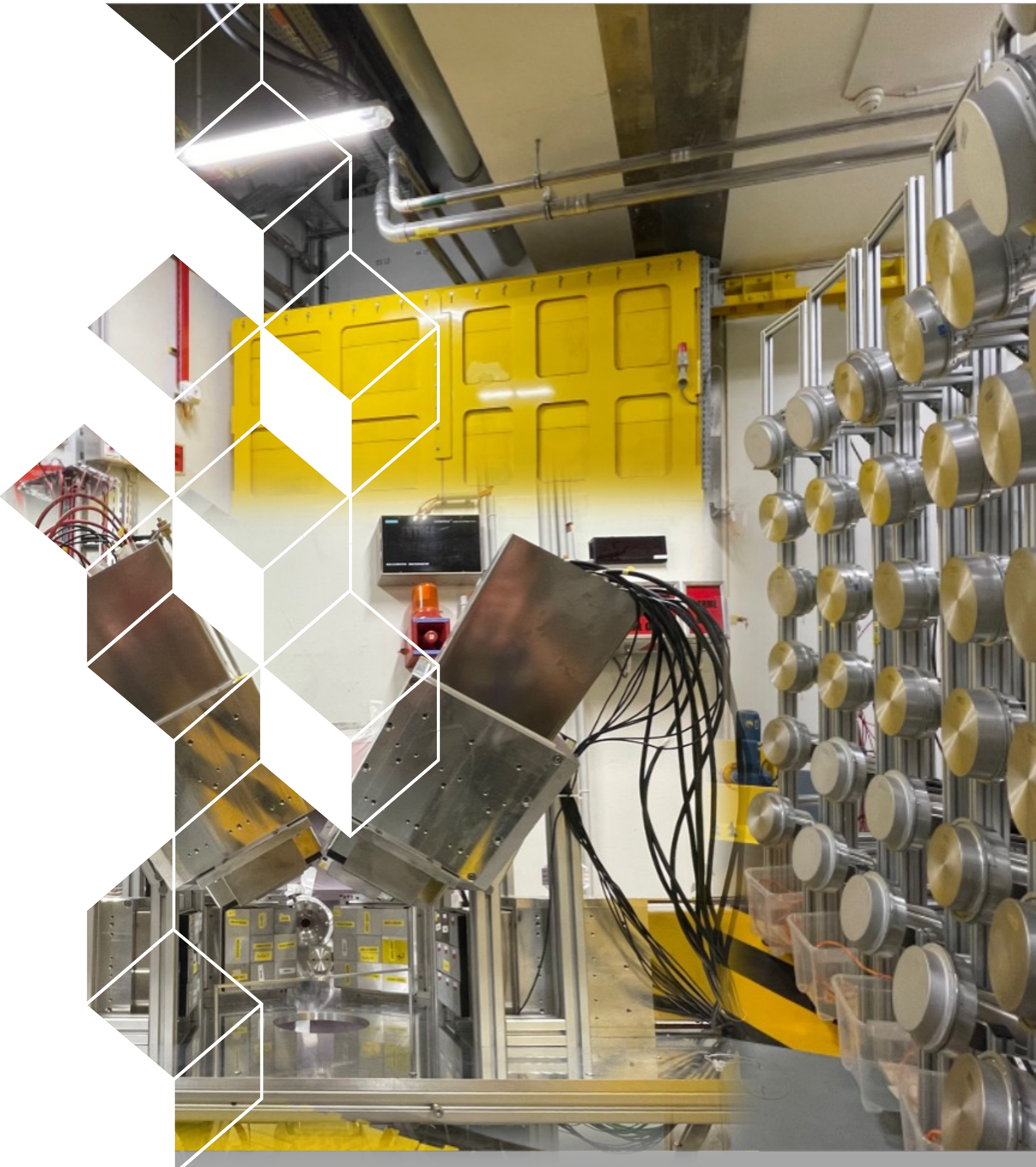
Study of the Pygmy Dipole Resonance using neutron inelastic scattering at GANIL-SPIRAL2/NFS

COMEX 2023

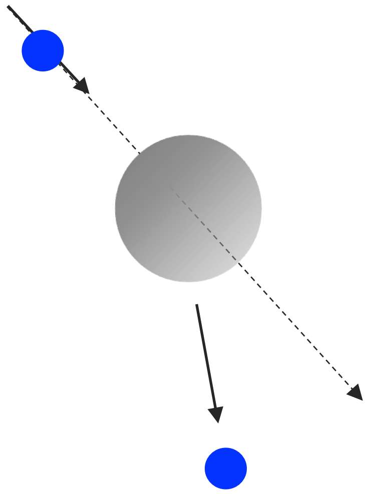
Marine Vandebrouck



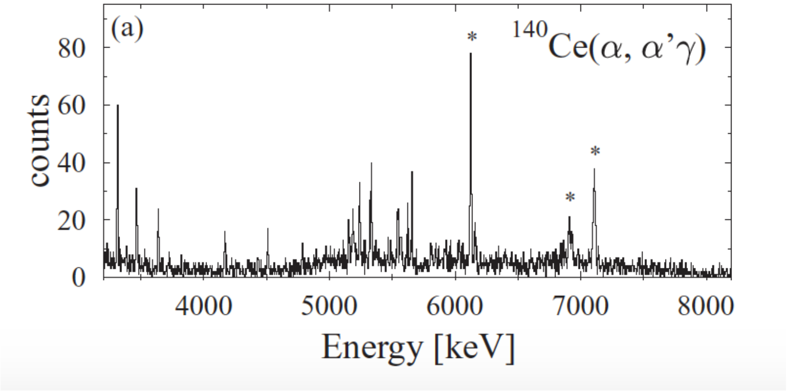
What is the nature of a nuclear excitation ?

In other words :
How protons and neutrons contribute to
the excitation strength ?

Tool
scattering reaction



Observables
Excitation energy, E_γ and cross section



D. Savran *et al.* Phys. Lett. B 786 (2018)

Interpretation
Comparison to microscopic calculations

ρ
Transition density

$$M_{p(n)} = \int \rho_{fi}^{p(n)}(r)\, r^{L+2}\, dr$$

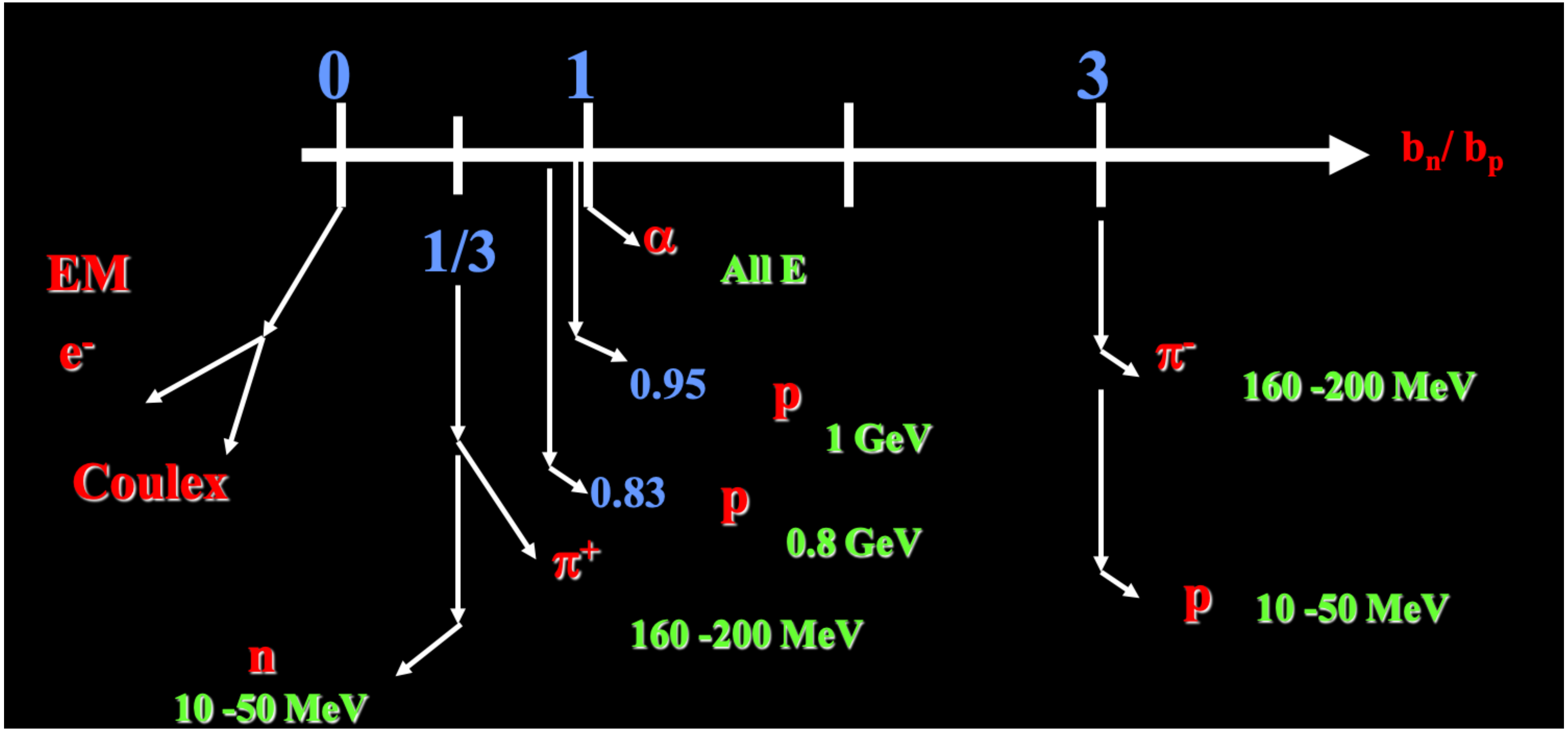
M
Multipole moment

L
Multipolarity of the transition

Complementarity of the scattering experiments

During a scattering experiment, a linear combination of M_n and M_p is probed : $M = b_n M_n + b_p M_p$

$b_{n,p}$ are the interaction strengths between the external field and n,p of the nucleus



A. Berstein *et al.* Phys. Lett. B 103, 255 (1981)
E. Khan, Phys. Rev. C 105, 014306 (2022)

Pygmy Dipole Resonance (PDR)

PDR
(Pygmy Dipole Resonance)

- oscillation of a neutron skin against a symmetric proton/neutron core
- additionnal E1 strength at lower energy

GDR
(Giant Dipole Resonance)

