Experiments on light-ion production in neutron-induced reactions

Lucas de Arruda

Department of Physics and Astronomy
Division of Applied and Nuclear Physics – UPPSALA UNIVERSITY

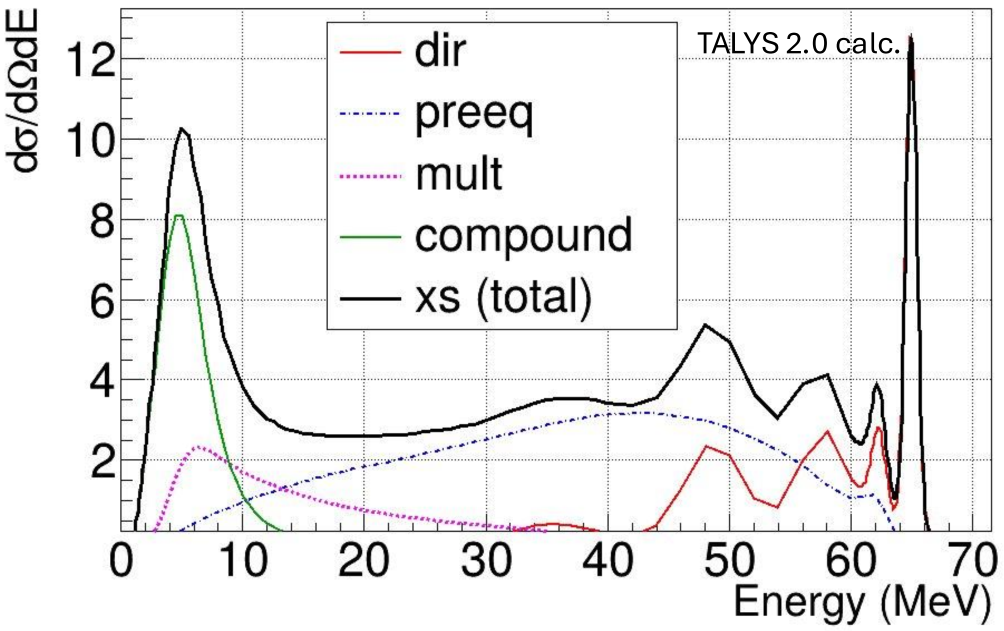
Annual Swedish Nuclear Physics and SFAIR meeting
2025-10-28

Summary

1. **Introduction:**
   a. Why measuring light ion production for neutron induced reactions
   b. Medley setup and Neutrons for Science (NFS) facility in GANIL
2. **Experimental campaigns**
3. **NFS' neutron flux reconstruction (RADNEXT project)**
4. **Some corrections needed – setup enhancement**
5. **Preliminary cross sections**
6. **Next steps**

Introduction: Why measuring light ion production for neutron induced reactions

Typical double differential cross section (DDX) spectrum:

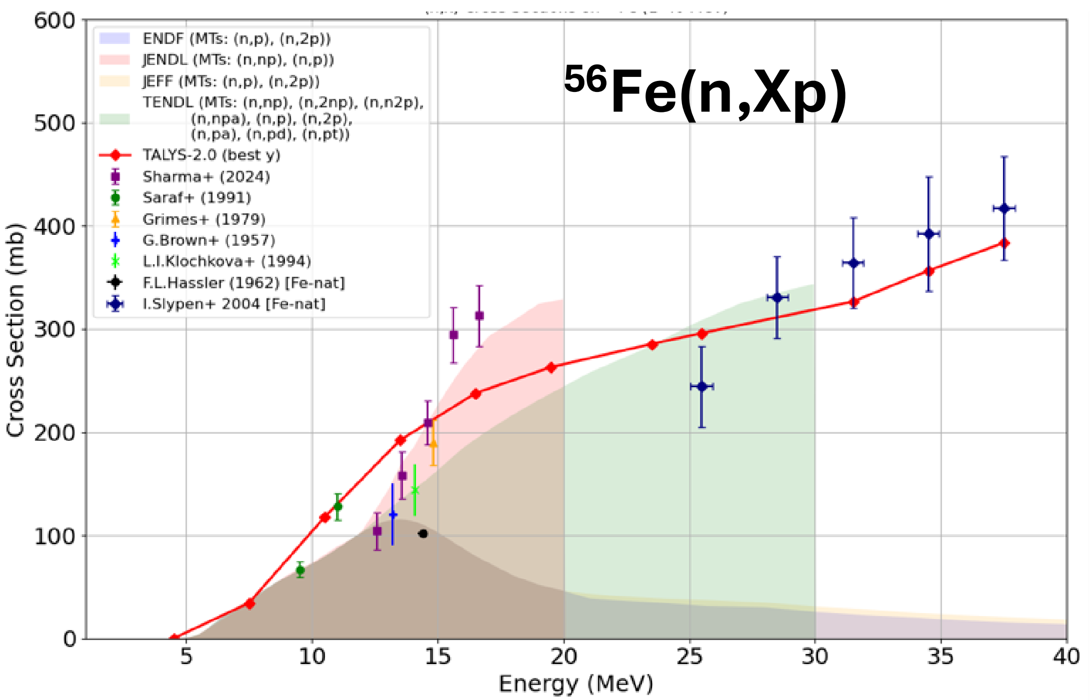


Three main mechanisms:

- Compound
  - Very slow
  - Isotropic emission
  - No memory of entrance channel
- Direct
  - Very fast
  - Forward-peaked
  - Few nucleons involved
- Pre-equilibrium
  - Partial equilibrium
  - Multiple nucleons involved
  - Semi-isotropic

Introduction: Why measuring light ion production for neutron induced reactions

- Very scarce data for a series of materials
- Several applications
- For some materials, the total cross sections are also scarce



In particular, considering **structural materials**:

- Swealling and embrittlement of the material due to formation of gas inside it.
- Interpretation of IFMIF-DONES (International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source) data.
- Improving theoretical models for pre-equilibrium emission
- Improving the data evaluations

And more diverse applications:

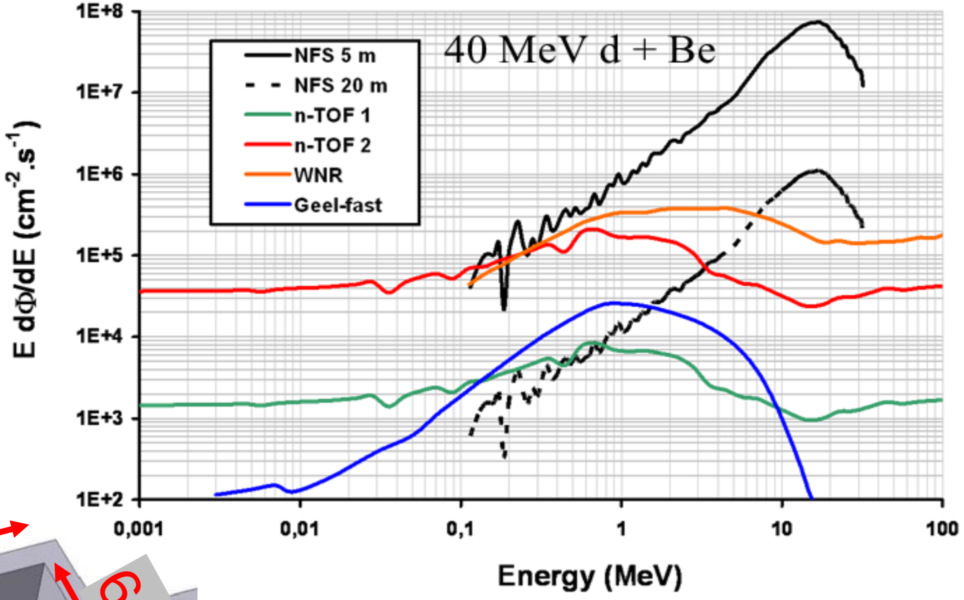
- Radiation protection
- Dosimetry for aviation and spaceflight, electronics (single-event effects)

