Three-Nucleon Forces in Deuteron Breakup Reaction

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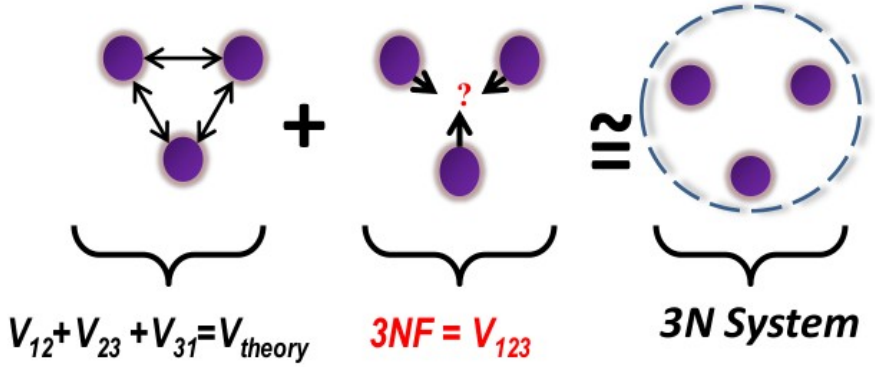
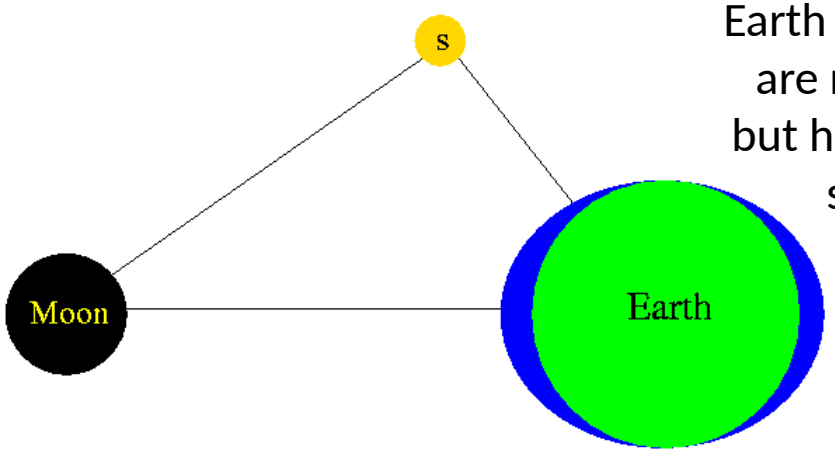
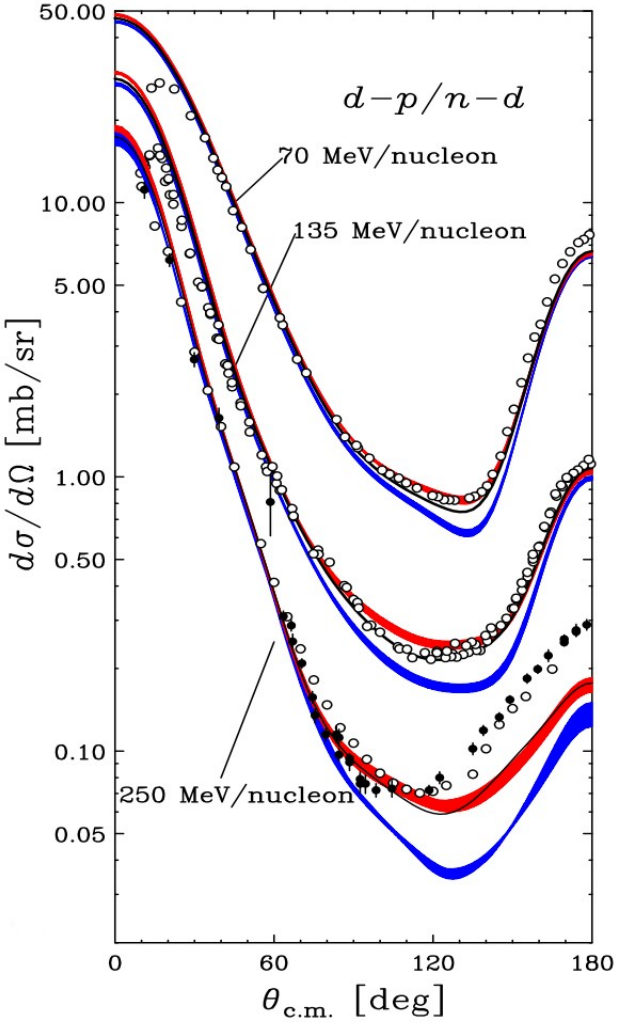
Important role of the 3NF in Few-Nucleon systems





