cea irfu

First nuclear structure measurement at GANIL-SPIRAL2/NFS :

The study of the Pygmy Dipole Resonance via neutron inelastic scattering at GANIL-SPIRAL2/NFS

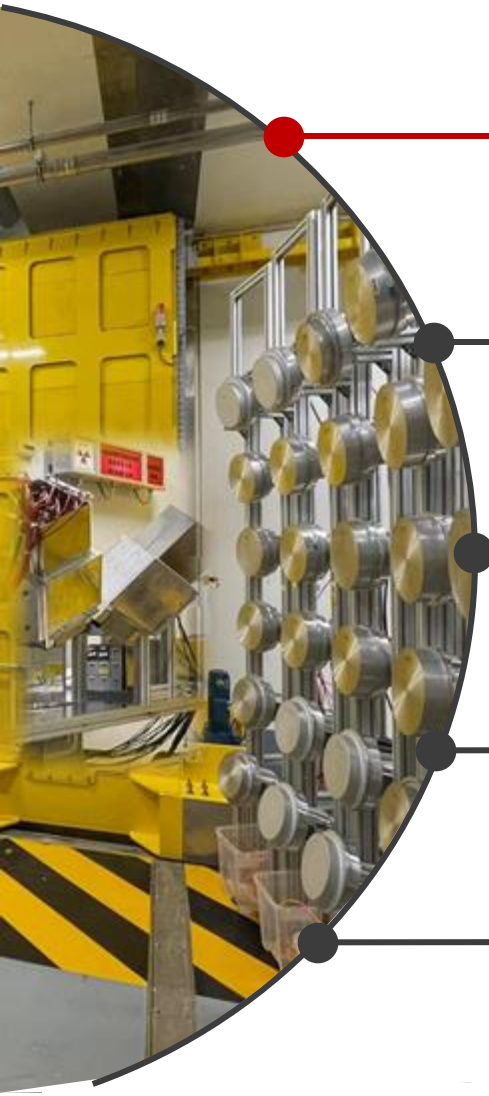
Périne MIRIOT-JAUBERT – 3^{rd} year PhD student

Thesis director : Marine VANDEBROUCK, CEA Saclay

Thesis supervisor : Iolanda MATEA, IJCLab, Orsay

PARIS and MONSTER collaborations

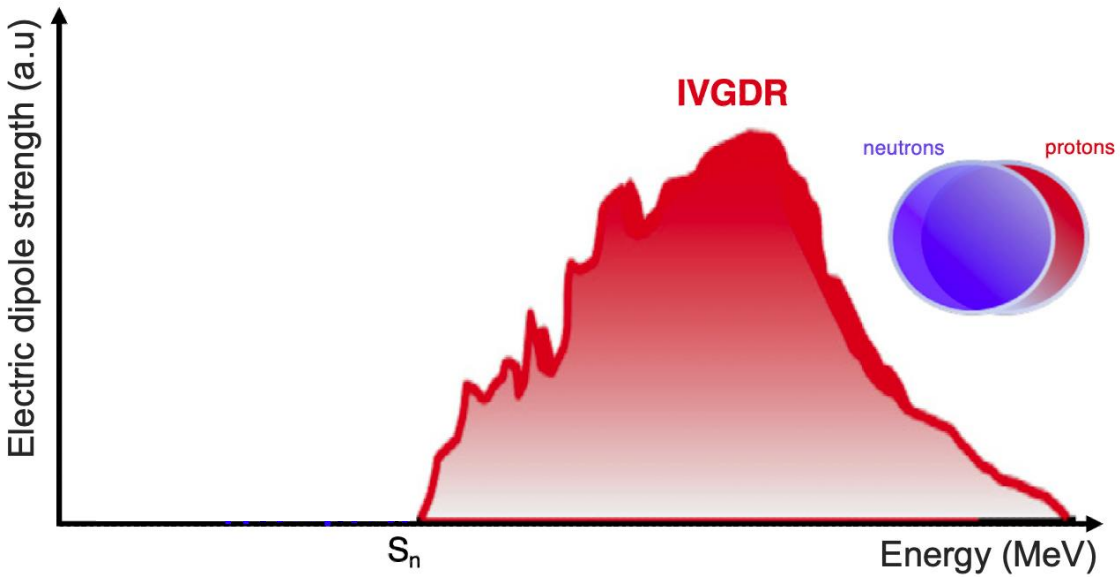
Outline – The study of the PDR in ^{140}Ce @ GANIL-SPIRAL2/NFS



- **Motivation**
- The experiment
- Analysis procedure
- Results
- Conclusion and perspectives

The Pygmy Dipole Resonance (PDR)

- **IVGDR (IsoVector Giant Dipole Resonance) :**
  - Present in **all nuclei**
  - **Collective** excitation modes with large cross-sections
  - **Macroscopic interpretation** : oscillation of the proton fluid against the neutron fluid



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

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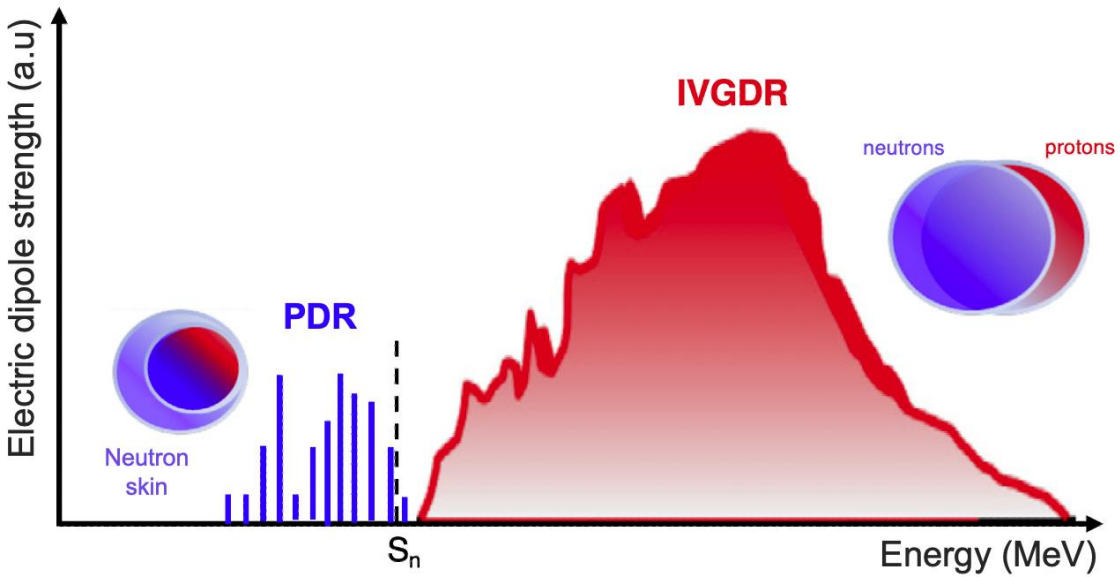

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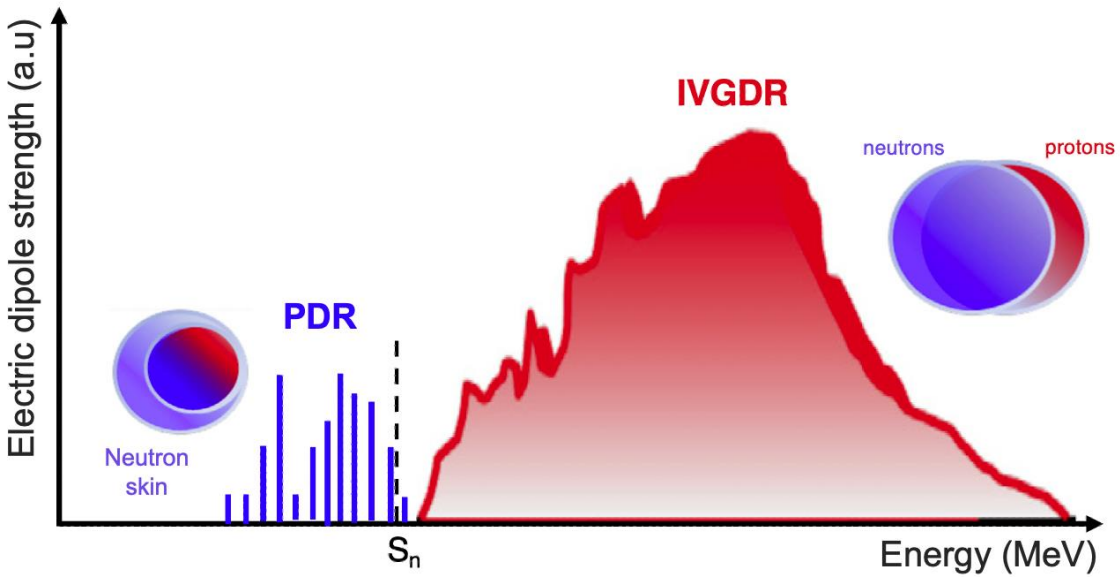

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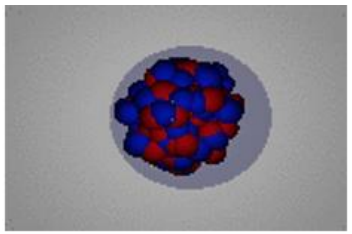
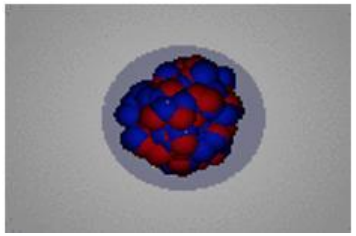
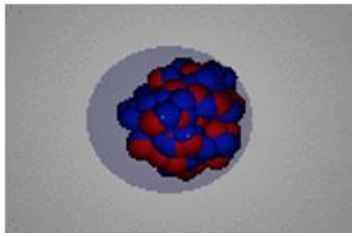
→ **Macroscopic interpretation ?**

Oscillation of a neutron skin against an isospin symetric core







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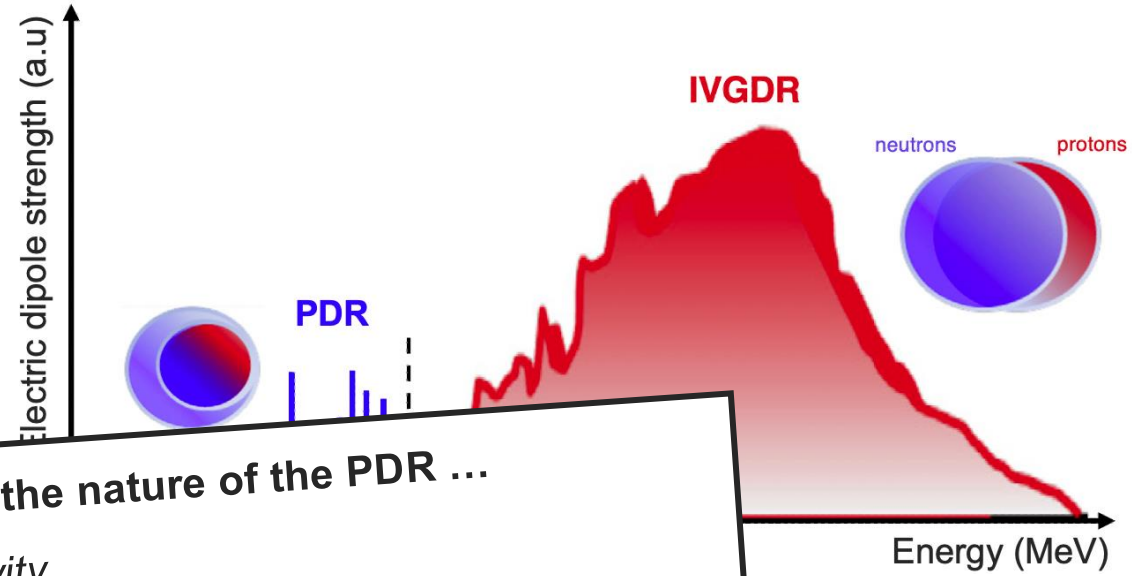


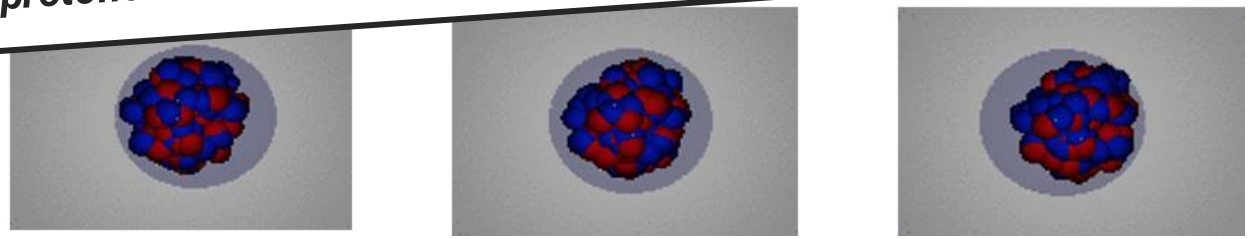
*B **106**, 360-434 (2019)]*

But still unresolved questions on the nature of the PDR …

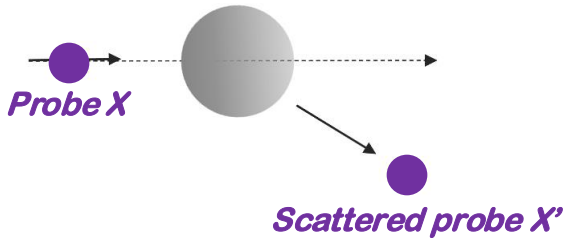
? *Collectivity*

? ***Isospin nature (Isoscalar or isovector)***

? ***Contributions of the protons and the neutrons***



Multi-messenger investigation of the PDR in ^{140}Ce



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]*

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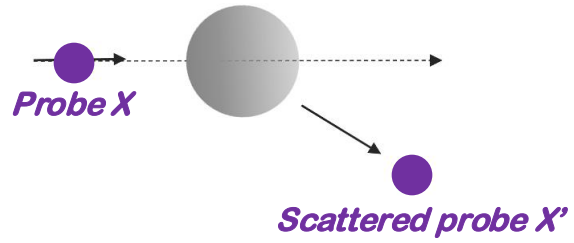

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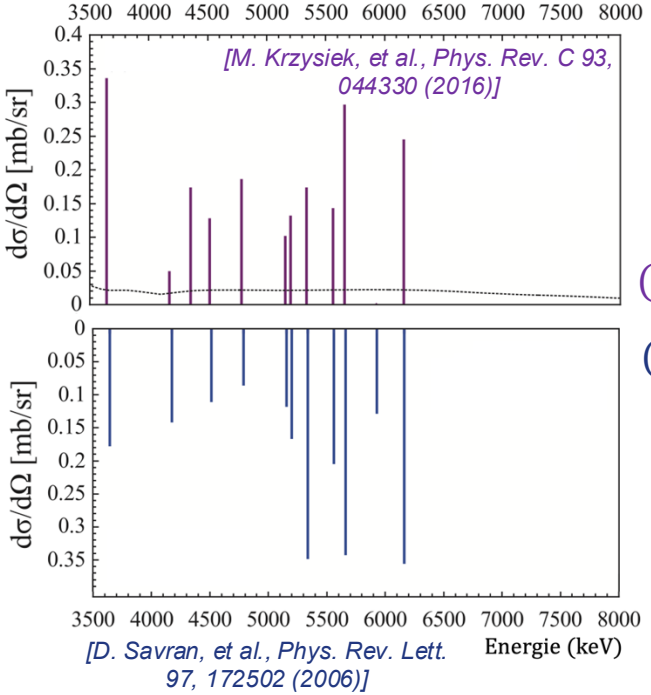


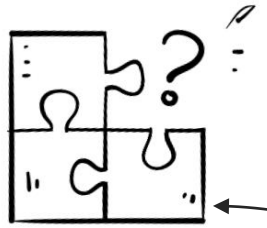
[D. Savran, et al., Phys. Rev. Lett. 97, 172502 (2006)]

$(^{17}O, ^{17}O')$

(α, α')

IS / IV
Surface / Volume
$b_n/b_p = 1$

Nature of the PDR



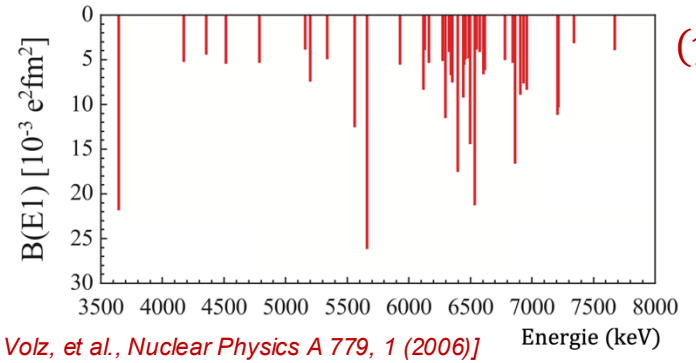
^{140}Ce

(γ, γ')

IS / IV
Surface / Volume
$b_n/b_p = 0$

(p, p')

