Deuteron breakup reactions at low energy

Testing the predictive power of chiral EFT N2LO: 2N-3N differences & Cut-off dependencies

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- Motivation for a double polarized pd breakup experiment
- Experimental planned@COSY
- Analysis method: sampling of theoretical grids
- Simulation & Sampling
- Preliminary results from an experimental study
- Summary

- For introduction to PAX experiments: Talk by P. Lenisa
- For 3NF theory: Talk by A. Nogga
- For experimental details and overviews see talks by
  • Cassiti: PAX detector
  • Bertelli: Experiment 2011 (Ay in pd breakup)
  • Lenisa: Silicon detectors
  • Khoukaz: Internal targets
People

- **Theory**: E. Epelbaum and A. Nogga

- **PAX Collaboration**: S Barsov, Z Bagdasarian, S Bertelli, D Chiladze, A Kacharava, P Lenisa, N Lomidze, B Lorentz, G Macharashvili, K Marcks von Würtemberg, S Merzlyakov, S Mikirtytychians, A Nass, D Oellers, F Rathmann, R Schleichert, H Ströher, PTE, M Tabidze, S Trusov, C Weidemann, M Zhabitsky and more ...for PAX and ANKE Collaborations

- **COSY crew**: D. Prasuhn and B.Lorentz et al.
Motivation: 3Nucleon Force - What is it?

IUCF Workshop Sep 1998 - Working Session II:
- Question: What do we mean by 3NF, and where is the best place to look for experimental evidence?

H. Witala (working session notes):
\[ H = T + \sum V_{ij} + V_{1,2,3} \]

“where the second term is all pairwise i.a. summed over the 3N. The rest is 3NF and takes into account any distorsion of NN potential energy caused by the presence of the third nucleon.”

Size of the 3NF interaction:
\[ \Delta V \sim \frac{V^2}{M^2} \rightarrow 0.5 – 1 \text{ MeV} \]
FIG. 10. (Color online) Difference between the present data at 135 MeV and the Faddeev calculation with the CD-Bonn potential. The effect of including the old or the new Tucson-Melbourne 3NFs is shown by the solid lines (TM) and the dashed lines (TM'). The dotted lines show the difference between calculations with the AV18 and the CD-Bonn potentials, both without a 3NF.

All three forces mentioned above have been adopted for insertion into Faddeev calculations \[35\], including angular momenta of the 3NF system up to 13/2 \[8\]. All theoretical 3NFs contain adjustable parameters that are determined experimentally. In particular, the overall strength of the 3NF potential is adjusted by varying the cutoff parameter \(\Lambda_{1}\) of the \(\pi-N\) form factor until the \(3H\) binding energy is reproduced. The adjusted cutoff parameter depends on the \(NN\) potential used \[43\].

D. Comparison of 3NF predictions with the data

The differences between our measurements and the Faddeev calculation with the CD-Bonn potential are plotted in Figs. 10 and 11, i.e., the calculation is the solid line. The effect of including the old (TM) or the new (TM') Tucson-Melbourne 3NFs is shown by the solid lines and the dashed lines, respectively. A comparison of these curves with the data is justified if calculations with different \(NN\) potentials 064003-16 pd elastic@135 MeV.
B. V. Przewoski et al. PHYSICAL REVIEW C 74, 064003 (2006)

FIG. 10. (Color online) Difference between the present data at 135 MeV and the Faddeev calculation with the CD-Bonn potential. The effect of including the old or the new Tucson-Melbourne 3NFs is shown by the solid lines (TM) and the dashed lines (TM'). The dotted lines show the difference between calculations with the AV18 and the CD-Bonn potentials, both without a 3NF. All three forces mentioned above have been adopted for insertion into Faddeev calculations [35], including angular momenta of the 3NF system up to $13/2$ [8]. All theoretical 3NFs contain adjustable parameters that are determined experimentally. In particular, the overall strength of the 3NF potential is adjusted by varying the cutoff parameter $\Lambda_{\pi-N}$ of the $\pi$-N form factor until the $3H$ binding energy is reproduced. The adjusted cutoff parameter depends on the NN potential used [43].

