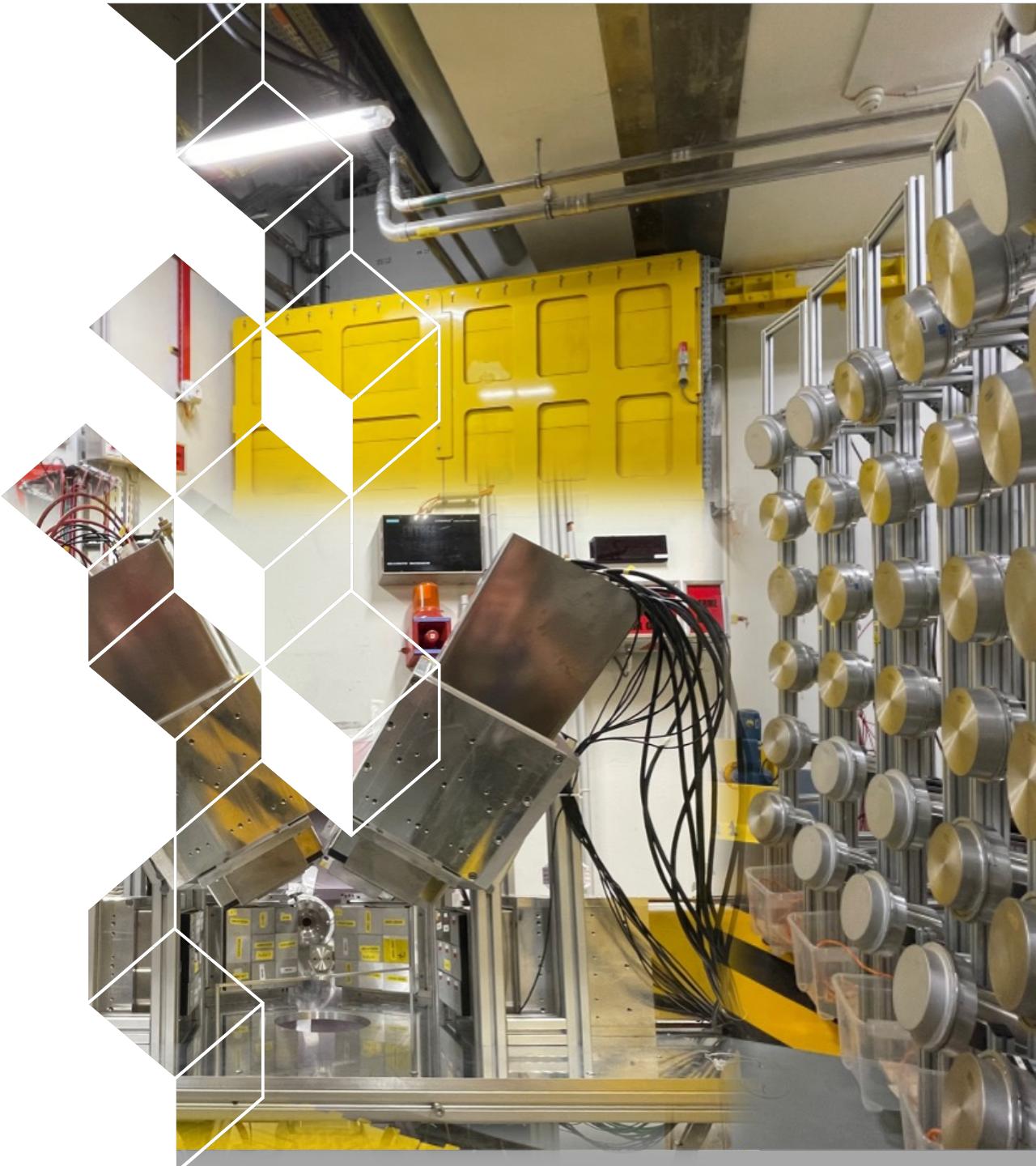




Study of the Pygmy Dipole Resonance using neutron inelastic scattering at GANIL-SPIRAL2/NFS

ARIS 2023

Marine Vandebrouck

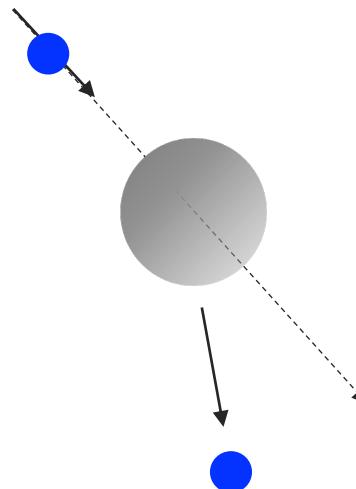


What is the nature of a nuclear excitation ?

In other words :

How protons and neutrons contribute to
the excitation strength ?

Tool
scattering reaction



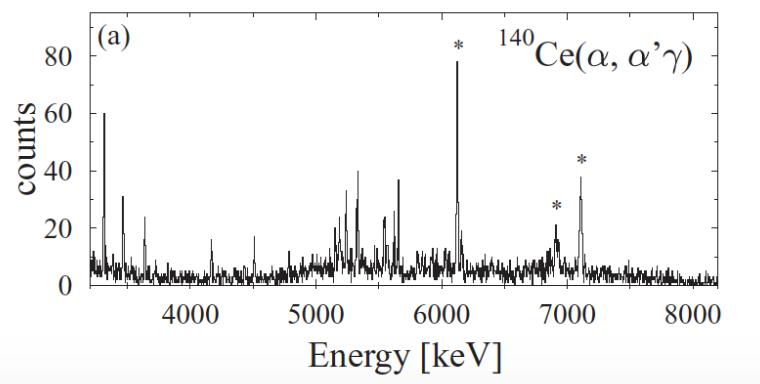
Observables

Excitation energy, E_γ and cross section



Interpretation

Comparison to microscopic calculations



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

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

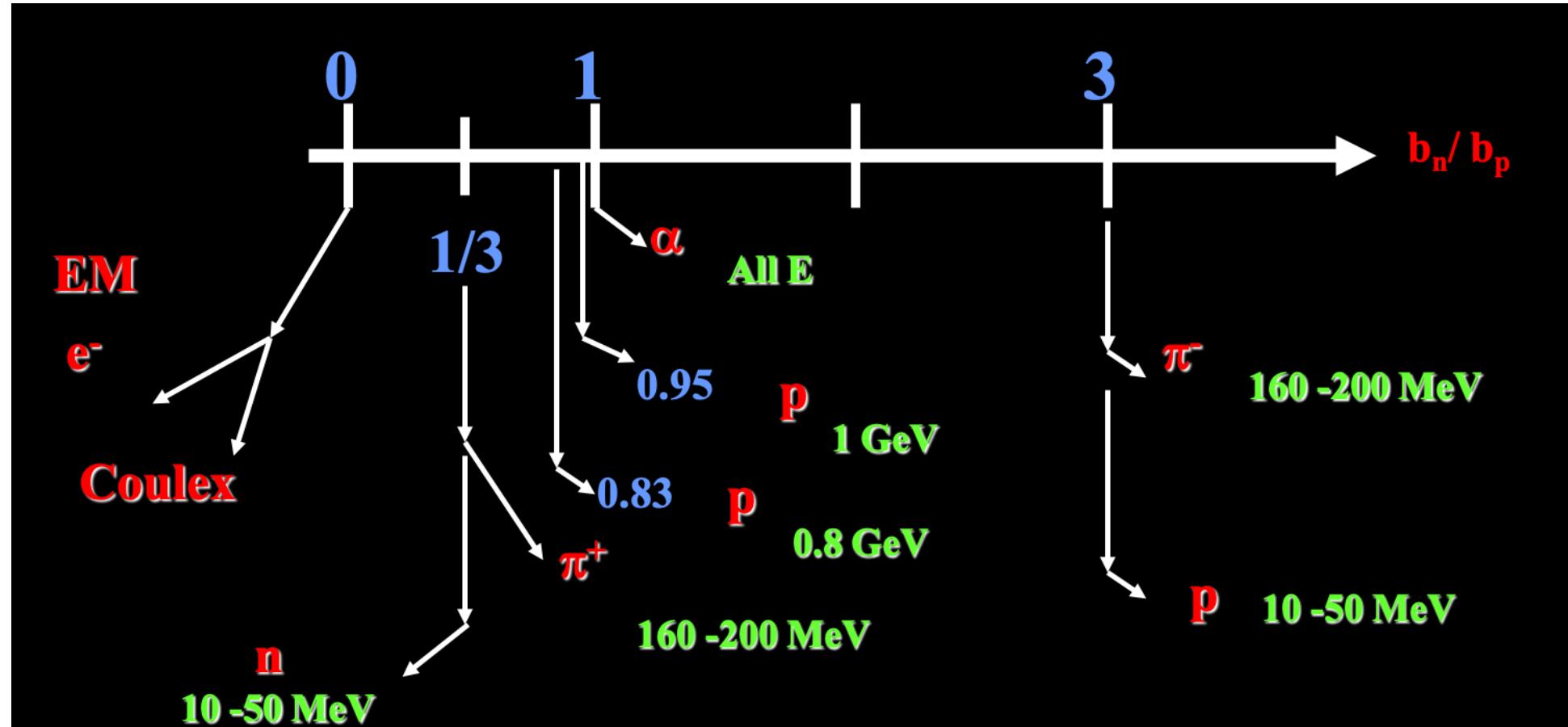
ρ
Transition density

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. Bernstein *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

