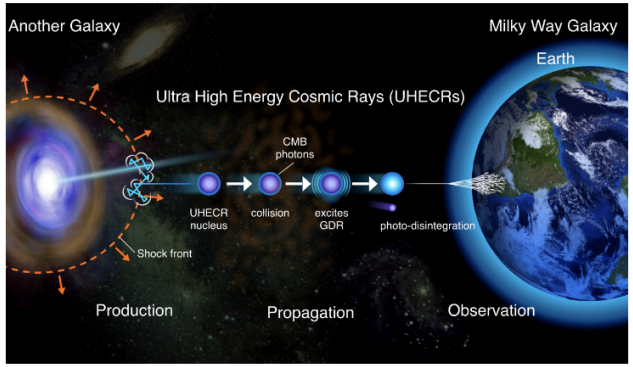
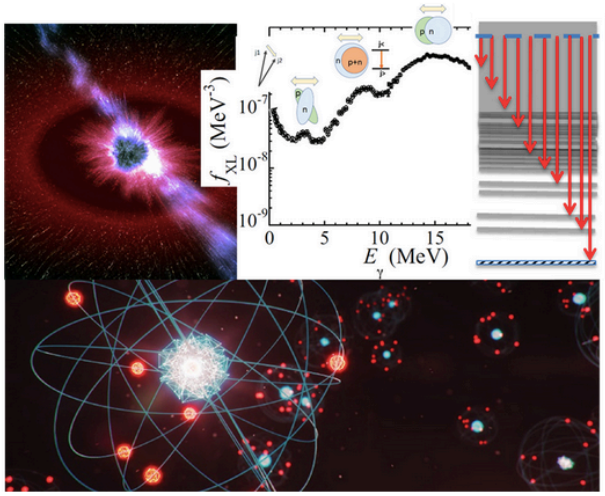
Dipole Excitations in Nuclei: Bridging Femtometer Physics with Cosmic-Scale Questions

PANDORA Project
Photo-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics





PANDORA
Photo-Absorption of Nuclei and Decay Observation for Reactions in Astrophysics

2

Kamila Sieja

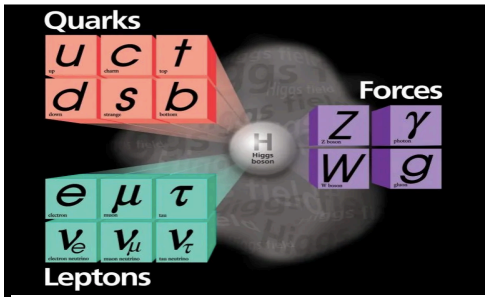
iPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

QMat QUANTUM SCIENCE AND NANOMATERIALS

Université de Strasbourg Excellence University

cnrs

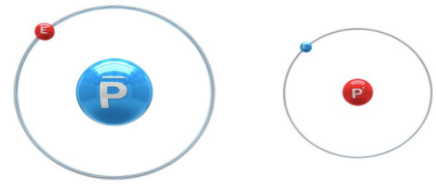
THEORY TEAM: ACTIVITIES

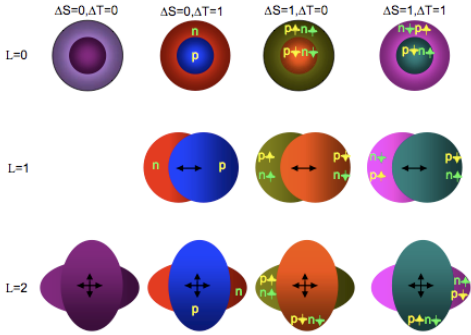


- **High-energy (particle) physics**

1. Effective field theories, Lie algebras

2. Physics beyond the Standard Model: from formal aspects to phenomenology

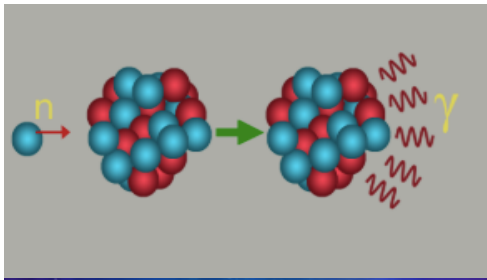




- **Low-energy (nuclear) physics**

1. Few-body systems:
-Weakly-bound systems, resonances, physics of antimatter

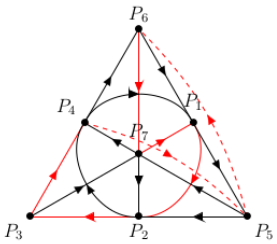
2. Many-body systems:
-Exotic nuclei, weak processes, applications in astrophysics
-Exotic symmetries, superheavy systems



