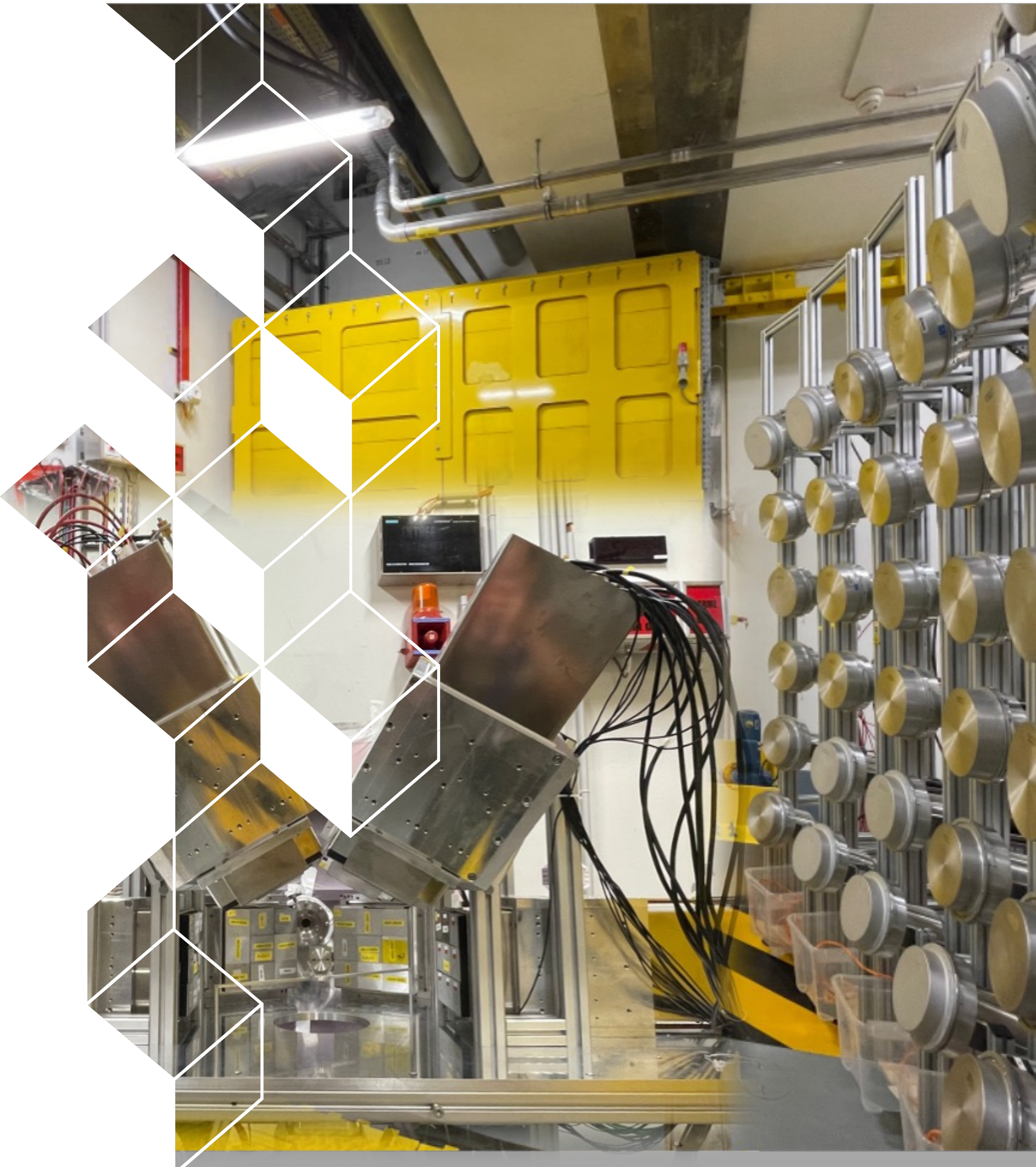
# Probing the Pygmy Dipole Resonance using neutron inelastic scattering

Colloque GANIL 2026

Marine Vandebrouck

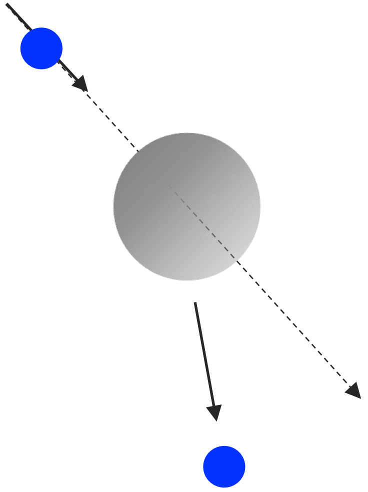
Program led with I. Matea (IJCLab) and P. Miriot-Jaubert (IPHC)



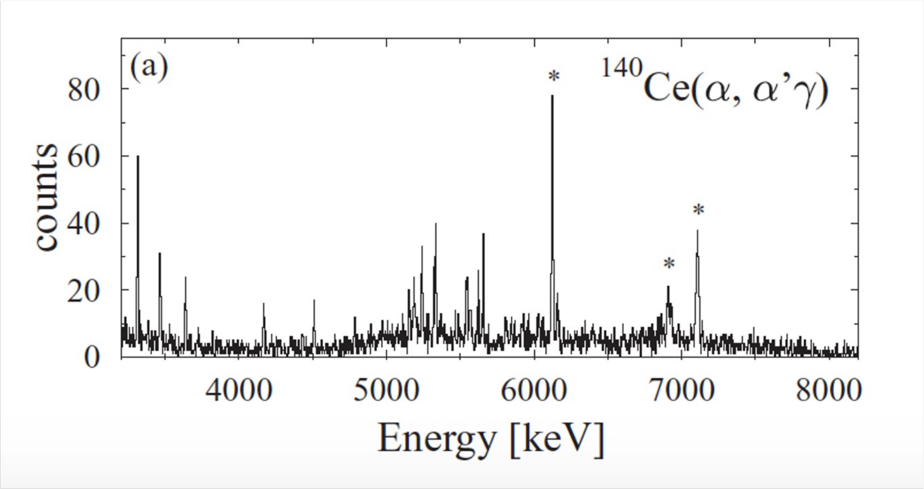
# Inelastic scattering reactions to pin down PDR structure of nuclei

# What is the nature of a nuclear excitation ?

**Tool**
scattering reaction



**Observables**
Excitation energy, $E_g$ and cross section




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

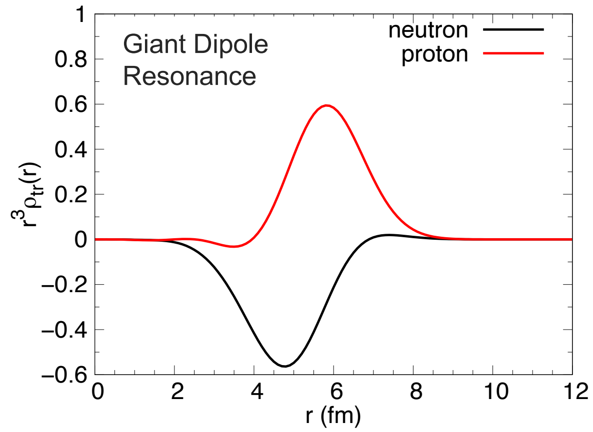
**Interpretation**
Comparison to microscopic calculations

*M*
**Multipole moment**

*L*
**Multipolarity of the transition**

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

ρ
**Transition density from g.s. to the excited state**
**Encode the contributions of p and n**

