Differential Cross Section for Proton Induced Deuteron Breakup at 108 MeV

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Three nucleon System

• Prediction of NN potentials alone:
  ➔ Fail to reproduce binding energies of 3N, 4N and heavier system
  ➔ Fail to reproduce minimum of the d(N,N)d elastic scattering cross section

• Introducing concept of three-nucleon forces: genuine (irreducible) interaction of three nucleons – direct consequence of internal structure of nucleons

• Systematic approach within ChPT

Why to Study System of 3N?

• Observables can be calculated in ab-inito regime
• The environment is non-trivial as compared to NN systems and probably reaches in dynamics
• The nuclear potentials tested in those simple systems can be used in more complicated ones
• TO LEARN ABOUT NUCLEAR INTERACTIONS
1) Experimental program:

- Measurement of $^2\text{H}(p, pd)$ elastic scattering at 108, 135 and 160 MeV
- Measurement of $^2\text{H}(p, pp)n$ breakup reaction at 108 and 160 MeV for over 100 kinematic configurations

2) Aim:

- Studies of 3NF
- Verification of predicted Coulomb and relativistic effects
- Tests of upcoming ChPT calculations
Breakup Reaction

- **Three nucleon** \((p,p,n)\) in the final state; nucleons are defined by its momenta → 9 kinematic variables;
- Energy-momentum conservation → five independent kinematic variables;
- \(^2\!H(p,pp)n\) was measured:
  - Energies
  - Directions
    \(\theta_1, \varphi_1, E_1, \theta_2, \varphi_2, E_2\)
- With absence of polarization the system is axially symmetric;
- \(\theta_1, \varphi_1, E_1, \theta_2, \varphi_2, E_2\)
  → \(\theta_1, \theta_2, S, \varphi_{12} (\varphi_1-\varphi_2)\)
Experimental Setup

A) The Forward Part of detector (Wall):
- Multi-Wire Proportional Chamber
- The E-$\Delta$E telescopes

B) The Central-Backward Part - Ball

FIRST RUN - ONLY THE FORWARD PART
MWPC + E-ΔE telescopes

- **MWPC** – 3 planes wires allowing reconstruct of the emission angle of a charged particle;
- The efficiency of **MWPC** is about 90%;
- **ΔE-E hodoscopes** are made of plastic scintillator material;
- **ΔE-E** – Particle Identifications.

- Angular acceptance of Wall:
  \[ \theta \in (10^\circ - 35^\circ) \]
  \[ \varphi \in \text{full } \varphi \]
- Angular resolution:
  \[ \Delta \theta \approx 0.5^\circ \]
  \[ \Delta \varphi \approx 0.5^\circ - 3^\circ \]
System of 149 phoswitches (phosphor sandwich) is a combination of scintillators with dissimilar pulse shape characteristics optically coupled to each other and to a common PMT.

- The shape and the construction — **20 identical hexagon** and **12 identical pentagon structures** which are further divided into **identical triangles** (represents here a single ball element)

- The target system inside the Ball:
  1) Liquid Deuterium Target $\text{LD}_2$ – relative measurement of breakup cross section
  2) Solid Target $\text{CD}_2$ – absolute measurement of elastic scattering cross section

- Together with Wall - angular acceptance of nearly $4\pi$
Particle Identification (PID)

- Based on $\Delta E-E$ technique;
- The events of interest are the coincidences of two charged particles:
  1) $pp$ (breakup reaction),
  2) $pd$ (elastic scattering),
- allows us to identify protons and deuterons;

FIRST DATA (2016)
Graphical cuts ("gates") were defined for each individual $\Delta E-E$ telescope;

Small overlap of gates is allowed;

three groups of events are well visible:

- the spot of deuterons coming from the elastic scattering,
- the long branch of protons coming from the breakup reaction,
- the spot of elastically-scattered protons.
Calibration of deposited energy

- **Proton beam** energies: 70, 83, 97, 108, 120 MeV;
- **Al**(p,p)**Al** scattering.

