北京大学
PEKING UNIVERSITY

Origin of Elements and Cosmic Evolution 2026
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Microscopic γ-ray strength function for r-process nucleosynthesis

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r-process

- **The origin of elements is one of the most fundamental scientific problems**

  "How were the elements from iron to uranium made?"

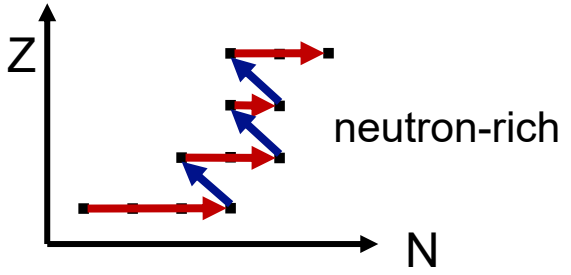
  National Research Council, Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century (2003).

- **The rapid neutron capture process (*r*-process) produces about half of the elements heavier than iron in the universe**

  E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Rev. Mod. Phys. 29, 547 (1957).
  J. J. Cowan, C. Sneden, J. E. Lawler, et al., Rev. Mod. Phys. 93, 015002 (2021).

neutron capture (n,γ) β-decay

$$(Z,N)+Xn \rightarrow (Z,N+X) \rightarrow (Z+1,N+X-1) \rightarrow \cdots$$



- **The (n,γ) reaction plays an important role in the *r*-process**

- **Measurement of the (n,γ) rates of neutron-rich nuclei is challenging**

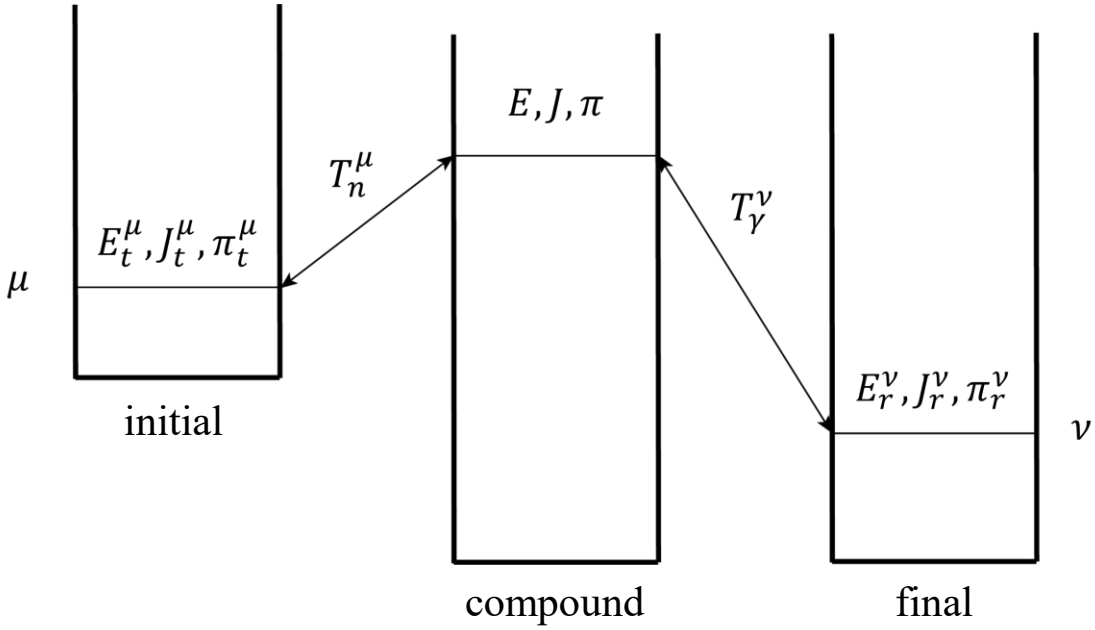
  A. C. Larsen, A. Spyrou, S. N. Liddick, and M. Guttormsen, Prog. Part. Nucl. Phys. 107, 69 (2019).