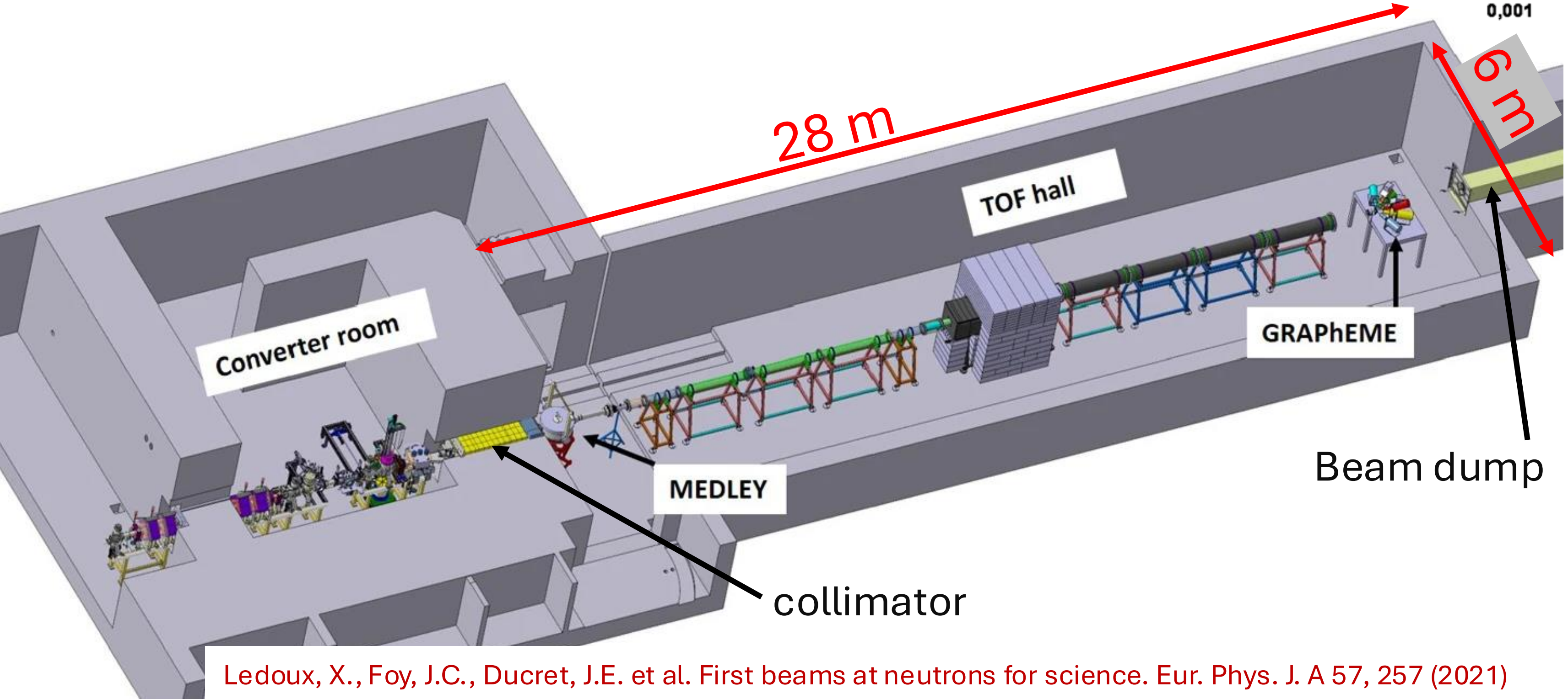
Introduction: Medley setup and **Neutrons for Science (NFS) facility in GANIL**

It is currently operating in Neutron For Science (NFS) facility, in GANIL, France.

- Very intense **white neutron** beam (up to 44 MeV)
- Relatively new facility

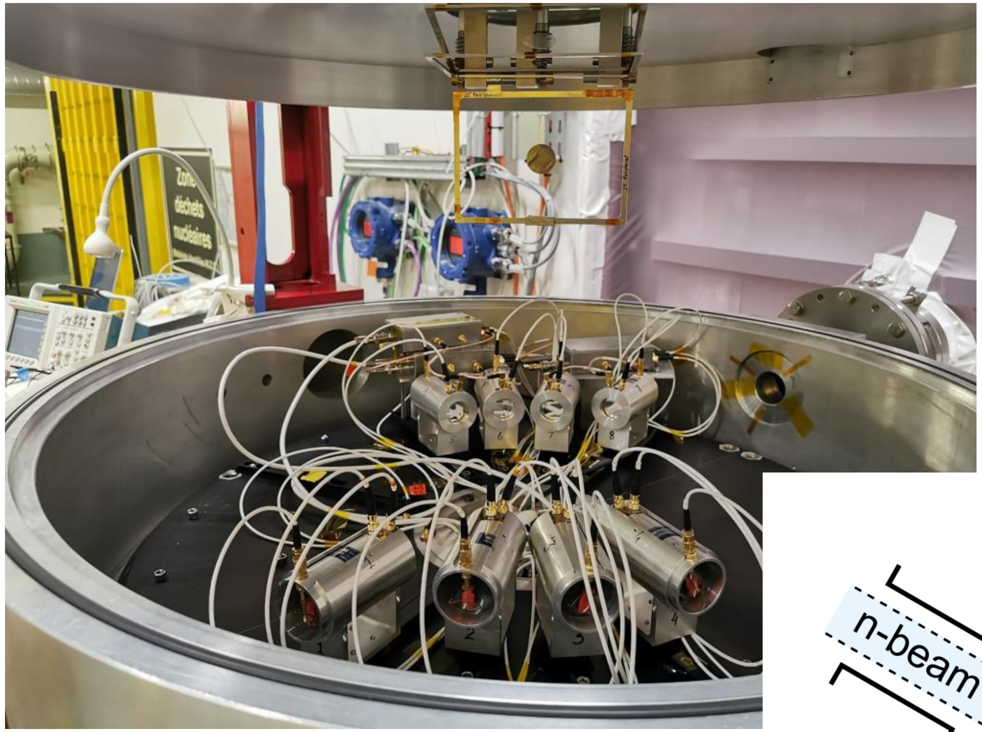
--> Ideal to measure DDXs with a few mb order of magnitude





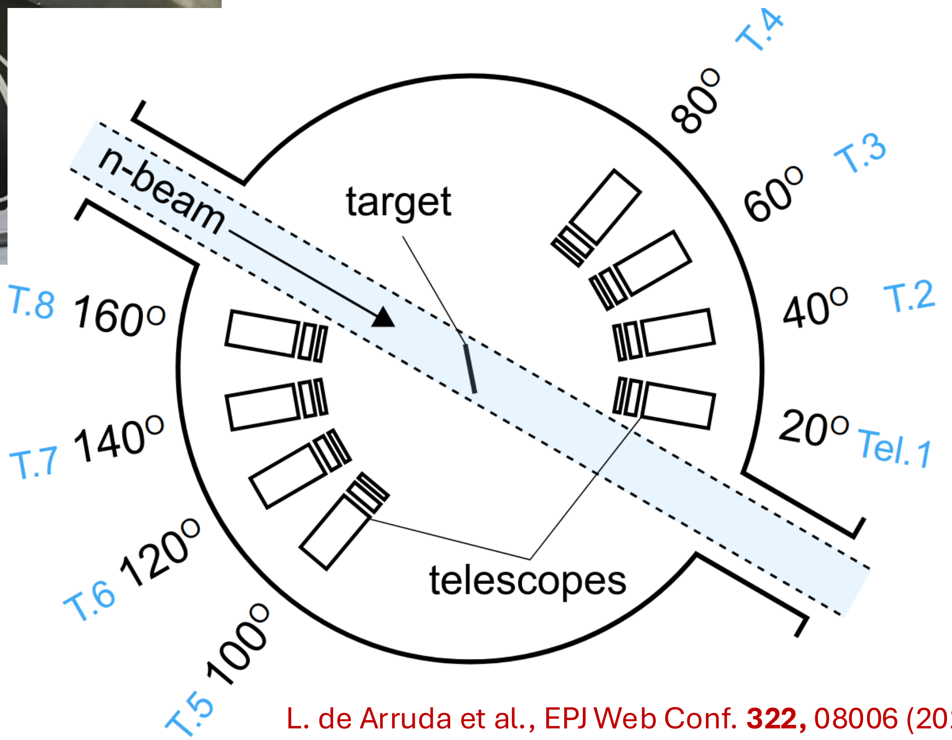
Ledoux, X., Foy, J.C., Ducret, J.E. et al. First beams at neutrons for science. Eur. Phys. J. A 57, 257 (2021)

