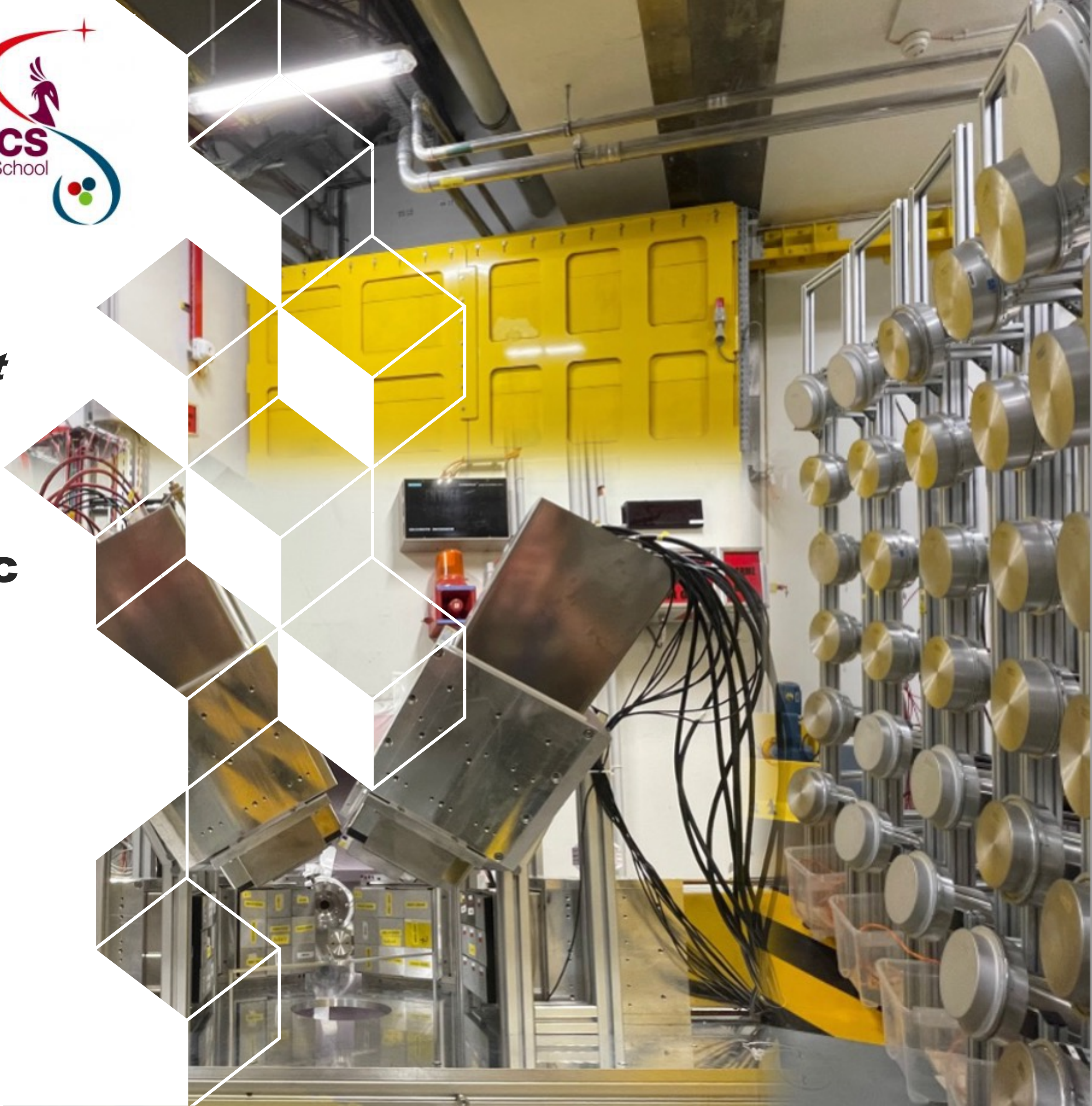
First nuclear structure measurement at GANIL-SPIRAL2/NFS :

The study of the Pygmy Dipole Resonance via neutron inelastic scattering

Périne MIRIOT-JAUBERT – 2^{nd} year PhD student

Thesis director : Marine VANDEBROUCK



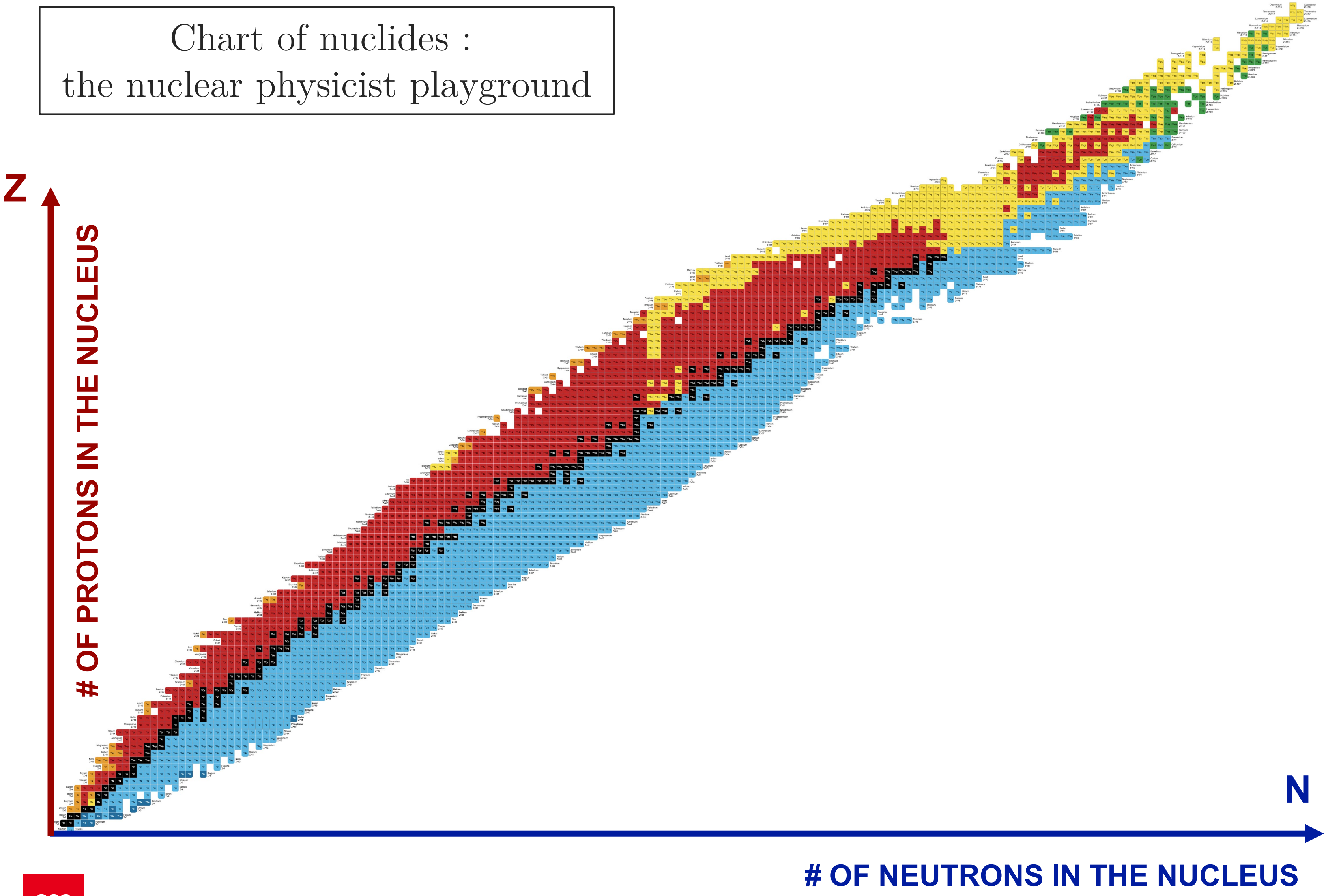
Contents

The study of the Pygmy Dipole Resonance (PDR) @ GANIL-SPIRAL2/NFS

What, Why and How to study the PDR ?

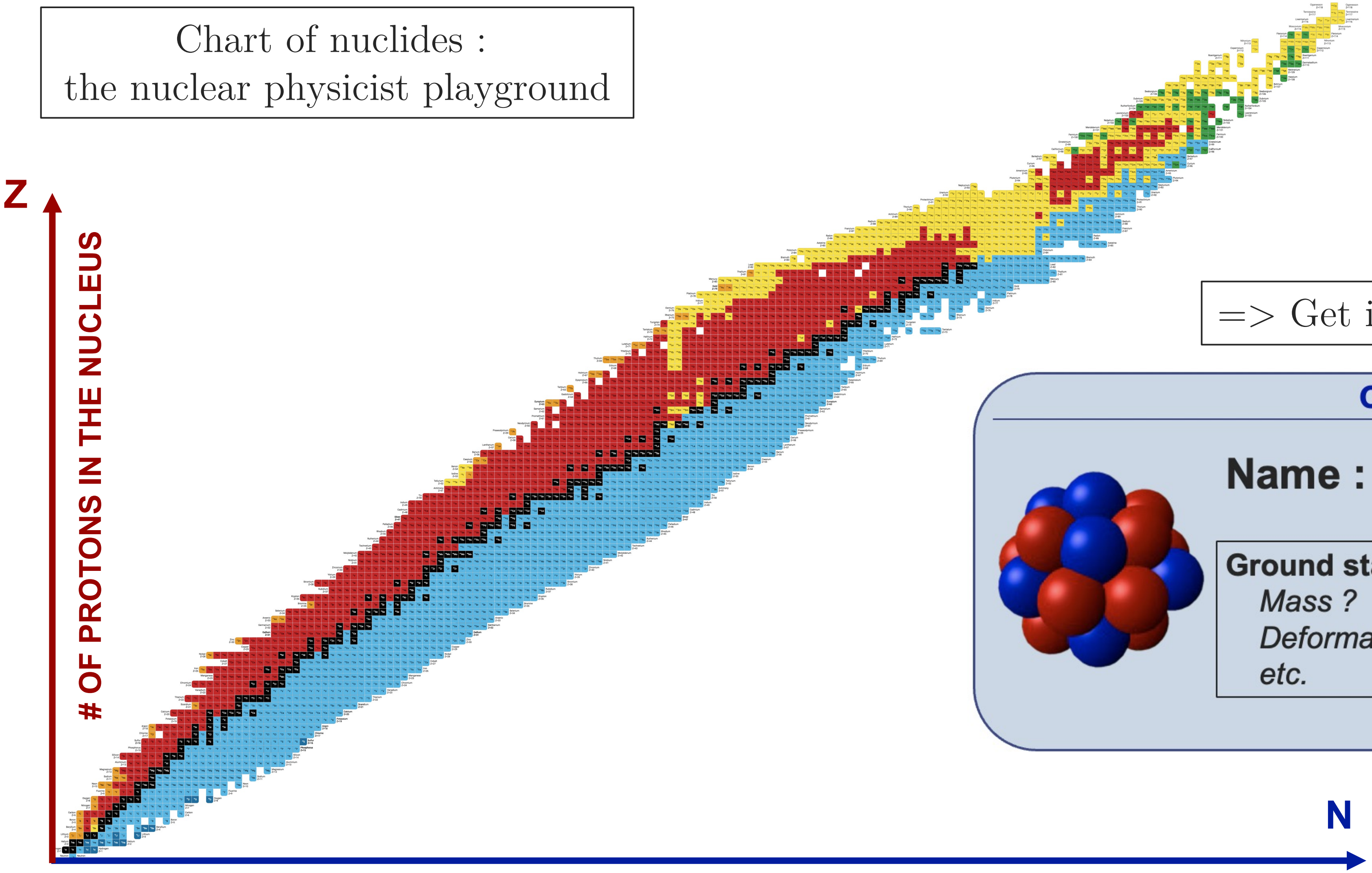
Why ? General motivation

Chart of nuclides :
the nuclear physicist playground



Why ? General motivation

Chart of nuclides :
the nuclear physicist playground



=> Get information on nuclei

Chart of nuclides

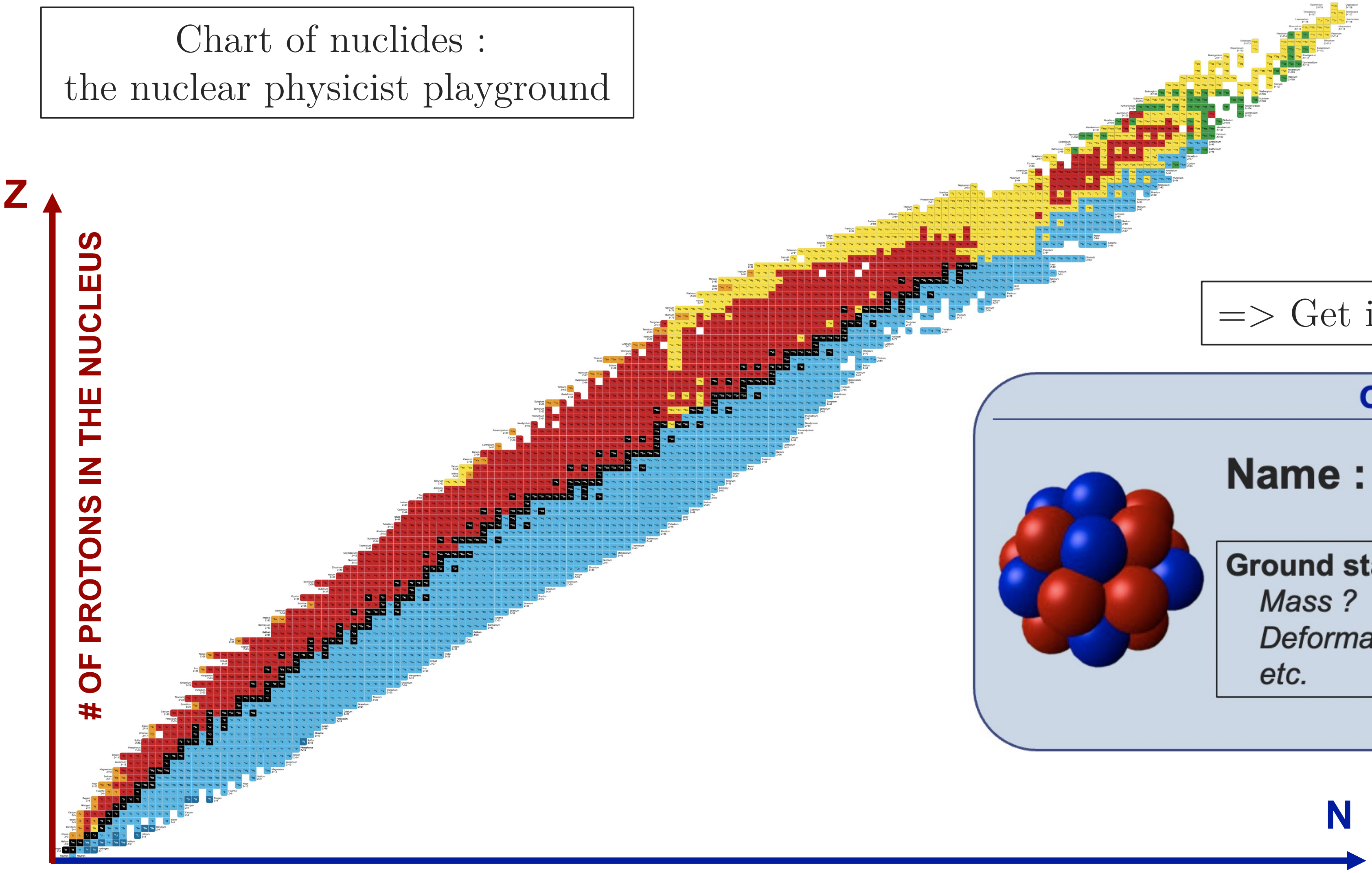
Name : $^A_Z X$

Ground state properties
- *Mass ?*
- *Deformation ?*
- *etc.*

Excited states
- *Level scheme ?*
- *Collective excitations ?*
- *Vibration, deformation ?*
- *etc.*

Why ? General motivation

Chart of nuclides :
the nuclear physicist playground



=> Get information on nuclei

Chart of nuclides

Name : ${}^{A}_{Z}X$

Ground state properties

Mass ?