IS / IV
Surface / Volume
$b_n/b_p = 3$



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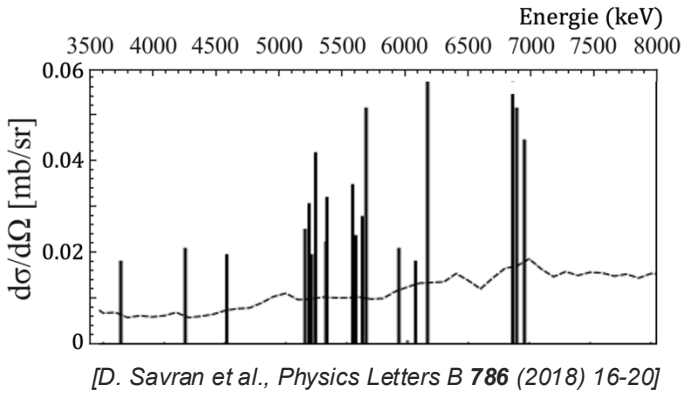

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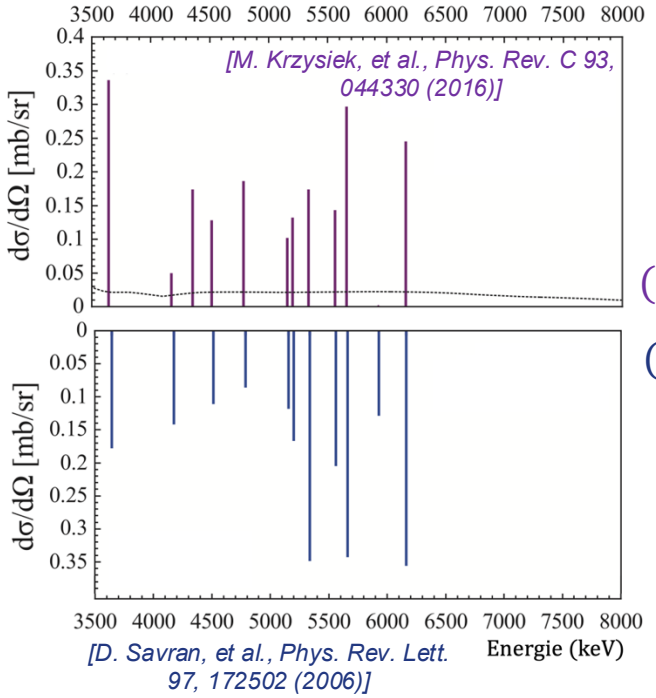

$(^{17}O, ^{17}O')$

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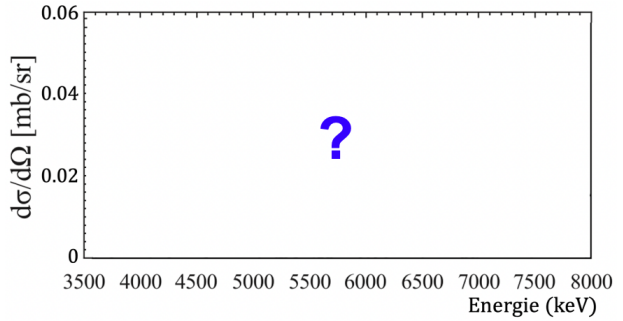
IS / IV
Surface / Volume
b_n/b_p = 1

This study: Neutron inelastic scattering (n, n')

IS / IV
Surface / Volume
b_n/b_p = 1/3



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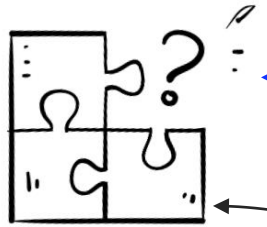
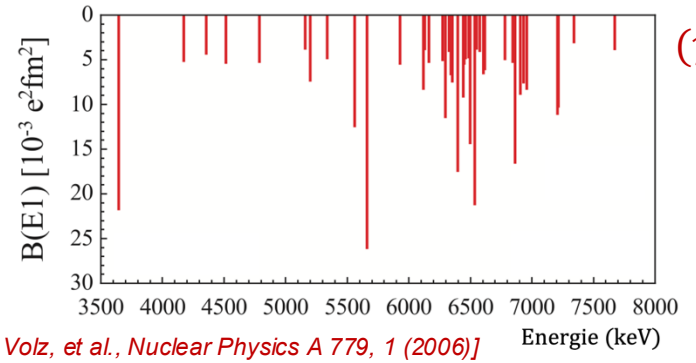


^{140}Ce



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(γ, γ')

IS / IV
Surface / Volume
b_n/b_p = 0

(p, p')

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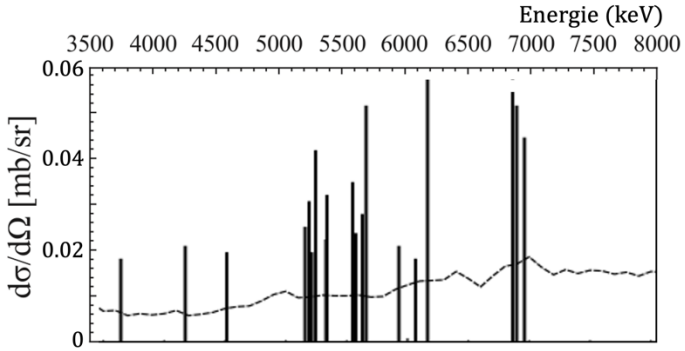

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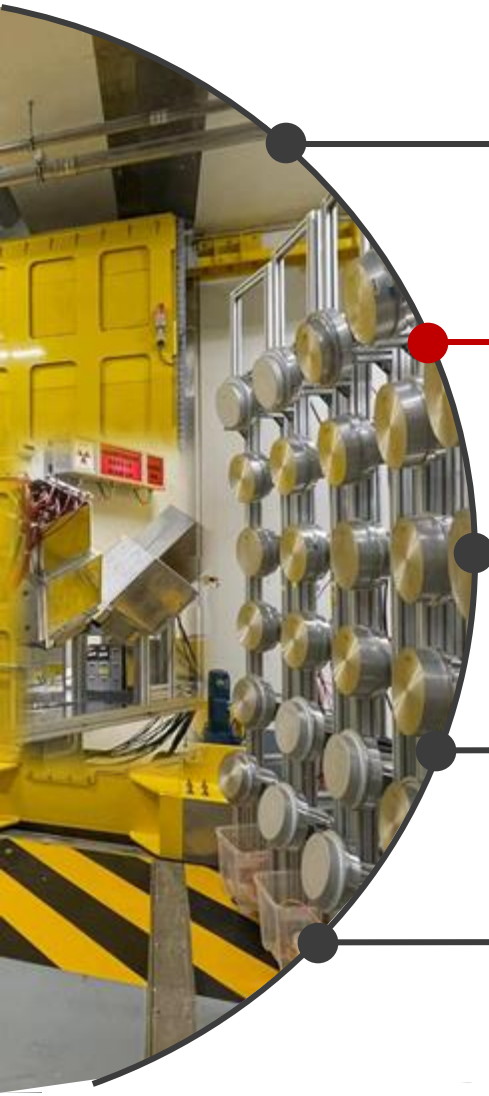
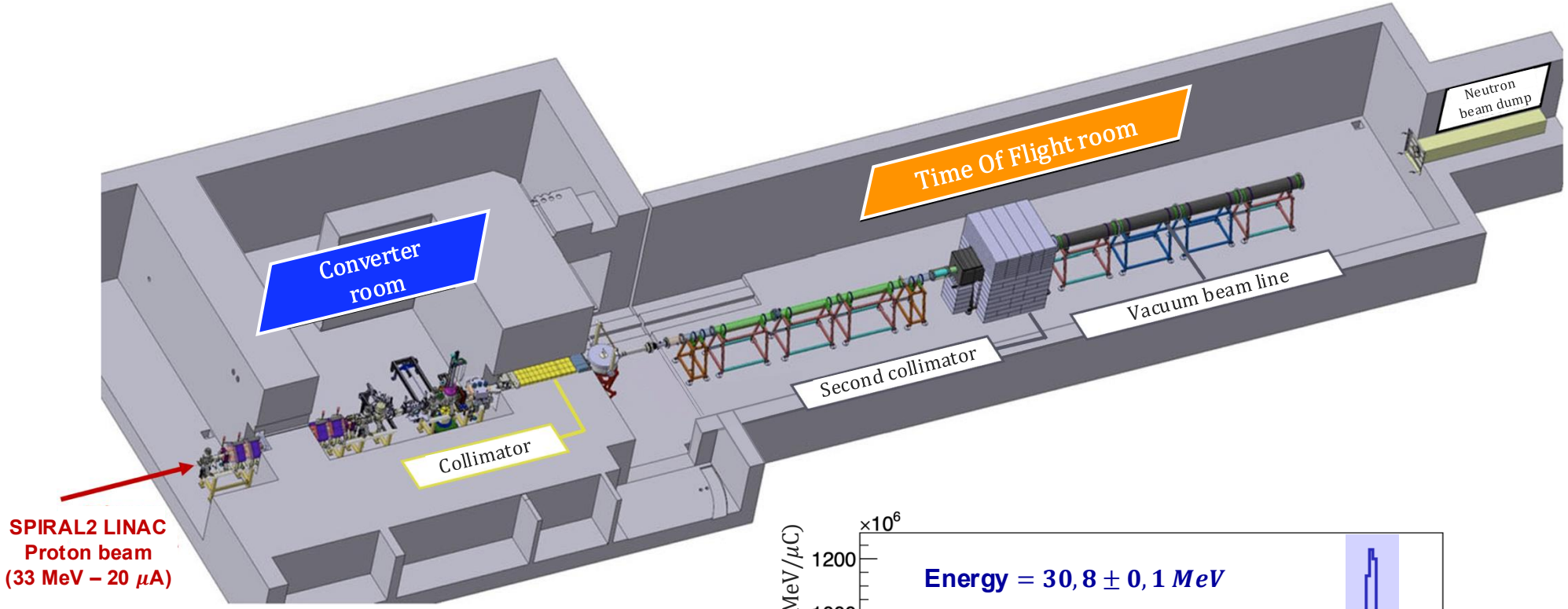


- Motivation
- **The E833 experiment at Neutrons For Science**
- Analysis procedure
- Results
- Conclusion and perspectives

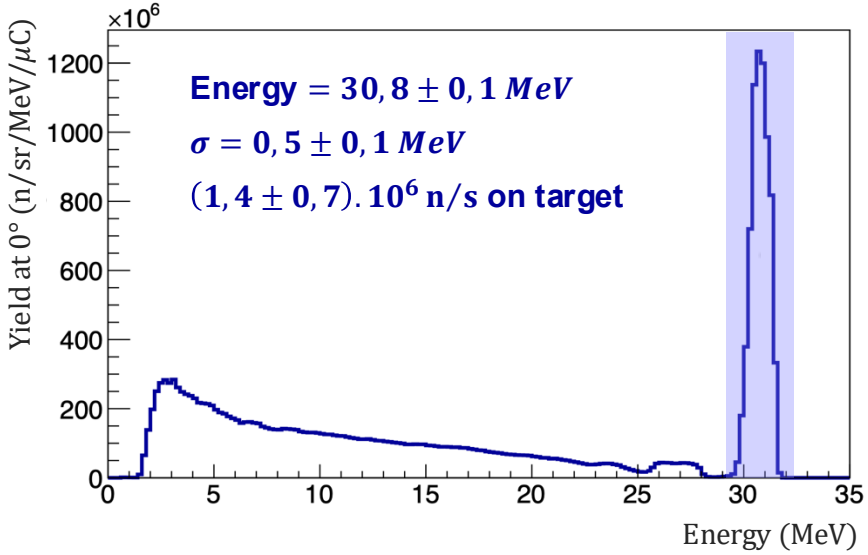
GANIL–SPIRAL2/NFS experimental area : a new opportunity



*[X. Ledoux et al., Eur. Phys. J. A, **57**, 257 (2021)]*

Generation of the neutron beam via the charge exchange reaction :

$^{7}Li(p,n)^{7}Be$



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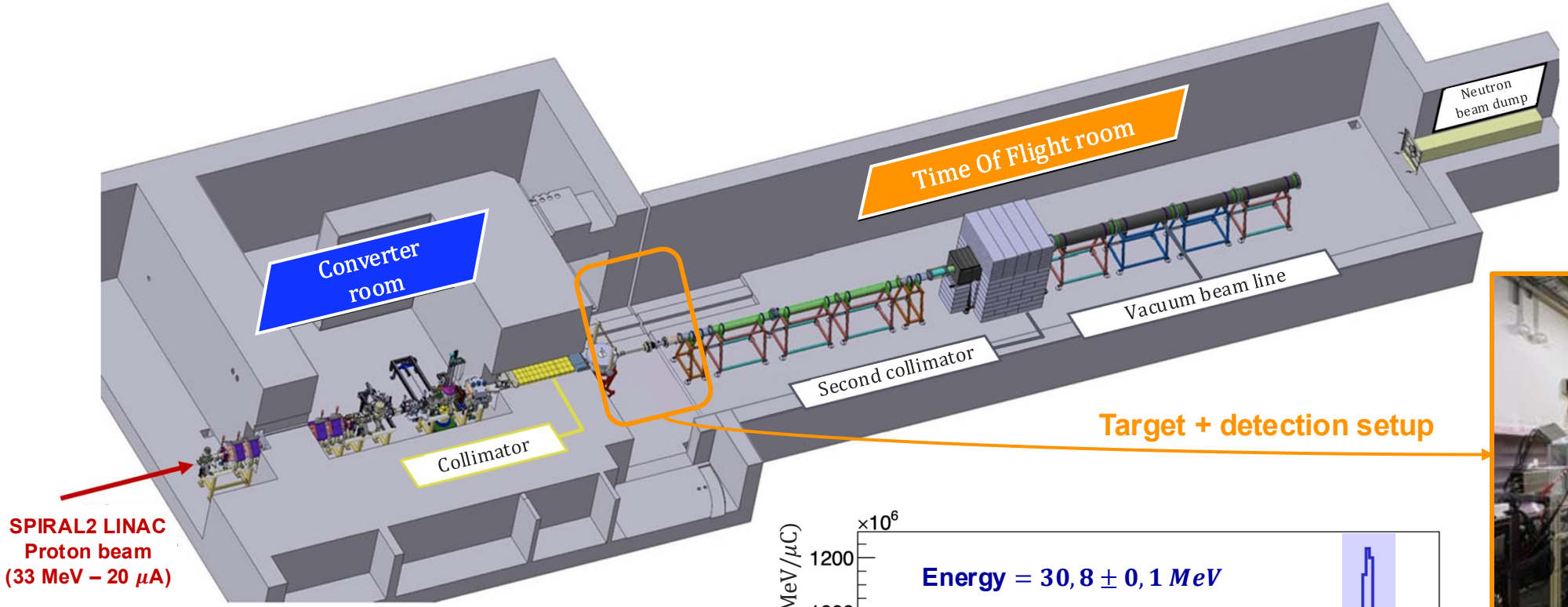

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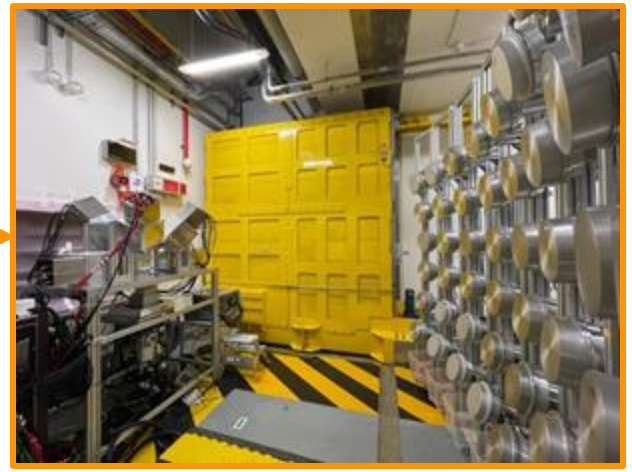
Target + detection setup



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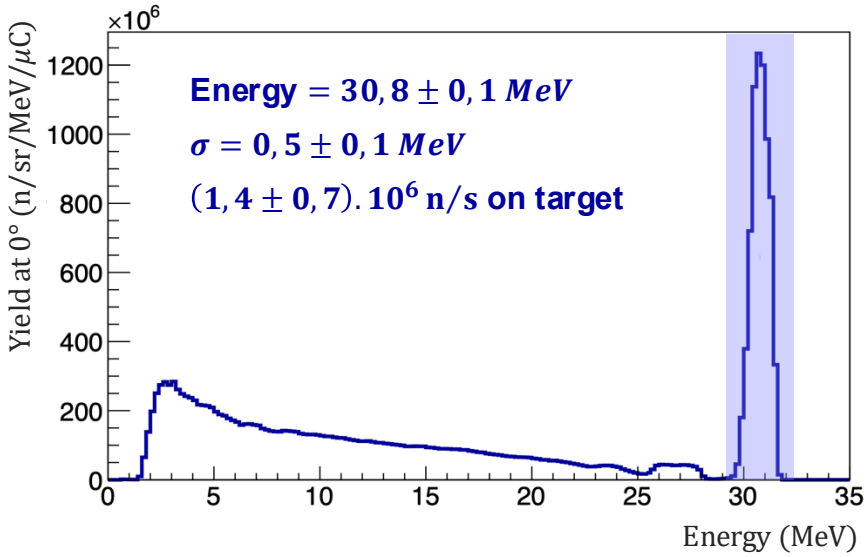