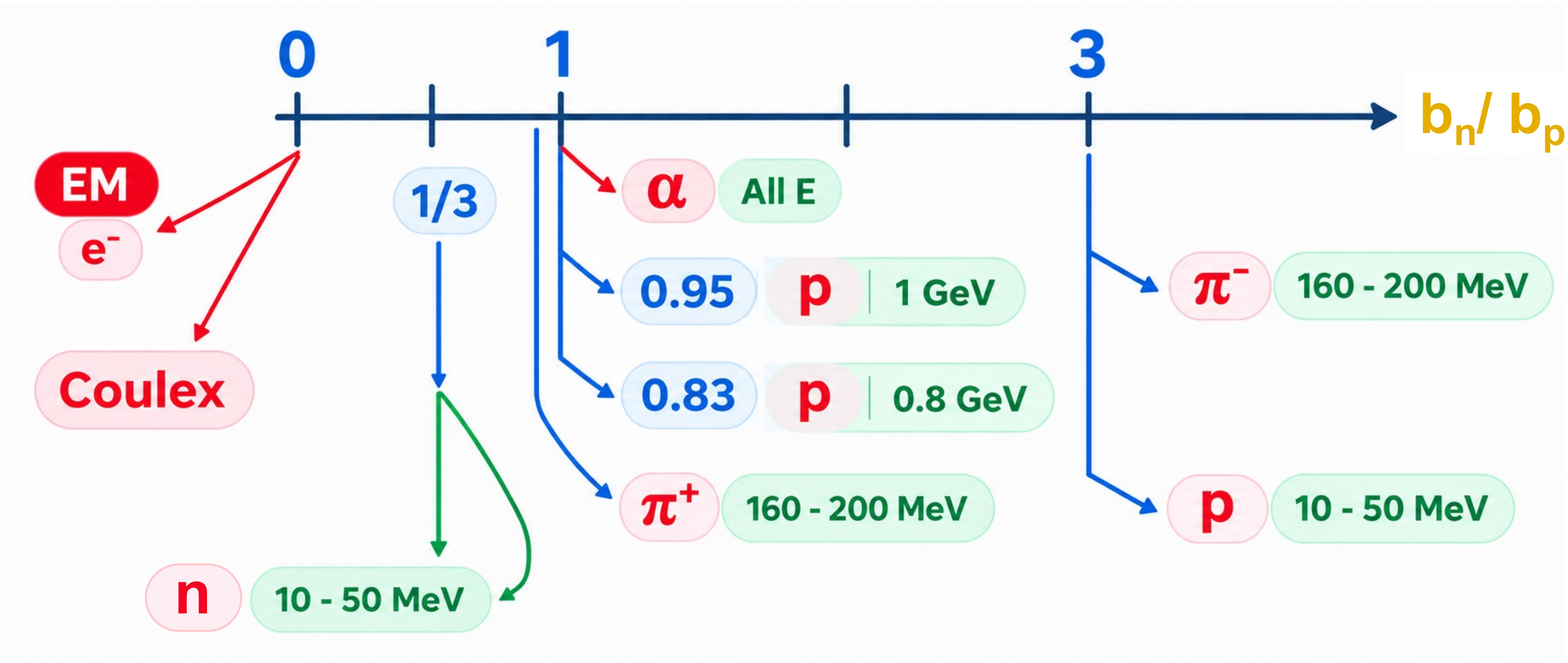



Courtesy S. Péru.
QRPA Calculations (Gogny D1M)

# Complementarity of the scattering experiments

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

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




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

# Pygmy Dipole Resonance (PDR)

**PDR**
**(Pygmy Dipole Resonance)**

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

**GDR**
**(Giant Dipole Resonance)**

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

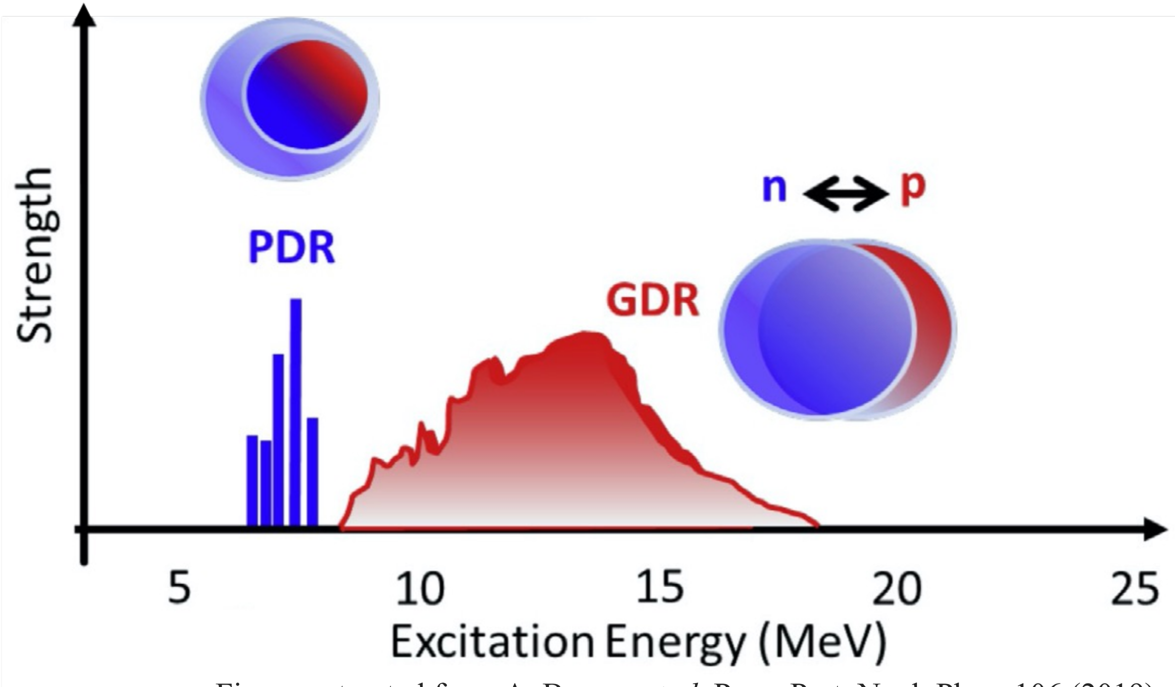


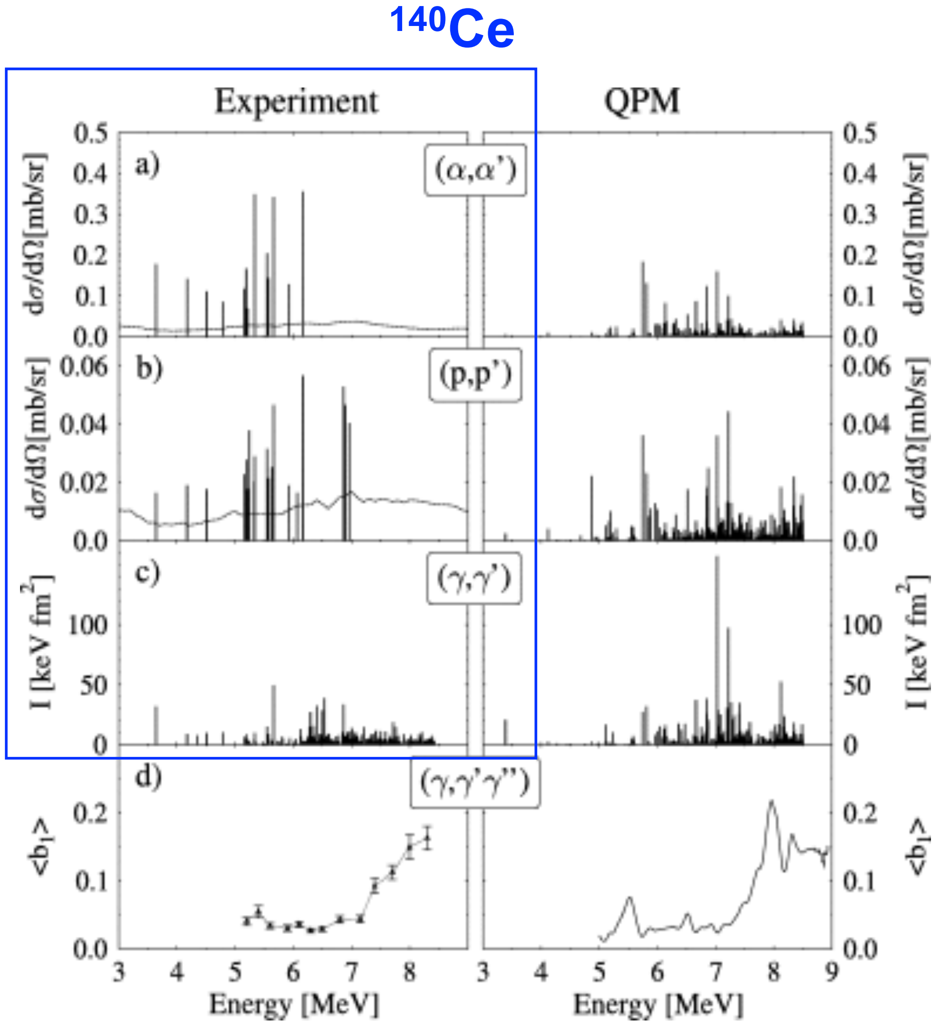
Figure extracted from A. Bracco *et al.* Prog. Part. Nucl. Phys. 106 (2019)

➢ Nuclear structure: study of the nature of dipole strength

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

⚠ PDR, in this presentation, refers to low-lying dipole states, whether or not they are interpreted as the oscillation of a neutron skin ⚠