Deformation ?

etc.

Excited states

Level scheme ?

Collective excitations ?

Vibration, deformation ?

etc.

What, Why ? From Giant Resonances ... to the PDR

Giant Resonances (GR)

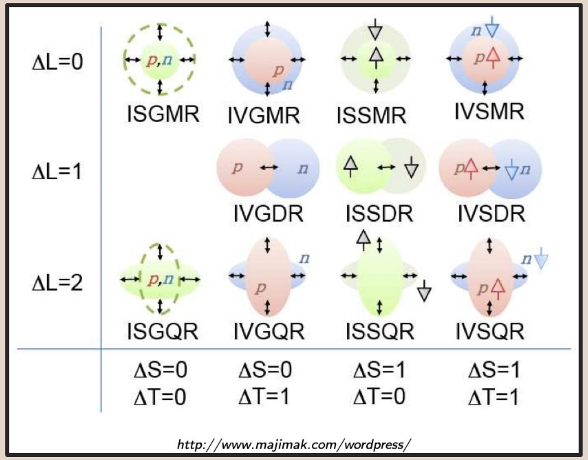
- **Collective** excitation modes
  (majority of nucleons involved)
- Present in **all nuclei**
- **Large cross-sections** *(= high probability)*

What, Why ? From Giant Resonances ... to the PDR

Giant Resonances (GR)

- **Collective** excitation modes
  (majority of nucleons involved)
- Present in **all nuclei**
- **Large cross-sections** *(= high probability)*

Classification with the quantum numbers of the transition (ground state -> GR)



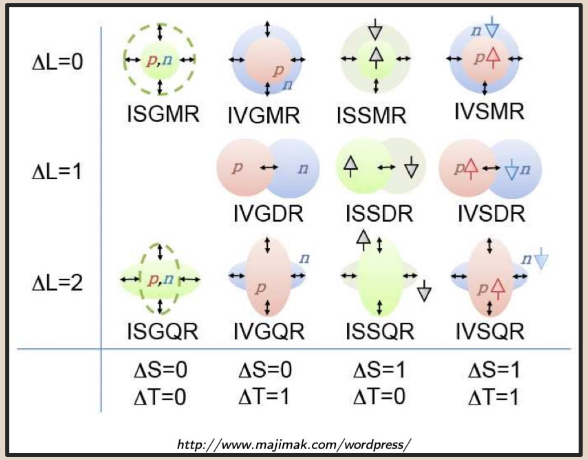
Macroscopic interpretation

What, Why ? From Giant Resonances … to the PDR

Giant Resonances (GR)

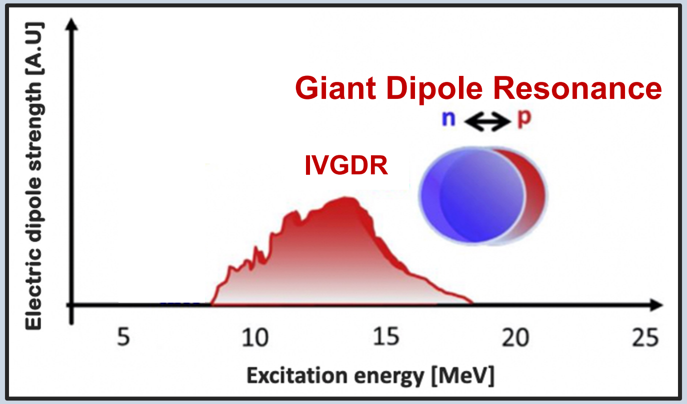
- **Collective** excitation modes
  (majority of nucleons involved)
- Present in **all nuclei**
- **Large cross-sections** *(= high probability)*

Classification with the quantum numbers of the transition (ground state -> GR)



Macroscopic interpretation

Dipole

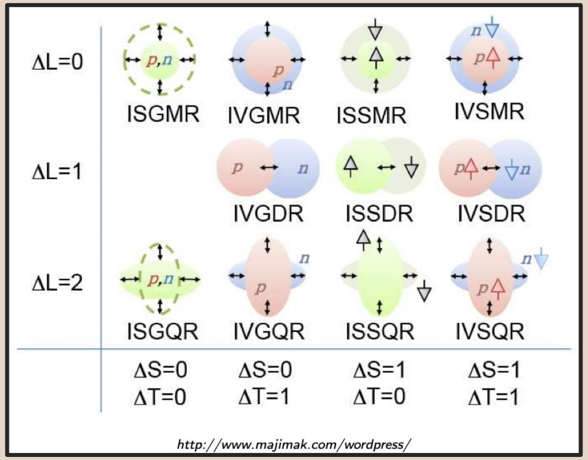


What, Why ? From Giant Resonances … to the PDR

Giant Resonances (GR)

- **Collective** excitation modes
  (majority of nucleons involved)
- Present in **all nuclei**
- **Large cross-sections** *(= high probability)*

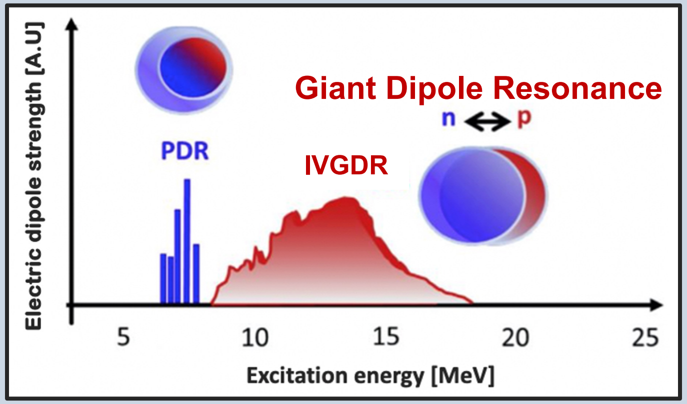
Classification with the quantum numbers of the transition (ground state -> GR)



Macroscopic interpretation

The Pigmy Dipole Resonance (PDR)

- **Low energy** excited states in the **dipole** response
- Characteristic of **neutron-rich nuclei**
- Around the neutron separation energy threshold

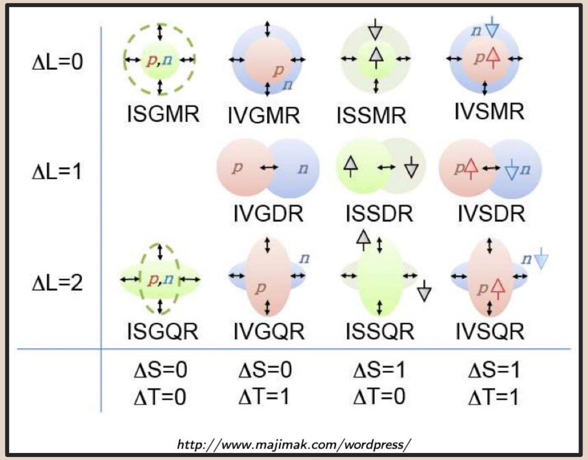


What, Why ? From Giant Resonances ... to the PDR

Giant Resonances (GR)

- **Collective** excitation modes
  (majority of nucleons involved)
- Present in **all nuclei**
- **Large cross-sections** *(= high probability)*

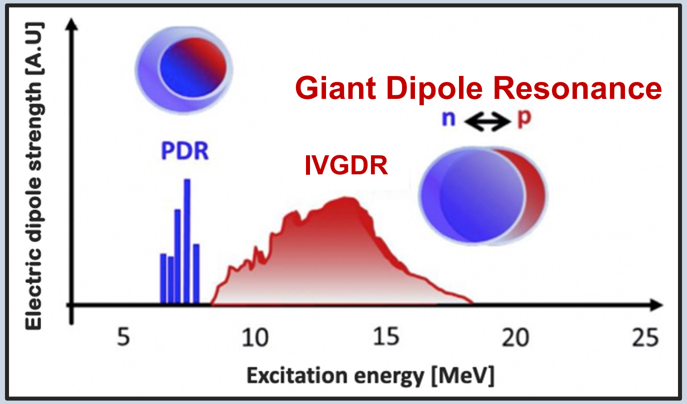
Classification with the quantum numbers of the transition (ground state -> GR)



Macroscopic interpretation

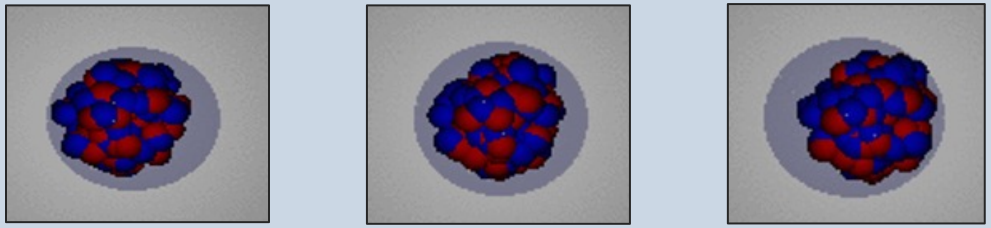
The Pigmy Dipole Resonance (PDR)

- **Low energy** excited states in the **dipole** response
- Characteristic of **neutron-rich nuclei**
- Around the neutron separation energy threshold



Macroscopic interpretation :

oscillation of a **neutron skin** around an isospin symmetric core

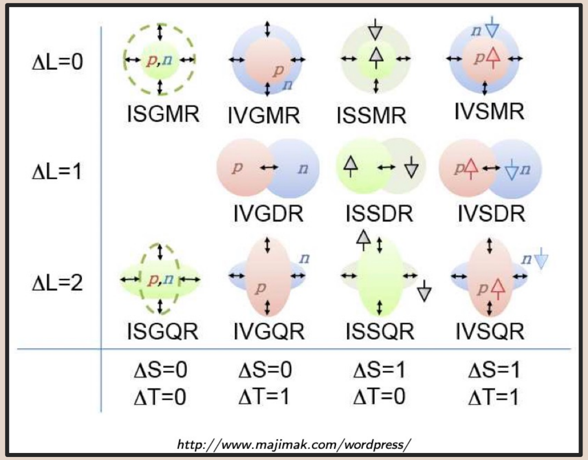


What, Why ? From Giant Resonances ... to the PDR

Giant Resonances (GR)

- **Collective** excitation modes
  (majority of nucleons involved)
- Present in **all nuclei**
- **Large cross-sections** *(= high probability)*

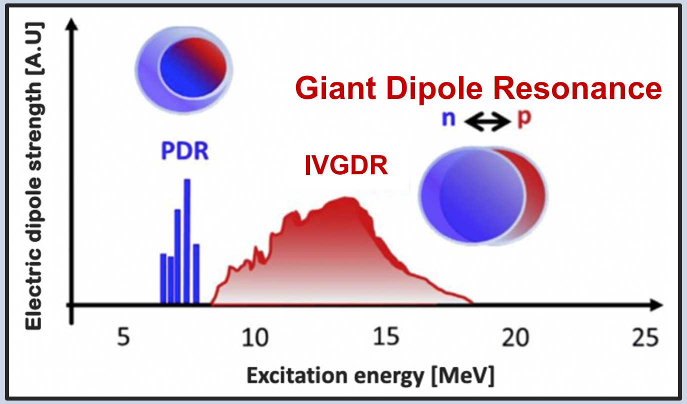
Classification with the quantum numbers of the transition (ground state -> GR)



Macroscopic interpretation

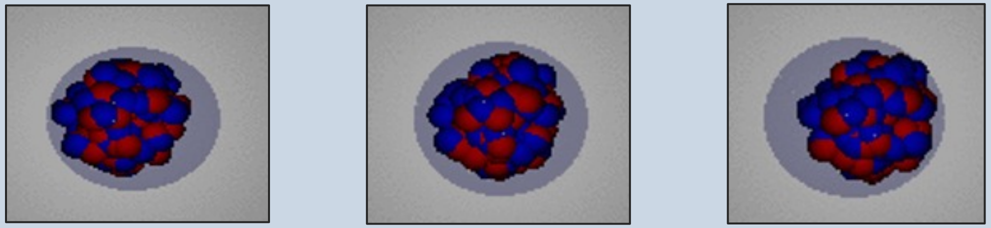
The Pigmy Dipole Resonance (PDR)

- **Low energy** excited states in the **dipole** response
- Characteristic of **neutron-rich nuclei**
- Around the neutron separation energy threshold



Macroscopic interpretation :

oscillation of a **neutron skin** around an isospin symmetric core



Applications :

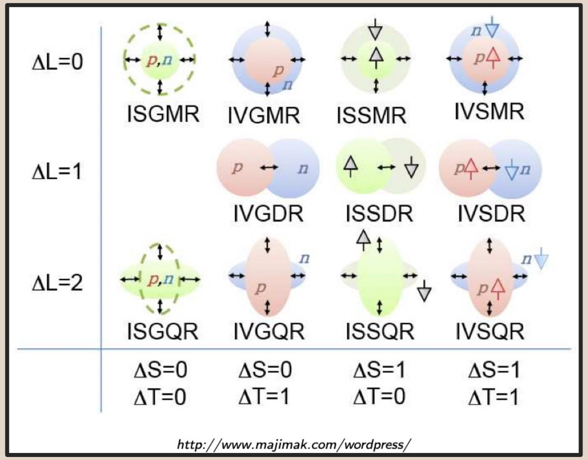
Astrophysical r-process - Nuclear equation of state - Neutron stars properties

What, Why ? From Giant Resonances ... to the PDR

Giant Resonances (GR)

- **Collective** excitation modes
  (majority of nucleons involved)
- Present in **all nuclei**
- **Large cross-sections** *(= high probability)*

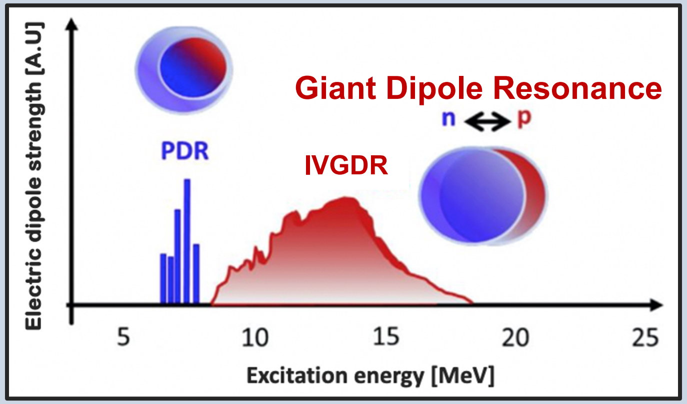
Classification with the quantum numbers of the transition (ground state -> GR)