The experimental setup – E833 experiment (Sept. 2022)

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

^{nat}Ce(n,n')^{nat}Ce*(γ)^{nat}Ce

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MONSTER modules (x 48) : n' detection

Liquid scintillators (BC501A / EJ301)

Angular coverage: 3 – 36°

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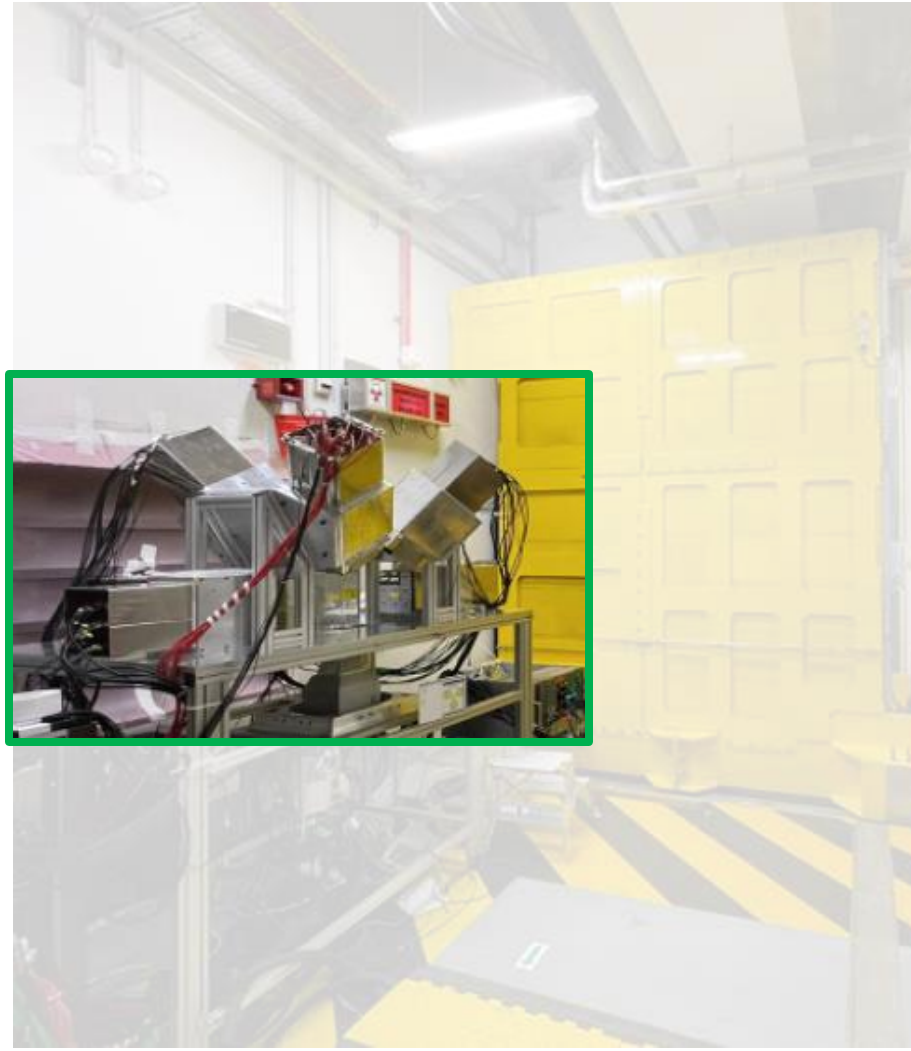

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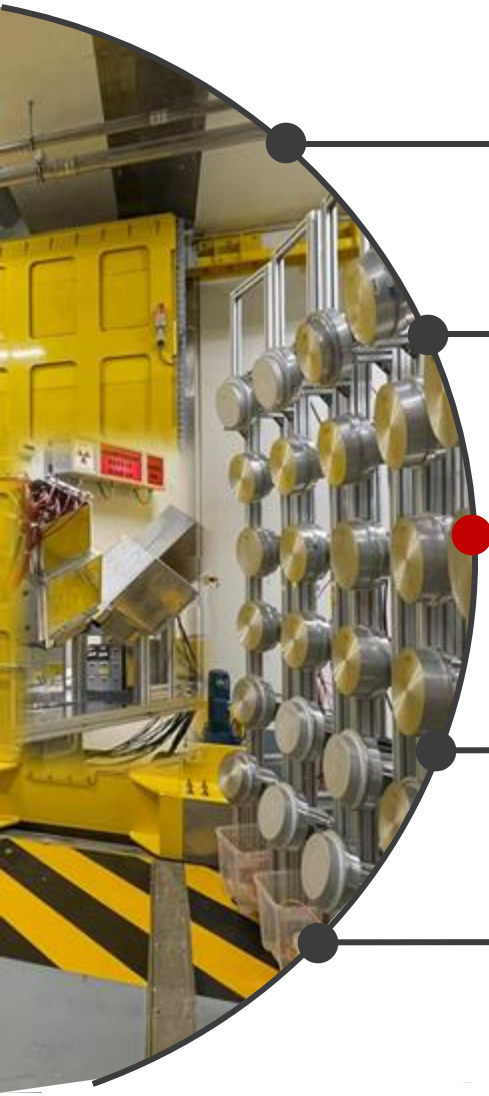
PARIS clusters (x 8) : détection γ

Scintillation cristals ($LaBr_3$:Ce / $CeBr_3$ + NaI:Tl)
8 clusters of 9 phoswichs each

Angular coverage: 45 – 165°

Outline – The study of the PDR in ^{140}Ce @ GANIL-SPIRAL2/NFS



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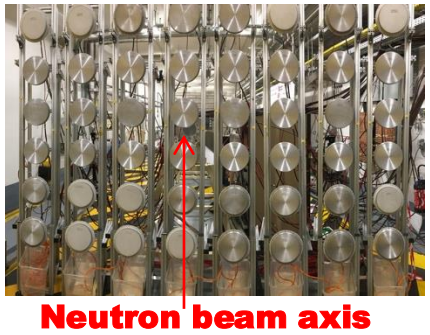
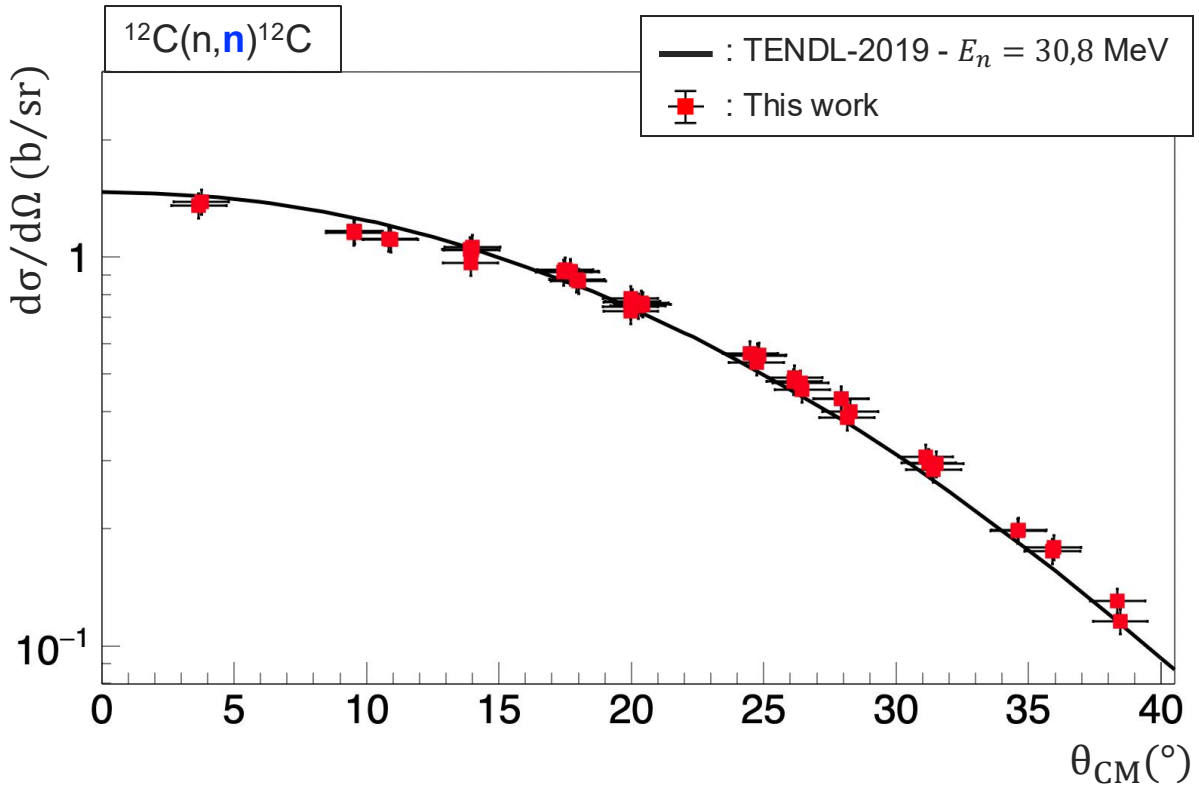
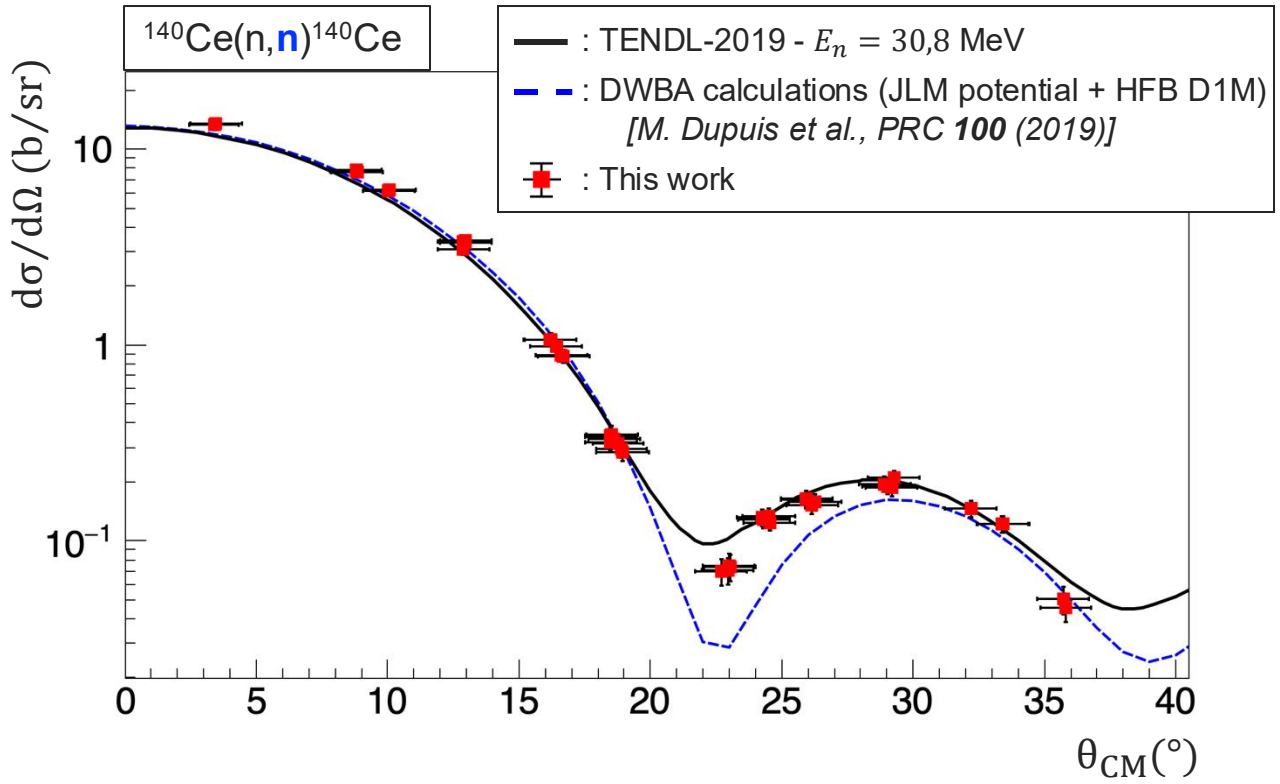
Elastic scattering analysis

✓ Validation of the analysis method for the **reconstruction of the scattered neutron**







Inelastic scattering analysis : ^{140}Ce(n,n')^{140}Ce*(γ)^{140}Ce

1/ Experimental studies
Scattering reactions

2/ Observables
Excitation energy - Angular distributions

3/ Interpretation
Comparison to microscopic calculations

Remark : Analysis procedure successfully validated using carbon as a benchmark

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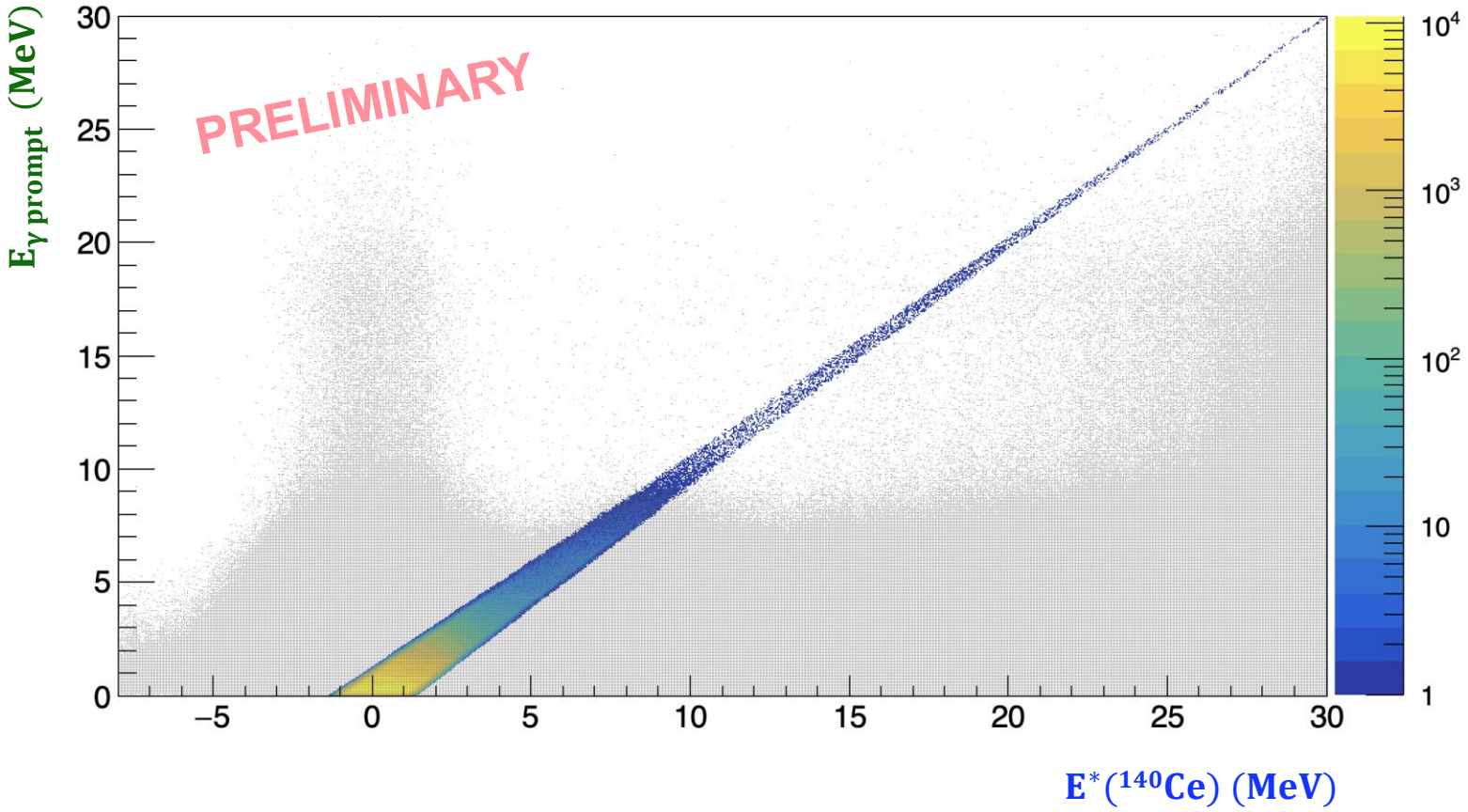

- Gate on the diagonal of the coincidence matrix to select **direct decays** to the ground state
- Resolution in energy does not allow to study single states => analysis for **200 keV slices** in energy

