Dynamics of three-nucleon systems at 100 MeV

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Introduction

Modern NN potentials in general reproduce:

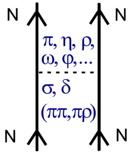
- properties of the nuclear matter (equation of state)
- binding energies of light nuclei
- global features of the bulk of the elastic scattering observables in 2N and 3N systems

Role of precise knowledge of few-nucleon system dynamics

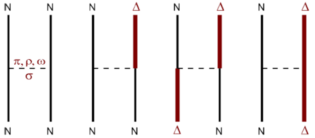
- fundamental for description of nuclei properties and nuclear processes,
- key feature for application in calculation/simulation codes (fast reaction stage – INC, QMD, etc.), radiation shielding, spallation targets, dosimetry, medical irradiation procedures, biological and astrophysical models, ...

Introduction - standard interaction models of 2N system

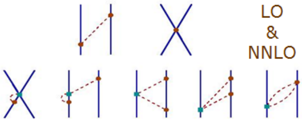
- Realistic potentials: meson exchange theory of NN forces - nucleonic degrees of freedom (AV18, CD Bonn, NijmI, NijmII)



- Coupled Channels (CC) potential: CD Bonn + explicit treatment of a single Δ-isobar degrees of freedom

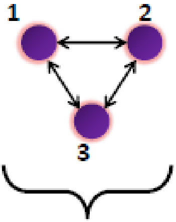


- Chiral Perturbation Theory (ChPT) potential: Effective Field Theory expansion of potential in powers ν of small external momenta Q, $(Q/\Lambda_\chi)^\nu$, with $\Lambda_\chi \approx 1$ GeV



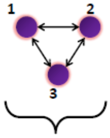
Introduction - 3N systems

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



$$V_{12}+V_{23}+V_{31}=V_{th.}$$

Introduction - 3N systems



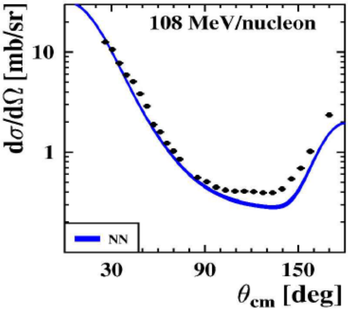
$V_{12}+V_{23}+V_{31}=V_{th.}$

Binding energies [MeV]

Model	^3H	^3He
CD Bonn	8.01	7.29
AV18	7.62	6.92
Nijm II	7.66	7.01
Experiment	**8.48**	**7.72**

NN potentials alone fail to reproduce binding energies of the 3N systems.

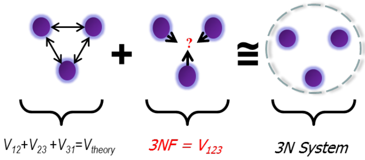
Elastic scattering N + d



K. Ermisch et al., PRC 68 (2003) 051001(R)

NN forces fail to reproduce minimum of the d(N,N)d elastic scattering cross section.

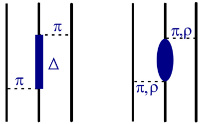
Introduction - 3N systems



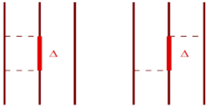
Introducing the concept of three-nucleon forces (3NF): genuine (irreducible) interaction of three nucleons.

Introduction - 3NF models

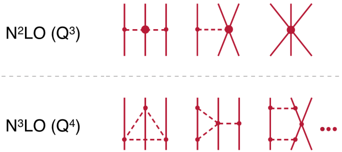
- Phenomenological three-nucleon forces: only weak connection to the NN potentials (e.g. TM99, Urbana IX, Brasil, Illinois);



- CC: Competing Δ-excitation effects (two nucleon dispersion and effective 3NF) – resulting net Δ influence is quite small;



- ChPT: three-nucleon forces appear naturally, fully consistent with the 2N graphs. (Under development, 3N system observables calculated up to N^{2}LO.)



