Three-nucleon interaction dynamics studied via the deuteron-proton breakup

Elżbieta Stephan
Institute of Physics, University of Silesia
Studies of the $^1\text{H}(\bar{d},pp)n$ Breakup at 130 MeV

University of Silesia, Katowice, Poland

Jagiellonian University, Kraków, Poland

KVI, Groningen, The Netherlands

Kraków-Bochum Group
EFT/ChPT Group
Hannover/Lisboa Group

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$^1\text{H}(\bar{d},pp)n$ Measurement at 130 MeV

Motivation

- Faddeev framework provides exact treatment for the 3N system
- Various approaches to construct the interaction (2N and 3N):
  - Realistic potentials + phenomenological 3NF models
  - Chiral Perturbation Theory
  - Coupled-Channels formalism with explicit $\Delta$
1H(d,pp)n Measurement at 130 MeV

Motivation

- Three-nucleon system is the simplest non-trivial environment to test predictions of the NN and 3N potential models
- Elastic scattering data demonstrate both success and problems of modern calculations
- Very few breakup data at medium energies (earlier PSI experiments provided only 14 kinematical configurations)
- In order to reach meaningful conclusions about the interaction models needed experimental coverage of large phase space regions
$^1\text{H}(\bar{d},pp)n$ Measurement at 130 MeV

Small Area Large Acceptance Detector

- 140 $\Delta E$-$E$ telescopes
- 3-plane MWPC
- Angular range: $\theta = (12^\circ, 38^\circ)$, $\varphi = (0^\circ, 360^\circ)$
$^1$H(d,pp)n Measurement at 130 MeV

Cross Section Results – Summary

✓ Nearly 1800 cross section data points
  • $\theta_1, \theta_2 = 15^\circ - 30^\circ$; grid $5^\circ$; $\Delta \theta = \pm 1^\circ$
  • an additional set for $\theta_1, \theta_2 = 13^\circ$
  • $\varphi_{12} = 40^\circ - 180^\circ$; grid $10^\circ - 20^\circ$; $\Delta \varphi = \pm 5^\circ$
  • $S [\text{MeV}] = 40 - 160$; grid 4; $\Delta S = \pm 2$
  ➢ Statistical accuracy 0.01 – 0.05
  ➢ Data very clean – accidentals below 2%
  ➢ Systematic errors – 3% – 5%

✓ Global comparisons with theory ($\chi^2$ test for all points, $\chi^2 = f(\varphi_{12}), \quad \chi^2 = f(E_{\text{rel}})$, tests of normalization)
$^1$H(\vec{d},pp)n Measurement at 130 MeV

Cross Section Results – Example
$^1\text{H}(\vec{d},pp)n$ Measurement at 130 MeV

Cross Section Results – Exploring Phase Space

Relative $\chi^2$ as a function of the relative azimuthal angle $\varphi_{12}$ between the two proton trajectories

For large $E_{\text{rel}}$ 3NF’s improve description of the data when combined with the NN potentials

In general: Including 3NF’s reduces global $\chi^2$ by about 30%

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

Cross Section Results – Discrepancies
\(^1\text{H}(\bar{d},pp)n\) Measurement at 130 MeV

Cross Section Results – Discrepancies Cured

Predictions with Coulomb reproduce data much better!

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Discrepancies at low $E_{\text{rel}}$ cured

Coupled Channel calculations

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Cross Section Results – Coulomb Effects

Acceptance limit of KVI experiment
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Coulomb effects – dedicated experiment

Small sample result of FZJ experiment (arbitrary normalization)

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Vector and Tensor Analyzing Powers

- A few times more additional data points (supplementing cross sections)
- Potentially stronger sensitivity to small ingredients (sums of interfering amplitudes)
- Small Coulomb effects - it can be easier to trace 3NF

<table>
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<th>7 states:</th>
<th>$\Delta P_z$</th>
<th>$\Delta P_{zz}$</th>
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<td>$P_{zz}^{max}$</td>
<td>$P_z$</td>
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Vector $(A_x, A_y)$ and tensor analyzing powers $(A_{xx}, A_{yy}, A_{xy})$ determined in the large part of the phase space

- Nearly 800 data points per observable
  - $\theta_1, \theta_2 = 15^\circ - 30^\circ$; grid 5$^\circ$; $\Delta \theta = \pm 2^\circ$
  - $\varphi_{12} = 40^\circ - 180^\circ$; grid 20$^\circ$; $\Delta \varphi = \pm 10^\circ$
  - $S$ [MeV] = 40 – 160; grid 4; $\Delta S = \pm 4$
- Statistical accuracy 0.01 – 0.05
- Systematic errors – analysis under way

