Improving nuclear structure calculations through new measurements of β-delayed neutron emitters

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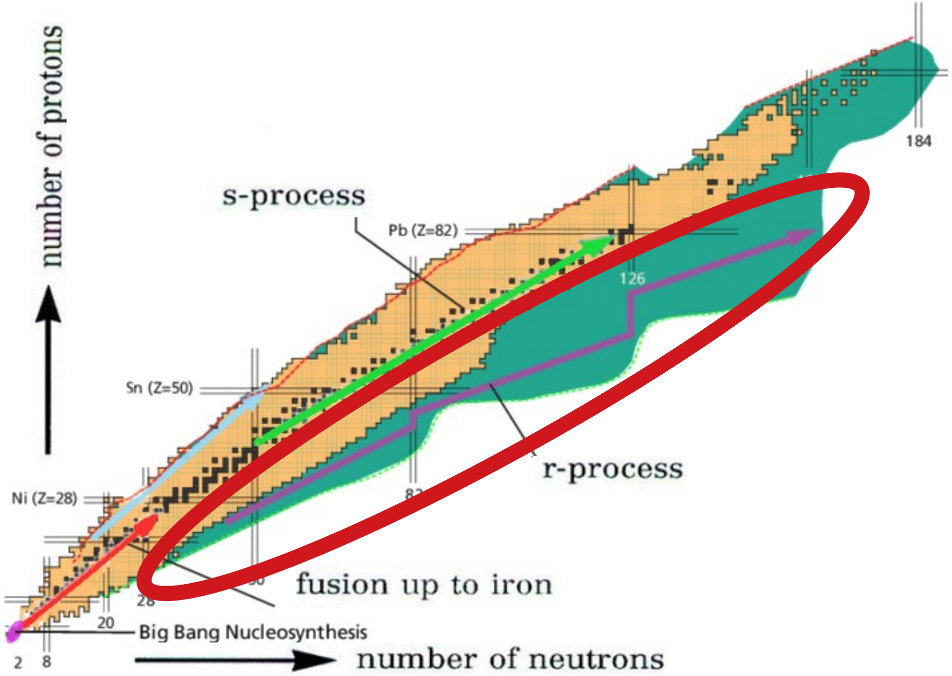
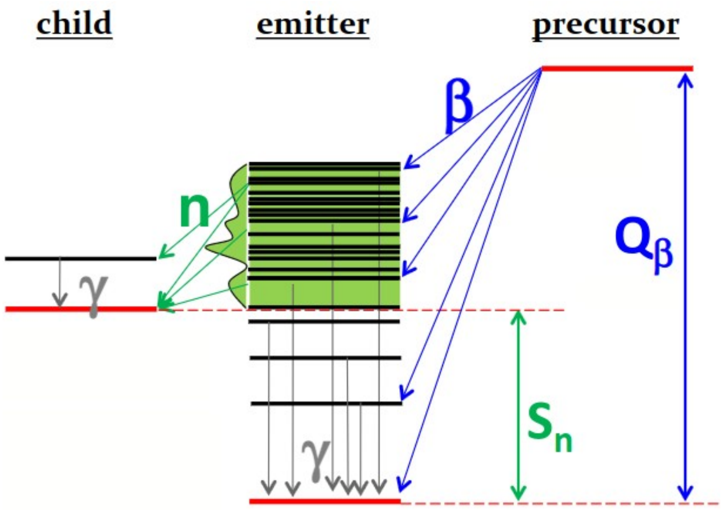
β-delayed neutron emission

Neutron-rich nuclei typically decay via β^- decay. The energy available for this process is given by the **Q_β value**. If **Q_β** is greater than the neutron separation energy (S_{xn}), neutrons may be emitted following the β^- decay. This process is known as **β-delayed neutron emission.**