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The differences between our measurements and the Faddeev calculation with the CD-Bonn potential are plotted in Figs. 10 and 11, i.e., the calculations are these red lines. The effect of including the old (TM) or the new (TM') Tucson-Melbourne 3NFs is shown by the solid lines and the dashed lines, respectively. A comparison of these curves with the data is justified if calculations with different NN potentials are compared.
The curves are explained in the caption for Fig. 1.

B. V. Przewoski, et. al, P. Thörngren Engblom

PRC 74, 064003 (2006)

FIGURE 1. Longitudinal proton analyzing power as a function of $C$.

FIGURE 2. Vector correlation coefficient $A_{yy}$ and $A_{zz}$.

FIG. 3. Tensor correlation coefficient $C_{xx}$.

$\Delta \phi$ and 4\% for the other two.

$\Delta \phi$.

The effect of including the old (TM) or the new (TM) Tucson-Melbourne 3NFs is shown by the solid lines and the dashed lines (TM), respectively. When the interaction is adjusted by varying the cutoff parameter $t$.

In particular, the overall strength of the 3NF potential is included one-third of the breakup events collected in all states, individual terms in Eq. (1) are singled out. The average has to be weighted by the cross section and the acceptance angle of the detector segments may locally reduce the efficiency, and instrumental constraints into account.

In order to take instrumental constraints into account, the overall strength of the 3NF potential is included one-third of the breakup events collected in all states, individual terms in Eq. (1) are singled out. The average has to be weighted by the cross section and the acceptance angle of the detector segments may locally reduce the efficiency, and instrumental constraints into account.

All theoretical 3NFs, including angular momentum exchange.

The authors wish to thank the IUCF Operations Group for their support.

$A_{yy}$, i.e., the calculation is zero at $0$.

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$A_{xy}$.

$A_{xz}$.

$A_{yz}$.

$A_{zx}$.

$A_{zy}$.

$A_{xyz}$.

$A_{y}$.

$A_{zz}$.

$A_{z}$.

$A_{d}$.

$A_{p}$.

$A_{\theta}$.

$A_{\phi}$.

$A_{\theta,\phi}$.

$A_{\theta,\phi,\chi}$.

$A_{\theta,\phi,\chi,\psi}$.

$A_{\theta,\phi,\chi,\psi,\omega}$.

$A_{\theta,\phi,\chi,\psi,\omega,\kappa}$.

$A_{\theta,\phi,\chi,\psi,\omega,\kappa,\eta}$.

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Calculations of very similar results and are treated as a group: they are presented in figures as bands and, in theoretical calculations using the realistic potentials (CDB, Nijm I, Nijm II, AV18) provide 130 MeV is improved when 3NF is included. The same conclusion that the description of the breakup data at the deuteron beam energy of 135 MeV than on their absolute normalization as obtained in the course of data analysis. Both ways predictions when the experimental cross section normalization is allowed to change slightly. Normalization. It seems to be worthwhile to study the agreement between the data and uncertainties, which in some particular regions are quite significant. They are, however, also neglected.

By the number of kinematical points in the data set under consideration. In this approach uncertainties, which in some particular regions are quite significant. They are, however, also neglected.

TM99) are treated in an analogous way. Predictions obtained within ChPT have well-defined uncertainties, which in some particular regions are quite significant. They are, however, also neglected.

In the case of analyzing powers for the breakup reaction at 100 and 130 MeV, the In the case of cross section data, the most relevant systematic factor is their absolute normalization. It seems to be worthwhile to study the agreement between the data and uncertainties, which in some particular regions are quite significant. They are, however, also neglected.

Examples for a few selected symmetric configurations are shown. Error bars show statistical uncertainties alone. The horizontal (cyan) band in each panel represents the systematic uncertainties.

\[ \chi^2 \]

\[ \sigma^2 \]

A comparison of the results of the vector analyzing power \( A_y \) at 135 MeV/nucleon measured at two beam energies, with various theoretical predictions specified in the legends. Published on 2014-07-10.

