Three- and Four-Nucleon dynamics at Intermediate Energies

By:
Ghanshyam Khatri
Outline

• Motivation
• Theoretical models
• 3N data-base
• Experiment with BINA: present work
  - Data Analysis Progress
• Experiment with WASA
  - Motivation
  - Very Preliminary results
• Summary
Motivation

Short-Range Strong Nuclear forces

- holds nucleons together in an Atomic Nuclei
- 1935: first theorized as meson exchange
- 1947: Pions experimentally observed
- today: many models available:
  Nijmegen - I & II, Argonne V18, CD Bonn, Reid-93, Paris ...
  ...reproduces nucleon-nucleon interaction data

BUT fails to describe system with A>2

<table>
<thead>
<tr>
<th>Model</th>
<th>$^3$H B.E. [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nijm I</td>
<td>7.72</td>
</tr>
<tr>
<td>Nijm II</td>
<td>7.62</td>
</tr>
<tr>
<td>AV18</td>
<td>7.62</td>
</tr>
<tr>
<td>Reid-93</td>
<td>7.63</td>
</tr>
<tr>
<td>Exp.</td>
<td>8.48</td>
</tr>
</tbody>
</table>


Perturbative QCD works only for high energy:
Residual color force

High precision data from Los Alamos
W. P. Abfalterer et al., *PRL* 81, 57 (1998)
**Motivation**

...adding 3NF in original 2NF helps!

<table>
<thead>
<tr>
<th>Model</th>
<th>$^3\text{H} \text{[MeV]}$</th>
<th>$^4\text{He} \text{[MeV]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2NF</td>
<td>7.62</td>
<td>24.2</td>
</tr>
<tr>
<td>2NF +3NF</td>
<td>8.47</td>
<td>28.3</td>
</tr>
<tr>
<td>Experiment</td>
<td>8.48</td>
<td>28.4</td>
</tr>
</tbody>
</table>

H. Witala et al. *PRL 81, 1183 (1998)*  
St. Kistryn et al. *PRC 68, 054004 (2003)*

**3NF contribution**

Hot-Spot to see 3NF: *intermediate energies* ?!
Theoretical Models

- Faddeev framework (based on pairwise N-N interactions)
  - provides exact treatment for the 3N system
  - also allows to include 3NF

- Calculations from: Prof. Witała and Prof. Glöckle

Main 2NF Models
- Nijmegen I & II
- CD Bonn (Charge Dependant)
- Argonne V18
- ...

Additional 3NF Models
- Tucson Melbourne (TM99)
- Urbana IX
- Illinois (IL2)
- ...

- Other Approaches:
  - Coupled Channels with Δ-isobar excitation (Prof. Deltuva, Portugal)
  - Chiral Perturbation Theory (ChPT) → only up to NNLO (Prof. Epelbaum, Germany)
Effects other than 3NFs? ...Yes

- Coulomb and Relativistic  
  *(but importance is limited in certain region of phase-space)*
- Recently coulomb effect was included successfully in the calculations with coupled channel calculations! *[Prof. Deltuva, Portugal]*

Relativistic effects: MAIN motivation behind *work@WASA* !!

4NF?
ChPT predicts 2NF>>3NF>>4NF (will be tested with *KVI-2011 data*)
Are we done? ...No!

- 3NFs helped to improve theories, but **still some discrepancy** remains.
- Do we understand the **exact form of 3NFs**?!!
  - *Include other ingredients*??
- Can we consider the validity through complete phase-space of 3N dynamics?
  - **Urgent need for systematic and High-Precision data-base**

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**3N Data Base**

**KVI-2011**

**proposed @WASA**

- **Available data**
- **Dot-Size show angular coverage of detection**

Rep. Prog. Phys. 75 **(2012)** 016301
N. Kalantar-Nayestanaki

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11 April, 2013  G. Khatri, tele-Symposium, Kraków
**BINA Experiment**

Wall covers θ=10-35°
+ Ball covers θ=up to 165°
≡ 4π Phase-Space

**MWPC:**
- CF4(80%) + Isobutene(20%) gas-mixture
- 20µm diameter tungsten wire

**Ball:**
Triangular fast scint. and slow phoswitch parts connected to PMT’s through lightguide

**Wire chamber (MWPC)**
Three planes X, Y & U
[118x118x148 wires]

150 phoswich Scintillators = Target chamber (~10^{-5} mbar)

**Forward scintillators (E-wall)**
[9x12x220 cm^3]

**Thin scintillators for particle identification (ΔE -wall)**
[1.8x10.8x0.1 cm^3]
Data Analysis: Progress

- Data collection in April-2011 with BINA-detector (in KVI, Groningen)
- Reactions: d+p , d+d (with deuteron beam@160MeV)
- Expected output channels:

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>d+p → d+p</td>
<td>elastic</td>
</tr>
<tr>
<td>d+p → p+p+n</td>
<td>3-body breakup</td>
</tr>
<tr>
<td>d+d → d+d</td>
<td>4-body breakup</td>
</tr>
<tr>
<td>d+d → t+p</td>
<td>n-transfer</td>
</tr>
<tr>
<td>d+d → d+p+n</td>
<td>3-body breakup</td>
</tr>
<tr>
<td>d+d → p+p+n+n</td>
<td>4-body breakup</td>
</tr>
</tbody>
</table>

Triggers:
2 charged particles in coincidence

TDC spectra of individual detectors

- Large Peak : coincidence events
- RF signal of cyclotron as reference
- Red lines define tdc gate for event selection
Coplanarity to select elastic dp channel: narrow peaks

Similar way used for selecting dd->dd and dd->tp channels.
**Data Analysis: Progress**

**dd reaction: kinematical spectra**

Only forward, so proton > 120 MeV

So triton < 40 MeV, such low energy

Hardly gets till end of WALL.
Hand draw illustration of angles dependence on beam center.
BLUE: ideal
RED: shifted

Beam center correction using \( dp \) elastic kinematics
Hand-drawn illustration of angles dependence on beam center.

BLUE: ideal

RED: shifted

**Data Analysis: Progress**

Beam center correction using dp elastic kinematics
Hand drawn illustration of angles dependence on beam center.

BLUE: ideal
RED: shifted

Beam center correction using dp elastic kinematics

\[ \theta_d \]

\[ \theta_p \]
Combining two PMT signals of an E-slab: $\sqrt{c_1c_2}$

Note: in case of dE-slabs, situation is different. We have cut in the center, so we rather take Exponential function of PMT signal with respect to the hit position along the dE-slab.
Combining two PMT signals of an E-slab: \( \sqrt{c_1c_2} \)

**dd data: single events**

**Central E-slabs (with hole) effect**

![Graphs showing data with and without central slabs](image)

- **With central slabs**
  - Graph showing data with central slabs.
  - Arrow indicating the central hole effect.
- **Without central slabs**
  - Graph showing data without central slabs.
  - Arrow indicating the absence of central hole effect.

Central hole leads to light reflection, which caused the PMT signal to behave badly.
Data Analysis: Progress

dE- distance from target

Geometry cross check:

Since dE was renewed, exact position was necessary to be determined.

Correlation between MWPC, E and dE gave Track number for few different expected values.
Data Analysis: Progress

MWPC reconstruction accuracy (dp elastic)

Odd/even grouped detectors

Two neighboring detectors fired

11 April, 2013

G. Khatri, tele-Symposium, Kraków
Data Analysis: Progress

Energy Calibration

Done in two steps:
1. Convert channel to deposited energy:
2. Convert deposited energy into energy at interaction points:

1. In this step we take events at specific $\theta$ value for different degrader thickens. The same procedure is simulated on Geant4 and the data (channel) plotted against simulated energy (MeV).

- Gauss fit
  - no degrader
  - 3mm degrader
  - 10mm degrader

Energy (or channel)
Data Analysis: Progress

Energy Calibration

2. Here Geant4 simulating is performed to relate the deposited energy with its initial energy at reaction point. This relation is compared for different angles and energies. At energies below 20 MeV, the straggling effect starts getting strong.
Why WASA ? :

- 4π detection  (will allow large phase-space coverage → detailed 3N dynamic)
- Low accidental background
- Available Energy Range (best of relativistic effects to study)

Proposal No: 214  (Jan, 2013)
Beam: d (unpolarized), 1 week
Energies: 340, 380, 400 (in MeV) in Supercycle mode
Additional 300 MeV runs also
Target: LH1 pellets
Luminosity: ~ 2x10²⁸ /cm²/s
Measurement: diff. cross-section for dp breakup reaction
Calculations predict large relativistic effect

**Diff. cross section** for Nd breakup @200 MeV/n

Where,

$S = \text{arc length along kin. curve}$

**Note:** here $pd$ breakup shown but the rel. effect should be of the same order in $dp$ breakup as well. The latter will be available soon.

*(personal communication with Prof Witala)*

R. Skibiński,
New calculation also predicts:

- Interplay between Rel. and 3NF
- Increasing 3NF effect with $E$

Nd breakup @200 MeV/n
$E_1 = $ energy of proton
WASA Experiment

Preliminary Results

dE-E identification

Seen clear separation of the d & p branches

Breakup kinematics: two protons from dp->ppn

\[ \theta_1 = 5^\circ \pm 1^\circ \]
\[ \theta_2 = 10^\circ \pm 1^\circ \]
\[ \phi_{12} = 90^\circ \pm 5^\circ \]

Solid line: calculated from 3body kinematics program
• Analysis of data from KVI @ 160 MeV is under progress.

• So far geometry checks, sorting of good data, and calibration have been done.

• Next steps will be: Efficiencies, PID and Cross-sec. Normalization.

• Currently BINA is being installed at CCB in Krakow: test experiments will performed by July, 2013.

• Analysis of WASA data is next exciting task.
Thank you for your attention !!!