Inelastic scattering analysis : ^{140}Ce(n,n')^{140}Ce*(γ)^{140}Ce

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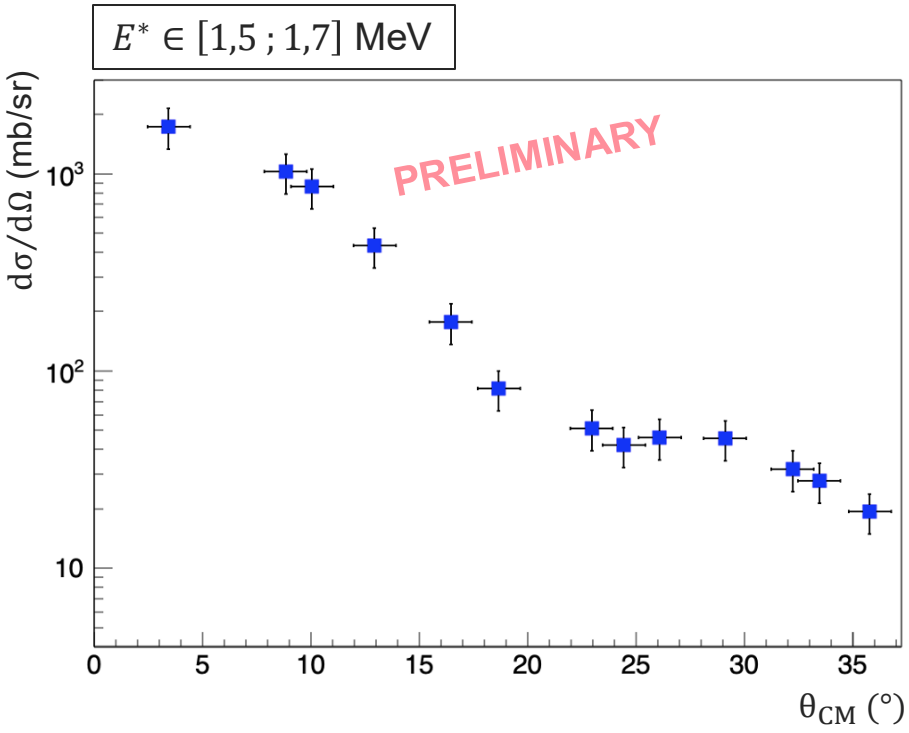
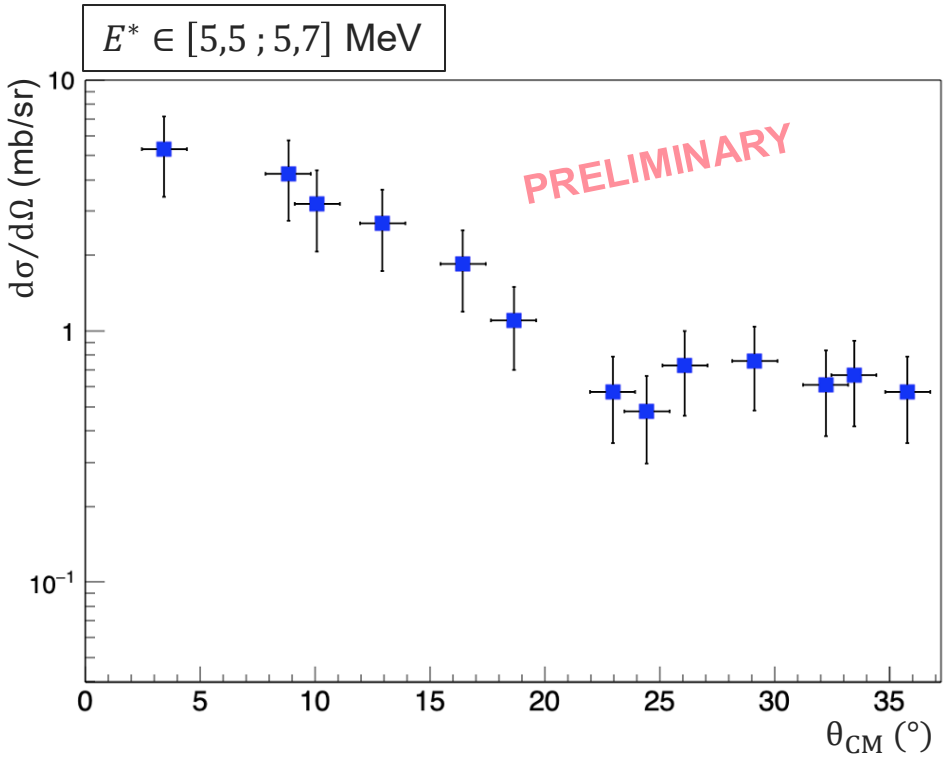
For each slice in energy : **angular distributions** for the scattered neutrons n' and ~~the γ rays~~





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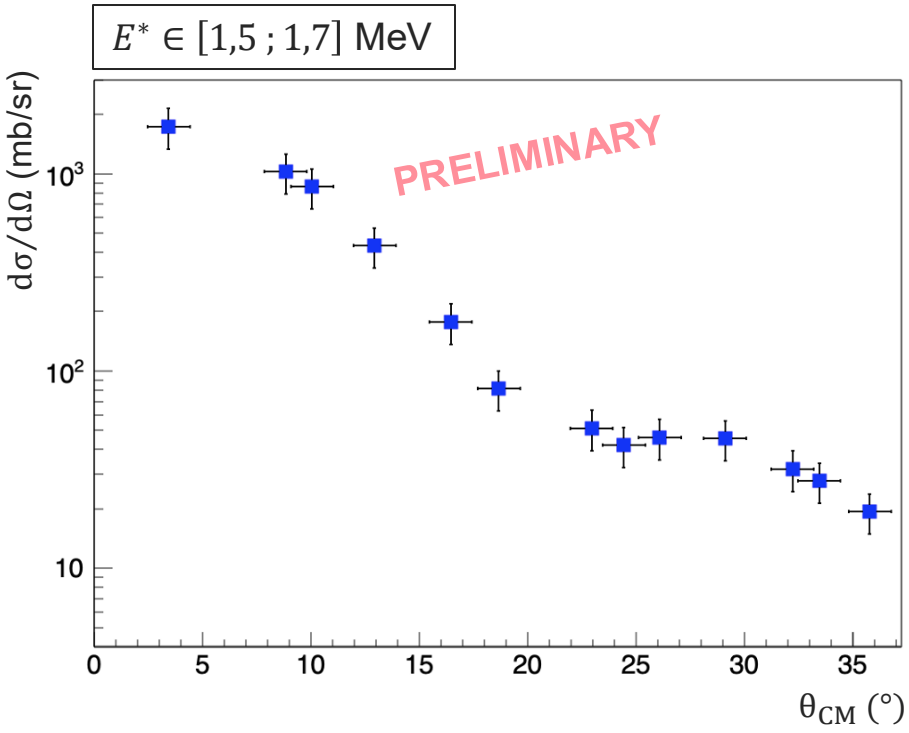

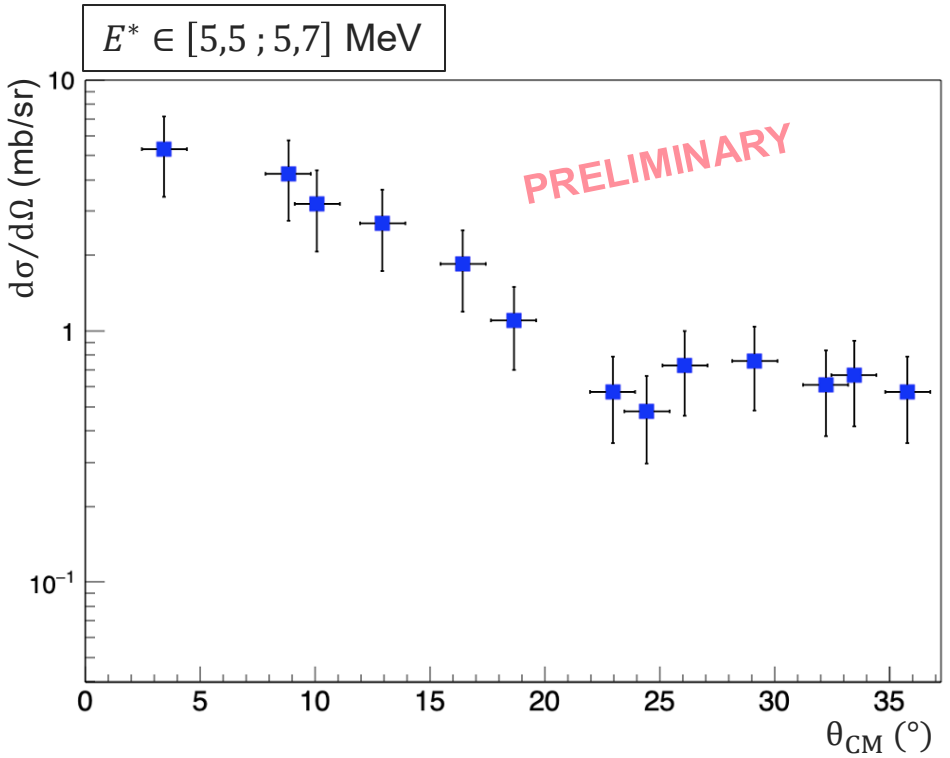

Contributions ?

1) Elastic scattering
= source of background

2) Excited states from several { multipolarities, isospin

Inelastic scattering analysis : ^{140}Ce(n,n')^{140}Ce*(γ)^{140}Ce

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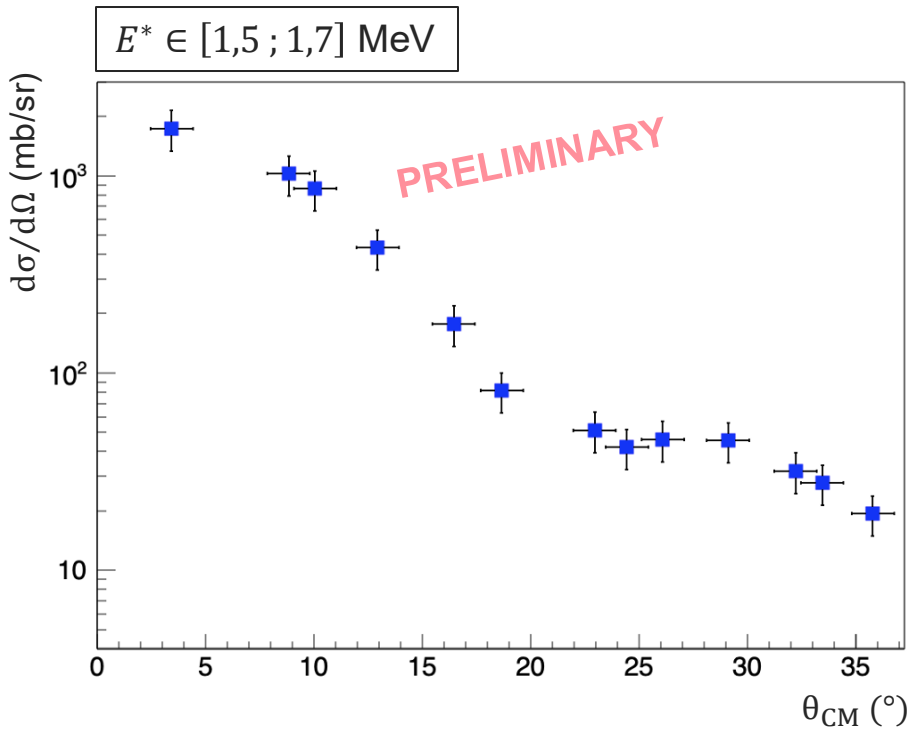
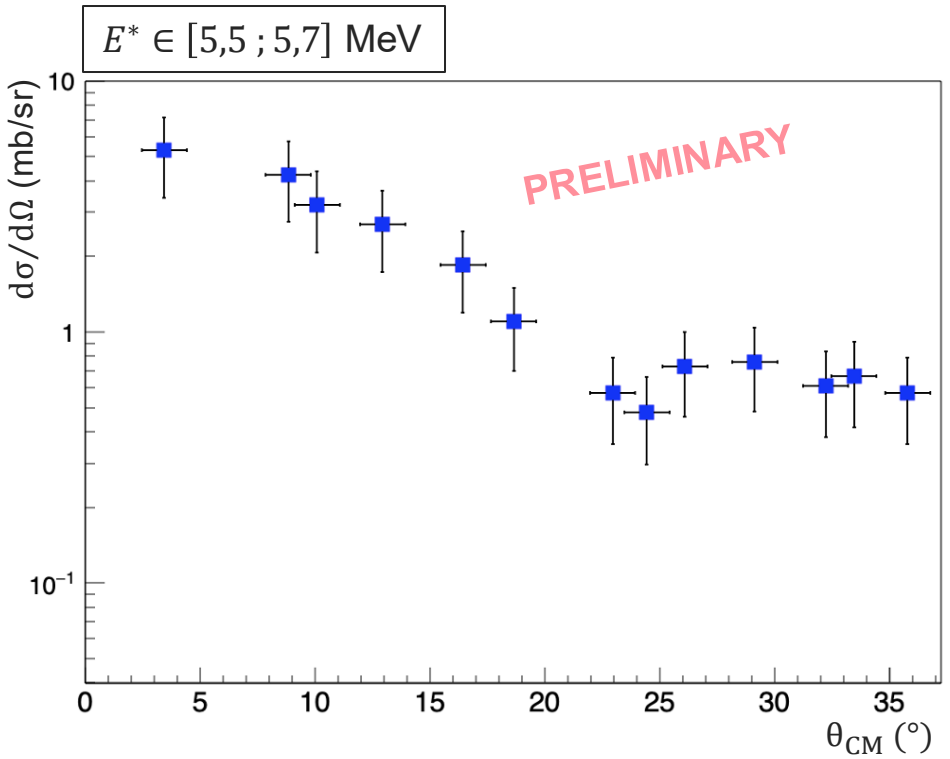
3/ Interpretation
Comparison to microscopic calculations

For each slice in energy : **angular distributions** for the scattered neutrons n' and ~~the γ rays~~





Contributions ?

1) Elastic scattering
= source of background

2) Excited states from several { multipolarities, isospin

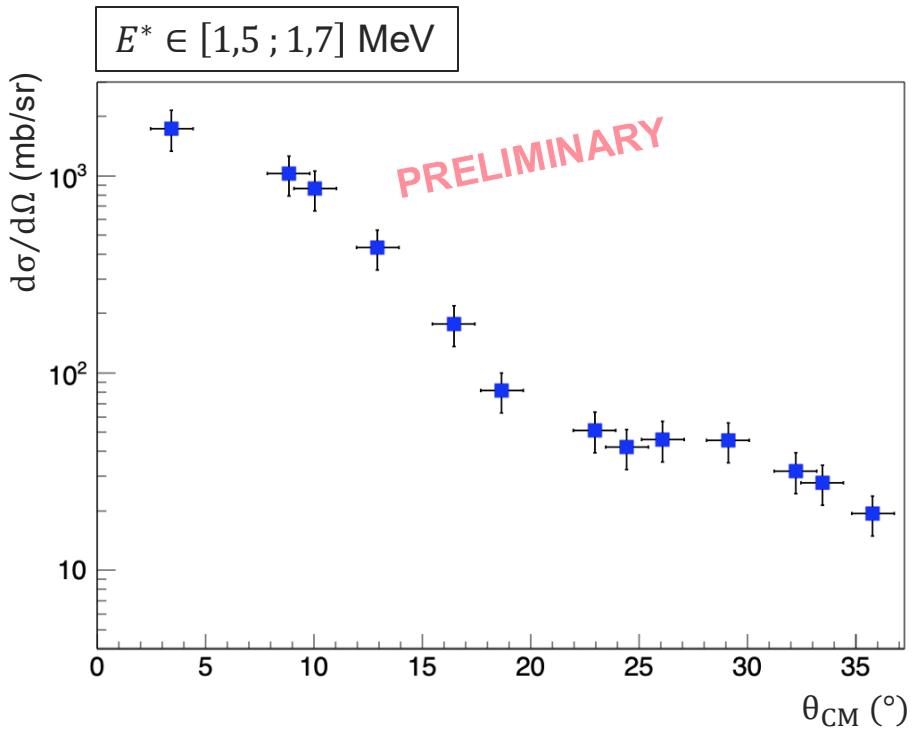
Inelastic scattering analysis : ^{140}Ce(n,n')^{140}Ce*(γ)^{140}Ce

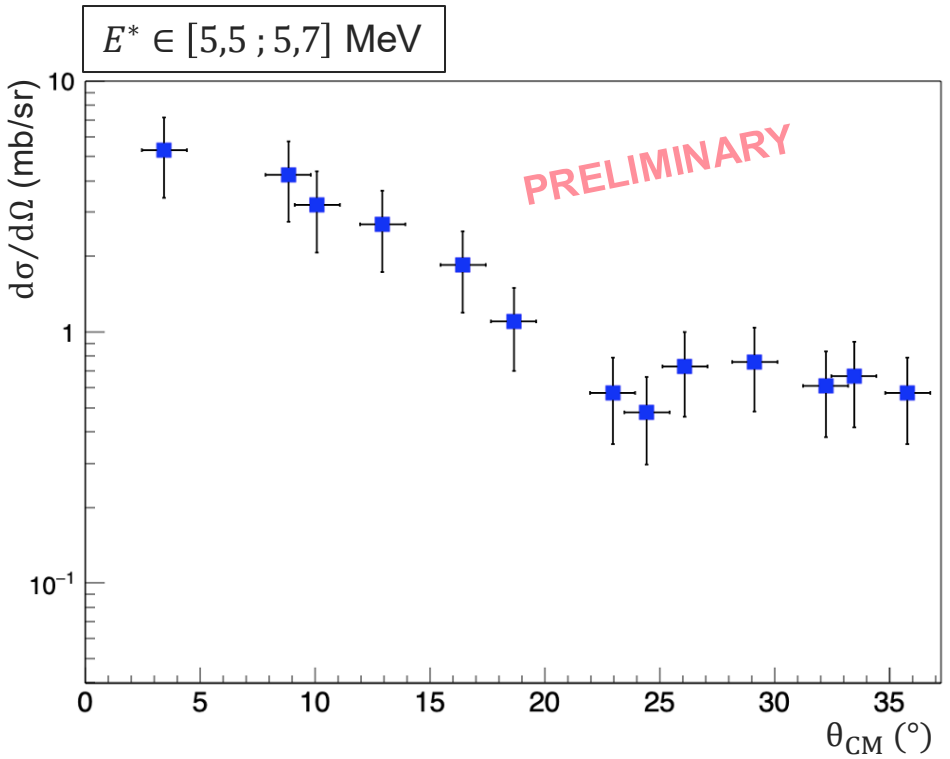
1/ Experimental studies
Scattering reactions

2/ Observables
Excitation energy - Angular distributions

3/ Interpretation
Comparison to microscopic calculations

For each slice in energy : **angular distributions** for the scattered neutrons n' and ~~the γ rays~~





Contributions ?