- **Currently, the r-process studies rely on the theoretical predictions for the required (n,γ) rates**

Neutron capture rate

- **Traditionally, the (n, γ) rates for *r*-process nuclei are determined within the statistical model**

$$n + t^{\mu} \rightarrow C^{*} \rightarrow r^{\nu} + \gamma$$



nuclear level density
γ-ray strength function
optical potential

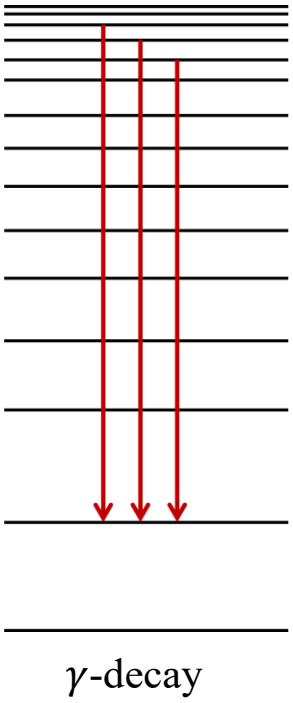
→ Hauser-Feshbach formula → (n, γ) cross section → (n, γ) reaction rate

Maxwell-Boltzmann average, nuclear partition function

γ-ray strength function

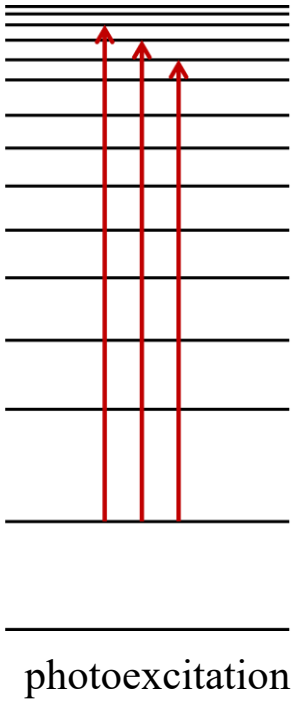
- **The γ-ray strength function (GSF) describes:**

The average response of the nucleus to an electromagnetic probe



- downward γ-ray strength function

$$\overleftarrow{f}_{XL}(E_i, I_i, \pi_i, E_\gamma) = \frac{\langle \Gamma_{XL}(E_i, I_i, \pi_i, E_\gamma) \rangle \, \rho(E_i, I_i, \pi_i)}{E_\gamma^{2L+1}}$$



- upward γ-ray strength function

$$\overrightarrow{f}_{XL}(E_f, I_f, \pi_f, E_\gamma) = \frac{\langle \Gamma_{XL}(E_f, I_f, \pi_f, E_\gamma) \rangle \, \rho(E_f, I_f, \pi_f)}{E_\gamma^{2L+1}}$$

$$\overrightarrow{f}_{XL}(E_f, I_f, \pi_f, E_\gamma) = \frac{1}{(2L+1)(\pi\hbar c)^2} \frac{\langle \sigma_{XL}(E_f, I_f, \pi_f, E_\gamma) \rangle}{E_\gamma^{2L-1}}$$