Macroscopic interpretation

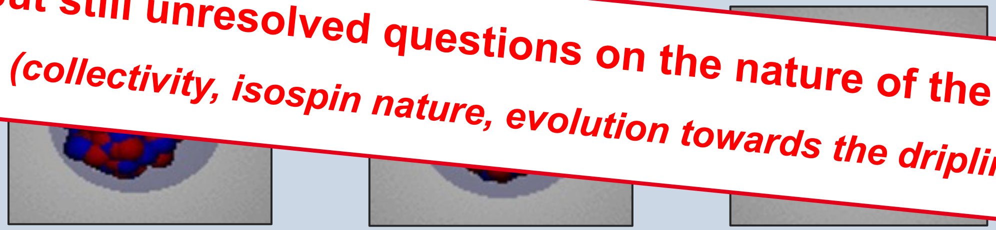
The Pigmy Dipole Resonance (PDR)

- **Low energy** excited states in the **dipole** response
- Characteristic of **neutron-rich nuclei**
- Around the neutron separation energy threshold



Macroscopic interpretation :

neutron skin around an isospin symmetric core



But still unresolved questions on the nature of the PDR …

(collectivity, isospin nature, evolution towards the dripline, …)

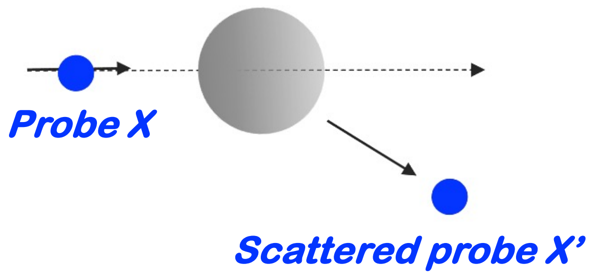
Applications :

Astrophysical r-process - Nuclear equation of state - Neutron stars properties

How ? Scattering experiments

General approach to study the nature of excitations : investigate the response to an external field

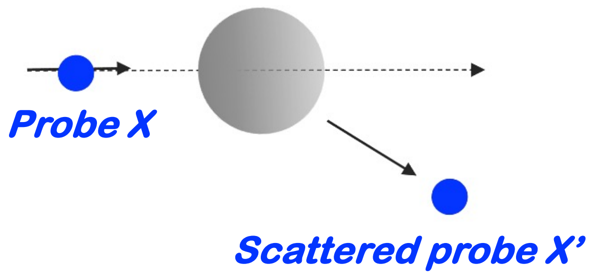
=> Performed with **scattering experiments (X,X')**.



How ? Scattering experiments

General approach to study the nature of excitations : investigate the response to an external field

=> Performed with **scattering experiments (X,X')**.



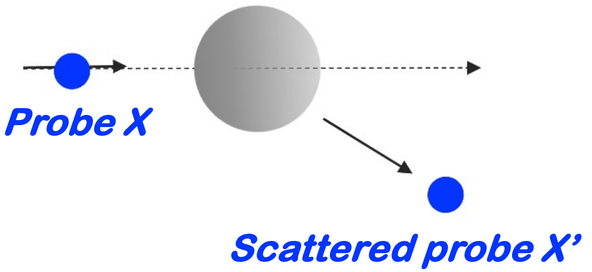
Different probes will not have the same ability to excite protons and neutrons

→ Interest of a **multi-messenger investigation** of the PDR

How ? Scattering experiments

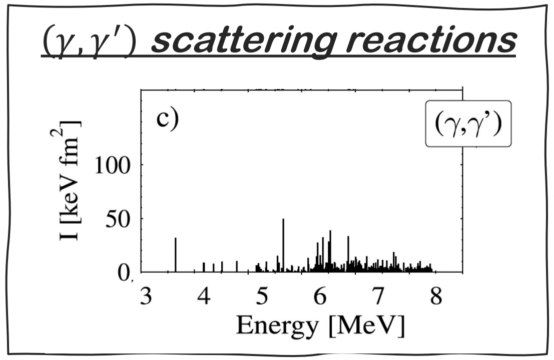
General approach to study the nature of excitations : investigate the response to an external field

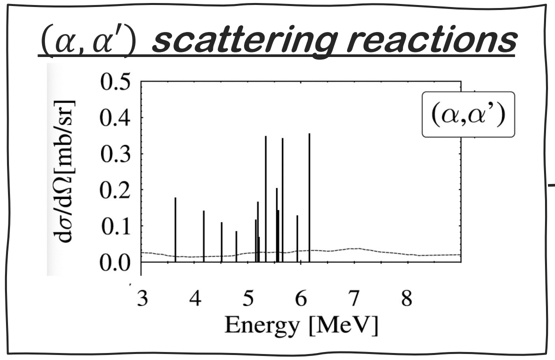
=> Performed with **scattering experiments (X,X')**.

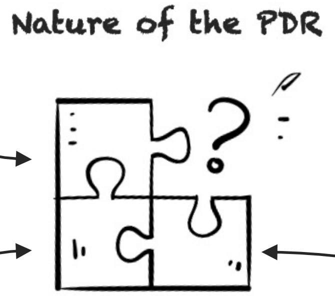


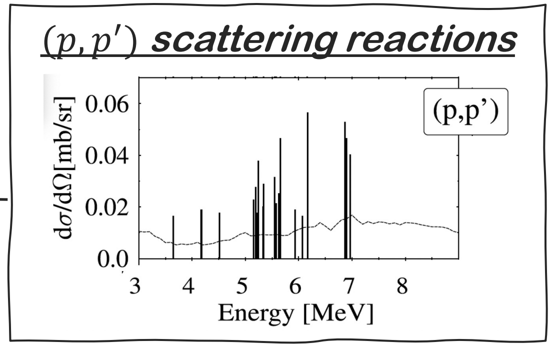
Different probes will not have the same ability to excite protons and neutrons

→ Interest of a **multi-messenger investigation** of the PDR







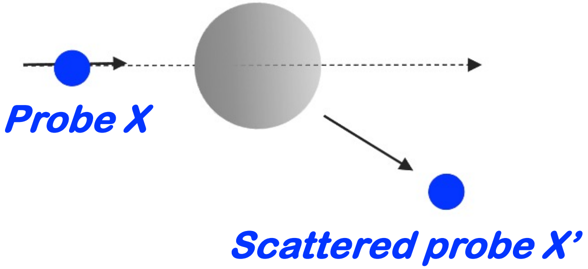


D. Savran et al., Physics Letters B ***786*** *(2018) 16-20*
Multi-messenger investigation of the Pygmy Dipole Resonance in ^{140}**Ce**

How ? Scattering experiments

General approach to study the nature of excitations : investigate the response to an external field

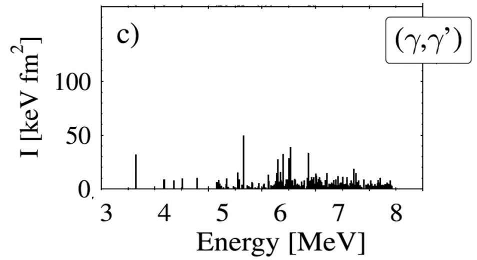
=> Performed with **scattering experiments (X,X')**.



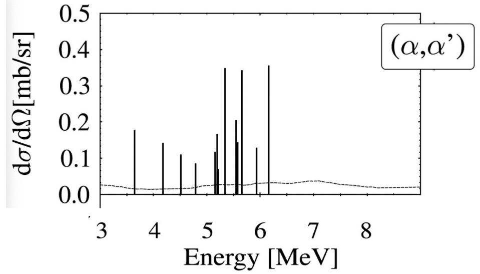
Different probes will not have the same ability to excite protons and neutrons

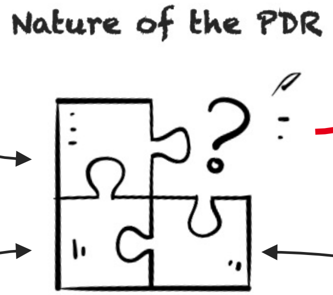
→ Interest of a **multi-messenger investigation** of the PDR

(γ,γ') scattering reactions



(α,α') scattering reactions



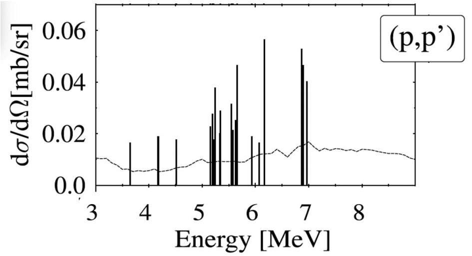


My PhD: (n,n') scattering reaction

Advantages :

- *elementary probe in nuclear physics*
- *electrically neutral*
- *complementary to the proton probe*

(p,p') scattering reactions



D. Savran et al., Physics Letters B ***786*** *(2018) 16-20*
Multi-messenger investigation of the Pygmy Dipole Resonance in ***^{140}Ce***

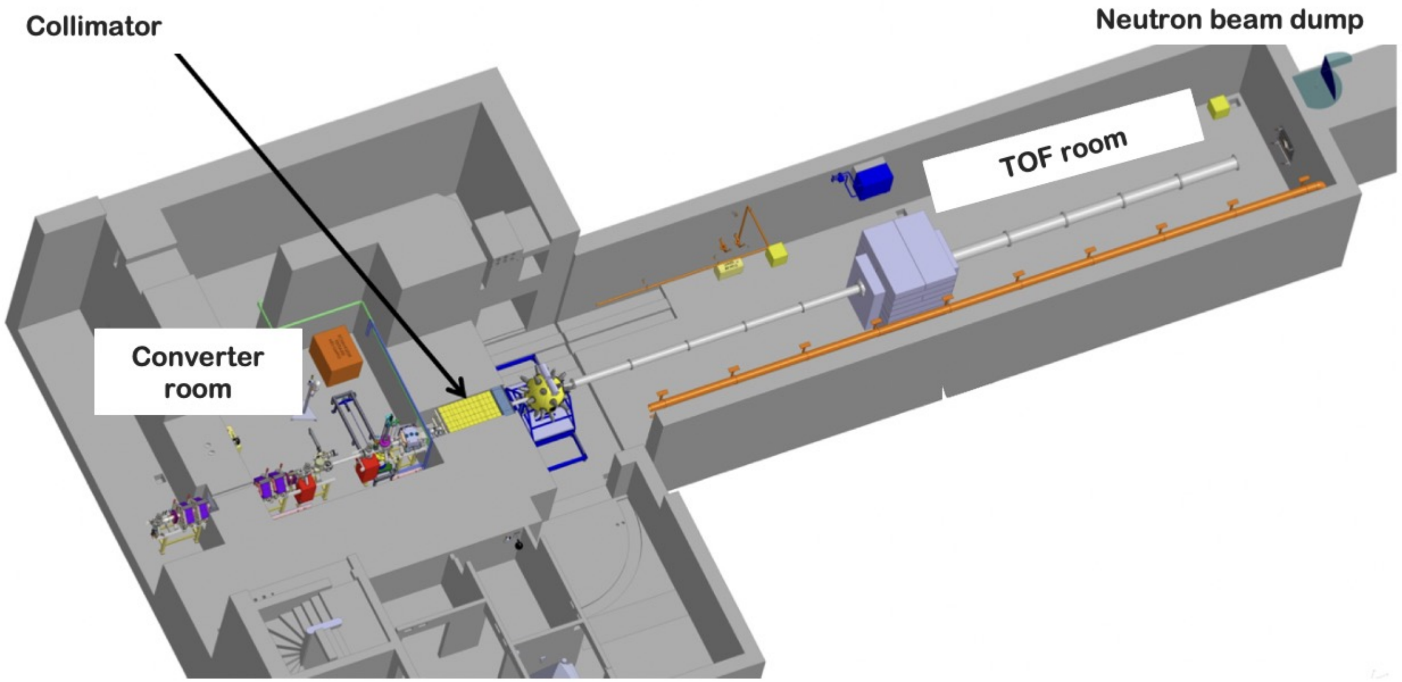
Contents

The study of the Pygmy Dipole Resonance (PDR) @ GANIL-SPIRAL2/NFS

What, Why and How to study the PDR ?

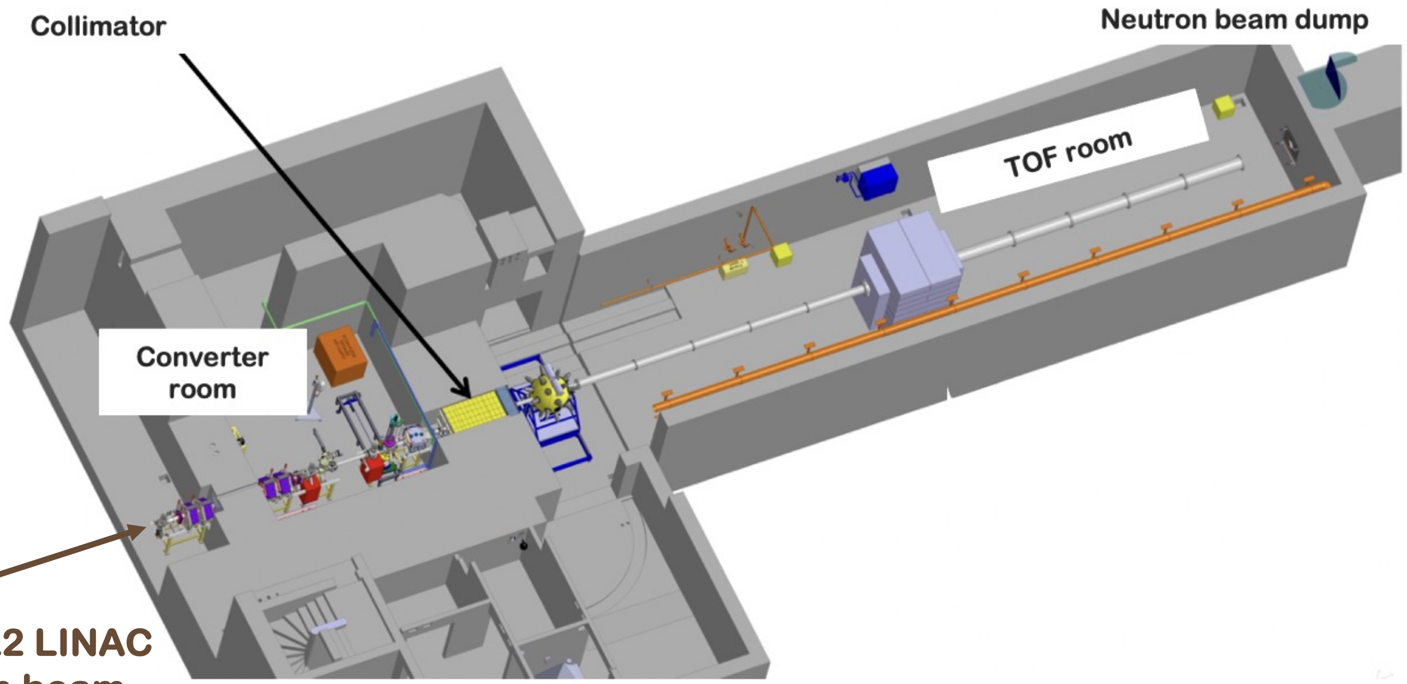
The experiment at Neutrons For Science (NFS)