# Microscopic structure of the PDR




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

Isoscalar probes ➡ 4-6 MeV

Proton probe ➡ selected states

Electromagnetic probe ➡ 4-8 MeV

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

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

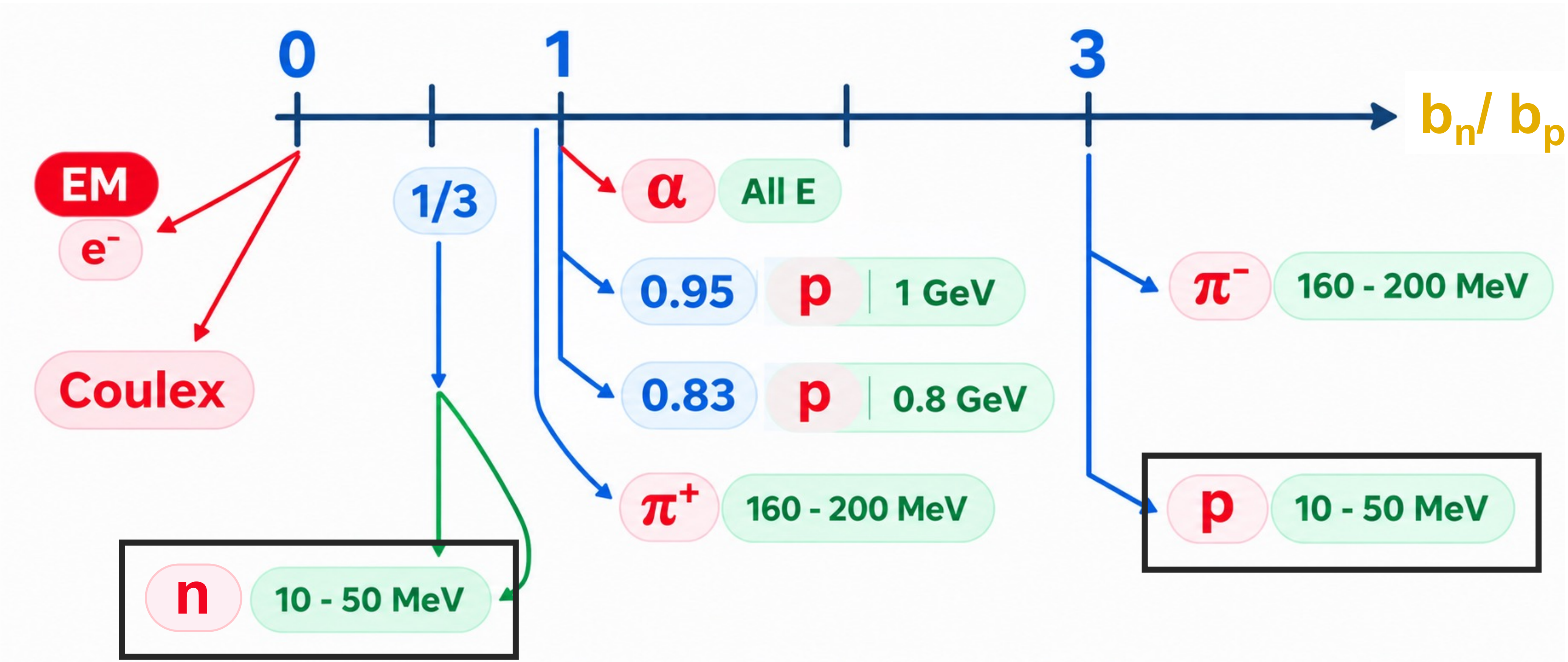
study **PDR in using (n,n')**

# (n,n') reaction @NFS to probe PDR

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

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

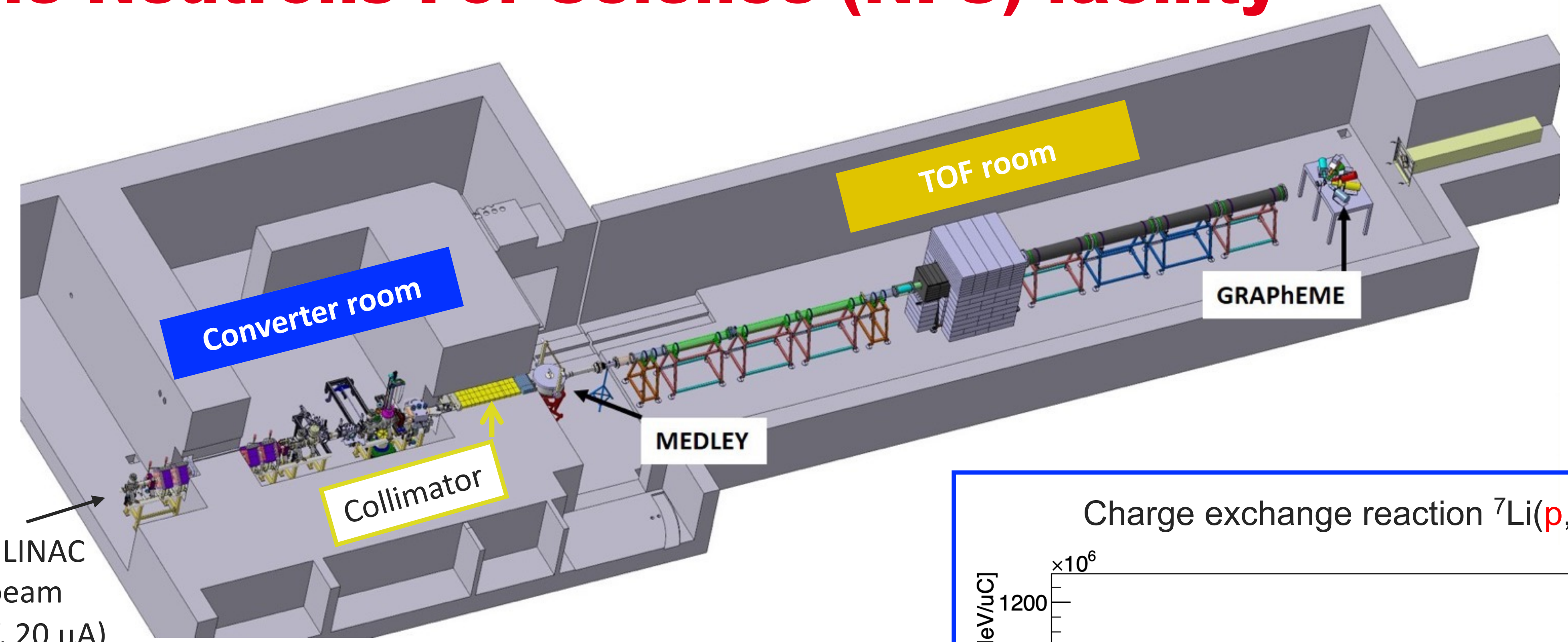
- which does not require Coulomb correction
- complementary to (p,p') and to other reactions





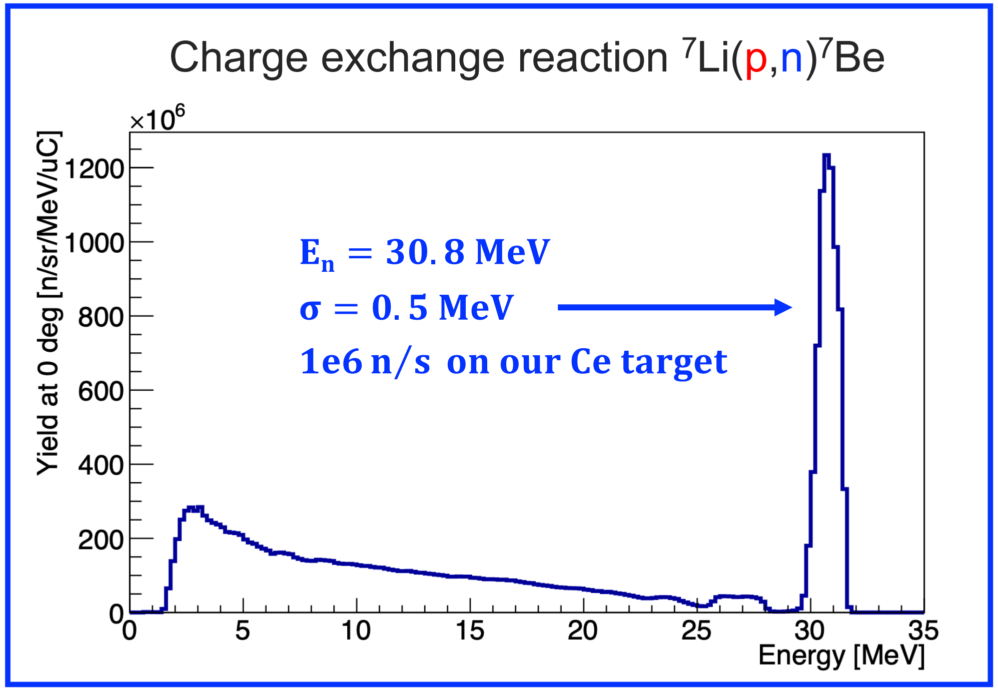
A. Berstein *et al.* Phys. Lett. B 103, 255 (1981)
E. Khan, Phys. Rev. C 105, 014306 (2022)

# The Neutrons For Science (NFS) facility




SPIRAL2 LINAC
Proton beam
(33 MeV, 20 μA)