Introduction: **Medley setup** and Neutrons for Science (NFS) facility in GANIL

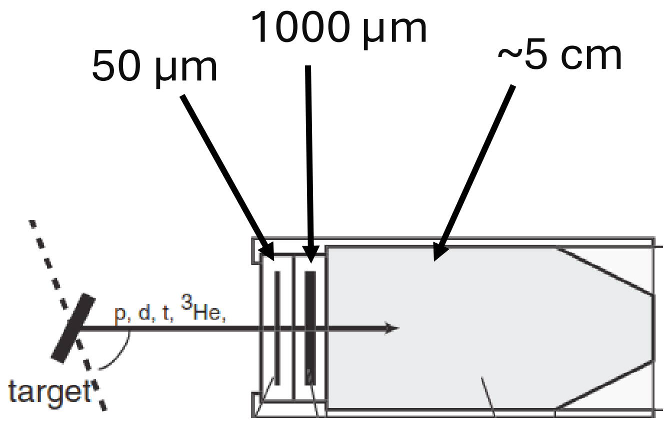


Medley setup was developed in Uppsala University, and is composed of:

- Eight (4x2) three-detector telescopes for PID
- Target holder (supporting up to three targets)
- Rotating table, possibility to exchange detector sets



L. de Arruda et al., EPJ Web Conf. **322,** 08006 (2025).

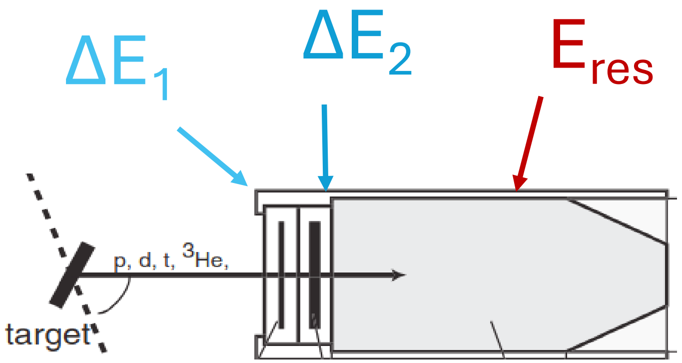


M. Hayashi et al., Proc. ND 2007, p. 1091-1094

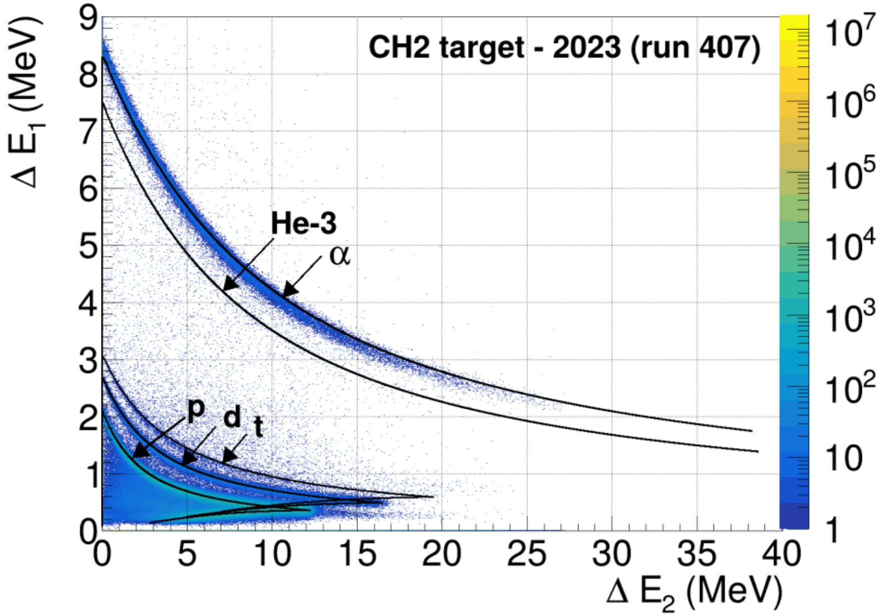
Introduction: **Medley setup** and Neutrons for Science (NFS) facility in GANIL

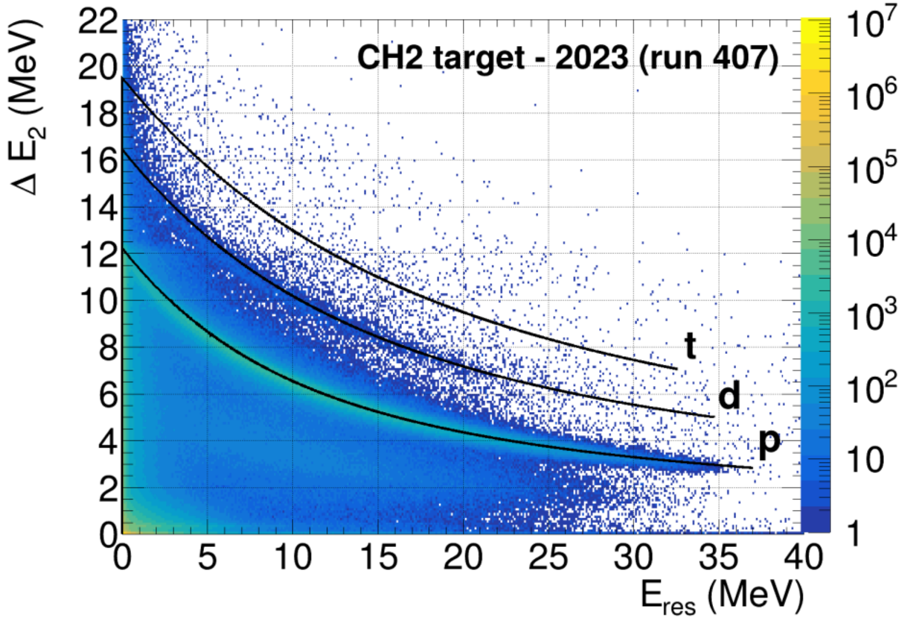
Ion identification

- Medley presents high capacity for distinguish H and He isotopes over a wide range
    - Correct combination of detectors
- => ΔE-ΔE-E PID method