GANIL – SPIRAL2 / NFS : a new opportunity



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

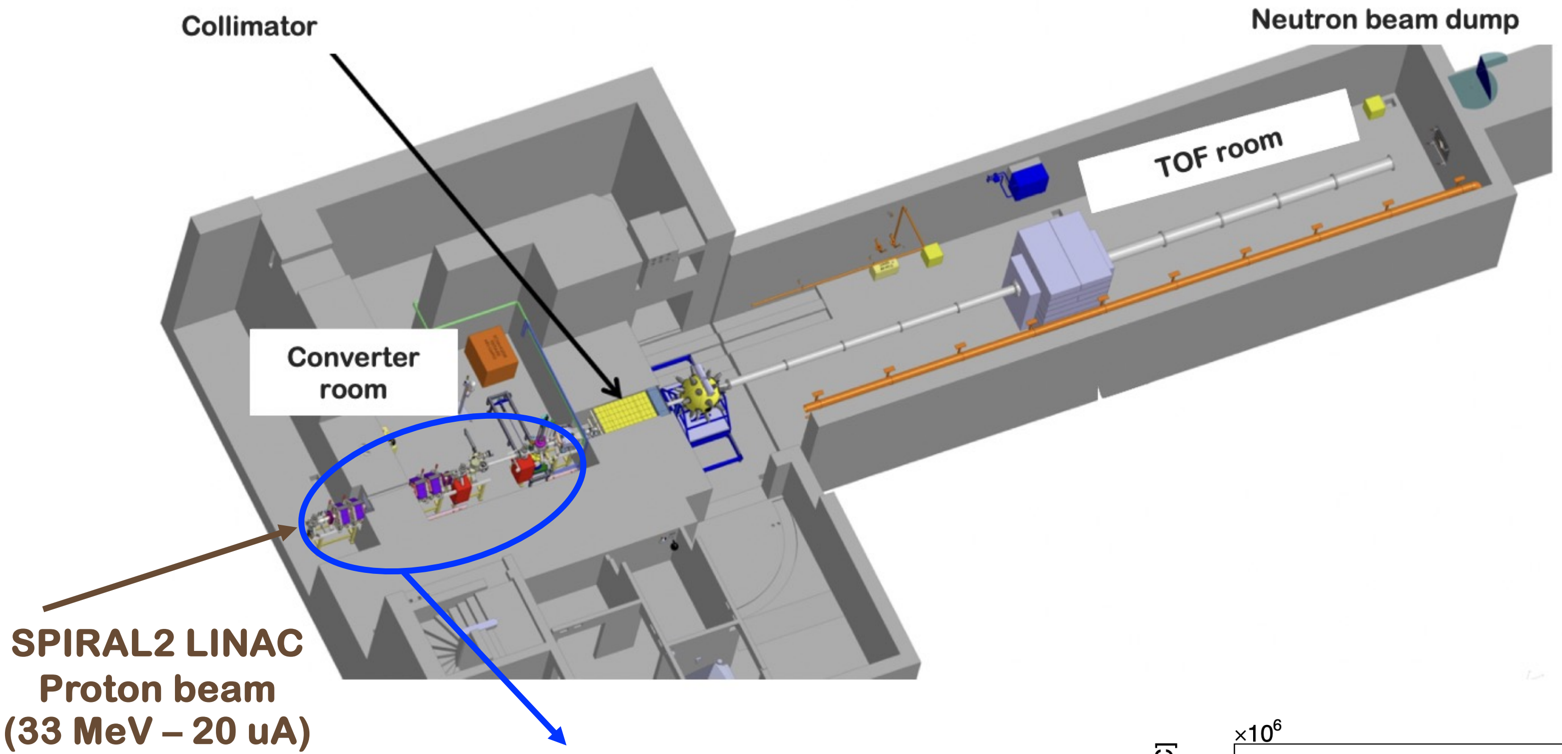
GANIL – SPIRAL2 / NFS : a new opportunity



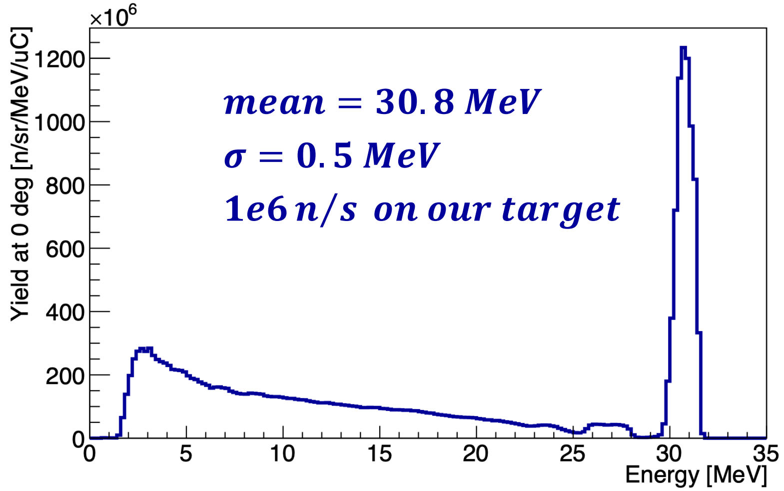
SPIRAL2 LINAC
Proton beam
(33 MeV – 20 uA)

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

GANIL – SPIRAL2 / NFS : a new opportunity

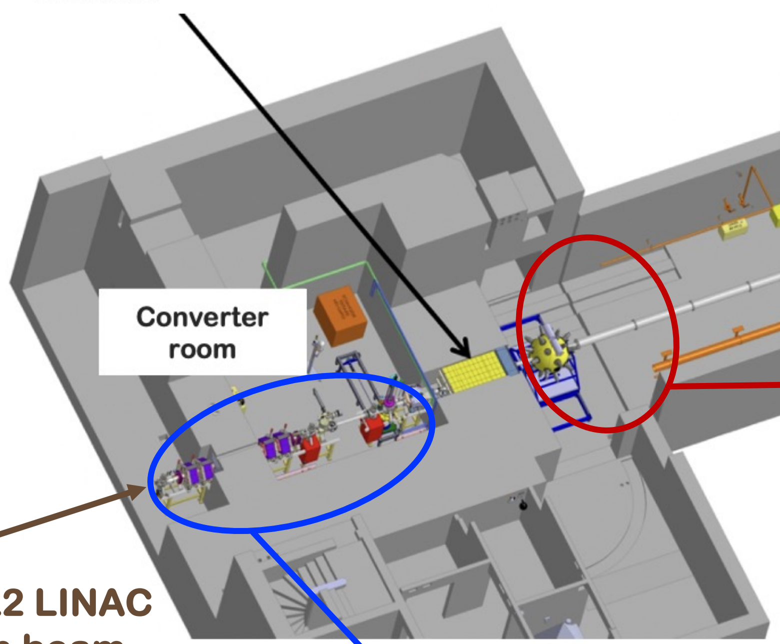


Generation of the neutron beam via a charge exchange reaction :
$^{7}Li(p,n)^{7}Be$



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

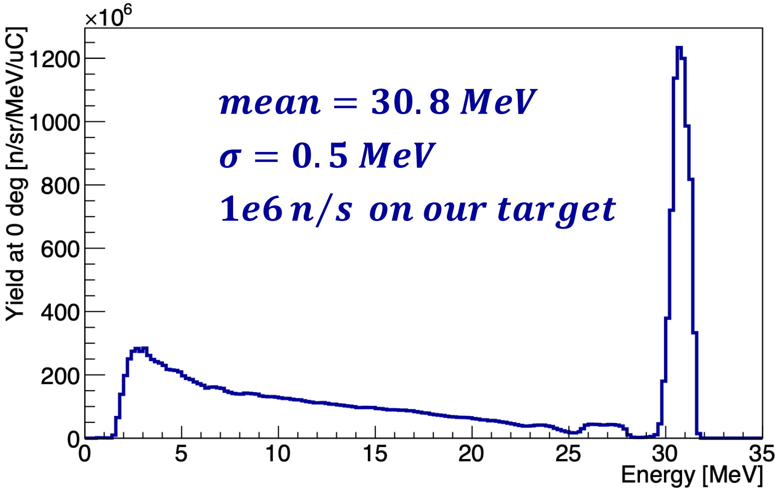
GANIL – SPIRAL2 / NFS : a new opportunity



Target + detectors

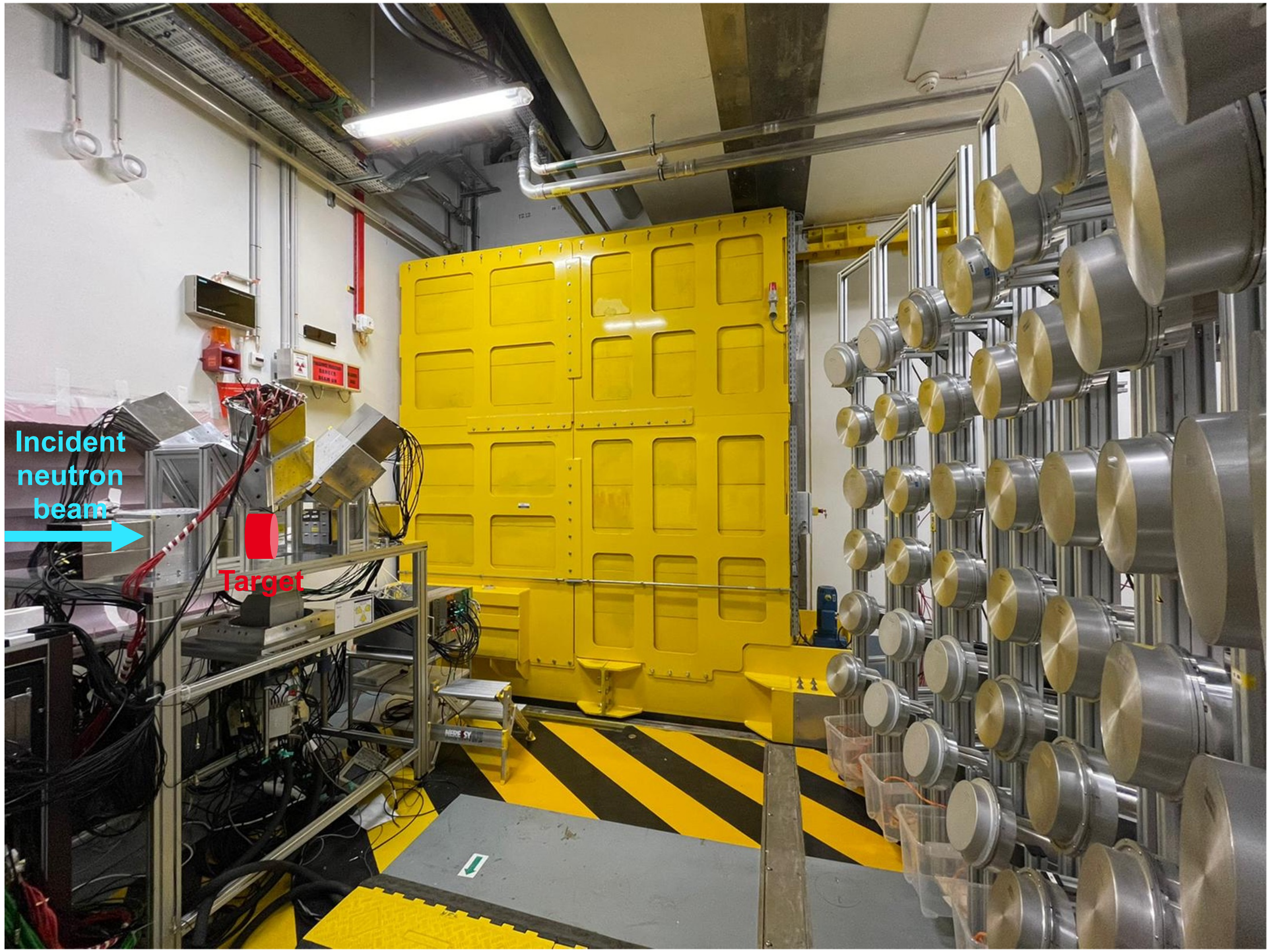
SPIRAL2 LINAC
Proton beam
(33 MeV – 20 uA)

Generation of the neutron beam via a charge exchange reaction :
$^{7}Li(p,n)^{7}Be$



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

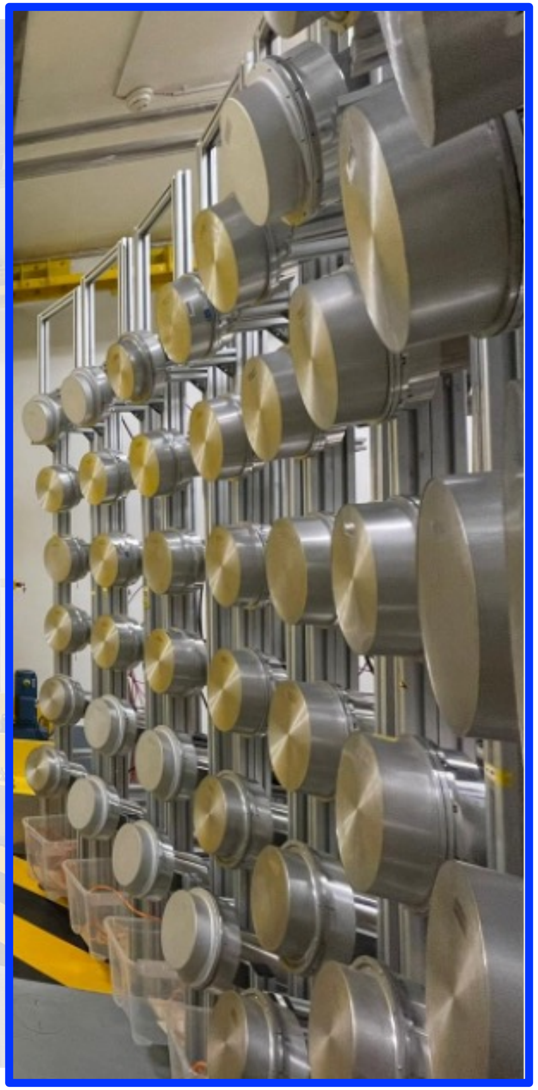
The experimental setup – E833 experiment



Study of the PDR in the ^{140}Ce (~ 88% in ^{nat}Ce) :

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

The experimental setup – E833 experiment



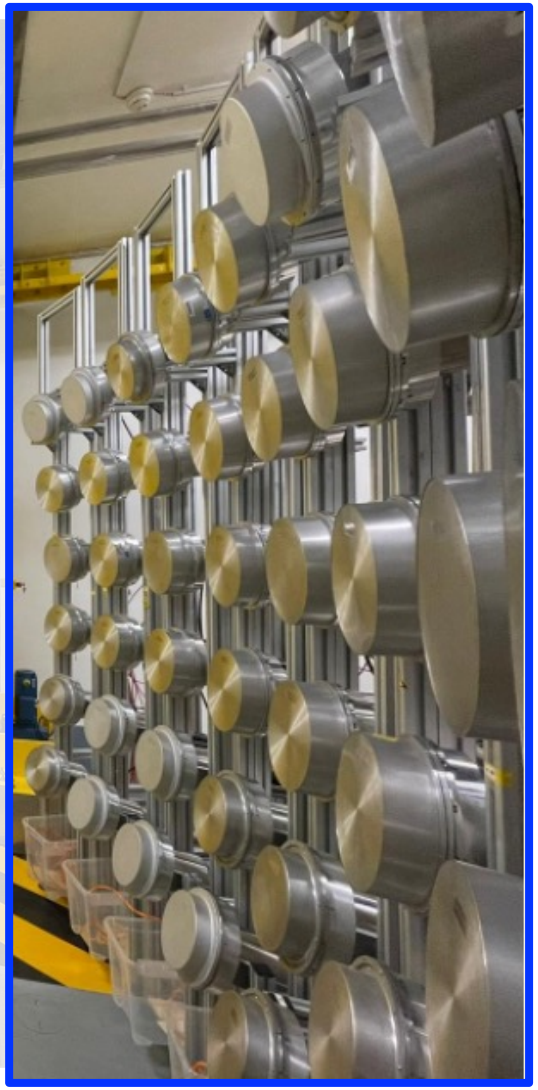
Study of the PDR in the ^{140}Ce (~ 88% in ^{nat}Ce) :