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



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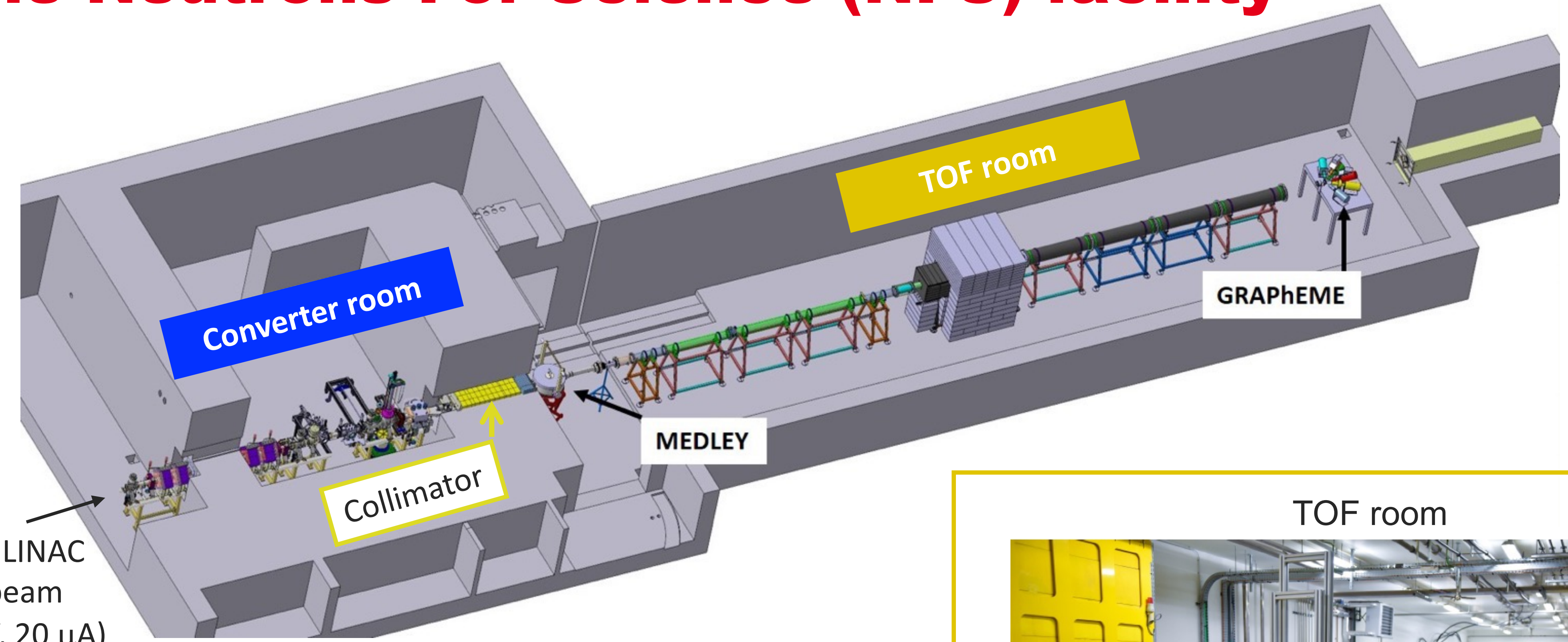



SPIRAL2 LINAC
Proton beam
(33 MeV, 20 µA)

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

TOF room

# E833 « Pygmy dipole resonance in $^{140}Ce$ using the (n,n'γ) reaction at NFS »

Spokespersons: M. Vandebrouck, I. Matea, T. Martinez

# Experimental setup

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

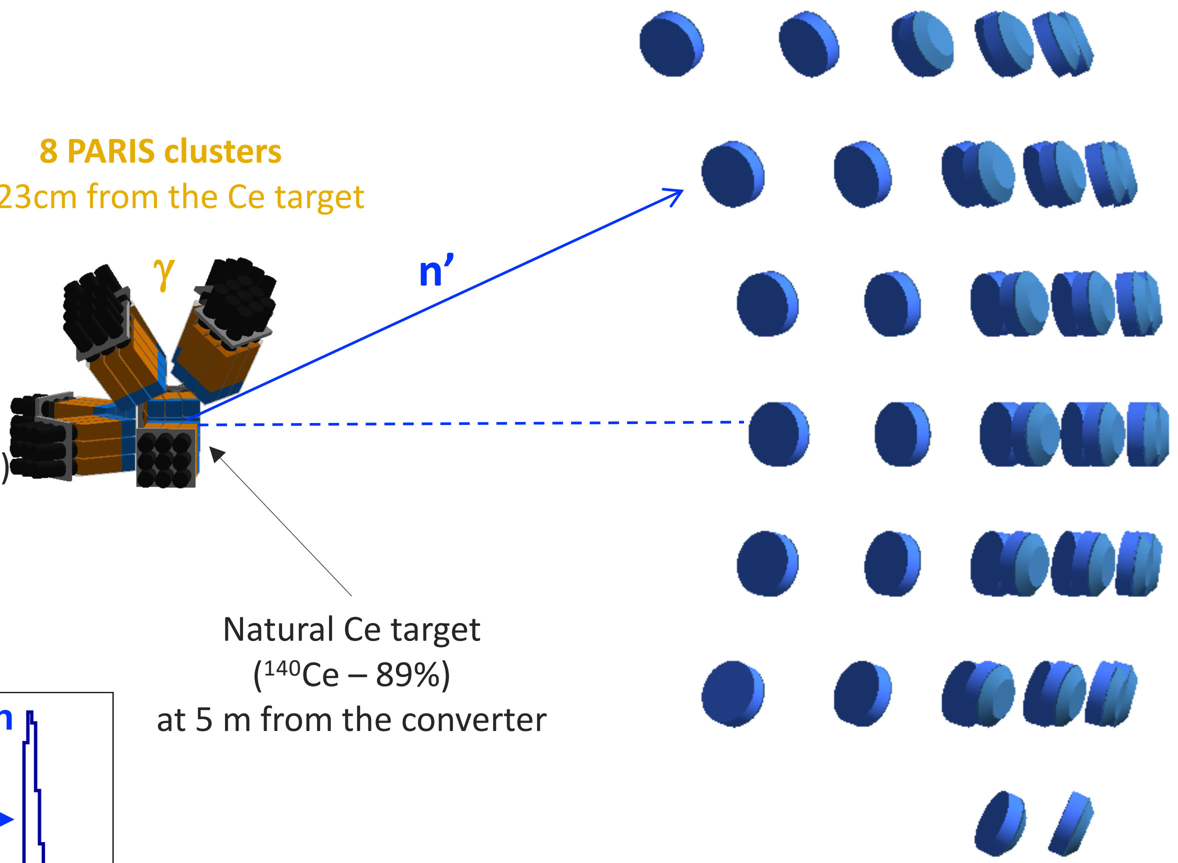
**p**

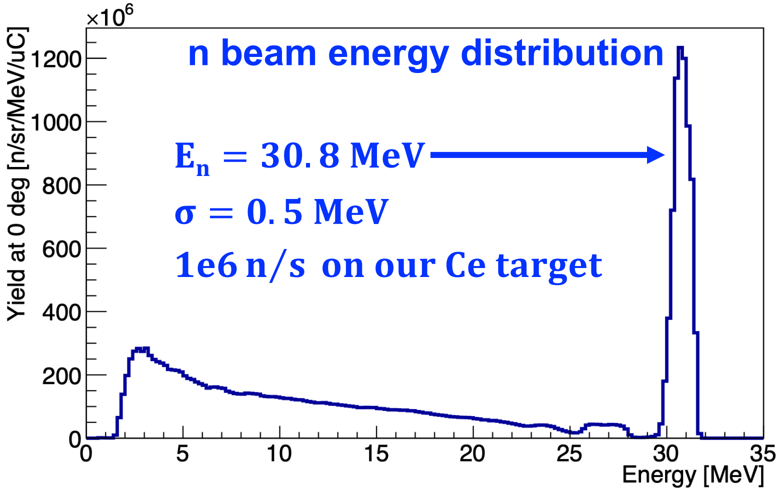
(33 MeV, 20 μA)

**n**

(30.8 MeV, $9.6 \times 10^4$ n/cm²/s)

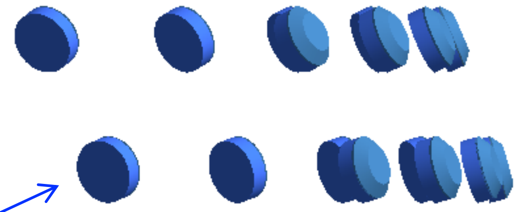
1.5 mm-thick Li converter
$^{7}Li(p,n)^{7}Be$



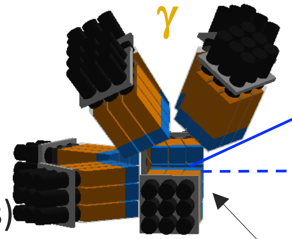
# Experimental setup

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



**48 MONSTER modules**
at 3m from the Ce target

**8 PARIS clusters**
at 23cm from the Ce target




n'

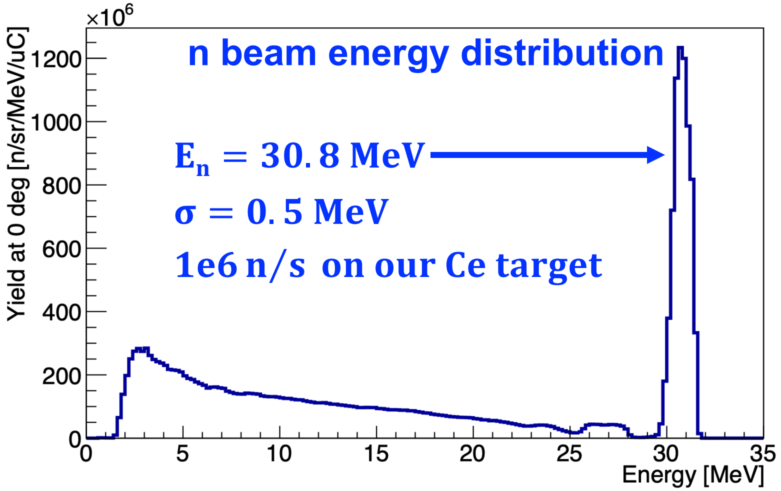
p

n

(33 MeV, 20 μA) (30.8 MeV, 9.6 x $10^4$ n/cm²/s)

