Microscopic description of β-decay rates of r-process nuclei

Diana Alvear Terrero[1,2,3]

In collaboration with

Gabriel Martínez-Pinedo[1,2,3] **Caroline E. P. Robin**[4,3] **Ante Ravlić**[5] **Thomas Neff**[3]

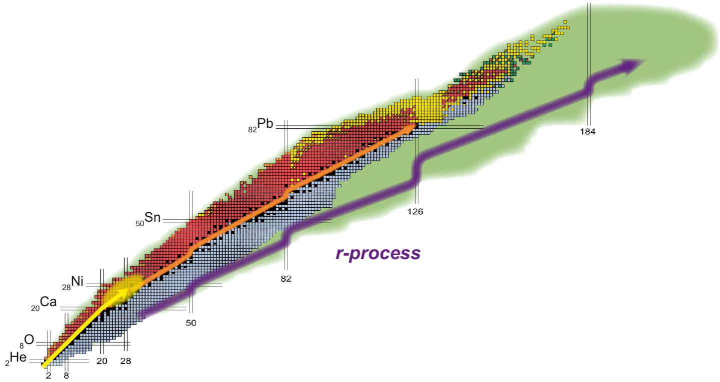
[1]Helmholtz Forschungsakademie Hessen für FAIR. [2]Technische Universität Darmstadt.
[3]GSI Helmholtzzentrum für Schwerionenforschung. [4]Fakultät für Physik, Universität Bielefeld.
[5]Facility for Rare Isotope Beams, Michigan State University.

45th International School of Nuclear Physics. September 20, 2024

The r-process.

- Path not fully accessible to experiments $\rightarrow$ theoretical predictions
- Inputs: β-decay half-lives, neutron-capture rates, fission rates, …

Determine the nuclear timescale for the r-process: competition with expansion timescale.



TECHNISCHE UNIVERSITÄT DARMSTADT

β-decay rates of r-process nuclei.

$$\overset{\text{g.s.}}{(Z,N)} \xrightarrow{\beta^-} (Z+1,N-1) \; + \; e^- + \bar{\nu}_e$$

L, J, S: $J_i^{\pi_i}$ $J_f^{\pi_f}$

$L = 0$: allowed (GT: $\Delta S = 1$)

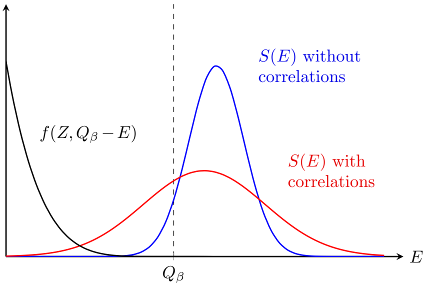
$L > 0$: forbidden (FF: $L = 1$, $\pi_i \neq \pi_f$)

- Allowed decays (GT):

$$\lambda = \frac{\ln 2}{T_{1/2}} \propto \int^{Q_\beta} f(Z, Q_\beta - E) S(E) dE$$

$$S(E) = \sum_f |\langle f|\hat{F}|i\rangle|^2 \delta(E - E_f + E_i)$$

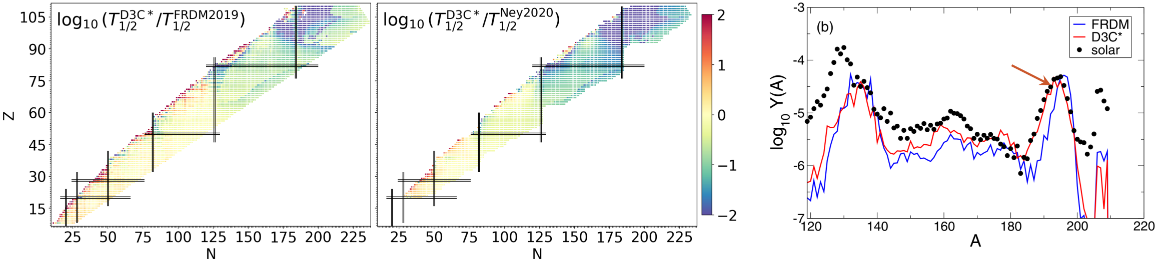
- Correlations relevant to the low-lying strength.



Global β-decay calculations within QRPA.