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

MONSTER modules (x 48) : n' detection

Liquid scintillators (BC501A / EJ301)

The experimental setup – E833 experiment



Study of the PDR in the ^{140}Ce (~ 88% in ^{nat}Ce) :

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

MONSTER modules (x 48) : n' detection

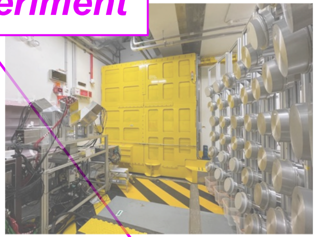
Liquid scintillators (BC501A / EJ301)

PARIS clusters (x 8) : γ detection

Scintillation crystals (LaBr / CeBr + NaI)
8 clusters of 9 phoswiches

Pre-analysis timeline

September 2022
E833 experiment



March 2022

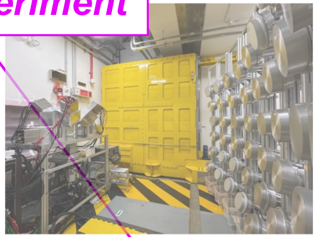
October 2022

M2 internship

time

Pre-analysis timeline

September 2022
E833 experiment



March 2022

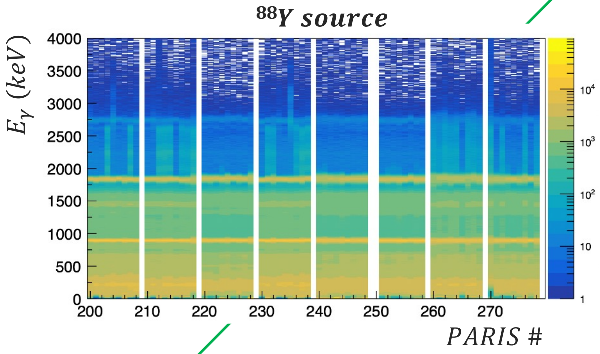
October 2022

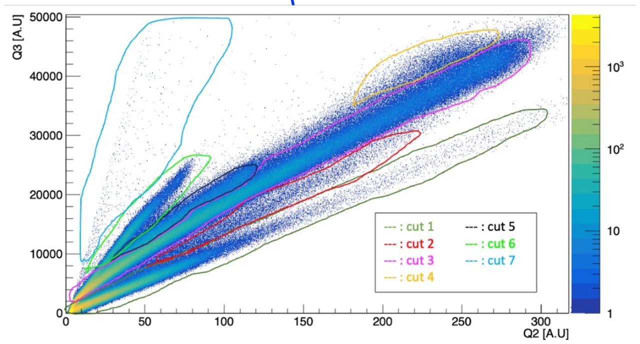
May 2022

X

M2 internship

time



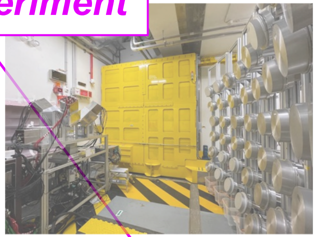


PARIS detector calibrations (time, energy) **and efficiency determination**

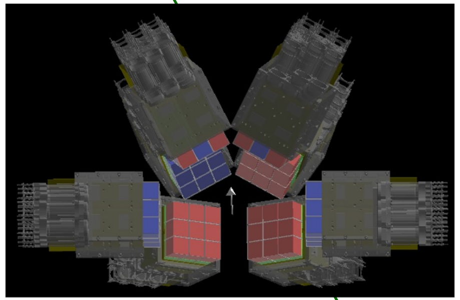
MONSTER detector calibrations (time, energy) **and n/γ discrimination**

Pre-analysis timeline

September 2022
E833 experiment

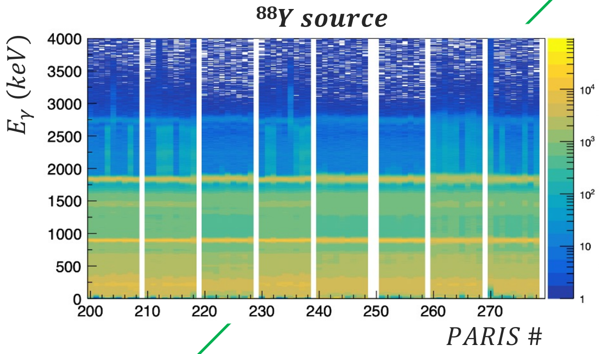


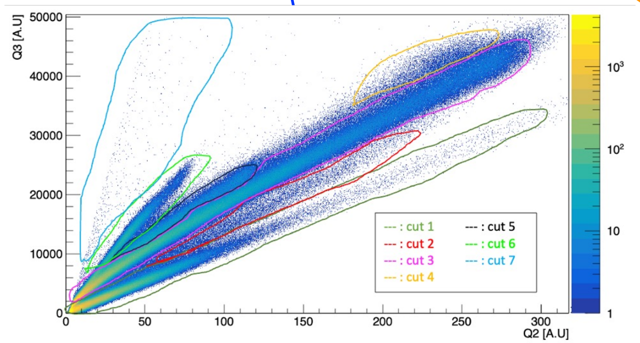
PARIS detectors simulations

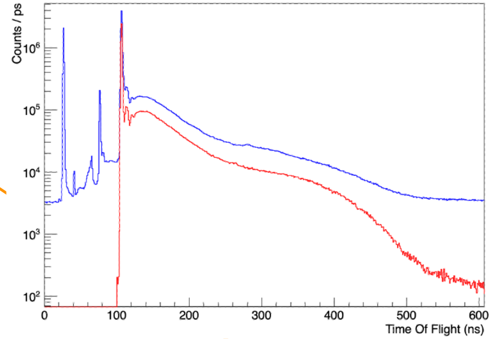


March 2022 — October 2022 — May 2022 — December 2023 — *time*

M2 internship







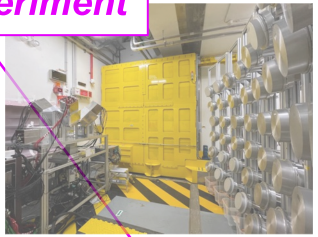
PARIS detector calibrations (time, energy) **and efficiency determination**

MONSTER detector calibrations (time, energy) **and n/γ discrimination**

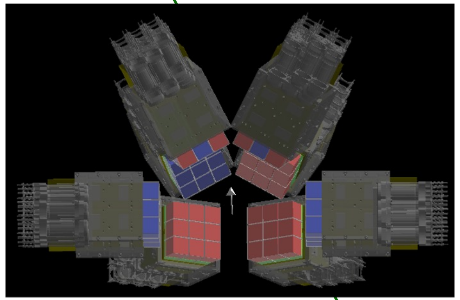
Accelerator signal study → Extraction of TOF MONSTER-HF

Pre-analysis timeline

September 2022
E833 experiment



PARIS detectors simulations



December 2023

March 2022

October 2022

May 2022

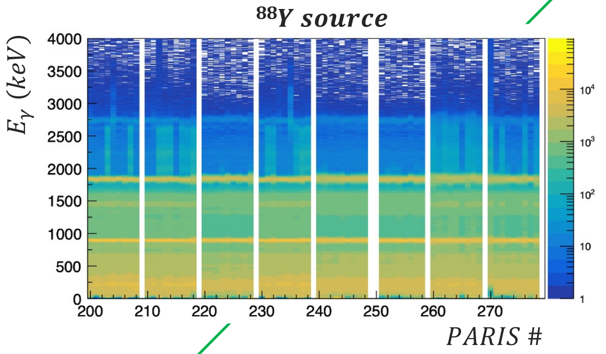
Elastic scattering analysis

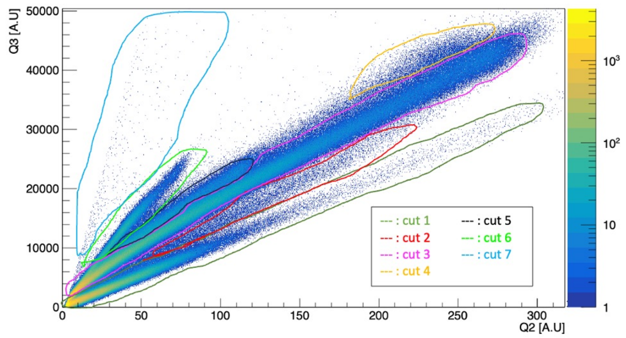
Study of the inelastic scattering channel

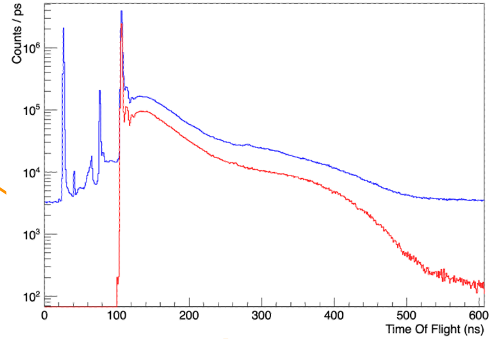
X

M2 internship

time







PARIS detector calibrations (time, energy) **and efficiency determination**

MONSTER detector calibrations (time, energy) **and n/γ discrimination**

Accelerator signal study
→ Extraction of TOF MONSTER-HF

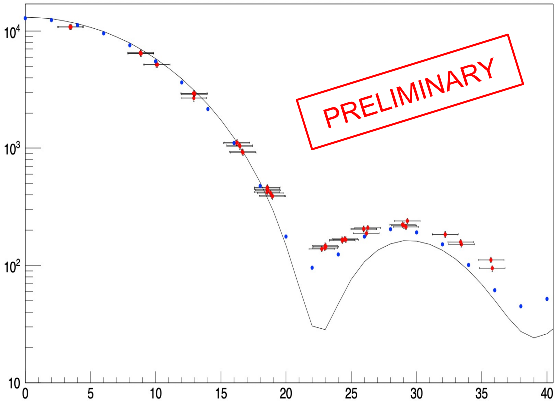
Contents

The study of the Pygmy Dipole Resonance (PDR) @ GANIL-SPIRAL2/NFS

What, Why and How to study the PDR ?

The experiment at Neutrons For Science (NFS)

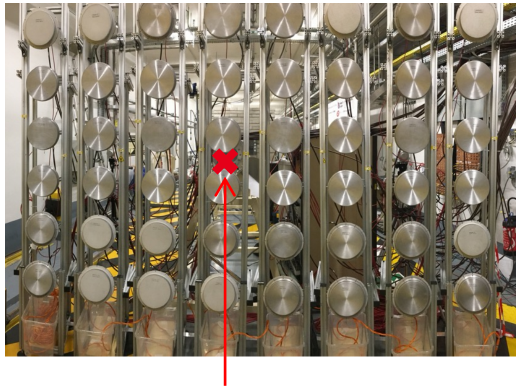
First results: the elastic scattering channel



First results : the elastic scattering channel

$^{nat}Ce(n,n')^{nat}Ce$

Detection of the scattered neutrons n' with the MONSTER modules :

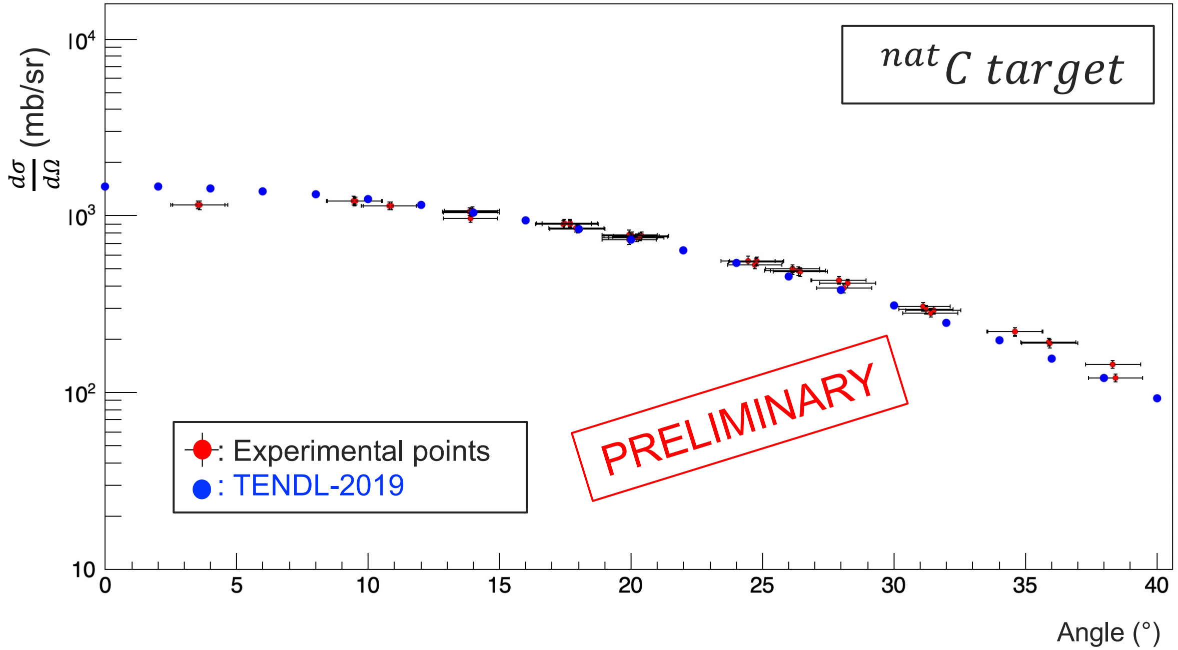


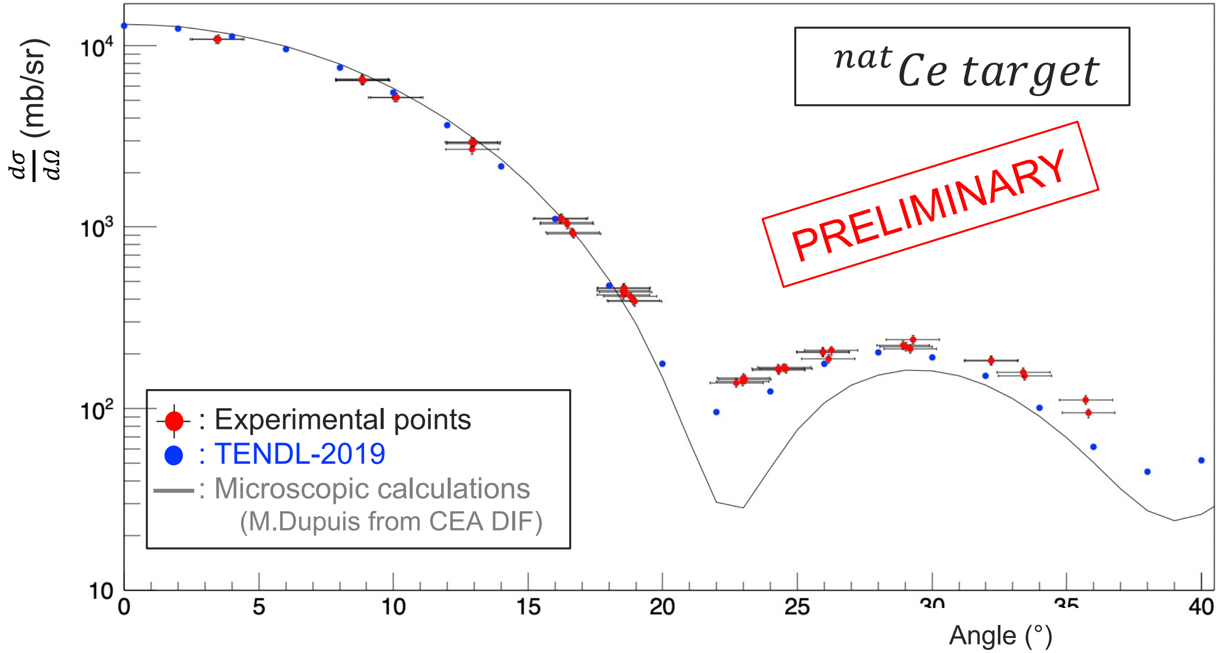
First results : the elastic scattering channel