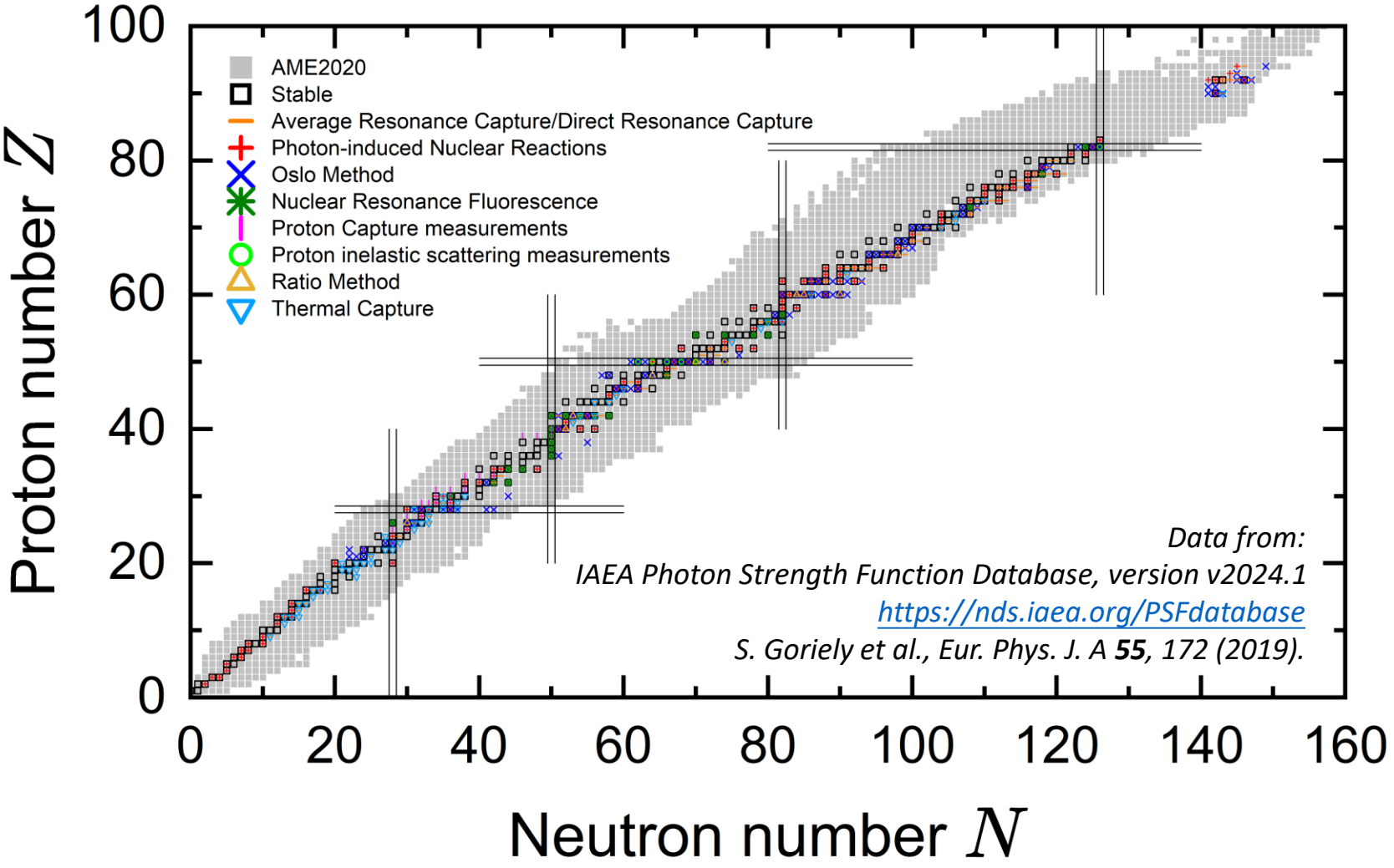
G.A. Bartholomew, et al., Adv. Nucl. Phys. 7, 229 (1973).

- The Brink-Axel hypothesis

$$f_{XL}(E_i, I_i, \pi_i, E_f, I_f, \pi_f, E_\gamma) = f_{XL}(E_\gamma)$$

D.M. Brink, Doctoral thesis, Oxford University, 1955.
P. Axel, Phys. Rev. 126, 671 (1962).

Experimental measurements



- **Experimental measurements of GSFs are mostly around the stability line.**
- **Data are still very limited in the neutron-rich region far from stability.**

Theoretical models

Phenomenological model

- Standard Lorentzian model — Brink1957NP; Axel1962PR
- Generalized Lorentzian model — Goriely+2019EPJA
- …

Nuclear shell-model

- Large-scale shell-model — Loens+2012EPJA; Sieja2017PRL
- Shell-model monte carlo approach — Fanto&Alhassid2024PRC
- Projected shell-model — Chen2025+PRL
- …