1) Elastic scattering
= source of background

2) Excited states from several { multipolarities, isospin

Need **theoretical predictions** for the angular distribution of the excited states

Inelastic scattering analysis : ^{140}Ce(n,n')^{140}Ce*(γ)^{140}Ce

1/ Experimental studies
Scattering reactions

2/ Observables
Excitation energy - Angular distributions

3/ Interpretation
Comparison to microscopic calculations

Microscopic predictions for ^{140}Ce :
HFB + **QRPA**, Gogny D1M interaction
*[S. Péru and M. Martini, Eur. Phys. J. A **50**, 88 (2014)]*

Input →

Reaction model for the ^{140}Ce(n,n') reaction at $E_n = 30{,}8$ MeV :
DWBA, JLM potential + QRPA transition densities
*[M. Dupuis et al., PRC **100** (2019)]*

Inelastic scattering analysis : ^{140}Ce(n,n')^{140}Ce*(γ)^{140}Ce

1/ Experimental studies
Scattering reactions

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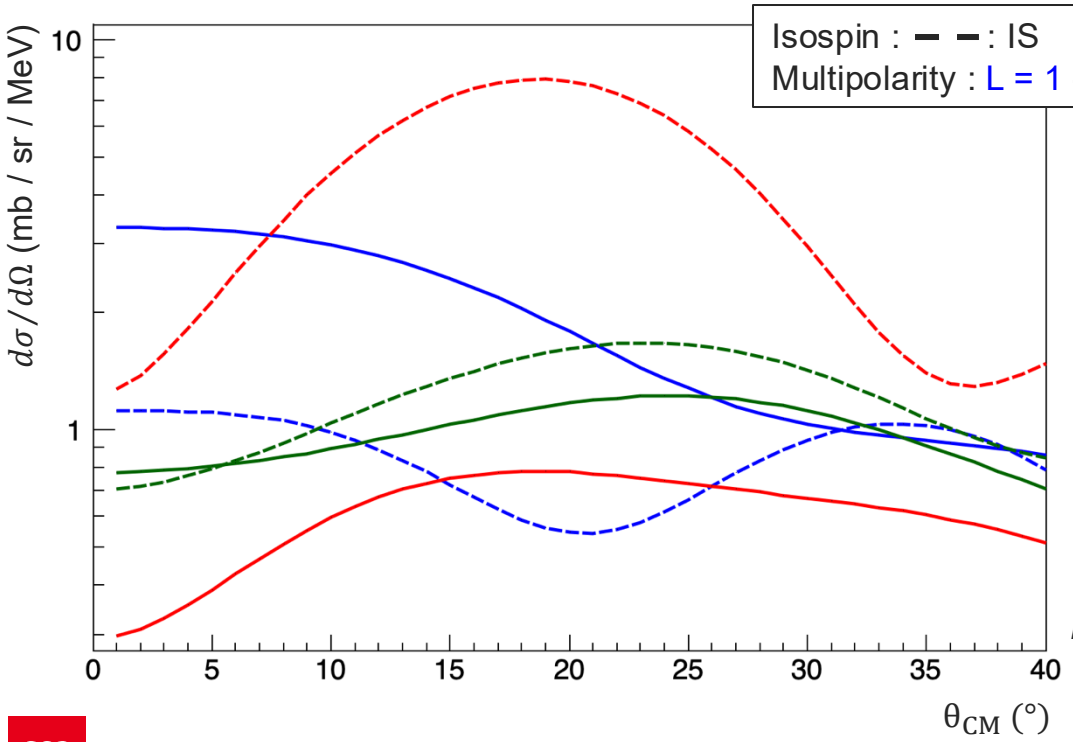


Angular distributions predicted for :

- Each multipolarity
- With and without distinction in isospin

Here : for $E^{*}_{théo} \in [14{,}9\ ;\ 15{,}1]$ *MeV*

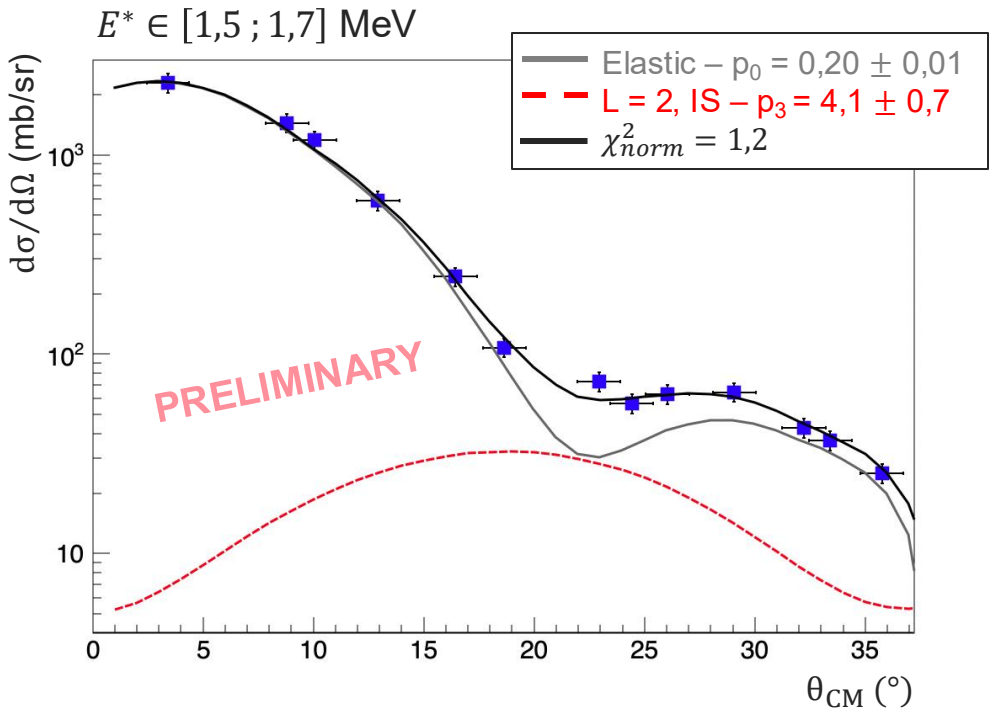
Inelastic scattering analysis : ^{140}Ce(n,n')^{140}Ce*(γ)^{140}Ce

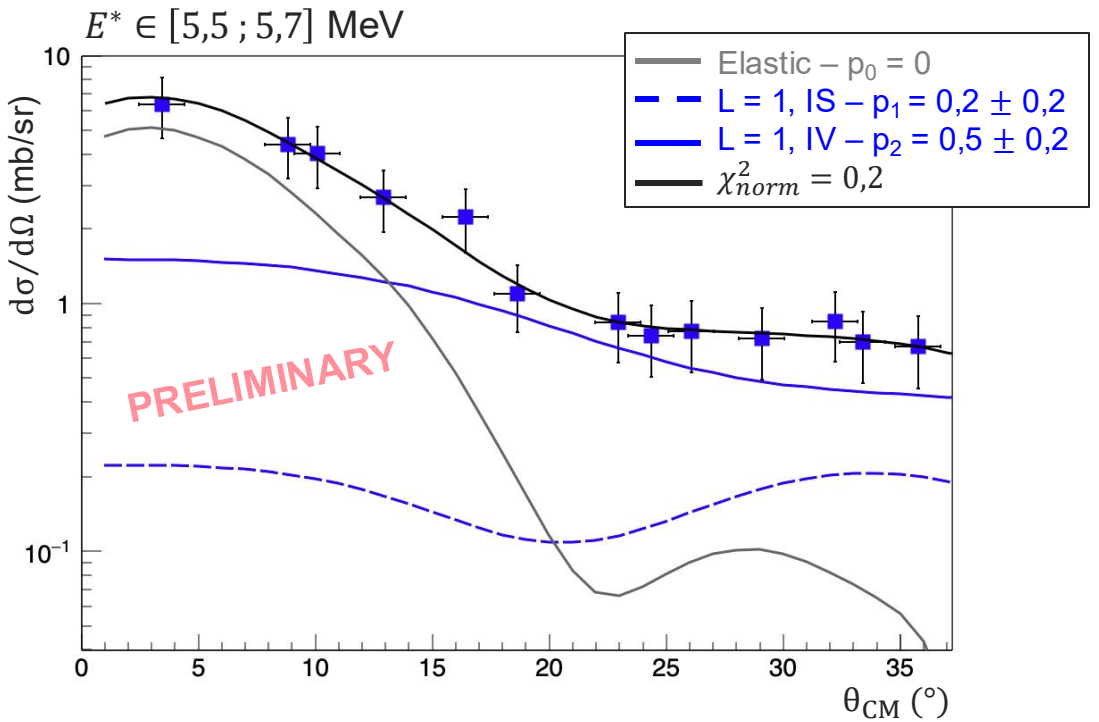
1/ Experimental studies
Scattering reactions

2/ Observables
Excitation energy - Angular distributions

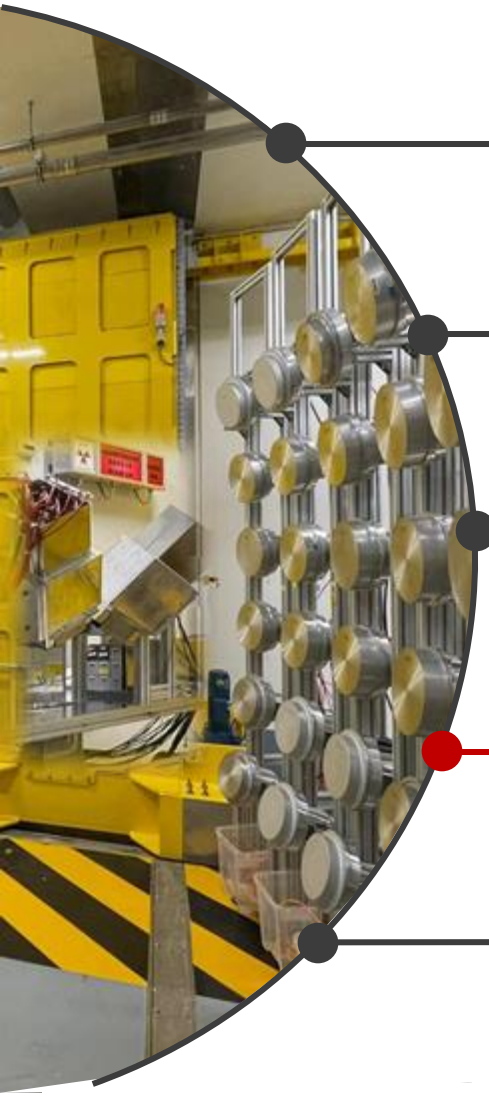
3/ Interpretation
Comparison to microscopic calculations

Multipole Decomposition Analysis : Fit of the experimental angular distribution with theoretical ones to extract, for each slice in energy, the contributions of the different multipolarities / isospin



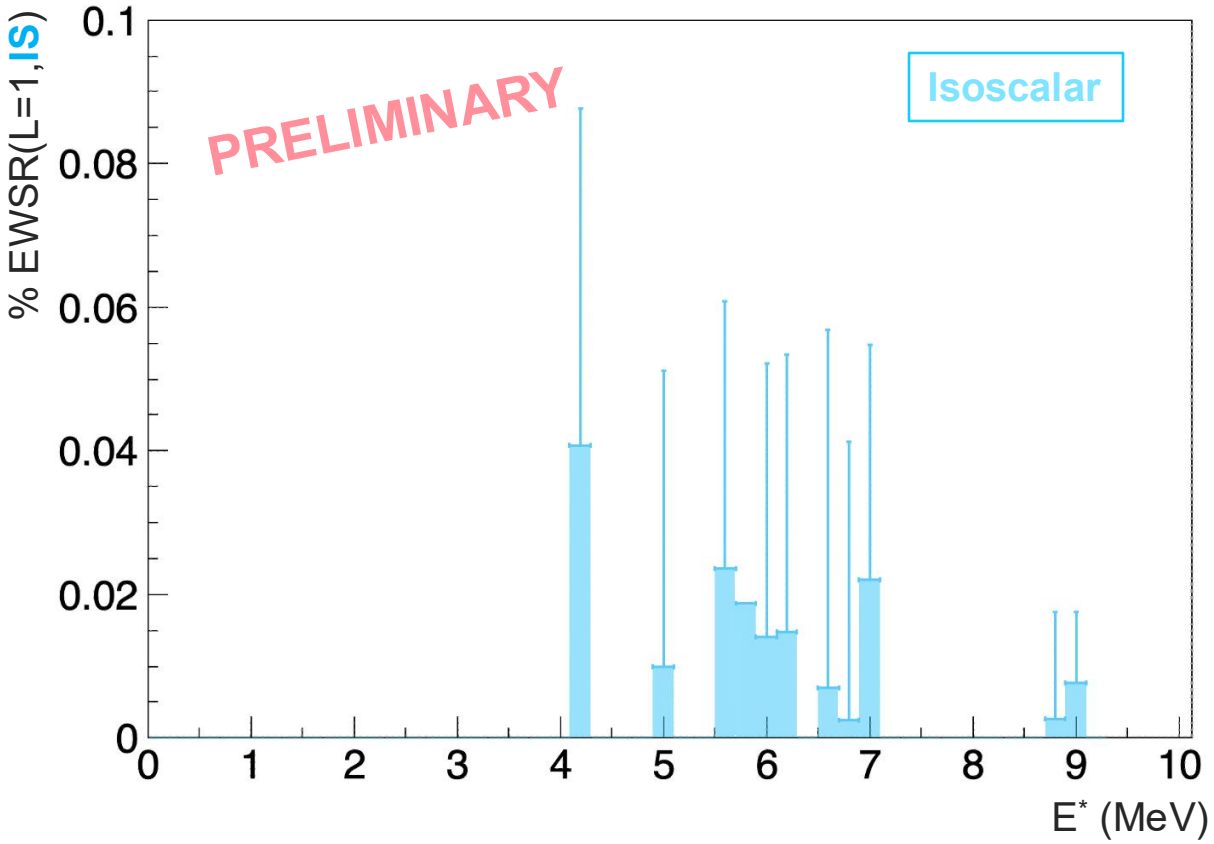


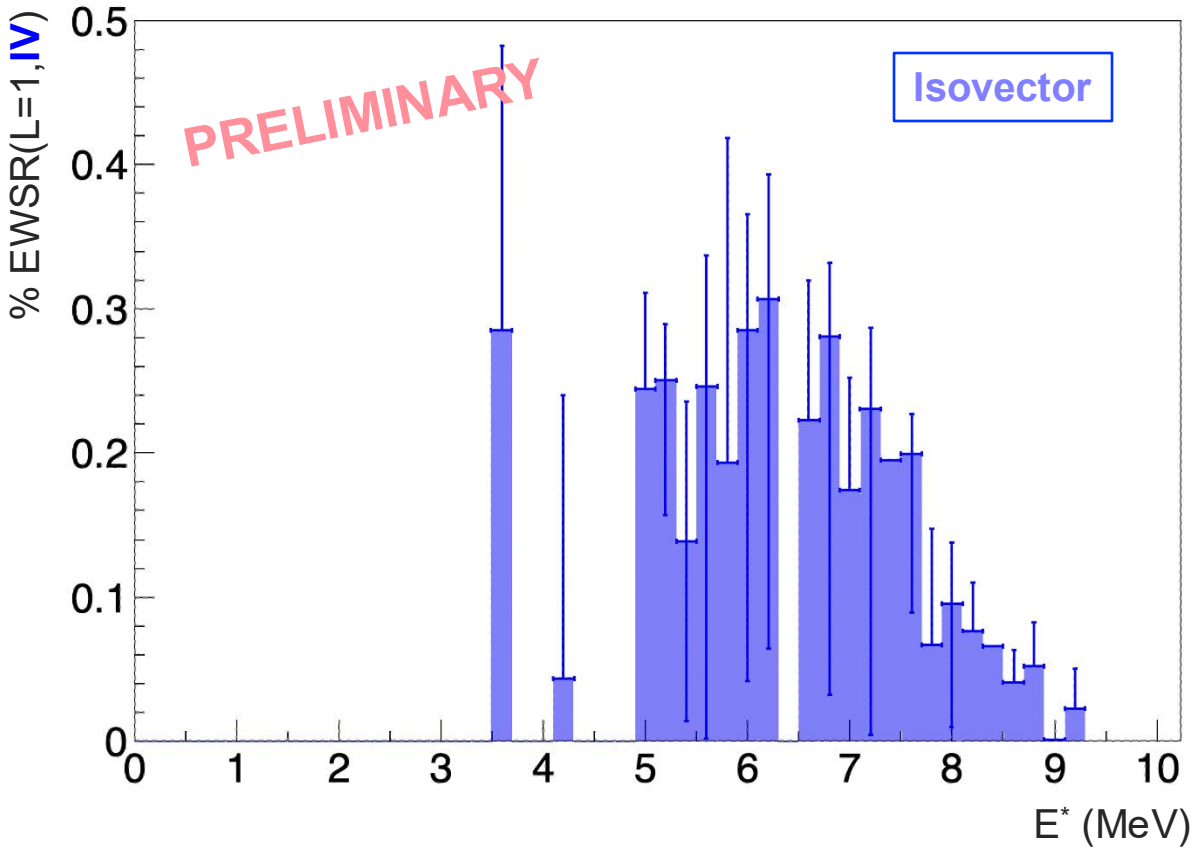
Outline – The study of the PDR in ^{140}Ce @ GANIL-SPIRAL2/NFS



