Polarization Observables in Few-Nucleon Scattering

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OCTOBER 20-24, 2014. PEKING UNIVERSITY, BEIJING, CHINA

SPIN 2014
The 21st International Spin Physics Symposium
Nucleon-Nucleon Interaction
Basis of Nuclear Physics

Modern NN potentials are in general able to
- reproduce properties of nuclear matter (eq. of state)
- reproduce (roughly) binding energies of light nuclei
- reproduce global features of the bulk of the scattering observables in 2N and (partly) in 3N systems

- Three-nucleon system is the simplest non-trivial environment to test predictions of observables obtained on the basis of NN potential models

- Introducing concept of three-nucleon forces: genuine (irreducible) interaction of all three nucleons
Three-Nucleon System
Standard Interaction Models

Realistic Potentials
CD Bonn, Nijm, AV

Coupled-Channels Potential (single $\Delta$)

Chiral Perturbation Theory
(2$\pi$ exchanges & contact terms)

LO & NNLO

TM99 3NF

NLO: all contributions cancel out!

NNLO: three possible topologies
Three-Nucleon Scattering at Medium Energies

- **Elastic**: $N + d \rightarrow N + d$
  - Beams of p or d
  - Various observables

- **Breakup**: $N + d \rightarrow N + N + N$
  - Beams of p or d
  - Various observables

- **Different effects to be traced**
  - Comparisons between channels
  - Influences of 3NF
  - Coulomb force action
  - Relativistic effects

\[\ldots \text{and their interplay!}\]
Experimental Tools of Few-Nucleon Physics

Large acceptance detectors

Spectrometer systems
3NF Effects
Elastic Nucleon-Deuteron Scattering

Predictions of NN potentials with 3NF models better reproduce minimum of the d(N,N)d scattering c.s.

![Graph](image)
3NF Effects
Elastic Nucleon-Deuteron Scattering

3NF help
alas, not completely

$\theta_{\text{cm}}=140^\circ$

(CDB+C+$\Delta$)

PRC 78 (2008) 014006
Elastic Deuteron-Nucleon Scattering

Beam Polarization

Elastic $^1\text{H}(\vec{d},\text{pd})$ scattering – azimuthal ($\varphi$) distribution at selected polar ($\theta$) angle, where $T_{ii}$’s are known

$$\sigma_p(\theta_p, \varphi_p) = \sigma_0(\theta_p) \cdot \left[ 1 + \sqrt{3} \cdot i T_{11}(\theta_p) \cdot P_z \cdot \cos \varphi_p - \frac{\sqrt{3}}{2} \cdot T_{22}(\theta_p) \cdot P_{zz} \cdot \cos 2 \varphi_p - \frac{\sqrt{2}}{4} \cdot T_{20}(\theta_p) \cdot P_{zz} \right]$$

<table>
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<th>7 states:</th>
<th>□ $P_z$</th>
<th>□ $P_{zz}$</th>
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<td>$P_z$ max</td>
<td>$P_{zz}$ max</td>
<td>$P_z$</td>
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<td>+1</td>
<td>0.219</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
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</tbody>
</table>

$P_z$ max = +1/3, $P_{zz}$ = -1

$P_z$ max = +1/3, $P_{zz}$ = +1
3NF Effects
Elastic Deuteron-Nucleon Scattering

- GeWall @ COSY
Different energy dependence of $T_{22}$ data and theory in angular regions.
3NF Effects
Elastic Deuteron-Nucleon Scattering

65 MeV/A

90 MeV/A

NN preferred ...

hmm ...

NN + 3NF
3NF Effects
Elastic Deuteron-Nucleon Scattering

\[ iT_{11} \quad T_{20} \quad T_{21} \quad T_{22} \]
More Dynamical Effects?
Coulomb force and relativity

Predictions for the $N$-$d$ elastic scattering

Coulomb

\[ \text{Effects small, located at extreme angles only!} \]
3N Systems
Elastic N-d Scattering

- Substantial number of observables for the elastic scattering channel, allowing multi-dimensional studies of 3NF and other effects
- Only fraction has been measured really systematically (RIKEN/RCNP/IUCF/KVI)
- Not completely clear picture - still much to explore!
- Complementary studies needed at much richer field: Nucleon-Deuteron Breakup
N-d Breakup Reaction