T. Rodríguez, Journal of Physics: Conference Series 503 (2014)

$$^{A}_{Z}X \longrightarrow {}^{A-1}_{Z+1}Y + n + e^- + \bar{\nu}_e$$



S. Strauss. (2016)

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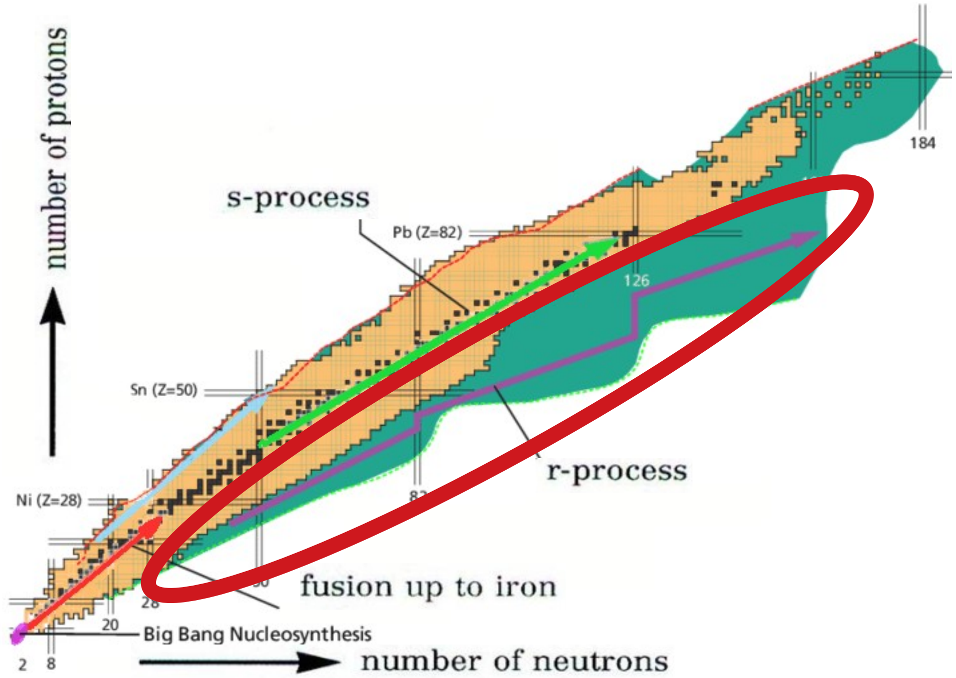


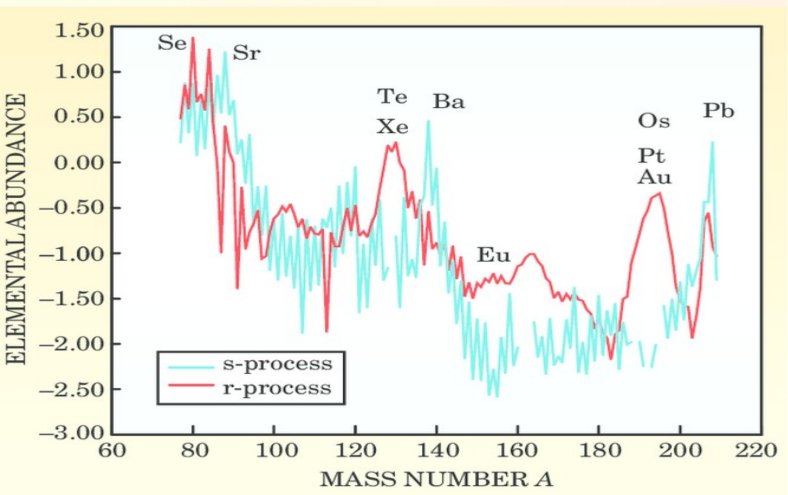
T. Rodríguez, Journal of Physics: Conference Series 503 (2014)

Physical magnitudes of interest for r-process simulations:

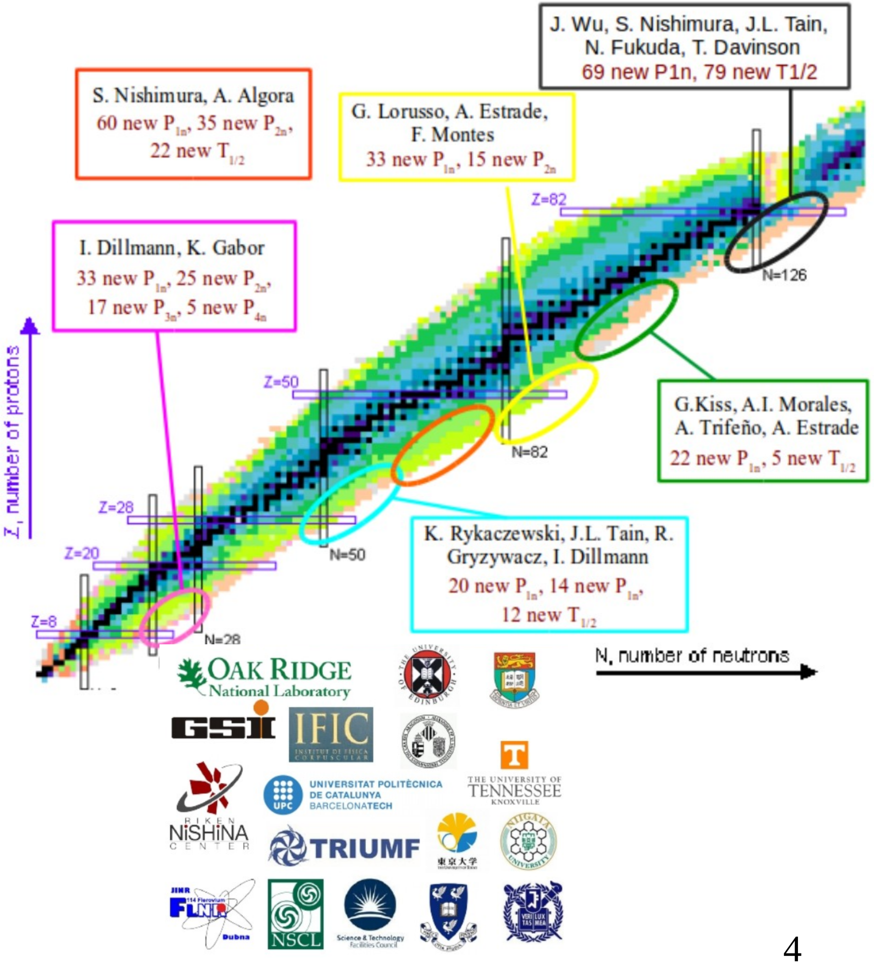
- Masses
- Neutron capture rates
- Half-life ($T_{1/2}$)
- β-delayed neutron emission probabilities (P_{xn})

