Deuteron Breakup in Collision with Proton measurements at intermediate energies

Elżbieta Stephan
University of Silesia, Poland
Starting point: 2 Nucleons

- Meson exchange theory of NN forces - *nucleonic degrees of freedom* (CD Bonn, Nijm I, Nijm II, AV18)
- CD Bonn + explicit treatment of a single Δ-isobar degrees of freedom – Coupled barion Channels
- Effective Field Theory – Chiral Perturbation Theory; expansion of potential in powers ν of small external momenta Q, \((Q/\Lambda_\chi)^\nu\), with \(\Lambda_\chi \approx 1\) GeV

### Realistic Potentials

### Coupled-Channels Potential (single Δ)

### Chiral Perturbation Theory Potential

(2π exchanges & contact terms)
Starting point: 2 Nucleons

- very rich data base: \( \sim 3000 \) data points for pp below 350 MeV
- phase shift analysis by Nijmegen group (PWA93)
- quality of description: \( \chi^2 \) close to 1
System of 3 Nucleons

Predictions of **NN potentials alone:**
- **fail** to reproduce binding energies of 3N, 4N and heavier systems
- **fail** to reproduce minimum of the d(N,N)d elastic scattering cross section

<table>
<thead>
<tr>
<th>Binding energy [MeV]</th>
<th>$^3$H</th>
<th>$^3$He</th>
<th>$^4$He</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental value</td>
<td>8.48</td>
<td>7.72</td>
<td>28.3</td>
</tr>
<tr>
<td>CD Bonn</td>
<td>8.01</td>
<td>7.29</td>
<td>26.3</td>
</tr>
<tr>
<td>CD Bonn + TM99</td>
<td>8.48</td>
<td>7.73</td>
<td>29.2</td>
</tr>
</tbody>
</table>

- Introducing concept of **three-nucleon forces:**
  - genuine (irreducible) interaction of three nucleons
  - as a consequence of internal nucleon structure

- **Systematic approach within ChPT**

E. Stephan UŚł

Bologna - EuNPC2018
Next step: System of 3 Nucleons

- Models of 3NF:

- Naturally appearing in Chiral Perturbation Theory at N2LO:
3N Systems - Reactions
what can be studied experimentally?

➢ Processes:
   ❖ Elastic scattering: N + d → N + d
   ❖ Breakup: N + d → N + n + p
   ❖ and electromagnetic processes

➢ Observables
   ❖ differential cross section
   ❖ vector&tensor analyzing powers
   ❖ polarization transfer, correlations

➢ Energy range - why "medium" and what does it mean?
   ❖ measurable 3NF effects
   ❖ below pion threshold

➢ Technique:
   ❖ spectrometers
   ❖ large acceptance detectors
3N Systems – Elastic Scattering
Differential Cross Section

- rich data set (RIKEN/RCNP/IUCF/KVI)
- 3NF helps
- yet with rising energy discrepancy appears - problem with 3NF models?
3N Systems – Elastic Scattering
Differential Cross Section

- rich data set (RIKEN/RCNP/IUCF/KVI)
- 3NF helps
  - yet with rising energy discrepancy appears - problem with 3NF models?

Effects small, located at extreme angles!
Coulomb interaction? Relativistic effects?

E. Stephan UŚI
Bologna - EuNPC2018
3N Systems – Elastic Scattering Analyzing Powers

- 3NF not always improves description - a lot of examples at various energies
- problem with spin part of 3NF?

130 MeV (65 MeV/nucleon)

Data agree with NN calculations

Bologna - EuNPC2018

- 100 MeV E. Stephan et al.,

Net 3NF effects in T22 depending on beam energy

Predicted, not observed

Predicted effect less energy dependent as observed in data
3N Systems-Breakup Reaction

- **Three nucleons** in the final state - 9 variables
- Energy-momentum conservation – 4 equations
  - Five independent kinematical variables
    - Complete (exclusive) exp. – measured ≥ 5
    - Inclusive exp. – measured ≤ 4 parameters

\(^1\text{H}(d,pp)n\) measured: directions and energies of two protons, i.e.
\(\theta_1,\phi_1, E_1\)
\(\theta_2,\phi_2, E_2\)
Large Acceptance Detectors for Few Nucleon System Studies

SALAD
θ = (12°, 35°)

GeWall
θ = (3°, 15°)

BINA
θ_{Wall} = (12°, 35°)
θ_{Ball} = (40°, 180°)

KVI-Groningen
θ_{FD} = (3°, 18°)
θ_{CD} = (20°, 169°)

CCB Krakow

WASA

COSY-Juelich

E. Stephan UŚI

Bologna - EuNPC2018
$^1\text{H}(\overrightarrow{d},pp)n$ Measurement at 130 MeV

Cross Section Results – 3NF & Coulomb Effects

\textbf{SALAD@KVI,} St. Kistryn et al., Phys. Rev C 72 , 044006 (2005)

E. Stephan UŚI
$^1\text{H}(\vec{d}, pp)n$ Measurement at 130 MeV

Cross Section Results – 3NF & Coulomb Effects

The best agreement is reached when both, the Coulomb force and the 3NF are taken into account!