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



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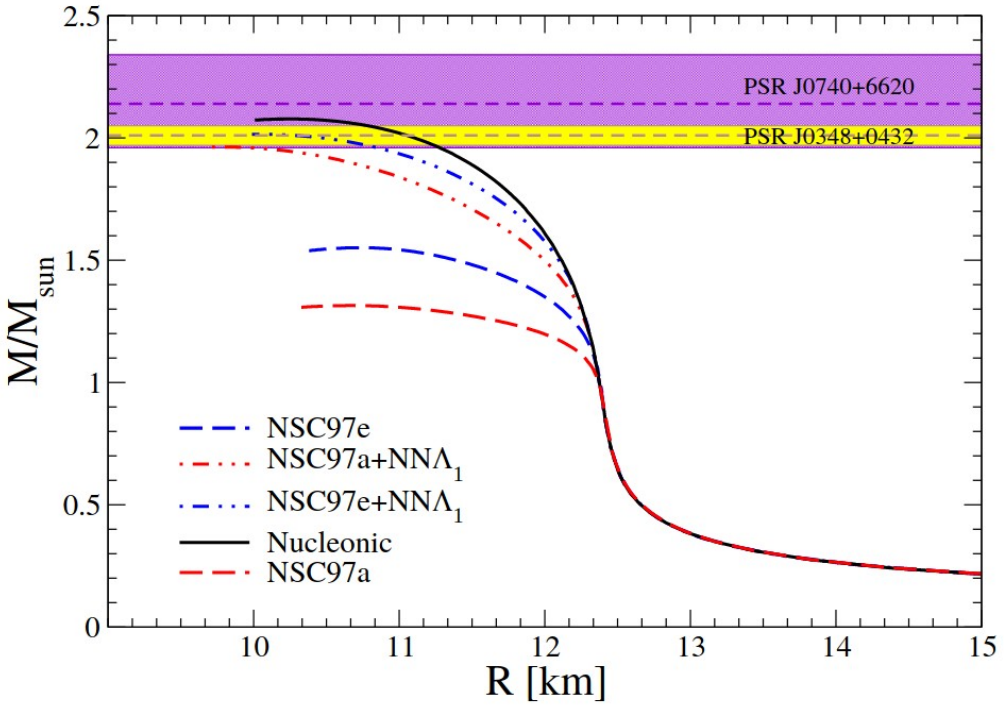

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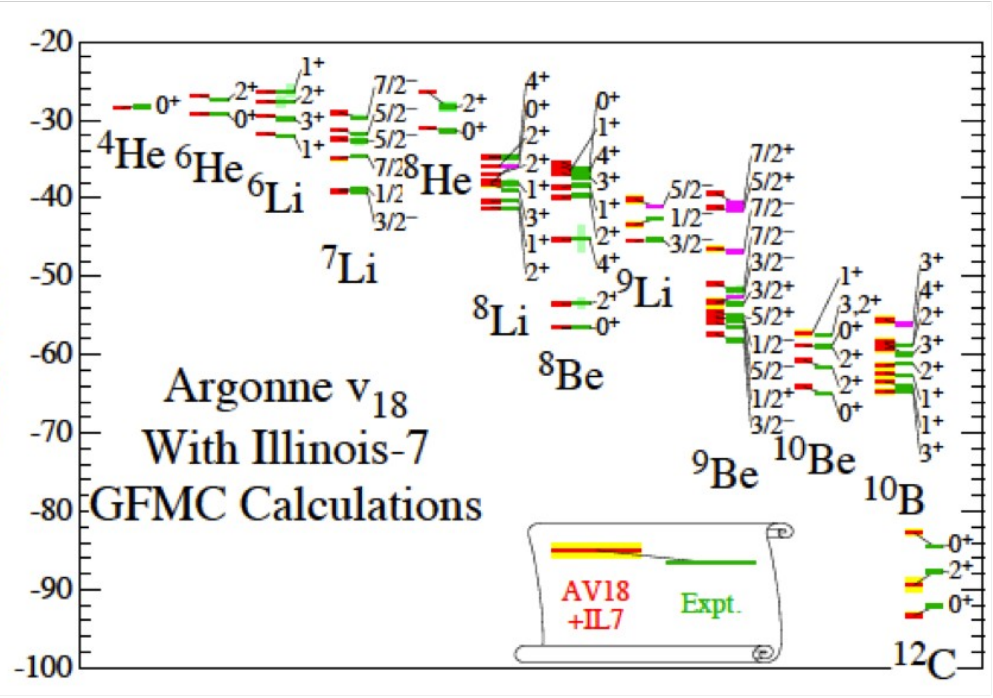