BRIKEN project

- Built the largest β-delayed neutron detector in the world to conduct experiments at the RIKEN Nishina Center (Japan).
- Over 80 participants from 18 international institutions.
- Studied the most experimentally accessible neutron-rich nuclei.



Cowan, John J. et. al. Physics Today (2004)



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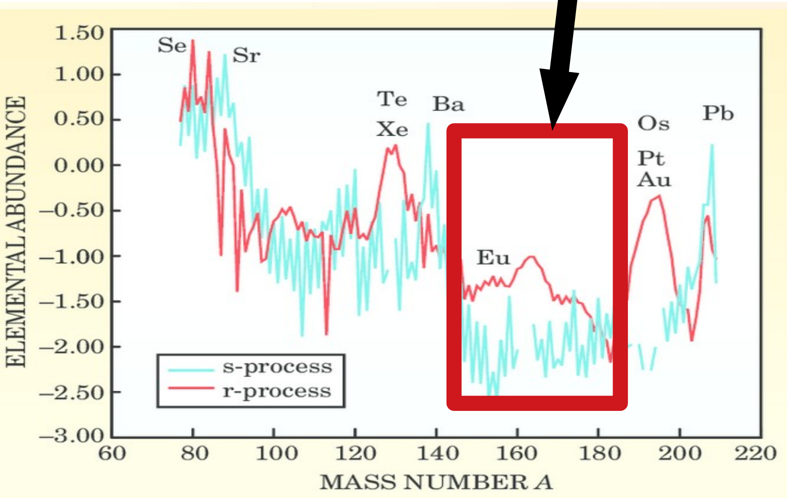
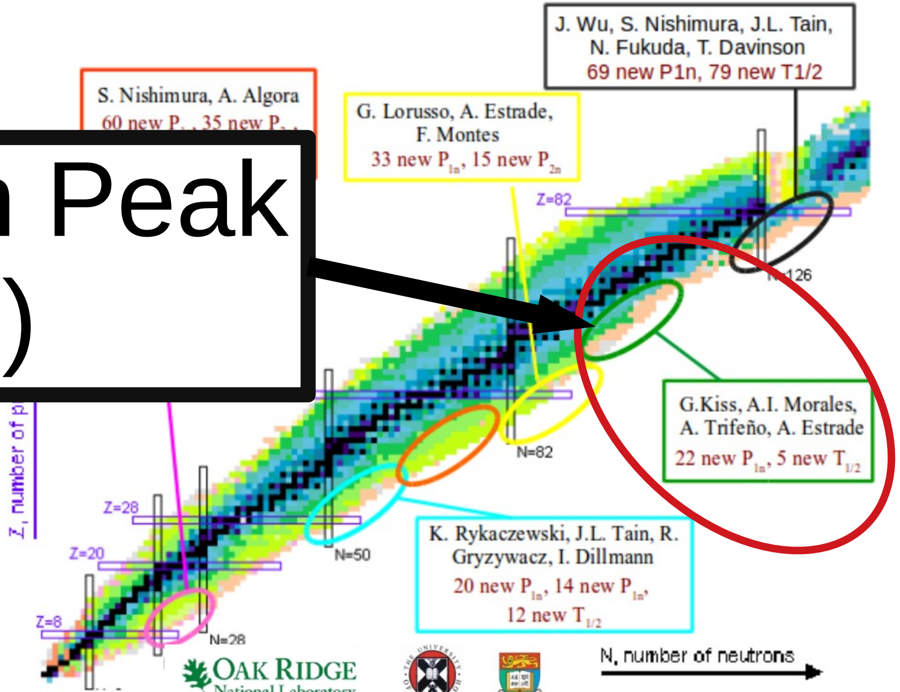
Rare-Earth Peak (REP)