Events are defined by:
- the **side** (S = right / left),
- the **E detector number** (N = 0, 1, ..., 9),
- the **polar angle** (θ = 12° - 34°; step = 2°).

Energy for each detector:

\[
C = \sqrt{c_1 * c_2}
\]

supress effects of light attenuation along the bar
Experimental data

Monte Carlo Simulation

Al(p,p)Al scattering

E detector number: N=3

Theta angle: \( \theta = 16^\circ \pm 1^\circ \)

Side: S=left

70 MeV

97 MeV

120 MeV
1. Linear calibration
   - $y = aC + b$
   - Range: $> 50$ MeV

2. Light quenching effect
   - $y = aC + b\sqrt{C}$
   - Departure from linearity for energies 0-50 MeV
Calibration - LD$_2$ target

- Transformation of deposited energy to initial energy
- Monte Carlo simulations of $E_{\text{loss}}$ between the reaction point and $E$ detector
- Simulation:
  - proton energy (15-100 MeV),
  - proton $\theta$ angle (12°-34°).
Kinematical configuration

- $^2\text{H}(p,pp)n$ reaction kinematics determined by proton momenta $\vec{p}_1, \vec{p}_2$

- Configuration was defined by emission angles of two outgoing protons:
  \[ \theta_1 \pm 1^\circ, \theta_2 \pm 1^\circ, \varphi_{12} \pm 5^\circ, \]

- The central line of the experimental band is lying on the theoretical kinematics.

It confirms the correct energy calibration
Background Subtraction

- Transformation of $E_2$ vs $E_1$ spectrum to $S$ (arclength variable) vs Distance of the points from kinematical curve;
- Each slice on the $S$ vs $D$ – distance spectrum is treated separately;
- The background is approximated by a linear function between the two limits of integration;
- The events below linear function are subtracted;

$$\theta_1 = 16^\circ, \theta_2 = 28^\circ, \phi_{12} = 160^\circ$$
\[ \theta_1 = 16^\circ, \, \theta_2 = 28^\circ, \, \varphi_{12} = 160^\circ \]

Arbitrary Data Normalization

averaged theories:
\[ \theta_1 \pm 1^\circ, \, \theta_2 \pm 1^\circ, \, \varphi_{12} \pm 5^\circ \]
\[ \theta_1 = 28^\circ, \theta_2 = 30^\circ, \varphi_{12} = 180^\circ \]

Arbitrary Data Normalization

averaged theories:

\[ \theta_1 \pm 1^\circ, \theta_2 \pm 1^\circ, \varphi_{12} \pm 5^\circ \]
Summary of Data Analysis

1. Particle Identification
2. Energy Calibration
3. Selection of Kinematics Configuration of Breakup Reaction
4. Background subtraction
5. Determination of Detection Efficiency
6. Normalization to Cross Section of Elastic Scattering
7. Comparison of Differential Cross Section for $^2\text{H}(p,pp)n$ Reaction at 108 MeV

DONE

IN PROGRESS

TO DO!
Outlook

- The preliminary analysis of the data taken with the BINA detector at CCB demonstrates a proper and efficient functioning of the forward part of this detector;
- New data will be collected with high statistics for 108, 135 and 160 MeV.

Thank you for your attention!
Theoretical calculations – Two Nucleons

1) **Realistic Potentials** – meson exchange theory of NN forces – phenomenological short range part (CD Bonn, Nijm I, Nijm II, AV18);

2) **Coupled-Channel Potential** with Δ-isobar excitation – CD Bonn + explicit treatment of a single Δ-isobar degrees of freedom;

3) **Chiral Perturbation Theory** (ChPT) – expansion of potential in powers \( \nu \) of small external momenta \( Q, (Q/\Lambda_\chi)^\nu \), with \( \Lambda_\chi \approx 1 \text{ GeV} \);

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**Realistic Potentials**

**Coupled-Channels Potential (single Δ)**

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