- oscillation of neutrons against protons
- exhausts ~ 100% E1 strength

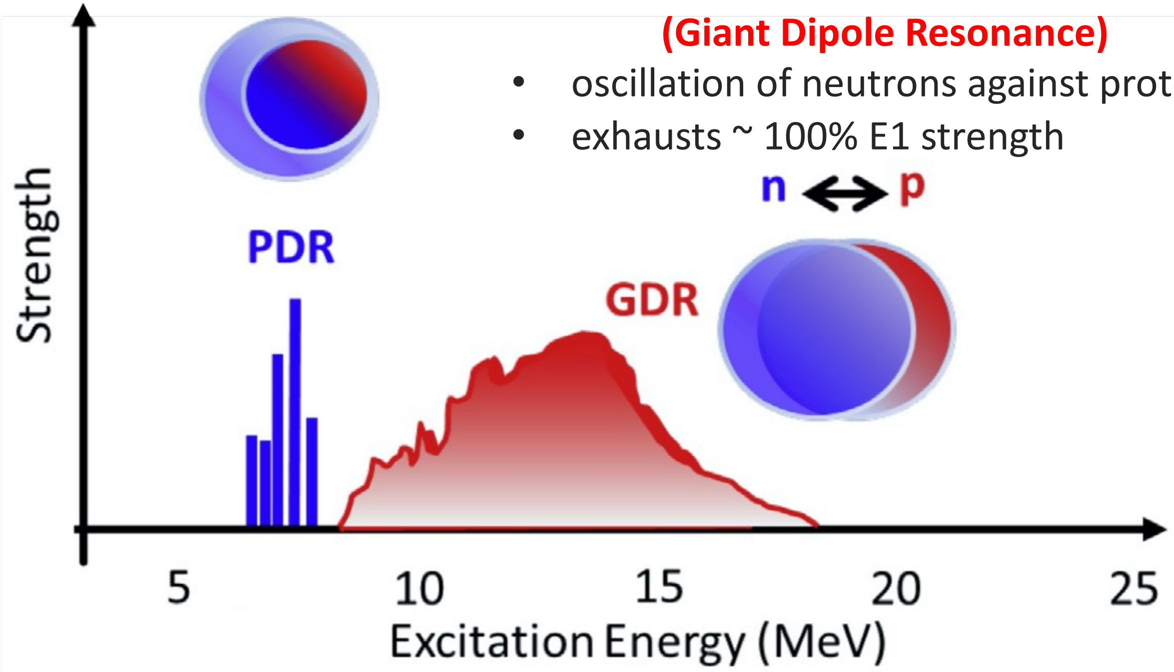
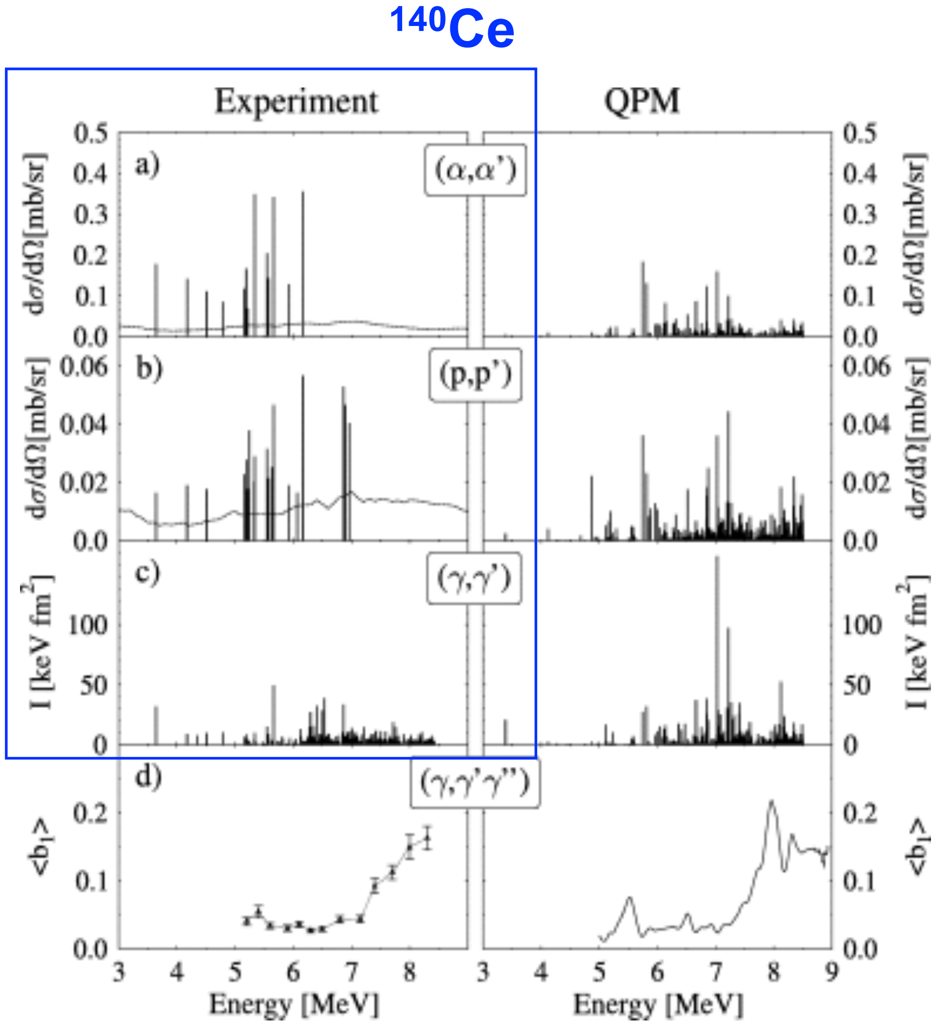


Figure extracted from A. Bracco *et al.* Prog. Part. Nucl. Phys. 106 (2019)

➢ Nuclear structure: study of the nature of dipole strength

➢ Astrophysical interest: PDR plays important role
- as a constraint of the Equation of State
- for the nucleosynthesis r process

Microscopic structure of the PDR



D. Savran *et al.* Phys. Lett. B 786 (2018)

Isoscalar probes ➡ 4-6 MeV

Proton probe ➡ selected states

Electromagnetic probe ➡ 4-8 MeV

If several models are able to reproduce E1 strength at lower energy than the GDR, they do not agree on the fine structure

New probes are necessary to resolve the complexity of the isospin character of the PDR

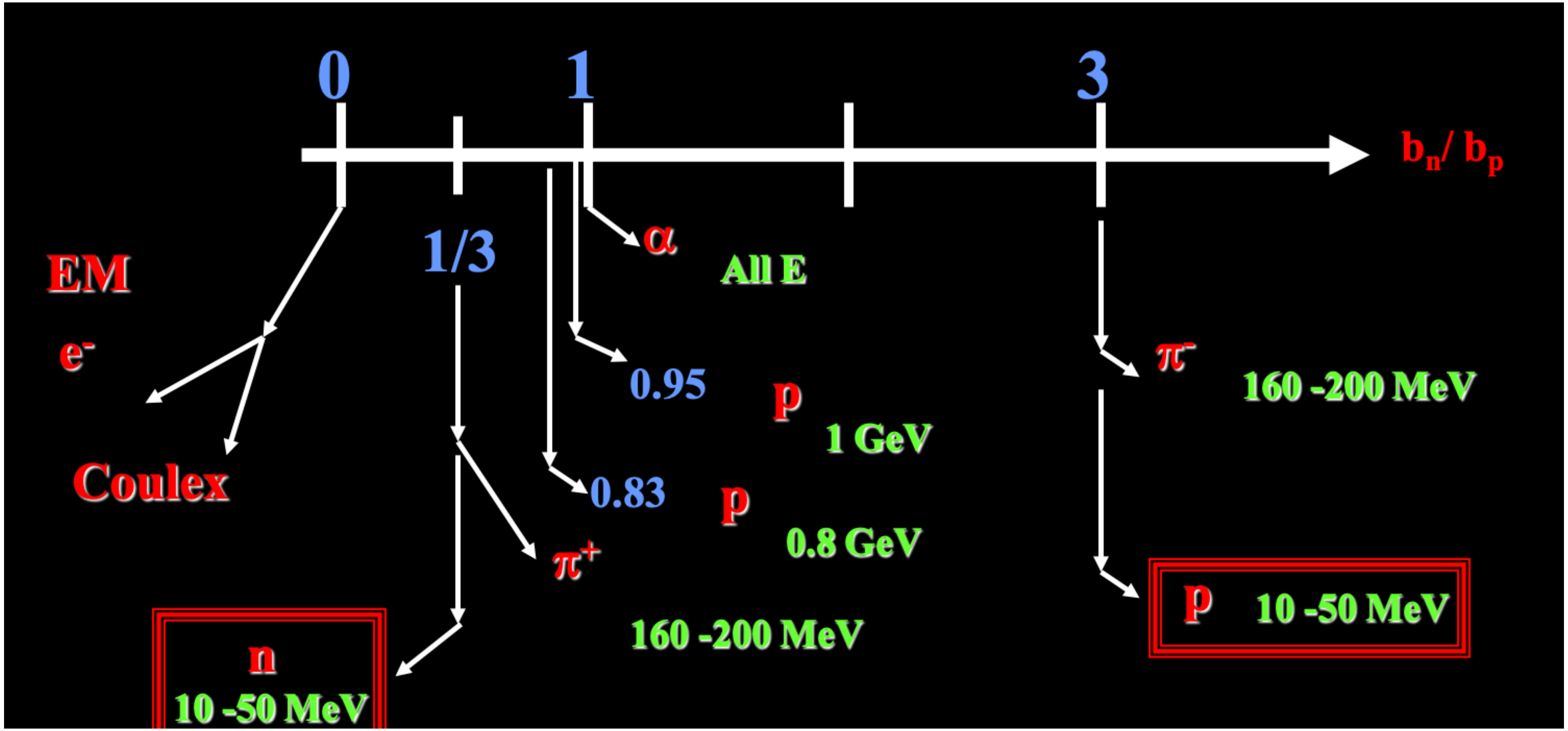
➡ study **PDR in ^{140}Ce using (n,n')**

Goal of the PDR study using (n,n’) reaction

Goal of the PDR study using (n,n’)

WHY is it interesting ? (n,n’) is an elementary probe:

- which does not require Coulomb correction
- complementary to (p,p’) and to other reactions

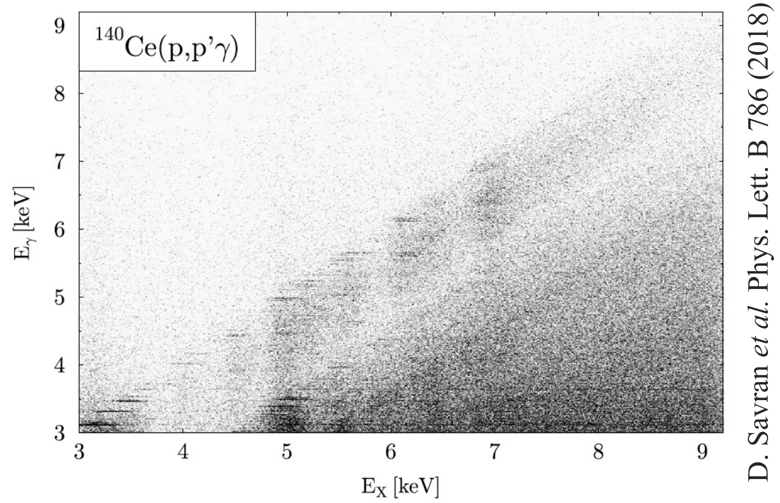


A. Berstein *et al.* Phys. Lett. B 103, 255 (1981)
E. Khan, Phys. Rev. C 105, 014306 (2022)

Goal of the PDR study using (n,n’)

