Experimental Investigation of Few-Nucleon Dynamics at Medium Energies

by

Ghanshyam Khatri
Outline

- Introduction
- Three-body (3N) force
- Experimental tools
- BINA Detector and it’s status at CCB (Krakow)
- 3N data base: present and future
- Results
- Conclusion
Introduction
Introduction

Residual of the strong forces

Nuclear Force

holds protons and neutrons together in an atomic Nuclei
Introduction

Nuclear Force

✓ 1935: Yukawa presented a Theory
✓ 1947: Powell proved the theory by experiments

➢ Today, many different Theoretical models are available to exactly describe the nuclear force between any two nucleons.

(Note: Nucleons is a general term for Protons and Neutrons)
Nuclear Force

- **1935**: Yukawa presented a Theory
- **1947**: Powell proved the theory by experiments

Today, many different Theoretical models are available to exactly describe the nuclear force between **any two nucleons**.

(Note: **Nucleons** is a general term for **Protons and Neutrons**)

...but FAILS to describe Interaction between more than two nucleons!

Even for the simplest Atomic Nucleus e.g. $^3$H and $^3$He

<table>
<thead>
<tr>
<th>Model</th>
<th>[MeV]</th>
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<tbody>
<tr>
<td>Nijm I</td>
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</tr>
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<td>Reid-93</td>
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Binding Energy of Triton

High precision data from Los Alamos W. P. Abfalterer et al., PRL 81, 57 (1998)
Adding 3NF in original 2NF helps!

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$$V_{12} + V_{23} + V_{31} = V_{\text{theory}}$$

$$3NF = V_{123}$$

3N System
Three-body force

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

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Three-body forces in nature; example

$V_{12} + V_{23} + V_{31} = V_{\text{theory}}$

$3\text{NF} = V_{123}$

Moon — Earth

3N System
Three-body force

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Three-body forces in nature; example

$V_{12} + V_{23} + V_{31} = V_{\text{theory}}$

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3N System

Earth (and nucleon) are not point like but having internal structure

But still there are discrepancies between data and theories! Need detailed study of 3NF.
**Experimental Tools**

Nucleon - Deuteron Scattering (Relatively Simplest but not simple):

**Elastic:** $\text{N} + \text{d} \rightarrow \text{N} + \text{d}$
- Very limited phase-space

**Breakup:** $\text{N} + \text{d} \rightarrow \text{N} + \text{N} + \text{N}$
- rich phase-space: a large amount of kinematical config.
Experimental Tools

Nucleon - Deuteron Scattering (Relatively Simplest but not simple):

Elastic: $N + d \rightarrow N + d$

- Very limited phase-space

Breakup: $N + d \rightarrow N + N + N$

- rich phase-space: a large amount of kinematical config.

**deuteron-nucleon breakup reaction** is best suited to study 3N interactions
BINA Detector

Big Instrument for Nuclear-polarisation Analysis

Wire chamber (MWPC)

Beam + Target

ΔE

E

TARGET

Dedicated for few-body! High-precision data!
BINA Detector

Big Instrument for Nuclear-polarisation Analysis

Wire chamber (MWPC)

Ball + Target

E

ΔE

Beam

TARGET

Dedicated for few-body!
High-precision data!
BINA in Kraków

BINA @ Cyclotron Center Bronowice

2012

2014
### 3N Data Base: Present and Future

#### Nd elastic scattering

<table>
<thead>
<tr>
<th>MeV/n</th>
<th>100</th>
<th>200</th>
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<tr>
<td>$\frac{d\sigma}{d\Omega}$</td>
<td><img src="image1" alt="Data Points" /></td>
<td><img src="image2" alt="Data Points" /></td>
</tr>
<tr>
<td>$\frac{d\sigma}{d\Omega}$</td>
<td><img src="image3" alt="Data Points" /></td>
<td><img src="image4" alt="Data Points" /></td>
</tr>
<tr>
<td>$p \frac{A_y}{n}$</td>
<td><img src="image5" alt="Data Points" /></td>
<td><img src="image6" alt="Data Points" /></td>
</tr>
<tr>
<td>$d \frac{A_y}{d}(d)$</td>
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<td><img src="image8" alt="Data Points" /></td>
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<tr>
<td>$A_{yy}$</td>
<td><img src="image9" alt="Data Points" /></td>
<td><img src="image10" alt="Data Points" /></td>
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#### Nd break-up

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△ KVI-2011
◇ WASA 2013

- p or d beam data
- neutron beam data

Note: dot size tells angular coverage
Few-body program very successful

Krakow-Katowice-KVI collaboration, new Cyclotron at CCB in Krakow

Energy Range of CCB suitable for this research (50 to 230 MeV)

