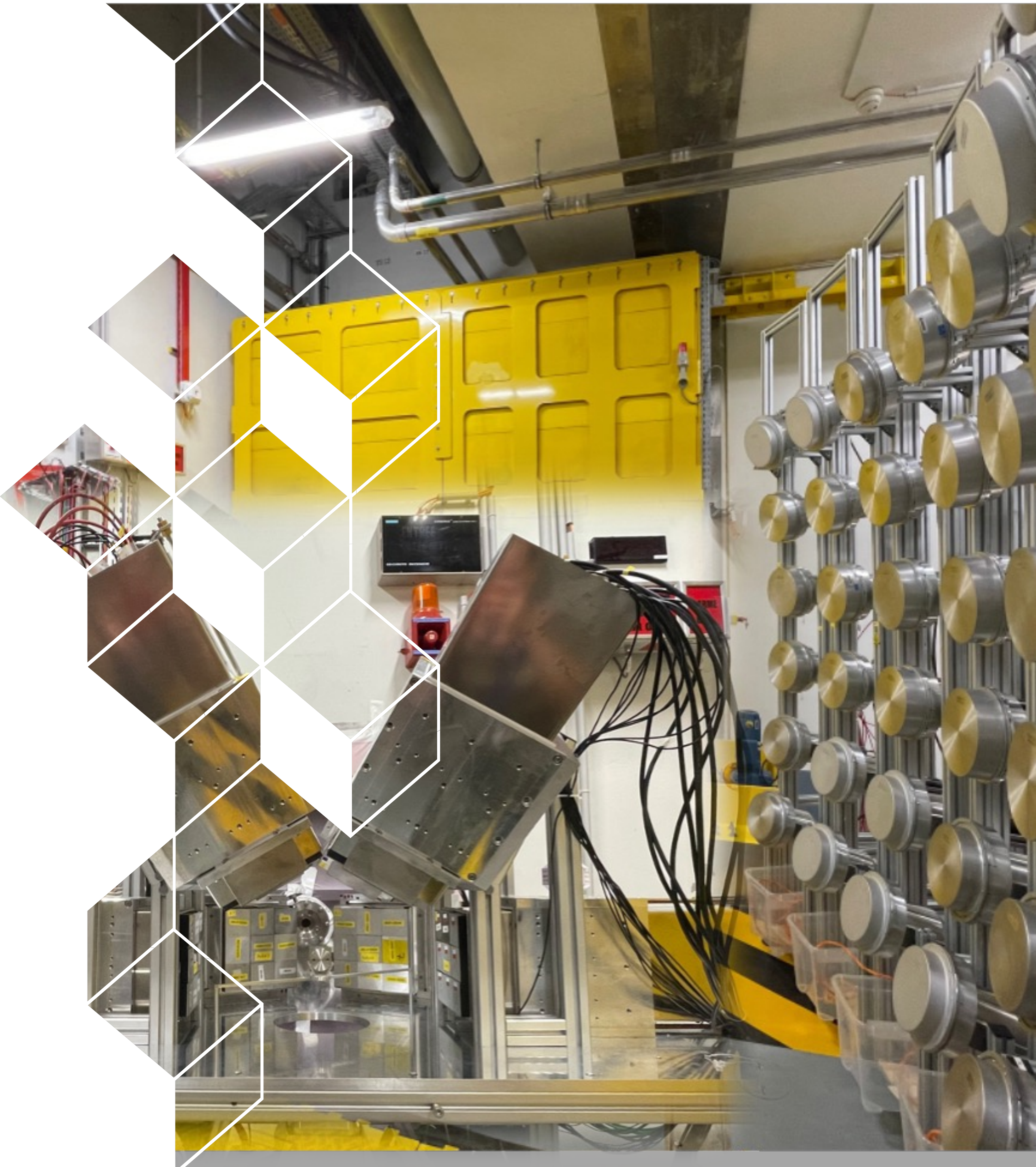
Nuclear structure inputs to constrain the symmetry energy – The complex pattern of the pygmy resonance



NUSYM 2024

Marine Vandebrouck

Notice before staring:
There is a overlap with Nunzia Martorana's talk

Outline

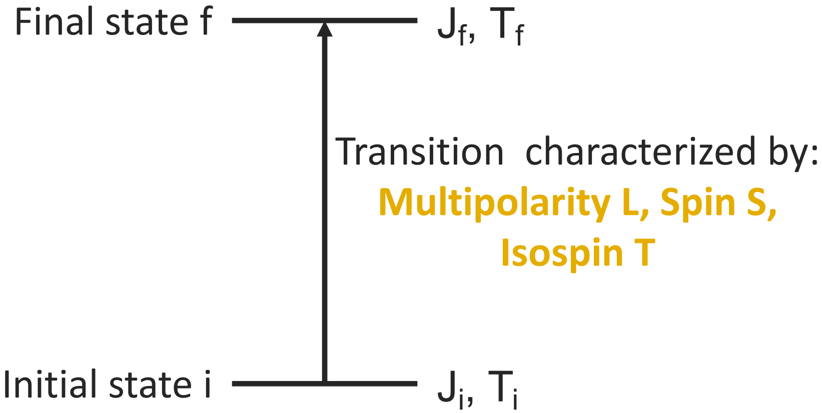
- Nuclear structure inputs to constrain EoS, easy or not?
- Complex pattern of PDR, what are we probing with the different reactions?
- Illustration with (n,n') reaction

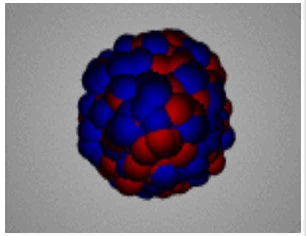
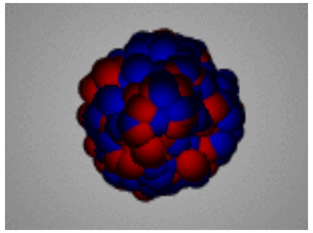
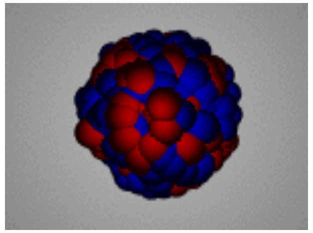
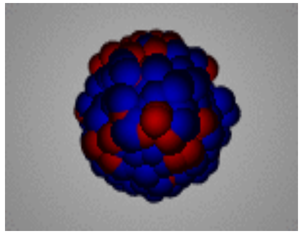
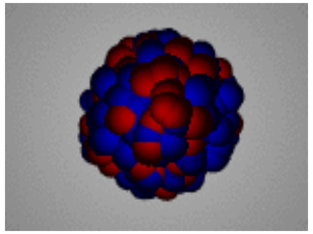
Nuclear structure inputs to constrain EoS, easy or not?

On the nuclear structure side

Giant resonances (GR)

- Giant resonances are **collective excitation modes** characterized by different **quantum numbers**



Electric (S = 0) GR	T = 0 isoscalar	T = 1 isovectorial
L = 0 monopole (GMR)		
L = 1 dipole (GDR)		
L = 2 quadrupole (GQR)		

On the nuclear structure side

The 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

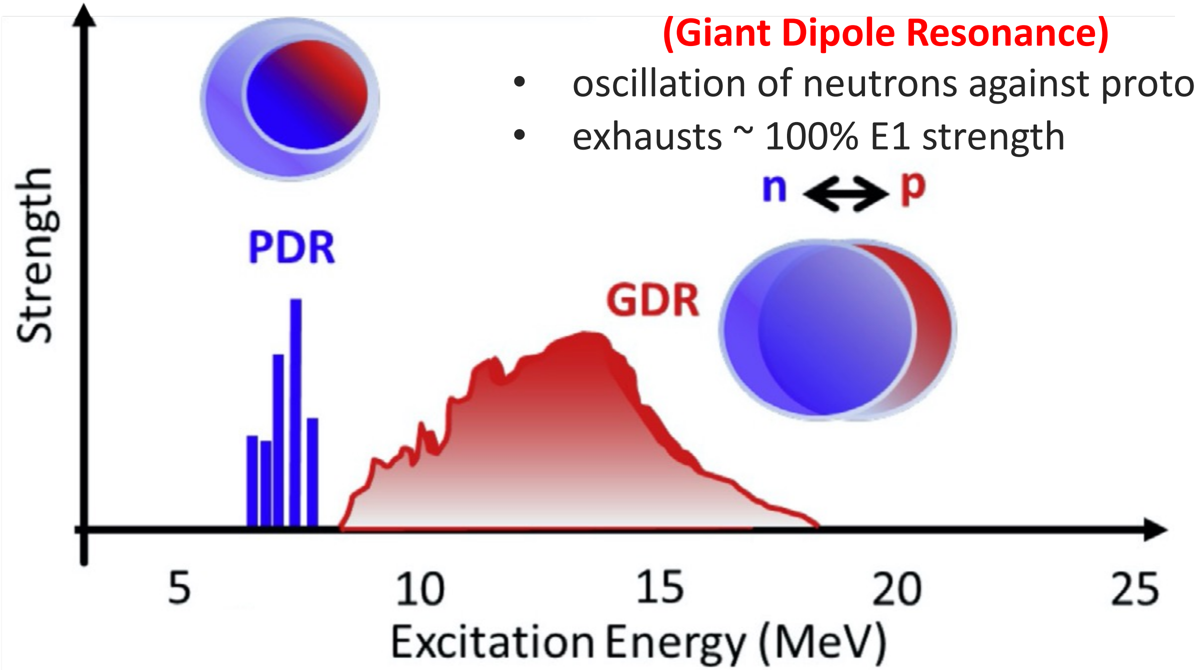


Figure extracted from A. Bracco *et al.* Prog. Part. Nucl. Phys. 106 (2019)