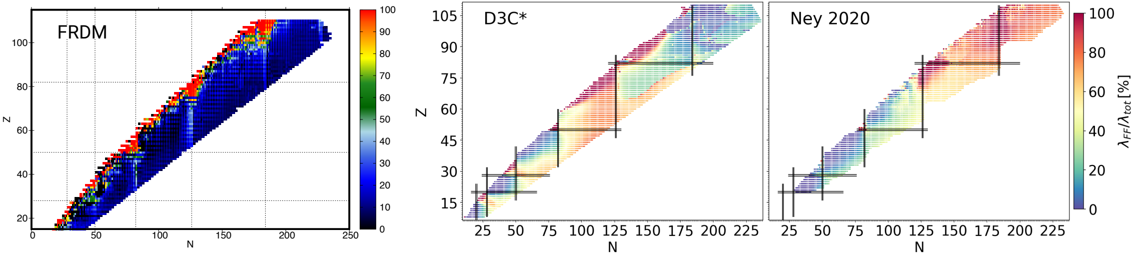
- **FRDM** + gross theory for FF[1]
- relativistic microscopic self-consistent spherical approach with **D3C*** functional[2]

  shorter half-lives for $N > 126 \Rightarrow$ shift of the third abundance peak ($A \sim 195$)
- non-relativistic microscopic self-consistent deformed approach with SKO' functional (**Ney 2020**)[3]



[1]P. Möller et al., Phys. Rev. C **67**, 055802 (2003), P. Möller et al., Atomic Data and Nuclear Data Tables **125**, 1–192 (2019).
[2]T. Marketin et al., Phys. Rev. C **93**, 025805 (2016), M. Eichler et al., The Astrophysical Journal **808**, 30 (2015).
[3]E. M. Ney et al., Phys. Rev. C **102**, 034326 (2020).

Global β-decay calculations within QRPA.



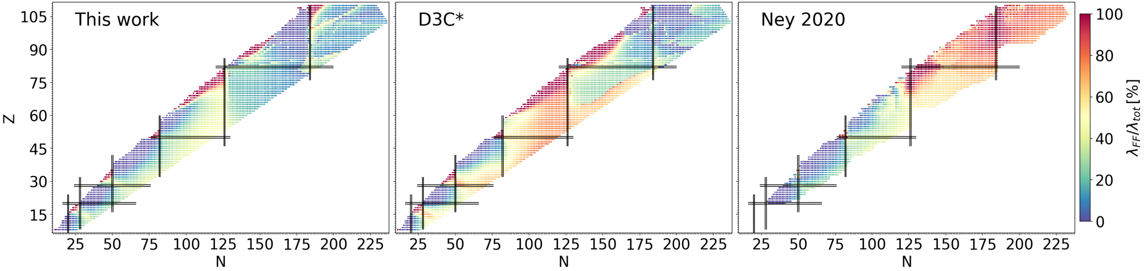
Very different predictions of the FF contribution to the rates

[4] P. Möller et al., Phys. Rev. C **67**, 055802 (2003), P. Möller et al., Atomic Data and Nuclear Data Tables **125**, 1–192 (2019).
[5] T. Marketin et al., Phys. Rev. C **93**, 025805 (2016).
[6] E. M. Ney et al., Phys. Rev. C **102**, 034326 (2020).

Global β-decay calculations within QRPA.

FF contribution to the rates

→ After some recent corrections to the code for the RMF approach with **D3C*** functional[7]

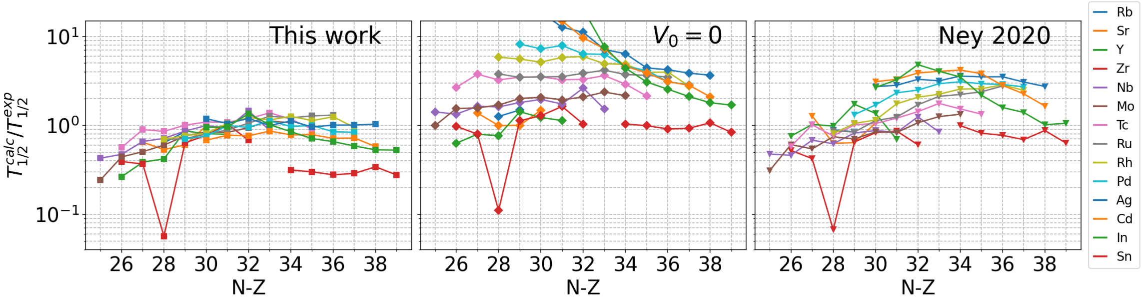


[7] C. E. P. Robin and G. Martínez-Pinedo, arXiv:2403.17115 (2024).

Global β-decay calculations within QRPA.