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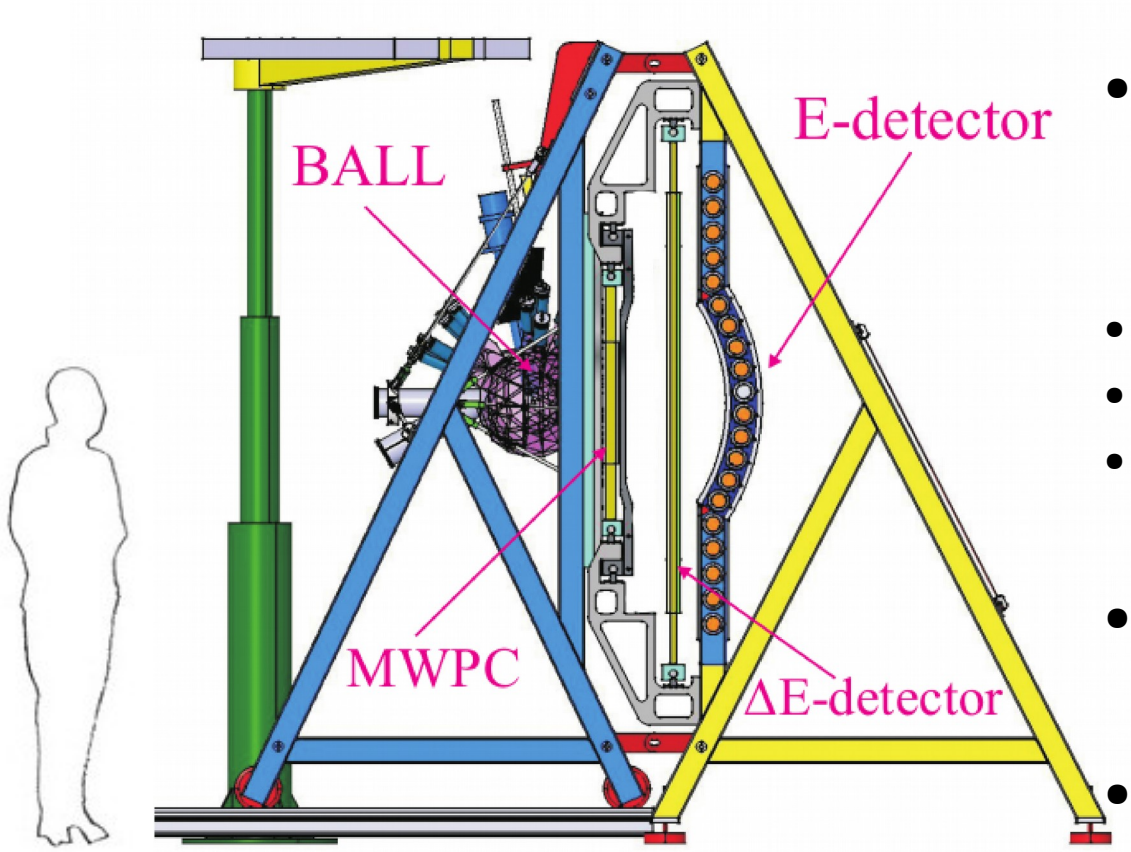
BINA Experiment