Introduction - 3N systems

Binding energies [MeV]

Model	^3H	^3He
CD Bonn	8.01	7.29
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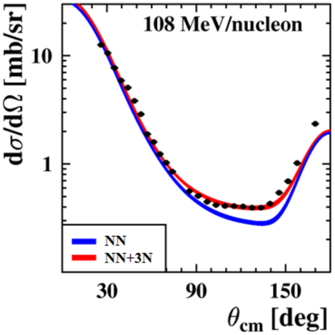
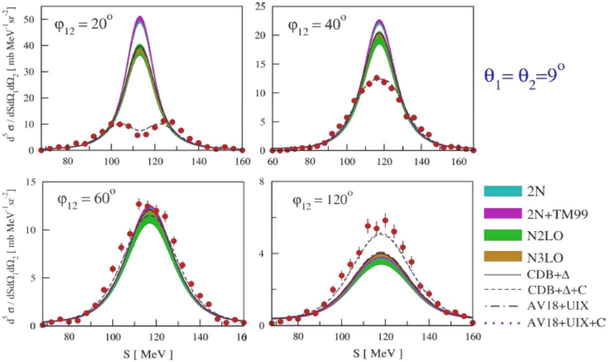
CD Bonn + TM99	8.48	7.73
Nijm II + TM99	8.39	7.72
AV18 + TM99	8.48	7.76
AV18 + UIX	8.48	7.76
CC CD Bonn + Δ	8.36	7.64
Experiment	**8.48**	**7.72**

Elastic scattering N + d



K. Ermisch et al., PRC **68** (2003) 051001(R)

Breakup reaction N + d @ 130 MeV



A. Deltuva et al., PRC 80, 056002 (2009)

I. Ciepał et al., FBS 56, 665 (2015)

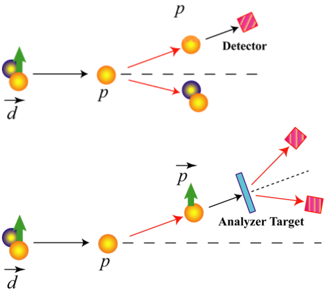
The dynamical effects of 3NF and Coulomb force should be included in theoretical calculations.

Experiments

The *Nd* system is one of the simplest to study dynamics of three nucleons. Experiments with polarized beams (or/and targets) give an opportunity to study a large number of observables (e.g. analyzing powers) sensitive to dynamical components, which are hidden in the unpolarized case.

Comparison of the high precision experimental data with rigorous theoretical calculations give an opportunity to study very subtle dynamical effects.

Experiments - 3N systems studied experimentally



Reaction mechanisms:

- elastic scattering $N+d \longrightarrow N+d$,
- breakup $N+d \longrightarrow N+n+p$,
- electromagnetic processes.

Observables:

- differential cross sections,
- vector and tensor analyzing powers,
- polarization correlation and transfer coefficients.

Different effects to be traced:

- comparisons between channels,
- influences of 3NF,
- Coulomb force action,
- relativistic effects.

Experiment dp@100MeV(50 AMeV)

Motivation for the breakup measurement at the beam energy of 100 MeV:

- expected 3N force effects: significant for elastic scattering and very small for the breakup reaction;
- low energy is appropriate for testing new calculations of chiral EFT.

Measured observables:

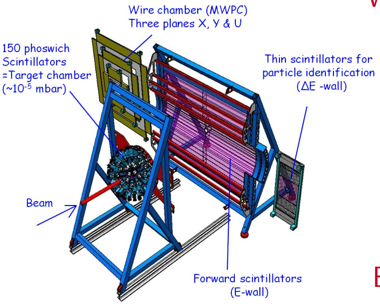
- differential cross sections,
- vector and tensor analyzing powers (St. Kistryn and E. Stephan, JPG:NPP 40 063101 (2013))

This measurement provided a benchmark for testing 3N systems at higher energies.

Experimental setup for dp measurement

Target: liquid hydrogen. **Beam:** polarized deuterons.

Big **I**nstrument for **N**uclear-polarization **A**nalysis **(BINA)**



WALL
- MWPC – three-plane (x, y, u);
- scintilator hodoscope: 12 horizontal detectors (ΔE) and 10 vertical stopping detectors (E), arranged perpendicularly to one another.

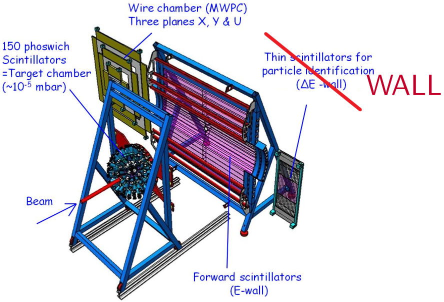
Covers laboratory polar angles between 12° and 35° with the full range of azimuthal angles up to 30°.

