Experimental studies of the three nucleon system dynamics in the proton induced deuteron breakup at 108 MeV

Angelina Łobejko\textsuperscript{1,2}

for the BINA Collaboration \textsuperscript{2,3,4,5,6,7}

1) Institute of Experimental Physics, University of Gdańsk
2) Institute of Physics, University of Silesia
3) Institute of Nuclear Physics, PAN, Kraków
4) Institute of Physics, Jagiellonian University, Kraków
5) Faculty of Physics, University of Warsaw, Warsaw
6) University of Groningen, The Netherlands
7) Tata Institute of Fundamental Research, TIFR Mumbai, India
8) Tohoku University, Sendai, Japan
Three Nucleon (3N) System

➢ Prediction of the nucleon-nucleon (NN) potentials:
  • Very well describe the experimental data for the 2N system;
  • Do not reproduce even the binding energy of the $^3$H and $^3$He and heavier systems;
  • Fail to reproduce the minimum of the d(N,N)d elastic scattering cross section;

➢ Introducing the Three-Nucleon Force (3NF) as a concept of additional dynamics related to the presence of the third nucleon solves these problems;

➢ In ChEFT, the 3NF naturally appears in the NNLO;

WHY DO WE WANT TO STUDY 3N SYSTEM

➢ Observables can be calculated in ab-inito regime;
➢ The environment is non-trivial as compared to NN systems and probably richer in dynamics;
➢ The nuclear potentials tested in those simple systems can be used in more complicated ones;
➢ To learn about nuclear interactions.
Studies of 3N System with BINA@CCB

BINA – Big Instrument for Nuclear-Polarization Analysis

➢ Experimental program:
  • Measurement of $^2\text{H}(p,pd)$ elastic scattering at 108, 135 and 160 MeV;
  • Measurement of $^2\text{H}(p,pp)n$ breakup reaction at 108 and 160 MeV for over 200 kinematic configurations;

➢ The aim:
  • Studies of 3NF;
  • Verification of predicted Coulomb and relativistic effects;
  • Tests of upcoming ChEFT calculations;
Experimental setup

• The forward part of detector (Wall):
  1. Multi-Wire Proportional Chamber (MWPC):
     ➢ 3 anode wire planes to reconstruct the exact information about emission angle of the outgoing charged particles
  2. ΔE-E hodoscopes:
     ➢ Two layers of plastic scintillators: 24 vertically-placed thin transmission-ΔE strips and 10 horizontally-placed thick stopping-E bars

• The backward part of detector (Ball):
  ➢ System of 149 phosswitch (phosfor sanwich) - combination of scintillators with dissimilar pulse shape characteristics optically coupled to each other and to a common PMT
  ➢ The target system located inside the Ball:
    1) LD₂ target
    2) Al target with a thin ZnS layer (callibration runs)

DATA REGISTERED ONLY BY THE FORWARD WALL!
The measurement of the $^2\text{H}(p,pp)n$ at 108 MeV

- Results of the **first experimental run** at 2016;
- Particle Identification procedure is based on the $\Delta E$-$E$ technique;
  - Perpendicular arrangement allows to build **two-dimensionnal spectra** where protons and deuterons distribution can be well distinguished;
  - The gates are **wide enough** to avoid a significant loss of particles -> the slight overlap of them is allowed;
- The **excellent efficiency** of the Wall detectors;
- The events identified as **proton-proton coincidences** were analyzed event-by-event and sorted according to angular configurations;

\[ \theta_1 = 15^\circ, \theta_2 = 19^\circ, \varphi_{12} = 160^\circ \]
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Data analysis of the elastic scattering:

- **Deuterons** from elastic scattering were the basis of the normalization procedure to a known cross section at 108 MeV – Ermişc et al., Phys. Rev. C 71, 064004 (2005) – data with the systematic uncertainty between 4.4% - 6.5%