HIGH-ENERGY (PARTICLE) PHYSICS

PHYSICS SUBJECTS:

- Supersymmetry, supergravity
- Lie groups
- Quantum field theory : effective field theories for particle physics, scattering amplitudes, symmetries
- Particle physics beyond-the-Standard-Model : strong CP problem, axions, flavor
- Early-universe cosmology : dark matter, cosmic strings



PhD thesis:

S. Beaudoin (PhD ongoing)

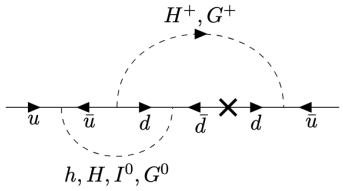
« Axions, cordes cosmiques et monopoles magnétiques »

V. Saulquin (PhD ongoing)

« Nouveaux modèles de physique des particules inspirés par le problème CP fort et les symétries de saveur »

Q. Bonnefoy

M. Rausch de Traubenberg



J. Polonyi (emeritus)

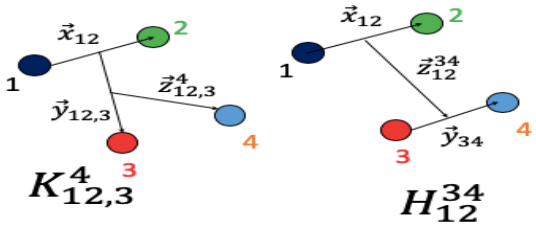
S. Beaudoin

V. Saulquin

FEW-BODY SYSTEMS

PHYSICS SUBJECTS:

- 3-5 particle systems atomic, molecular, nuclear
- Weakly-bound systems, resonances
- Physics of antimatter, interaction between matter and antimatter
- Experiments GBAR and PUMA @CERN



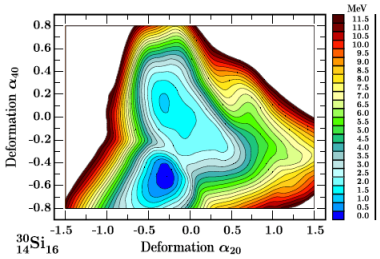
ANR FBCUBES

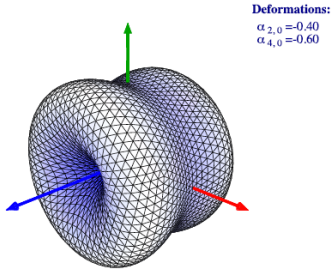
M. Dufour **R. Lazauskas** **M. Schäfer (post-doc)**

MANY-BODY SYSTEMS (1)

PHYSICS SUBJECTS:

- K-isomers, shape isomers, Gallagher-Moszkowski splitting in odd-odd nuclei, fission
- High-rank symmetries
- Multidisciplinary applications: hyperfine structure





J. Bartel (emeritus) **J. Dudek (emeritus)** **H.Molique**

MANY-BODY SYSTEMS (2): valence-space approaches

PHYSICS SUBJECTS:

- Exotic nuclei: spectroscopy, shell evolution, shape changes
- Dipole excitations
- Weak-decays (beta and duble-beta)
- Reactions of interest for astrophysics (r-process, UHECR)

TOOLS:

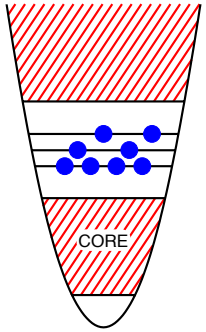
- Effective interactions
- Codes CI-SM and DNO-SM (PGCM):
- ANTOINE, NATHAN, CARINA