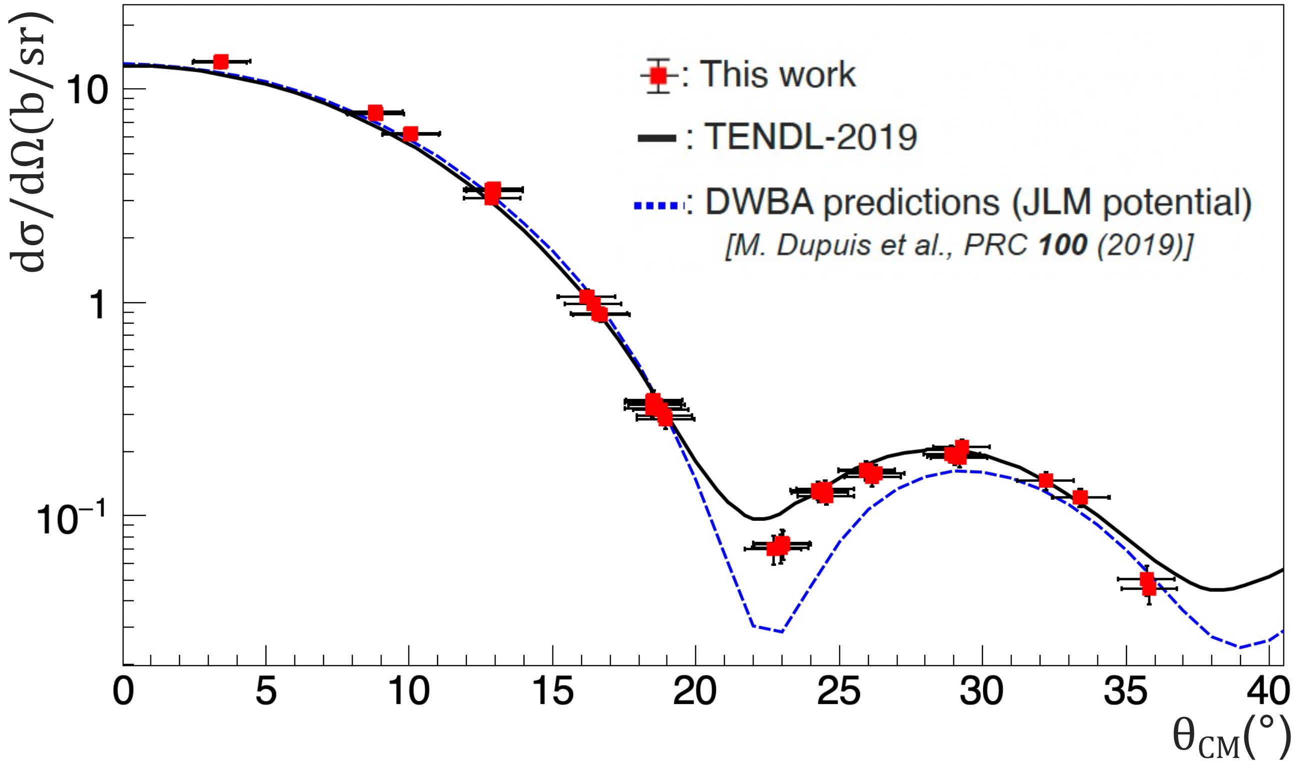
1.5 mm-thick Li converter
$^7Li(p,n)^7Be$

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

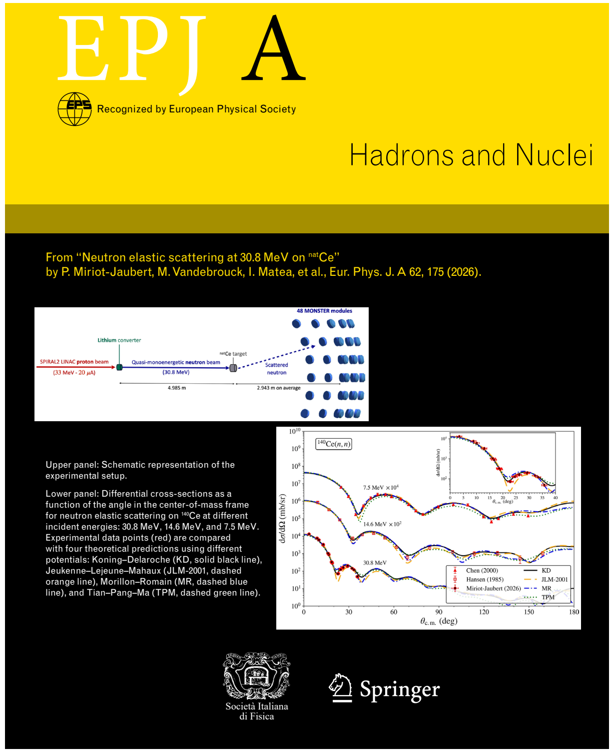



# Benchmark of the analysis

1) Study of the elastic scattering channel $^{140}$Ce(n,n)




- ✓ First measurement for incident neutron energy above 20 MeV
- ✓ P. Miriot-Jaubert *et al*, EPJA 62 (2026)