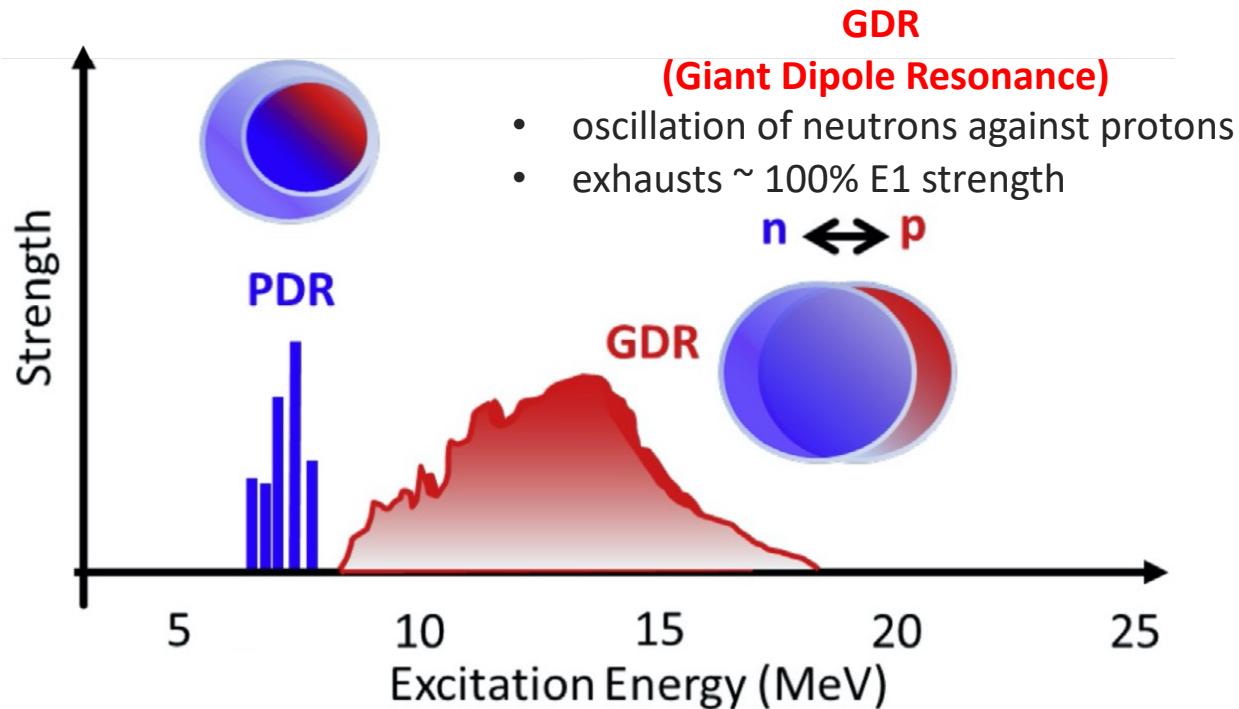
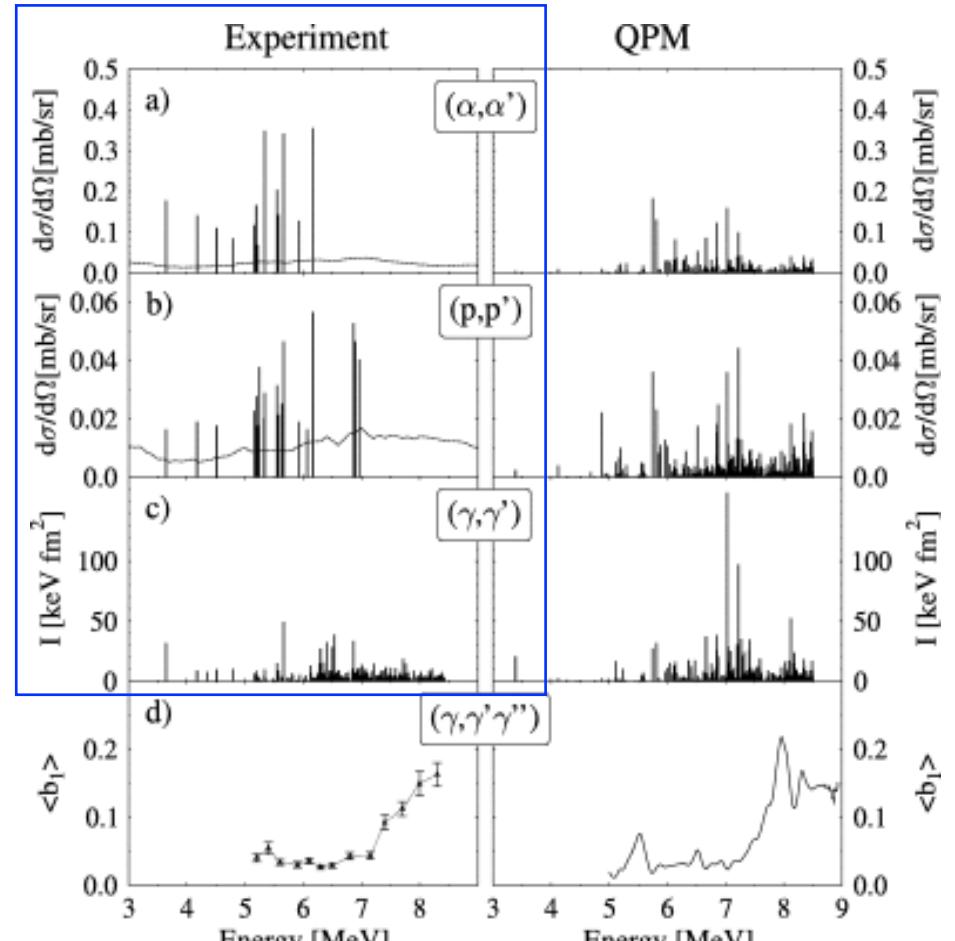


Figure extracted from A. Bracco *et al.* Prog. Part. Nucl. Phys. 106 (2019)

- 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

^{140}Ce



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

Isoscalar probes \rightarrow 4-6 MeV

Proton probe \rightarrow selected states

Electromagnetic probe \rightarrow 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')



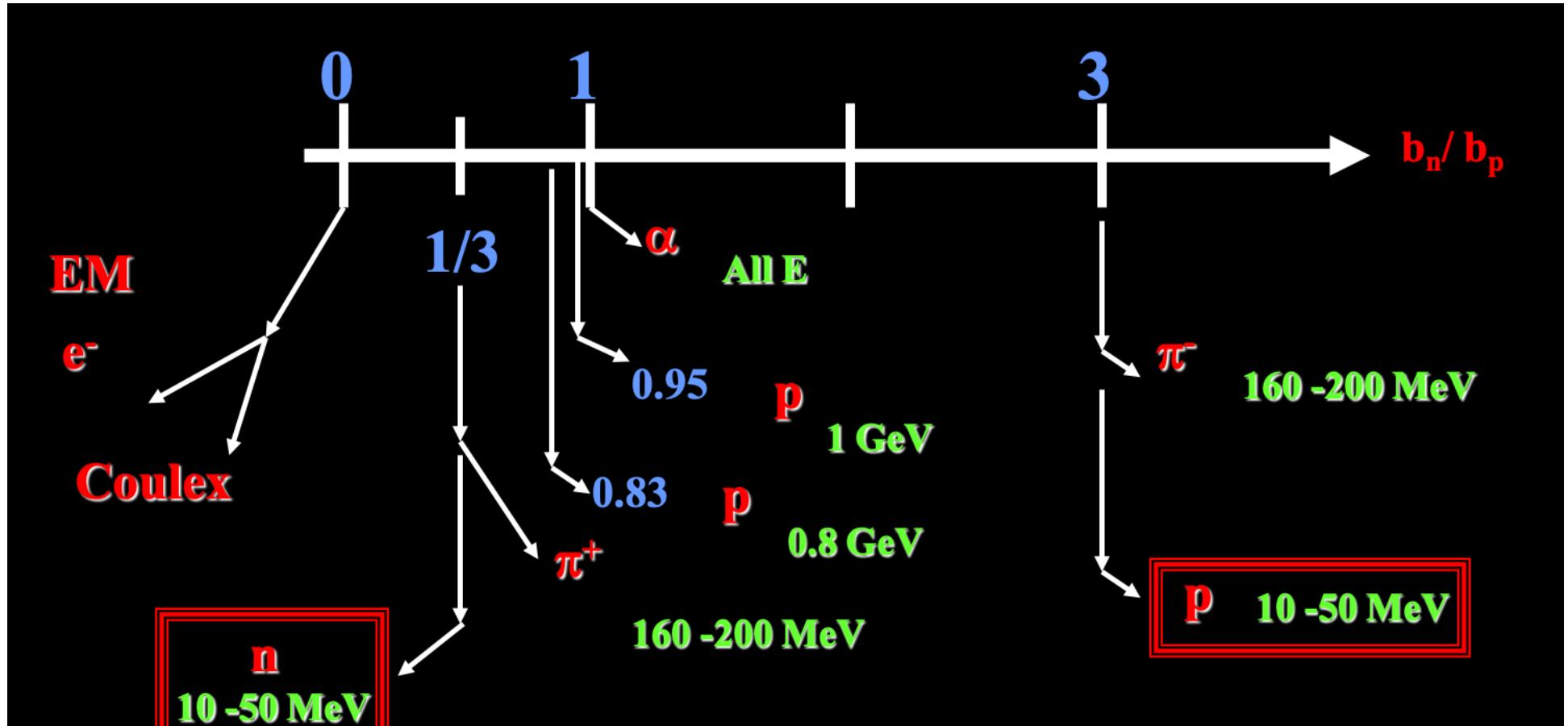
Goal of the PDR study using (n,n') reaction