K. Sieja

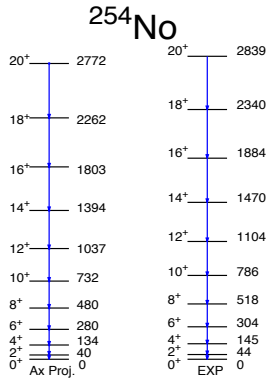
O. Le Noan

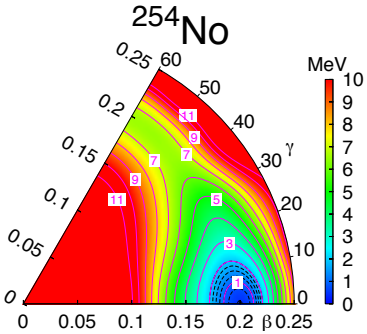
D. D. Dao

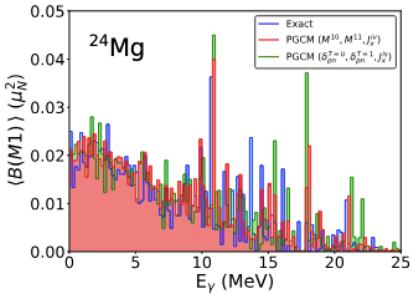
F. Nowacki



Dipole Excitations in Atomic Nuclei: Theoretical Models and Applications
(PhD O. Le Noan+ QMAT project 2024-2026)





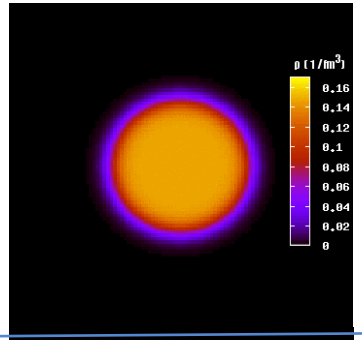


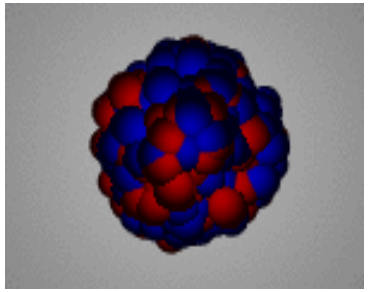
The Collective Response of the Nucleus: Giant Resonances

Isoscalar (In phase)
$\Delta T = 0$

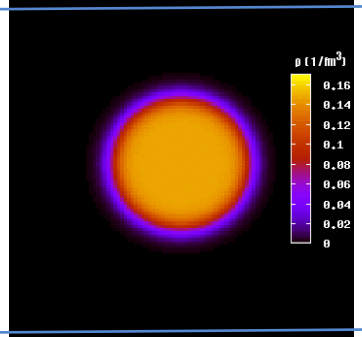
Isovector (Out of phase)
$\Delta T = 1$

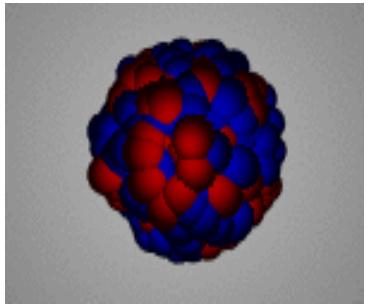
Monopole
$\Delta L = 0$
(GMR)



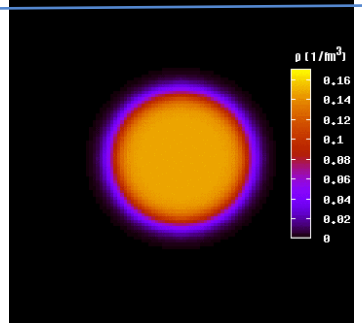


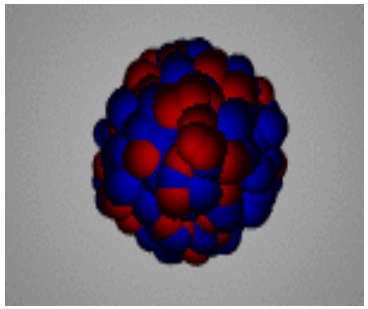
Dipole
$\Delta L = 1$
(GDR)