- Operated at KVI (the Netherland)

- d+p → p+p+n (3N system)
- d+d → d+p+n (4N system)
- d+d → ^{3}He+n (4N)

- 160 MeV deuteron beam

- Liquid H_2 or D_2 target

- High angular acceptance

Three-Nucleon Forces in Deuteron Breakup Reaction

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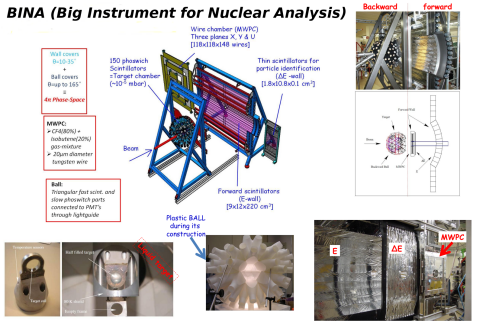
On behalf of the BINA experiment

Motivation

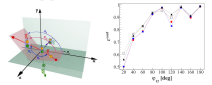
- Understanding the exact nature of the nuclear forces is one of the long-standing question in nuclear physics. Nowadays high quality nucleon-nucleon (NN) potentials exist, such as Argonne ver.18 (AV18) , CD Bonn, CD Bonn+Δ (CDB+Δ), Nijmegen I, II. They reproduce the NN scattering observables with very high precision expressed by $\chi^2 \approx 1$. However, all of the NN potentials alone fail to describe the observables in systems composed of three or more nucleons.
- One of the missing component in the interaction is the three-nucleon force (3NF). The existence of 3NF is due to the fact that the nucleons have an internal structure as they are made of quarks and gluons. In last two decades various theoretical models of 3NFs have been developed. Some of them, like **Tucson-Melbourne** [1] or **Urbana-IX** [2] are semi-fenomenological. The most fundamental approach stems from **Chiral Perturbation Theory** (ChPT). The three-nucleon interaction appears at N^{3}LO of the chiral expansion [3]. Worth mentioning is also the **coupled-channel** approach with explicitly included Δ isobar degree of freedom [4]. Currently, observables for four-nucleon systems are calculated only within the coupled-channel approach, in the so-called Single Scattering Approximation (SSA) [5].
- To test these models, precise experimental data are needed. The ideal laboratories to study the 3NF effects are the ones composed of three and four nucleons and the deuteron breakup reactions (dp, pd, dd) at intermediate energies. Such systems offer variety of exit channels with opportunity to study different aspects of few-nucleon dynamics. Besides 3NF, also the coulomb interaction or the relativistic effects can be studied.

Experiment

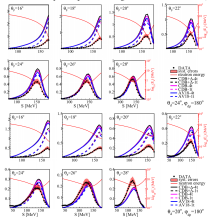


^{2}H(d,dp)n reaction @160 MeV

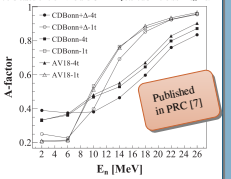
The three-body breakup reaction in 4N systems. Cross sections are calculated based on the Single Scattering Approximation [5].



Left panel: A schematic view of the breakup reaction with the angles (polar θ, azimuthal ϕ and relative azimuthal $\Delta\phi$) depicted which are used in the definition of two-particle configurations. *Right panel:* Configurational efficiency of BINA representing the lost of events due to the detector acceptance (particles hitting the same detector element).



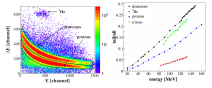
Examples of the dd→dpn differential cross section at various angular configurations. The experimental points are compared to calculations based on the AV18 and CDB+Δ potentials in the SSA regime.



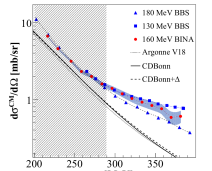
The quality of the description of the cross section data, expressed as a function of the (unobserved) neutron energy. Theoretical predictions are only valid in the quasi-free scattering region, where the spectator energy (neutron) is low enough.