Nuclear density functional theory

- Skyrme-HF-BCS + QRPA — Goriely&Khan2002NPA
- Skyrme HFB + QRPA — Goriely+2004NPA; Xu+2024PRC; Xu+2026PRC
- Gogny HFB + QRPA — Martini+2016PRC; Goriely+2018PRC
- RMF-BCS + QPVC — Litvinova+2009NPA
- RMF-BCS + CRPA — Daoutidis&Goriely2012PRC
- RHB + QFAM — L. González-Miret Zaragoza+2025PRC;Chen+2026ADNDT
- …

- **The nuclear density functional theory has been applied in the systemic calculation of GSFs across the whole nuclear chart.**

This work

- **The deformed relativistic Hartree-Bogoliubov theory in continuum (DRHBc) is well suited for describing neutron-rich nuclei, as it simultaneously accounts for deformation, pairing correlations, and continuum effects**

  S.-G. Zhou, J. Meng, P. Ring, and E.-G. Zhao, Phys. Rev. C 82, 11301 (2010).
  L. Li, J. Meng, P. Ring, E.-G. Zhao, and S.-G. Zhou, Phys. Rev. C 85, 24312 (2012).

- **Based on the DRHBc theory with the PC-PK1 functional, the DRHBc mass table has been constructed, achieving an rms mass deviation of 1.444 MeV, the smallest among microscopic nuclear mass models to date**

  https://drhbctable.jcnp.org/

  DRHBc Mass Table Collaboration, At. Data Nucl. Data Tables 144, 101488 (2022).
  DRHBc Mass Table Collaboration, At. Data Nucl. Data Tables 158, 101661 (2024).
  arXiv:2610.04886

- **Building on this success, we aim to establish a unified, microscopic, and self-consistent nuclear input database for r-process studies**

- **To extend the DRHBc framework to nuclear excited states, the quasi-particle finite-amplitude method (QFAM) has been developed to investigate collective excitations of exotic nuclei**

  X. Sun and J. Meng, Phys. Rev. C 105, 44312 (2022).
  X. F. Jiang, Z. Z. Li, X. W. Sun, and J. Meng, Phys. Lett. B 874, 140264 (2026).

- **In this work, we calculate γ-ray strength functions using DRHBc+QFAM**

DRHBc theory

In DRHBc theory, the relativistic Hartree-Bogoliubov (RHB) equation treats self-consistently the mean-field and pairing correlations

$$\begin{pmatrix} \hat{h}_D - \lambda_\tau & \hat{\Delta} \\ -\hat{\Delta}^* & -\hat{h}_D^* + \lambda_\tau \end{pmatrix} \begin{pmatrix} U_k \\ V_k \end{pmatrix} = E_k \begin{pmatrix} U_k \\ V_k \end{pmatrix}$$

λ_τ is fermi energy, E_k is quasiparticle energy, U_k, V_k are quasiparticle wavefunctions, $\hat{h}_D$ is Dirac Hamiltonian

$$\hat{h}_D(\boldsymbol{r}) = \boldsymbol{\alpha} \cdot (\boldsymbol{p} - \boldsymbol{V}) + V^0 + \beta(M + S)$$

The pairing potential is

$$\hat{\Delta}_{lm} = \frac{1}{2} \sum_{pq} \langle lm | V^{pp} | pq \rangle_a \kappa_{pq}$$

The potentials and densities are expanded by the Legendre polynomials

$$f(\boldsymbol{r}) = \sum_\lambda f_\lambda(r) P_\lambda(\cos\theta), \quad \lambda = 0, 2, 4, \ldots, \lambda_{\max}$$

(Axial symmetry + spatial reflection symmetry)

The RHB equation is solved in the Dirac-Woods-Saxon (DWS) basis

QFAM

- **The quasiparticle finite amplitude method (QFAM) based on DRHBc theory has been developed for the noncharge-exchange excitations**