- Motivation
- The experiment
- Analysis procedure
- **Results**
- Conclusion and perspectives

Results – Dipole contributions



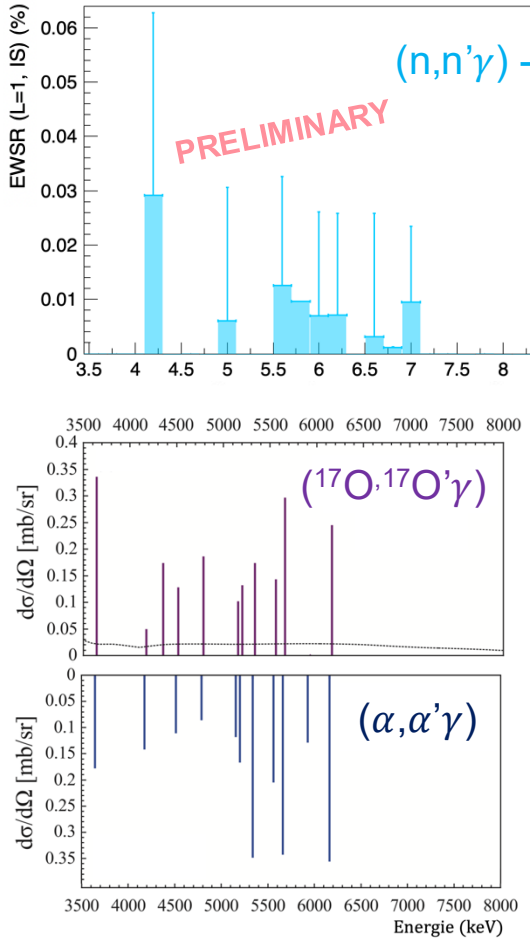


Total contribution to the EWSR L = 1, IS : **0,15** $^{+0,30}_{-}$ %

Total contribution to the EWSR L = 1, IV : **3,08** $^{+1,08}_{-1,08}$ **%**

Interpretation - A) Isospin of the populated states

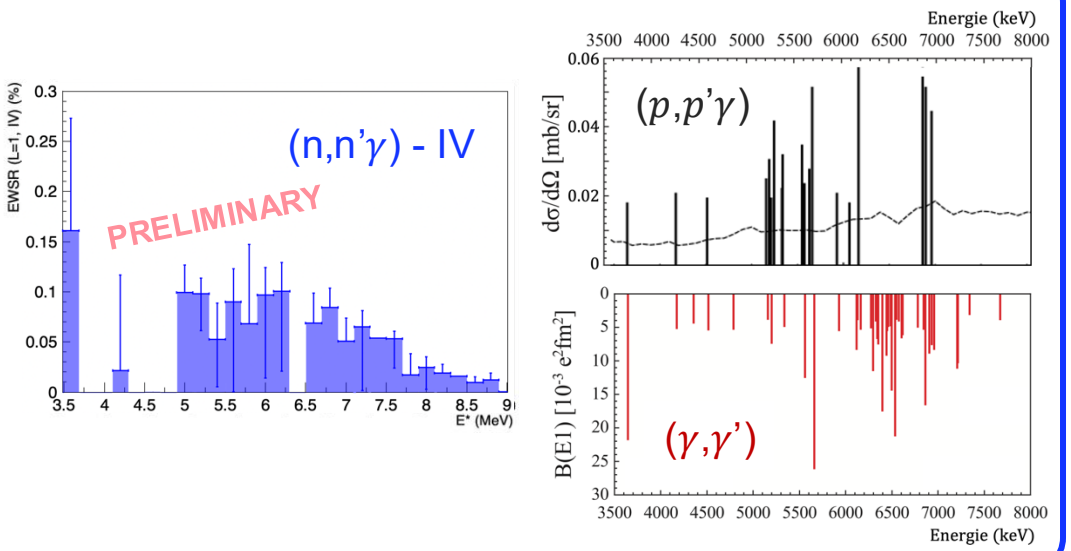
Isoscalar probes (IS)



Isoscalar states populated up to 6,2 or 7 MeV

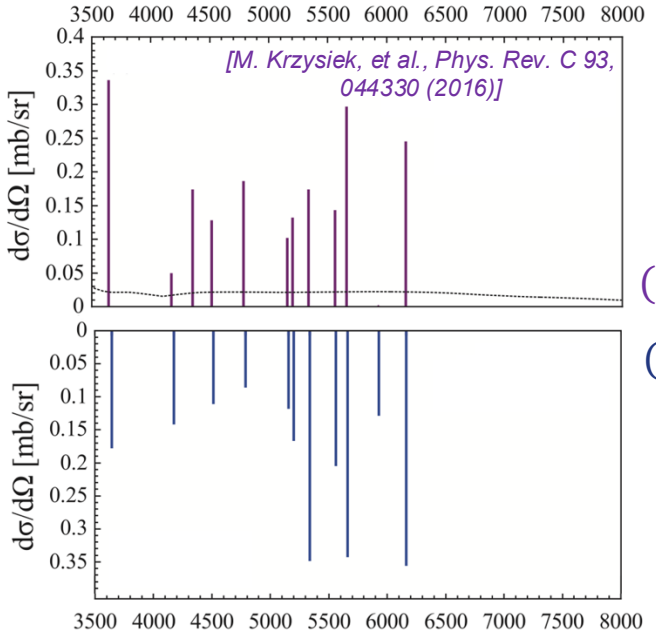
- ✓ **No isoscalar contribution in the high energy region of the PDR**

Isovector probes (IV) and mixed probes (IS+IV)



- ✓ **Populated states in the whole energy region of the PDR, up to the neutron emission threshold**

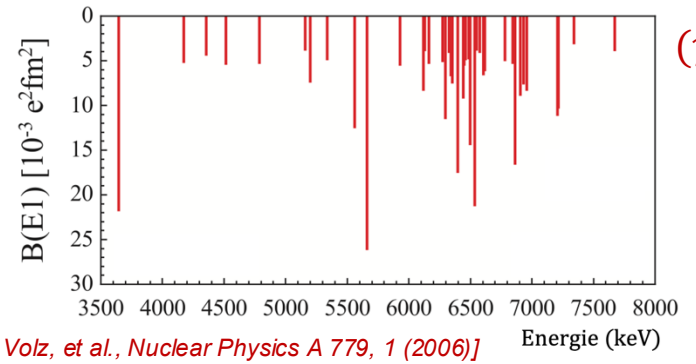
Interpretation - B) Multi-messenger investigation



$(^{17}O, ^{17}O')$

(α, α')

IS / IV
Surface / Volume
b_n/b_p = 1

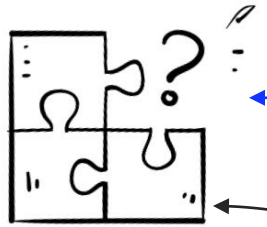


[S. Volz, et al., Nuclear Physics A 779, 1 (2006)]

(γ, γ')

IS / IV
Surface / Volume
b_n/b_p = 0

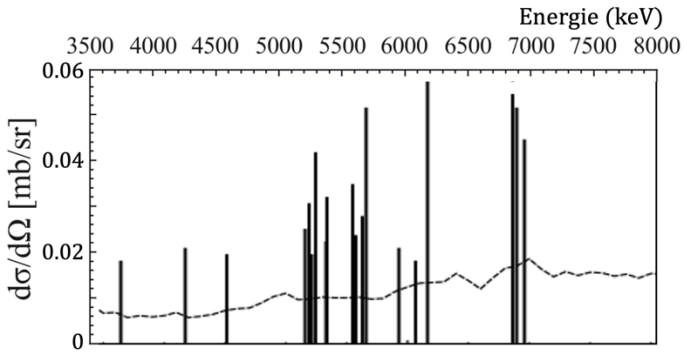
Nature of the PDR



^{140}Ce

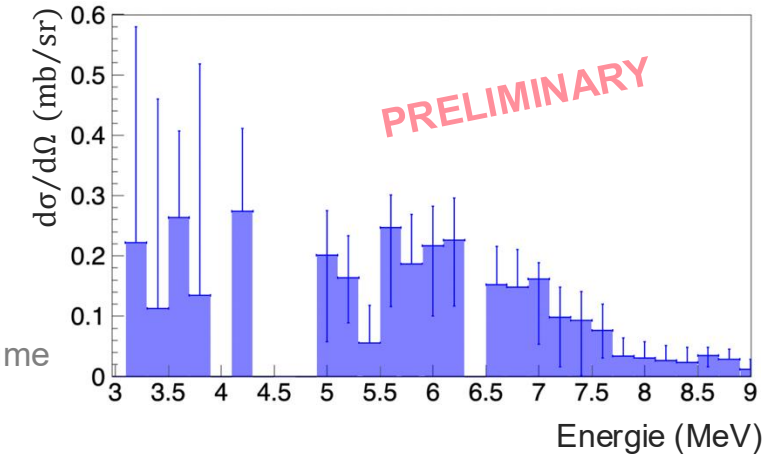
(p, p')

IS / IV
Surface / Volume
b_n/b_p = 3



This study: Neutron inelastic scattering (n, n')

IS / IV
Surface / Volume
b_n/b_p = 1/3



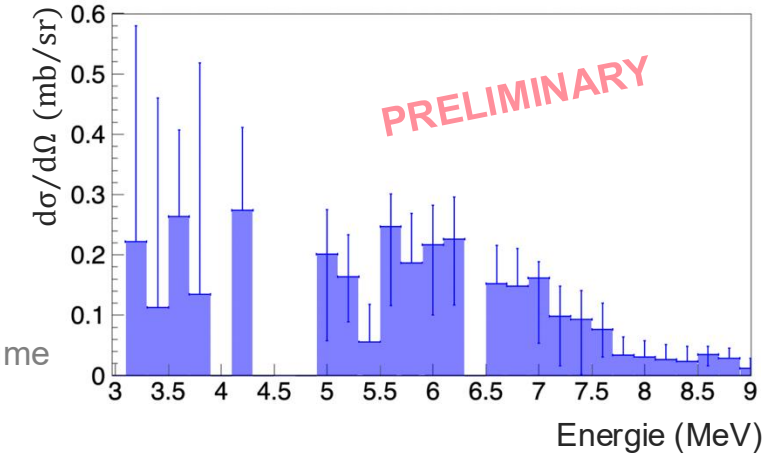
Interpretation - C) Nature of the PDR states ?

Ongoing work :

Exploit the complementarity of the **proton** and the **neutron** probes to test toy models on the nature of the PDR states

- Identify those that reproduce both data simultaneously, independently of microscopic models
- Then compare with results from several microscopic models (QRPA, SRPA, QPM, …)

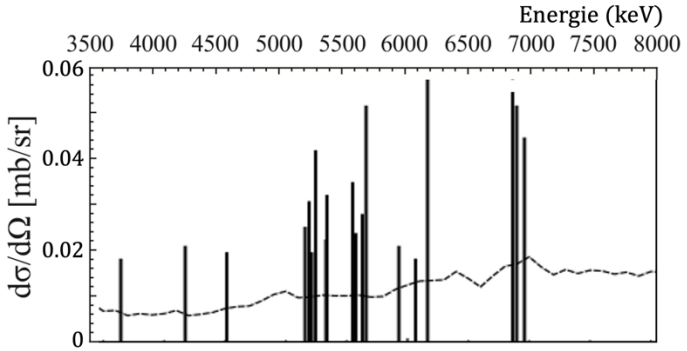
This study: Neutron inelastic scattering (n, n')



IS / IV
Surface / Volume
$b_n/b_p = 1/3$

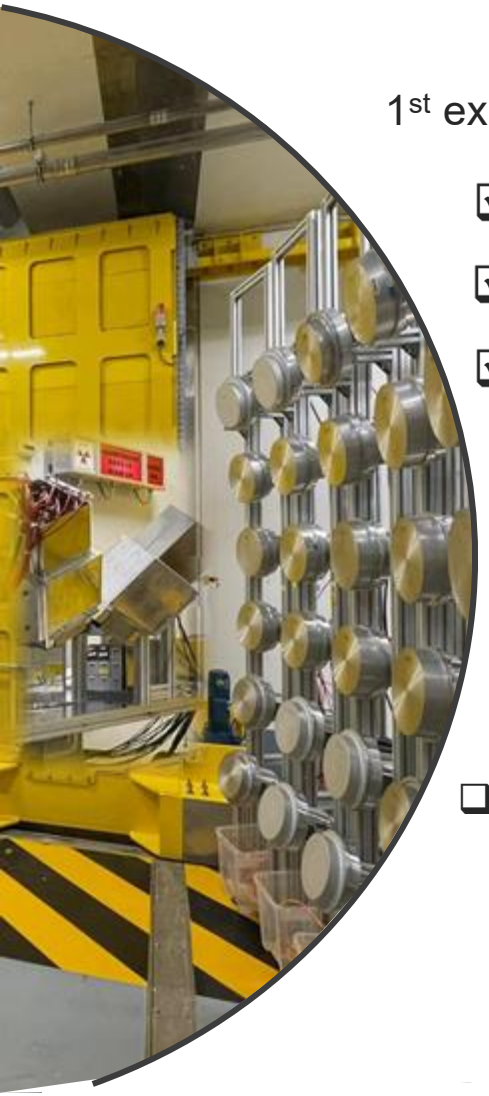
$(\mathbf{p}, \mathbf{p}')$

IS / IV
Surface / Volume
$b_n/b_p = 3$



*[D. Savran et al., Physics Letters B **786** (2018) 16-20]*

Conclusion and perspectives

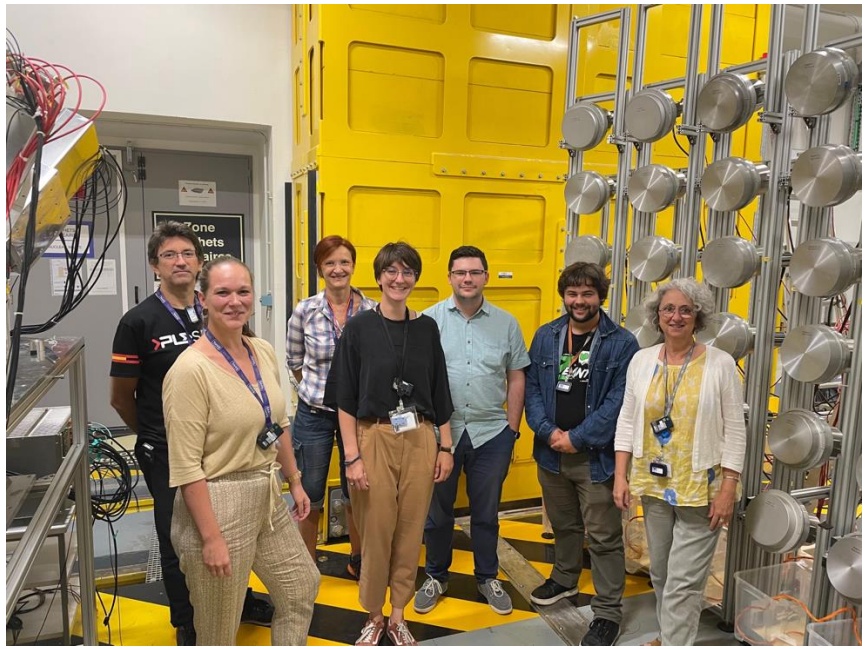


1st experimental study of the **Pygmy Dipole Resonance using neutron inelastic scattering, on ^{140}Ce**

- ☑ Experiment in September 2022 @ GANIL-SPIRAL2/**NFS**
- ☑ Benchmarking of the analysis on carbon
- ☑ Extraction of the **dipole strength** from scattered neutron angular distribution and consistent results with other experimental studies
  - Few % of the EWSR exhausted
  - Isoscalar strength in the low-energy region of the PDR
  - Isovector strength in the whole energy region of the PDR (up to neutron emission threshold)

- ❑ Next step for the analysis : **extract information on the nature of the PDR states using the complementarity of the proton and the neutron probes independently of microscopic models**

Thank you for your attention !