M. Hayashi et al., Proc. ND 2007, p. 1091-1094

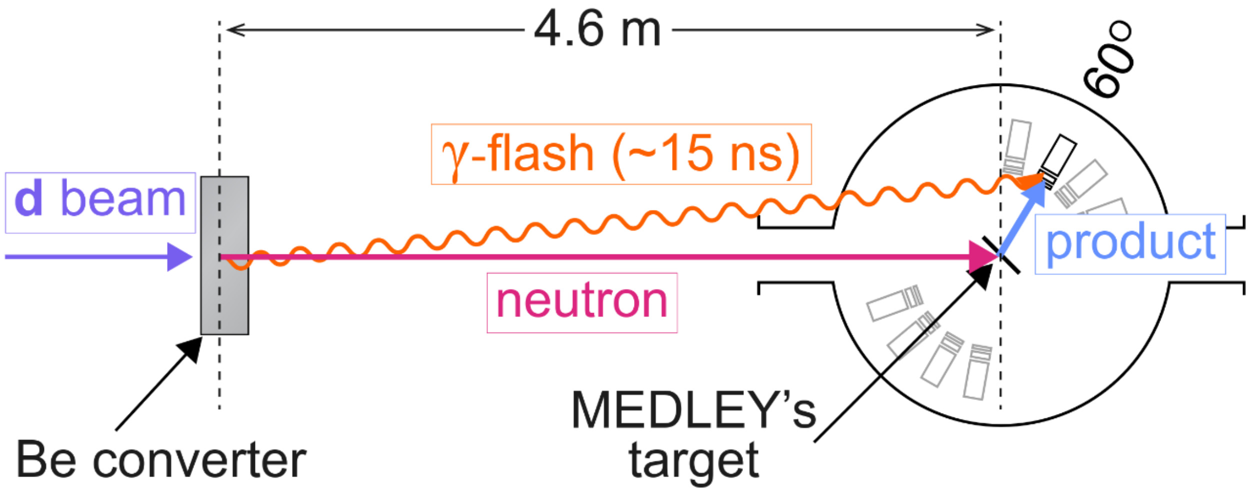


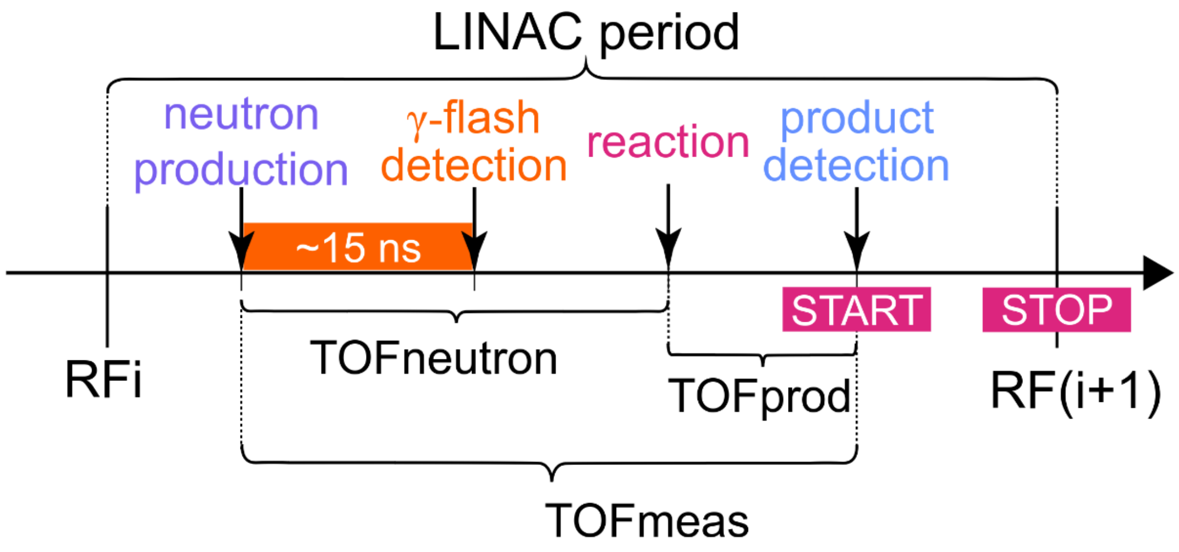


Introduction: **Medley setup** and Neutrons for Science (NFS) facility in GANIL

Time of Flight (ToF) measurement

- ToF measurement is possible given that our Si detectors are sensitive **enough** to the gamma flash generated when the neutron beam is produced
- The setup has a good timing resolution to operate very close to the target, maximizing its efficiency
- The NFS' spectral neutron flux is measured for every experimental campaign; the result is them used to evaluate the DDXs, minimizing systematic errors

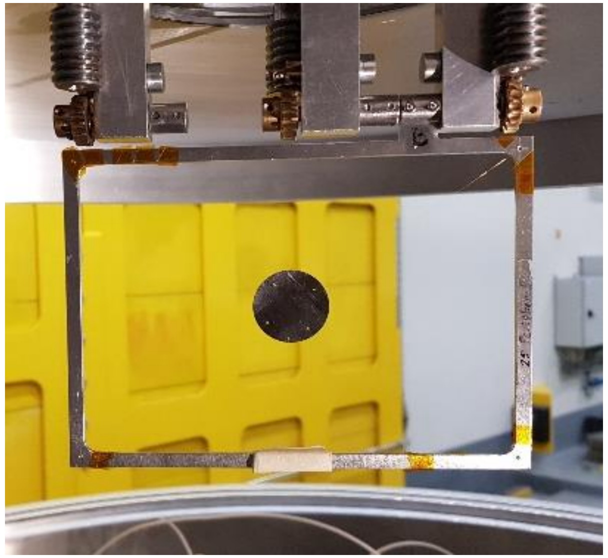




Experimental Campaigns

- Several experiments were carried out with Medley at NFS:

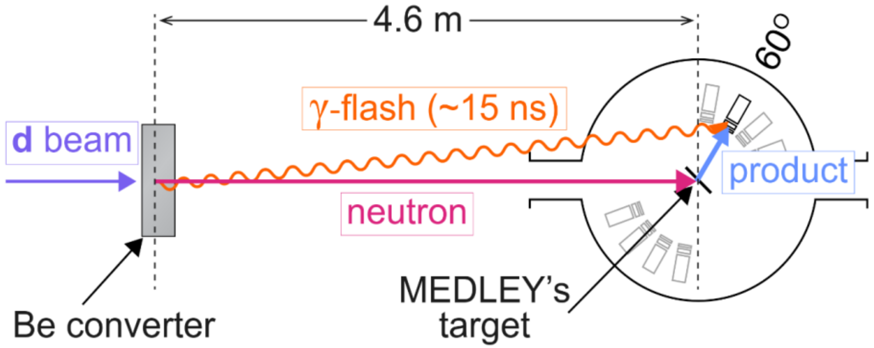
1. **LIONS (Light ION production Studies with Medley) - 2021/2022**
   a. Carbon
2. **GARIC (GAs pRoduction In Chromium by neutrons) - 2022/2023**
   a. Chromium
3. **CATRIN (Characterization of neutron fields at the emerging NFS facility) - 2022 (RADNEXT project) - Fininshed**
   a. Characterization of the neutron flux using Medley
4. **GARROS (Gas pRoduction in iROn by neutronS) - 2024**
   a. Iron
5. **Gas production study in copper - 2024**
   a. Project conducted by collaborators from UKAEA
6. **GARSIO: Gas production in silicon and oxygen by neutrons – Approved**
   a. Silicon and Oxygen

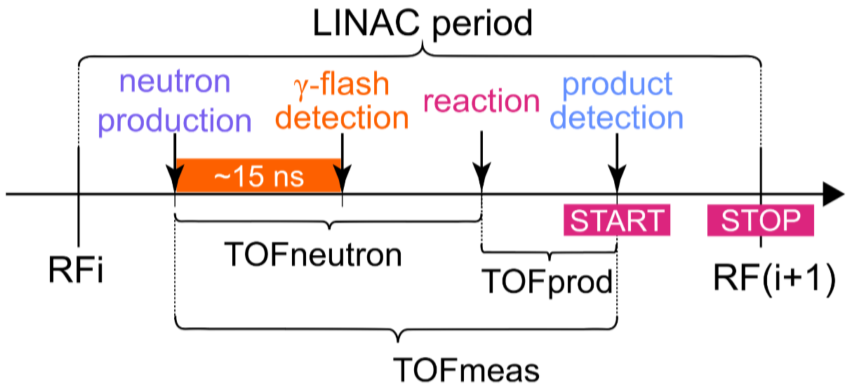


Target installed in Medley.