- Coverage of large phase-space regions
- Precise, rich sets of data needed for **systematic studies** of various effects

- Specific configurations sensitive to different dynamical effects

$^1\text{H}(d,pp)n$ measured: directions and energies of two protons, i.e. $\theta_1, \varphi_1, E_1$ $\theta_2, \varphi_2, E_2$
$^1$H($\vec{d}$,pp)n Measurements at 130 MeV
Cross Section and Analyzing Power Results

- 1800 cross section data points
  - $\theta_1, \theta_2 = (13^\circ) 15^\circ - 30^\circ$; grid 5$^\circ$; $\Delta\theta = \pm1^\circ$
  - $\varphi_{12} = 40^\circ - 180^\circ$; grid 10$^\circ$ - 20$^\circ$; $\Delta\varphi = \pm5^\circ$
  - $S$ [MeV] = 40 - 160; grid 4; $\Delta S = \pm2$

- 5*800 data points $A_x$, $A_y$, $A_{xx}$, $A_{xy}$, $A_{yy}$
  - $\theta_1, \theta_2 = 15^\circ - 30^\circ$; grid 5$^\circ$; $\Delta\theta = \pm2^\circ$
  - $\varphi_{12} = 40^\circ - 180^\circ$; grid 20$^\circ$; $\Delta\varphi = \pm10^\circ$
  - $S$ [MeV] = 40 - 160; grid 8; $\Delta S = \pm4$

- 2700 cross section data points
  - $\theta_1, \theta_2 = 5^\circ - 13^\circ$; grid 2$^\circ$; $\Delta\theta = \pm1^\circ$
  - $\varphi_{12} = 20^\circ - 180^\circ$; grid 20$^\circ$; $\Delta\varphi = \pm5^\circ$
  - $S$ [MeV] = 40 - 180; grid 8; $\Delta S = \pm4$

- 2*300 data points $A_x$, $A_y$
  - $\theta_1, \theta_2 = 6^\circ - 12^\circ$; grid 3$^\circ$; $\Delta\theta = \pm1.5^\circ$
  - $\varphi_{12} = 60^\circ - 180^\circ$; grid 40$^\circ$; $\Delta\varphi = \pm20^\circ$
  - $S$ [MeV] = 40 - 160; grid 16; $\Delta S = \pm8$
$^1\text{H}(\vec{d},pp)n$ Measurement at 130 MeV
Cross Section Results – Examples

\[ \frac{d^2\sigma}{d\Omega_1 d\Omega_2} \text{[mb MeV}^{-1}\text{sr}^{-2}] \]

\[ \phi_{12} = 20^\circ \]
\[ \phi_{12} = 40^\circ \]

\[ \theta_1 = \theta_2 = 9^\circ \]

\[ \phi_{12} = 60^\circ \]
\[ \phi_{12} = 120^\circ \]

- 2N
- 2N+TM99
- N2LO
- N3LO
- CDB+$\Delta$
- CDB+$\Delta$+C
- AV18+UIX
- AV18+UIX+C

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

Breakup Analyzing Powers – Extraction

Azimuthal ($\Phi$) distribution at every kinematical point $(\theta_1, \theta_2, \varphi_{12}, S) \equiv (\zeta', \varphi_{12})$, with known $P_z$ and $P_{zz}$ of rate asymmetry $f_p(\zeta', \varphi_{12}, \Phi)$ for pol. and unpol. states

$$f_p(\zeta', \varphi_{12}, \Phi) = P_z \left( -\frac{3}{2} \sin \phi \cdot A_x + \frac{3}{2} \cos \phi \cdot A_y \right) + P_{zz} \left( -\frac{1}{2} \sin 2\phi \cdot A_{xy} \right) +$$

$$+ P_{zz} \left( \frac{1}{2} \sin^2 \phi \cdot A_{xx} + \frac{1}{2} \cos^2 \phi \cdot A_{yy} \right)$$

$A \equiv A(\zeta', \varphi_{12})$
$^1\text{H}(d,pp)n$ Measurement at 130 MeV
Analyzing Power Results – Parity Test of Data

Parity-forbidden combinations

\[ O_\beta(\zeta',\varphi_{12}) = A_\beta(\zeta',\varphi_{12}) + (-1)^{1-\mu} \cdot A_\beta(\zeta',-\varphi_{12}) \]
$^1$H(\(\vec{d},pp\))n Measurement at 130 MeV