- ➢ Many experiments performed, in different nuclei, using different probes … have revealed a complex structure of the PDR

- ➢ Today, still open questions related to:
  - the collectivity
  - nature of the 1^- states (isoscalar/isovector)
    ⇨ "isospin splitting" phenomenon
  - different behavior in stable and unstable nuclei

  …

  see N. Martorana's talk

- ➢ ⚠ PDR definition

On the equation of state (EoS) side

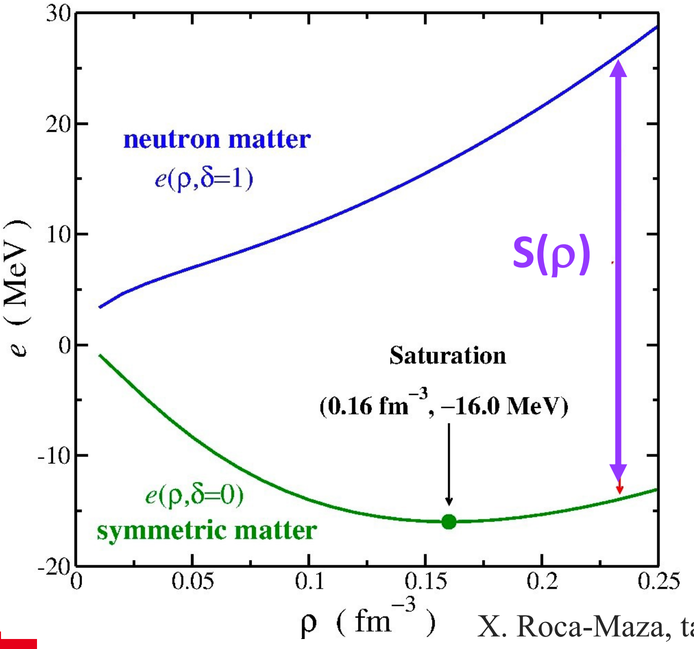
- EoS describes the energy per nucleon in nuclear matter (infinite nuclear system) as a function of the density (ρ) and the asymmetry (δ)

$$\frac{E}{A} = (E_0 + E_{sym}\delta^2) + L_{sym}x\delta^2 + \frac{1}{2}(K_0 + K_{sym}\delta^2)x^2 + \ldots$$

$$x = \frac{\rho - \rho_0}{3\rho_0} \qquad I = \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

E_{sym} = Symmetry energy, L_{sym} = Slope of the symmetry energy

K_0 = K = Incompressibility of symmetric nuclear matter

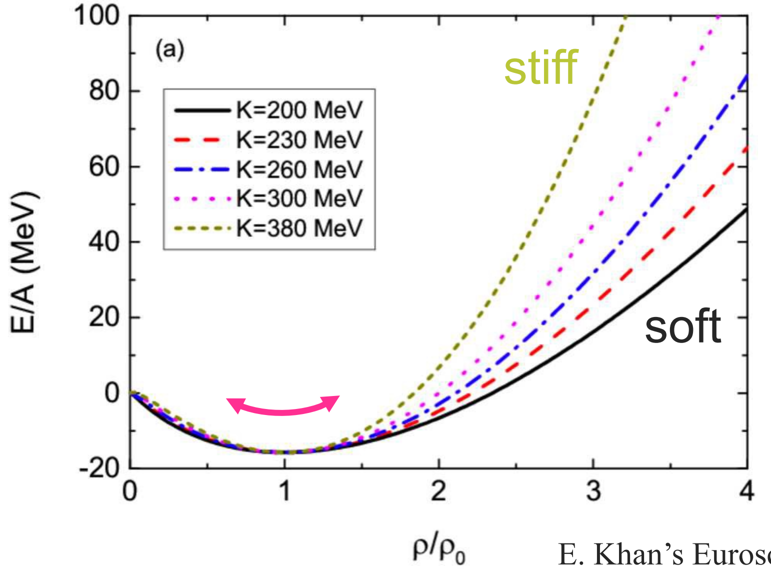


X. Roca-Maza, talk COMEX7 2023

$$S(\rho) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \ldots$$

Sensitivity to the IVGDR/PDR strength and dipole polarizability

see N. Martorana's talk



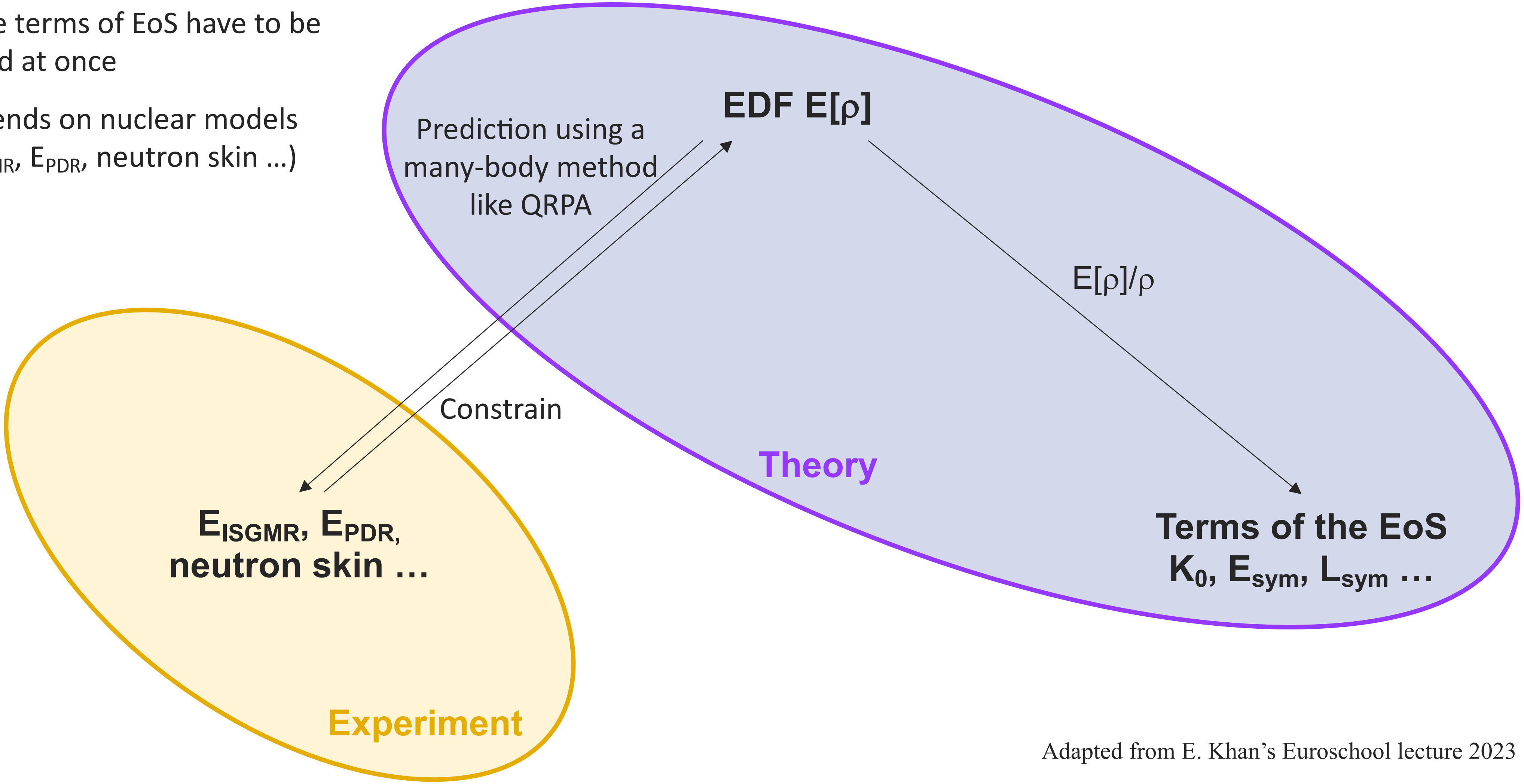
E. Khan's Euroschool lecture 2023

Sensitivity to the ISGMR

How link GR and EoS?

- A microscopic method to constrain EoS using energy density functional approach (EDF)
  - ⇨ Limitations: all the terms of EoS have to be correctly predicted at once
  - ⇨ Method that depends on nuclear models (from EDF to E_{ISGMR}, E_{PDR}, neutron skin …)

NOT EASY !



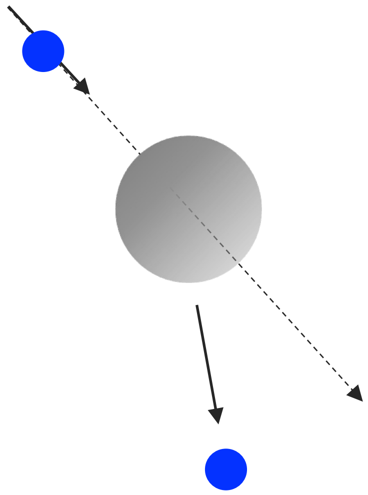
Adapted from E. Khan's Euroschool lecture 2023

Complex pattern of PDR, what are we probing with the different reactions?