$^{nat}Ce(n,n')^{nat}Ce$

Detection of the scattered neutrons n' with the MONSTER modules :

Results :





Contents

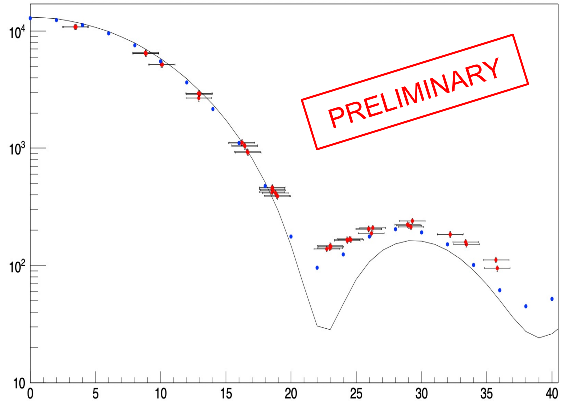
The study of the Pygmy Dipole Resonance (PDR) @ GANIL-SPIRAL2/NFS

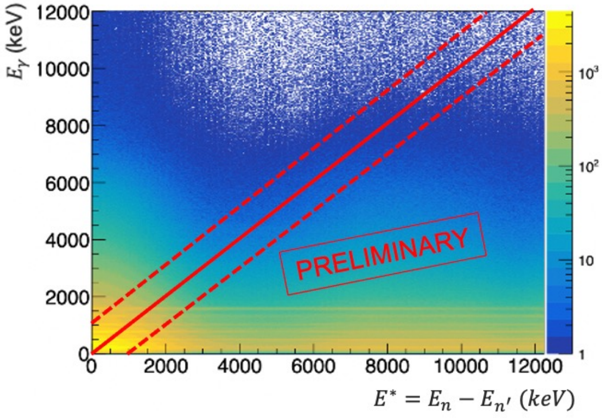
What, Why and How to study the PDR ?

The experiment at Neutrons For Science (NFS)

First results: the elastic scattering channel

Inelastic scattering : analysis procedure

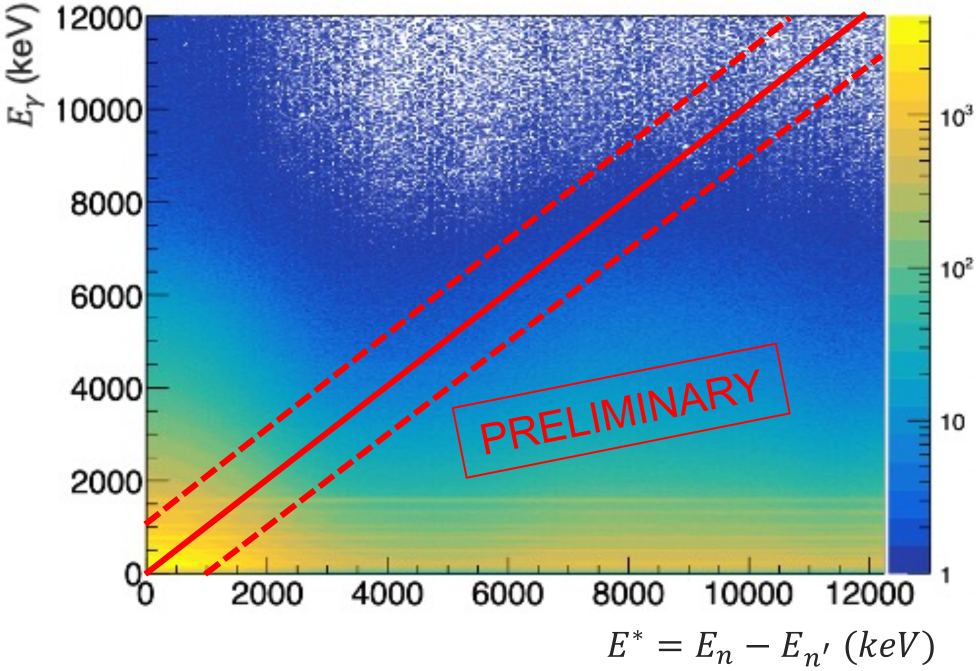




The inelastic scattering : analysis procedure

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

1) γ selection in PARIS - n’ selection in MONSTER in coincidence

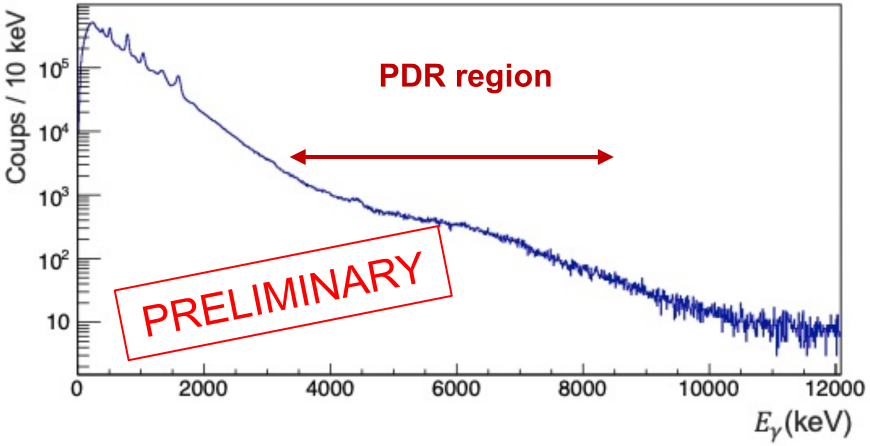


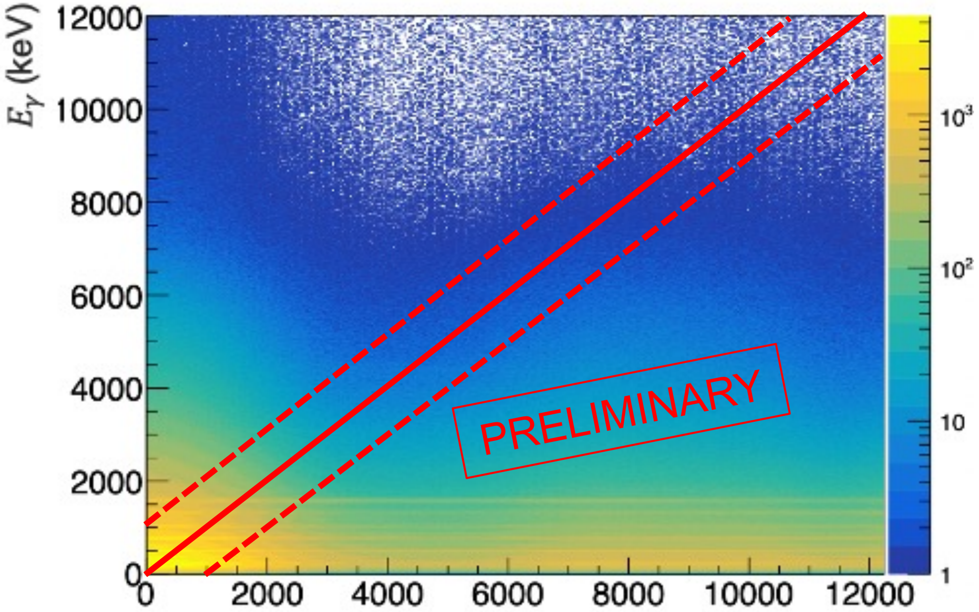
The inelastic scattering : analysis procedure

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

1) γ selection in PARIS - n' selection in MONSTER in coincidence

2) Projection on the E_γ and E^* axes



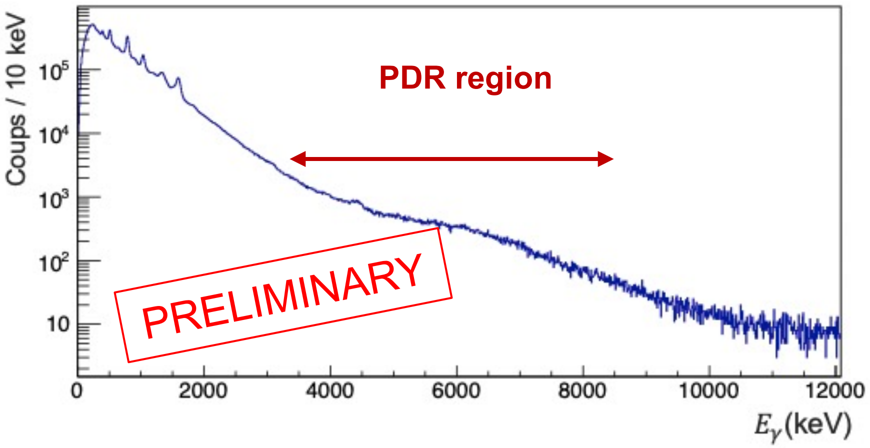


The inelastic scattering : analysis procedure

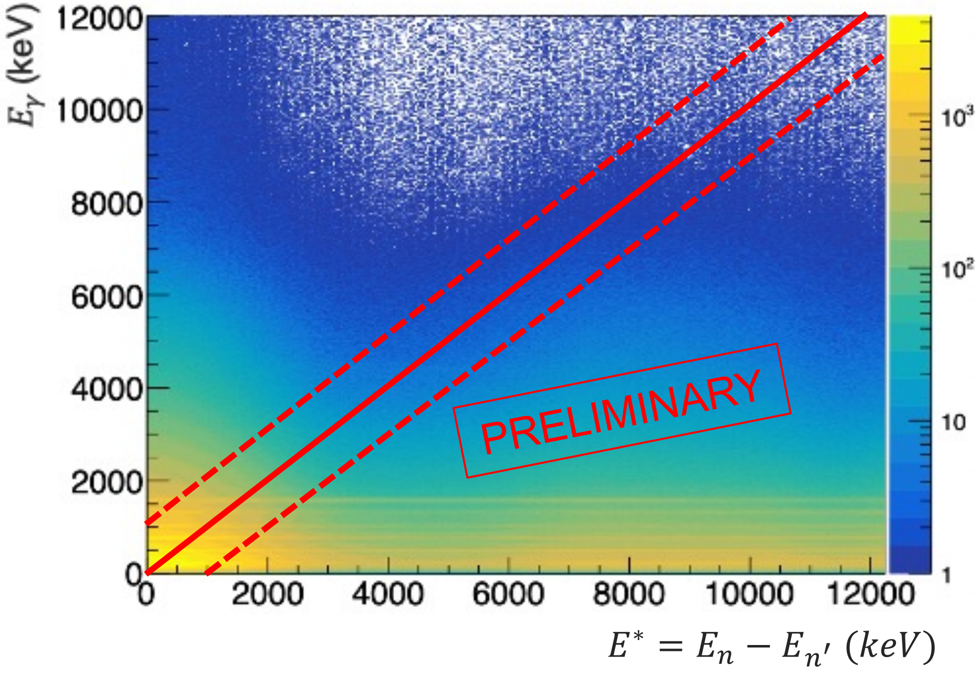
$^{nat}Ce(n,n')^{nat}Ce^*(\gamma)^{nat}Ce$

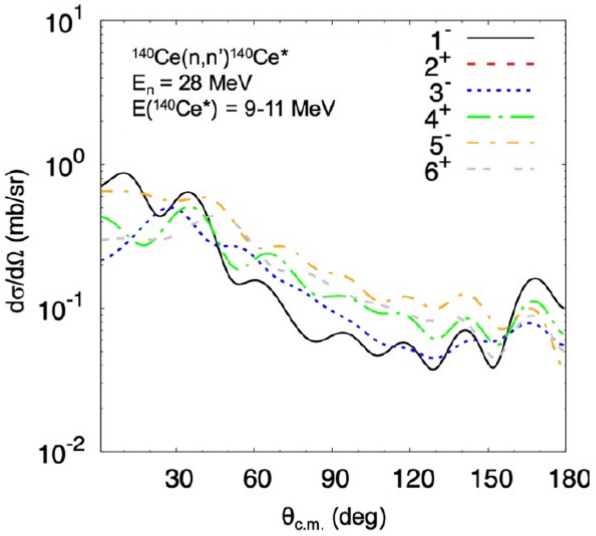
1) γ selection in PARIS - n' selection in MONSTER in coincidence

2) Projection on the E_γ and E^* axes



3) Multipole Decomposition Analysis : selection of dipole states



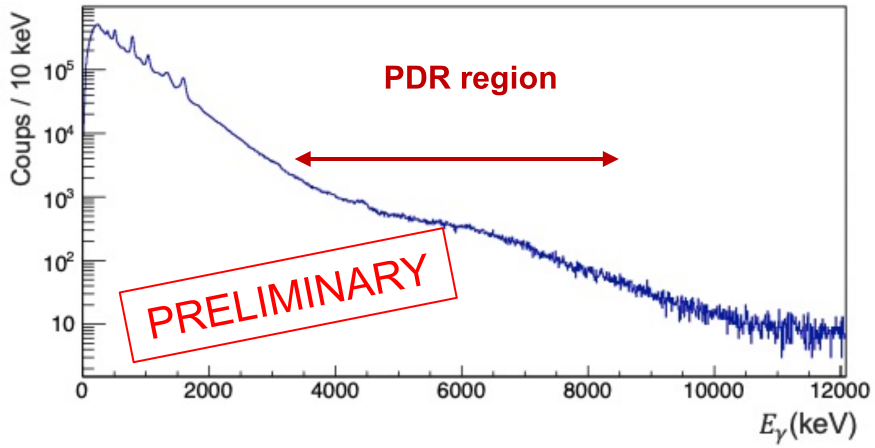


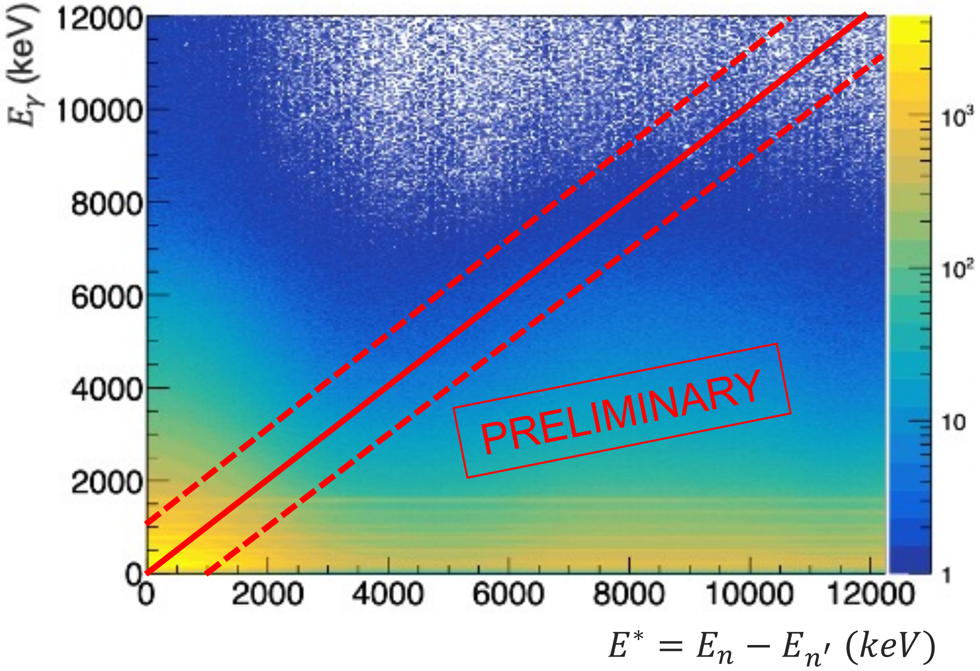
The inelastic scattering : analysis procedure