BALL 149 phoswitch scintilators. Covers laboratory polar angles up to 165° and the full range of azimuthal angles.

Experiment dp@100MeV(50 AMeV)

Target: liquid hydrogen. **Beam:** polarized deuterons.

Big **I**nstrument for **N**uclear-polarization **A**nalysis **(BINA)**



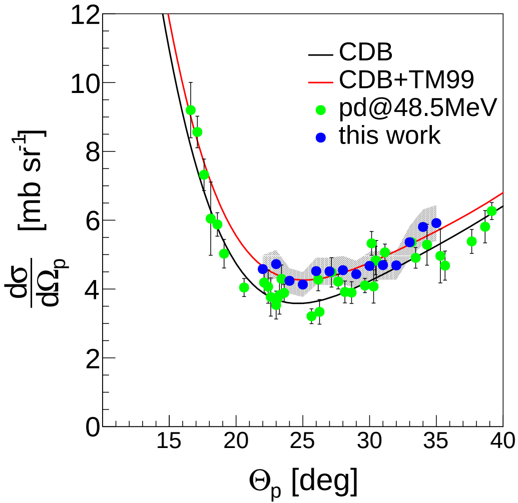
- MWPC – three-plane (x, y, u);
- scintilator: 10 vertical stopping detectors (E).

Covers laboratory polar angles between 12° and 35° with the full range of azimuthal angles up to 30°.

Current analysis:

- all particles have been registered only in WALL;

Elastic scattering - results

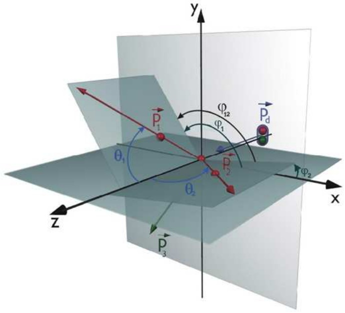


Theoretical calculations: H. Witała, private communication.

V.I. Grancev *et al.*, *Ukr. Fiz. Zhur. 28 506 (1983)*

Breakup reaction - results

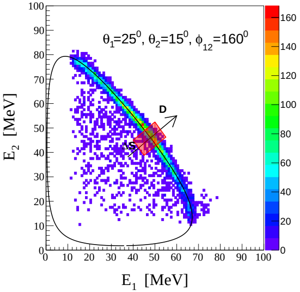
$$p + d \to p^{(1)} + p^{(2)} + n$$



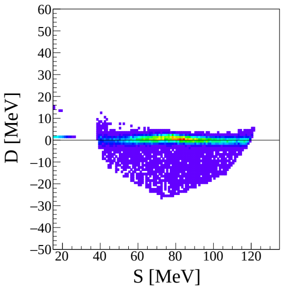
Measured directions and energies of two protons: θ_1, φ_1,E_1, θ_2, φ_2, E_2.

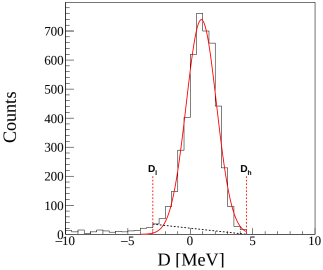
A kinematic configuration is defined by the emission angles:
$\theta_1 \pm 1^\circ$, $\theta_2 \pm 1^\circ$, $\phi_{12} \pm 10^\circ$.

Breakup reaction - results



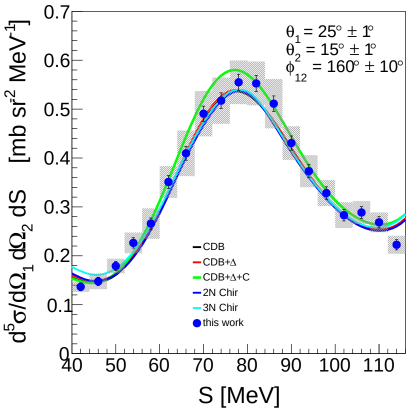
- transformation of E_2 vs E_1 spectrum to D (distance of points from the kinematic curve) vs S (arclength variable)
- each slice on the D vs S spectrum is treated separately
- the background is approximated by a linear function between the two integration limits





Breakup reaction - results

Including configurational efficiency and luminosity



- The 3N force effect is negligible.
- The Coulomb force effect is visible and couldn't be neglected.