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



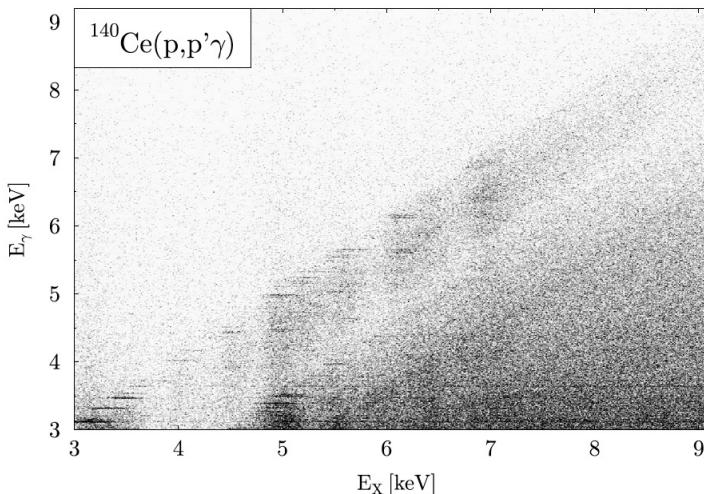
A. Bernstein *et al.* Phys. Lett. B 103, 255 (1981)
E. Khan, Phys. Rev. C 105, 014306 (2022)



Goal of the PDR study using (n,n')

HOW do we proceed ? Experiment $^{140}\text{Ce}(n,n')^{140}\text{Ce}^*(\gamma)^{140}\text{Ce} \leftrightarrow ^{140}\text{Ce}(n,n'\gamma)^{140}\text{Ce}$

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



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

BUT :

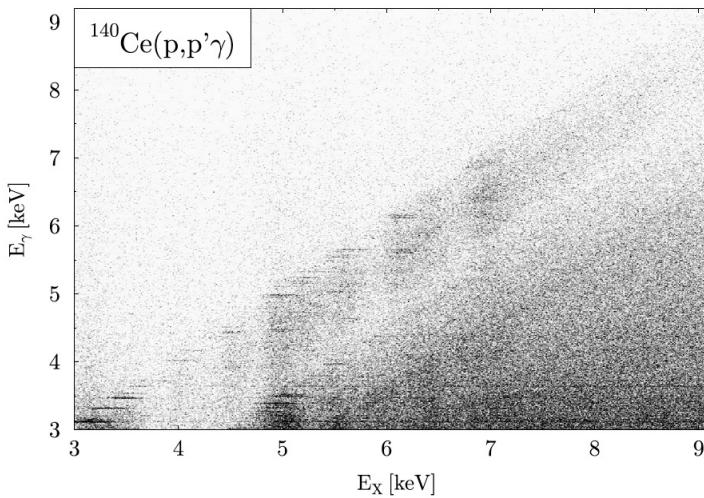
- $E_x = E^*(^{140}\text{Ce})$ reconstructed using the n' TOF. Few MeV energy resolution
- PARIS scintillators instead Ge detector. 2-3% energy resolution in the PDR energy region

More difficult !

Goal of the PDR study using (n,n')

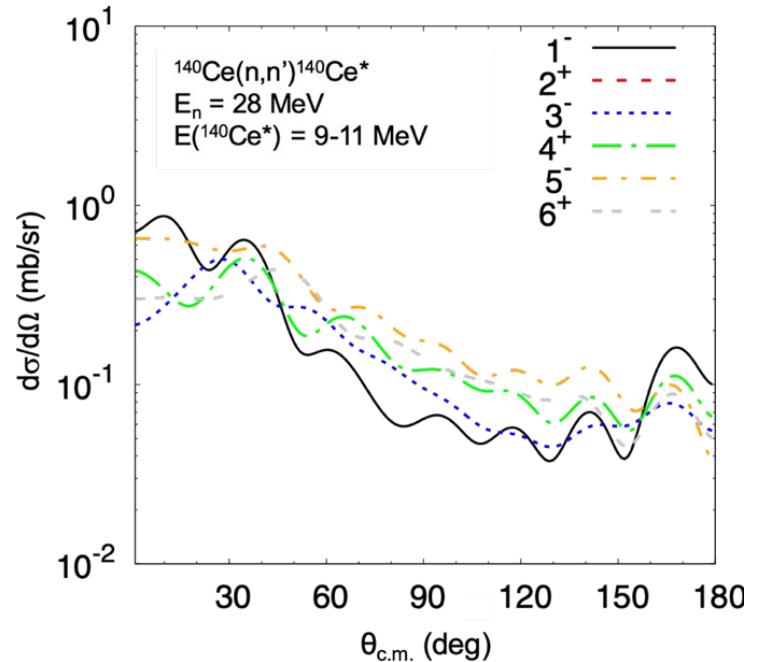
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D. Savran *et al.* Phys. Lett. B 786 (2018)

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



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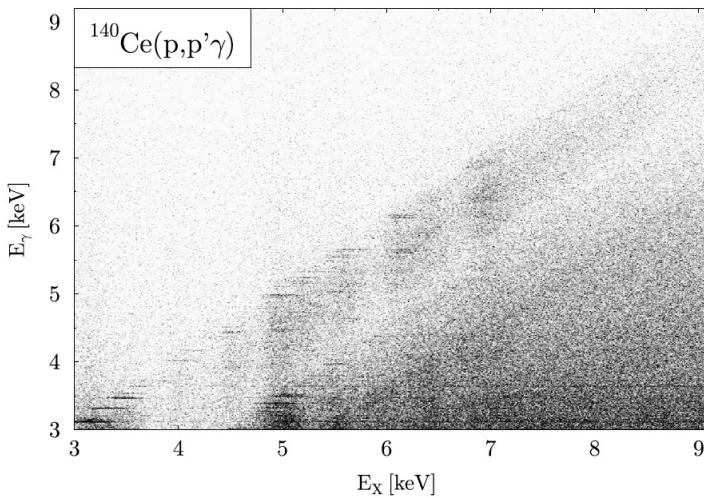
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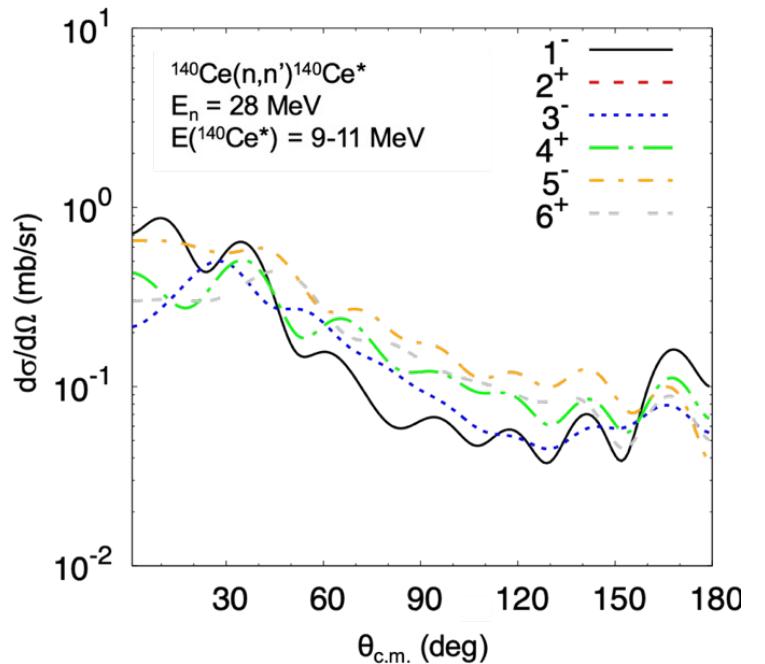
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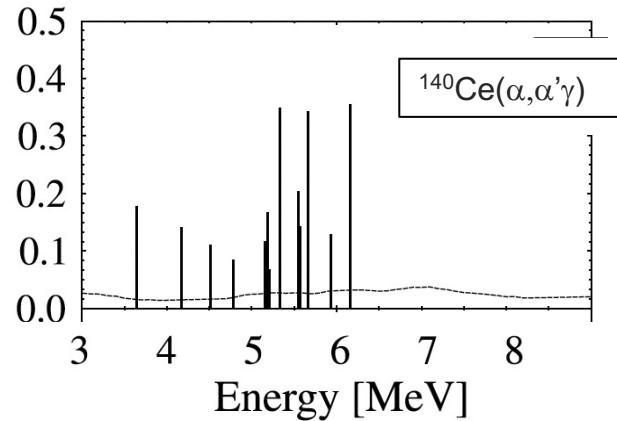


BUT :

- $E^*(^{140}\text{Ce})$ reconstructed using the n' TOF. Few MeV energy resolution
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More difficult !

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 $^{140}\text{Ce}(n,n')^{140}\text{Ce}^*(\gamma)^{140}\text{Ce} \leftrightarrow ^{140}\text{Ce}(n,n'\gamma)^{140}\text{Ce}$

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

Goal of the PDR study using (n,n')

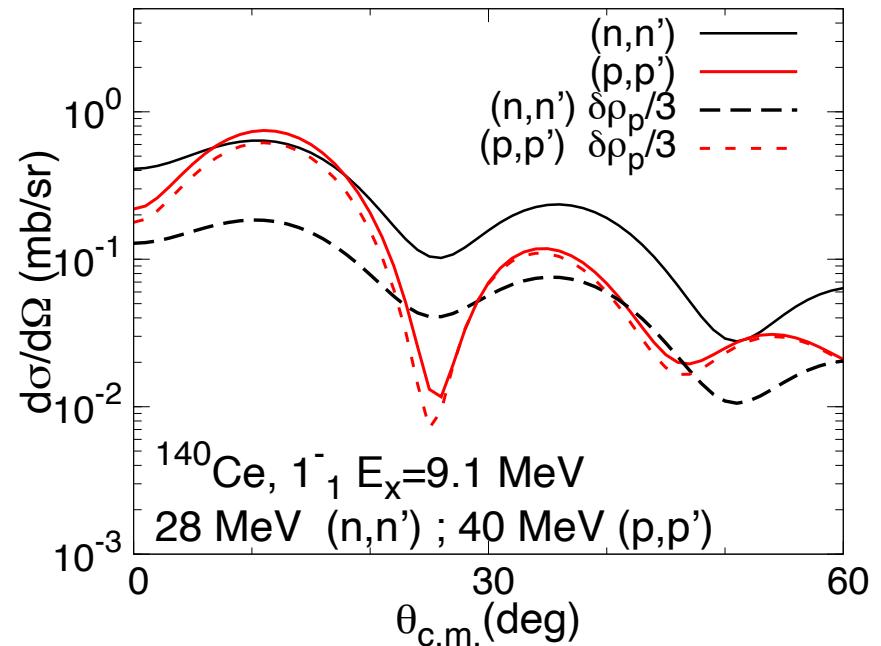
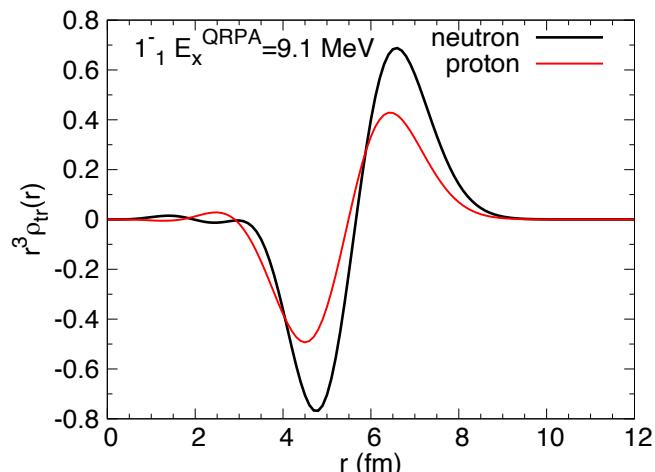
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Example of calculations: QRPA transition densities (Gogny D1M interaction) + DWBA calculations using a microscopic density-dependent potential model approach