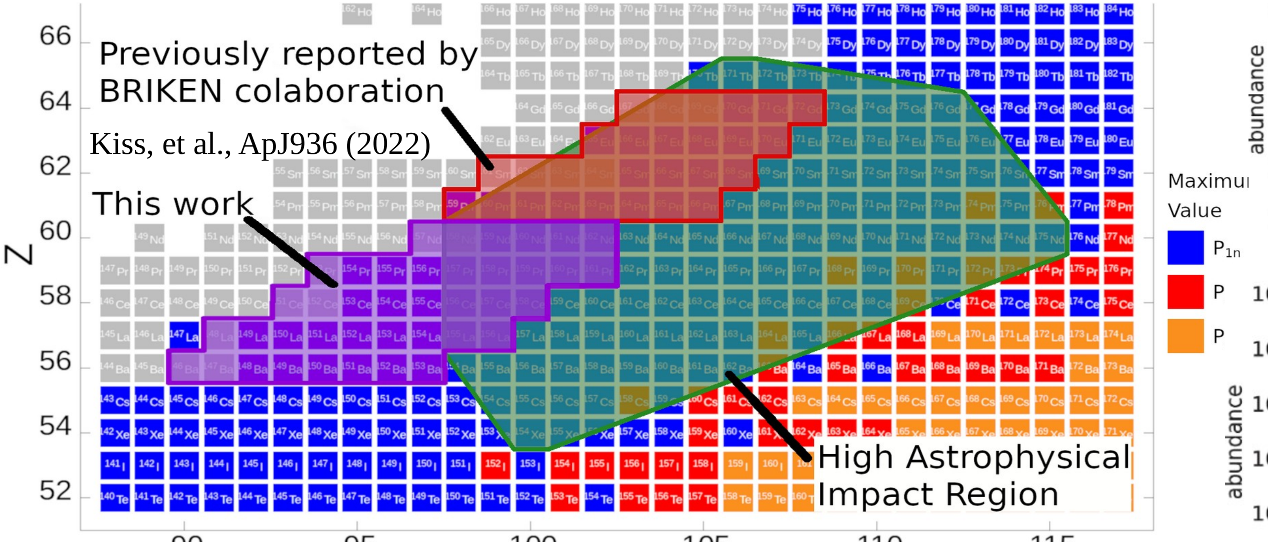


Cowan, John J. et. al. Physics Today (2004)

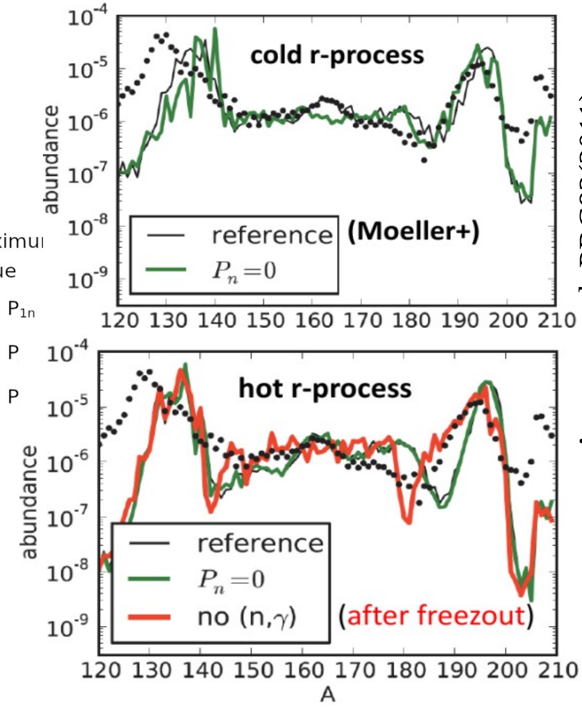


β-delayed neutron emission on REP

According to theoretical models and sensitivity studies, $T_{1/2}$ and P_{xn} of very neutron-rich nuclei for $55 \leq Z \leq 64$ are the most influential ones on the formation of the REP.