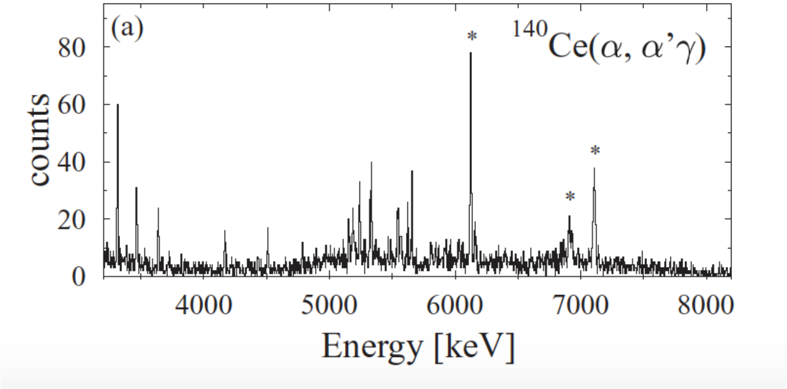
What is the nature of a nuclear excitation ?

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

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

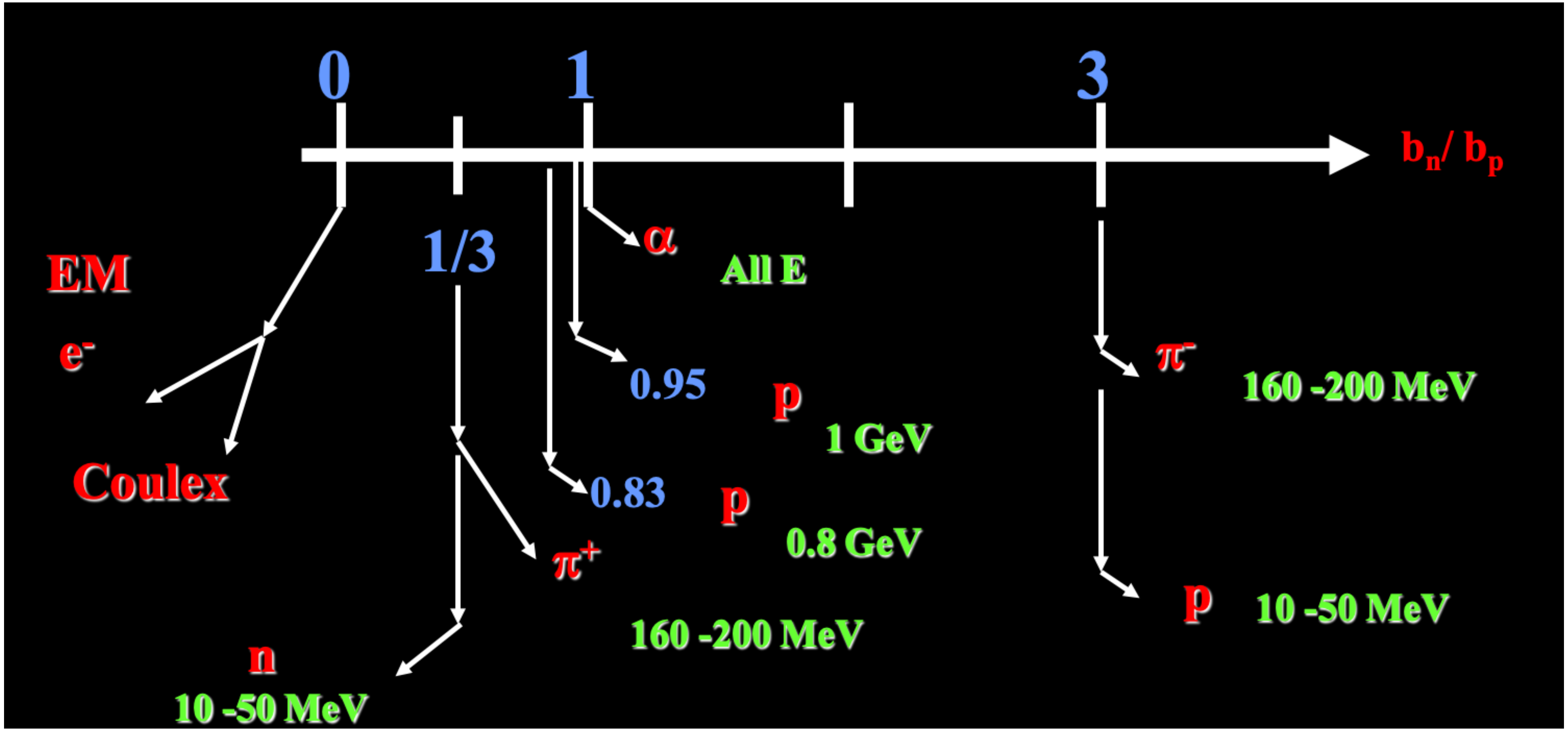
M
Multipole moment

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 : $M = b_n M_n + b_p M_p$

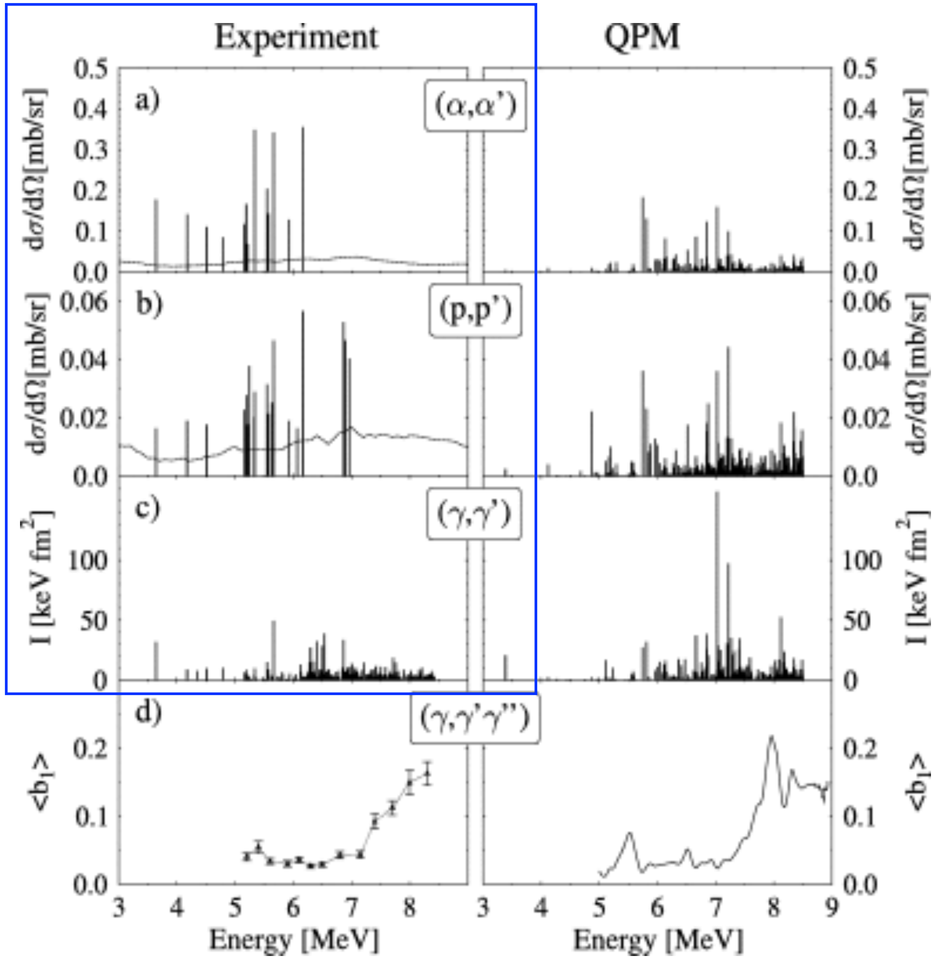
$b_{n,p}$ are the interaction strengths between the external field and n,p of the nucleus



