nucleons in the center-of-mass system, where the momenta of the three outgoing particles have the same magnitudes and lie in the plane normal to the beam direction. Space Star is a special case of a more general category of Star configurations defined, depending on the plane inclination angle $\alpha$ (Fig. 1), as:

— in-Plane Star ($\alpha = 0°$ or $\alpha = 180°$),

— Space Star ($\alpha = 90°$),

— off-Plane Star ($\alpha$ angle between those two extremes).

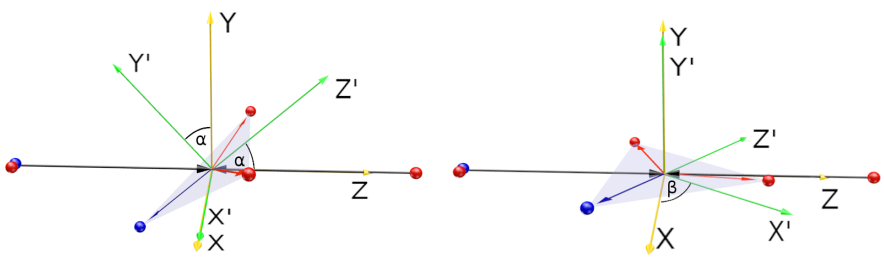


Fig. 1. Definitions of $\alpha$ and $\beta$ angles in the center-of-mass system. Example on the right-hand side corresponds to $\alpha = 0°$.

In subsequent experiments, it was observed that the discrepancies between the experiment and the theory disappear as the $\alpha$ angle was changed from Space to in-Plane Star [8]. Moreover, the Space Star Anomaly tends to decrease for higher reaction energies [9–11]. However, the studies at intermediate energies were scarce and they require more systematic approach. In the presented work, rotation by an angle $\beta$ around the beam direction (Fig. 1) has been introduced to increase the available configuration space.

### *1.2. BINA detector*

An upcoming experiment at CCB (Cyclotron Centre Bronowice, Institute of Nuclear Physics, Polish Academy of Sciences in Kraków) using the BINA (Big Instrument for Nuclear-polarization Analysis) detector will provide new data concerning the Star configurations in the $^2\mathrm{H}(p,pp)n$ breakup reaction at intermediate proton beam energies (108 MeV, 135 MeV and 160 MeV) [12]. BINA consists of two detection systems, Wall and Ball, covering together polar angles $\theta \in (10°; 165°)$ (Fig. 2). Ball consists of 149 phoswich detectors surrounding a liquid deuterium target. The entire vacuum scattering chamber is separated from air by a kapton–kevlar window. Wall consists of a three-plane Multi-Wire Proportional Chamber (MWPC) to determine the position of passing particles and an array of ($\Delta E$–$E$) telescopes used for measuring energy and for particle identification.

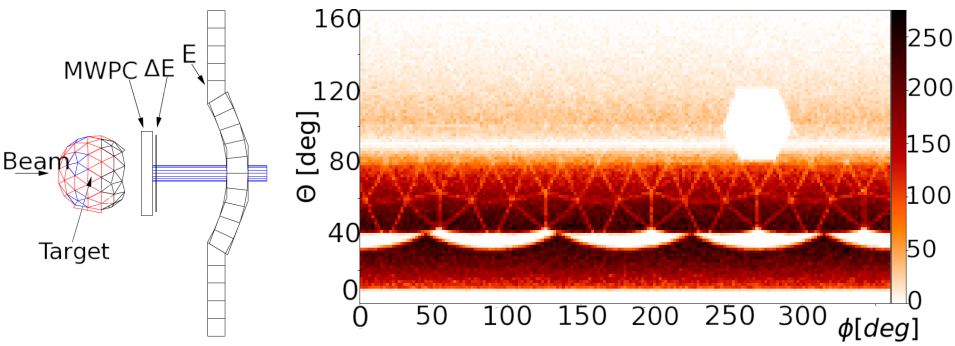


Fig. 2. Left: A schematic view of the BINA detector. Right: Angular distribution of events registered in scintillator detectors as obtained from the simulation ($2\times10^6$ events) for a $^2\mathrm{H}(p,pp)n$ reaction at 160 MeV.

For the purpose of preliminary analysis and to identify angular ranges related to the Star conditions, a dedicated simulation was developed. As a result, angular distribution of protons originating from the star configurations was determined. Moreover, the acceptance of the detection system for proton–proton coincidences was obtained. Since Wall has higher angular

resolution than Ball, three distinct scenarios were analysed: registering of two protons in Wall, two protons in Ball, and that of one proton in Wall and one proton in Ball.