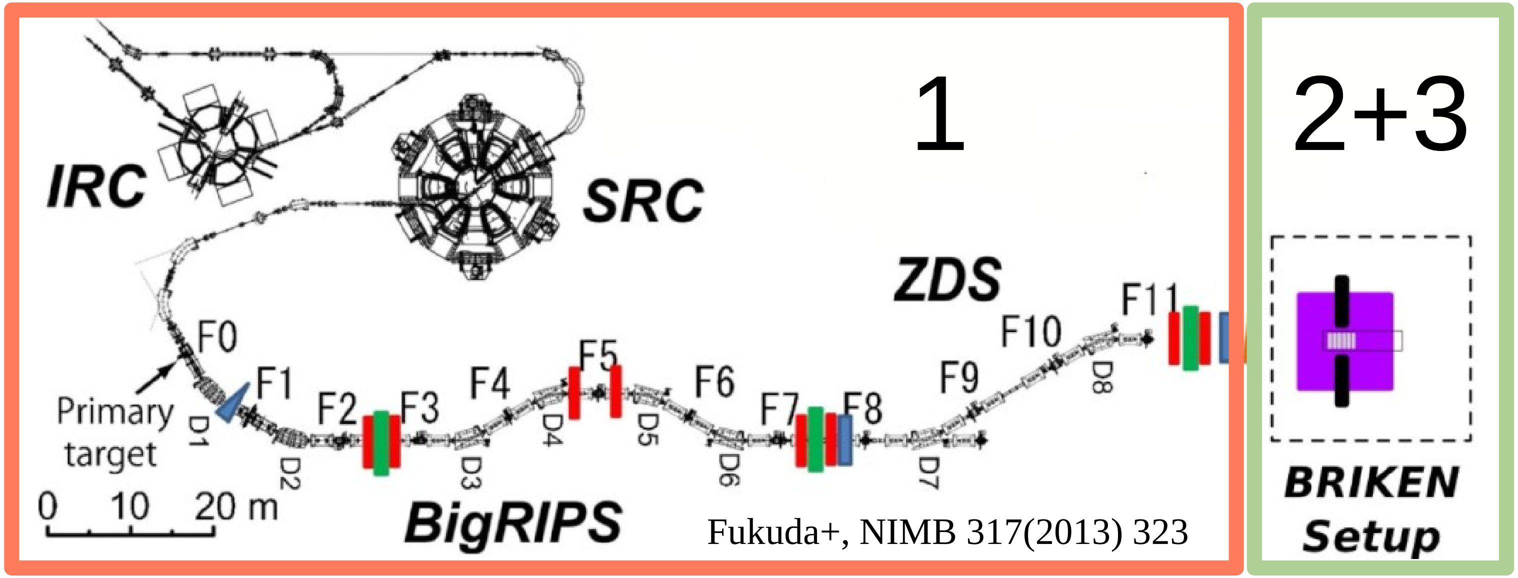
Mumpower et al, PRC86 (2012)



Arcones et al, PRC83(2011)

Experimental setup

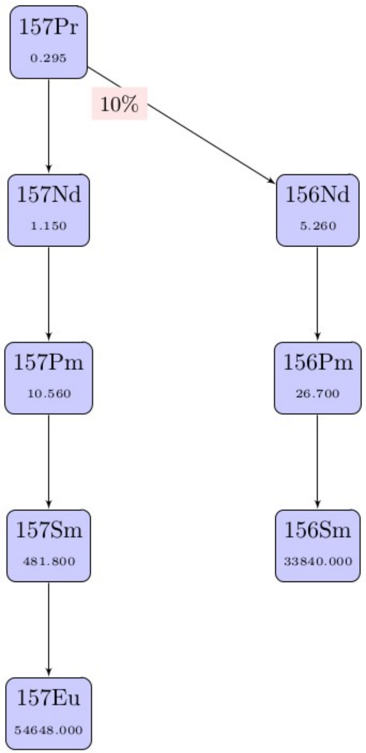
1. Production + Separation + Identification
2. Implantation + β-decay detection
3. Neutron (+gamma) detection

