Experimental Investigation of Few-Nucleon Dynamics at Medium Energies

by
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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)
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)

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

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

| Model   | [MeV] |
|---------|-------|
| Nijm I  | 7.72  |
| Nijm II | 7.62  |
| AV18    | 7.62  |
| Reid-93 | 7.63  |
| Exp.    | 8.48  |

Binding Energy of Triton

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

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

| Model       | $^3\text{H}$ [MeV] | $^4\text{He}$ [MeV] |
|-------------|---------------------|----------------------|
| 2NF         | 7.62                | 24.2                 |
| 2NF +3NF    | 8.47                | 28.3                 |
| Experiment  | **8.48**            | **28.4**             |

\[ V_{12} + V_{23} + V_{31} = V_{\text{theory}} \]

3NF = $V_{123}$

3N System
Three-body forces in nature; example

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\[ 3NF = V_{123} \]

Three-body force

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**Three-body force**

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Three-body forces in nature; example

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

$3NF = V_{123}$

3N System

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: $N + d \rightarrow N + d$

- Very limited phase-space

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

- Rich phase-space: a large amount of kinematical config.
Experimental Tools

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

**Big Instrument for Nuclear-polarisation Analysis**

- **Wire chamber (MWPC)**
- **Ball + Target**
- **Beam**
- **ΔE**

**TARGET**

Dedicated for few-body!
High-precision data!
Big Instrument for Nuclear-polarisation Analysis

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 | Nd break-up |
|-----------------------|-------------|
| **MeV/n**             | **MeV/n**   |
| 100                   | 100         |
| 200                   | 200         |

| Variable                      | 100   | 200   |
|-------------------------------|-------|-------|
| $\frac{d\sigma}{d\Omega}$    |       |       |
| $\frac{d\sigma}{d\Omega}$    |       |       |
| $A_y(N)$                      |       |       |
| $A_y(d)$                      |       |       |
| $A_{yy}$                      |       |       |
| $A_{xx}$                      |       |       |
| $A_{xz}$                      |       |       |

**Note:** dot size tells angular coverage

### KVI-2011

- p or d beam data
- neutron beam data

**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

**d+d - EVEN MORE COMPLICATED SYSTEM**

\[
\begin{align*}
d + d &\rightarrow d + d & \quad \text{... elastic} \\
d + d &\rightarrow d + p + n & \quad \text{... three-body final state} \\
d + d &\rightarrow p + p + n + n & \quad \text{... four-body final state} \\
d + d &\rightarrow d + p ( + n_{\text{spectator}} ) & \quad \text{... QFS} \\
d + d &\rightarrow p + p ( + 2n_{\text{spectator}} ) & \quad \text{... double QFS} \\
d + d &\rightarrow ^3\text{H} + p & \quad \text{... neutron transfer} \\
d + d &\rightarrow ^3\text{He} + n & \quad \text{... proton transfer}
\end{align*}
\]

Theoretical calculations
Will be available for
Two-body final states

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

all data
Most basic analysis steps:

**step 1:** Presort

Results

all data
Most basic analysis steps:

**step 1:** Presort

Selection of the reaction-channels:

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

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

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

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

**step 1:** Presort

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

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

**step 3:** Cross sections

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

**BINA@CCB**
preparation tests, liquid-target expert

**Grants:**
SONATA-BIS Preludium 7 (application)

visiting facilities, learned and gained experience
KVI, FZ-Juelich, Lisbon

MPD FEW-BODY PROJECT

Publications & Conferences
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?!
Experimental Tools: Three-Nucleon Scattering @ Medium Energies

- **Elastic: N + d → N + d**

**Coulomb**

- 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

arclength variable \(S\)
distance from kinematical curve \(D\)
Introduction

Ab-initio calculations for light nuclei

Argonne v18
With Illinois-2
GFMC Calculations
6 November 2002

Courtesy S. Pieper, Argonne

Energy (MeV)
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!

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

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

**3N dynamics**

**Models vs. Data**

pd elastic scattering cross sections