^{2}H(d,^{3}He)n reaction @160 MeV

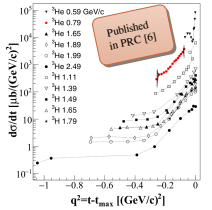
Proton transfer reaction in 4N systems. There are no theoretical predictions at this energy range.



Left panel: Example of the E-ΔE identification spectrum drawn for one selected telescope. Proton and deuteron branches are clearly visible while ^{3}He ions are seen in the upper side of the figure. *Right panel:* Percentage of the particles losses due to the hadronic interactions inside the detector material.



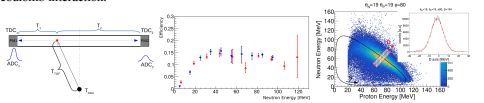
The dd elastic scattering is used for the data normalization. 160 MeV data from the BINA experiments (red dots) are presented together with the 130 (blue squares) and 180 MeV (blue triangle) BBS data and with theoretical predictions. The marked area refers to the region used in the normalization procedure.



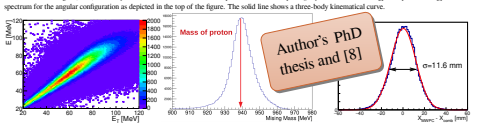
The differential cross section of the proton transfer reaction in dd collisions measured at various deuteron beam momenta. The data from the BINA experiment are shown as red points.

^{1}H(d,pn)p reaction @160 MeV

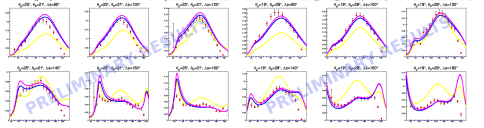
The three-body breakup reaction with the neutron measured instead of the proton. Having determined the ^{1}H(d,pn)p differential cross section one can compare it with the ^{1}H(d,pp)n cross sections at the same kinematic conditions. This can give additional insight into the coulomb interaction.



Left panel: The schematic idea of detecting neutrons in the BINA detector. Particle interact with the long and thick slabs of the E-scintillators and produce light which is collected from both ends by PMs. The asymmetry of signals gives the X position along the scintillator. The energy of the particle is also calculated from its time of flight (TOF). *Center panel:* Neutron detection efficiency of the BINA setup. *Right panel:* Neutron energy vs. proton energy correlation spectrum for the angular configuration as depicted in the top of the figure. The solid line shows a three-body kinematical curve.



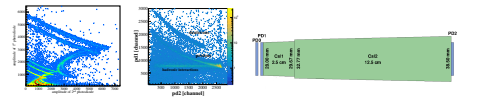
Left panel: Histogram of the particle energy (protons) at the reaction point versus the energy obtained from the TOF method. This figure illustrates the accuracy and the TOF resolution. *Left panel:* Missing mass spectra of the unobserved proton. *Right panel:* The resolution of the position reconstruction based on the left-right signal asymmetry in the E-detector slab.



Examples of the dp breakup differential cross section, in which the proton and neutron are detected. Experimental data are presented together with the SSA predictions. Blue line represents the calculations based on the CD Bonn potential, while magenta line represents the CD Bonn combined with the Tucson-Melbourne99 3NF calculations.

Outlook

- A dedicated experiment aimed at studying the relativistic effects in the pd breakup reaction is now under preparation at Cyclotrone Center Bronowice (CCB) in Kraków, Poland. The experiment will use the array of the KRATTA detectors [10]. The modules will be placed at specific angular configurations, where the 3NF effects are expected to be negligible while the relativistic effects are predicted to be large [9].



Two E-ΔE identification spectra of the KRATTA detectors. *Left panel:* First photodiod (PD0) vs. second one (PD1), *Center panel:* PD1 vs. third photodiod (PD2). *Right panel:* The layout of the single module. This versatile and modular detector is often used during the experiments at CCB.

- There is ongoing analysis of ^{2}H(d,t)p neutron transfer channel. The analysis intend to use machine learning technique like the Artificial Neural Network for the particle identification and background subtraction.

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