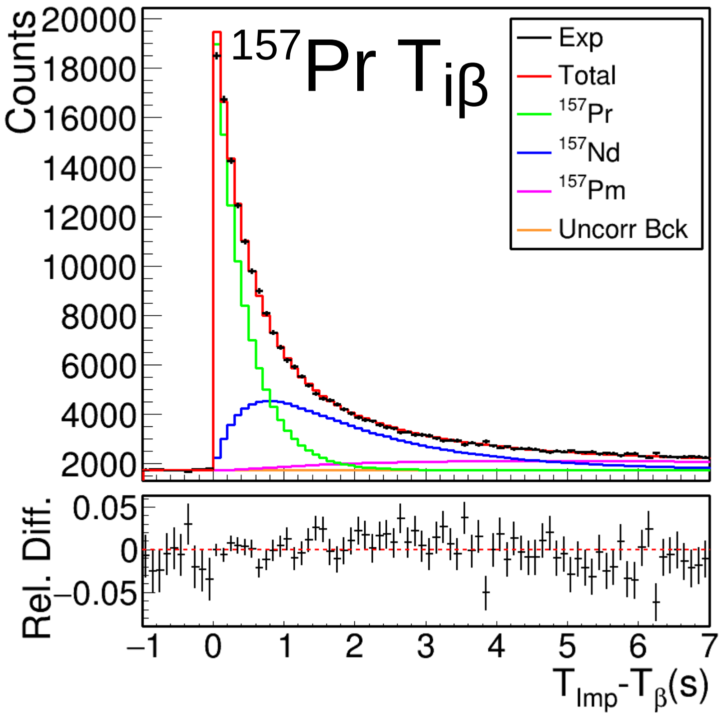


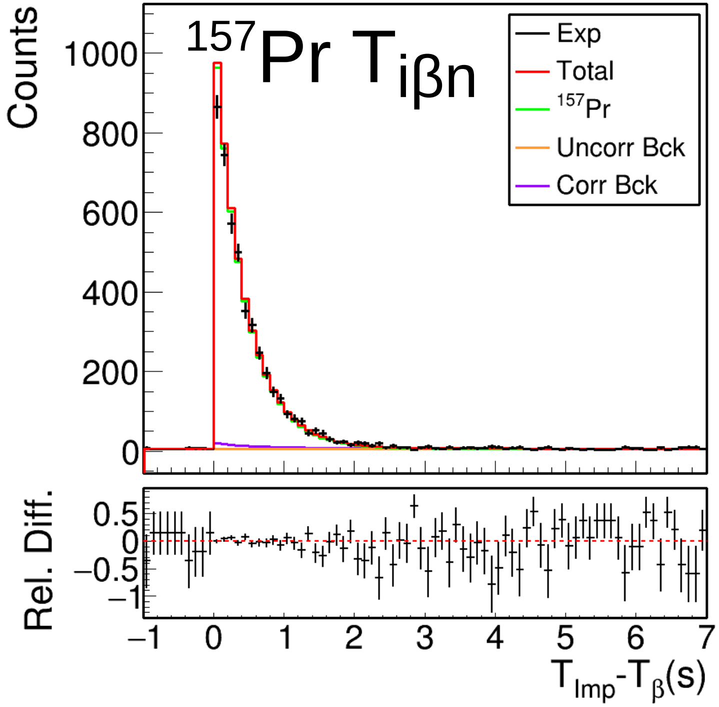
Fukuda+, NIMB 317(2013) 323

Fitting procedure

For the analysis, we perform a self-consistent fitting procedure* to obtain $T_{1/2}$ and P_{1n} values using Bateman equations.