HOW do we proceed ? Experiment ^{140}Ce(n,n’)^{140}Ce*(γ)^{140}Ce ↔ ^{140}Ce(n,n’γ)^{140}Ce

1. Detect n’ and γ in coincidence in order to select direct γ decays



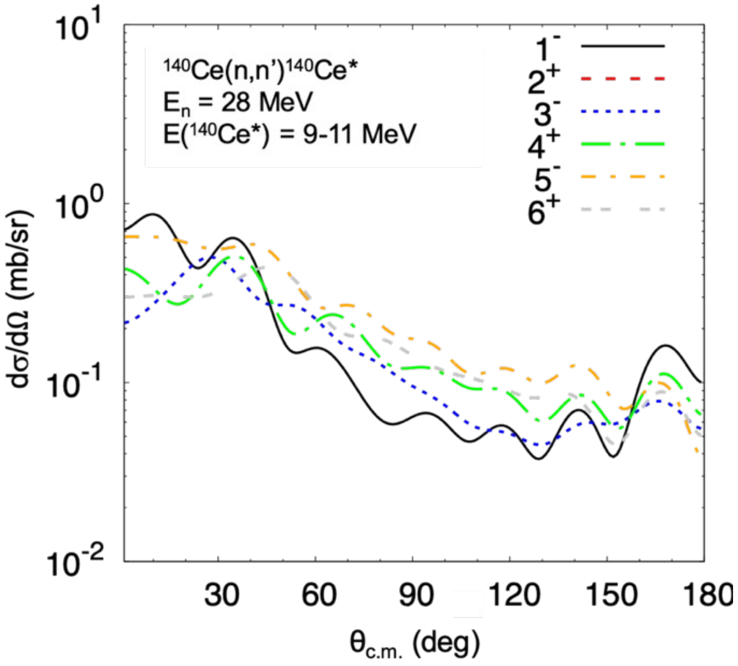
D. Savran *et al.* Phys. Lett. B 786 (2018)

BUT :

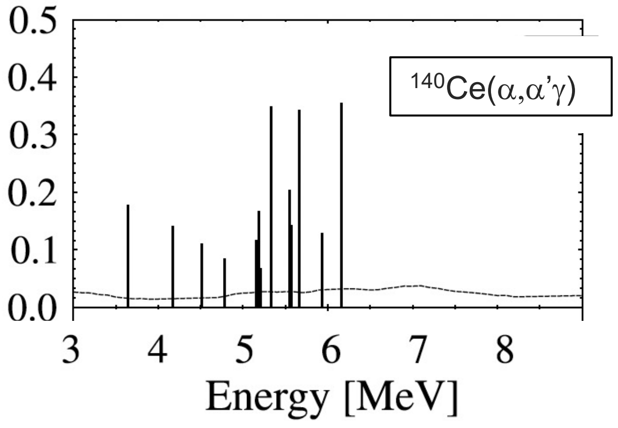
- Ex = E*(^{140}Ce) reconstructed using the n’ TOF. Few MeV energy resolution
- PARIS scintillators instead Ge detector. 2-3% energy resolution in the PDR energy region

More difficult !

2. Measure the n’ and γ angular distributions of a given excitation energy range to assess the 1$^-$ strength.



3. For each 1$^-$ excited state/energy range: extract the (n,n’) cross section



D. Savran *et al.* Phys. Lett. B 786 (2018)

Goal of the PDR study using (n,n’)

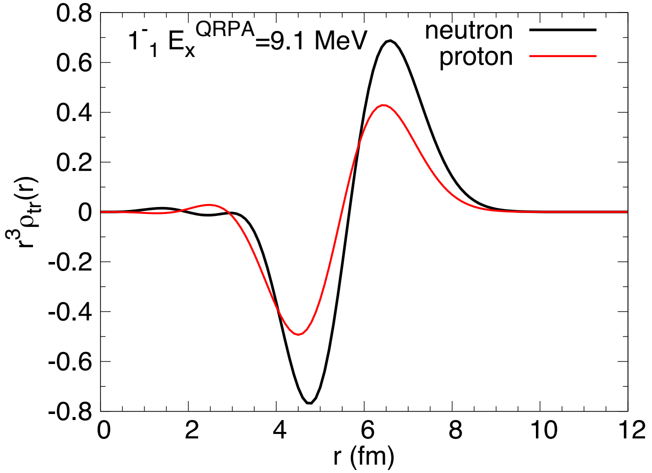
HOW do we proceed ? Experiment **^{140}Ce(n,n’)^{140}Ce*(γ)^{140}Ce ↔ ^{140}Ce(n,n’γ)^{140}Ce**

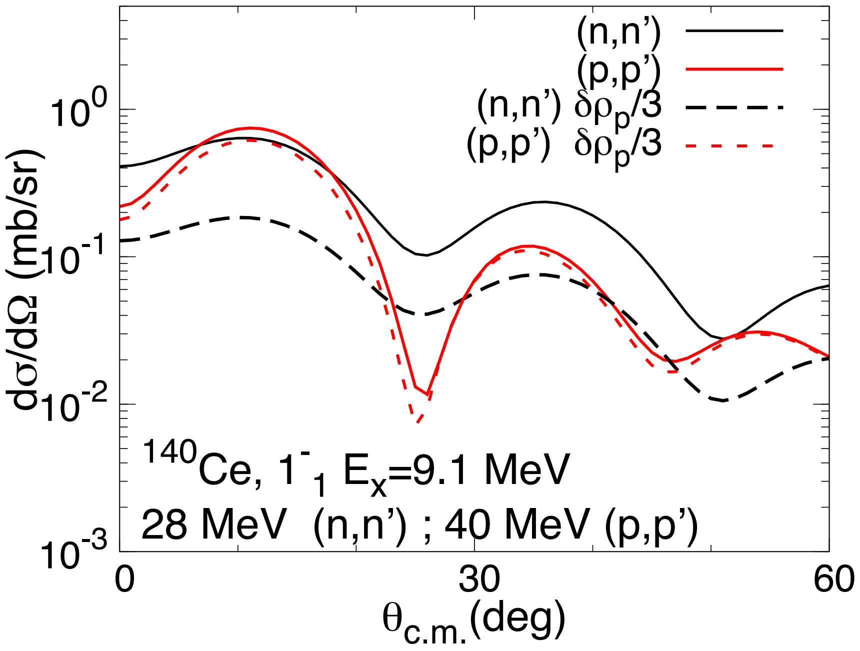
4. Interpretation

- Compare the measured (n,n’) to theoretical cross sections
- Compare the (p,p’) data of the literature to the calculations

The comparison exp. vs theory for (n,n’) and for (p,p’) will **pin down the role of protons and neutrons in the PDR**

Example of calculations: QRPA transition densities (Gogny D1M interaction) + DWBA calculations using a microscopic density-dependent potential model approach





QRPA (S. Péru) + DWBA-JLM (M. Dupuis)
QRPA S. Péru *et al.*, CEA DAM EPJA 55:232 (2009)
DWBA with JLM M. Dupuis *et al.*, PRC100, 044607 (2019)

The experimental setup at GANIL-SPIRAL2/NFS

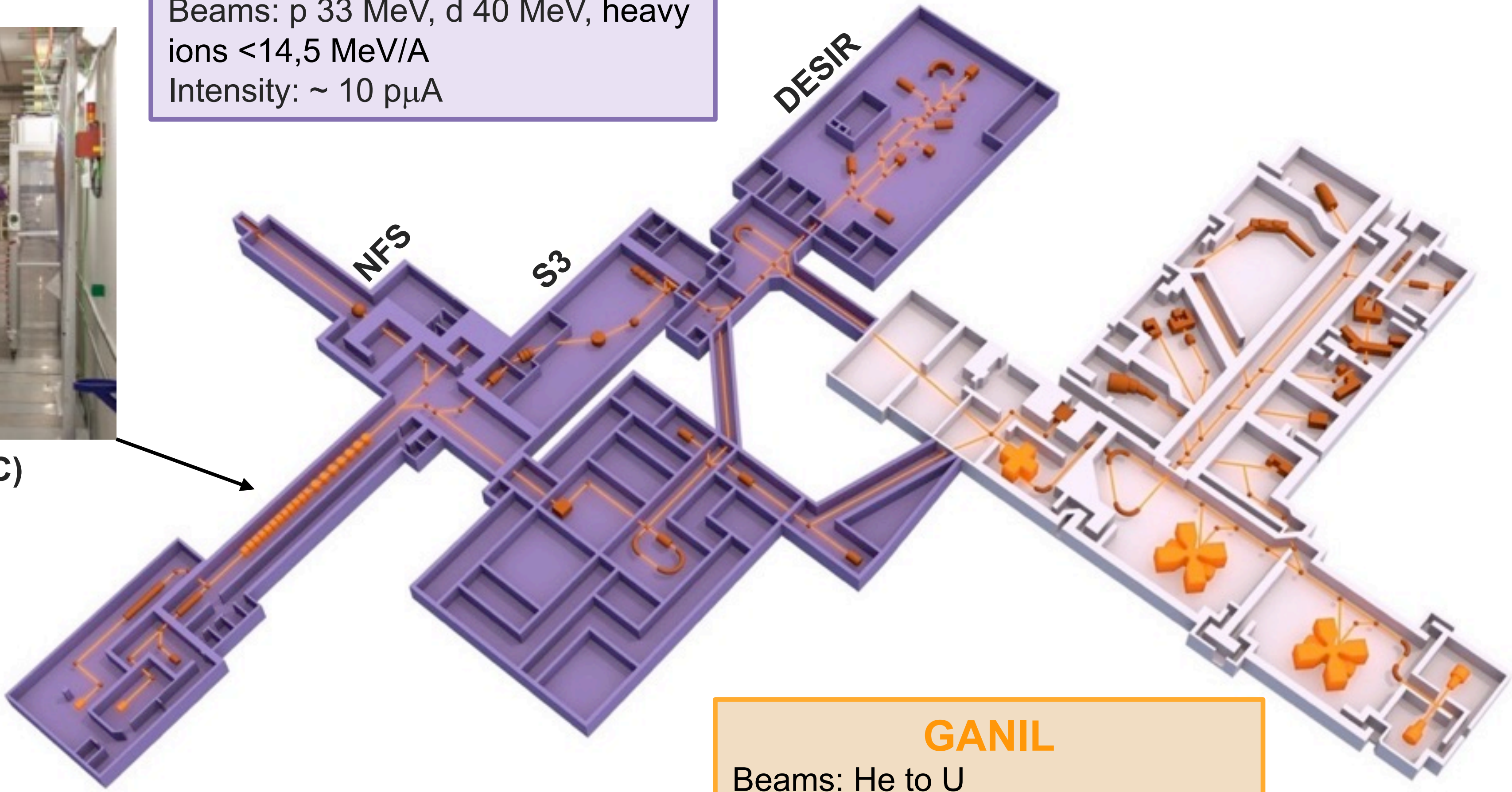
GANIL-SPIRAL2

LINEAR ACCELERATOR (LINAC)