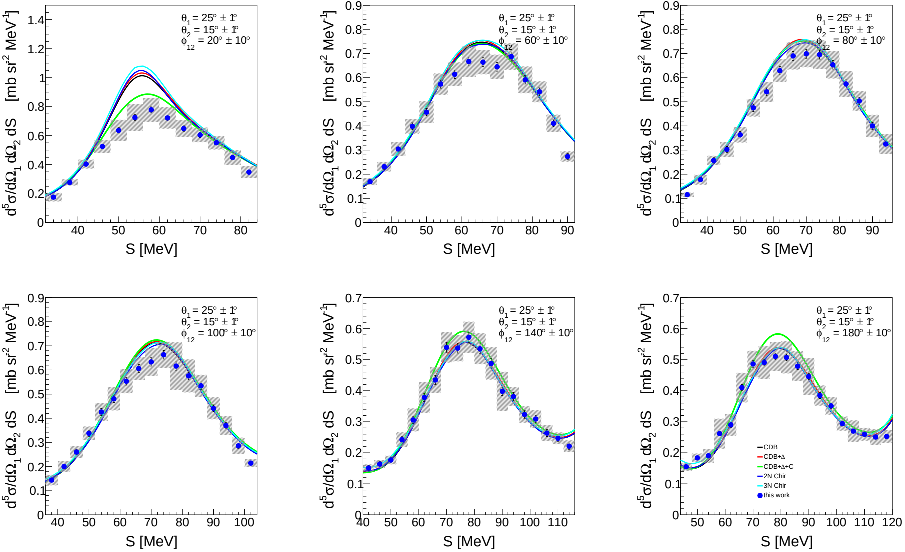
S – length along the kinematic curve

Theoretical calculations:

A. Deltuva, private communication.

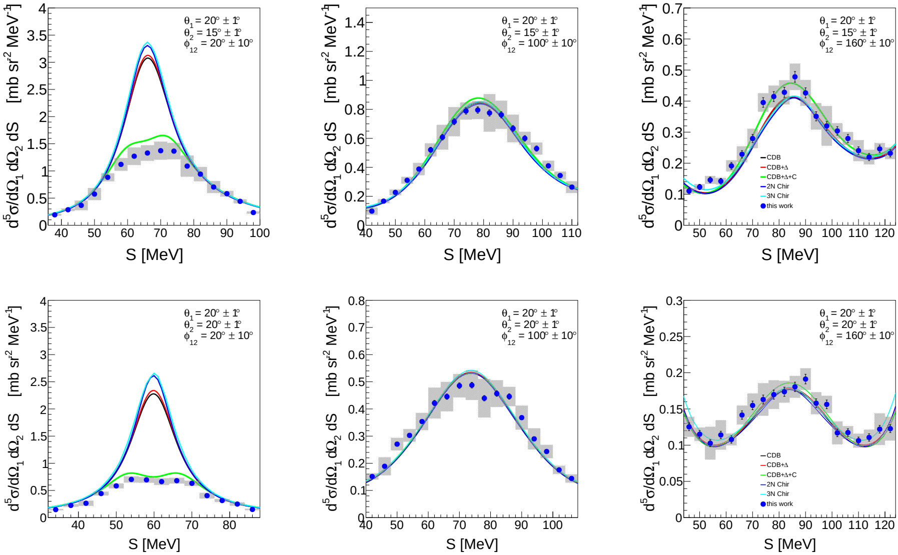
R. Skibiński, private communication.

Breakup reaction - results



S – length along the kinematic curve

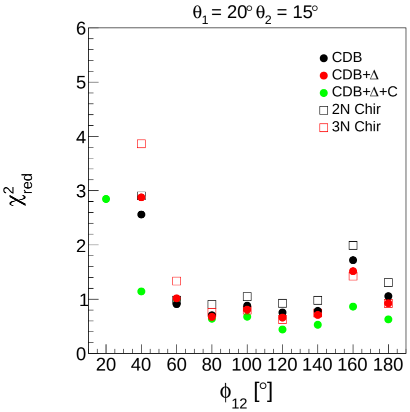
Breakup reaction

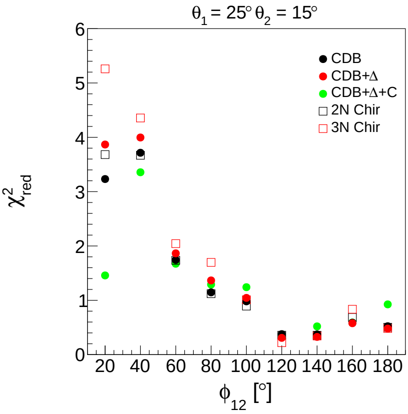


S – length along the kinematic curve

Breakup reaction - χ^2

$$\chi^2_{red} = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{\sigma_i^{exp} - \sigma_i^{th}}{\Delta\sigma_i^{exp}}\right)^2 \qquad \Delta\sigma_i^{exp} = \sqrt{(\Delta\sigma_i^{exp,stat})^2 + (\Delta\sigma_i^{exp,syst})^2}$$