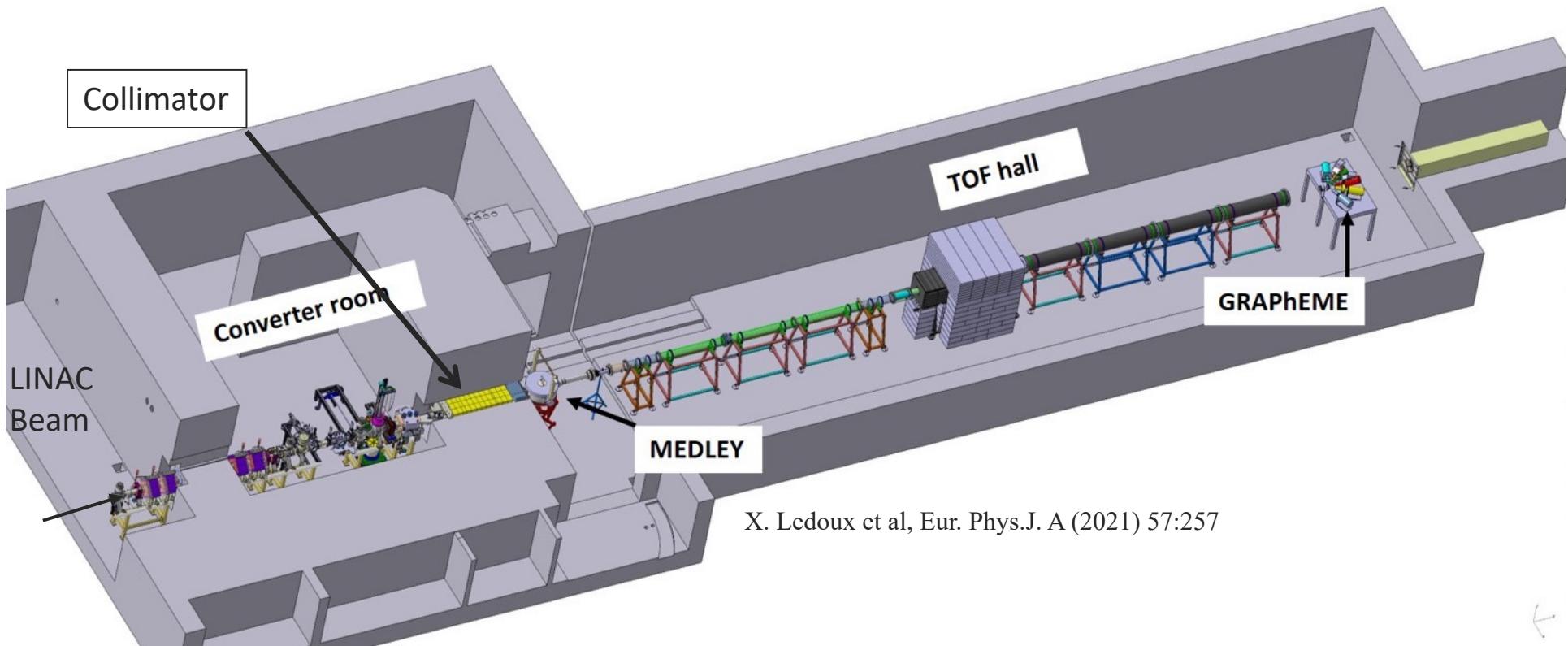


QRPA (S. Péru) + DWBA-JLM (M. Dupuis)
QRPA S. Péru *et al.*, CEA DAM EPJA 55:232 (2009)
DWBA with JLM M. Dupuis *et al.*, PRC100, 044607 (2019)



The experimental setup at GANIL-SPIRAL2/NFS

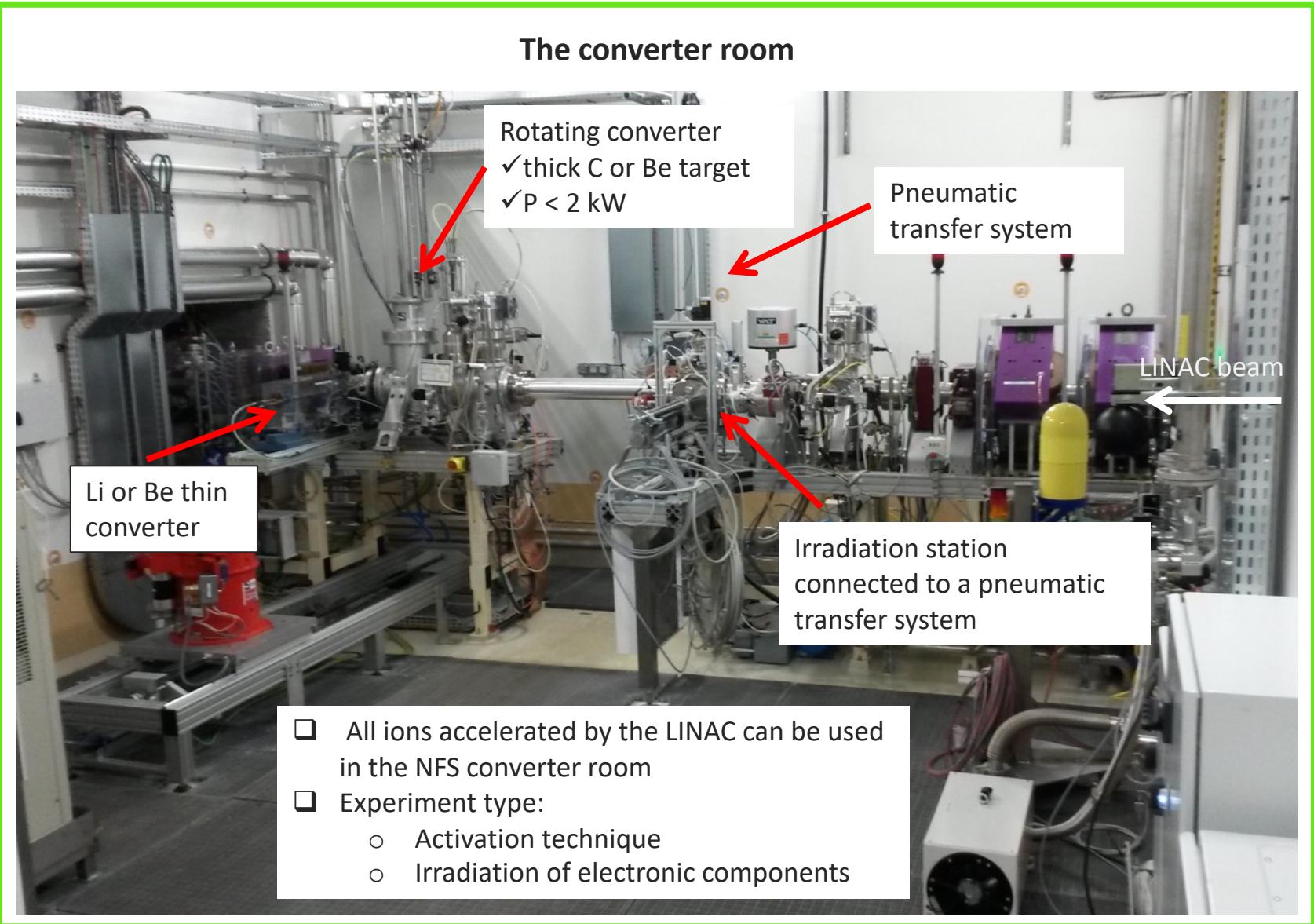
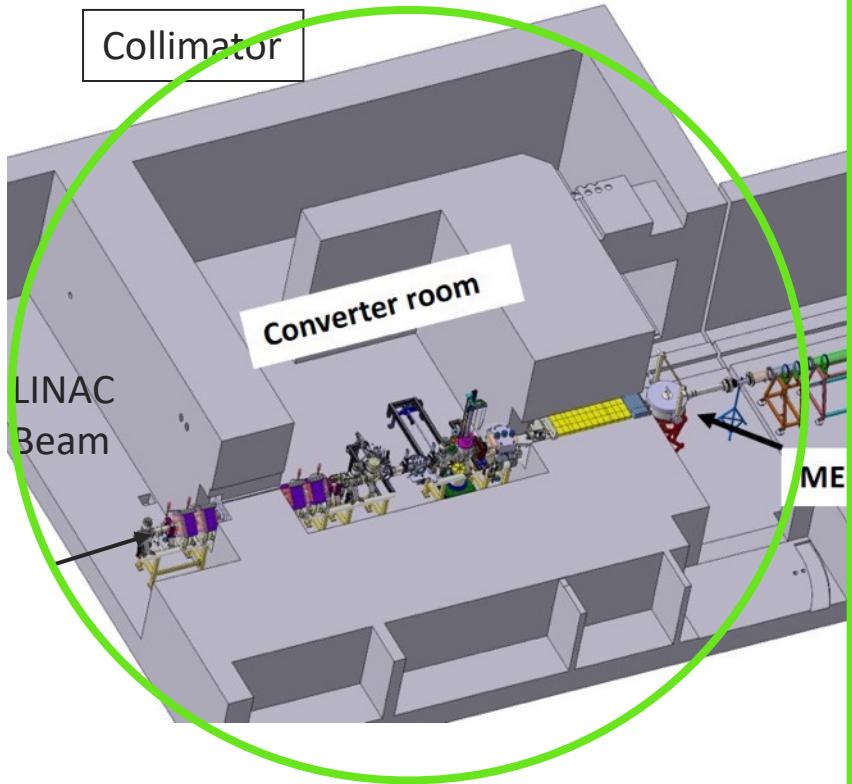
The Neutrons For Science (NFS) facility