The few hundreds data points per observable

EXP:

$\theta_p = 25^\circ \pm 1^\circ$

$\theta_n = 30^\circ \pm 1^\circ$

$\theta_{12} = 160^\circ \pm 5^\circ$

3NF effects


SALAD@KVI, St. Kistryn et al., Phys. Rev C 72, 044006 (2005)

E. Stephan UŚI
\(^1\text{H}(d,pp)n\) Breakup Cross Section

3NF+Coulomb

65 MeV/nucleon

\(\theta_1 = \theta_2 = 5^\circ\)

170 MeV/nucleon

\(\theta_1 = \theta_2 = 9^\circ\)

Prominent Coulomb effects at p-p FSI in wide range of beam energies

GeWall@COSY, I. Ciepał et al.

WASA@COSY, B. Kłos et al.
$^1$H(d,pp)n and $^2$H(p,pp)n Breakup Cross Section

Relativistic Effects

$^2$H(n,pn)n, 200 MeV
$^1$H(d,pp)n, 170 MeV/nucleon


θ₂=37.5°, φ₁₂=180°
$^1\text{H}(d,pp)n$ breakup at 130 MeV

Tensor analyzing power

Problem with TM99 3NF
### pd Breakup Reaction \( \sqrt{s} = 200 - 250 \text{ MeV/A} \)

<table>
<thead>
<tr>
<th>Observable</th>
<th>ChPT</th>
<th>Coul+ 3NF</th>
<th>3NF+ relat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{d\sigma}{d\Omega} )</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
<tr>
<td>( \vec{p} )</td>
<td>( A_y^p )</td>
<td><img src="image4" alt="Diagram" /></td>
<td><img src="image5" alt="Diagram" /></td>
</tr>
<tr>
<td>( A_z^p )</td>
<td><img src="image6" alt="Diagram" /></td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
</tr>
<tr>
<td>( \vec{d} )</td>
<td>( A_y^d )</td>
<td><img src="image9" alt="Diagram" /></td>
<td><img src="image10" alt="Diagram" /></td>
</tr>
<tr>
<td>( A_{yy} )</td>
<td><img src="image11" alt="Diagram" /></td>
<td><img src="image12" alt="Diagram" /></td>
<td><img src="image13" alt="Diagram" /></td>
</tr>
<tr>
<td>( A_{xx} )</td>
<td><img src="image14" alt="Diagram" /></td>
<td><img src="image15" alt="Diagram" /></td>
<td><img src="image16" alt="Diagram" /></td>
</tr>
<tr>
<td>( A_{xz} )</td>
<td><img src="image17" alt="Diagram" /></td>
<td><img src="image18" alt="Diagram" /></td>
<td><img src="image19" alt="Diagram" /></td>
</tr>
<tr>
<td>( \bar{d} \to \vec{p} )</td>
<td>( K_{yy}^{' y'} )</td>
<td><img src="image20" alt="Diagram" /></td>
<td><img src="image21" alt="Diagram" /></td>
</tr>
<tr>
<td>( \vec{p} \bar{d} )</td>
<td>( C_{ij} )</td>
<td><img src="image22" alt="Diagram" /></td>
<td><img src="image23" alt="Diagram" /></td>
</tr>
</tbody>
</table>

**WASA**

**KVI**

**CCB**

Bologna - EuNPC2018
Proton-Deuteron Collisions: role of 3 NF

**Elastic Scattering vs Breakup Reaction**

<table>
<thead>
<tr>
<th></th>
<th>p-d Elastic Scattering</th>
<th>Deuteron Breakup in p-d</th>
</tr>
</thead>
<tbody>
<tr>
<td>3NF - influence on the cross section</td>
<td>significant, confirmed problem at energies &gt;100 MeV</td>
<td>significant, confirmed ? (relativistic effects)</td>
</tr>
<tr>
<td>3NF - polarization observables</td>
<td>inconclusive</td>
<td>inconclusive</td>
</tr>
<tr>
<td>Coulomb interaction - influence on the cross section</td>
<td>negligible</td>
<td>significant, dominating at pp FSI, confirmed</td>
</tr>
<tr>
<td>relativistic effects</td>
<td>negligible</td>
<td>large effects in calculations, experimental confirmation needed</td>
</tr>
</tbody>
</table>
Nucleon-Deuteron Breakup
Recent achievements in theoretical calculations

- ChPT
  - awaited new ChPT calculations, at N2LO / N3LO

- Realistic potentials
  - calculations including each ingredient separately:
    - 3NF (Witała et al., Deltuva et al.),
    - Coulomb (Deltuva et al.),
    - relativistic (Witała et al.) approach
      - all the effects are important at medium energies!
  - calculations including Coulomb interaction and 3NF (A.Deluva et al.)
Thank you for your attention!