Copyright 2010 Elsevier. Right: results for the beam energy of 135 MeV. Adapted from Figure 21. Reproduced with permission from J. Phys. G: Nucl. Part. Phys.
$^1\text{H}(d, p1p2)n@135\text{ MeV/Nucleon}$

\[ (\theta_1, \theta_2, \phi_{12}) = (28^\circ, 31^\circ, 180^\circ) \]

\[ A_y^d \]

\[ A_{xx} \]

\[ A_{yy} \]

\[ A_{xz} \]

S [MeV]

AV18, CD-Bonn
Nijmegen I, Nijmegen II

+ TM' (99) 3NF

AV18 + Urbana IX 3NF

K. Sekiguchi et al., PRC 79, 054008 (2009)
Comparison between data and theoretical predictions:

Combining 3N forces with NN-potentials sometimes lead to

→ improved agreement

→ worse agreement

→ no effect

Kalantar-Nayestanakir, Epelbaum, Messchendorp,Nogga; Rep.Prog.Phys 1108.1227 (2011)

...Progress require theoretical development & support...
Modern theory of nuclear forces

Epelbaum, Prog. Part. Nucl. Phys. 57 (2006) 57

◆Chiral effective field theory:
  - Systematic & model independent framework for low-energy few-nucleon physics
  - Few body forces enter naturally with increasing order

◆At N2LO - first nonvanishing terms from the chiral Three-Nucleon Force (3NF)
  - Two-pion exchange
  - One-pion exchange
  - Contact interaction

Why pd bup? 3 particles in the final state $\rightarrow$ 5 independent variables

$S_{\text{curve}}(E_1, E_2)$

$\theta_1, \theta_2, \Delta \varphi = 30, 31, 180 \, \text{deg}$

G.G. Ohlsen, NIM 179 (1981) 283
Why pd bup? 3 particles in the final state \( \rightarrow \) 5 independent variables

\[
\begin{align*}
\theta_1, \theta_2, \Delta \varphi &= 30, 31, 180 \text{ deg} \\
S &= 0 \text{ MeV} \\
FSI(p_2n) &
\end{align*}
\]

Exploit the rich kinematics

Jacobi momenta cm:
\[
\begin{align*}
p &= \frac{1}{2} ( p_1 - p_2 ) \\
q &= - ( p_1 + p_2 ) \\
\{ p, \theta p, \phi p, \theta q, \phi q \}
\end{align*}
\]

G.G. Ohlsen, NIM 179 (1981) 283
Why spin? & Why double polarized?

\[ \sigma = \sigma_0 (1 + p_y A_y(p) + p_z A_z(p) + \frac{3}{2} q_y A_y(d) + \frac{3}{2} q_z A_z(d)) + \frac{3}{4} (q_x p_x + q_y p_y)(C_{x,x} + C_{y,y}) + \frac{3}{4} (q_x p_x - q_y p_y)(C_{x,x} - C_{y,y}) + \frac{3}{4} (q_y p_x - q_x p_y)(C_{y,x} - C_{x,y}) + \frac{3}{2} q_x p_z C_{x,z} + \frac{3}{2} q_z p_x C_{z,x} + \frac{3}{2} q_z p_z C_{z,z} + \frac{1}{6} (q_{xx} - q_{yy})(A_{xx} - A_{yy}) + \frac{1}{2} q_{zz} A_{zz} + \frac{2}{3} q_{xz} A_{xz} + \frac{1}{6} (q_{xx} - q_{yy}) p_y (C_{xx,y} - C_{yy,y}) + \frac{1}{2} q_{zz} p_z C_{zz,z} + \frac{1}{2} q_{zz} p_y C_{zz,y} + \frac{2}{3} q_{xy} p_x C_{xy,x} + \frac{2}{3} q_{xz} p_y C_{xz,y} + \frac{2}{3} q_{yz} p_x C_{yz,x} + \frac{2}{3} q_{xy} p_z C_{xy,z} + \frac{2}{3} q_{yz} p_z C_{yz,z} + \frac{1}{3} (q_{xz} p_x + q_{yz} p_y)(C_{xz,x} + C_{yz,y}) \]
The last two columns also a few observables are included requiring longitudinally polarized
simultaneously. With the longitudinal \( q \) of 45 degrees which can be accomplished by running current through two guide field coils.
The last two columns refer to the situation when the deuteron spin alignment axis is at
beam direction \( q_{\text{longitudinal}} \) and some combinations thereof. For
possible in proton deuteron breakup showing the required polarization alignment directions.