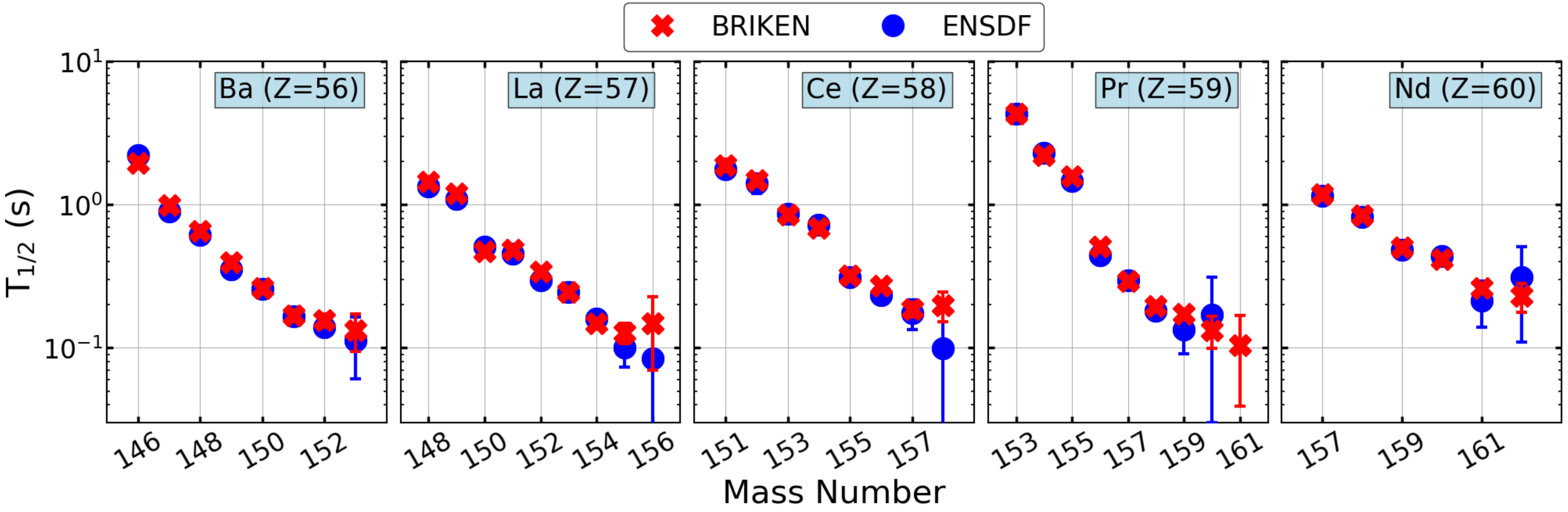




*A. Tolosa-Delgado et al. NIM A 925 (2019) 133-147

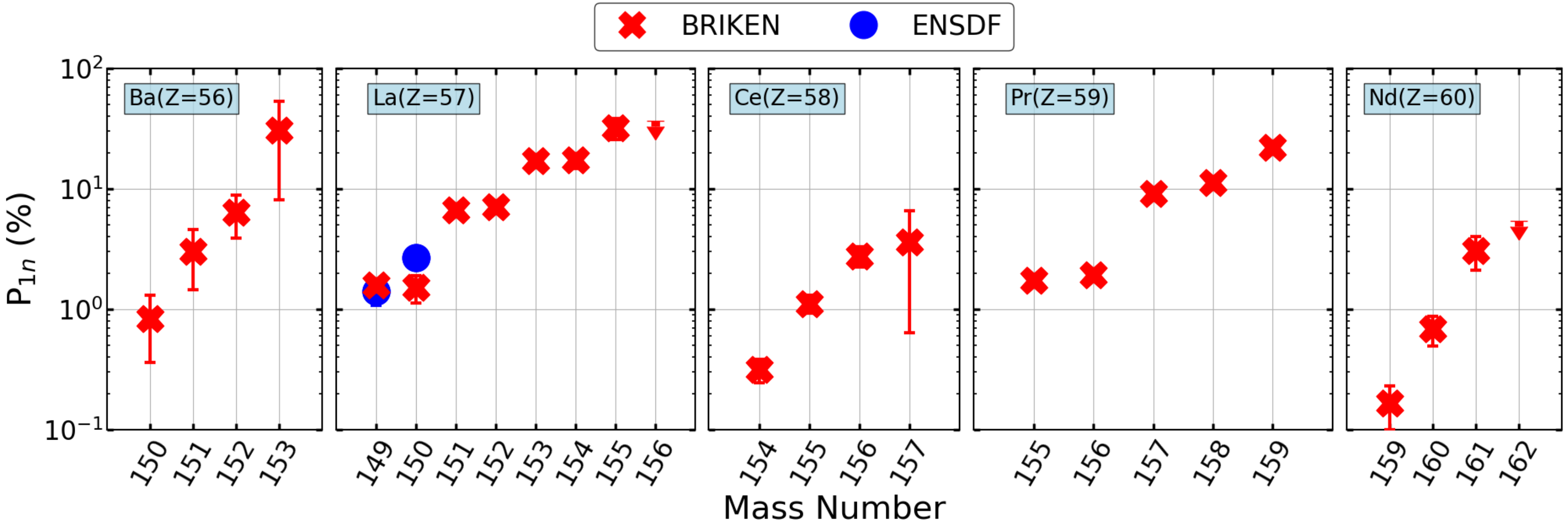
$T_{1/2}$ results

- **39 $T_{1/2}$ values** have been remeasured.
- **1 new $T_{1/2}$.**

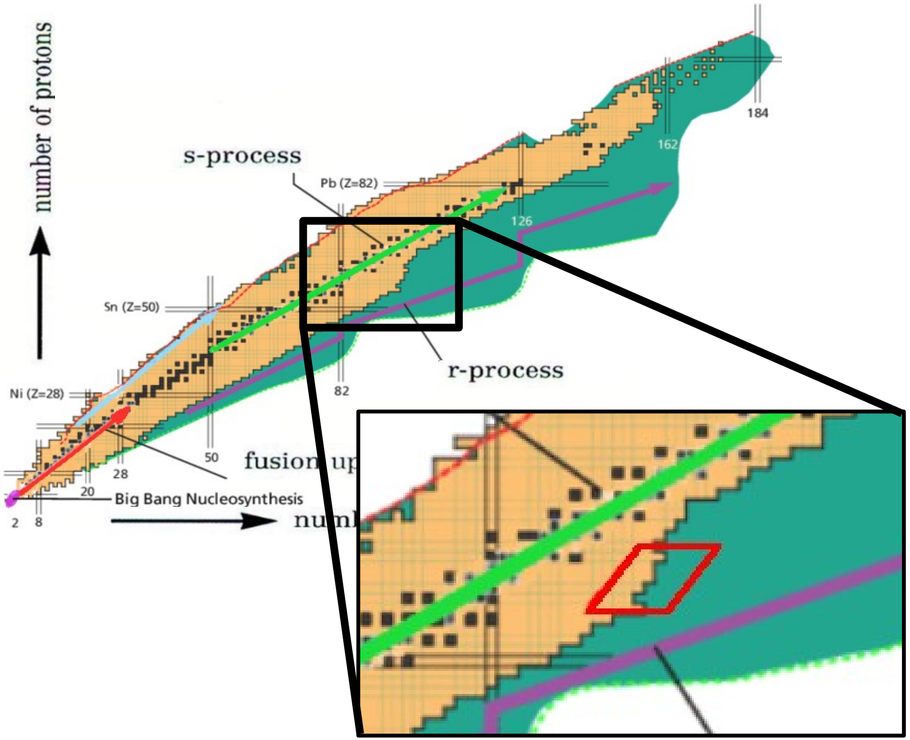


P_{1n} results

- **21 new P_{1n}** values.
- **2 P_{1n}** values have been remeasured.