## 2. Results

The core of the simulation was created using the Geant4 framework [13]. The PLUTO toolkit (HADES@GSI) [14] specifying kinematics of the $^2\mathrm{H}(p,pp)n$ reaction was used in the particle generation module. Furthermore, an internal method for calculation of the Star kinematics was introduced with the aim to generate such events or to filter them out. In the course of the simulation, information about energy, detector number, positions in MWPC,

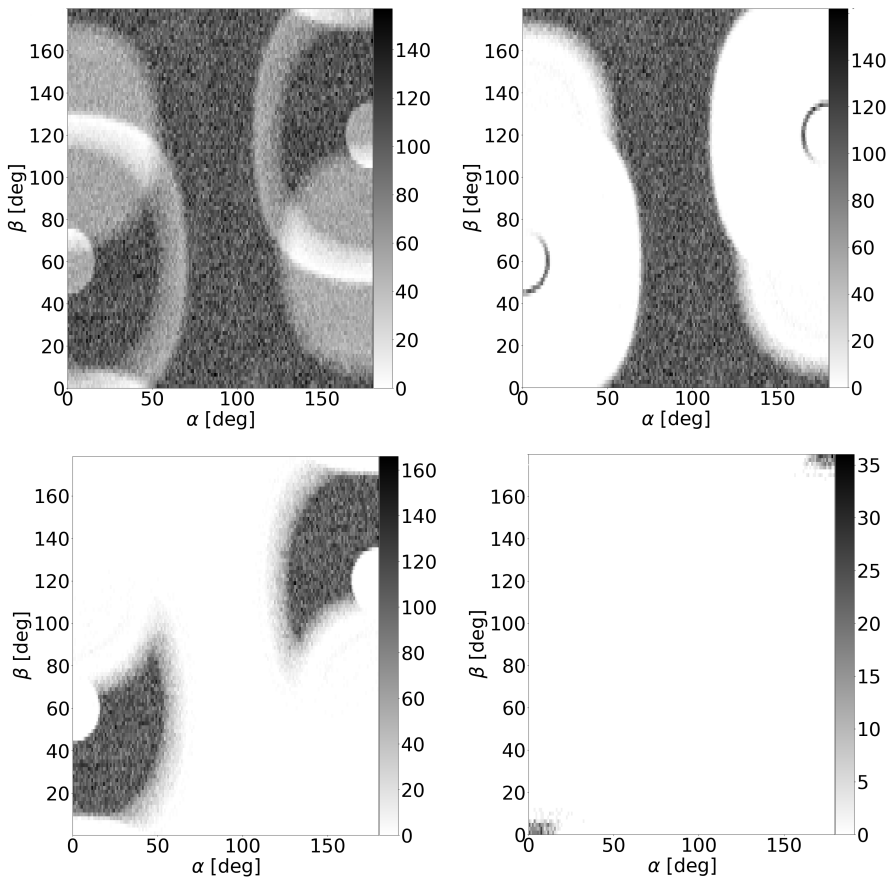


Fig. 3. The acceptance of the BINA detector for registering protons from the Star configurations as obtained on the basis of simulations: single events (top left) and proton–proton coincidence events for Ball–Ball (top right), Ball–Wall (bottom left) and Wall–Wall (bottom right).

scattering angles ($\theta$ and $\phi$) in the laboratory system and the Star angles ($\alpha$ and $\beta$) in the center-of-mass system were recorded. In the first part of the simulation, events were generated specifically for the entire set of the Star configurations to inspect the relationship between the scattering angles ($\theta$, $\phi$) and the ($\alpha$, $\beta$) angles. Then, the $^2\mathrm{H}(p,pp)n$ reaction at 160 MeV was simulated in the full phase space using the PLUTO module and the events meeting the Star conditions were selected. Further, information about proton–proton coincidences registered in each part of the detector was extracted to obtain the distributions of the detection acceptance (Fig. 3).