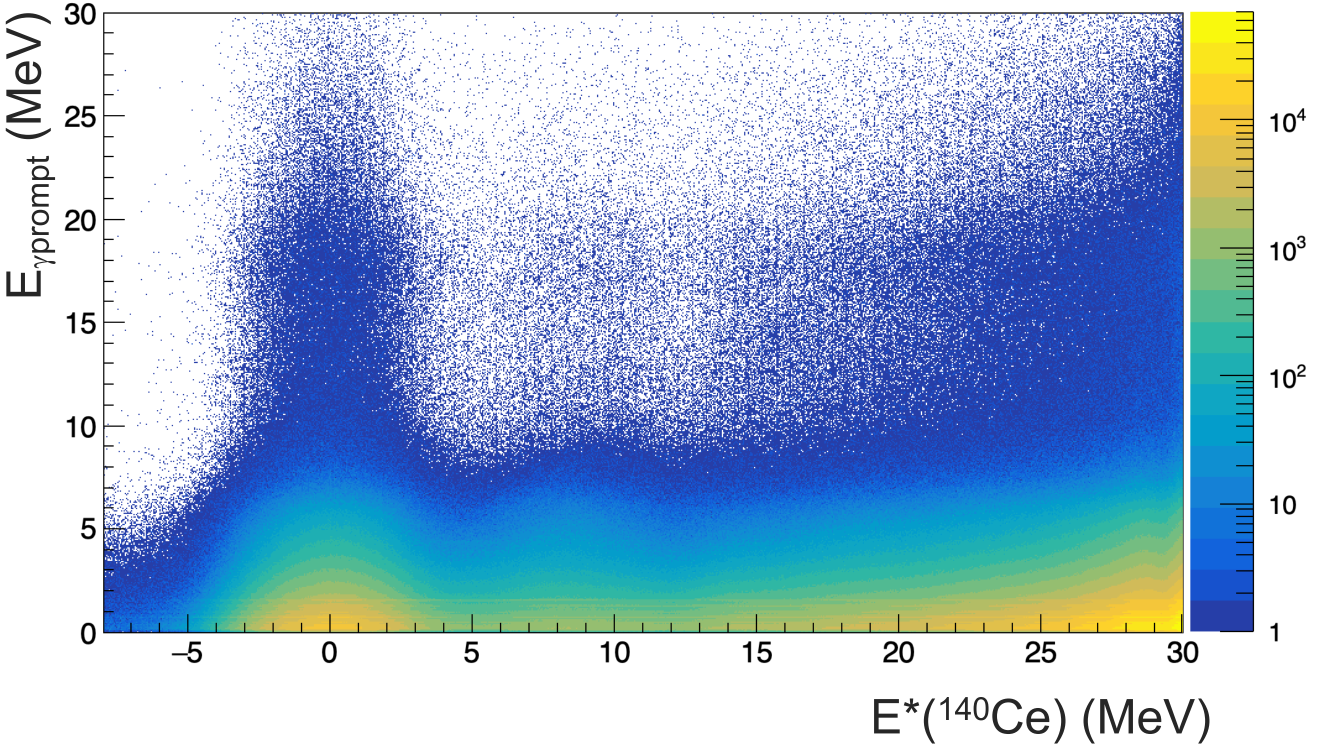



2) Study of the inelastic scattering channel using $^{12}$C target

P. Miriot-Jaubert *et al.*, Acta Phys. Pol. B Proc. Suppl. 18, 2-A35 (2025)

# Main steps of the analysis

3) Study of the inelastic scattering channel using $^{nat}Ce$ target



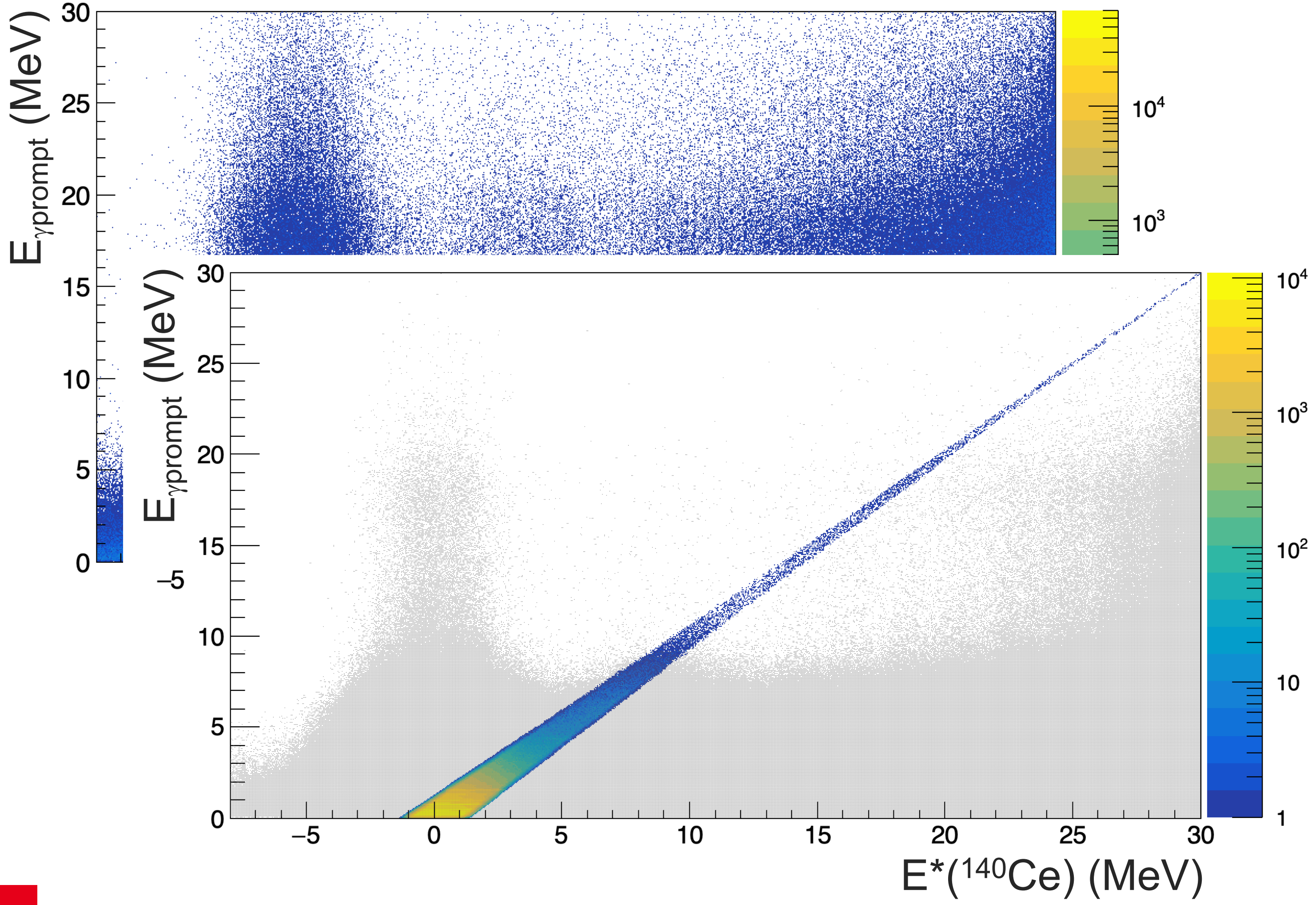

✓ Background reduction:

– $\gamma_{prompt}$ selection in PARIS (selection of reaction from 30.8 MeV incident neutrons)

- Background subtraction using "Off $\gamma_{prompt}$" contribution and beam+Al shell background

# Main steps of the analysis

3) Study of the inelastic scattering channel using $^{nat}Ce$ target




- ✓ Background reduction:
  - $\gamma_{prompt}$ selection in PARIS (selection of reaction from 30.8 MeV incident neutrons)
  - Background subtraction using “Off $\gamma_{prompt}$ “ contribution and beam+Al shell background
- ✓ Diagonal selection

# Main steps of the analysis

3) Study of the inelastic scattering channel using $^{nat}$Ce target

$$\frac{d\sigma}{d\Omega}(exp) = p_0\frac{d\sigma}{d\Omega}(\text{elastic}) + p_1\frac{d\sigma}{d\Omega}(L=1,\text{IS}) + p_2\frac{d\sigma}{d\Omega}(L=1,\text{IV})$$
$$+ p_3\frac{d\sigma}{d\Omega}(L=2,\text{IS}) + p_4\frac{d\sigma}{d\Omega}(L=2,\text{IV})$$
$$+ p_5\frac{d\sigma}{d\Omega}(L=3,\text{IS}) + p_6\frac{d\sigma}{d\Omega}(L=3,\text{IV})$$

- ✓ Background reduction
- ✓ Diagonal selection
- ✓ Multipole decomposition analysis (MDA)

Predicted scattered neutron angular distributions come from :

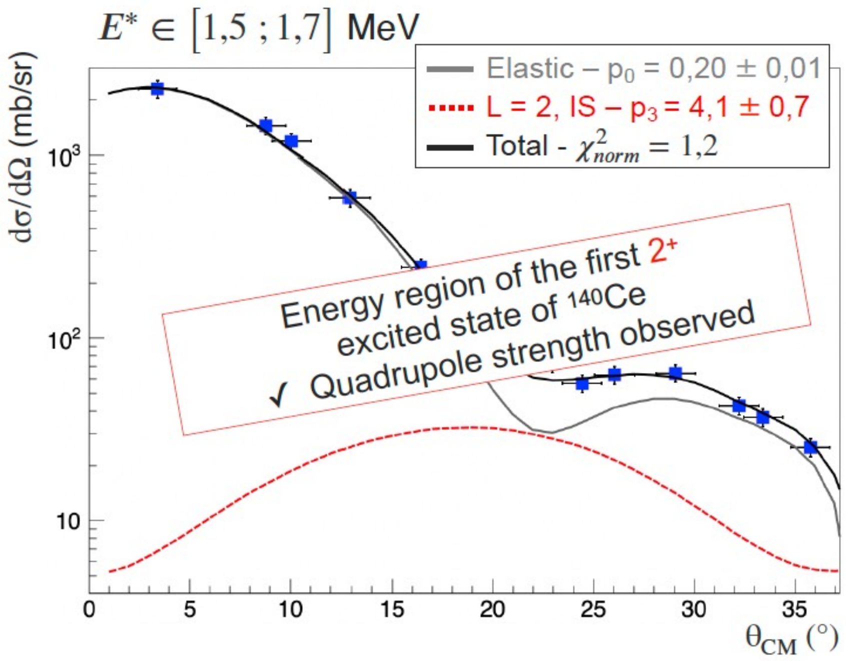
| Microscopic predictions for $^{140}$Ce :<br>HFB + **QRPA**, **Gogny** D1M interaction<br>*[S. Péru and M. Martini, Eur. Phys. J. A **50**, 88 (2014)]* | + | **DWBA** reaction model - $^{140}$Ce(n,n') at $E_n = 30{,}8$ MeV :<br>**JLM potential** + QRPA **transition densities**<br>*[M. Dupuis et al., PRC **100** (2019)]* |
|---|---|---|