SPIRAL2

Beams: p 33 MeV, d 40 MeV, heavy ions <14,5 MeV/A

Intensity: ~ 10 pμA



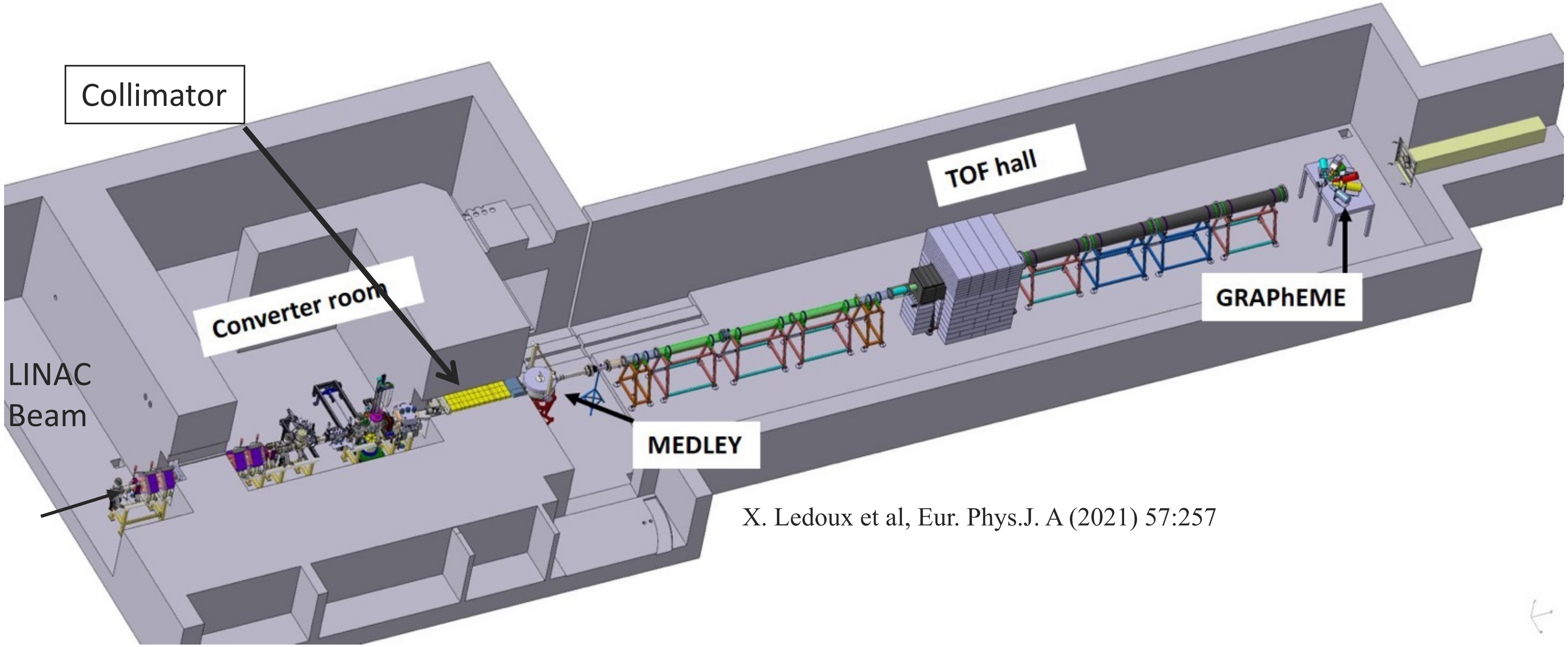
GANIL

Beams: He to U

Energy: few to 100 MeV/nucleon

Intensity: ~ pμA

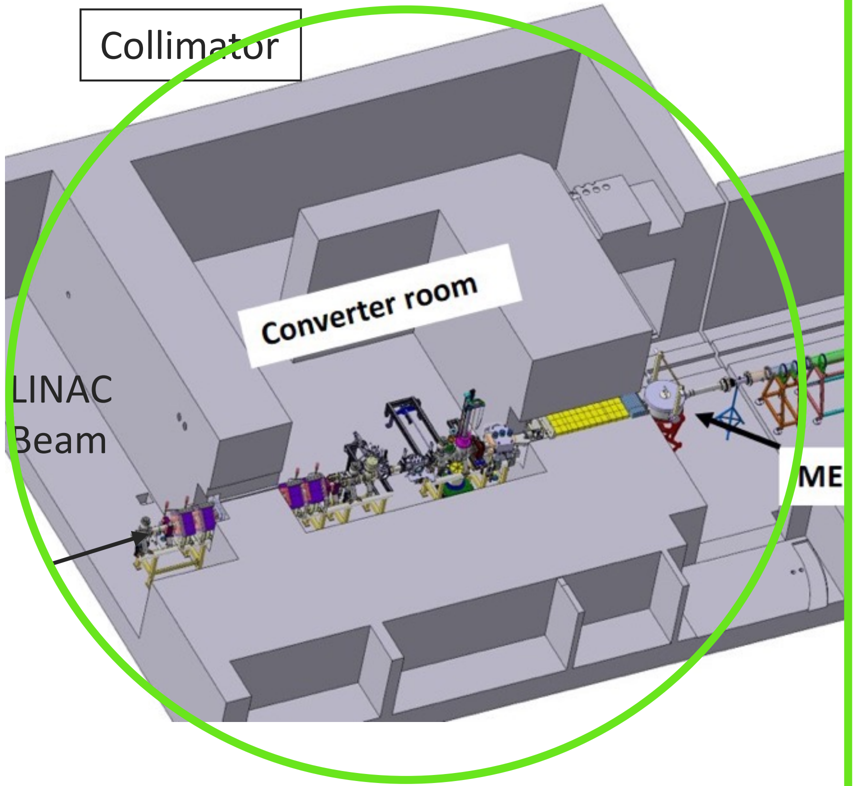
The Neutrons For Science (NFS) facility



X. Ledoux et al, Eur. Phys.J. A (2021) 57:257

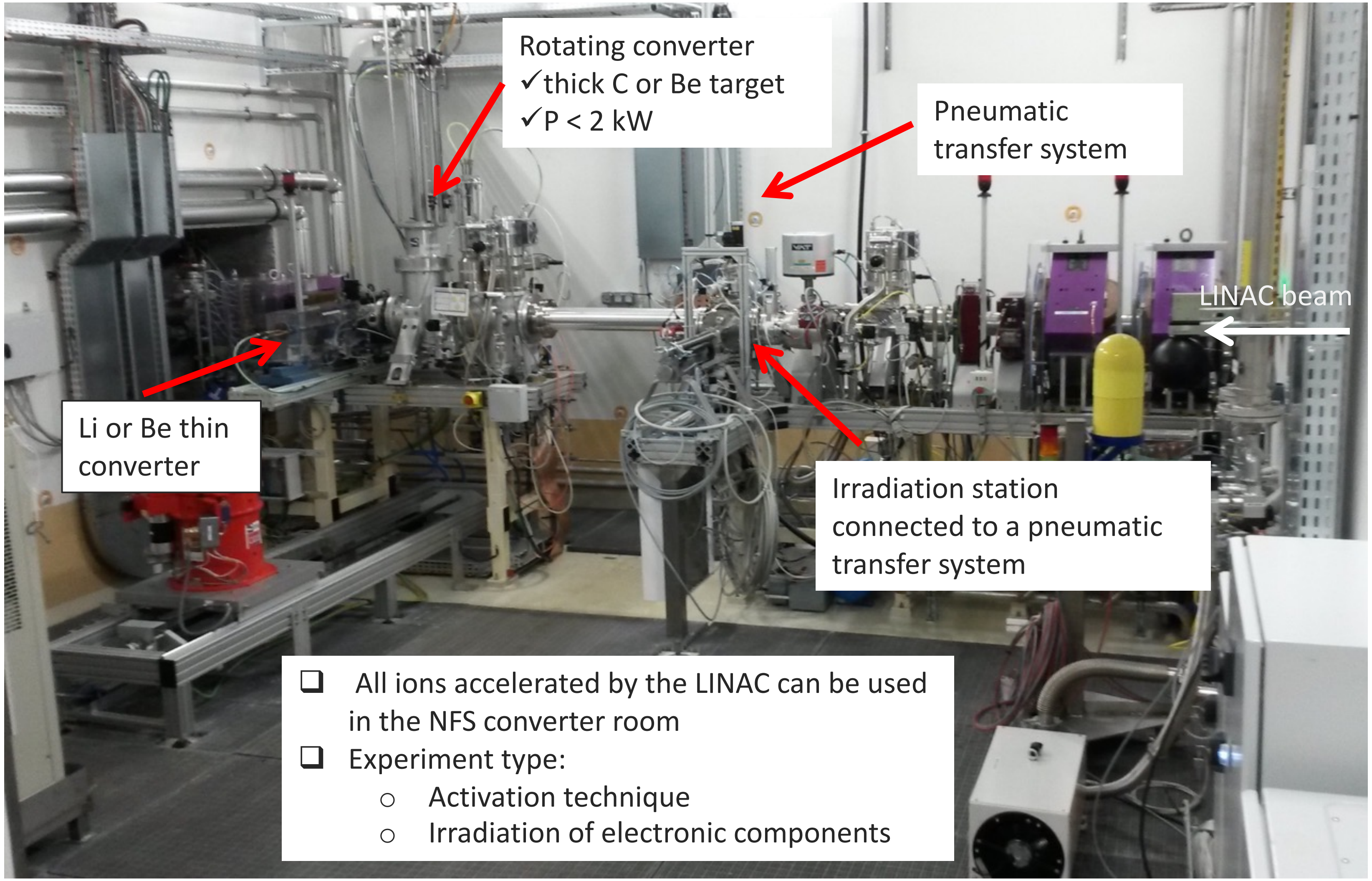
Courtesy P. Roussel-Chomaz

The Neutrons For Science (NFS) facility



Courtesy P. Roussel-Chomaz

The converter room



Rotating converter
✓thick C or Be target
✓P < 2 kW

Pneumatic transfer system

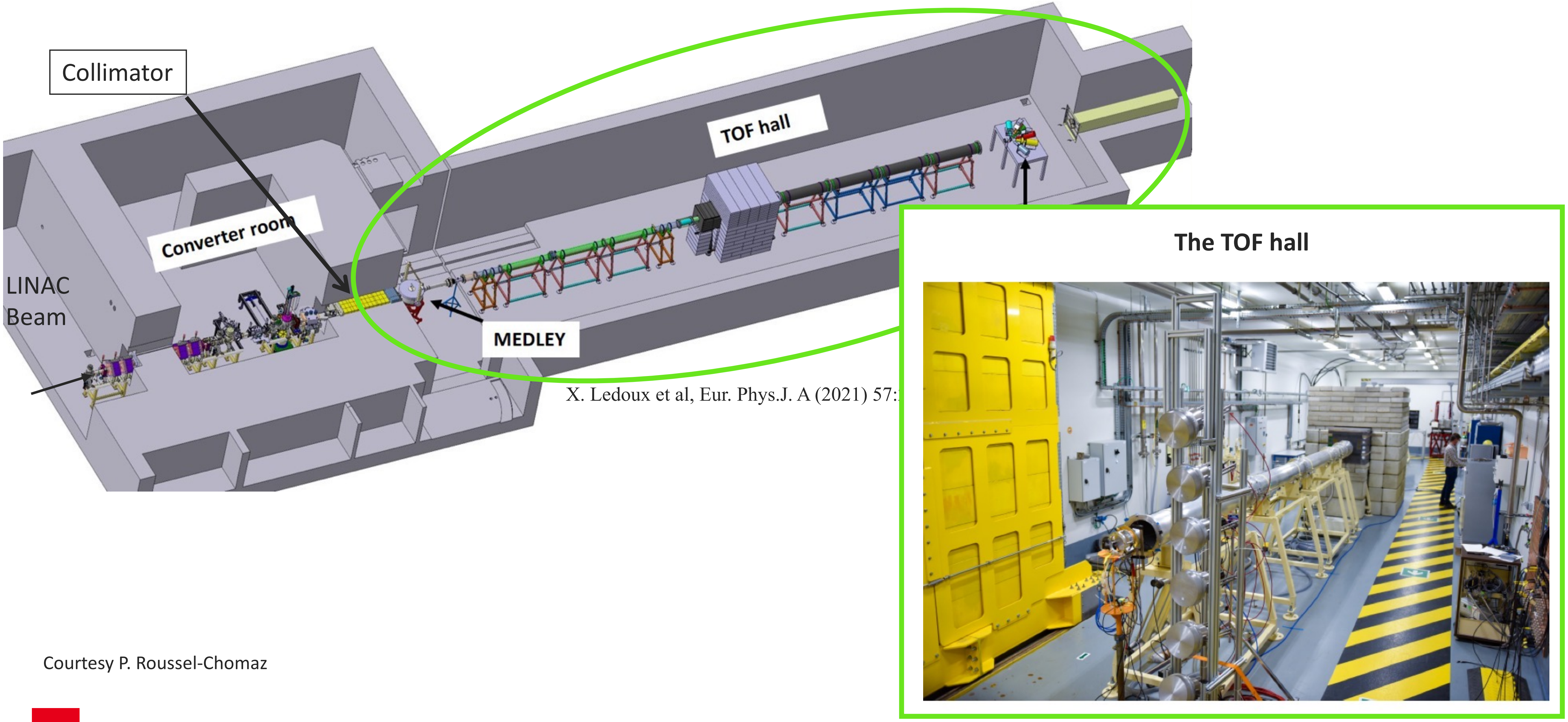
LINAC beam

Li or Be thin converter

Irradiation station connected to a pneumatic transfer system

- ❑ All ions accelerated by the LINAC can be used in the NFS converter room
- ❑ Experiment type:
  - ○ Activation technique