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

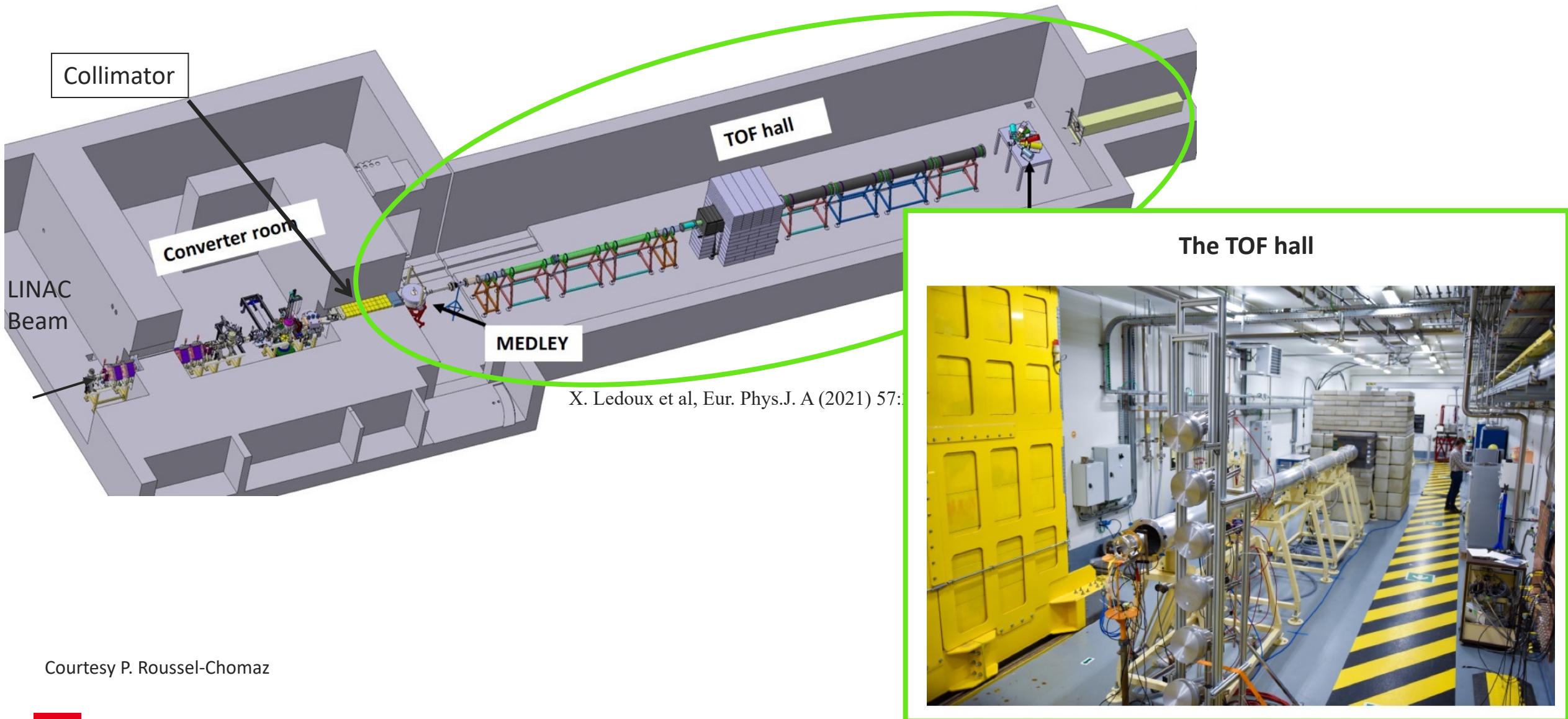
Courtesy P. Roussel-Chomaz

The Neutrons For Science (NFS) facility





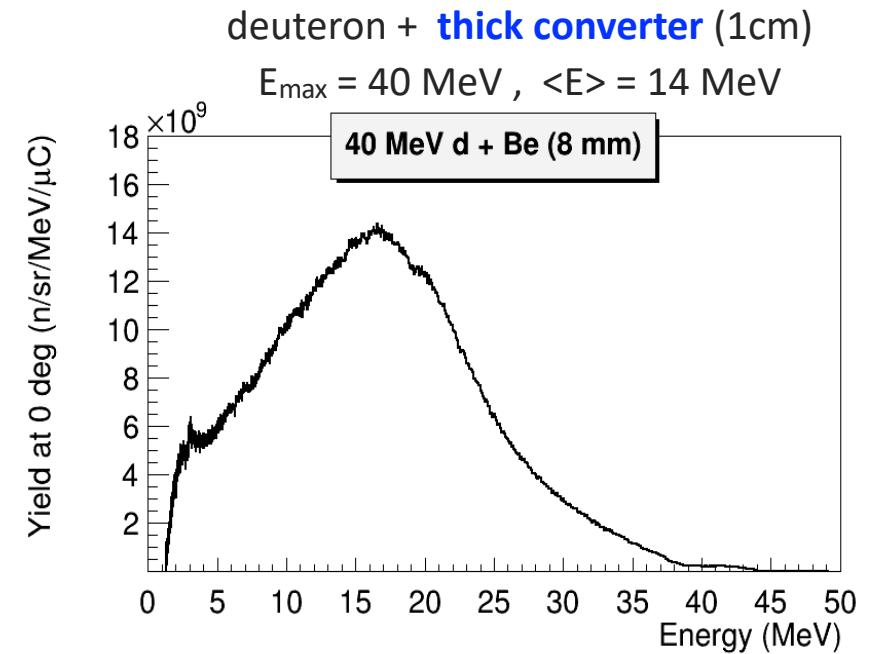
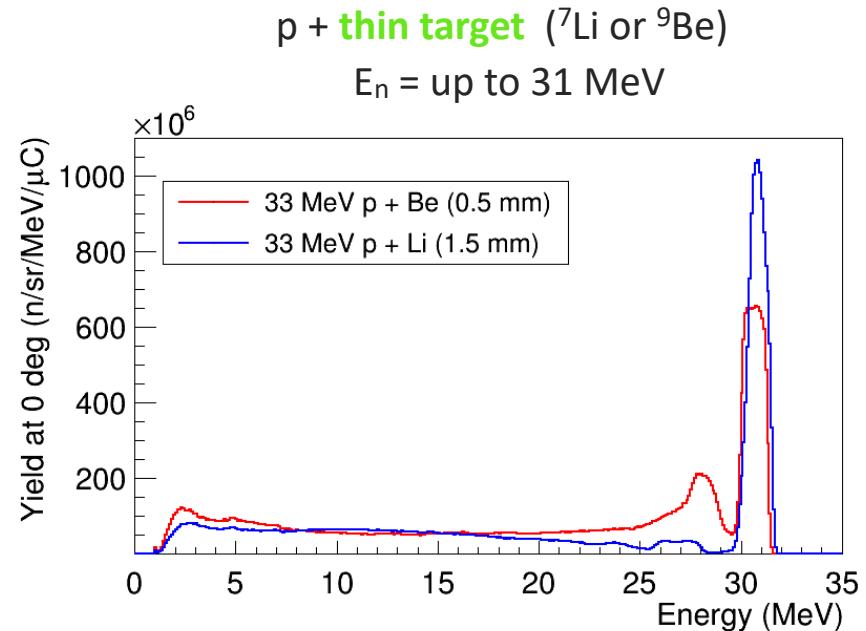
The Neutrons For Science (NFS) facility