NFS' neutron flux reconstruction (RADNEXT project)

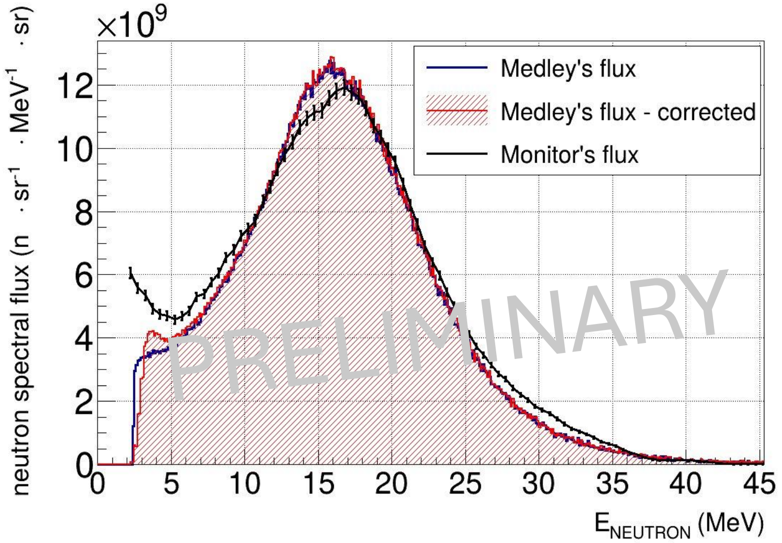
Using a CH_2 and a C target, we can measure the (n,p) elastic scattering. From this point, two methods can be used to obtain the spectral neutron flux:





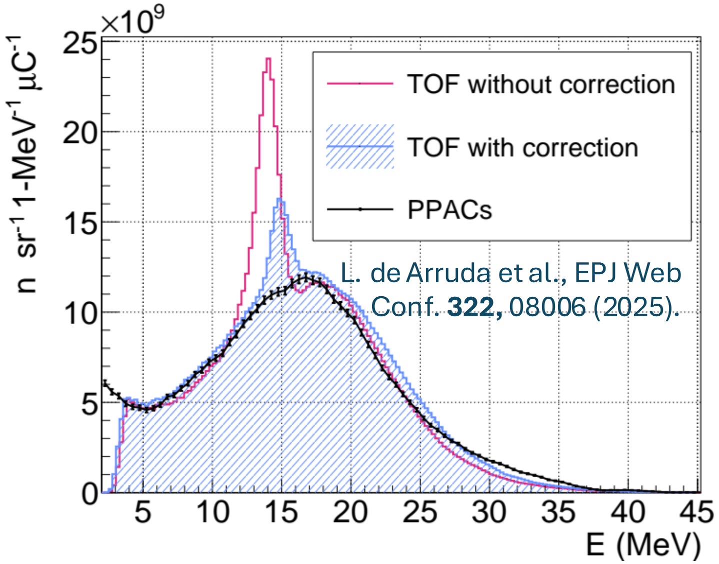
Direct method: reconstruction En from Ep for (n,p) events:

$$E_p = E_n \frac{4M_p M_n cos^2\theta_{LAB}}{(M_p + M_n)^2}$$



ToF method: From $TOF_{neutron} \Rightarrow E_{neutron}$

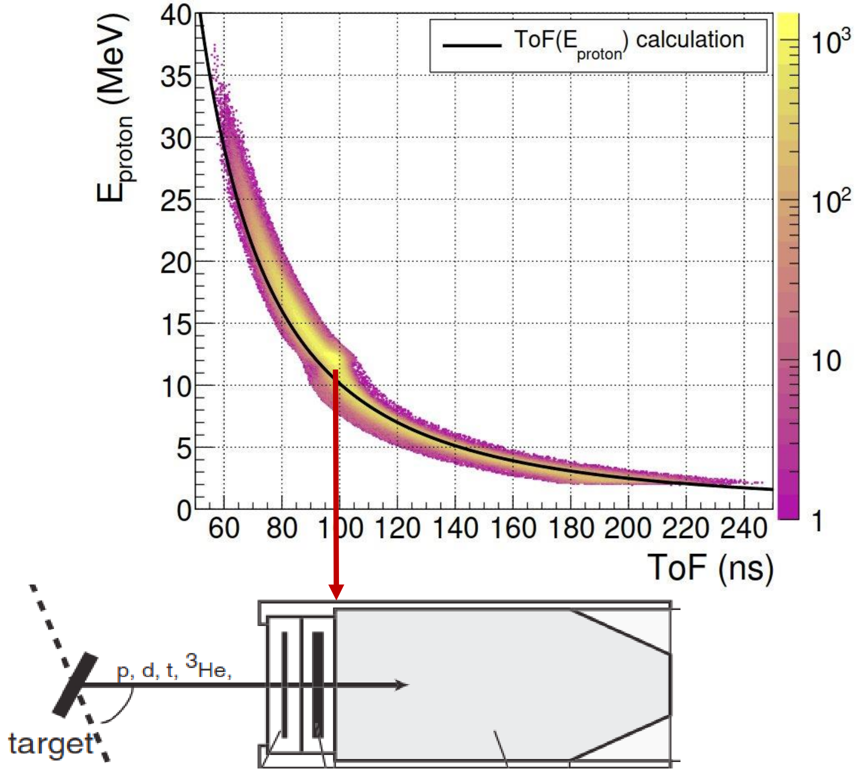
$$N_p(E_n) = \varphi(E_n) \cdot \frac{1}{D^2} \cdot N_H \cdot \frac{d\sigma}{d\Omega}(E_n, \theta_{LAB}) \cdot \Delta\Omega_{tel} \cdot Q$$



Some corrections needed – setup enhancement

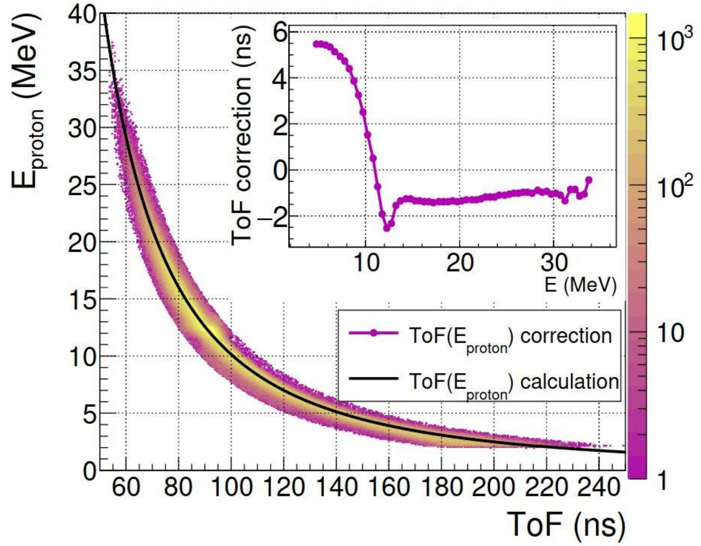
- Timing correction
- Energy correction
- Thick target correction

A difference of pulse shape when the particle punches through the detector* introduces a walk effect on our CFD filter
--> deviation in measured ToF