Breakup reaction - *A*-factor

$$A = \frac{1}{N}\sum_{i=1}^{N}\frac{|\sigma_i^{exp} - \sigma_i^{th}|}{\sigma_i^{exp} + \sigma_i^{th}}$$

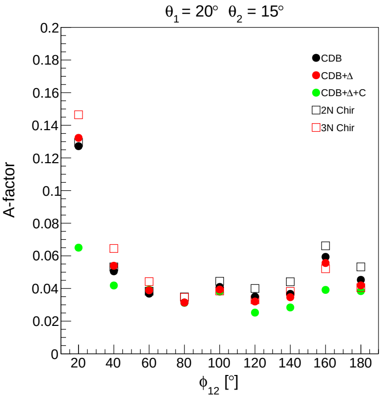
Its value is independent of the absolute value of the cross section nor of the experimental uncertainties.

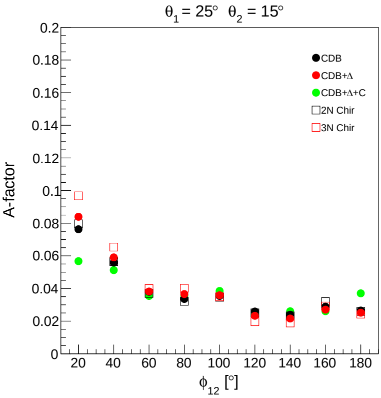
Its value belongs to the interval [0, 1]

$$A = \begin{cases} 0 & \text{perfect agreement th and exp} \\ 1 & \text{total discrepancy th and exp} \end{cases} .$$

S.K. Sharma et al., EPJ A 53, 150 (2017)

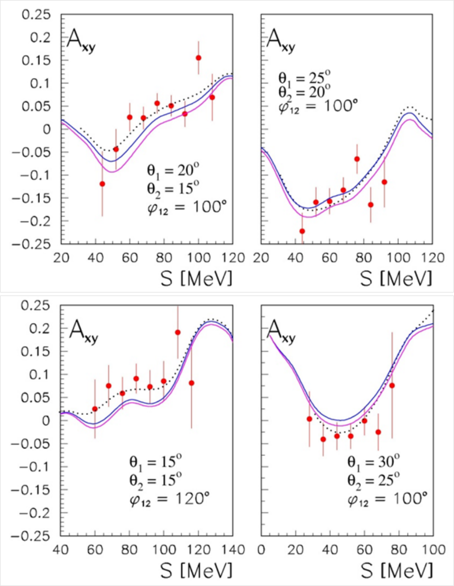
Breakup reaction - *A*-factor





Very small values of the *A*-factor $\longrightarrow$ $\sigma_i^{exp} \approx \sigma_i^{th}$ and therefore the *A*-factor value may be interpreted as a half of the average relative distance between the experimental and theoretical cross sections. For example A $=$ 0.02 appears when the average relative distance of data and calculated values is equal to 4%.

Breakup reaction – Tensor analyzing power



CD Bonn

CD Bonn + TM99

CD Bonn + Δ + C (dotted line)

- Predicted influence of the 3NF effects is small.
- The Coulomb force effect is visible and couldn't be neglected.

Summary and Outlook dp@100MeV(50 AMeV)

1. The shape of the experimental cross section for the elastic scattering distribution is in a good agreement with the theoretical calculations.
2. Predicted effects of 3NF for the elastic scattering cross sections are significant.
3. Around 1400 experimental points of the differential cross section for 87 kinematic configurations of the deuteron breakup were measured.
4. Results for breakup confirm the theoretical predictions:

4a. the 3NF effects are negligible

4b. the Coulomb force effect is visible for particular kinematic configurations.

- Quantitative analysis of the dynamical effects in the experimental data.
- In comparison with theory uncertainty of ChEFT calculations will be included.