Sensitivity to isoscalar pairing strength (V_0) and comparison with experiment[8]

- For constant V_0, the effect along one chain depends on the single particle states being filled.

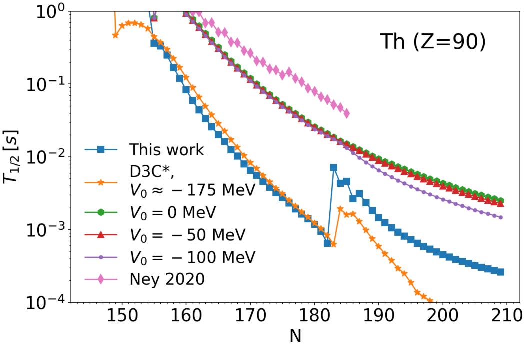


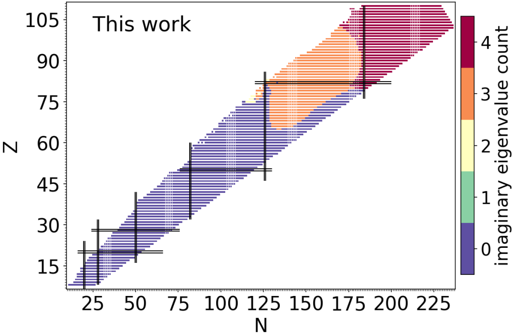
Within QRPA scheme, the inclusion of V_0 is needed.

[8] G. Lorusso et al., Phys. Rev. Lett. **114**, 192501 (2015).

Global β-decay calculations within QRPA.

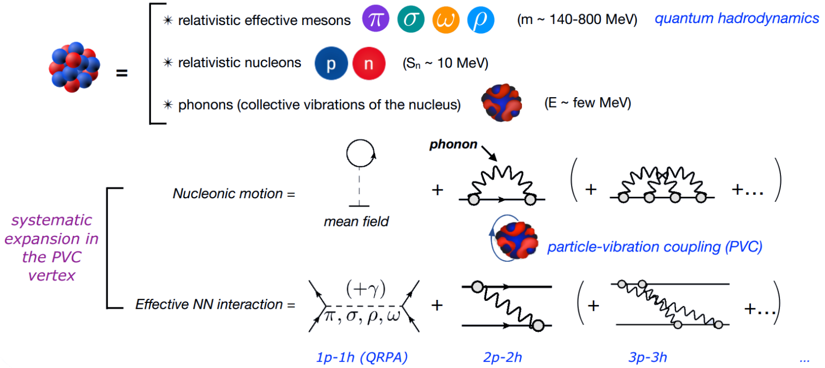
- Large V_0 values can produce problems in the QRPA when moving to the heavy and superheavy region $\rightarrow$ Need a better prescription for V_0.

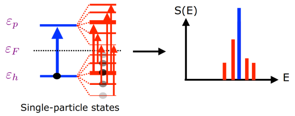




The need of V_0 points to missing correlations.

Extensions: particle-vibration coupling.[9]

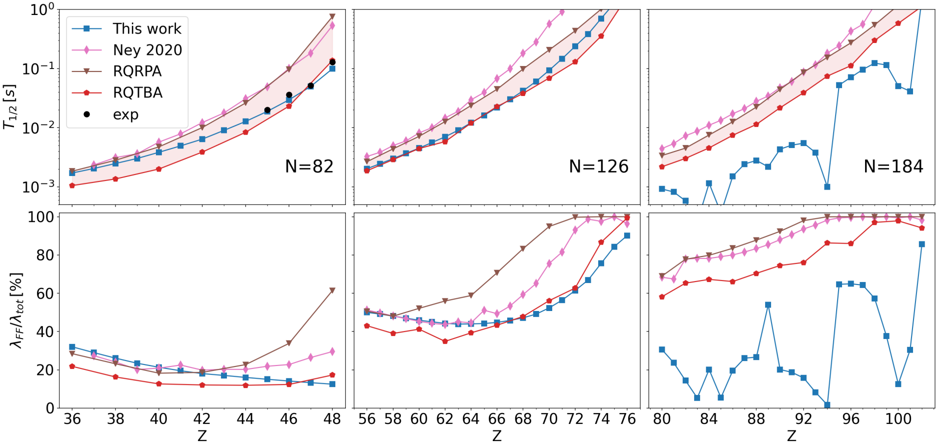




- No adjustable proton-neutron pairing needed.
- So far limited to spherical systems.