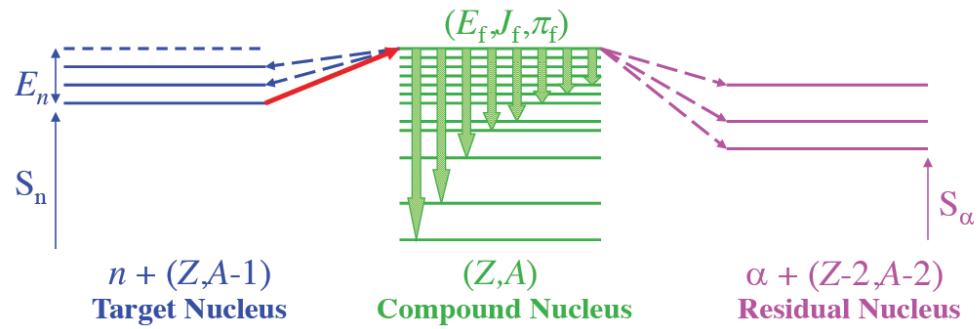
Quadrupole
$\Delta L = 2$
(GQR)

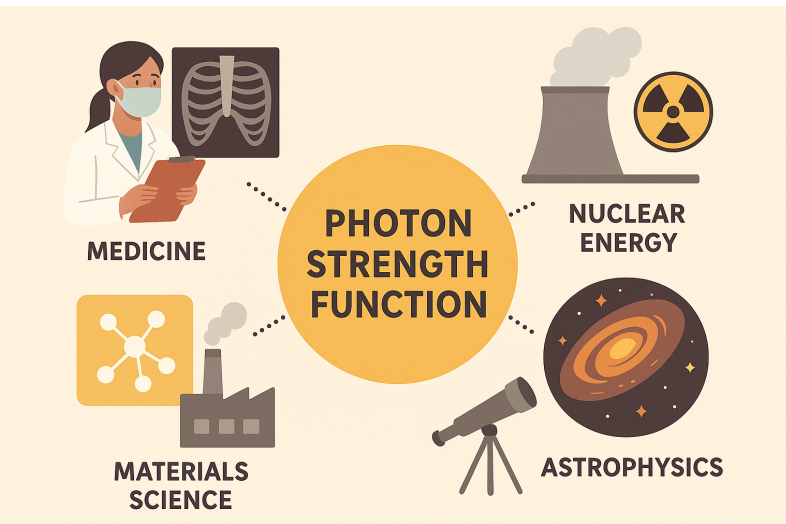




Nuclear Dipole Excitations: from Academic to Industrial Applications

- Fundamental mode of nuclear excitations
- Dominated by E1 mode (with a smaller contribution of the M1)
- Basic input to nuclear reaction codes





generated by AI

$$\sigma^{\mu\nu}_{(n,\gamma)}(E_i,n) = \frac{\pi\hbar^2}{2M_{i,n}E_{i,n}} \frac{1}{(2J_i^\mu+1)(2J_n+1)} \sum_{J,\pi}(2J+1)\frac{T_n^\mu T_\gamma^\nu}{T_n^\mu + T_\gamma^\nu}$$

for $E_n \sim$keV $\quad T_n^\mu \gg T_\gamma^\nu \longrightarrow \boldsymbol{\sigma^{\mu\nu} \sim T_\gamma^\nu}$

For a given multipolarity

$$T_{XL}(E,J,\pi,E^\nu,J^\nu,\pi^\nu) = 2\pi E_\gamma^{2L+1} f_{XL}(E,E_\gamma)$$