  - ○ Irradiation of electronic components

The Neutrons For Science (NFS) facility



X. Ledoux et al, Eur. Phys.J. A (2021) 57:

The TOF hall

Courtesy P. Roussel-Chomaz

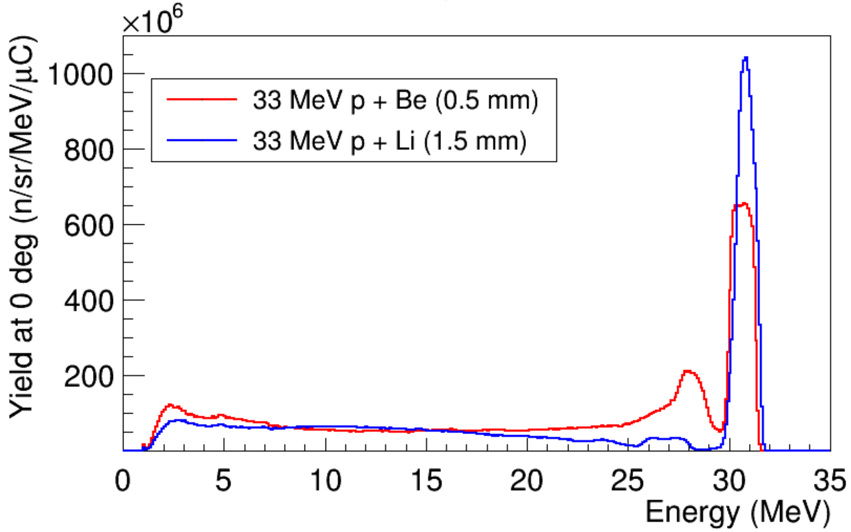
The Neutrons For Science (NFS) facility

Quasi-mono-energetic / continuous neutron spectra

Courtesy P. Roussel-Chomaz

p + **thin target** (^{7}Li or ^{9}Be)

E_n = up to 31 MeV

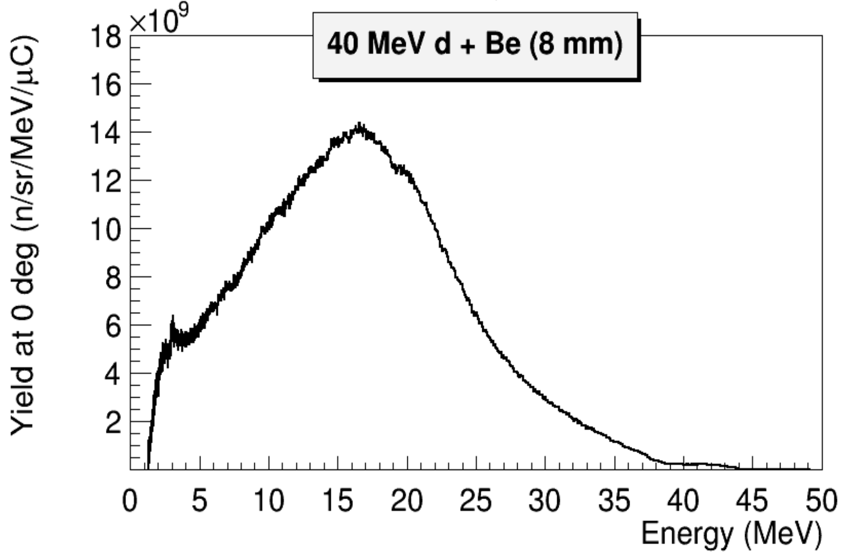


E MeV	Flux at 5 m
5	1,7.10^4 n/cm^2/MeV/s
10	5.10^3 n/cm^2/MeV/s
20	2,3.10^4 n/cm^2/MeV/s
30	1,2.10^5 n/cm^2/MeV/s

Example :
p + Li at 20 µA
Neutron yield in the mono-energetic peak 1,2 10^9 n/sr/µC

deuteron + **thick converter** (1cm)

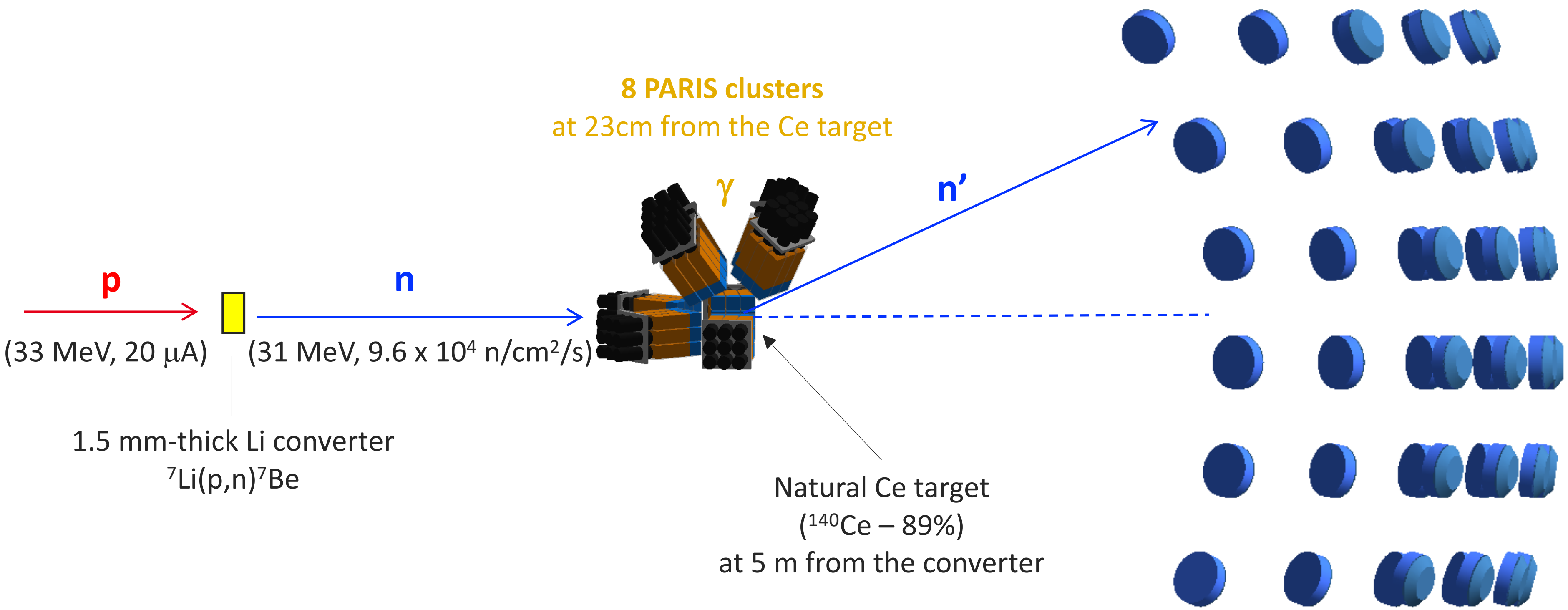
E_{max} = 40 MeV , <E> = 14 MeV



E MeV	Flux at 5 m
0-40	6.10^7 n/cm^2/s
5	2.10^6 n/cm^2/MeV/s
14	5.10^6 n/cm^2/MeV/s
30	6.10^5 n/cm^2/MeV/s