P. Miriot-Jaubert [1], M. Vandebrouck [1], I. Matea [2], D. Doré [1], S. Péru [11], M. Dupuis [11], X. Ledoux [13], T. Martinez [7], A. Perez de Rada Fiol [7], M. Ciemala [4], D. Thisse [1], E. Rey-Herme [1]

N. L. Achouri[3], D. Beaumel[2], P. Bednarczyk[4], Y. Blumenfeld[2], A. Bracco[5], S. Brambilla[5], S. Calinescu[6], F. Camera[5], D. Cano Ott[7], W. Catford[8], A. Corsi[1], F. Crespi[5], Y. Demane[9], W. Dong[2], O. Dorvaux[10], J. Dudouet[9], D. Etasse[3], S. Erturk[12], A. M. Frelin[13], J. Gerl[14], J. Gibelin[3], M. N. Harakeh[15][13], D. Jenkins[16], S. Kihel[10], M. Kmiecik[4], M. Lebois[2], S. Leoni[5],M. Lewitowicz[13], A. Maj[4], I. Mazumdar[17], V. Nanal[17], P. Napiorkowski[18], D. Ramos[13], Ch. Schmitt[10],M. Stanoiu[6], O. Stezowski[9], Ch. Theisen[1]†, L. Thulliez[1], G. Tocabens[1], J. Wilson[2], M. Zieblinski[4]

And the PARIS and MONSTER collaborations

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(2) Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
(3) Normandie Université, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, 14000 Caen, France
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(14) GSI Helmholtzzentrum fur Schwerionenforschung GmbH, 64291 Darmstadt, Germany
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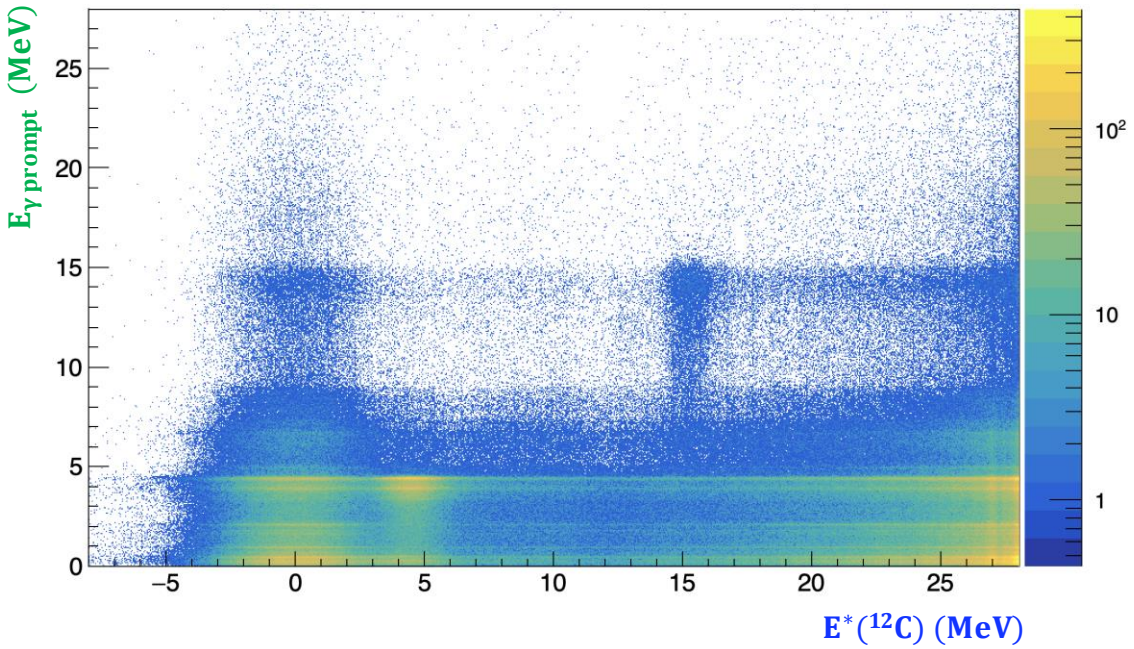
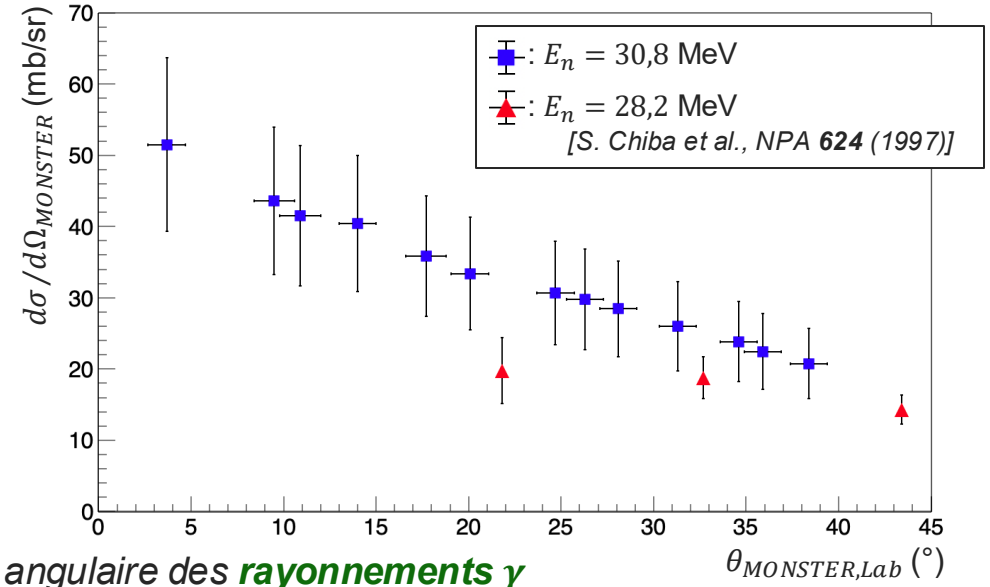
(19) Université de Bordeaux, CNRS/IN2P3, LP2i, 33170 Cradignan, France
† Deceased

Benchmark inelastic scattering: $^{12}C(n,n')^{12}C^*(\gamma)^{12}C$

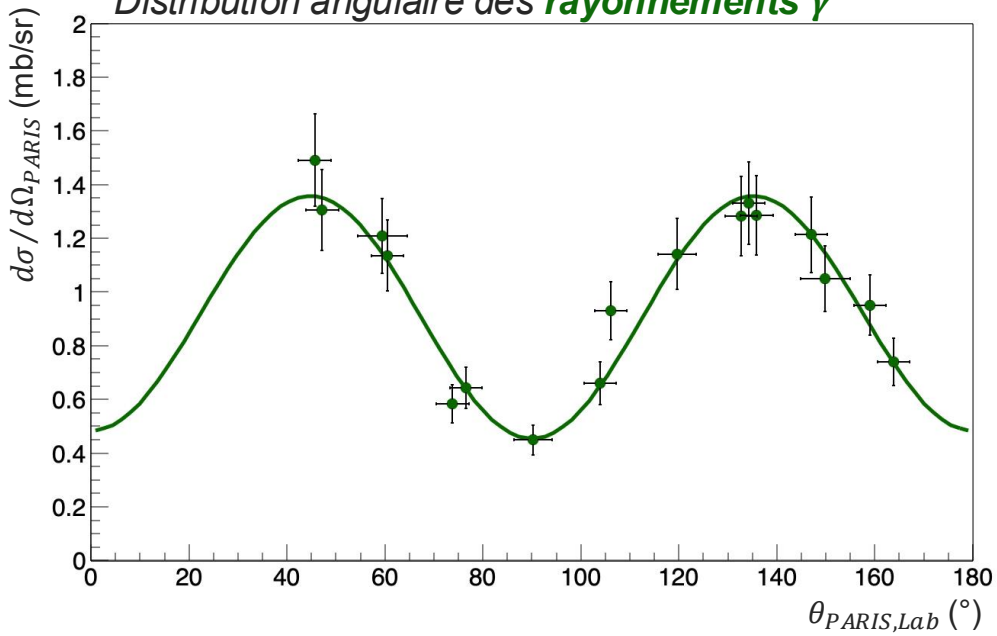
Analysis of the first excited state of ^{12}C : 2^+ at 4,440 MeV



Scattered neutrons ***n' angular distribution***

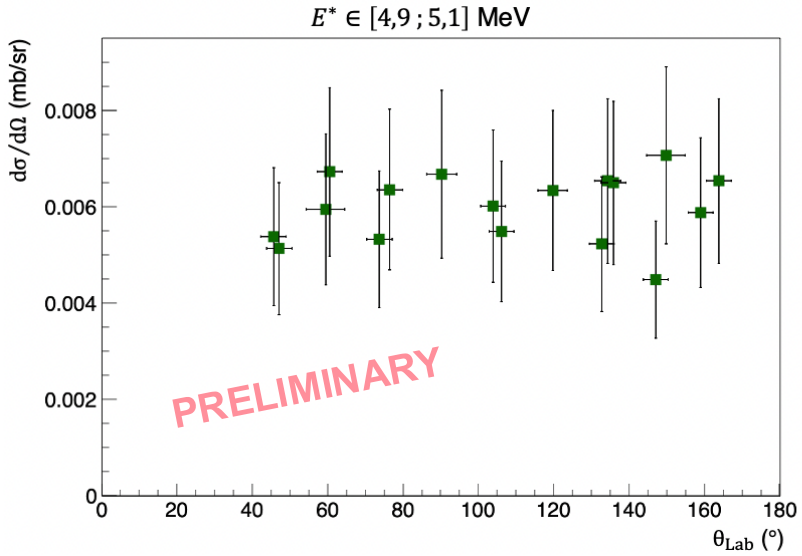


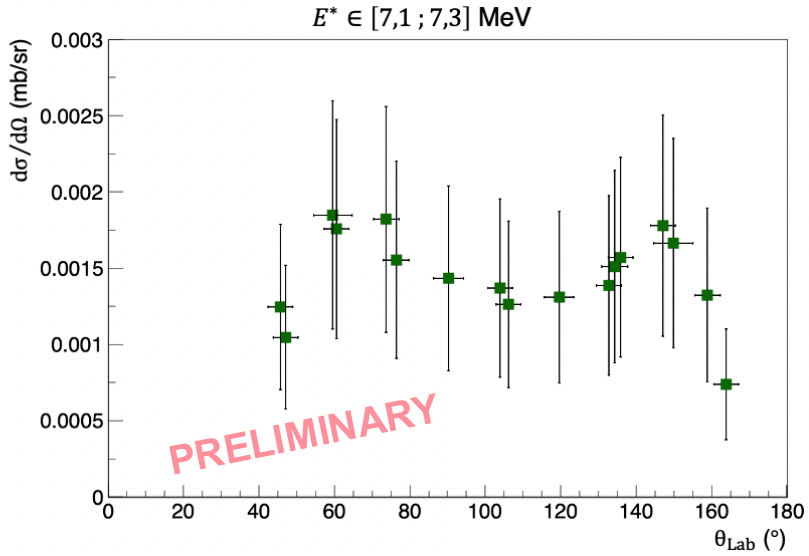
Distribution angulaire des ***rayonnements γ***



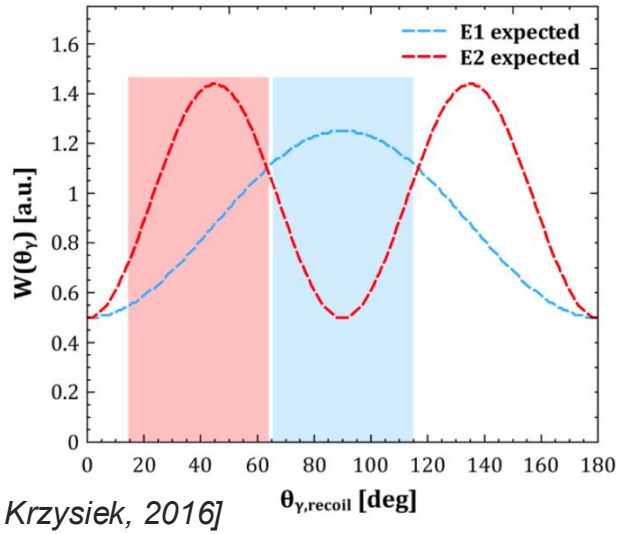
Results with PARIS ?

1) Angular distributions

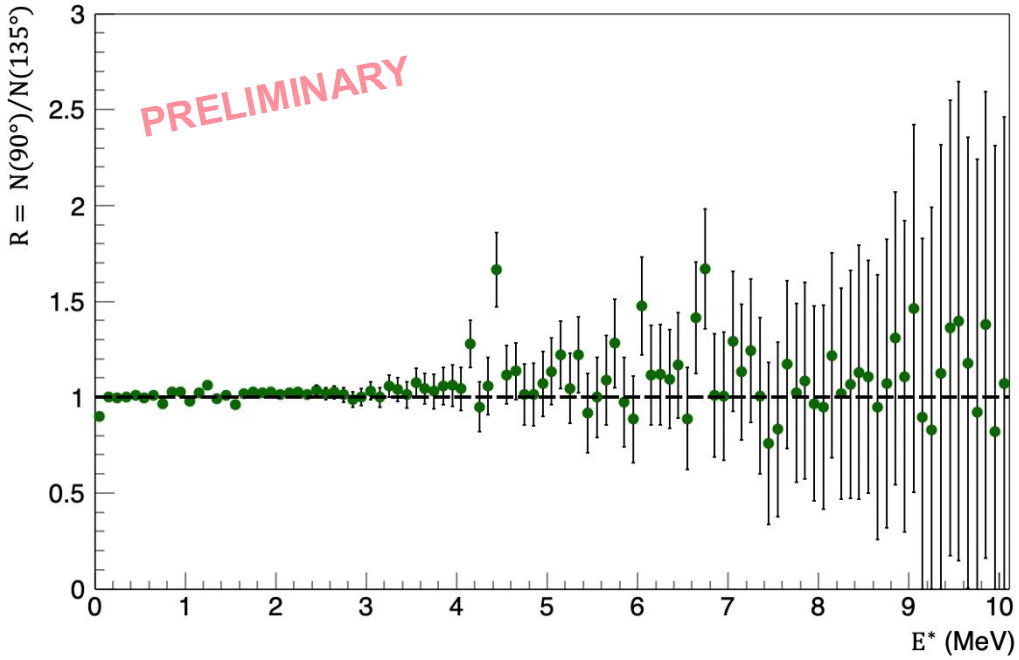




2) Ratio $\frac{N(90°)}{N(45\ ou\ 135°)}$

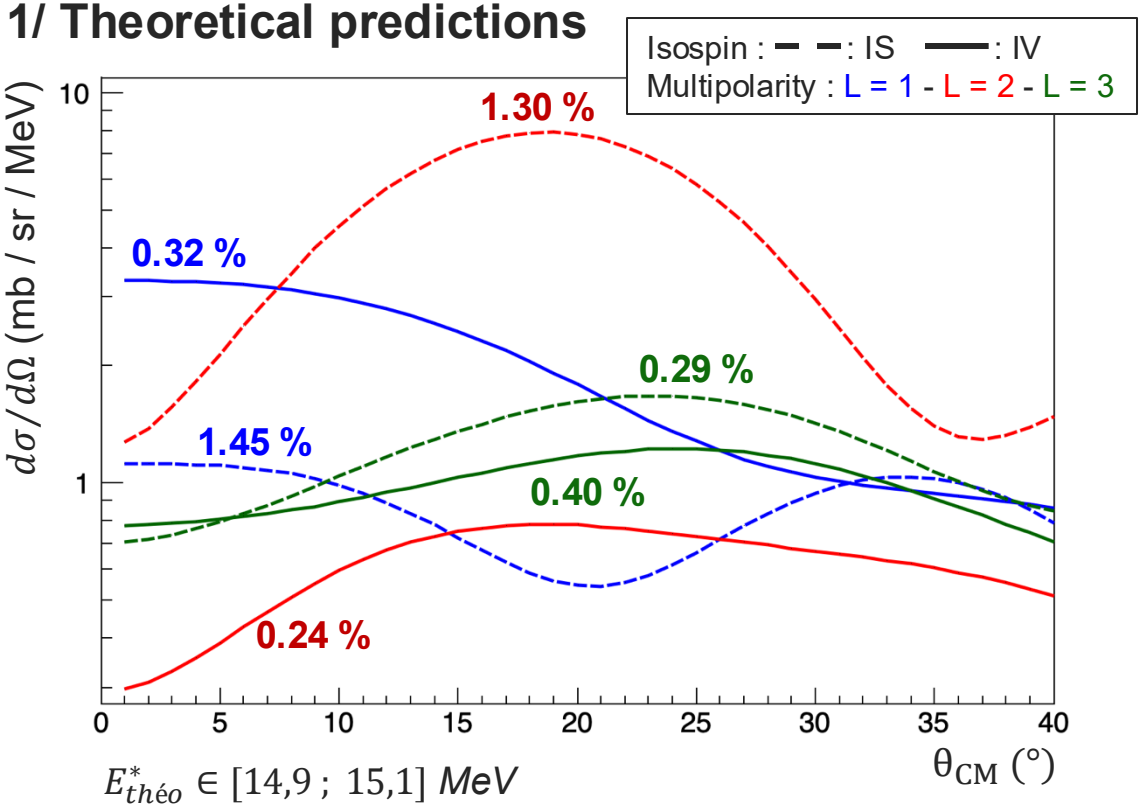


[PhD thesis Mateusz Krzysiek, 2016]