For a weak harmonic external field with the frequency ω

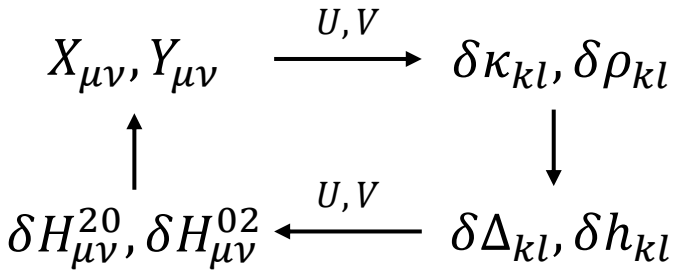
$$\hat{F}(t) = \hat{F}e^{-\mathrm{i}\omega t} + \hat{F}^{\dagger}e^{\mathrm{i}\omega t}$$

in the small amplitude limit, the nucleus oscillate around the equilibrium with the same frequency ω. The linear response equation in the quasi-particle basis can be obtained

$$\delta\mathcal{R}(\omega) = \begin{pmatrix} 0 & X \\ Y & 0 \end{pmatrix}$$

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

QFAM solves the linear response equation by iteration for a given frequency ω



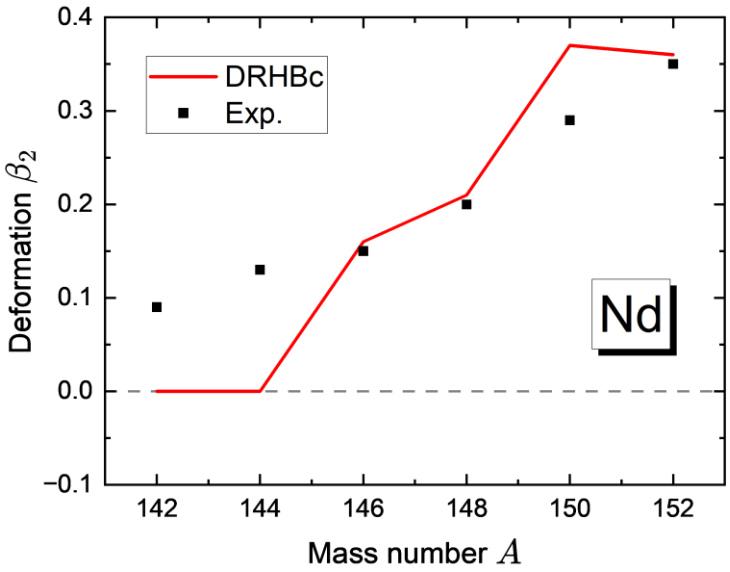
U, V, and E_μ are provided by DRHBc

X. Sun and J. Meng, Phys. Rev. C 105, 44312 (2022).
X. F. Jiang, Z. Z. Li, X. W. Sun, and J. Meng, Phys. Lett. B 874, 140264 (2026).

Numerical details

The DRHBc calculation

- Relativistic density functional: PC-PK1
- Pairing strength: −325.0 MeV fm^3
- Pairing window: 100 MeV
- Box size: R_{box} = 20 fm
- Mesh size: Δr = 0.1 fm
- Energy cutoff: E_{cut} = 150 MeV
- Angular momentum cutoff: J_{max} = 23/2 $\hbar$
- Legendre expansion order: λ_{max} = 6