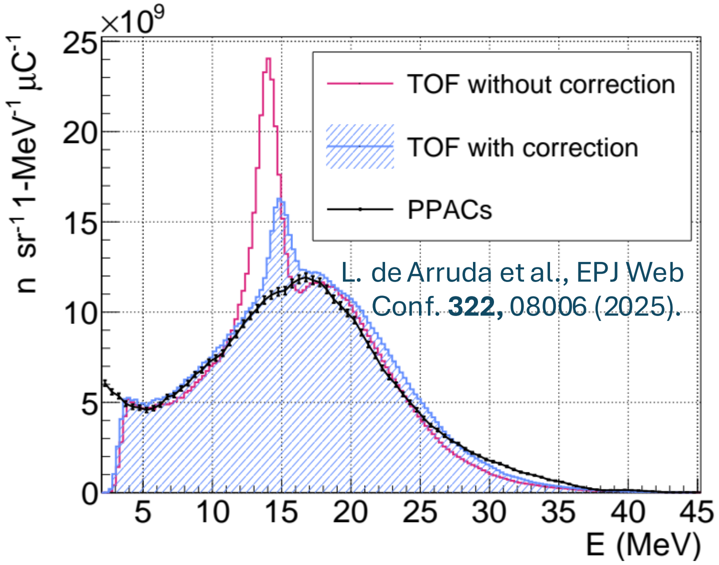


*The second silicon is our timing detector.

First order correction for this effect was produced:



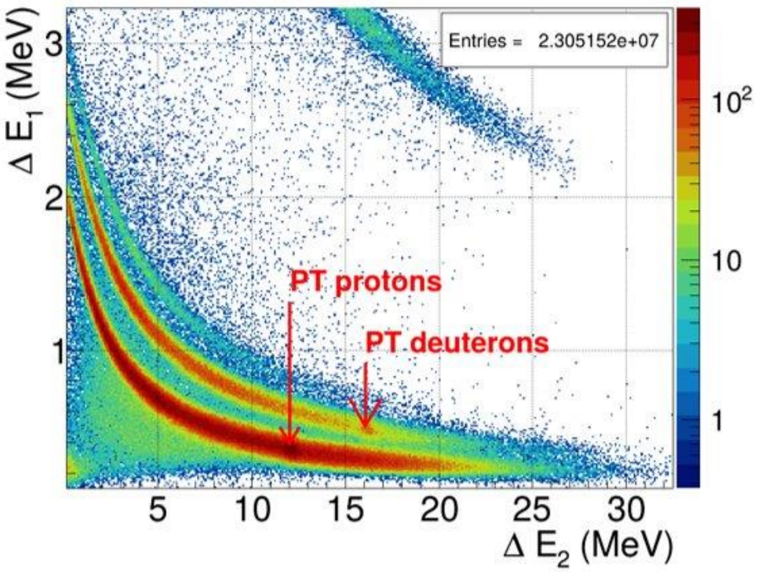
Enhancing the obtained spectral flux (via ToF):

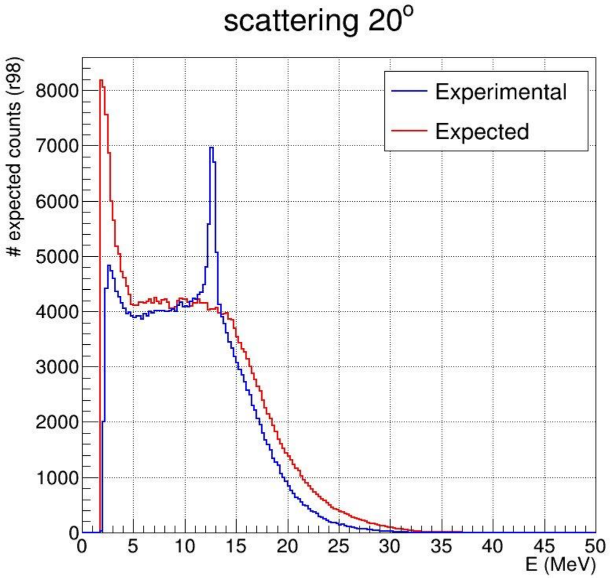


Some corrections needed – setup enhancement

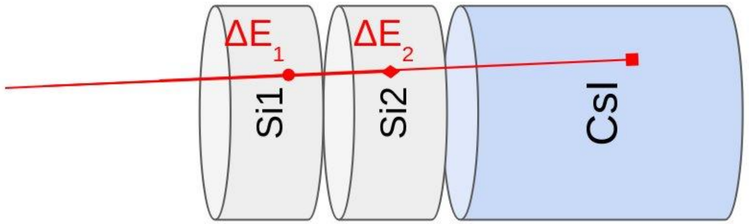
- Timing correction
- Energy correction
- Thick target correction

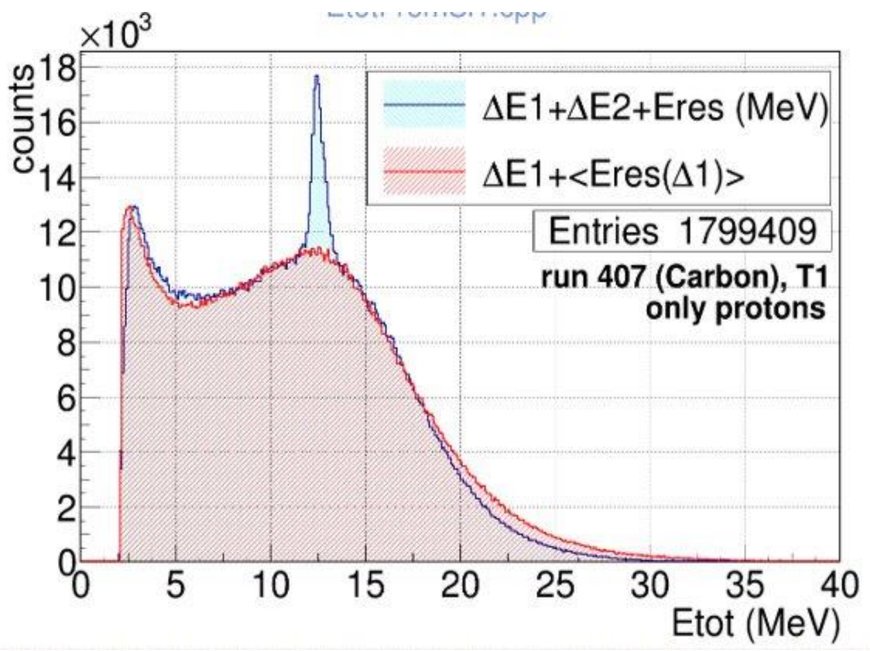
It is also needed to correct for the energy lost between the Si2 and the CsI (matching problem):





It is carried out by calculating the expected remaining energy for an **identified particle** to correct the events' total energy:

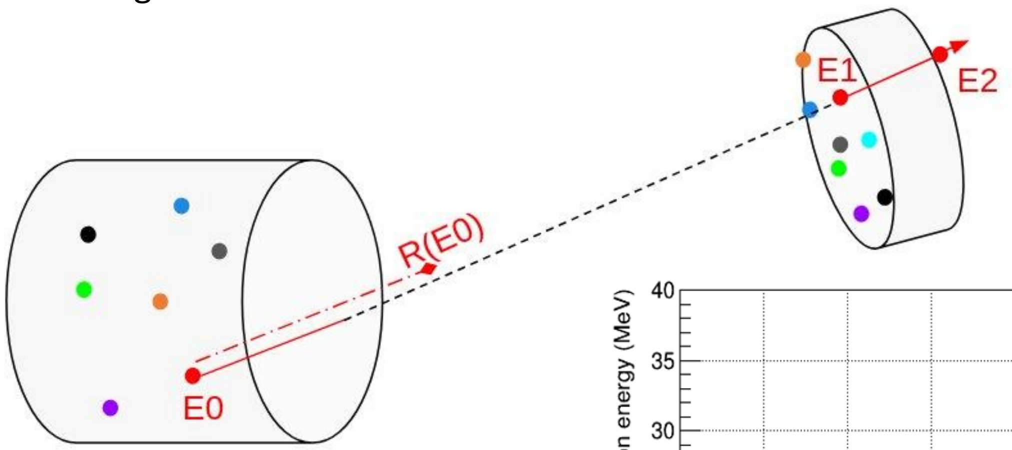


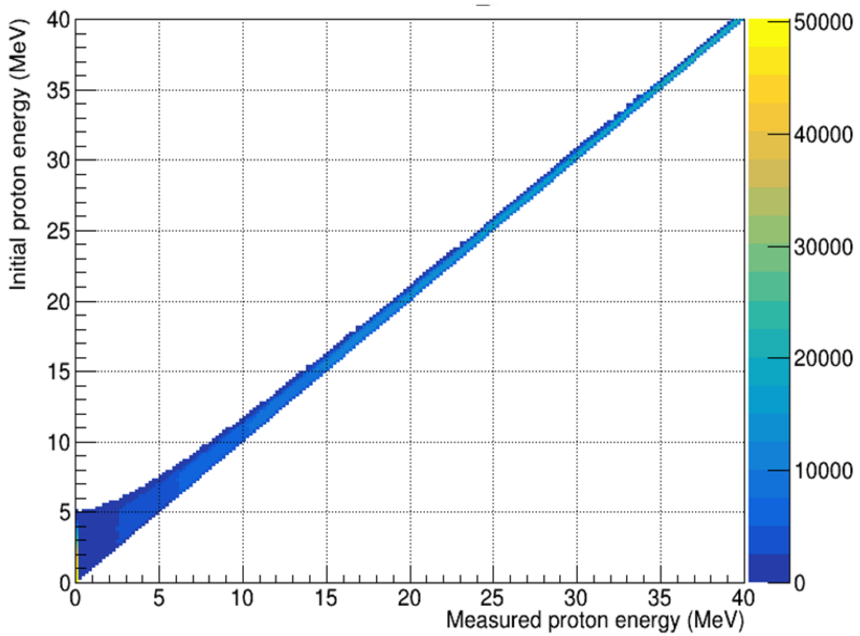


Some corrections needed – setup enhancement

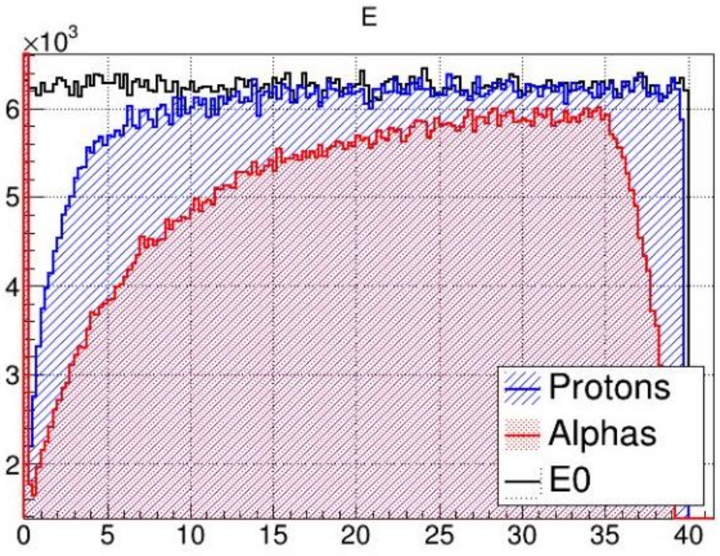
- Timing correction
- Energy correction
- Thick target correction

We need to correct our measurements for the losses of energy within the target:

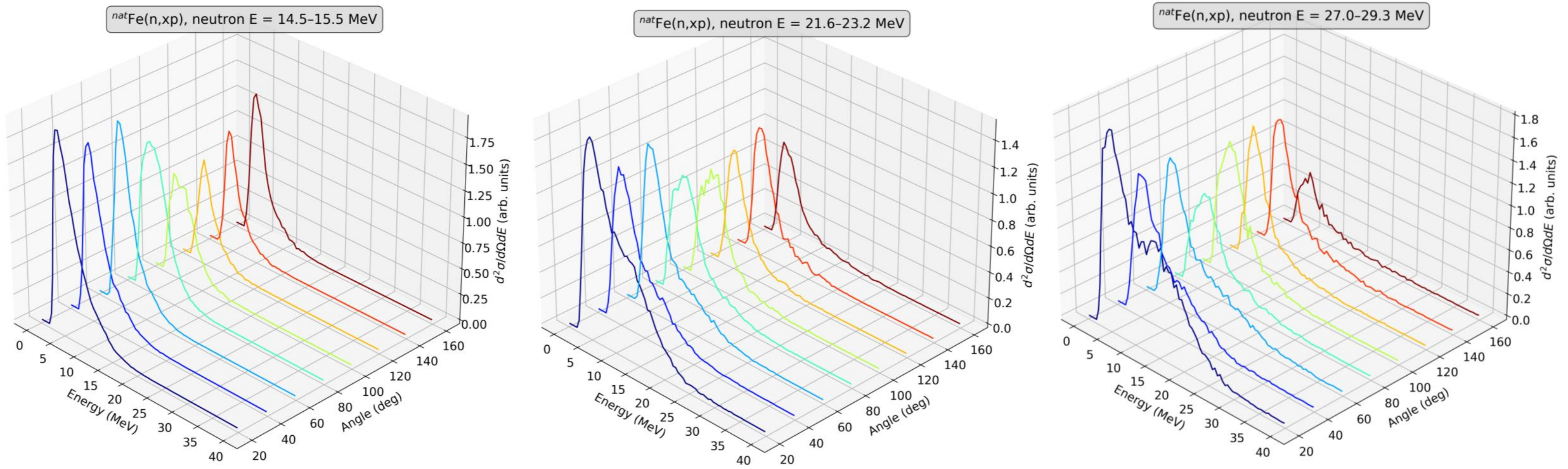




- This is done using MC + energy loss calculations.
- First version is completed but there are still a few details to implement:



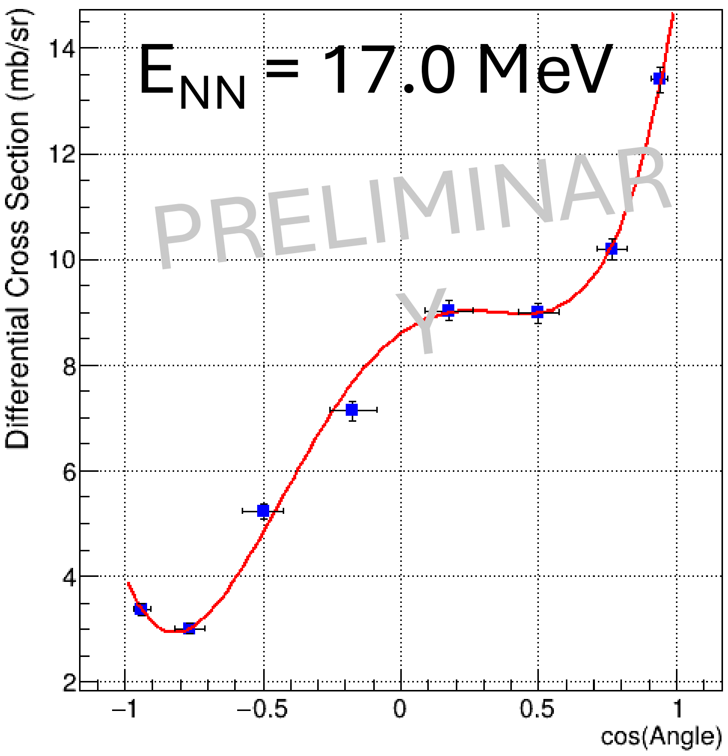
Fe(n,Xp) double differential cross sections