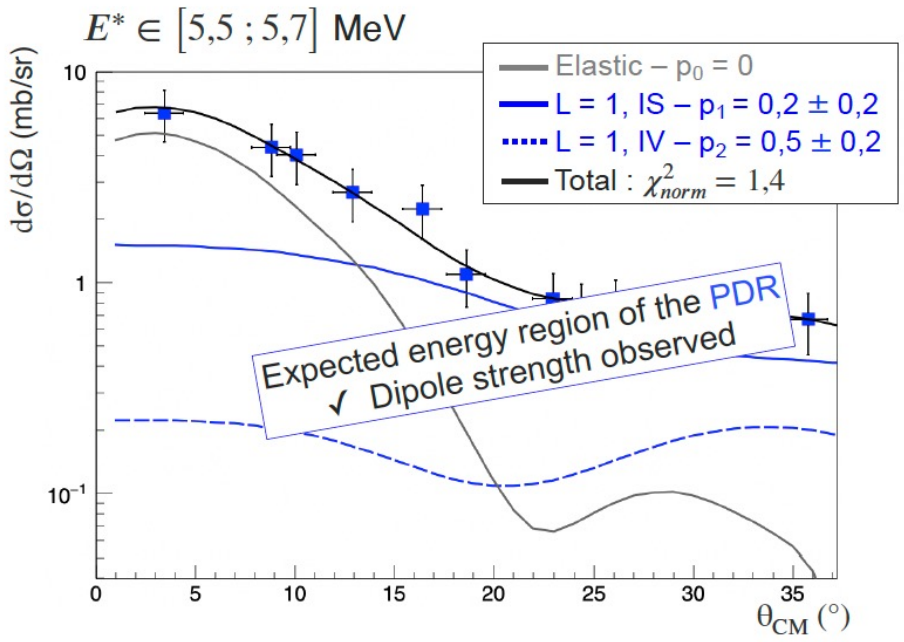
# Main steps of the analysis

3) Study of the inelastic scattering channel using $^{nat}Ce$ target

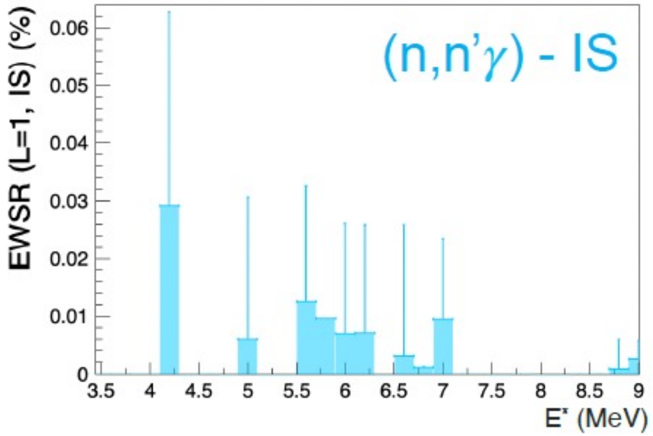
$$\frac{d\sigma}{d\Omega}(exp) = p_0\frac{d\sigma}{d\Omega}(\text{elastic}) + p_1\frac{d\sigma}{d\Omega}(L=1,\text{IS}) + p_2\frac{d\sigma}{d\Omega}(L=1,\text{IV}) + p_3\frac{d\sigma}{d\Omega}(L=2,\text{IS}) + p_4\frac{d\sigma}{d\Omega}(L=2,\text{IV}) + p_5\frac{d\sigma}{d\Omega}(L=3,\text{IS}) + p_6\frac{d\sigma}{d\Omega}(L=3,\text{IV})$$

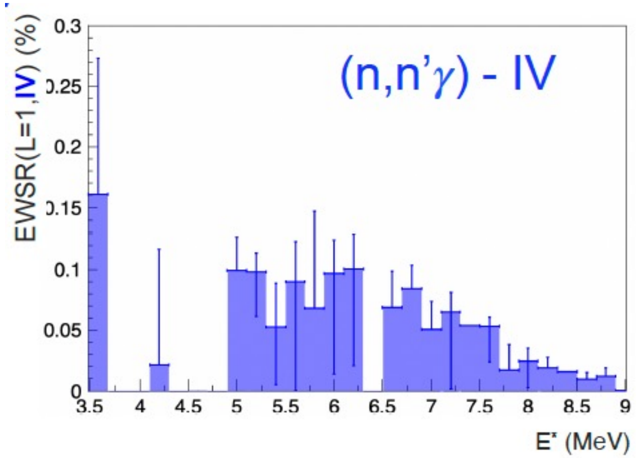
- ✓ Background reduction
- ✓ Diagonal selection
- ✓ Multipole decomposition analysis (MDA)

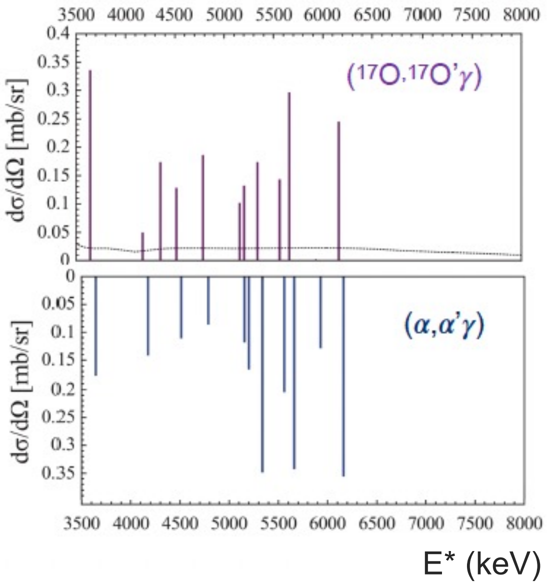


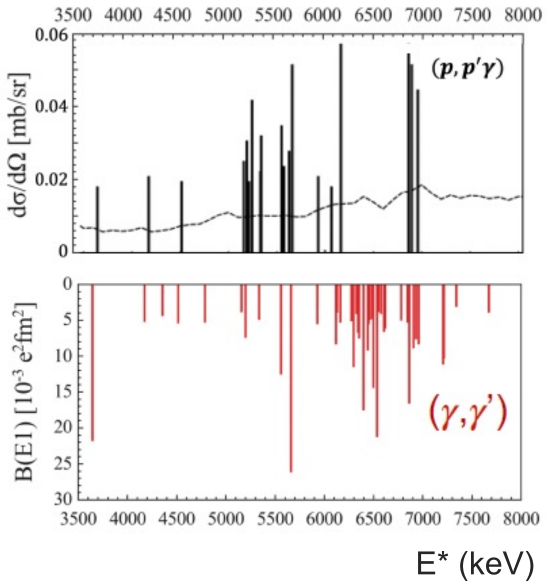
# Results




M. Krzysiek *et al.* Phys. Rev. C 93 (2016)
D. Savran *et al.* Phys. Rev. Lett. 97 (2006)




D. Savran *et al.* Phys. Lett. B 786 (2018)
S. Volz *et al.* Nucl. Phys. A 779 (2006)

- **Isoscalar (IS) L = 1**

Contribution up to 7MeV. No states observed at higher energy.

- **Isovector (IV) L = 1**

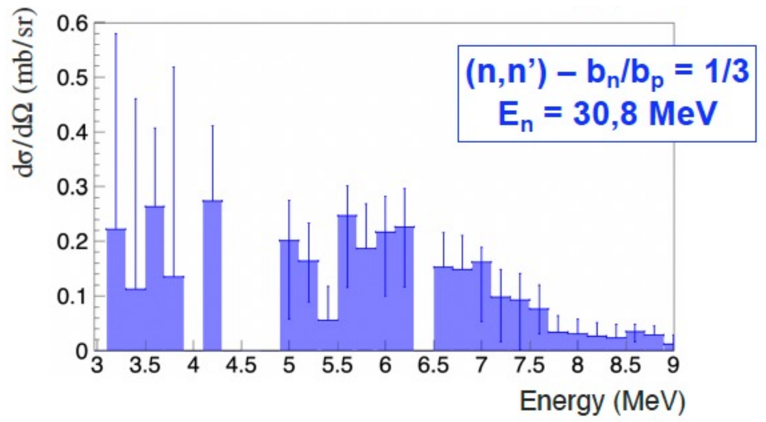
States populated in the whole energy region.

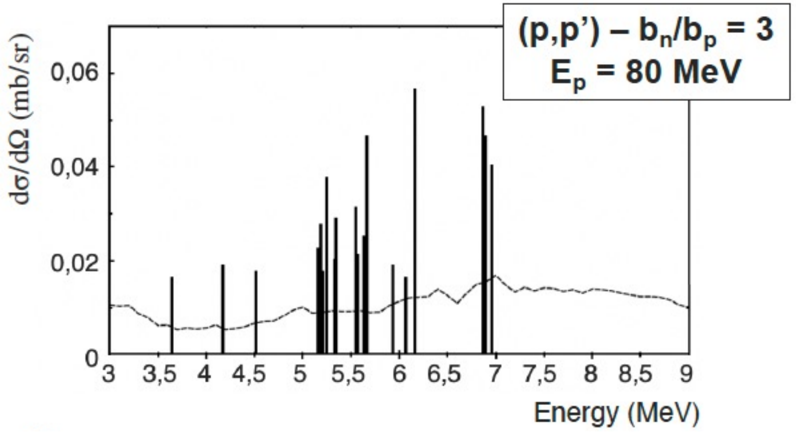
- Results compatible with what has been observed before using other probes

✓ P. Miriot-Jaubert *et al*, in preparation

# Interpretation to be continued

➢ **L = 1 dσ/dΩ populated in $^{140}$Ce(n,n') at 30.8 MeV**
Comparison with $^{140}$Ce(p,p')

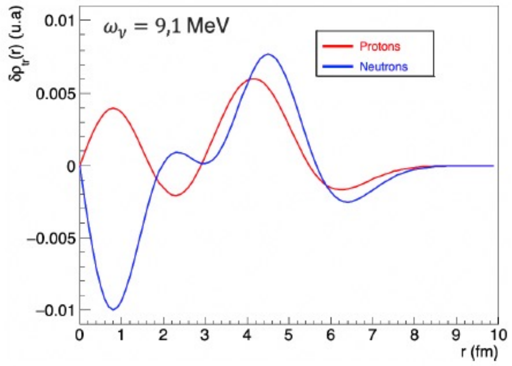



D. Savran *et al.* Phys. Lett. B 786 (2018)

➢ We want to exploit the complementarity of the two probes to test the nature of the low-lying dipole states in $^{140}$Ce through their transition densities

Generation of transition densities
(« toy model »)




DWBA predictions for **(p,p')** and **(n,n')** reactions
$$\Rightarrow \frac{d\sigma}{d\Omega} \text{ (mb/sr)}$$

Reproduction of experimental data ?