**Corrections:** hadronic interactions, Wall efficiency, Edge events, configurational efficiency;

**Statistical** and **systematic uncertainties** taken into account;

<table>
<thead>
<tr>
<th>Sources of errors</th>
<th>The impact on breakup cross section [%]</th>
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</thead>
<tbody>
<tr>
<td>Statistical uncertainties</td>
<td>2 – 11%</td>
</tr>
<tr>
<td><strong>Total systematic error</strong></td>
<td>3.9 – 8.5%</td>
</tr>
<tr>
<td>Normalization</td>
<td>3%</td>
</tr>
<tr>
<td>Particle identification</td>
<td>1%</td>
</tr>
<tr>
<td>Configurational efficiency</td>
<td>0.01 – 7%</td>
</tr>
<tr>
<td>Hadronic interaction</td>
<td>1%</td>
</tr>
<tr>
<td>Energy calibration</td>
<td></td>
</tr>
<tr>
<td>+ angle reconstruction</td>
<td></td>
</tr>
<tr>
<td>+ detector efficiency</td>
<td>1%</td>
</tr>
<tr>
<td>+ Trigger efficiency</td>
<td>3%</td>
</tr>
</tbody>
</table>

- \( L = 8.69 \times 10^6 \pm 0.27 \times 10^6 \)
Results and comparison with theory

➢ The differential cross section obtained for a set of **84 angular configurations**; polar angles $\theta$ from $13^\circ$ to $33^\circ$, and azimuthal angle $\varphi_{12}$ from $50^\circ$ to $190^\circ$ → **503 data points**;

➢ $\varphi_{12}=20^\circ$ and $\varphi_{12}=40^\circ$ are determined by Coulomb interactions, so further $\chi^2_{\text{red}}$ analysis ignores these configurations;
Results and comparison with theory

The global $\chi^2_{\text{red}}$ results strongly depend on the theoretical model;

- Calculations with Coulomb force have the best agreement;
- The effect of the 3NF introduced in $\Delta$ form is negligible;
- The TM99 and UIX model of 3NF introduce effects which are more significant.

$\chi^2_{\text{red}} = \frac{1}{N} \sum_{i=10}^{N} \left( \frac{\sigma_i^{\text{exp}} - \sigma_i^{\text{th}}}{\Delta \sigma_i^{\text{tot}}} \right)^2$

Adding $\Delta$-isobar slightly spoils the agreement between data and calculations;

But 3NF in the form of UIX improves the $\chi^2_{\text{red}}$
Results and comparison with theory

➢ **Giant disagreement** between the data and theories

➢ **Significant improvement** in the description when the **Coulomb force** is included;
Results and comparison with theory

The best agreement of cross-section distribution shapes is obtained for normalization greater by $1.2\%$

- The value of the cross section multiplied by a factor ranging from $0.95$ to $1.25$, and the $\chi^2$ was again determined;
- By a fitting the parabola we can find the minimum chi-square value: $\chi^2_{\text{red}} = 2.332$ for a factor of $1.12$
- The higher polar angles $\theta_1$ and $\theta_2$;
- The greatest discrepancy is for $\phi_{12}=120^\circ$, $\phi_{12}=140^\circ$

Problematic areas: correction related to configuration efficiency averaged over several configurations

The higher polar angles $\theta_1$ and $\theta_2$;
Discussion of the experimental results

Additional test

- The value of the cross section multiplied by a factor ranging from 0.95 to 1.25, and the \( \chi^2_{\text{red}} \) was again determined;
- By fitting a parabola we can find the minimum chi-square value:

\[
\chi^2_{\text{red}} = 2.332 \text{ for a factor of 1.12}
\]

The best agreement of cross-section distribution shapes is obtained for normalization greater by 12%
Summary and outlook

➢ The Coulomb interaction has to be necessarily included in the theoretical description;
➢ The effect of the 3NF introduced in Δ form is negligible; the UIX model of 3NF introduces effects which are more significant in the presented data;
➢ Analysis of the global chi-square and the additional test suggest that the best agreement of cross-section distribution shapes is obtained for normalization greater by 12%;
➢ Verification of normalization - direct measurement of the absolute value of the differential cross-section by using the solid CD$_2$ target and determine the luminosity value;
➢ Combining the current data with the data set collected in 2019 which should double our statistics;
➢ Comparing our results with the newly developed ChEFT (only for the NNLO with the 3NF) – the most interesting ideas, but presented results indicates the necessity to include the Coulomb interaction into calculation.
Thank you for your attention!