Studying the relationship between $\theta$, $\alpha$ and $\beta$ angles, several characteristic groups of events can be identified (Fig. 4). The point 90°, 57° in the $\theta$ *vs.* $\alpha$ plane corresponds to the Space Star. For this particular configuration, the $\beta$ angle is equivalent to the azimuthal angle, thus variations of $\beta$ have no influence on $\theta$. There are two (three if a neutron was be detected) characteristic points in the $\theta$ *vs.* $\beta$ plane, for which $\beta$ is constant, regardless of the $\alpha$ variations. The consequence of this observation is that there is one, arbitrarily chosen, single detector at $\theta = 57°$ that registers protons from the Space Star and all other Star configurations. Therefore, it is possible to study the entire space of configurations requiring coincidence with only one detector element in the Ball segment.

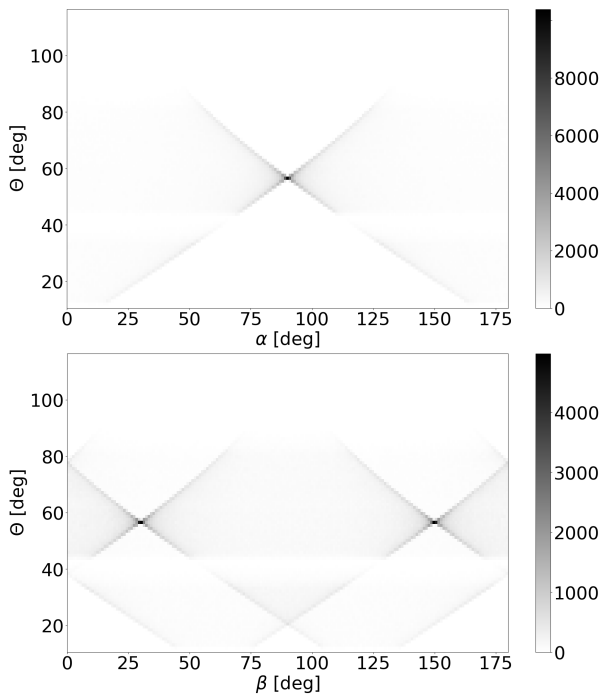


Fig. 4. $\theta$ *vs.* $\alpha$ and $\theta$ *vs.* $\beta$ relations for the whole set of the Star configurations.

## 3. Summary

The particle angular distributions for the $^2$H$(p,pp)n$ breakup reactions at 108, 135 and 160 MeV present no significant differences. For the $^2$H$(p,pp)n$ reaction, all Space Star events are registered in Ball segments ($\theta \approx 57°$). In addition, thanks to the parametrisation of events with the $\beta$ angle, it was shown that requiring coincidence with one particular element of Ball provides data for all the Star conditions. The studies limited to $\beta = 0°$ would suffer from a limited number of coincidences in Wall, corresponding to $\alpha$ angles between 0° and 40°. Therefore, the concept of rotation over $\beta$ enables widening the range of Star configurations accessible for a precise analysis in the BINA experiments. The simulation tool will be further used to determine the accuracy of selection of the Star configurations related to the angular resolution of BINA and will be developed by including the theoretical cross section for the studied reaction.

This project is supported by the National Science Centre, Poland (NCN) grants No. 2016/23/D/ST2/01703 and No. 2012/05/B/ST2/02556.

REFERENCES

[1] K. Ermisch, *Phys. Rev. C* **68**, 051001(R) (2003).
[2] S.A. Coon, H.K. Han, *Few-Body Syst.* **30**, 131 (2001).
[3] B.S. Pudliner *et al.*, *Phys. Rev. Lett.* **74**, 4396 (1995).
[4] P.U. Sauer, *Phys. Rev. C* **68**, 024005 (2003).
[5] U.G. Meißner *et al.*, *Phys. Rev. C* **66**, 064001 (2002).
[6] J. Strate *et al.*, *Nucl. Phys. A* **501**, 51 (1989).
[7] K. Ohnaka *et al.*, *Few-Body Syst.* **55**, 725 (2014).
[8] K. Ishibashi *et al.*, *Few-Body Syst.* **54**, 295 (2013).
[9] G. Rauprich *et al.*, *Nucl. Phys. A* **535**, 313 (1991).
[10] H. Patberg *et al.*, *Phys. Rev. C* **53**, 1497 (1996).
[11] J. Zejma *et al.*, *Phys. Rev. C* **55**, 42 (1997).
[12] A. Łobejko *et al.*, *Acta Phys. Pol. B* **50**, 361 (2019).
[13] S. Agostinelli *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **506**, 250 (2003).
[14] I. Frohlich *et al.*, *PoS* **ACAT2007**, 076 (2007).