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

Illustration if the isospin splitting phenomenon

^{140}Ce



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

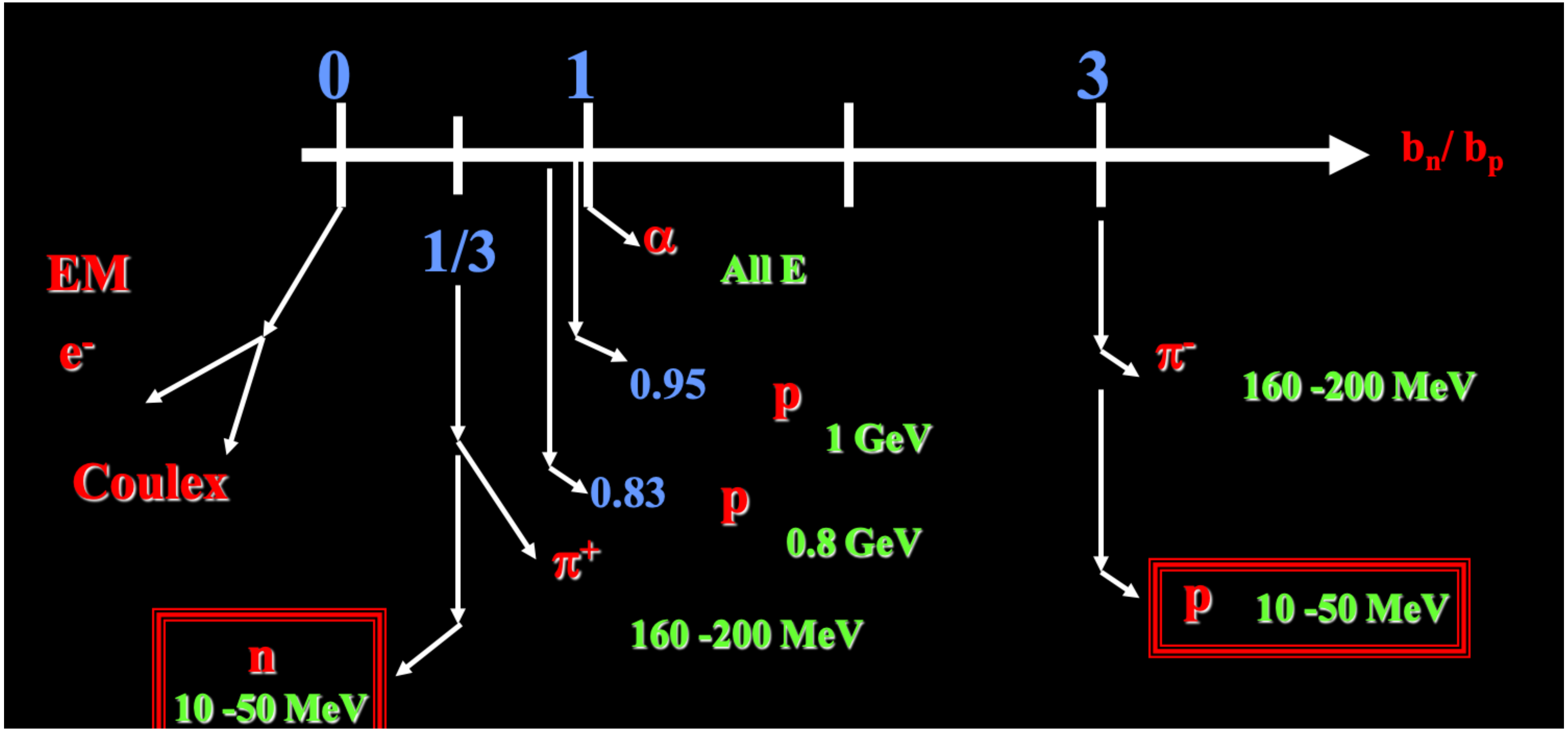
➡ study **PDR using (n,n')** for the first time

Experiment performed in 2022 at SPIRAL2/NFS

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

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

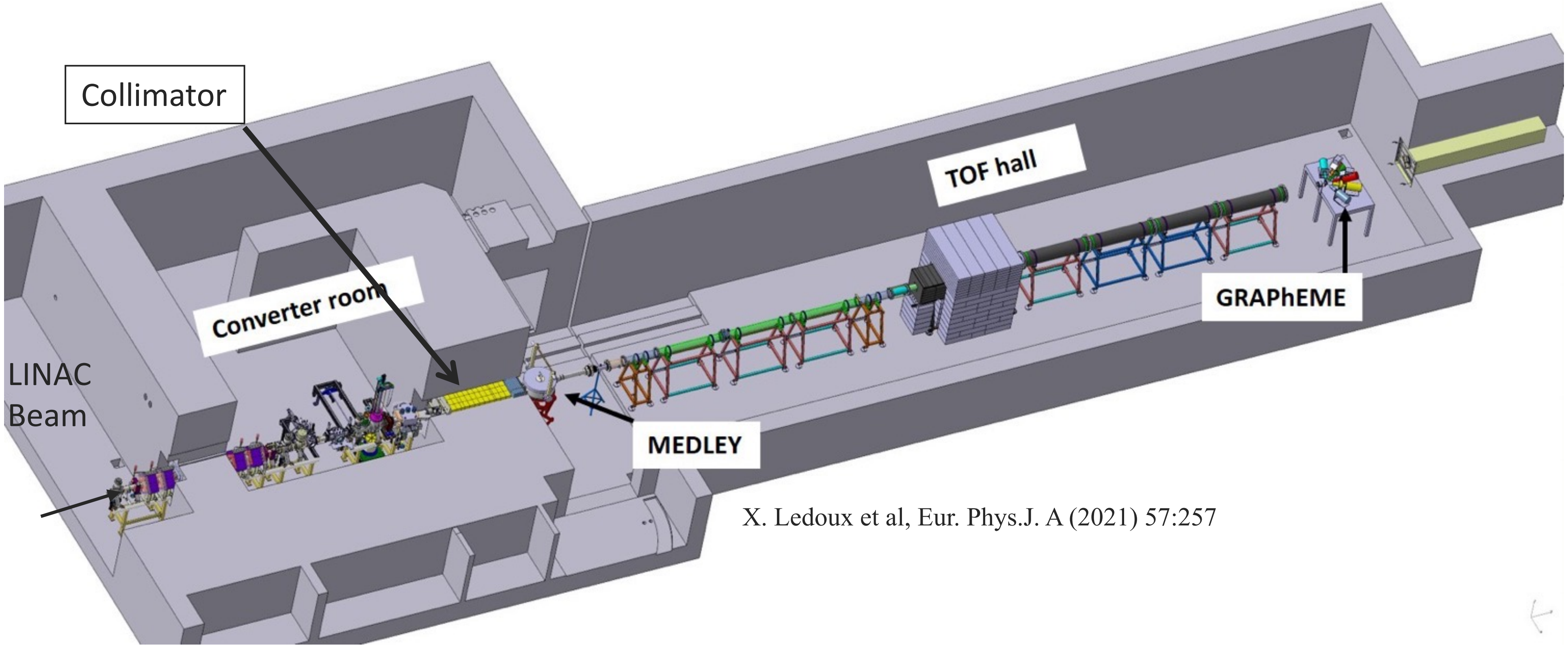
- which does not require Coulomb correction
- complementary to (p,p') and to other reactions