f_{XL}=*Photon Strength Function (PSF)*

TALYS code: Modeling of Nuclear Reactions

A. Koning, S. Hilaire, S. Goriely at al. Eur. Phys. J A59 (2023) 131

Nuclear Physics Meets the Sources of the Ultra-High Energy Cosmic Rays

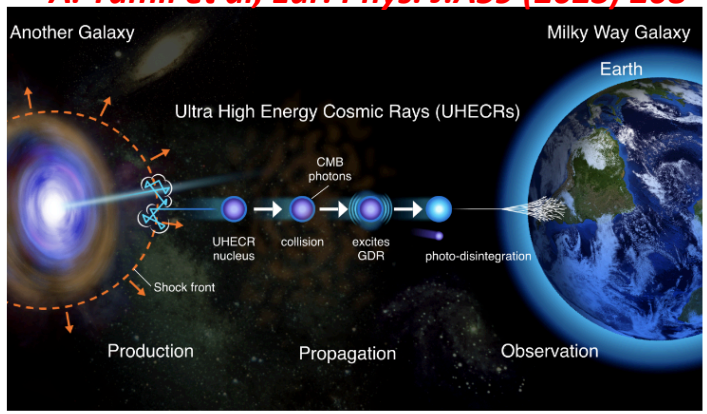
PANDORA Project

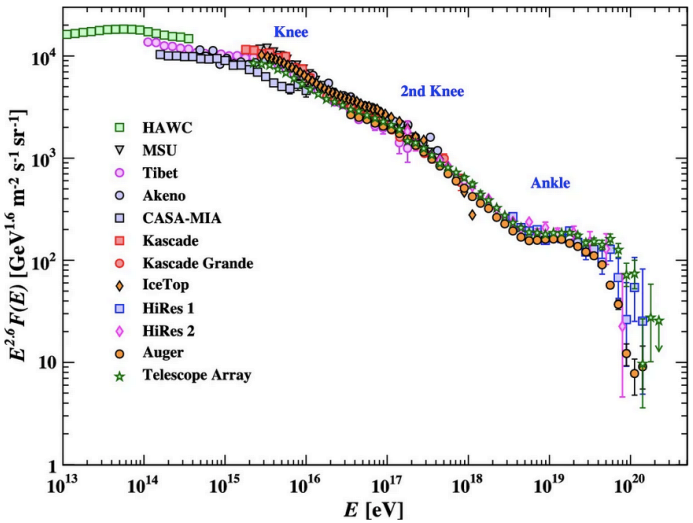
Photo-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics

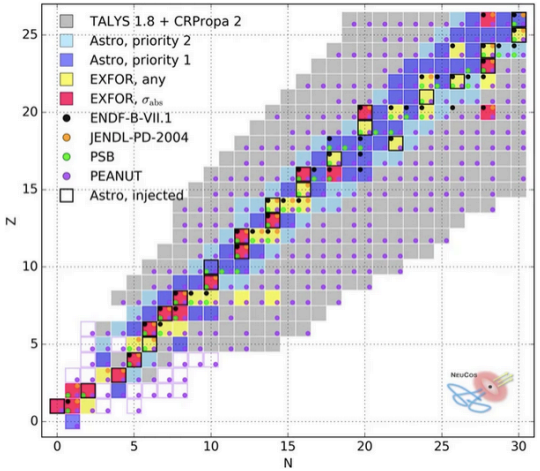
A. Tamii et al, Eur. Phys. J.A59 (2023) 208

After >50 years of studying UHECR open questions remain :

- Where do they come from?
- How they are accelerated?

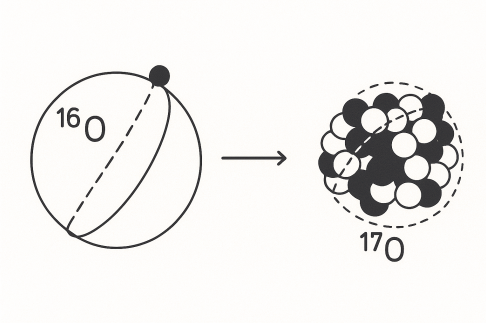




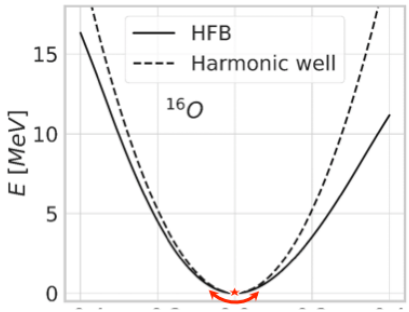


*Boncioli, D., Fedynitch, A. & Winter, W., Sci Rep **7**, 4882 (2017).*

Many-body methods to compute dipole response



$$H_{\mathrm{MF}} = \sum_i [T_i + U(r_i)] \Longleftrightarrow H = \sum_i T_i + \sum_{i<j} V_{ij} \; + \ldots$$