The Neutrons For Science (NFS) facility

Quasi-mono-energetic / continuous neutron spectra

Courtesy P. Roussel-Chomaz



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

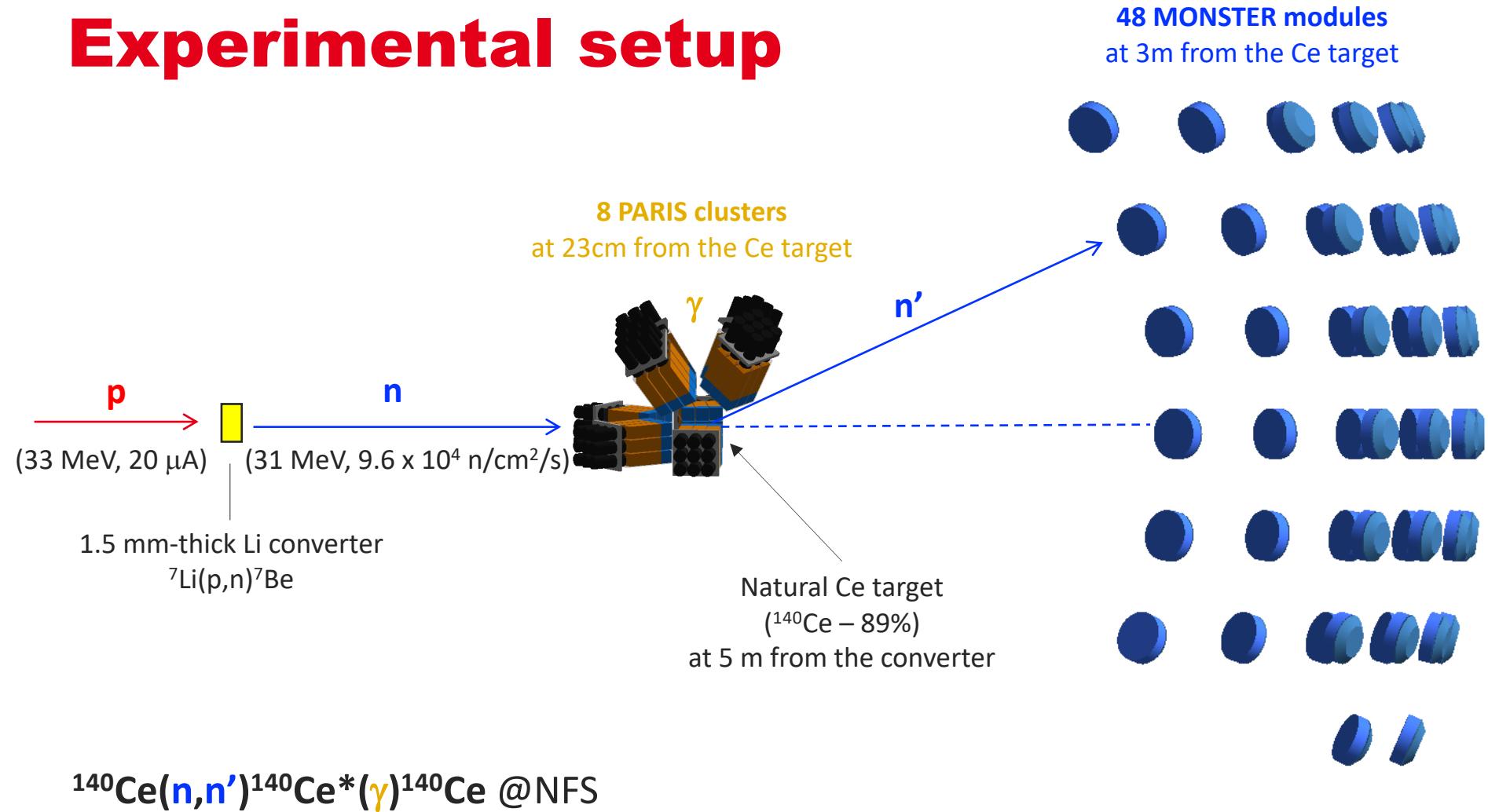
Example :
 p + Li at 20 μA
 Neutron yield in the mono-energetic peak $1,2 \cdot 10^9$ n/sr/ μC

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 $1,8 \cdot 10^{13}$ n/s

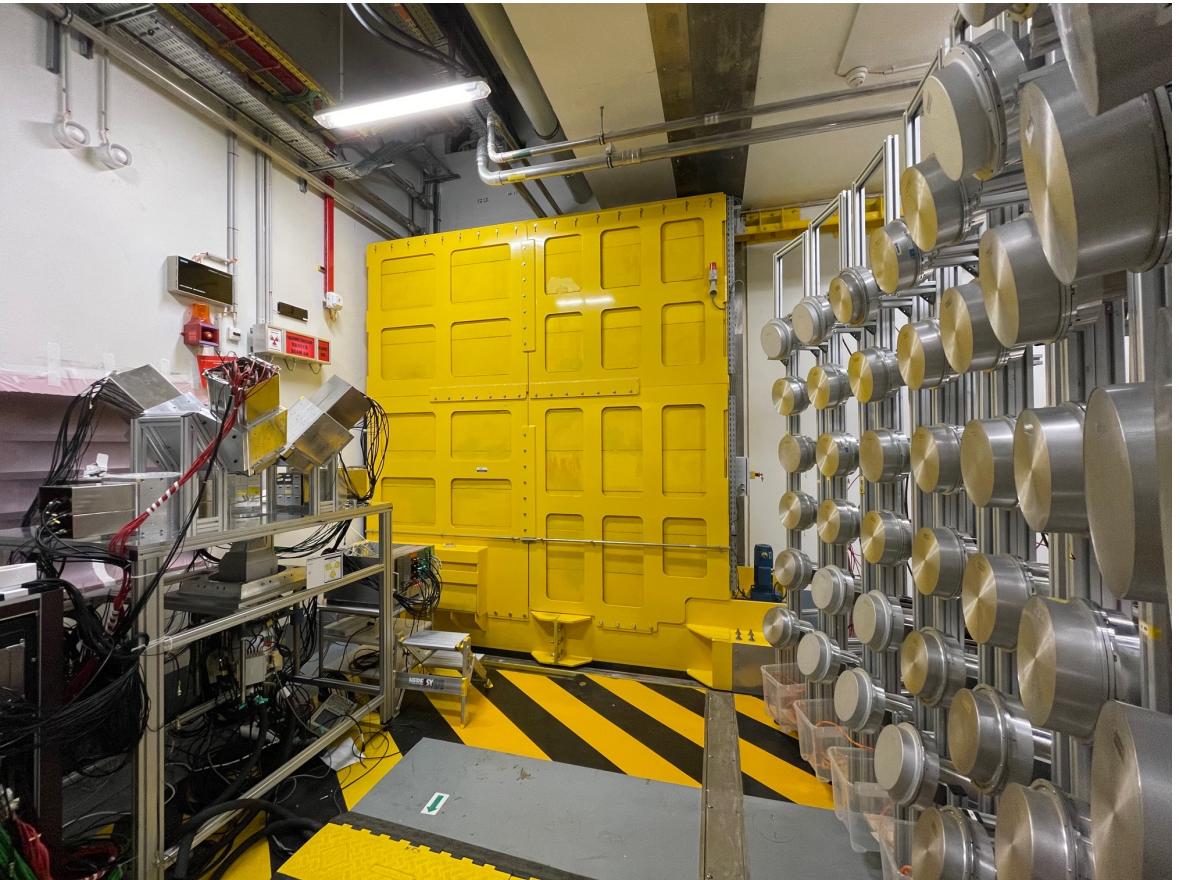
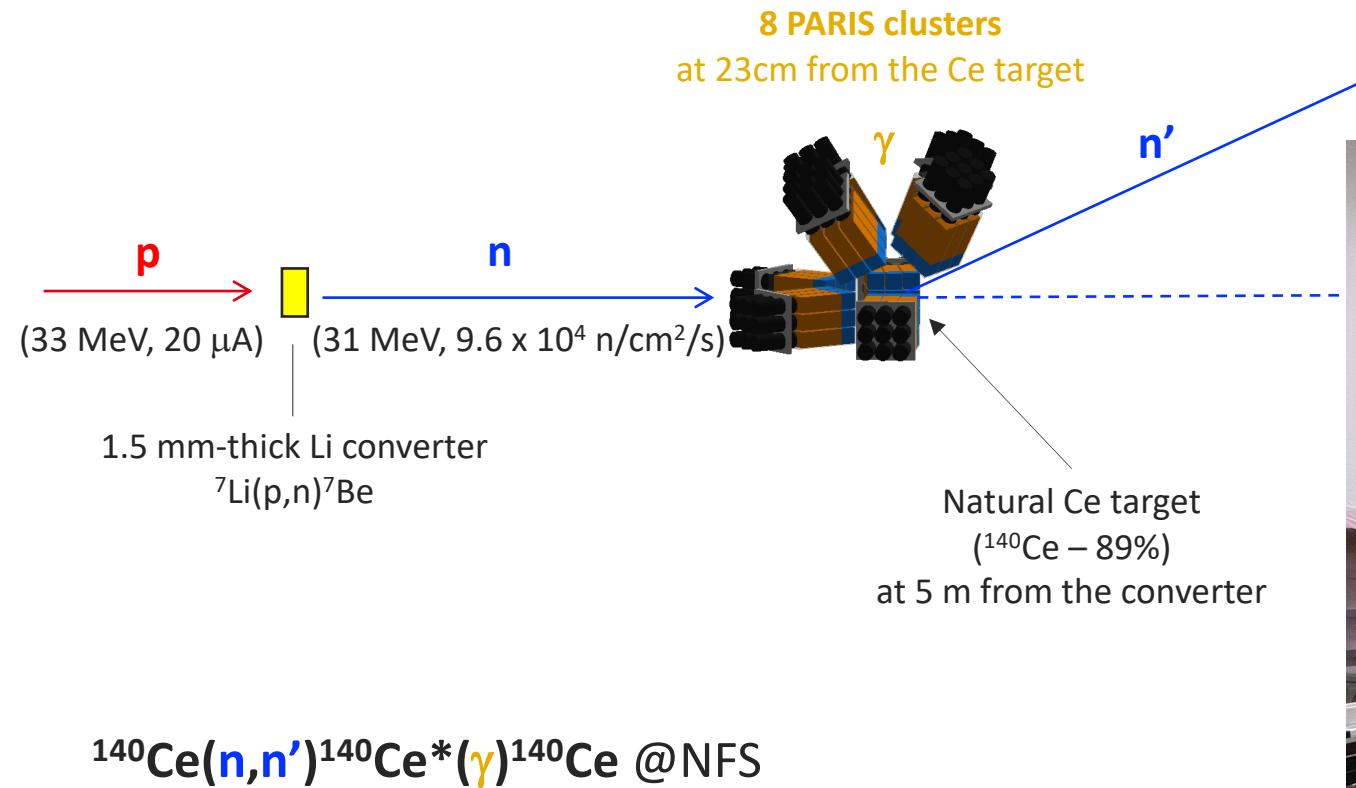