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

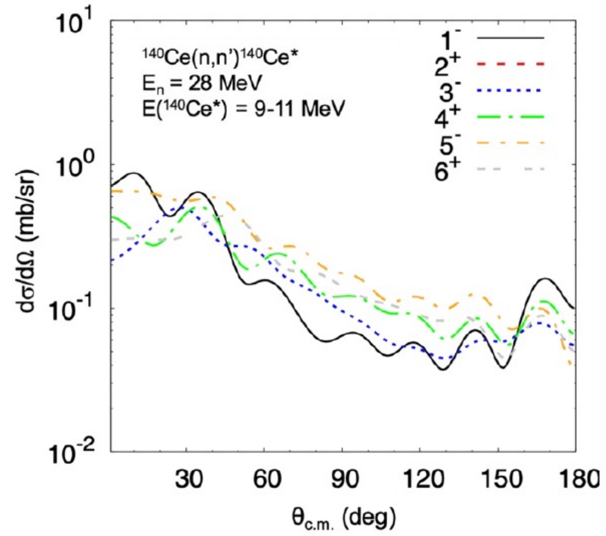
1) γ selection in PARIS - n' selection in MONSTER in coincidence

2) Projection on the E_γ and E^* axes





3) Multipole Decomposition Analysis : selection of dipole states



4) PDR states and cross-sections

Thank you for your attention !

P. Miriot-Jaubert
M. Vandebrouck
D. Doré
I. Matea
X. Ledoux

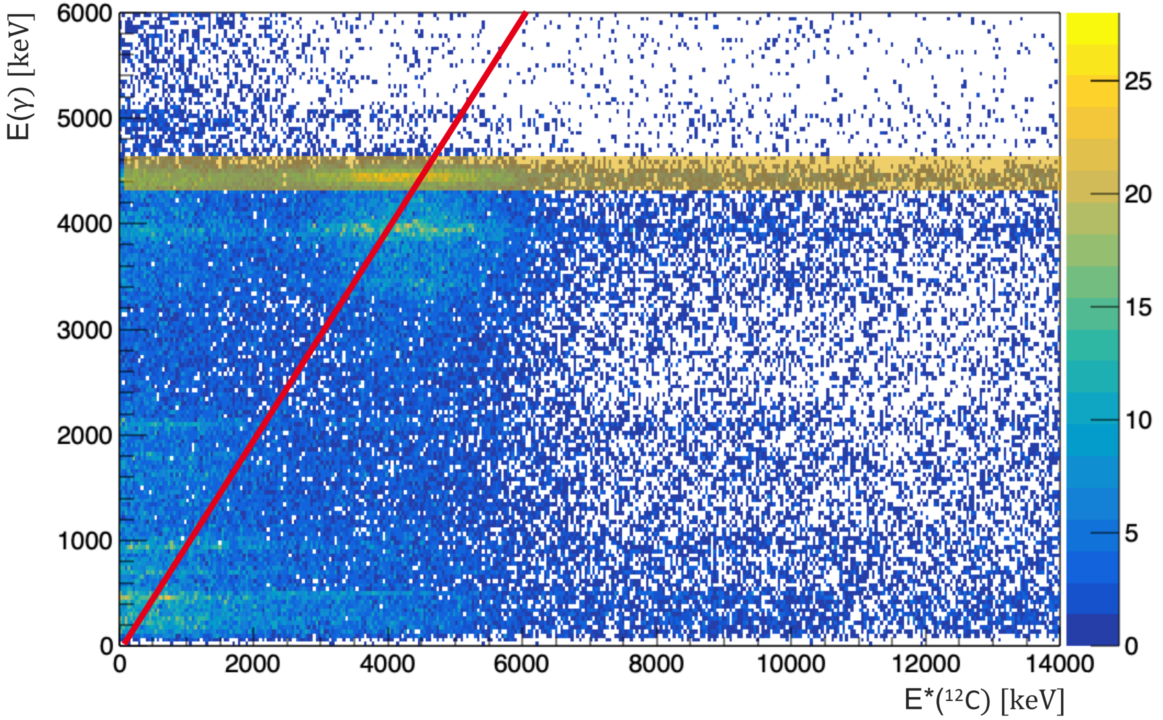
PARIS and MONSTER collaborations

ANNEXES

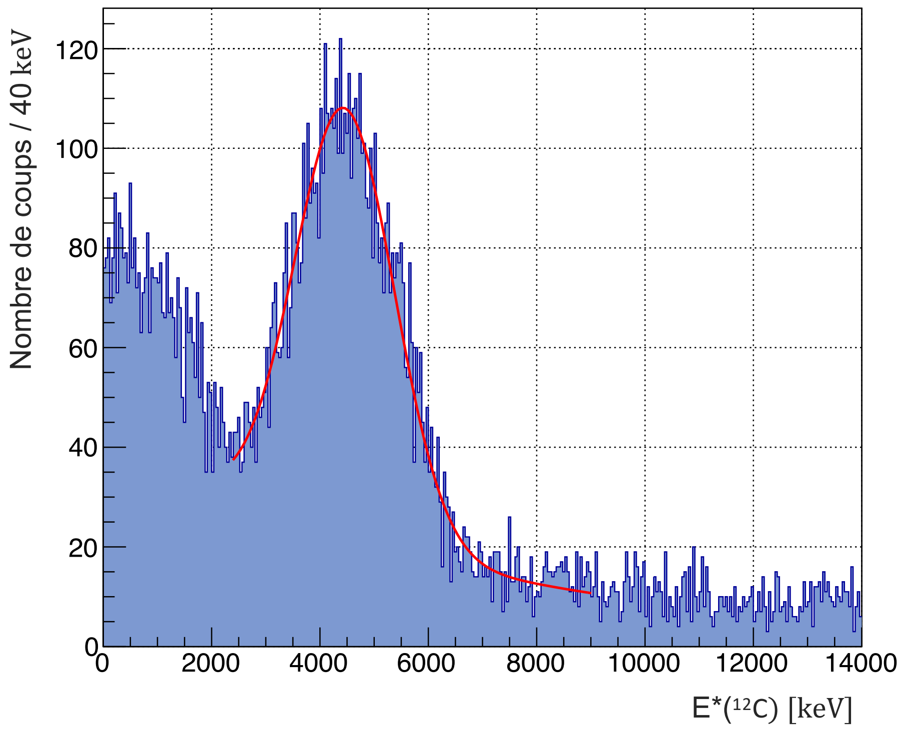
Diffusion inélastique sur le Carbone

Diffusion inélastique sur le carbone : $^{12}C(n,n')^{12}C^*(\gamma)^{12}C$

Etude de l'état excité à 4.439 MeV

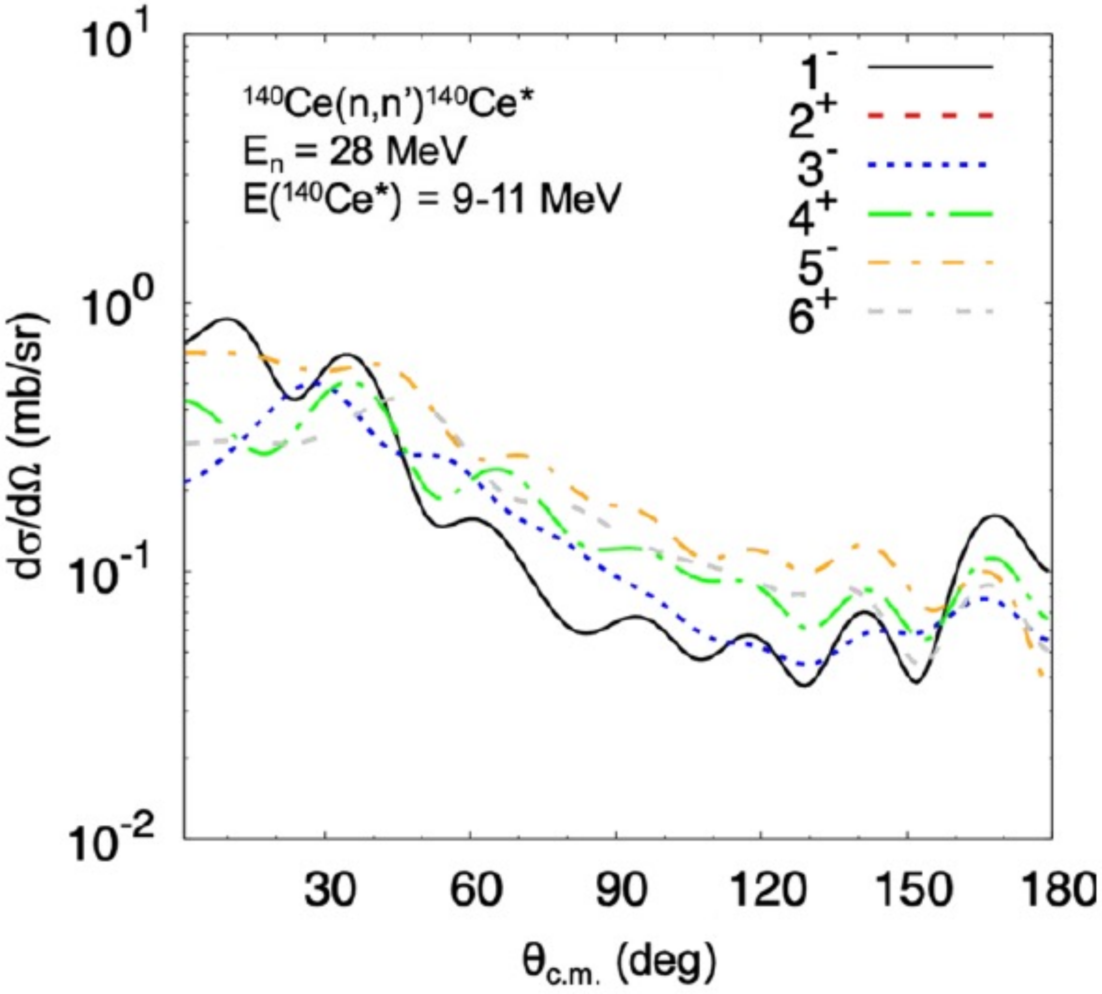


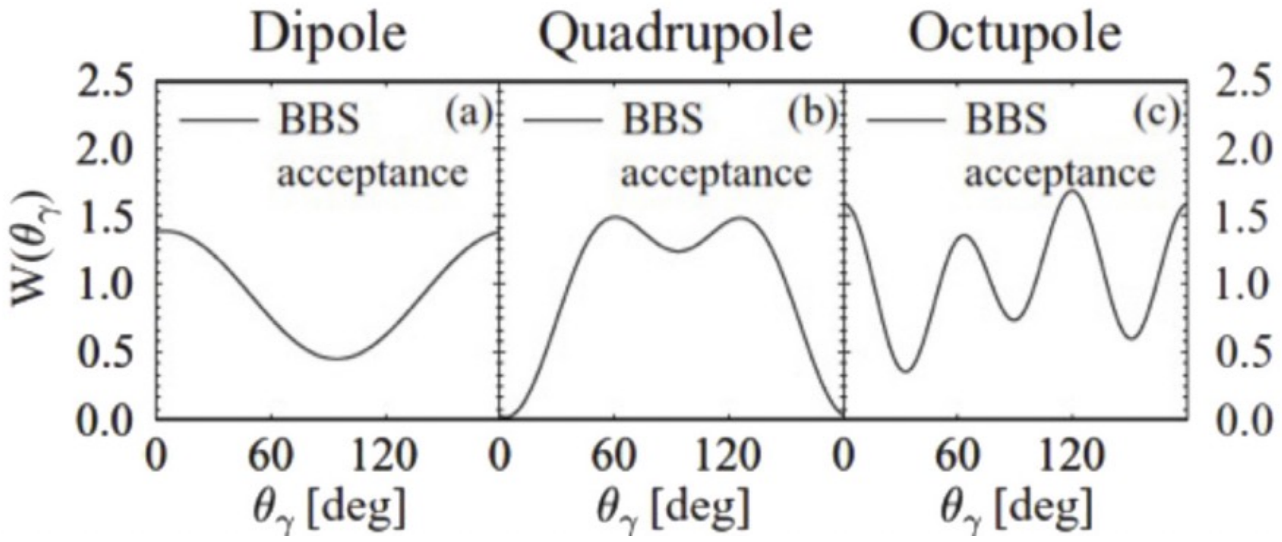
Projection sur E*(^{12}C)



Valeur moyenne : 4454 +/- 30 keV
FWHM : 922 +/- 32 keV

Multipole decomposition



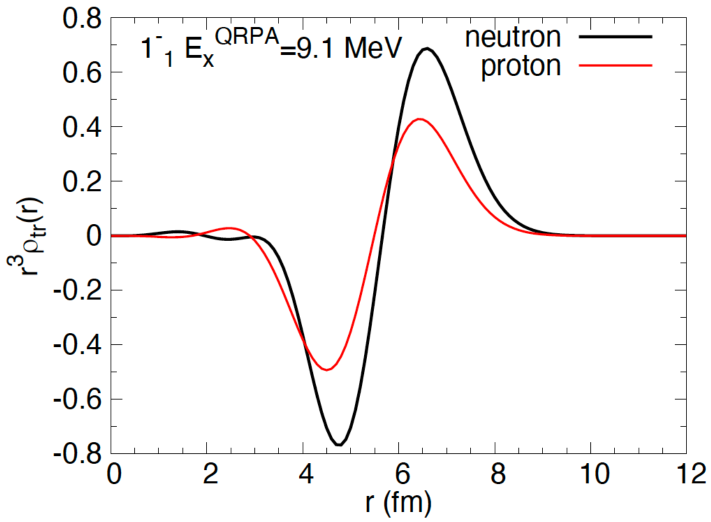


$$\frac{d\sigma^2}{d\Omega_\alpha d\Omega_\gamma} = \frac{1}{4\pi}\frac{\Gamma_0}{\Gamma}W(\Omega_\gamma)\frac{d\sigma}{d\Omega_\alpha}$$

*A. Bracco, E.G. Lanza and A. Tamii, Phys. Rev. B **106**, 360-433 (2019).*

Microscopic calculations

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



Transition densities :
inputs for the inelastic cross sections calculations

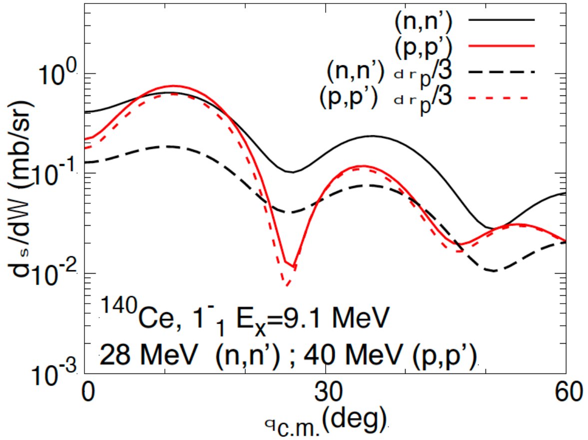


Figure 4: Differential cross sections as a function of the angle in the center of mass for the first 1^- state (predicted in HFB+QRPA calculations) in ^{140}Ce populated using the (n,n') reaction (black) and in the (p,p') reaction (red). The same differential (n,n') and (p,p') cross sections are represented with dashed lines but after a reduction of the proton transition density by a factor 3.