Example :
40 MeV d + Be at 50 µA
Neutron yield in 4π 1,8 10^{13} n/s

Experimental setup



48 MONSTER modules
at 3m from the Ce target

8 PARIS clusters
at 23cm from the Ce target

(33 MeV, 20 µA)

(31 MeV, 9.6 x 10^4 n/cm^2/s)

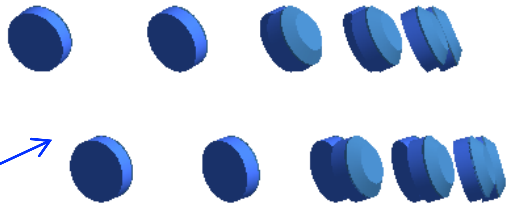
1.5 mm-thick Li converter
^{7}Li(p,n)^{7}Be

Natural Ce target
(^{140}Ce – 89%)
at 5 m from the converter

^{140}Ce(n,n')^{140}Ce*(γ)^{140}Ce @NFS

Experimental setup

48 MONSTER modules
at 3m from the Ce target



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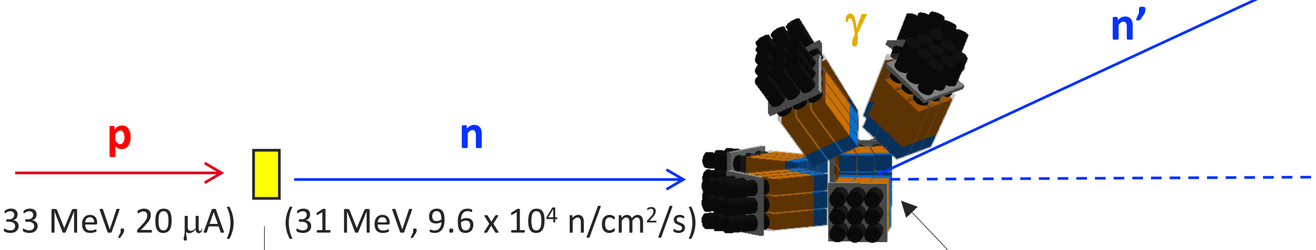

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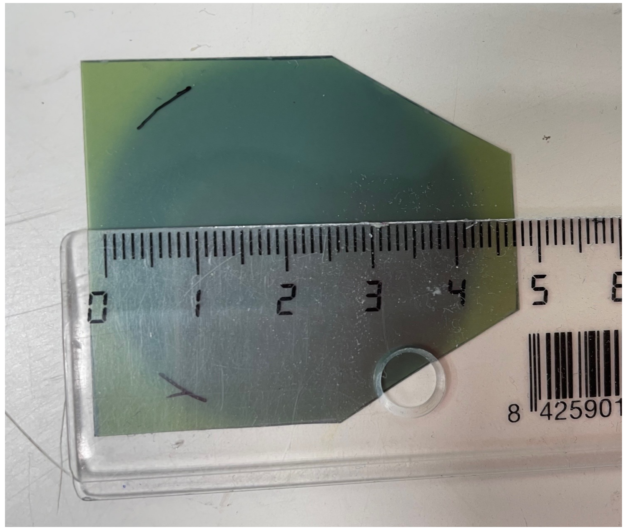
Neutron beam characteristics

Measurement of the neutron beam

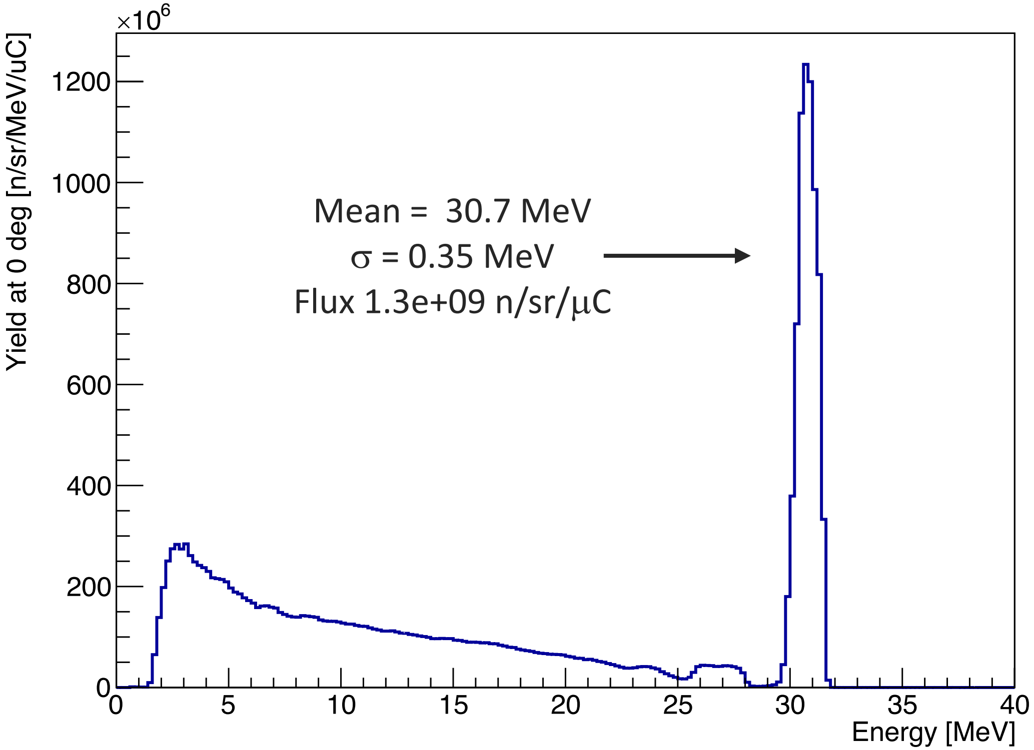
Beam size on target

- ➢ To check the neutron beam size at the Ce target position, a photographic plate has been placed at the entrance



Neutron beam spot at the target place
(∅ = 4 cm)

Intensity

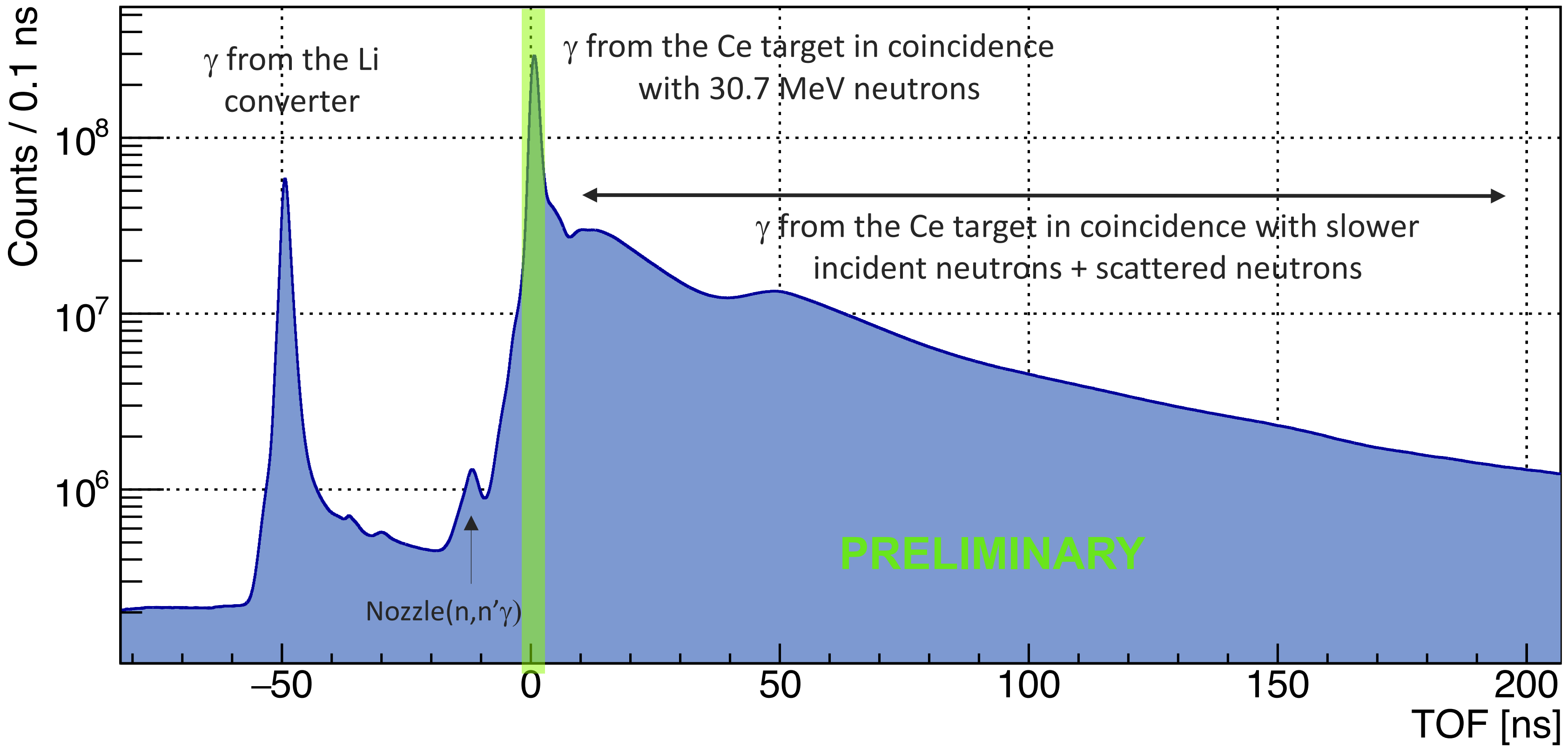


Mean = 30.7 MeV
σ = 0.35 MeV
Flux 1.3e+09 n/sr/μC

- Intensity extracted with uncertainty < 5%
- How clean the tail ?

How do we select 30.7 MeV incoming neutrons ?