Beam \( q \) of \( 45 \) degrees is accessible only using longitudinally
polarized beam and diagonal target spin alignment. The tensor-vector correlation coe-
ficient \( C \) goes to zero in breakup reactions in coplanar kinematical configurations. In the
Table 3: Tabulated here are the \( z_{5} \) spin correlation observables and \( 7 \) analyzing powers

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EXPERIMENTAL SETUP

COSY Cooler synchrotron & storage ring

600 - 3700 MeV/c

Polarized proton & deuterons

PAX interaction point

ABS
Scattering chamber

Low beta quadropoles

BRP
PAX detector development
COSY & AD

Talk by V. Carassiti

3 detector layers
φ-symmetric
4 quarters

Detector setup front view

Hermes 300 μm  PAX 300 μm  PAX 1.5 mm

Double-sided silicon strip sensors
Pitch 0.7 mm  vertex resolution ≤ 1mm
Experiment 2DO:
Double polarized pd bup @30-50 MeV @COSY

◆ To test the predictive power of the Modern theory of nuclear forces (talk by Nogga)

➢ Validity of chiral EFT – N2LO

‘Low’ energy ~30-50 MeV proton beam energy

◆ Proton deuteron breakup → 3 nucleon interactions
- Rich variety of kinematical configurations
  • Five independent kinematical parameters
- Using polarized beam & vector-tensor polarized target

---→ 22 independent spin observables
  • 7 analyzing powers
  • 6 vector-tensor correlation
  • 9 tensor-tensor correlation parameters

More information:
COSY Proposal 202, PTE et al., Measurement of Spin Observables in the pd Breakup Reaction,
3 particles in the final state: Comparison of theory to experimental data

- **Problem 1:**
  - Complexity of 3-particle final states
    - five independent kinematic variables (3 x dof – 4)
    - what part of phase space to integrate over
    - ...acceptance + efficiency + systematics...

- **Solution 1:**
  - Expose theory to the experiment
    - Analysis \(\rightarrow\) event list of accepted events
    - Calculate the theoretical prediction for each event

- **Problem 2:**
  - Time consuming & cumbersome (complexity of theory)

- **Solution 2:**
  - Use pre-calculated grids covering phase space
  - Examples: Azz@135 MeV/A
  - Ay(N}@49.3 MeV proton beam energy
The sampling method – a shortcut

- **Applicable to kinematically complete measurements**
  1) Determine the theoretical $O^{\text{th}}$ for each analyzed event
  2) Sum these values and divide by the number of events

**NOTE:** This can be done for any chosen observable as function of any independent parameter of interest

In simple terms:

$$O^{\text{th}}(\gamma) = \langle O^{\text{th}} \rangle = \frac{\sum O^{\text{th}}(x_k)}{N(\gamma)}$$

- **In other words:**
  - expose the theory to the experiment
3 particles in the final state: Comparison of theory to experimental data

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PTE *et al.*, AIP Conf. Proc. 768, 65 (2005), nucl-ex/0410006

The sampling method & dp @ 270 MeV

- Tensor analyzing powers in dp at 135 MeV/A
- Theory CD-Bonn w. & w.o. 3N forces
- Theoretical grids by: Kurosz-Zolnierczuk
A. Nogga: Theory grids

- Theoretical framework N2LO w. & w.o. 3NF: Epelbaum & Nogga

- Data or simulation: (analyzed event list or list of bup events isotropically generated)

- Multidimensional interpolation on a theory (n2lo) grid event by event

<table>
<thead>
<tr>
<th>GRID SPACING</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>p # of steps</td>
<td>20</td>
</tr>
<tr>
<td>θp # of steps</td>
<td>9</td>
</tr>
<tr>
<td>θp [deg]</td>
<td>5..90</td>
</tr>
<tr>
<td>θq # steps</td>
<td>18</td>
</tr>
<tr>
<td>θq [deg]</td>
<td>10..180</td>
</tr>
<tr>
<td>φp,q # steps</td>
<td>37</td>
</tr>
<tr>
<td>φp,q [deg]</td>
<td>0..360</td>
</tr>
<tr>
<td># of grid points</td>
<td>4,435,560</td>
</tr>
</tbody>
</table>
Five versions w. different cutoffs and corresponding 3NF contact terms