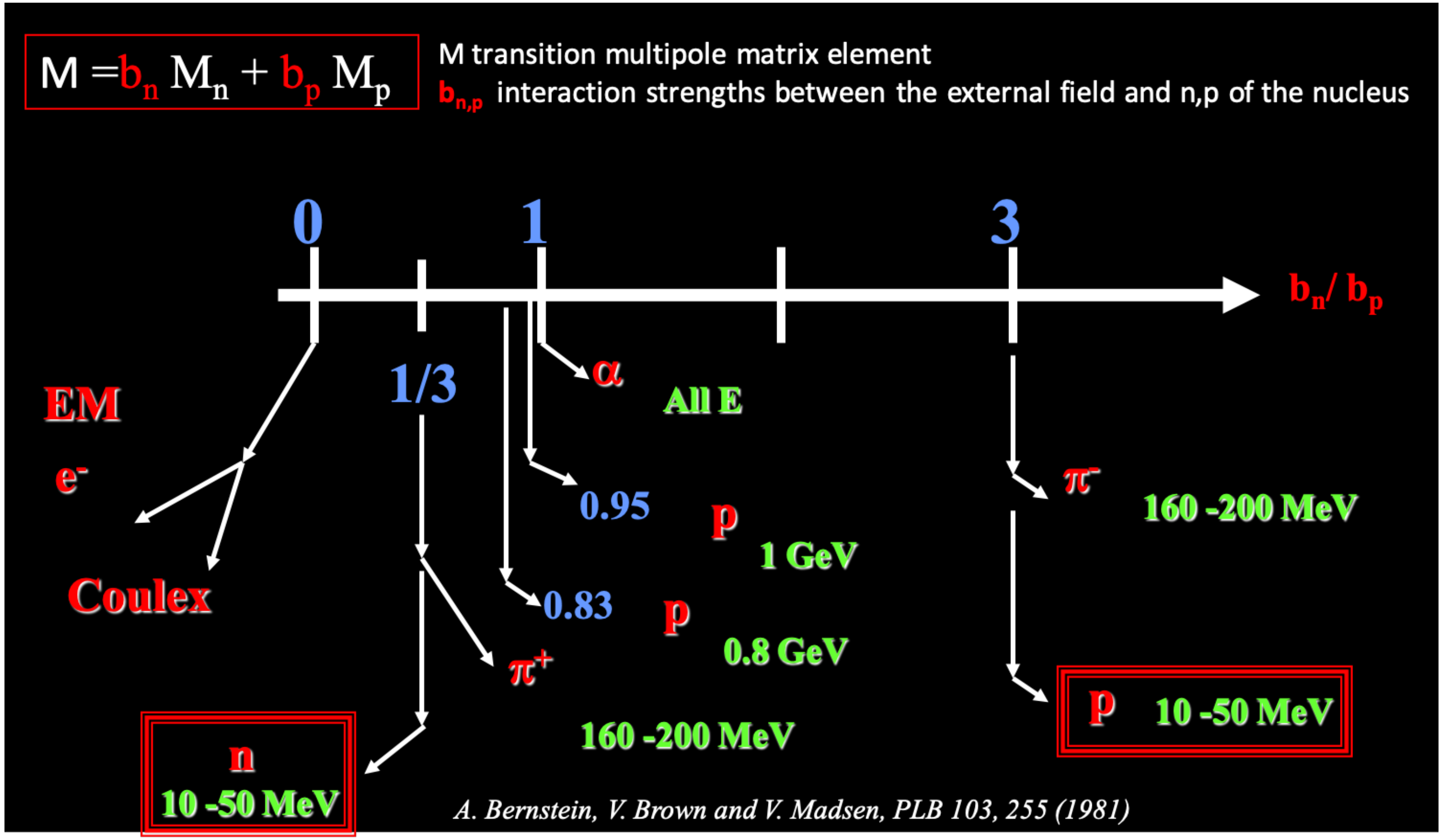
Link with experimental results

Transition density

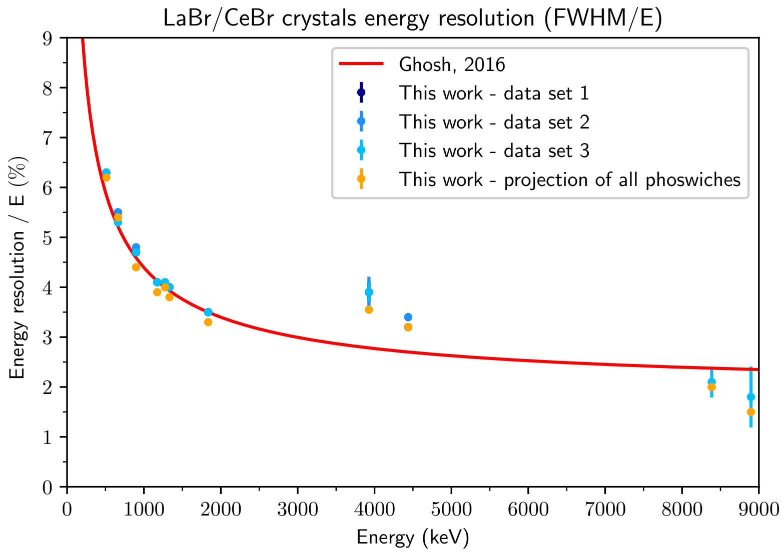
$$M_{p(n)} = \int \rho_{fi}^{p(n)}(r) r^{L+2} dr$$

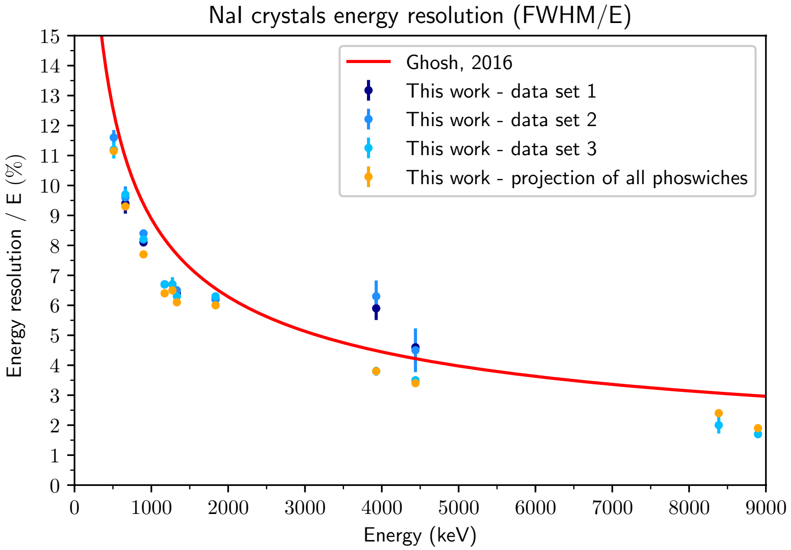
Multipole moment — Multipolarity of the transition

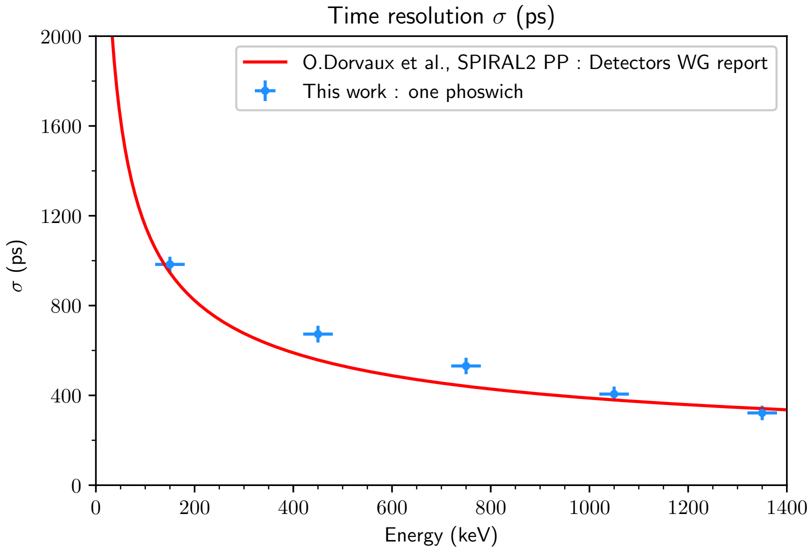
Can be more directly tested experimentally from the cross sections

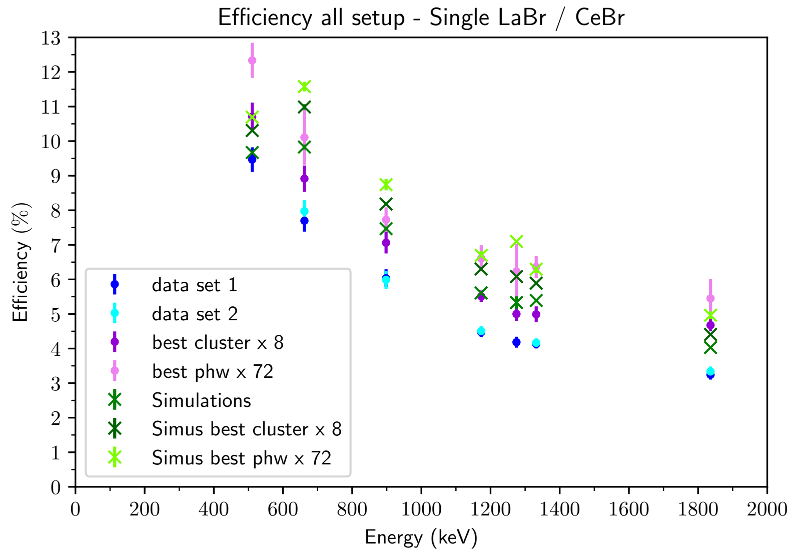


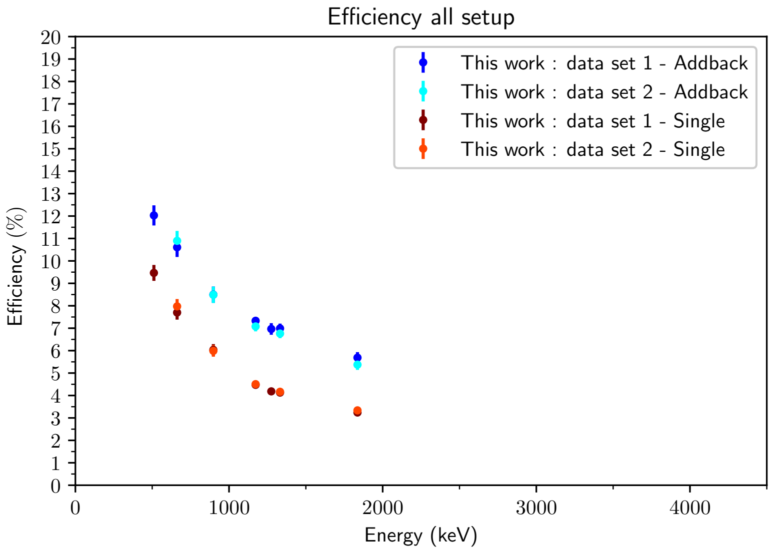
Etalonnage des détecteurs - PARIS







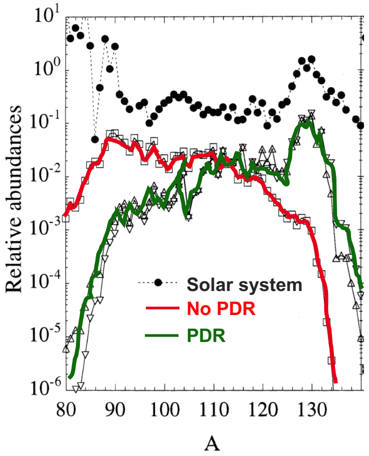




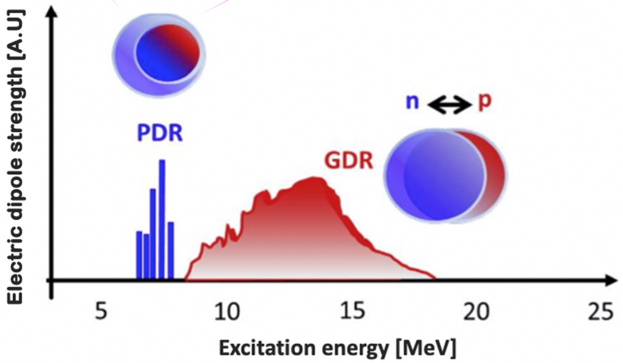
Interest ? Nuclear structure and ...

Astrophysical r-process

- ➢ Wide open doorway states in the neutron-capture process
- ➢ Enhances **radiative neutron capture rates**
- 💡 Important role for **nuclear abundances** of elements formed via this process (A ~ 130)



S. Goriely, Physics Letters B ***436*** *(1998) 10-18.*



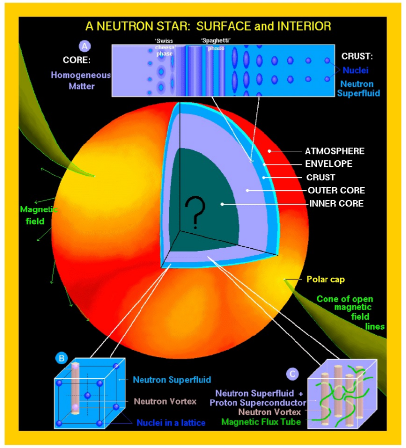
A. Bracco, E.G. Lanza and A. Tamii, Phys. Rev. B ***106****, 360-433 (2019).*

Nuclear Equation Of State (EoS)

- ➢ EoS : tool to describe nuclear matter

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,0) + S(\rho)\delta^2 + O(\delta^4)$$

- ➢ Pygmy strength correlated to the **symmetry energy** in the EoS
- 💡 Implications for **neutron-star properties**



A. Carbone et al., Phys. Rev. C ***81****, 041301 (2010).*