Multipole Decomposition Analysis

1/ Theoretical predictions



Total transition amplitude limited by macroscopic properties of nuclei = « **sum rules** »

=> EWSR (Energy Weighted Sum Rule) : $\sum \boldsymbol{E_\omega} \times \boldsymbol{B(E\lambda, 0 \rightarrow \omega)}$

=> Each curve exhausts a given % of the corresponding EWSR

2/ MDA

χ^2 minimisation of the experimental angular distribution

=> **coefficient p_i** associated to each curve used in the MDA

3/ Extraction of the experimental contributions to the EWSR

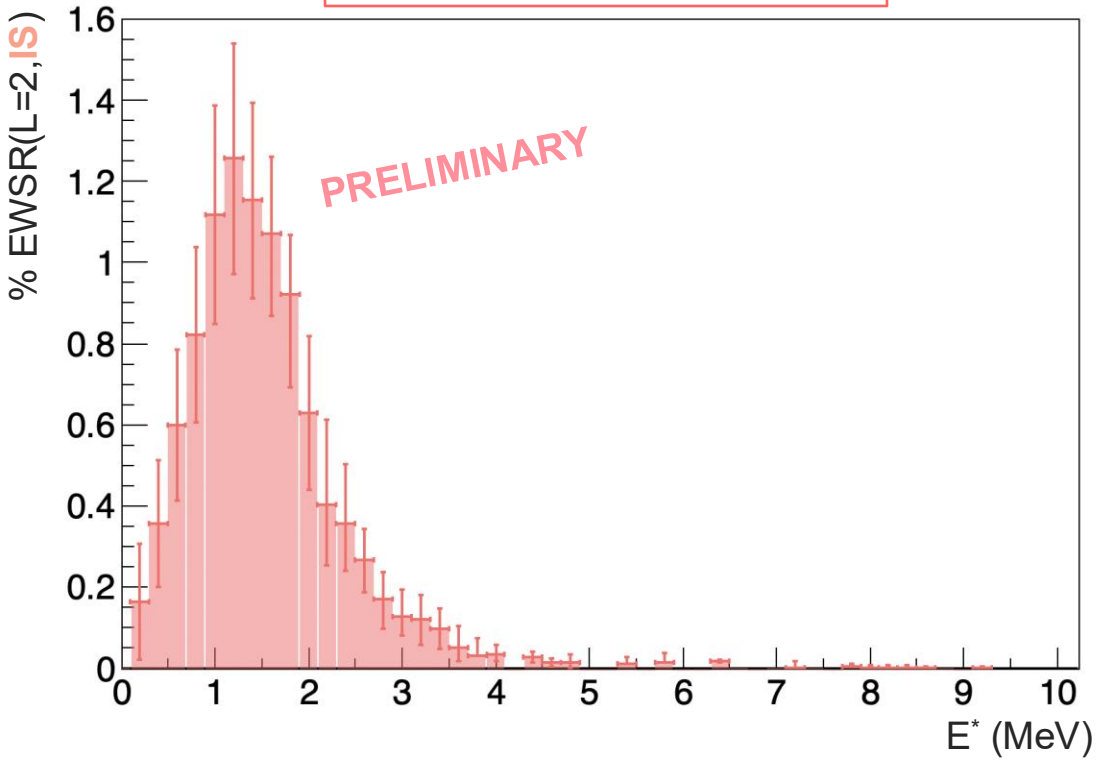
% EWSR depends on the energy:

- $\boldsymbol{E^*_{théo}}$ used for each curve
- $\boldsymbol{E^*_{exp}}$ for the fitted experimental curve

$$\Rightarrow \%\, EWSR^{exp} = \%\, EWSR^{théo} \times \boldsymbol{p_i} \times \frac{\boldsymbol{E^*_{exp}}}{\boldsymbol{E^*_{théo}}}$$

Results MDA – Strength distributions

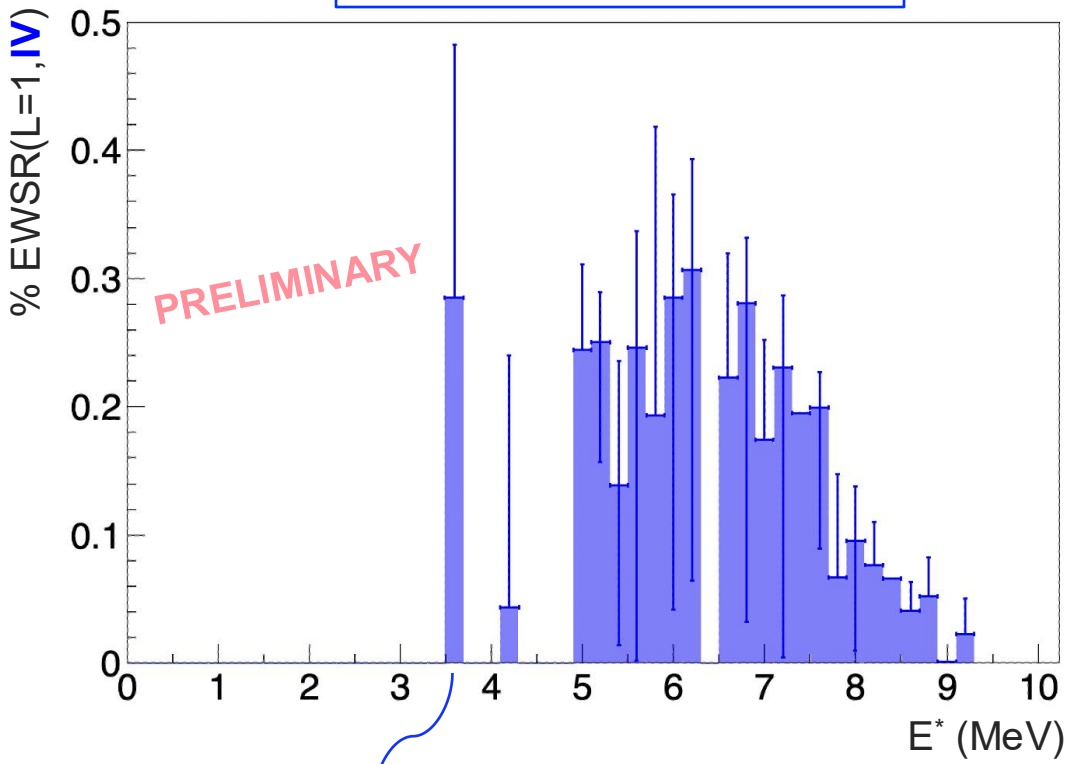
L = 2 Isoscalar contribution



✓ First excited state of ^{140}Ce well observed (2^+)

	NNDC	This work	QRPA predictions
Energy (MeV)	1.596	1.54 +/- 0.06	2.21
EWSR (L=2, IS) (%)	----	$9.8^{+2.9}_{-2.8}$	11.12

L = 1 isovector contribution



First 1^- at $E^* \in [3.5,3.7]$ MeV
=> double phonon $2^+ \otimes 3^-$ known at 3.644 MeV
=> Excluded for PDR analysis

Results MDA – Comparison with experiments / predictions

This work – (n,n'γ)

Contribution	L = 1 – IS PRELIMINARY	L = 1 - IV
Contribution à l'EWSR (%)	$0{,}15 \pm^{0{,}30}$ %	$3{,}08 \pm^{1{,}08}_{1{,}08}$ %
∑ B(E1↑) (4-9 MeV)	★ $700 \pm^{1}{}^{200}$ e²fm⁶	★ $2{,}47 \pm^{0{,}94}_{0{,}86}$ e²fm²

Other experimental studies

Réaction	(^{17}O,^{17}O'γ)	(γ, γ')
Contribution à l'EWSR (%)	$0{,}44 \pm 0{,}12$ %	$0{,}38 \pm 0{,}07$ %
∑ B(E1↑) (4-9 MeV)	★ 2 000 ± 600 e²fm⁶	★ 0,31 ± 0,06 e²fm²
	[M. Krzysiek, et al., Phys. Rev. C 93, 044330 (2016)]	*[S. Volz, et al., Nuclear Physics A 779, 1 (2006)]*

QRPA predicitons

*[S. Péru et M. Martini, Eur. Phys. J. A **50**, 88 (2014)]*

∑ B(E1↑) (9-15 MeV)	★ 16 119 e²fm⁶	★ 2,99 e²fm²

Sensitivity of the probes

Microscopic predictions for ^{140}Ce:
HFB + **QRPA**, Gogny D1M interaction
*[S. Péru and M. Martini, Eur. Phys. J. A **50**, 88 (2014)]*

Observables – integrated values

$$M_{n/p} = \int \delta\rho^{n/p}(\vec{r}) \times r^{\lambda+2} \times \mathrm{dr}$$

Transition densities

=> Protons and neutron contributions to the excitation encoded

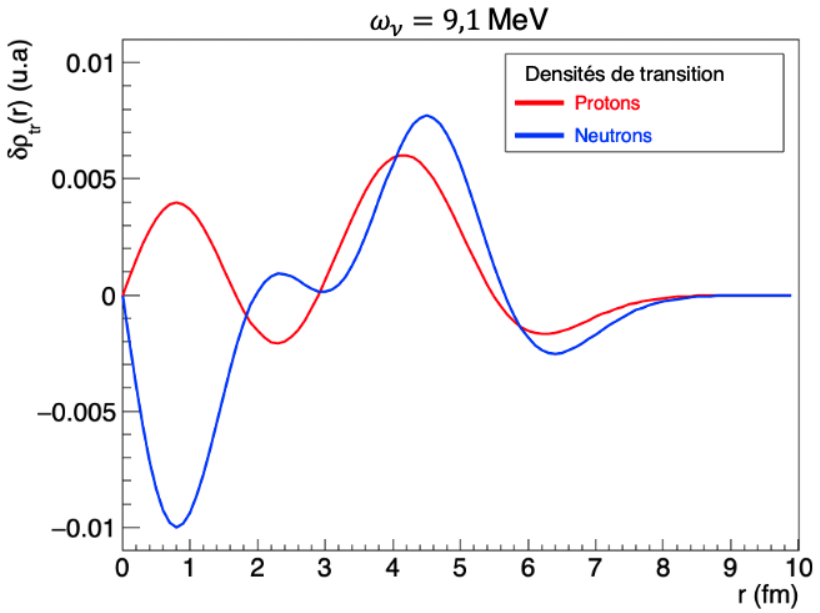
During scattering reaction:

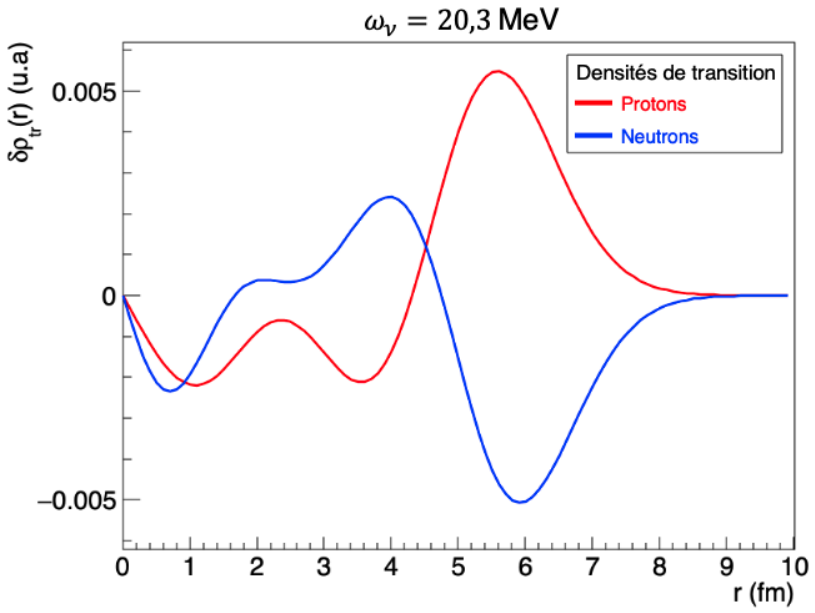
$$M = b_n M_n + b_p M_p$$

Sensitivity of the probe
Interaction probability between the probes and protons / neutrons

Probe	b_n / b_p
γ	0
α, ^{17}O	1
p (10 – 50 MeV)	**3**
p (1 GeV)	0,95
n (10 – 50 MeV)	**1/3**

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





Nature of the PDR from (p,p') and (n,n') probes

- The complementarity of the probes…

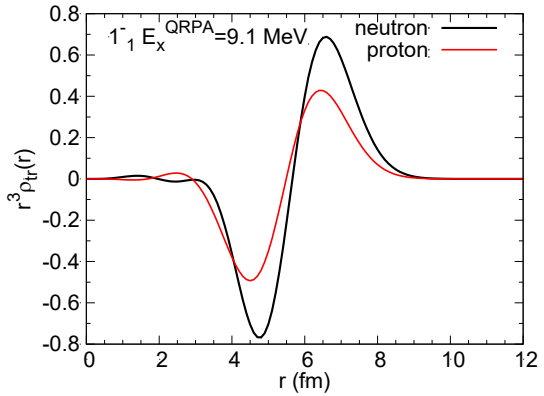
(p,p') – b_n/b_p = 3
E_p = 80 MeV

*[D. Savran et al., Physics Letters B **786** (2018) 16-20]*

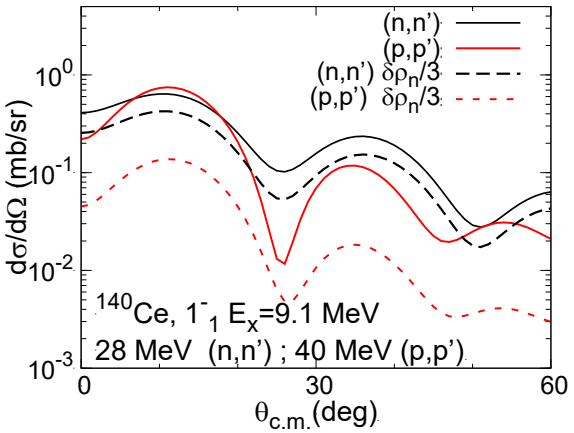
(n,n') – b_n/b_p = 1/3
E_n = 30,8 MeV

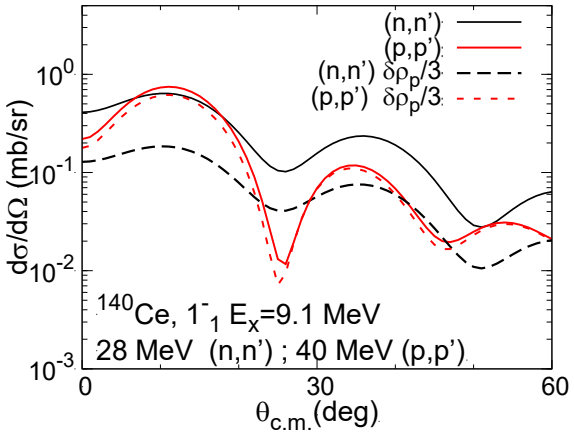
[This work]

QRPA predictions



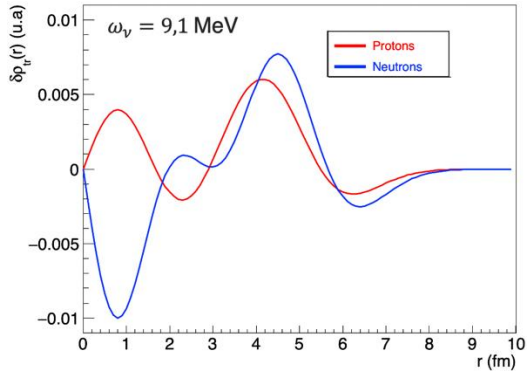
$\delta\rho_n/3$ $\delta\rho_p/3$





- … can allow to test the nature of the populated state *via* their transition densities

toy model » for transition densitiy generation



DWBA calculations for the two reaction **(p,p')** and **(n,n')**

$\Rightarrow \frac{d\sigma}{d\Omega}$ (mb/sr)

Reproduction of experimental results ?

No

Yes

Information on the nature of the populated states

Microscopic transition densities (QRPA, SRPA, QPM, …)