[9] C. Robin and E. Litvinova, Phys. Rev. C **98**, 051301 (2018), C. Robin and E. Litvinova, European Physical Journal A **52**, 205, 205 (2016).

Extensions: particle-vibration coupling.[10]



[10] C. E. P. Robin and G. Martínez-Pinedo, arXiv:2403.17115 (2024).

Extensions: particle-vibration coupling & deformation.

Efficiency of FAM-QRPA allows to account for deformation

Procedure:[11,12]

- Extract qPVC vertices from like-particle FAM-QRPA[13]
- Add the vertices to the deformed β-decay calculation (in collaboration with A. Ravlić)[14]

[11] E. Litvinova and Y. Zhang, Phys. Rev. C **104**, 044303 (2021), Y. Zhang et al., Phys. Rev. C **105**, 044326 (2022).
[12] Q. Liu et al., Phys. Rev. C **109**, 044308 (2024).
[13] A. Bjelčić and T. Nikšić, Computer Physics Communications **287**, 108689 (2023).
[14] A. Ravli ć et al., Phys. Rev. C **110**, 024323 (2024).

Extensions: particle-vibration coupling & deformation.

Procedure:[11,12]

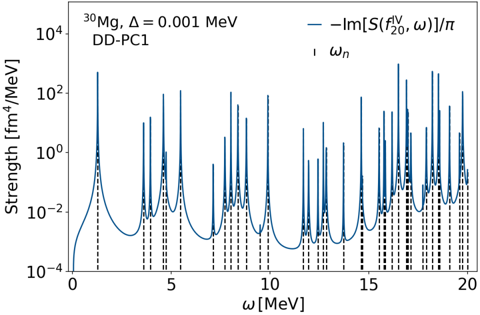
- Extract qPVC vertices from like-particle FAM-QRPA[13]

For all multipole excitations:

- Solve FAM equations with initial Δ
- Identify ω_n peaks

$$\delta H(\omega) = \begin{pmatrix} \delta H^{(11)}(\omega) & \delta H^{(20)}(\omega) \\ -\delta H^{(02)}(\omega) & -\delta H^{(11)^T}(\omega) \end{pmatrix}$$

$$\Gamma^{(ij)n}_{\mu\nu} = \lim_{\Delta \to 0} \sqrt{\frac{\Delta}{\pi S(\omega_n)}}\, \delta H^{(ij)}_{\mu\nu}(\omega_n + i\Delta)$$

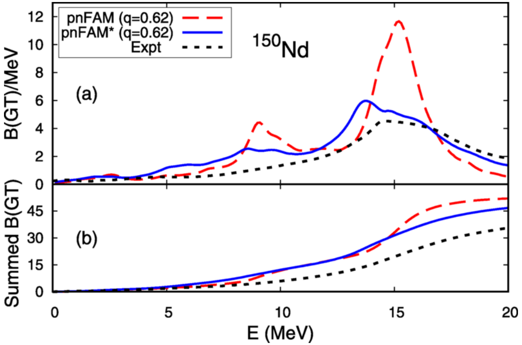


[11] E. Litvinova and Y. Zhang, Phys. Rev. C **104**, 044303 (2021), Y. Zhang et al., Phys. Rev. C **105**, 044326 (2022).
[12] Q. Liu et al., Phys. Rev. C **109**, 044308 (2024).
[13] A. Bjelčić and T. Nikšić, Computer Physics Communications **287**, 108689 (2023).

Extensions: particle-vibration coupling & deformation.

Effects of PVC on the Gamow-Teller strength with the Skyrme pnFAM[14]

- Phonons calculated with:
  - $L \leq 6$
  - 40 excitation frequencies from 0 MeV to 20 MeV
  - $\Delta = 0.5$ MeV



[14] Q. Liu et al., Phys. Rev. C **109**, 044308 (2024).

Summary and outlook.

- Towards improvement of global β-decay rates calculations within relativistic description taking into account the particle-vibration coupling and deformation of the nuclei.
- At QRPA level:
  - Corrections and update of previous relativistic QRPA β-decay rates calculation *(in progress)*.
  - Need a prescription for the $T = 0$ pairing strength that does not introduce artefacts.
- Beyond QRPA:
  - Inclusion of the phonons reduces the half-lives, bringing them closer to the experiment without the need for proton-neutron pairing.
  - Calculation of the deformed like-particle phonon matrices *(in progress)*.
  - Implementation in the deformed code pending (in collaboration with A. Ravlić)

Thank you for your attention!