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

Illustration with (n,n’) reaction

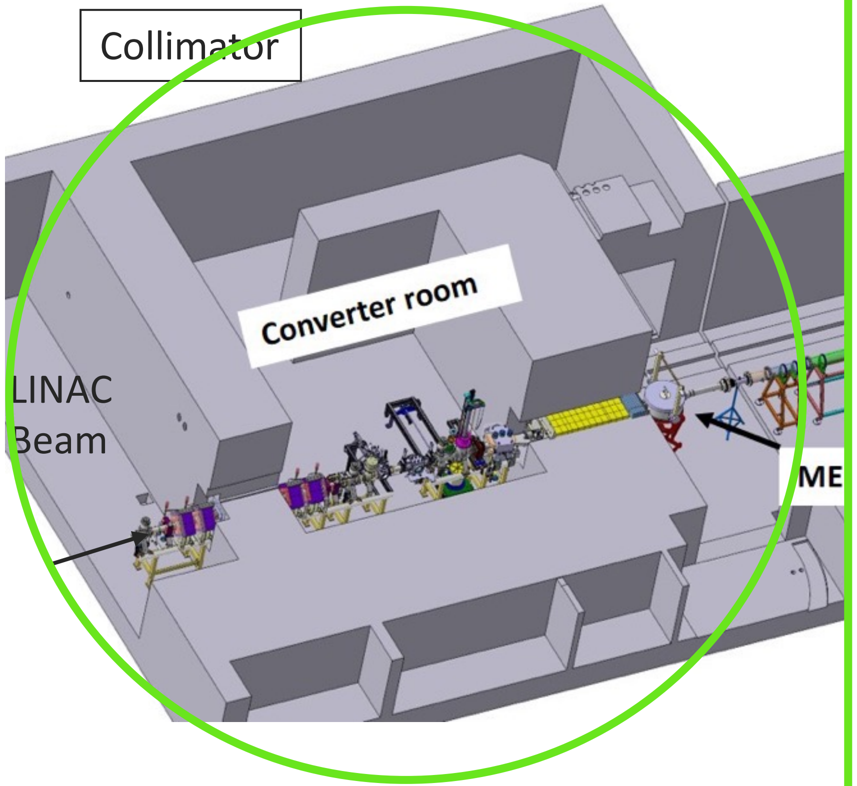
The Neutrons For Science (NFS) facility



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

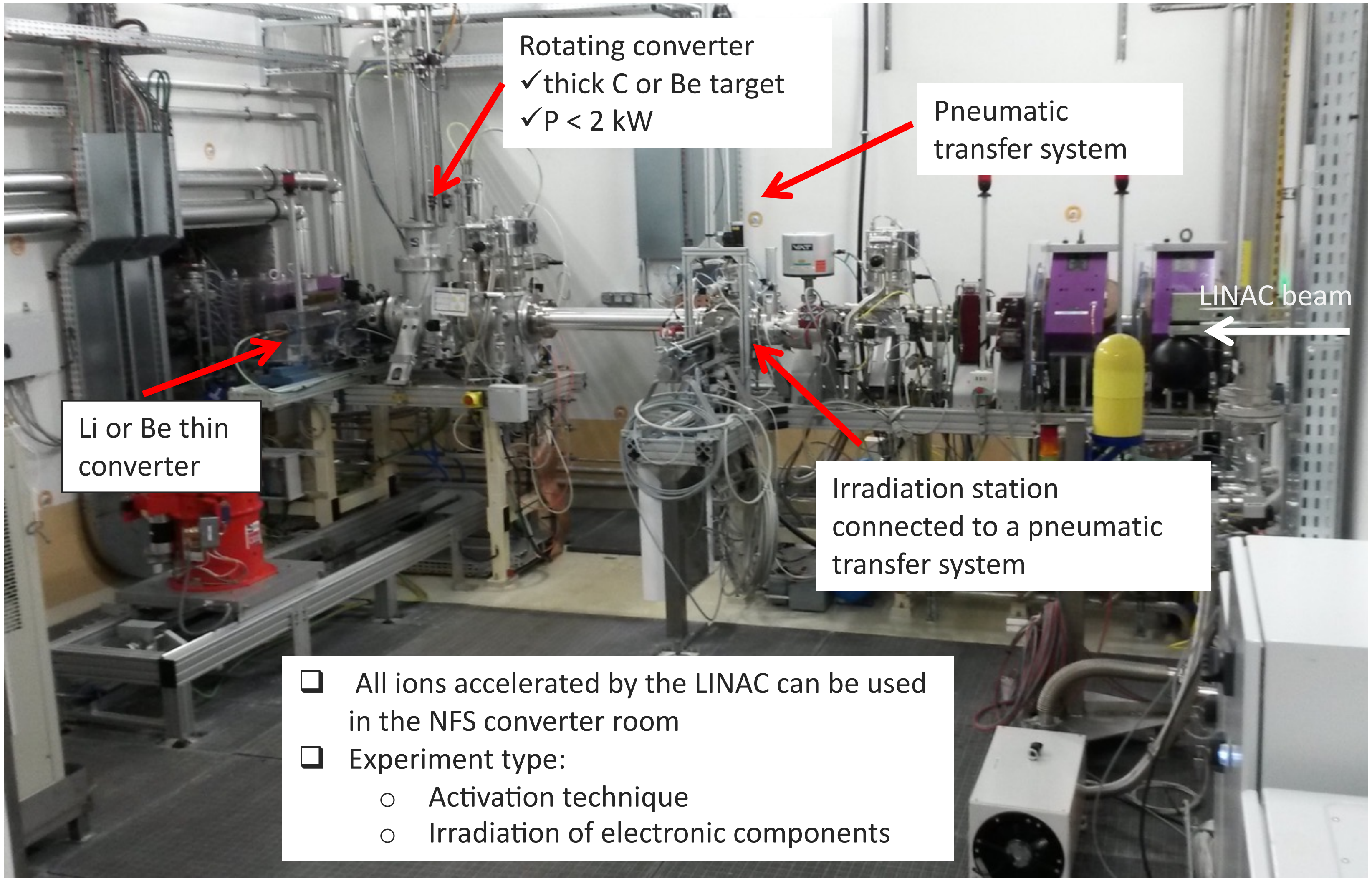
Courtesy X. Ledoux/P. Roussel-Chomaz

The Neutrons For Science (NFS) facility



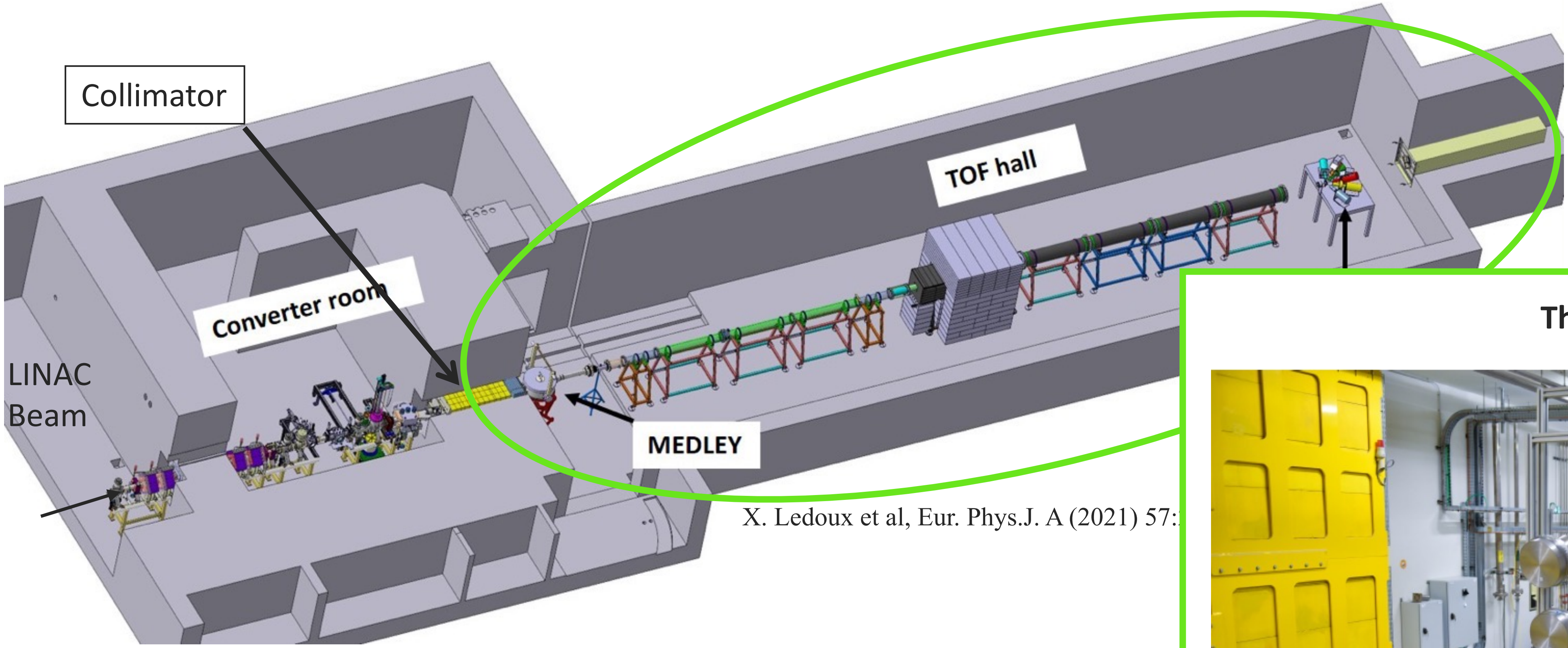
Courtesy X. Ledoux/P. Roussel-Chomaz

The converter room



- ❑ 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 X. Ledoux/P. Roussel-Chomaz

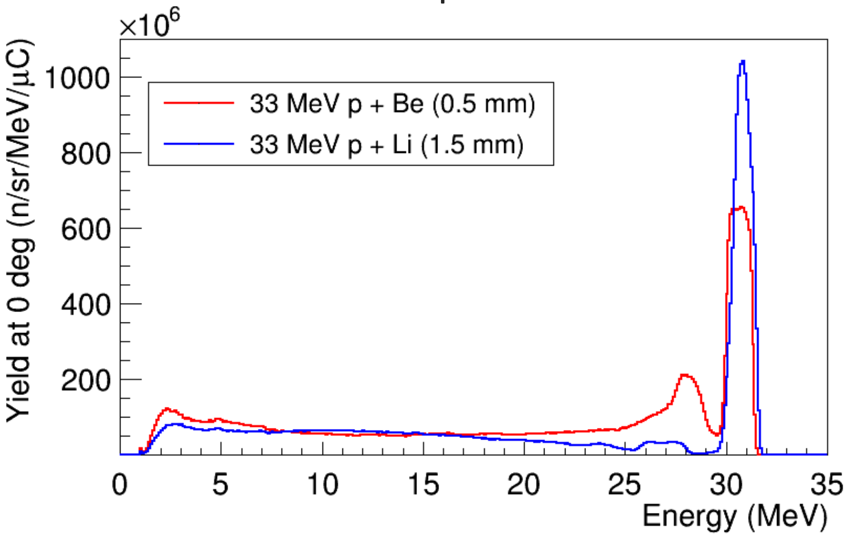
The Neutrons For Science (NFS) facility

Quasi-mono-energetic / continuous neutron spectra

Courtesy X. Ledoux/P. Roussel-Chomaz

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

E_n = up to 31 MeV

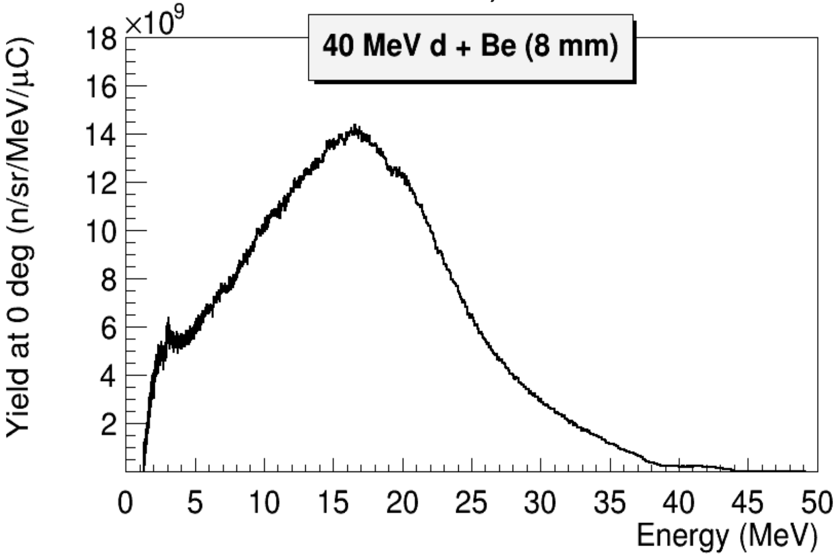


E MeV	Flux at 5 m
5	1,7.10^4 n/cm^2/MeV/s
10	5.10^3 n/cm^2/MeV/s
20	2,3.10^4 n/cm^2/MeV/s
30	1,2.10^5 n/cm^2/MeV/s