Analyzing Power Results

$E_d = 130$ MeV

$\theta_1, \theta_2 = 15^\circ - 30^\circ$

\[ \sum_{i=1}^{N=900} \frac{[A_{\text{exp}}(\xi_i) - A_{\text{th}}(\xi_i)]^2}{N} \]

\[ \chi^2 / \text{ndf} \]

$^2\text{H}(p, pp)n$ Breakup Reaction
Analyzing Powers vs. Cross Sections

Deviations $d^5\sigma$ and $A_y$ anti-phased in $\Phi_{12}$

$E_p = 135$ MeV
$\theta = 14^\circ - 30^\circ$

M. Eslami-Kalantari et al.
$^{1}\text{H}(d,pp)n$ Breakup Reaction
Polarization Transfer Coefficients

$E_d = 270$ MeV
$\theta_1, \theta_2 = 28^\circ - 32^\circ$, $\Phi_{12} = 180^\circ$

Double-scattering experiment for breakup!

$^{2}\text{H}(p,pp)n$ vs. $^{2}\text{H}(p,d)p$
Spin-Isospin Selectivity

$E_p = 190\text{ MeV}$
$\theta = 14^\circ - 30^\circ$

H. Mardanpour et al.,

$^{2}\text{H}(p,^{2}\text{He})n$  $^{2}\text{H}(p,^{2}\text{H})p$

$\theta_1 = \theta_2$, small $\phi_{12}$
$E_{pp} < 1\text{ MeV}$
$(pp) \approx ^{2}\text{He}$
3N Systems
N-d Breakup Reaction

- Variety of observables and configurations (wide phase space) for the breakup reaction, field of tests for different dynamic ingredients
- Sets (a few only) of rich, systematic and precise data are (at last) available
- Picture very ambiguous - still much to be learnt!
- Comparisons between beam energies - need of new variables
N-d Breakup Reaction
Invariant Variables

Defining configurations in terms of angles and energies makes comparisons of experiments performed at different energies difficult.

Using 4-momenta we can define:

\[ s_{pp} = (p_{p1} + p_{p2})^2 \]
\[ s_{pn} = (p_{p1} + p_n)^2 \]
\[ t_n = (p_d / 2 - p_n)^2 \]
\[ t_p = (p_p - p_{p2})^2 \]

More intuitively:

Then eg:

FSI: \[ E_{rel}^{pp} = 0 \]
\[ E_{rel}^{pn} = 0 \]

QFS: \[ E_{tr}^p = 0 \]
\[ E_{tr}^n = 0 \]
3N Systems
N-d Breakup Reaction

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- Are we ready for next step: Four-Nucleon System studies?
Four-Nucleon Systems

$E_d = 130$ MeV

$\theta = 15^\circ - 30^\circ$

A. Ramazani-Moghaddam-Arani et al.

Elastic $\bar{d} - d$

3-body breakup $d+d \rightarrow d+p+n$

$\theta_d=25^\circ$, $\theta_p=20^\circ$
Few-Nucleon Systems
Summary

- Rich, systematic and precise sets of data available (elastic scattering - many, breakup - a few)
  - basis for comparing different approaches which predict the 3N system observables
- Showed significant 3NF effects
- Found large influence of the Coulomb force on c.s.
- Relativistic effects to be studied in detail
- Interplay of different ingredients of 3N system dynamics - inspection started!
  - Discrepancies → hints of imperfections in 3NF models
- General picture not quite clear - needed studies to provide evidences of trends in deficiencies
Few-Nucleon Studies
Outlook & Wishes

- **Prospects for further results:**
  - Evaluating the data accumulated in several experiments at KVI and COSY
  - More measurements:
    - Japan: RIKEN, RCNP, RIBF, ...
    - Projects @ COSY Jülich
    - BINA @ IFJ PAN Cracow

- ** Awaited theoretical achievements:**
  - 3NF at N$^3$LO (close ahead...)
  - ChPT with $\Delta$ (work in progress...)
  - Realistic potentials with Coulomb
  - Relativistic potentials with 3NF
  - Rigorous calculations for 4N system (dreamed for !)
Few-Body Systems Remain Attractive!

Thank You for attention