Quasiparticle Random Phase Approximation (QRPA)

$$i\partial_t \mathcal{R}(t) = [\mathcal{H}(t) + \mathcal{F}(t), \mathcal{R}(t)],$$

$$\boxed{\begin{aligned} (E_\mu + E_\nu - \omega) X_{\mu\nu}(\omega) + \delta H^{20}(\omega) &= -F^{20}(\omega) \\ (E_\mu + E_\nu + \omega) Y_{\mu\nu}(\omega) + \delta H^{02}(\omega) &= -F^{02}(\omega) \end{aligned}}$$

Configuration Interaction Shell Model (CI-SM)

$$|\Psi_0\rangle = C_0|\Phi_0\rangle + \sum_{i\alpha} C_{i\alpha}|\Phi_{i\alpha}\rangle + C_{ij\alpha\beta}|\Phi_{ij\alpha\beta}\rangle + \cdots$$

$$E = \langle\Psi_0|\hat{H}|\Psi_0\rangle$$

Projected Generator Coordinate Method (PGCM)

$$|\,\Psi^\sigma_{GCM}\,\rangle = \int f_\sigma(\vec{q})\;|\,\Phi(\vec{q})\,\rangle\; d\vec{q}$$

$$E_\sigma[\,|\,\Psi^\sigma_{GCM}\,\rangle\,] = \frac{\langle\,\Psi^\sigma_{GCM}\,|\,\hat{H}\,|\,\Psi^\sigma_{GCM}\,\rangle}{\langle\,\Psi^\sigma_{GCM}\,|\,\Psi^\sigma_{GCM}\,\rangle} =$$

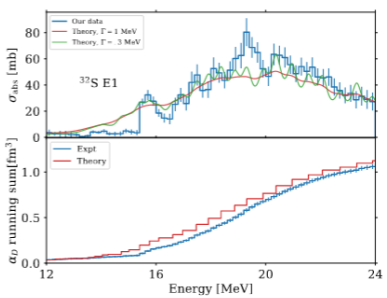
$$= \frac{\int \langle\,\Phi(\vec{q})\,|\,\hat{H}\,|\,\Phi(\vec{q}\,')\,\rangle f^*_\sigma(\vec{q})\; f_\sigma(\vec{q}\,')\, d\vec{q}\, d\vec{q}\,'}{\int \langle\,\Phi(\vec{q})\,|\,\Phi(\vec{q}\,')\,\rangle\, f^*_\sigma(\vec{q})\; f_\sigma(\vec{q}\,')\, d\vec{q}\, d\vec{q}\,'}$$

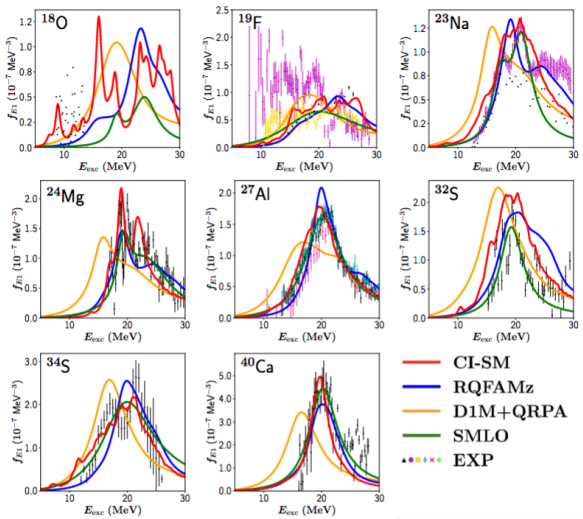
Benchmark of many-body methods:

1. *M. Frosini, W. Ryssens and* ***K. Sieja,*** *Phys. Rev. C* ***110****, 014307 (2024)*
2. *S. Bofos, J. Martinez, B. Bally, T. Duguet, M. Frosini, T. Rodriguez and* ***K. Sieja,*** *Phys. Rev. C****112,*** *064312 (2025)*

Impact of Photonuclear Reaction Models on Propagation Ultra-High Energy Cosmic Rays

*R. Fearick, **O. Le Noan**, H. Matsubara, P. von Neumann-Cosel, **K. Sieja** and A. Tamii, in preparation.*