No need to travelling abroad, (US, Japan and now in Poland)

Strong collaboration with theory group of prof Witała in UJ, Kraków

Future: polarized target, opens a new line of research
Results

- Experiment performed at KVI with BINA in April 2011.
  - beam: deuteron,
  - energy: 160 MeV,
  - target: Liquid Deuterium

- Important Remarks: a step forward with 4N, theories are limited

```
\textbf{d+d - EVEN MORE COMPLICATED SYSTEM}

\text{d + d} \rightarrow \text{d + d} \hspace{1cm} \text{... elastic}
\text{d + d} \rightarrow \text{d + p + n} \hspace{1cm} \text{... three-body final state}
\text{d + d} \rightarrow \text{p + p + n + n} \hspace{1cm} \text{... four-body final state}
\text{d + d} \rightarrow \text{d + p ( + n_{\text{spectator}})} \hspace{1cm} \text{... QFS}
\text{d + d} \rightarrow \text{p + p ( + 2n_{\text{spectator}})} \hspace{1cm} \text{... double QFS}
\text{d + d} \rightarrow \text{^{3}H + p} \hspace{1cm} \text{... neutron transfer}
\text{d + d} \rightarrow \text{^{3}He + n} \hspace{1cm} \text{... proton transfer}
```

Theoretical calculations will be available for two-body final states

(private communication with A. Deltuva)
Most basic analysis steps:

all data
Results

Most basic analysis steps:

**step 1:** Presort

![Data Analysis Diagram]
Most basic analysis steps:

**step 1:** Presort

**step 2:** Selection of the reaction-channels

\[ d+d \rightarrow d+p+n \]
Most basic analysis steps:

**step 1:** Presort

**OUR GOAL**

all data

**step 2:**
Selection of the reaction-channels

\[ d+d \rightarrow d+p+n \]

**step 3:** cross sections

Results

\[ \theta_d = 20 \pm 1, \theta_p = 30 \pm 1, \phi_{12} = 180 \pm 5 \]
Achievements

- BINA@CCB preparation tests, liquid-target expert
- Visiting facilities, learned and gained experience KVI, FZ-Juelich, Lisbon
- Publications & Conferences
- MPD FEW-BODY PROJECT
- Grants: SONATA-BIS Preludium 7 (application)
Conclusion and Outlook

- Current data analysis of 160MeV data on dp and dd reactions at final stage

- Theoreticians have been requested to provide calculations for dd reaction

- BINA has been put into operation in Krakow, two tests with BINA were done successfully, 2013 and 2014

- Future: Polarised target, we recently communicated with Japanese expert this month.
Thank you for your attention !!!
Backup slides
**Introduction**

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3N System

Hot-Spot to see 3NF: medium energies ?!

3NF contribution
Three-body force

Experimental Tools: Three-Nucleon Scattering
@ Medium Energies

☐ Elastic: \( N + d \rightarrow N + d \)

Coulomb

\[
\frac{d\sigma}{d\Omega} \text{ (mb/sr)}
\]

\[
\theta_{c.m.} \text{ [deg]}
\]

Effects small, located at extreme angles only!
Three nucleons in the final state
- 9 variables

Energy-momentum conservation
- 4 equations

Five independent kinematical variables:
\[ \theta_1, \theta_2, \phi_{12} = \phi_1 - \phi_2, E_1, E_2 \]

\(^1\text{H}(d,pp)n\) measured: directions and energies of two protons

Diagram:
- \(D\): Distance from kinematical curve
- \(S\): Arclength variable

\[ \theta_1 = 9^\circ, \theta_2 = 11^\circ, \phi_{12} = 60^\circ \]
Introduction

Ab-initio calculations for light nuclei

Argonne v18
With Illinois-2
GFMC Calculations
6 November 2002
Introduction

Ab-initio calculations for light nuclei

Argonne v18
With Illinois-2
GFMC Calculations
6 November 2002
Three-body forces in a NUCLEAR system!

\[ H = -\sum_{i=1}^{3} \frac{\hbar^2}{2m_i} + \sum_{i>j=1}^{3} v_{ij} \]
Three-body forces in a NUCLEAR system!

\[ H = -\sum_{i=1}^{3} \frac{\hbar^2}{2m_i} + \sum_{i>j=1}^{3} V_{ij} + V \]
$p + d \to p + d$

K. Ermisch et al.,
PRC 68, 054004 (2003),
PRC 71, 064004 (2005)