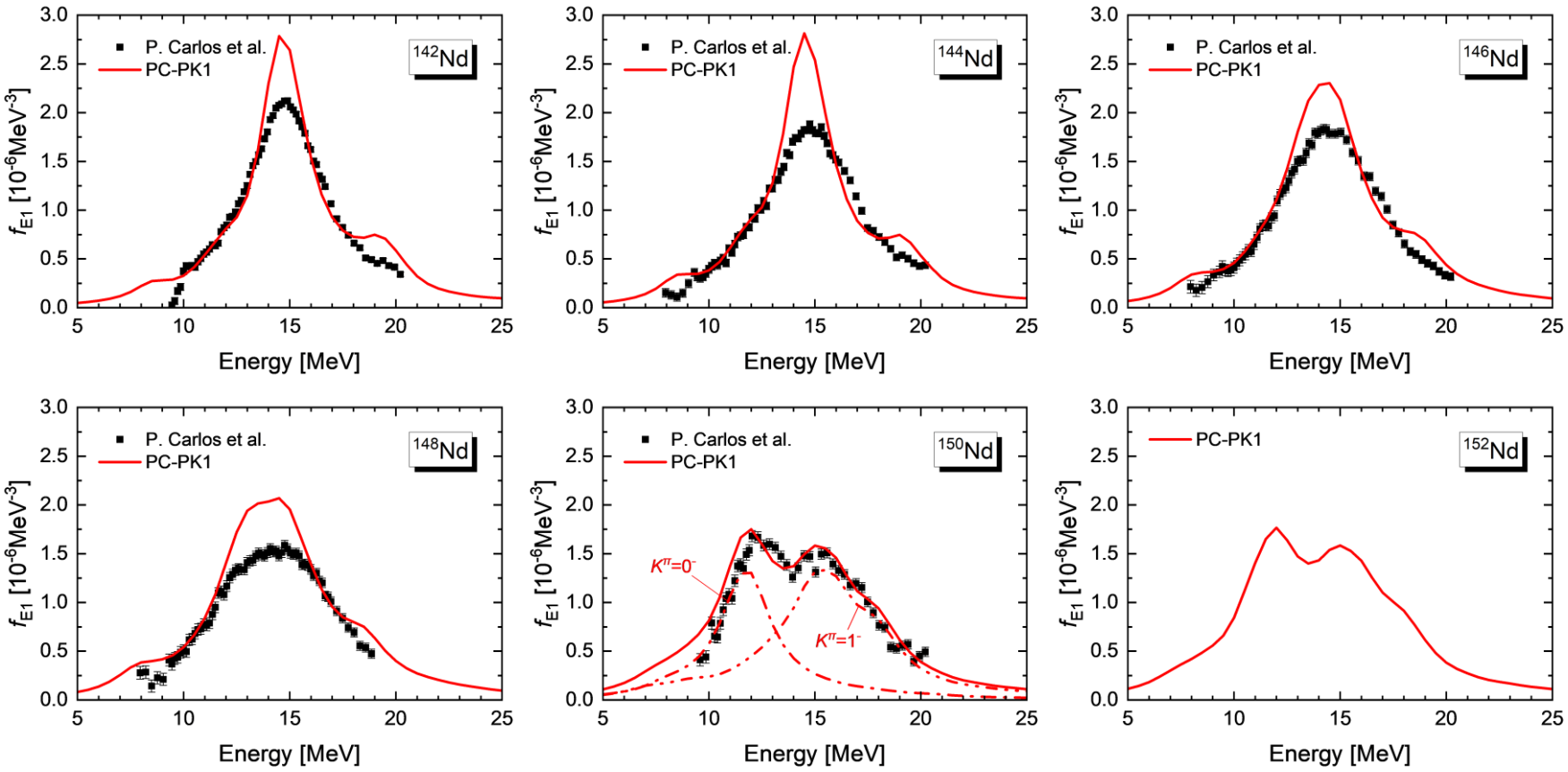


The QFAM calculation

- Scalar/vector spherical harmonics expansion order: L_{max} = 6
- Smearing width: Γ = 2 MeV
- No additional truncation on the two-quasiparticle configuration space