➡ Use Time of Flight between PARIS and HF to select gammas coming from 30.7 MeV neutron interaction on the Ce target

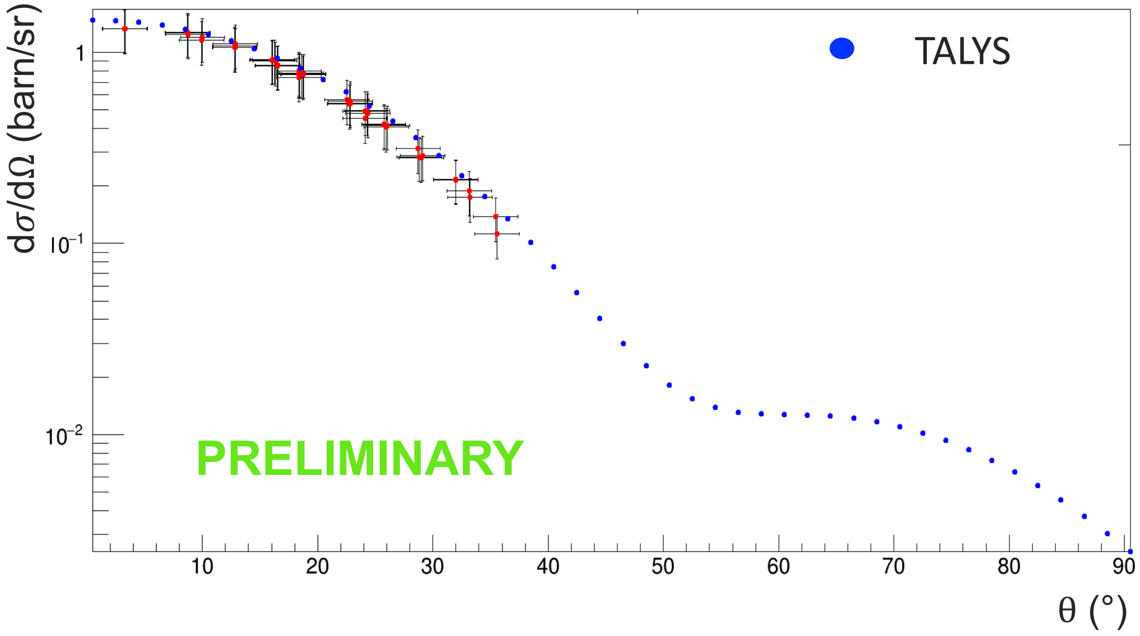


Online and first preliminary results

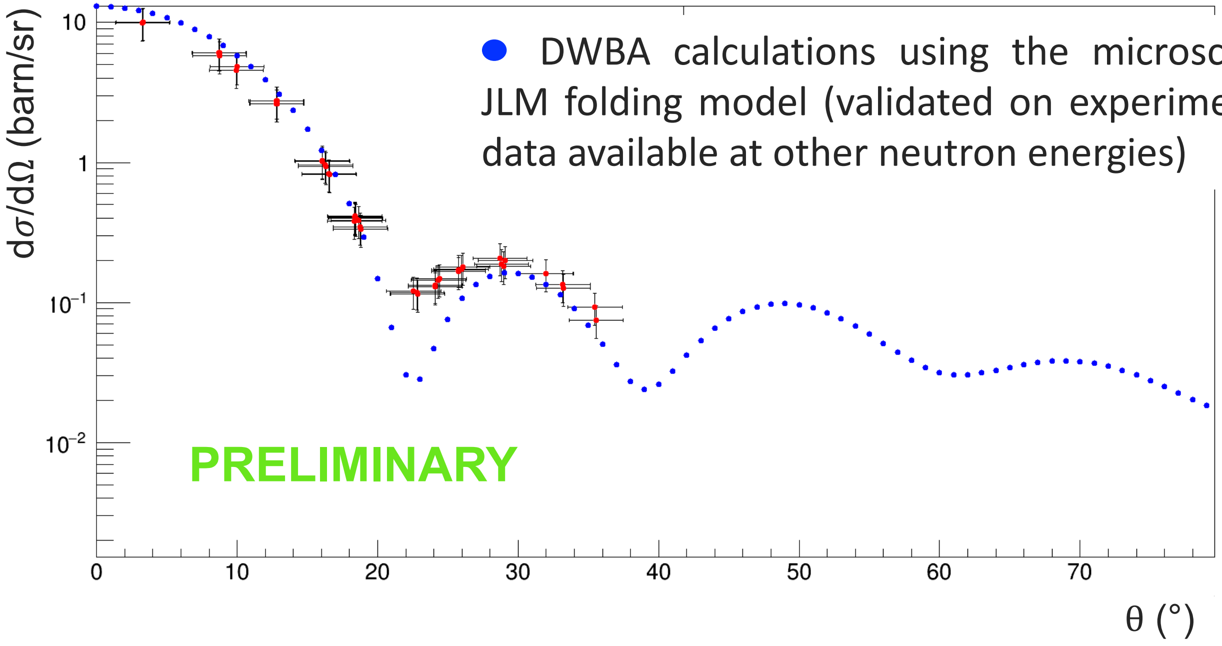
Online and first premilimary results

1) Elastic scattering reaction channel

$^{12}C(n,n)^{12}C$



$^{140}Ce(n,n)^{140}Ce$



● DWBA calculations using the microscopic JLM folding model (validated on experimental data available at other neutron energies)

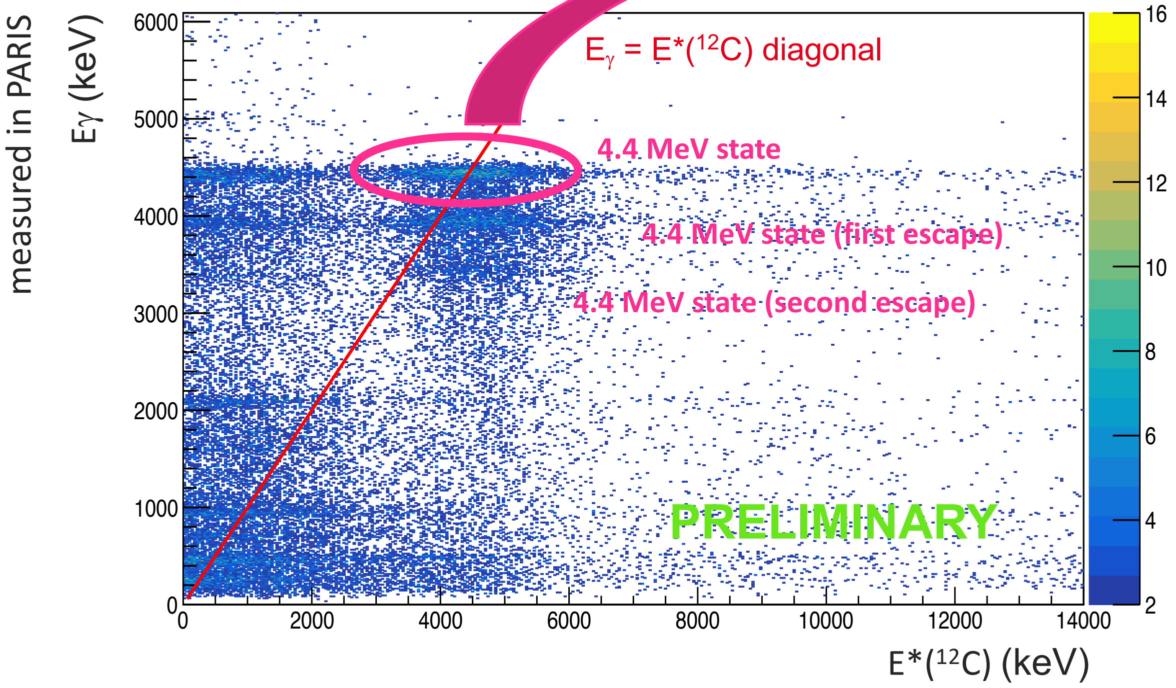
● Experimental points

Extracted differential cross-section without any normalization, assuming 8% intrinsic efficiency at 30.7 MeV for each MONSTER detector

Online and first premilimary results

2) Inelastic scattering reaction channel : study of the first 2^+ of ^{12}C (E(2^+)= 4.439 MeV)

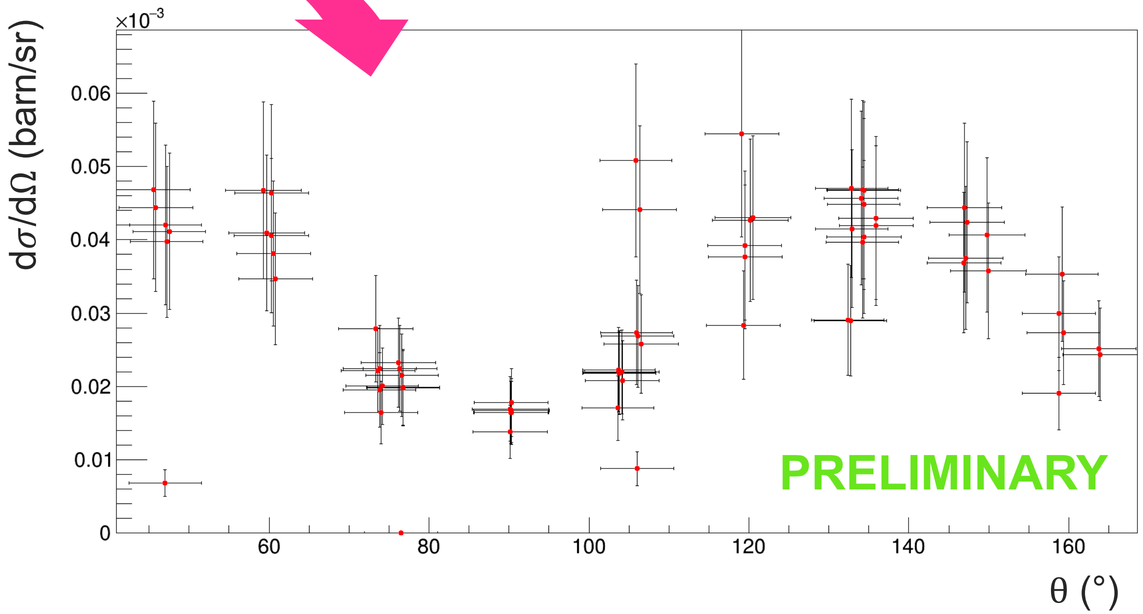
$^{12}C(n,n')^{12}C^*(\gamma)^{12}C$



reconstructed using the neutron time of flight (MONSTER)