Experimental setup





Experimental setup



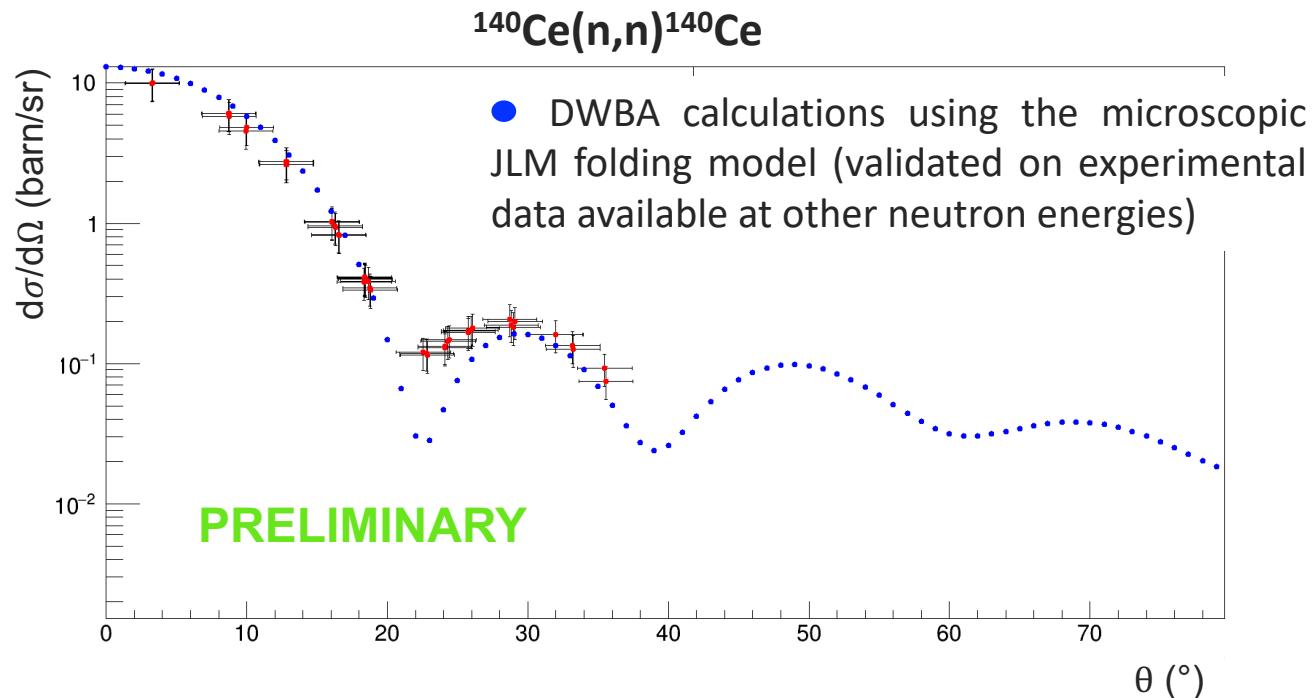
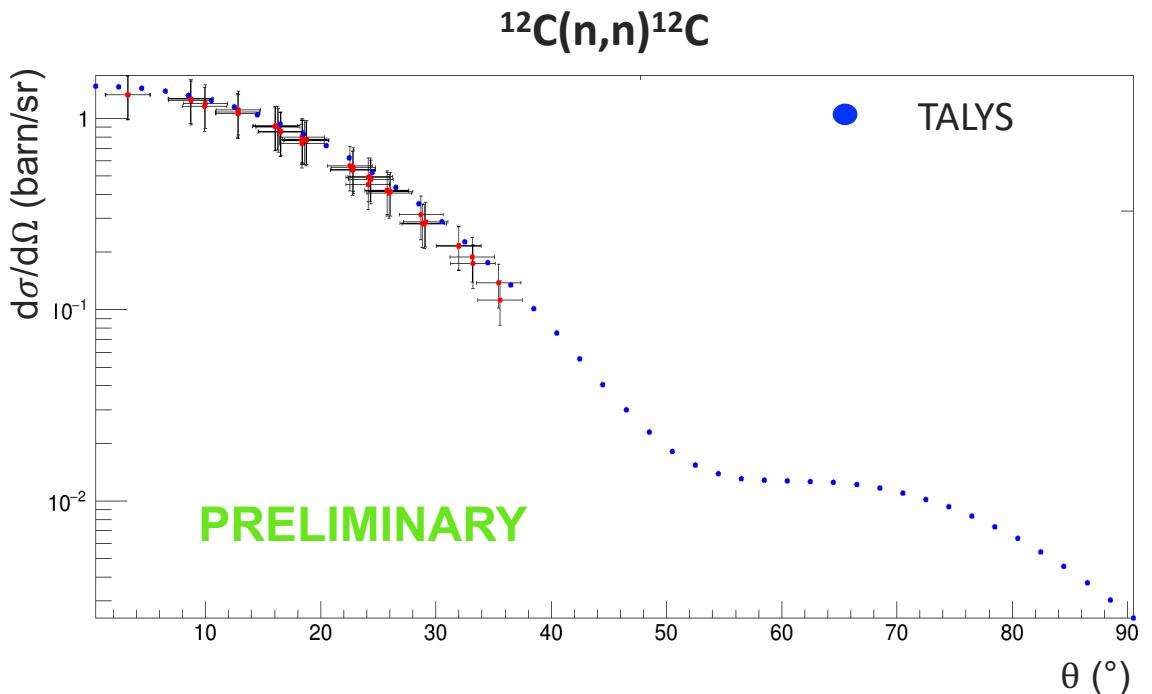