No

Yes

Information on the populated PDR states

Microscopic transition densities to test models

# Perspectives:
# E914_25 « Probing low energy dipole strength in $^{88}$Sr with (n,n'γ) reaction at NFS »

Spokespersons: I. Matea, M. Vandebrouck, P. Miriot-Jaubert

# Future experiment: $^{88}$Sr(n,n’) at NFS

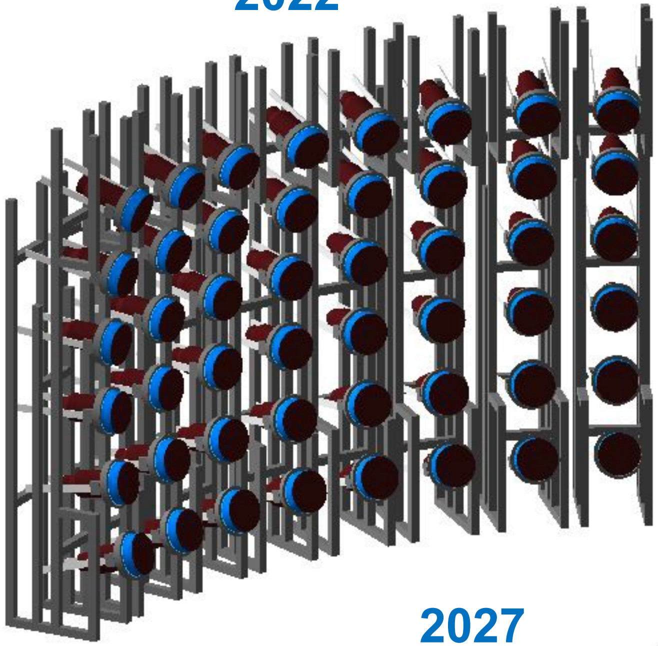
➢ Measurement in $^{88}$Sr - Why is it interesting ?

1) N = 50 nucleus
- Reliable theoretical predictions
- Interesting comparison with $^{140}$Ce (different mass but similar structure)
- Not too fragmented strength

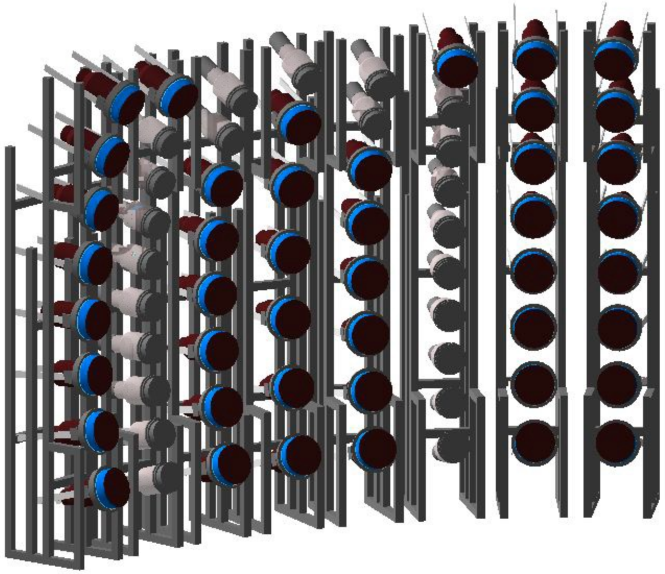
2) PDR well observed in ($\gamma$,$\gamma$’)
EWSR: 0.74(2)% in $^{88}$Sr (R. Schwengner *et al.* PRC 76, 034321 (2007))
versus 0.38(7)% in $^{140}$Ce (S. Votz *et al.* Nucl. Phys. A 779, 1 (2006))

3) Possible proton contribution to the PDR
T. Otsuka *et al.* arXiv:1806.11262 (2018)

2022

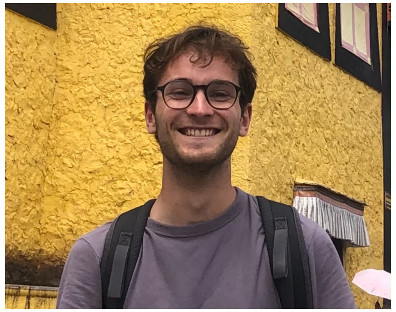


2027

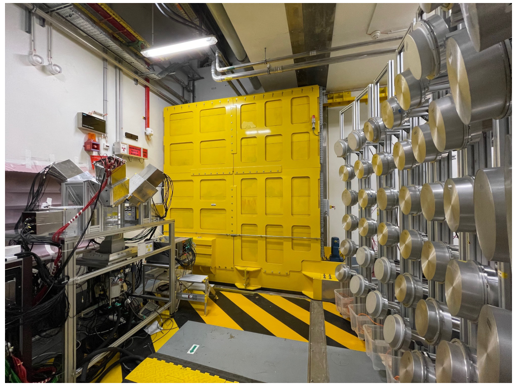


➢ Modification of the neutron detection setup to increase granularity

NPTOOL simulations performed by M. Grillot.
2022: 48 MONSTER
2027: 44 MONSTER + 23 VENDETA



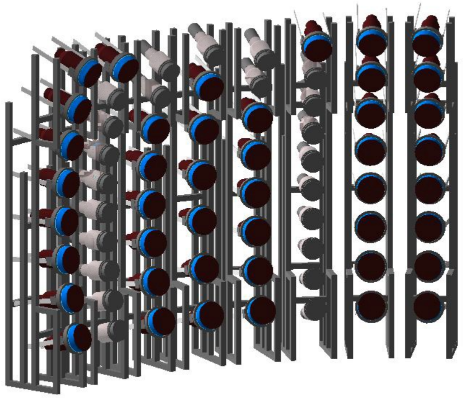
# Conclusion



## ➢ First measurement of the low-lying dipole strength using (n,n')

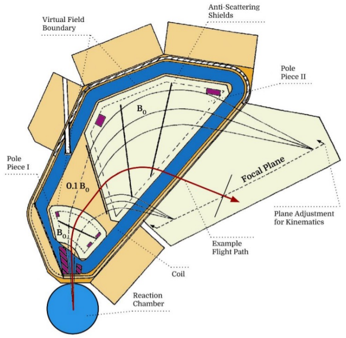
- ✓ Study in $^{140}$Ce at NFS
- ✓ Results compatible with previous investigations using other probes
- ✓ Interpretation to be continued, using the complementarity of (p,p') and (n,n'), to pin down the nature of these dipole states

## ➢ Next experiment accepted $^{88}$Sr(n,n') at NFS



- ✓ Improvement of the neutron detection
- ✓ Experiment should be performed in summer 2027

## ➢ Complementary approaches

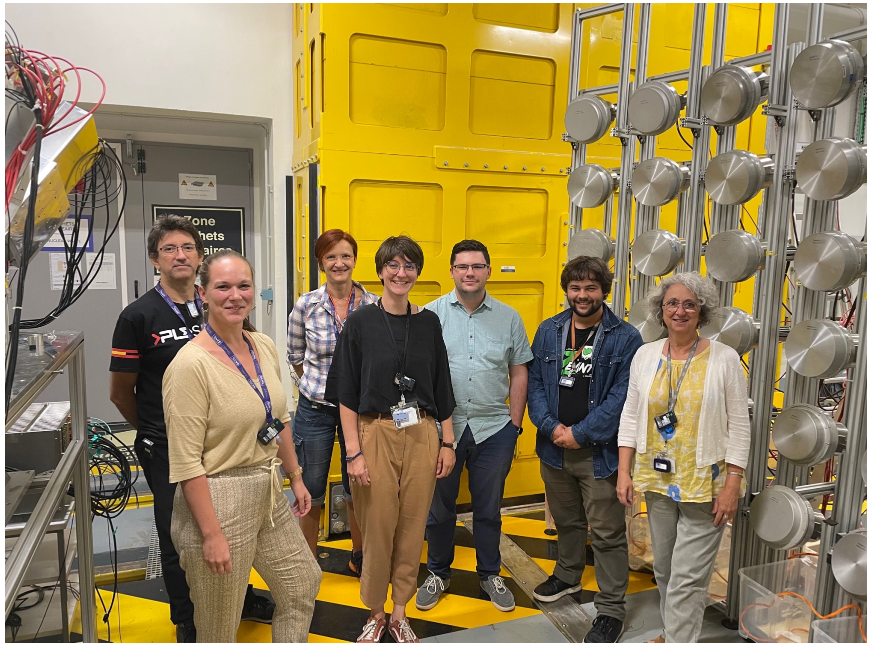



- ✓ "Spectroscopy of $^{88}$Sr and structure of low-spin states: single neutron transfer $^{87}$Sr(d,p) with Split-Pole magnetic spectrograph at ALTO" accepted experiment.
  Spokespersons P. Miriot-Jaubert and I. Matea
- ✓ Possible experiments using (p,p') at CCB, Poland.

# Collaboration


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

N. L. Achouri[3], L. Al Ayoubi[2], D. Beaumel[2], Y. Blumenfeld[2], S. Calinescu[6], D. Cano Ott[7], M. Ciemala [4], A. Corsi[1], F. Crespi[5], Y. Demane[9], W. Dong[2], O. Dorvaux[10], J. Dudouet[9], D. Etasse[3], A. M. Frelin[13], J. Gibelin[3], M. N. Harakeh[15][13], M. Kmiecik[4], M. Lebois[2], M. Lewitowicz[13], A. Maj[4], D. Ramos[13], Ch. Schmitt[10], M. Stanoiu[6], O. Stezowski[9], Ch. Theisen[1]†, L. Thulliez[1], G. Tocabens[1], M. Zielinska[1], PARIS and MONSTER collaborations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† Deceased