$^{12}C(n,n')^{12}C^*(\gamma)^{12}C$

γ angular distribution in PARIS



➡ Selection of direct γ decay

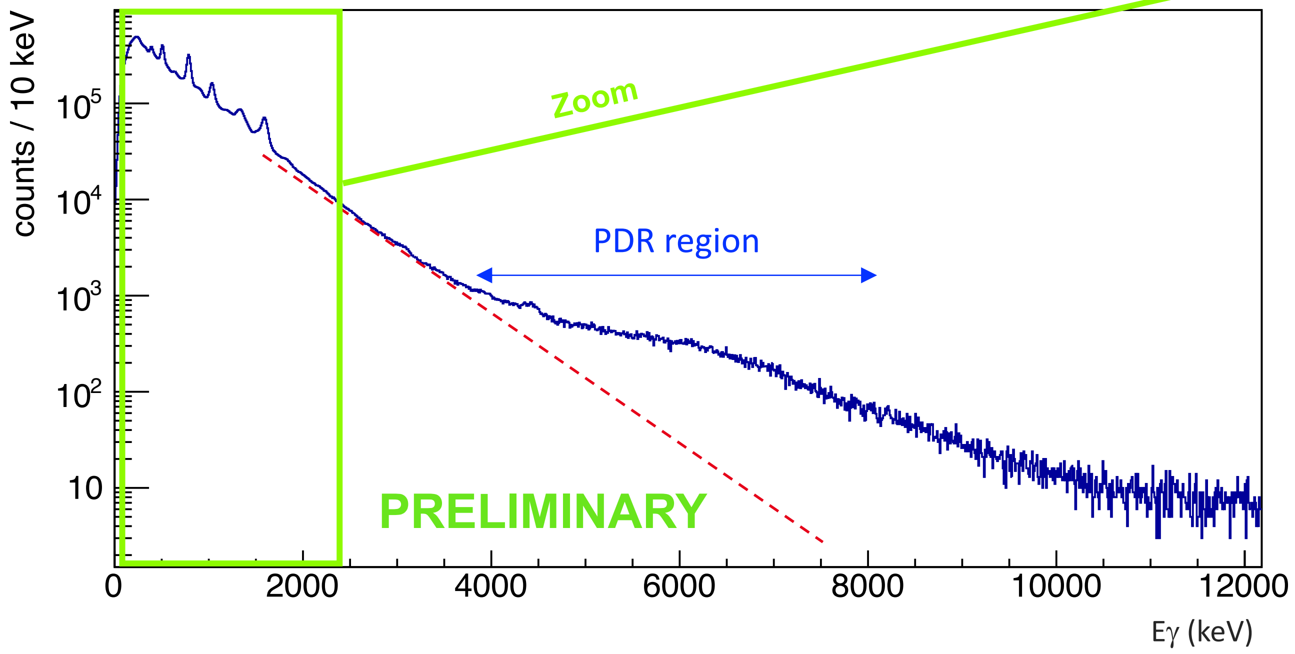
➡ Minimum at 90°, 2^+ state ?

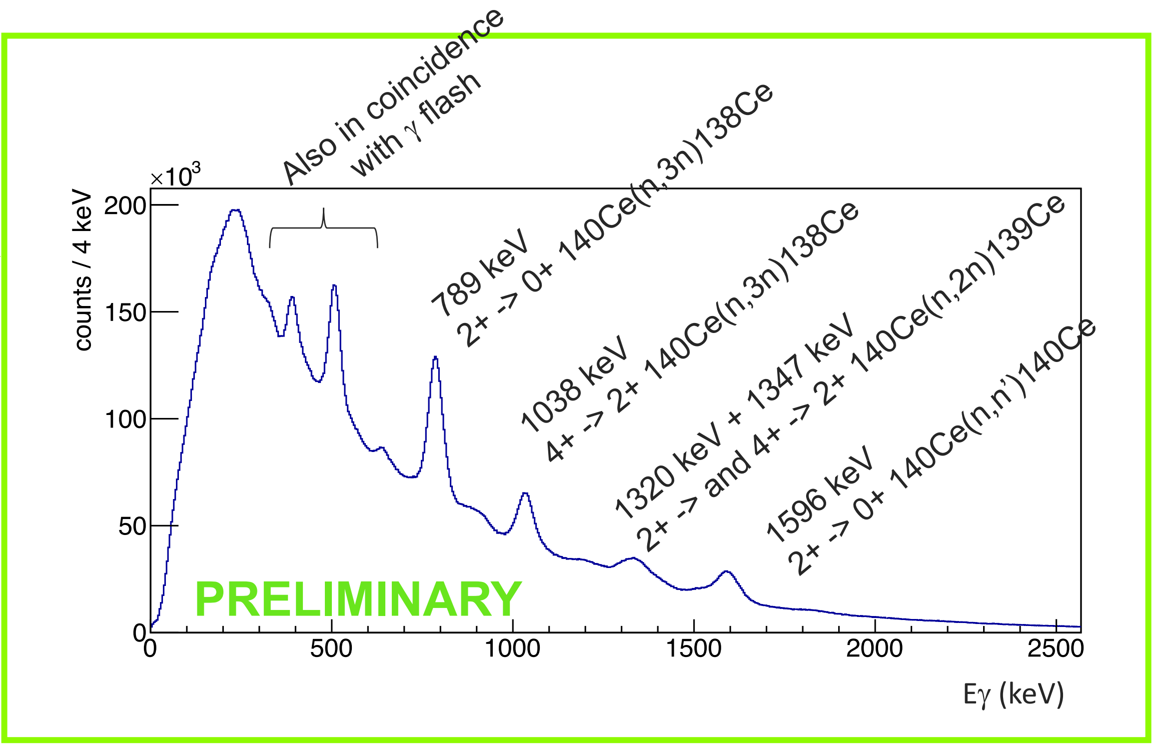
Online and first premilimary results

3) Inelastic scattering reaction channel : toward PDR in ^{140}Ce

^{140}Ce(n,n')^{140}Ce*(γ)^{140}Ce

Selection of the events along the E_γ = E*(^{140}Ce) diagonal



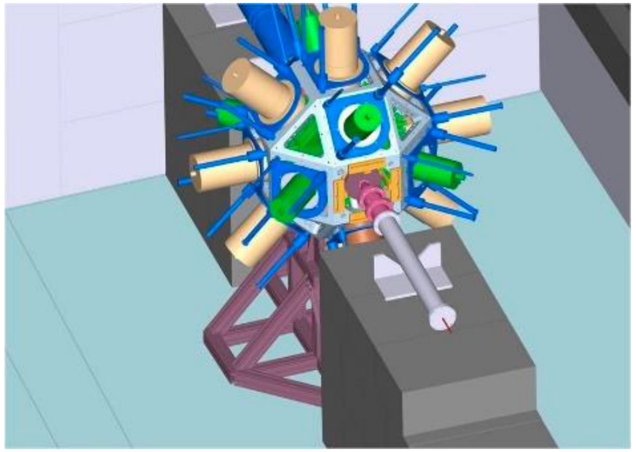


- Events in the PDR energy region not observed in other reaction channels (n,xn)
- next step : study of the γ and n angular distributions

Conclusion and outlook

- Experiment dedicated to the study of the **PDR using (n,n')** reaction performed in September 2022
  - the experiment went well
  - ongoing analysis
- **First nuclear structure experiment at NFS** (and so at SPIRAL2 !)
- **NFS is unique in term of flux** for fast neutrons
- If this study is successful, it can **open a original program** dedicated to the study of nuclear structure using fast neutrons

Next step September 2023 at NFS
Study of the ^{56}Ni structure using ^{58}Ni(n,3n) with EXOGAM
(spokesperson E. Clément)



Collaboration

M. Vandebrouck[1], I. Matea[2],
Y. Blumenfeld[2], A. Bogenschutz[1], D. Doré[1], M. Dupuis[3], A.M. Frelin[4], V. Lapoux[1], X. Ledoux[4], T. Martinez[6], P. Miriot-Jaubert[1], S. Peru[3], D. Ramos[4], E. Rey-Herme[1], D. Thisse1, N.L. Achouri[5], L. Al Ayoubi[2] , D. Beaumel[2], E. Berthoumieux[1], S. Calinescu[11], D. Cano Ott[6], M. Ciemala[7], A. Corsi[1], F. Crespi[12], Y. Demane[10], W. Dong[2] , O. Dorvaux[8], J. Dudouet[10], D. Etasse[5] , J. Gibelin[5], F. Gunsing[1], M. Harakeh[9,4], M. Kmiecik[7], M. Lebois[2], M. Lewitowicz[4], M. Mac Cormick[2] , A. Maj[7], D. Ramos[4], Ch. Schmitt[8], M. Stanoui[11] , O. Stezowski[10], Ch. Theisen[1], L. Thulliez[1], G. Tocabens[2] ,
PARIS and MONSTER Collaborations

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2. IJCLab (France)
3. CEA Bruyères le Chatel DAM/DIF (France)
4. GANIL (France)
5. LPC Caen (France)
6. CIEMAT (Spain)
7. Institut of Nuclear Physics PAN Krakow (Poland)
8. Université de Strasbourg, Institut Pluridisciplinaire Hubert Curien
9. KVI-CART (The Netherlands)
10. IP2I Lyon (France)
11. IFIN-HH, Bucharest (Romania)
12. Milano University and INFN (Italy)

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IJCLab
Irène Joliot-Curie
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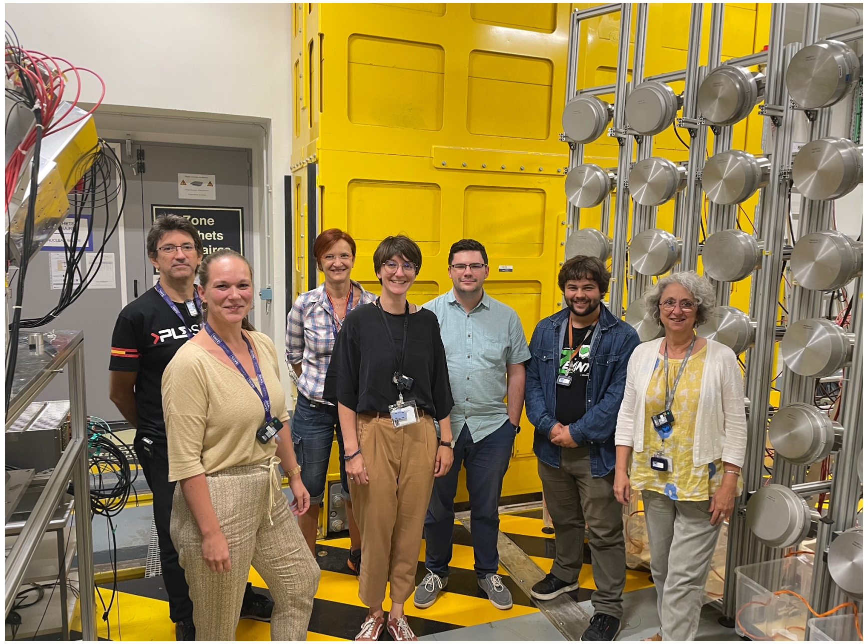
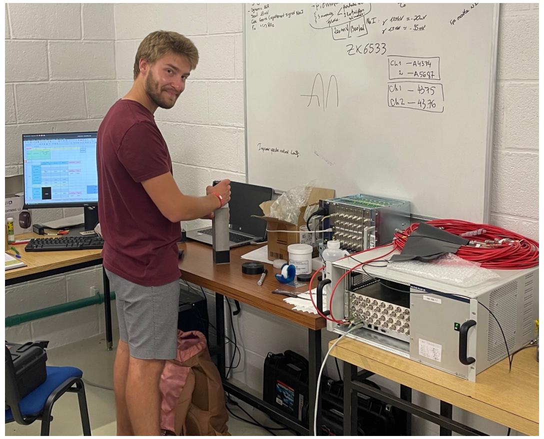
GANIL spiral2
laboratoire commun CEA/DRF CNRS/IN2P3





P2IO
Physique des 2 Infinis et des Origines

See Périne Miriot-Jaubert's poster

Thank you for your attention !