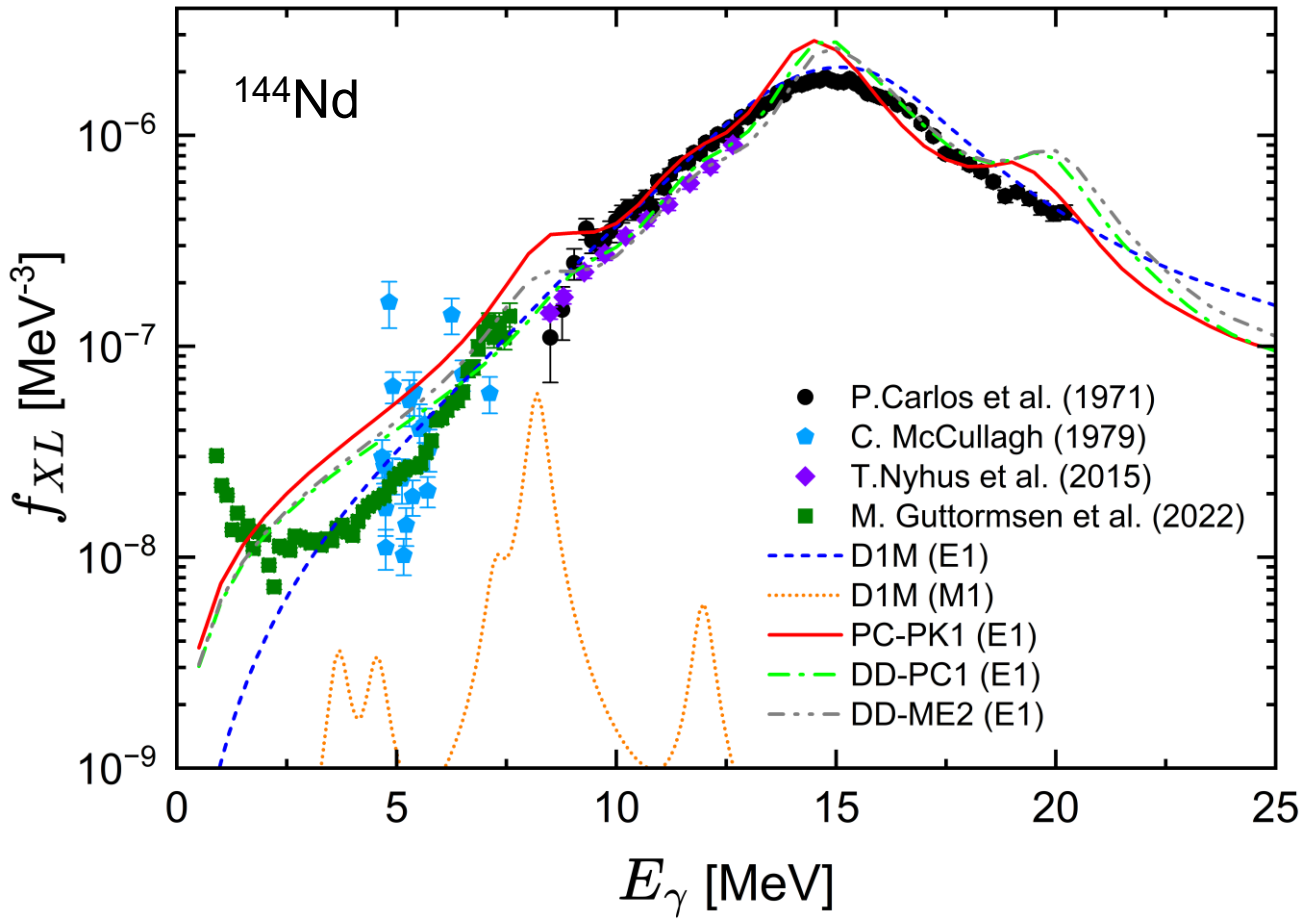
Preliminary results for the even-even isotopes $^{142-152}$Nd are presented