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

Search for PDR in ^{140}Ce @NFS

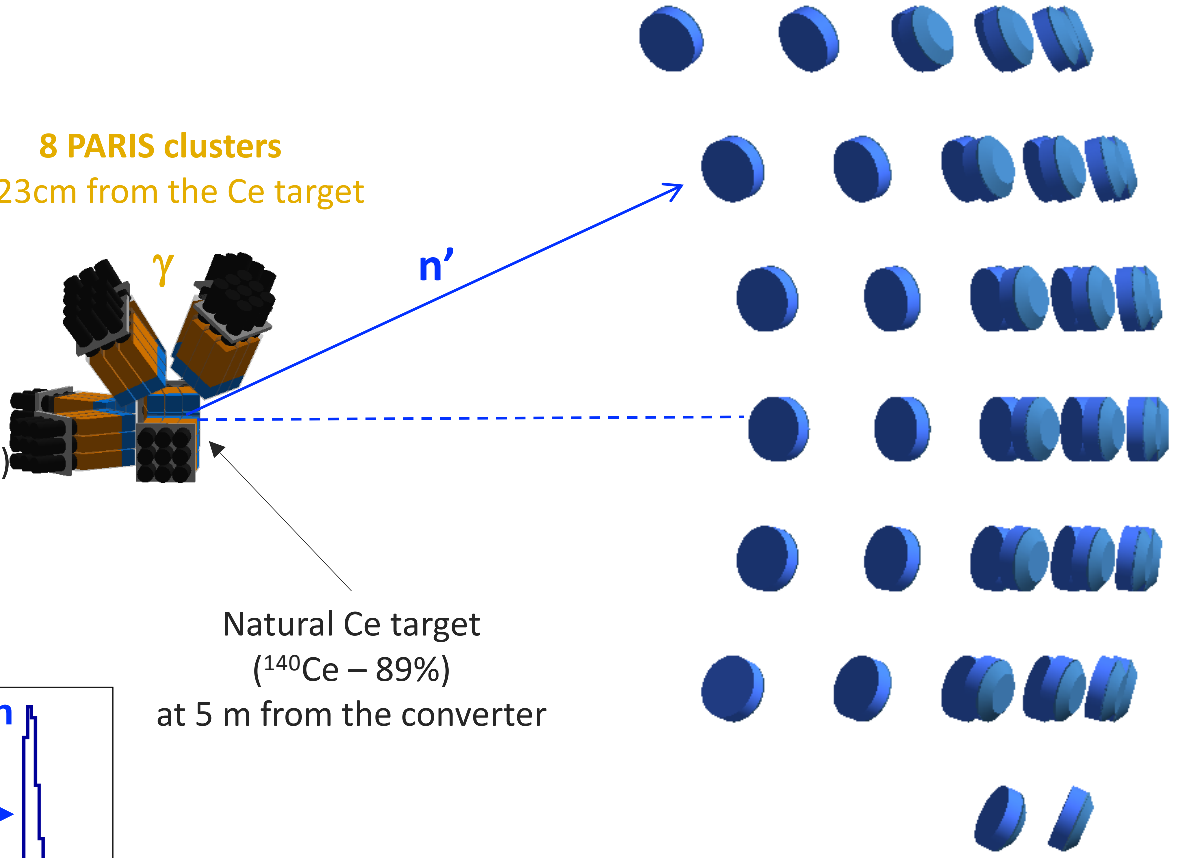
$^{140}Ce(n,n')^{140}Ce^{*}(\gamma)^{140}Ce$

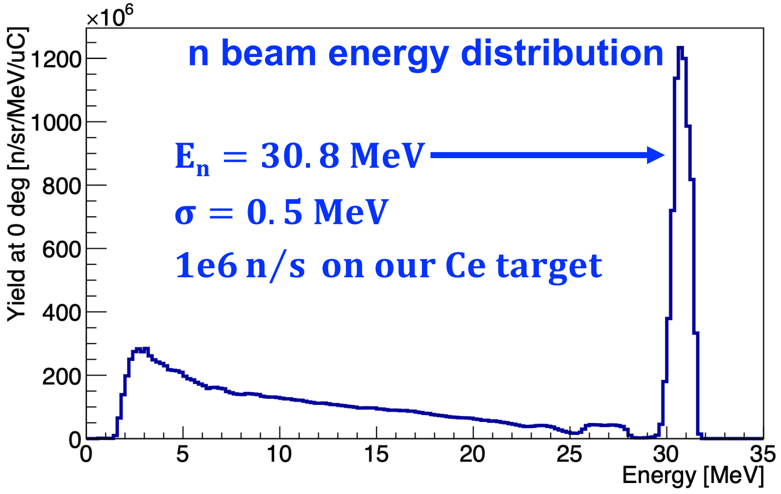
p

n

(33 MeV, 20 μA) (30.8 MeV, 9.6 x 10^4 n/cm^2/s)

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

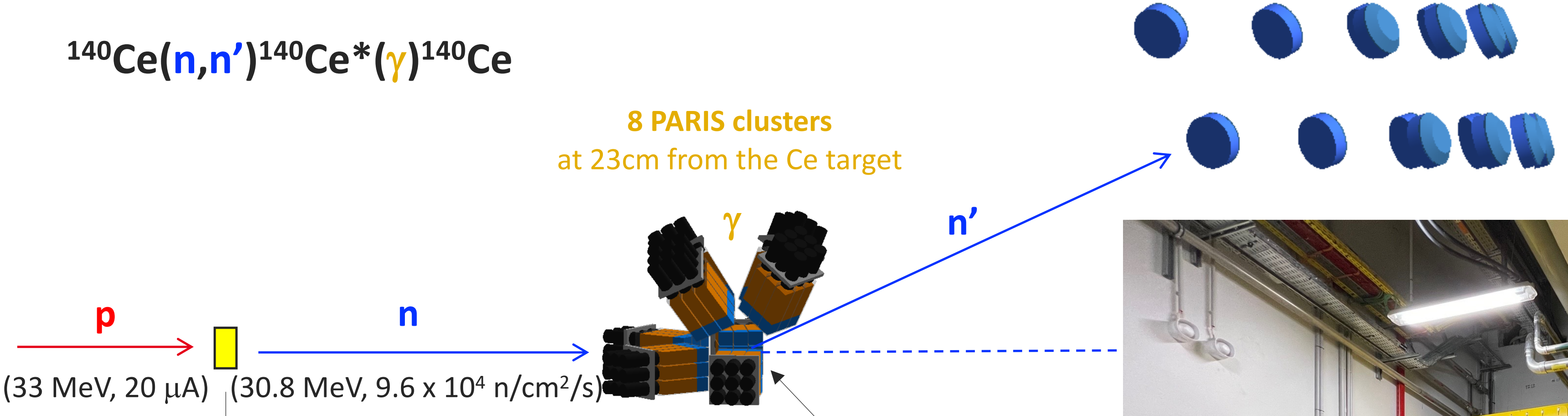




Search for PDR in ^{140}Ce @NFS

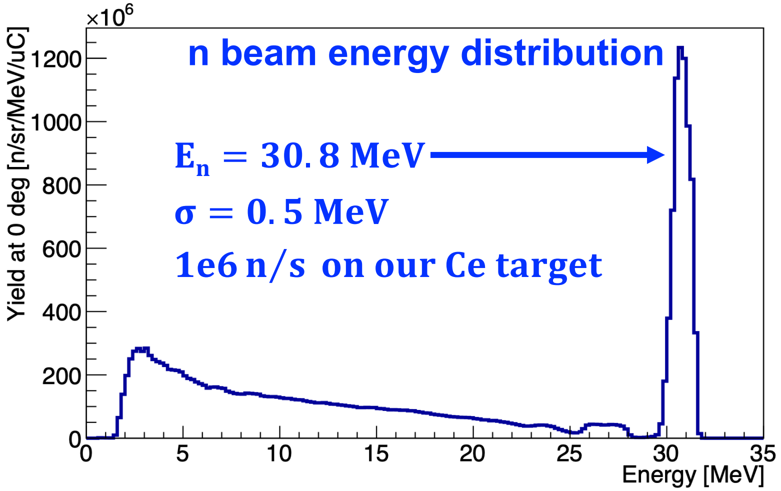
$^{140}Ce(n,n')^{140}Ce^*(\gamma)^{140}Ce$