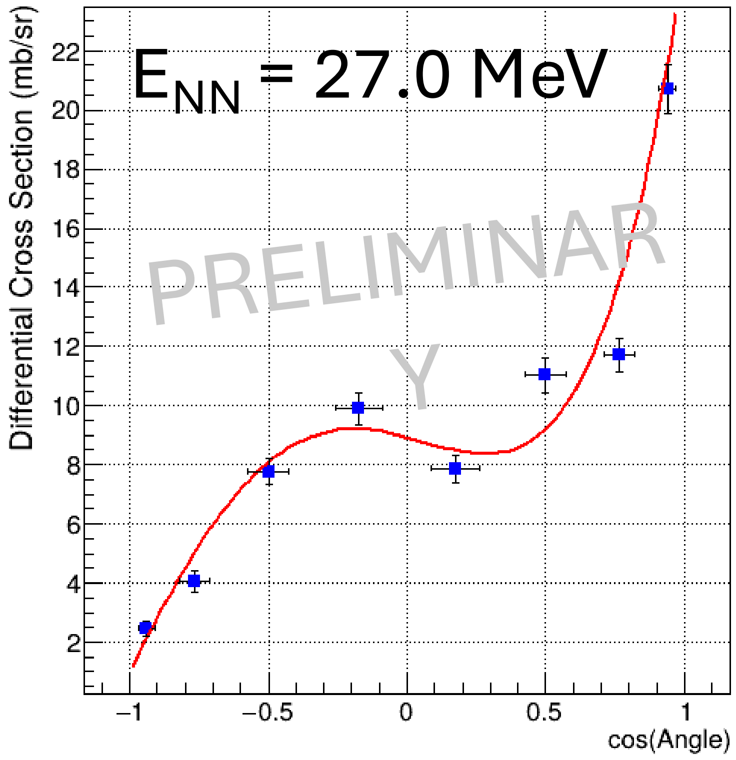


- The first results with DDX were successfully obtained

Preliminary cross sections

Proton differential cross sections – angular



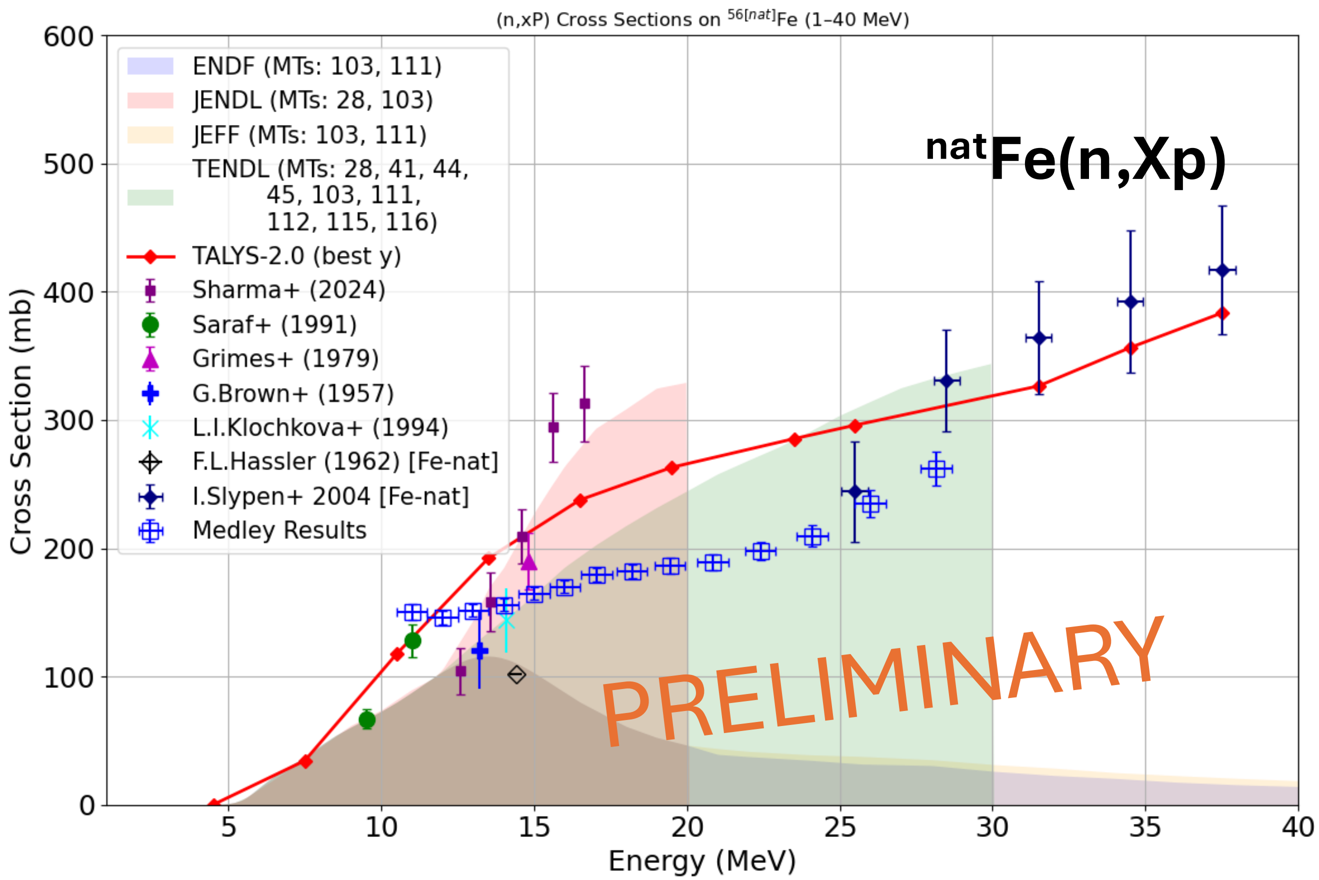


- Integrating in dE we can obtain the angular differential cross section as a function of neutron energy
- Fitting Legendre's polynomials allow us to obtain the total cross section for each neutron energy

Preliminary cross sections

Proton total cross sections – First results

Proton production cross sections



- Comparison of the total proton production cross section show some agreement with the models
- Some uncertainties still need to be considered
- Some corrections for accounting the detector thresholds are needed

Summary and next steps

- We measure double differential cross sections, and total cross sections for light ions.
- Medley proved to work properly under white neutron beam, providing a good amount of valuable data which is under analysis.
- Several challenges were identified and solved during the last months; the first preliminary results were obtained.
- The cross sections seems to agree with the models in the mid neutron energy range.
- Fine tuning of the methods and techniques for treating the data are being carried out.

Thank you for your attention!

Experiments on light-ion production in neutron-induced reactions

Lucas de Arruda

Department of Physics and Astronomy

Division of Applied and Nuclear Physics -- UPPSALA UNIVERSITY

Annual Swedish Nuclear Physics and SFAIR meeting

2025-10-28

This work has received support from the European Union’s research and training pro- gram under grant agreements with numbers 847552 (SANDA), 847594 (ARIEL), and 101057511 (EURO-LABS). Part of this work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). It also received funding from the European Union’s 2020 research and innovation program under grant agreement No 101008126, corresponding to the RADNEXT project. The authors would like to acknowledge the funding received from the Swedish Center for Nuclear Technology (SKC) and from the Swedish Radiation Authority (SSM)