Global comparisons with theory ($\chi^2$ test)
$^1\text{H}(\vec{d},pp)n$ Measurement at 130 MeV

Vector Analyzing Power Results

ChPT N2LO

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$^1$H(\overline{d},pp)n Measurement at 130 MeV
Tensor Analyzing Power Results

Description not satisfactory!
Tensor Analyzing Power Results
configurations with predicted strong 3NF effects

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Tensor Analyzing Power Results

$\chi^2$/d.o.f. vs. $E_{\text{rel}}$ (MeV)

- $A_{xy}$
- $A_{yy}$

NN, ChPT N3LO

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Conclusions:

- Systematic, precise set of cross sections and analyzing power data obtained at \( E_d = 130 \text{ MeV} \)
  - basis for comparing different approaches which predict the 3N system observables
- Significant 3NF effects observed in cross section
- Found large influence of Coulomb force
- Vector analyzing powers reveal very low sensitivity to 3NF
  - best description given by ChPT (2NLO) – will this fact be confirmed by full calculation at 3NLO or at lower energy?
- Tensor analyzing power sensitive to 3NF, but...
  - current models of 3NF do not provide precise description of \( A_{xx} \) and \( A_{xy} \) – problems with spin part of 3NF?
BINA detection system at KVI

BINA Detector

Phoswich Ball

Stopping (E) Wall

ΔE Wall

MWPC
Rich set of high precision cross sections and analyzing powers data:

- Data at $E_d = 130$ MeV supplemented with results for forward proton angles (GeWall@COSY)
- Complete set for $E_d = 100$ MeV (BINA)
- Measurements for pd systems at 180 and 135 MeV (BINA)

Developments in theoretical calculations for 3N system (3N force, Coulomb interaction, relativistic effects, higher order in ChPT ...)

Studies of breakup processes in dd system (BINA) at 130 MeV
Thank you for your attention!
\[ \sigma_p(\zeta, \varphi_1) = \sigma_0(\zeta) \cdot \left[ 1 + P_z \cdot \left( -\frac{3}{2} \sin \varphi_1 A_x + \frac{3}{2} \cos \varphi_1 A_y \right) + P_{zz} \cdot \left( -\sin \varphi_1 \cos \varphi_1 A_{xy} \right) + P_{zz} \cdot \left( \frac{1}{2} \sin^2 \varphi_1 A_{xx} + \frac{1}{2} \cos^2 \varphi_1 A_{yy} \right) \right] \]

\[ \zeta = (\theta_1, \theta_2, \varphi_{12}, S) \]

\[ a = -\frac{3}{2} P_x A_x(\zeta) \]
\[ b = \frac{3}{2} P_y A_y(\zeta) \]
\[ c = -P_{xy} A_{xy}(\zeta) \]
\[ d = \frac{1}{2} P_{xx} A_{xx}(\zeta) \]
\[ e = \frac{1}{2} P_{yy} A_{yy}(\zeta) \]

\[ \frac{N_P - N_0}{N_0} = a \cdot \sin \varphi_1 + b \cdot \cos \varphi_1 + c \cdot \sin \varphi_1 \cdot \cos \varphi_1 + d \cdot \sin^2 \varphi_1 + e \cdot \cos^2 \varphi_1 \]

\[ \theta_1 = 25^\circ \]
\[ \theta_2 = 20^\circ \]
\[ \varphi_{12} = 120^\circ \]
\[ S = 96MeV \]
Tensor Analyzing Power Results
examples of $A_{xx}$, symmetric configurations with $\varphi_{12}=60^0, 120^0$
Analyzing Power Results

\[ A_x \]
\[ \phi_{12} = 140^\circ \]

\[ \theta_1, \theta_2 = 15^\circ, 15^\circ \]
\[ \theta_1, \theta_2 = 20^\circ, 15^\circ \]
\[ \theta_1, \theta_2 = 25^\circ, 15^\circ \]
\[ \theta_1, \theta_2 = 30^\circ, 15^\circ \]

\[ \theta_1, \theta_2 = 20^\circ, 20^\circ \]
\[ \theta_1, \theta_2 = 25^\circ, 20^\circ \]
\[ \theta_1, \theta_2 = 30^\circ, 20^\circ \]
\[ \theta_1, \theta_2 = 25^\circ, 25^\circ \]
\[ \theta_1, \theta_2 = 30^\circ, 25^\circ \]

\[ S \ [\text{MeV}] \]

Legend:
- 2N
- 2N+TM99
- N2LO
- N3LO