- Integrations of the Lippman-Schwinger eq.
- Internal loops of the diagrams contributing to the potential
- \( c_D, c_E \) dimensionless parameters fixed from 3N low-energy observables

<table>
<thead>
<tr>
<th>( \Lambda )</th>
<th>( \tilde{\Lambda} )</th>
<th>( c_D )</th>
<th>( c_E )</th>
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</thead>
<tbody>
<tr>
<td>450</td>
<td>500</td>
<td>-0.14</td>
<td>-0.32</td>
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<tr>
<td>600</td>
<td>500</td>
<td>-4.71</td>
<td>-2.12</td>
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<tr>
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Example of sampling: Axz @49 MeV (phase space)
Example of sampling: Axz @49 MeV (phase space)

Using cuts in phase space for sensitivity studies comparing 3N & 2N calculations at n2lo
Example of sampling: Cxz,y @49 MeV (phase space)
Observable of interest for TRIC experiment (Eversheim)
Ay (N)@50 MeV

- Vertically polarized proton beam 49.3 MeV
- Deuterium cluster gas target
- Left-Right Silicon Detector Telescopes

- Experimental & analysis details → Talk by Bertelli

Rear view of the geometry
Theoretical grids by A. Nogga
Five versions of n2lo-grids at different cutoffs
Ay(N)@50 MeV & Limited phase space & Sampling n2lo(3N)

- Five versions of n2lo(3N) grids at different cutoffs
- Phase space isotropic distributed events
  - Geometry as using Left-Right Si telescopes →
  - Limited acceptance in $p$, $\theta p$, $\theta q$, $\phi p$

$p$ [100,170] MeV/c
$\theta p$ [65,90] deg
$\theta q$ [10,80] deg
$\phi p$ ~ ±30 deg
(left-right detectors)
Ay(N)@50 MeV & Geant phase space & Sampling n2lo(3N)

- Five versions of n2lo grids at different cutoffs
- Geant simulation:
  - Phase space isotropically distributed events + geant4
  - Left-Right Si detector telescopes → limited acceptance

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Original idea by Prof. H.-O. Meyer
Data analysis: PhD thesis by K. Marcks von Würtemberg

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Quantiles $n_{2lo}$ vs data

Quantiles $n_{2lo}(3N)$ vs $n_{2lo}(2N)$

$n_{2lo}$ 2N vs data, $n_{2lo}$ 3N vs data

Ay(N)@50MeV & Experimental data & Sampling $n_{2lo}(3N)$
Experimental study shows large cut-off dependencies in parts of phase space for n2lo chiral EFT.

Planned experiment @ COSY using the new PAX facility:

- Double polarized pd breakup at 30 – 50 MeV
  - Few previous measurements exist
  - Measure most observables with large phasespace coverage
  - Direct comparison of experiment & theory

Would provide precise data for constraints of chiral EFT in a relevant energy range 30-50 MeV
- New effects of 3NF that appear at N3LO can be accessed
- Cut-off dependencies can be studied in detail
Tomonaga’s “The Story of Spin”

“[Spin] It is a mysterious beast, and yet its practical effect prevails over the whole of science. The existence of spin, and the statistics associated with it, is the most subtle and ingenious design of Nature - without it the whole universe would collapse.”

- Foreword by Takeshi Oka

Thank you for your attention!
Tomonaga’s “The Story of Spin”

• “[Spin] It is a mysterious beast, and yet its practical effect prevails over the whole of science. The existence of spin, and the statistics associated with it, is the most subtle and ingenious design of Nature - without it the whole universe would collapse.”
  - Foreword by Takeshi Oka

Thank you for your attention!
Motivation II

\[ H = H_0 + V_{2N} + V_{3N} + V_{4N} + \ldots \]

\[ \text{Low-energy antiproton-proton scattering – long range part chEFT} \]

Zhou, Timmermans, PRC 86, 044003 (2012)