E1 γ-ray strength function



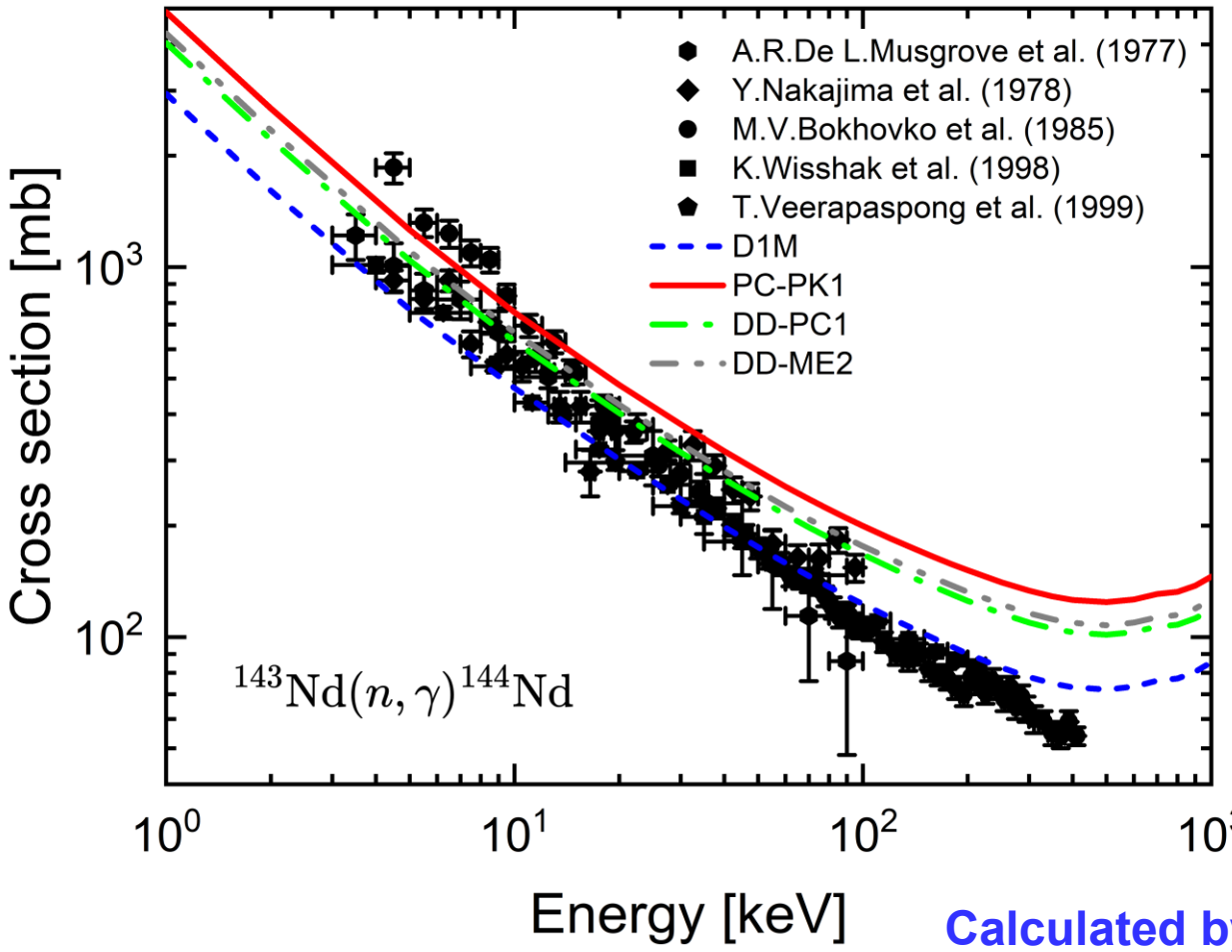
- The DRHBc+QFAM calculations with PC-PK1 reproduce the position of the giant resonance peak and the splitting in deformed nuclei.

E1 γ-ray strength function



- The DRHBc+QFAM calculations with PC-PK1 overall reproduce the evolution trend of the E1 GSF observed in the experimental data.
- Below the neutron threshold, the PC-PK1 calculations give a noticeably higher strength compared to other theoretical models.

Cross section



Calculated by TALYS-2.0

- Except for E1 GSF, all other input values use default values.
- The PC-PK1 calculations reproduce the experimental decreasing trend of the cross section, yielding overall higher values than other theoretical models.

Summary and outlook

- **Summary**
  - The γ-ray strength function is studied with quasi-particle finite amplitude method (QFAM) based on the DRHBc theory.
  - In $^{142-152}$Nd, the DRHBc+QFAM calculations with PC-PK1 show that:
    - Giant resonance peak positions and the splitting in deformed nuclei are reproduced.
    - The E1 strength evolution trend is reproduced, with noticeably higher strength below the neutron threshold compared to other theoretical models.
    - The calculated neutron capture cross section follows the experimental trend, yielding overall higher values than other theoretical models.
- **Outlook**
  - To provide unified and self-consistent nuclear physics inputs for *r*-process studies based on the DRHBc theory.



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The End

Thanks for your attention!