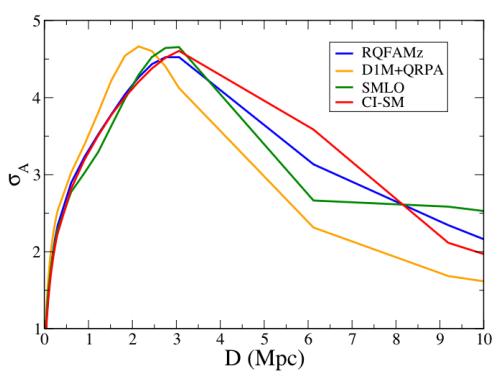


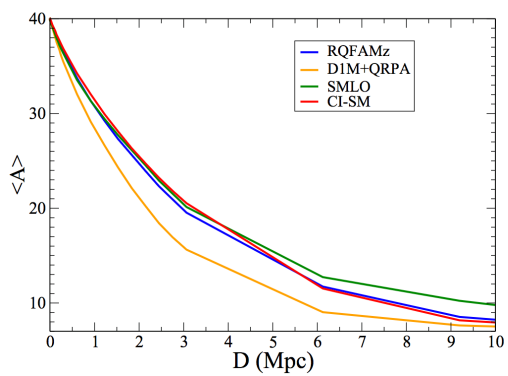


***O. Le Noan** and **K. Sieja**, PRC111 (2025) 064308.*

CI-SM PSF database for TALYS

$$\frac{dN_{Z,A}}{dt} = N_{Z+1,A}\lambda_\beta^{Z+1,A} + N_{Z-1,A}\lambda_\beta^{Z-1,A} + N_{Z,A+1}\lambda_{\gamma,n}^{Z,A+1} + N_{Z+1,A+1}\lambda_{\gamma,p}^{Z+1,A+1} + N_{Z+2,A+4}\lambda_{\gamma,\alpha}^{Z+2,A+4} + N_{Z,A+2}\lambda_{\gamma,2n}^{Z,A+2} + N_{Z+2,A+2}\lambda_{\gamma,2p}^{Z+2,A+2} + N_{Z+4,A+8}\lambda_{\gamma,2\alpha}^{Z+4,A+8} + N_{Z+1,A+2}\lambda_{\gamma,np}^{Z+1,A+2} + N_{Z+2,A+5}\lambda_{\gamma,n\alpha}^{Z+2,A+5} + N_{Z+3,A+5}\lambda_{\gamma,p\alpha}^{Z+3,A+5} - N_{Z,A}\left[\lambda_\beta^{Z,A} + \sum_x \lambda_{\gamma,x}^{Z,A}\right], \quad (9)$$