48 MONSTER modules
at 3m from the Ce target



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

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

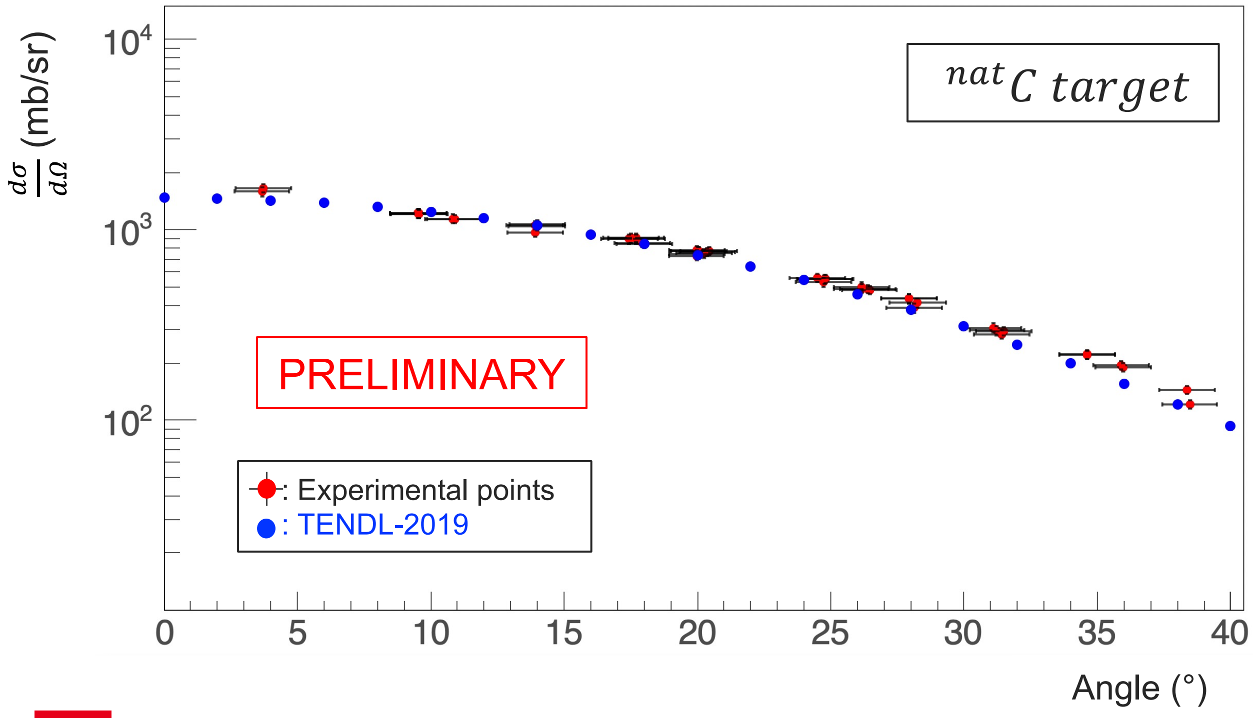


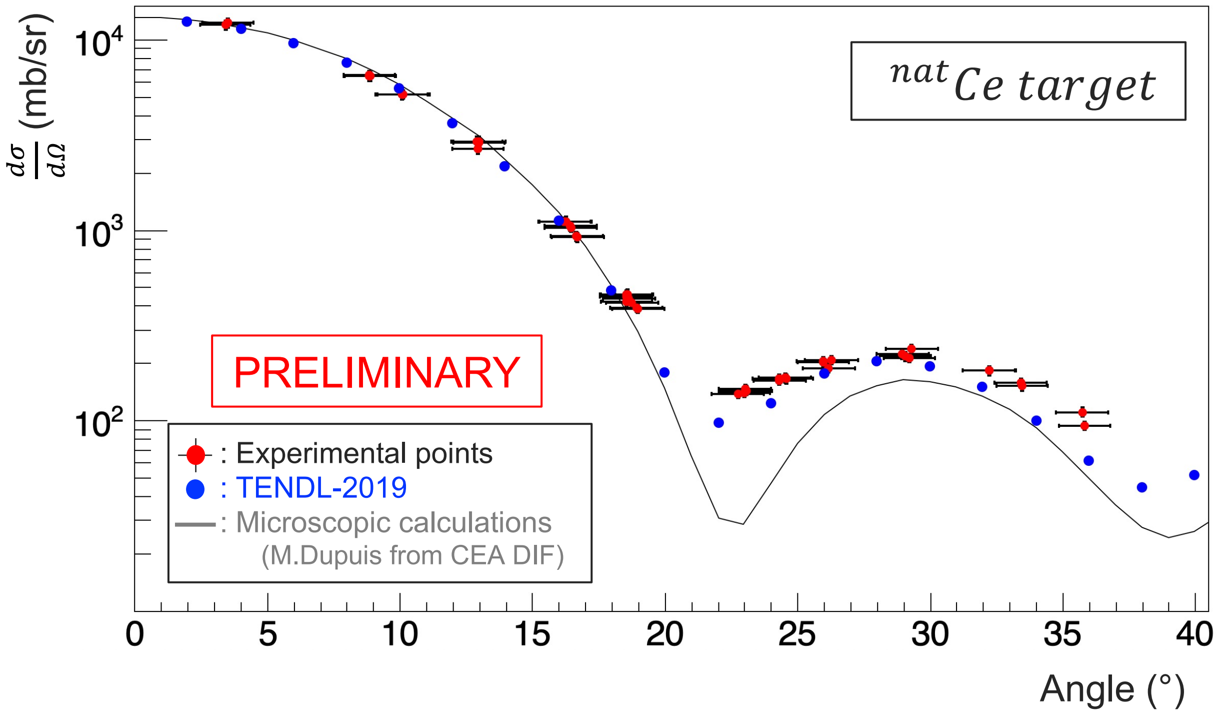
First preliminary results

Elastic scattering reaction channel

- Detection of the scattered neutrons **n** with MONSTER detectors
  ⇨ Validation of the scattered neutron energy reconstruction method
- New results for $^{nat}Ce(n,\mathbf{n})^{nat}Ce$ at this neutron energy (30.8 MeV)

Neutron beam axis



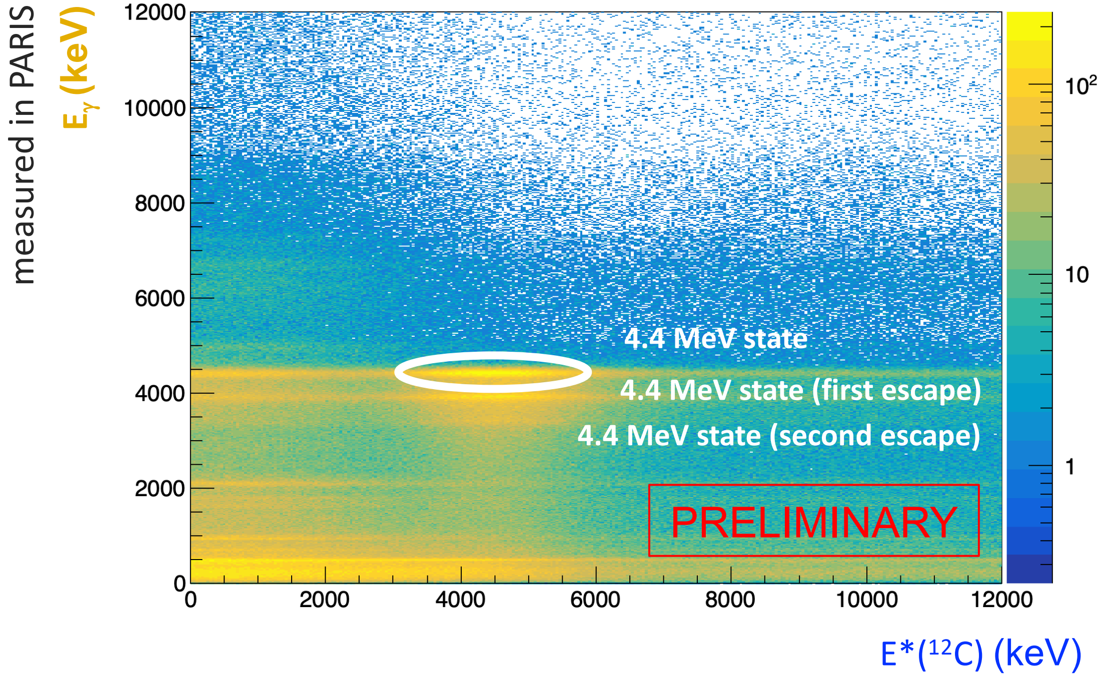


First preliminary results

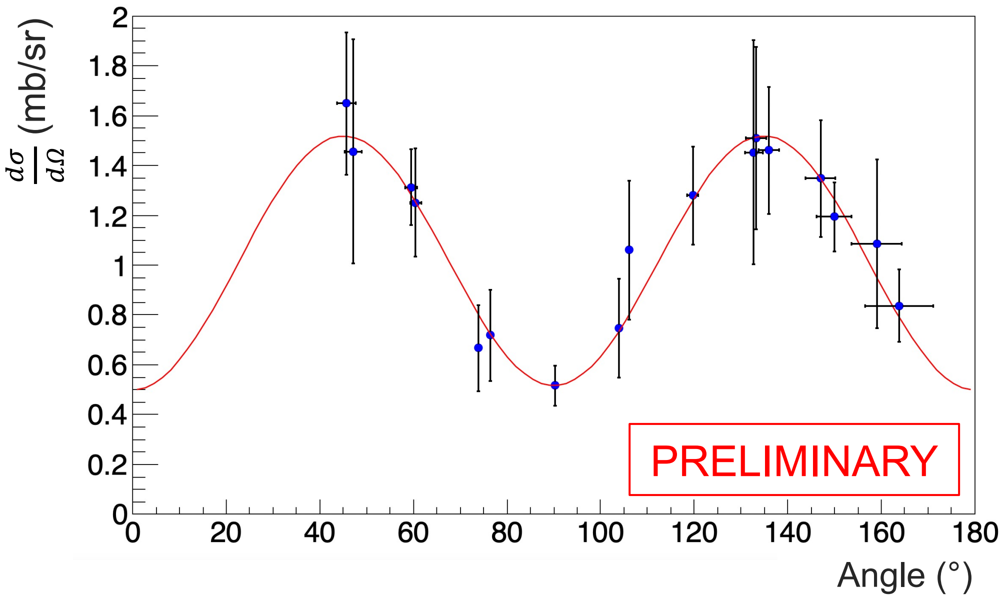
Inelastic scattering reaction channel

$^{12}C(n,n')^{12}C^*(\gamma)^{12}C$ - study of the first 2^+ of ^{12}C ($E(2^+)$= 4.439 MeV)