Online and first preliminary results



Online and first premiliary results

1) Elastic scattering reaction channel



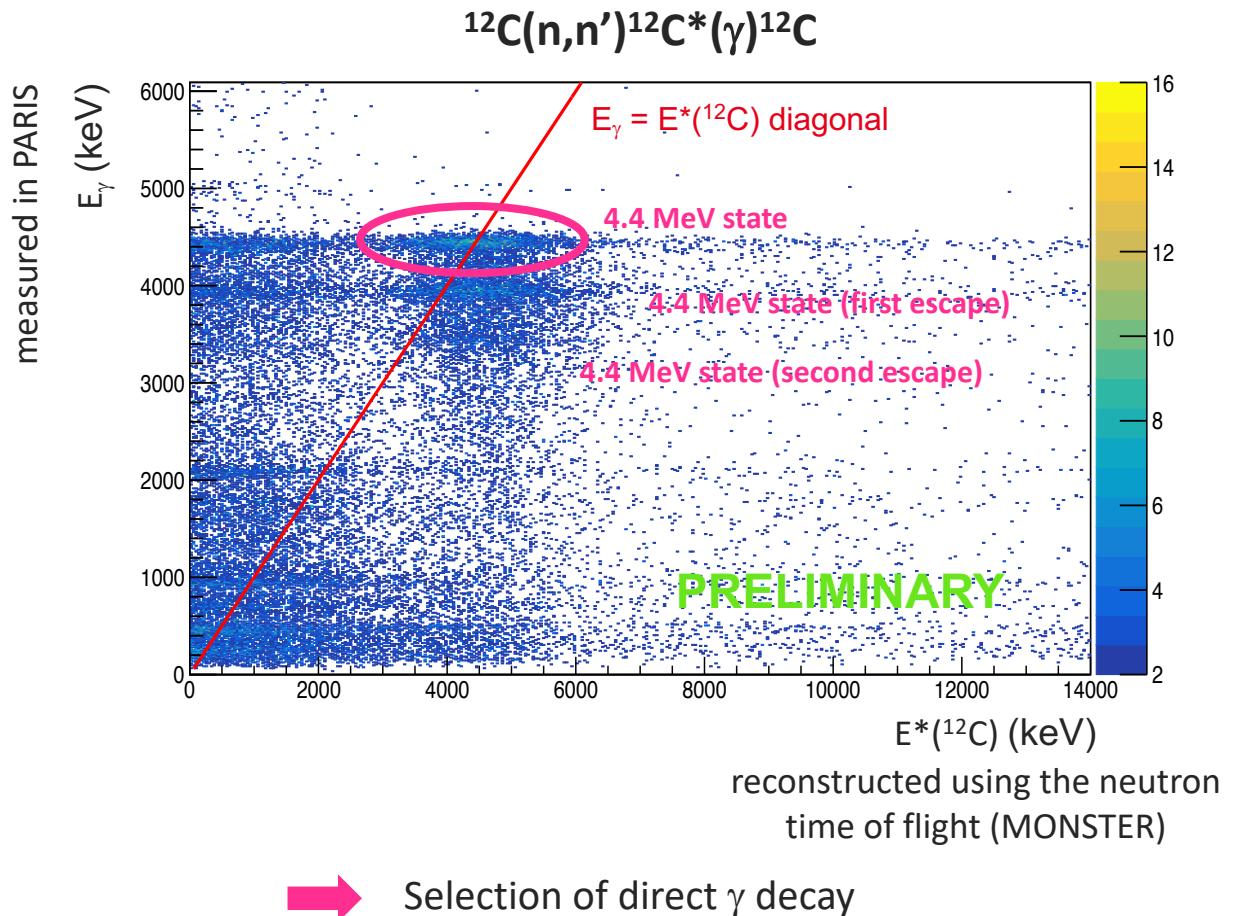
- Experimental points

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



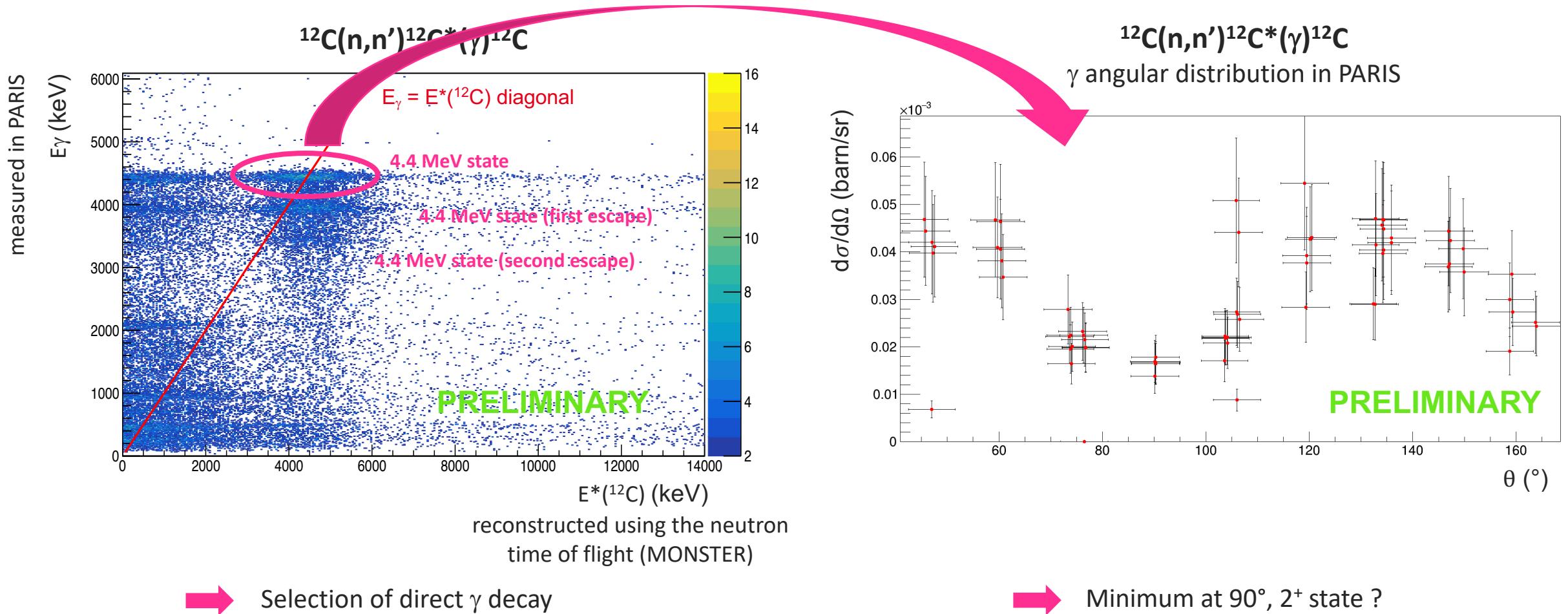
Online and first premiliary results

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



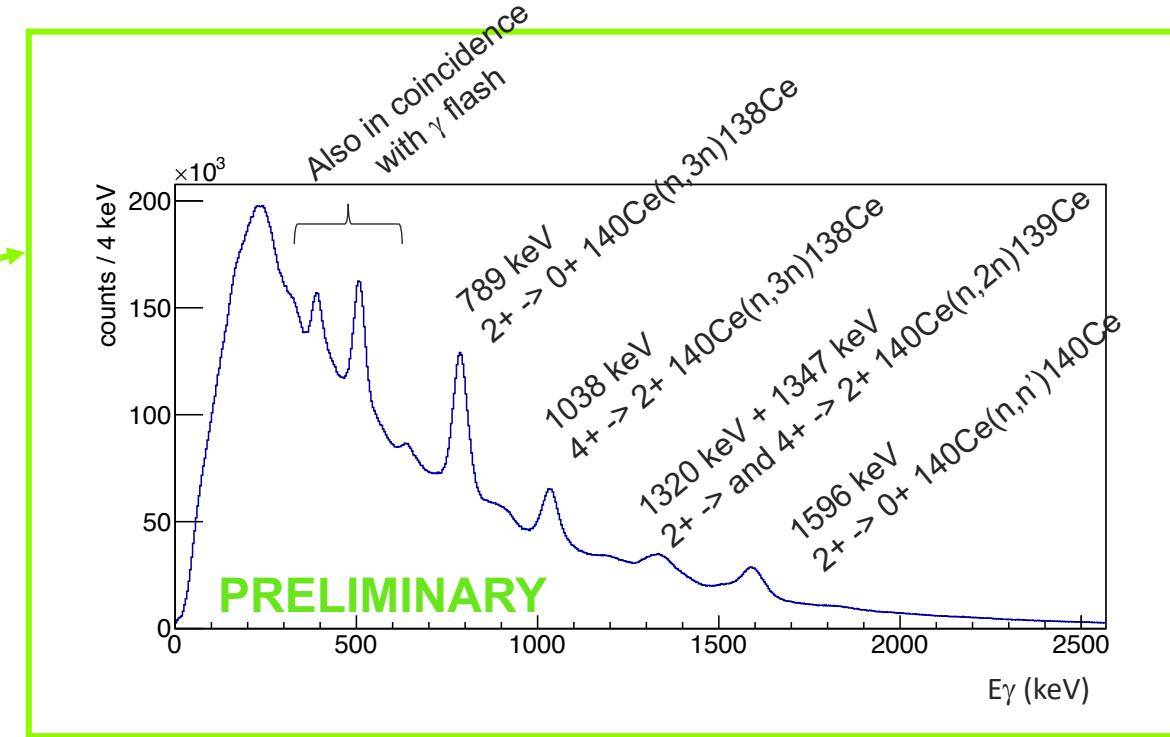
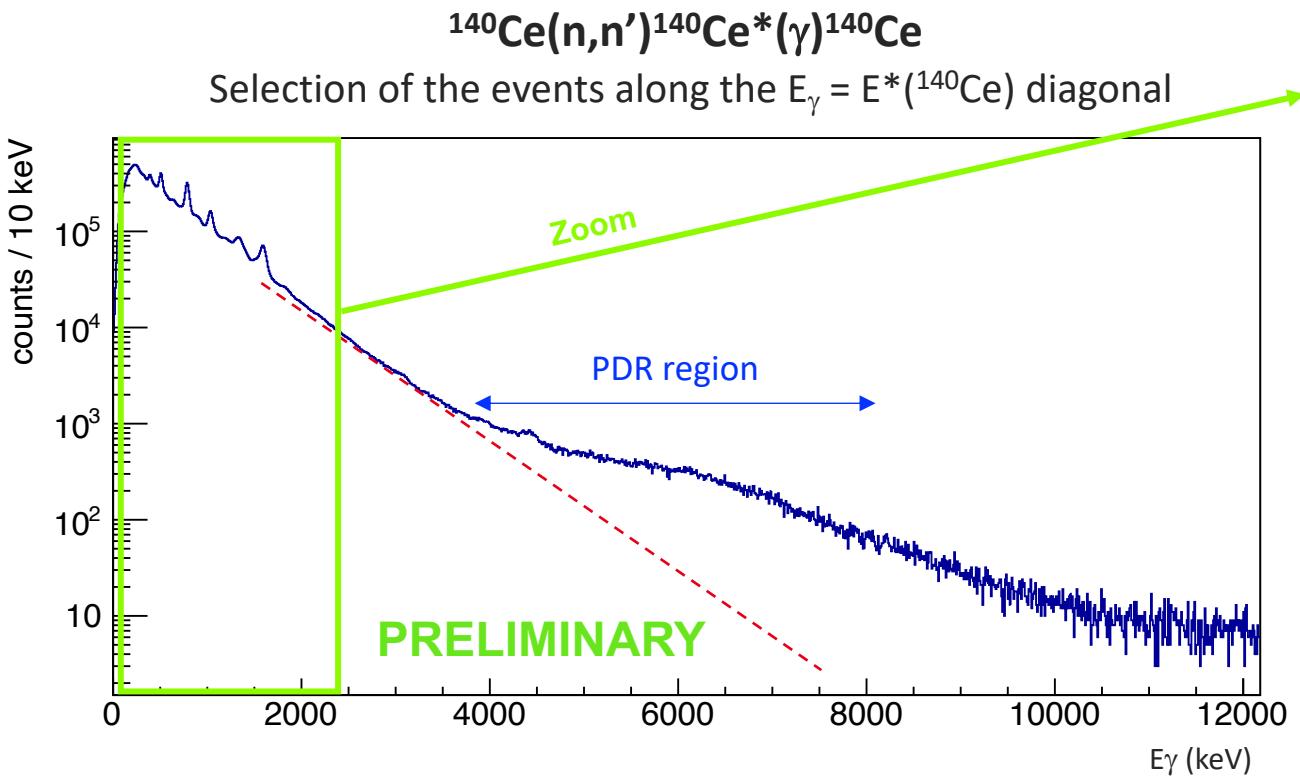
Online and first premiliary results

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



Online and first premiliary results

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

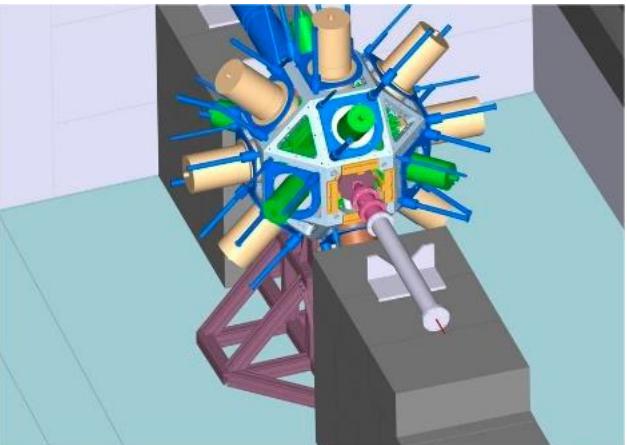


- Events in the PDR energy region not observed in other reaction channels (n,xn)
- next step : study of the γ and n angular distributions

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 $^{58}\text{Ni}(n,3n)$ with EXOGAM
(spokesperson E. Clément)





Collaboration

M. Vandebrouck¹, I. Matea²,

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PARIS and MONSTER Collaborations



1. CEA Saclay DRF/Irfu/DPPhN (France)
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)

Thank you for your attention !