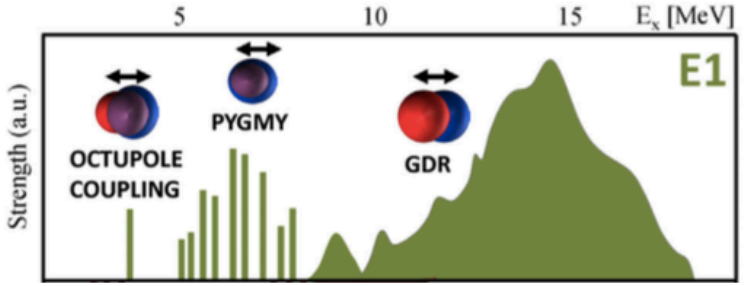


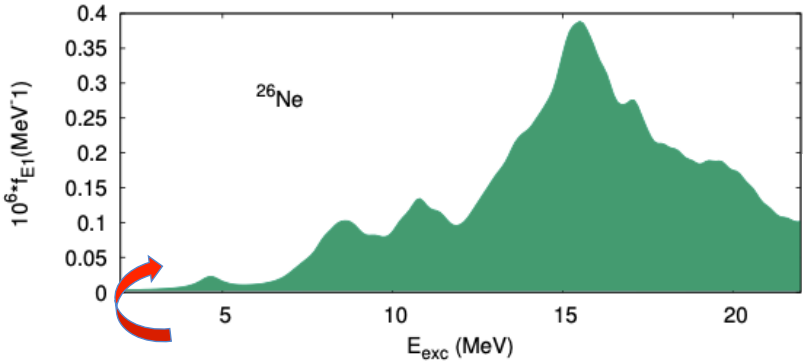


***O. Le Noan**, S. Goriely, E. Khan and **K. Sieja**, to be submitted.*

New Insights into the Nature of the Pygmy Dipole Resonance

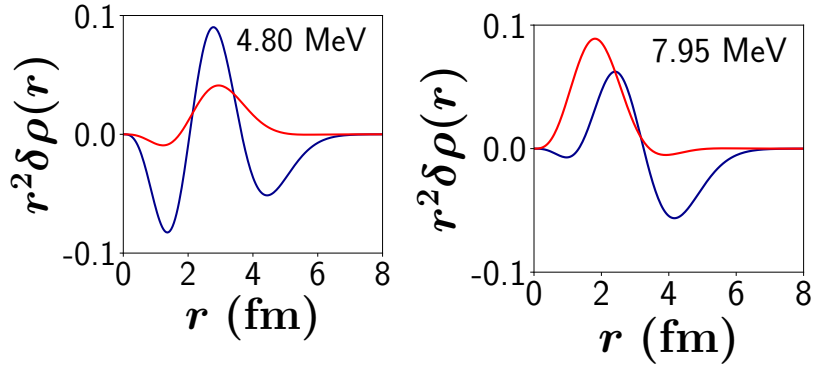
***O. Le Noan** and **K. Sieja**, PRC111 (2025) 064308.*

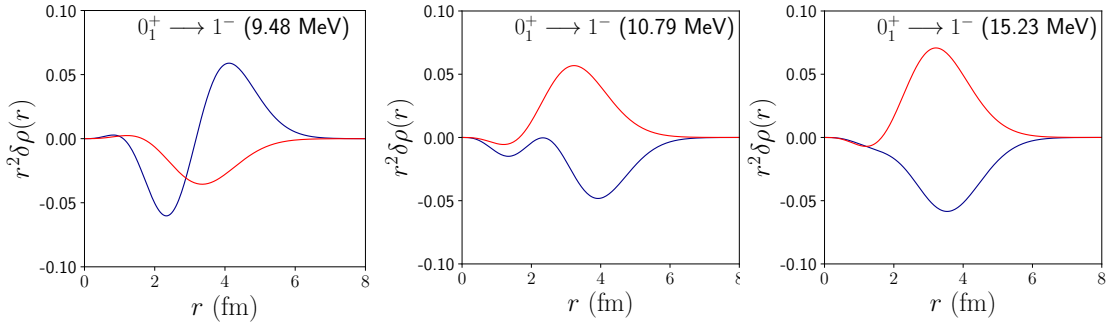




CI-SM computation

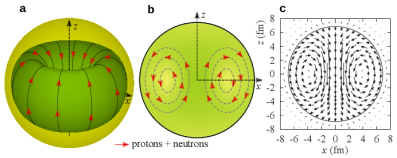
$$\delta\rho_{\nu 0}(\vec{r}) = \langle \nu | \sum_k \delta(\vec{r} - \vec{r}_k) | 0 \rangle \,,$$





Motivations to study PDR:

- PDR enhances probability of (n,γ) CS
  => influence on astrophysical r-process
- PDR relates to neutron-skin thickness
  => relation to neutron stars



P. von Neumann Cosel et al. Physics (2023)

Open questions:

- Evolution of PDR with angular momenta and deformation
- Isospin mixing of PDR (IS vs IV)
- Is PDR a toroidal mode?

Thank You !

<u>Thanks to:</u>
IPHC: O. Le Noan
CEA Saclay: T. Duguet
CEA Cadarache: S. Bofos, M. Frosini, A. Pastore
CEA DAM: S. Hilaire
IJCLab: E. Khan
TU Darmstadt: B. Bally
Universidad de Sevilla: T. R. Rodriguez
Universidad Autonoma de Madrid: J. Martinez-Larraz
Université Libre de Bruxelles: S. Goriely, W. Ryssens
University of Zagreb: N. Paar

PANDORA
Photo-Absorption of Nuclei and Decay Observation for Reactions in Astrophysics

IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

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