- Test bench using ^{12}C
- Detection of the scattered neutrons (**n'**) with MONSTER detectors in coincidence with γ in PARIS
  - ⇨ Coincidence matrix allows identification of excited states that decay by γ directly to the ^{12}C g.s. (events along the diagonal)
  - ⇨ Validation of the method for characterizing excited states: cross-section and multipolarity thanks to the γ angular distribution



reconstructed using **n'** time of flight (MONSTER)



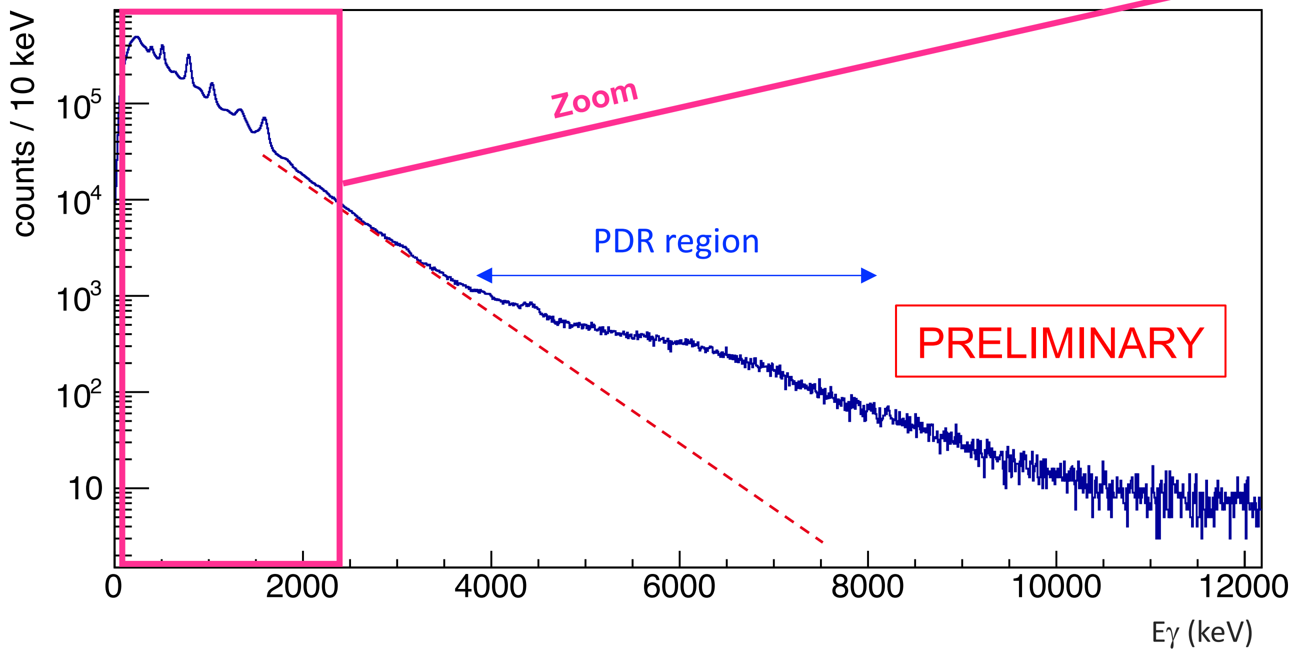
First preliminary results

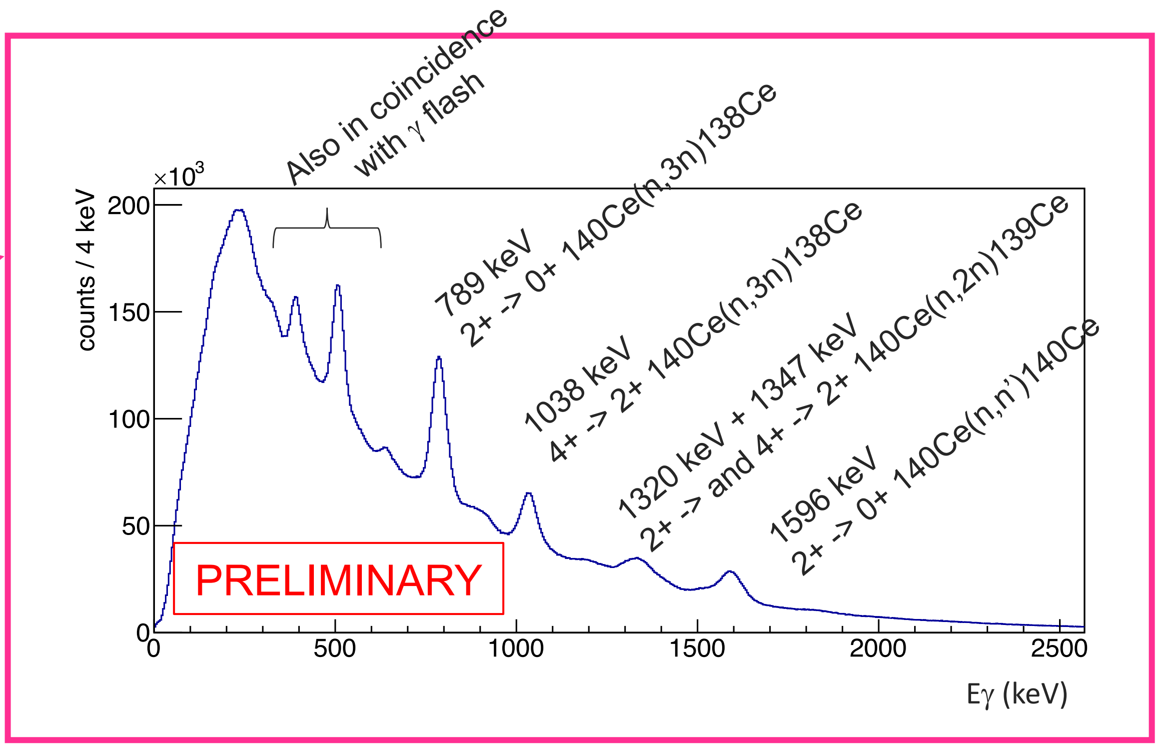
Inelastic scattering reaction channel

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

$^{nat}Ce(n,n')^{nat}Ce^*(\gamma)^{nat}Ce$

Selection of the events along the $E_\gamma = E^*(^{nat}Ce)$ 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

- Possibility to constrain EoS thanks to GR properties **BUT**
    1. Nuclear model dependence
    2. Need to very well characterize GR experimentally

- Concerning characterization of PDR, many programs are under way : (n,n') @NFS presented in this talk, see N. Martorana's talk for others programs

- In order to constrain EoS, it is interesting to combine experimental approaches, like heavy ions collisions for example

Thank you for your attention !

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] ,
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2. IJCLab (France)
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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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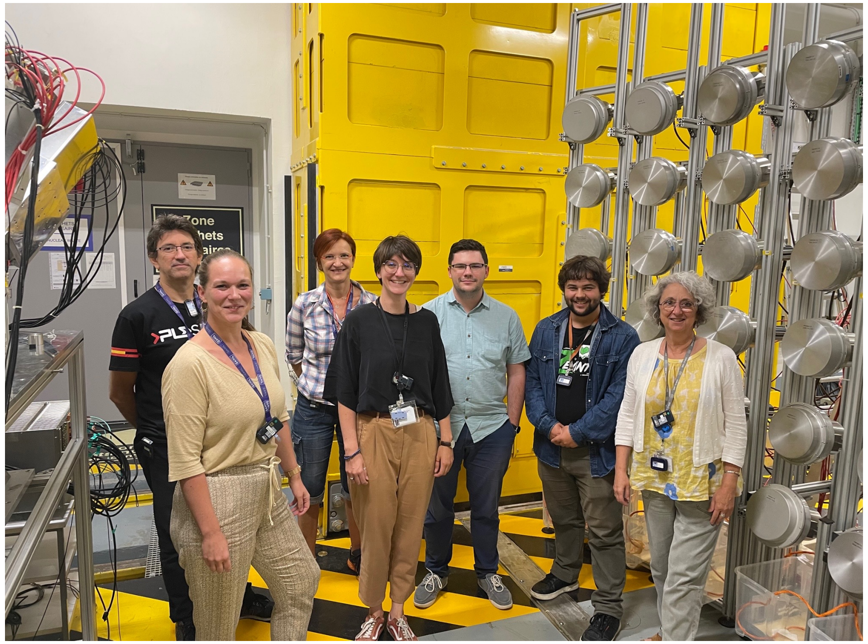
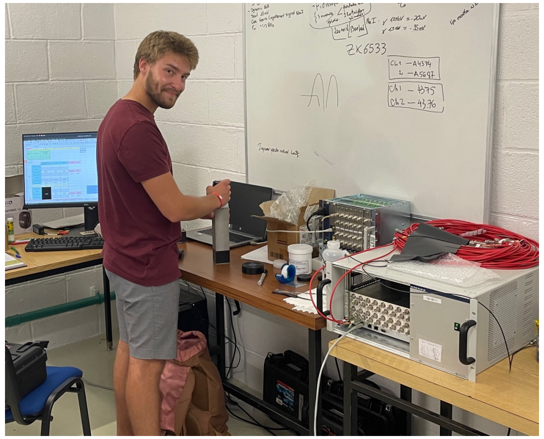
laboratoire commun CEA/DRF CNRS/IN2P3





P2IO
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