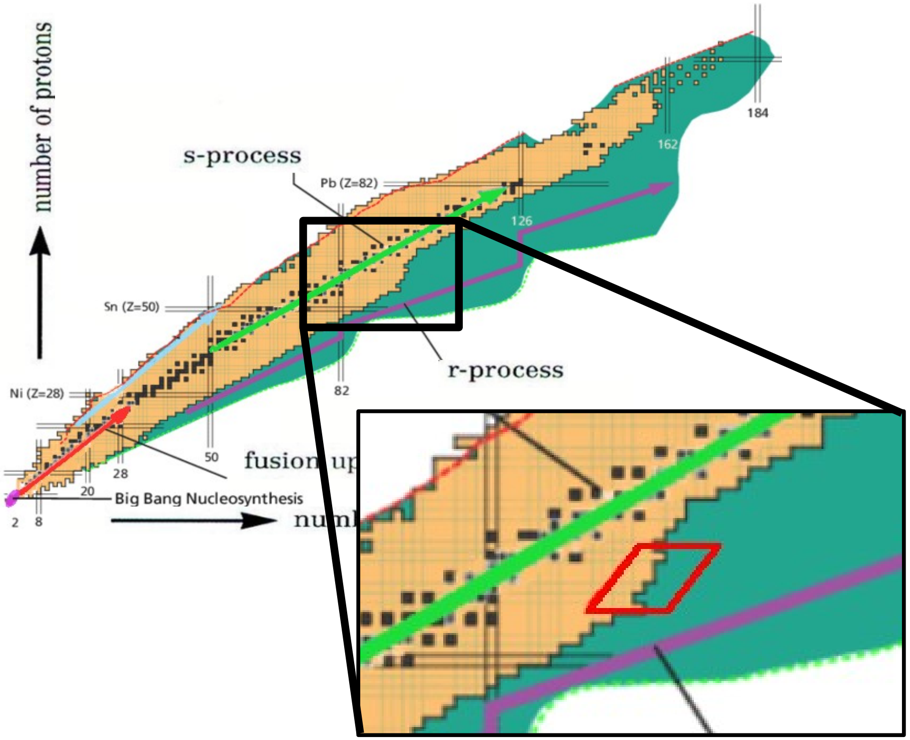
What can we do with this data?

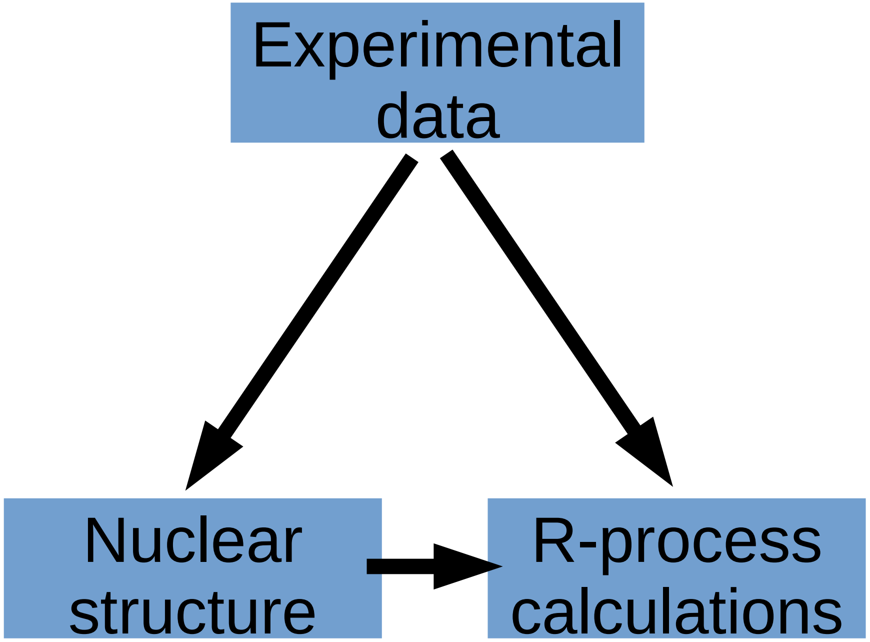


Experimental data

R-process calculations

What can we do with this data?



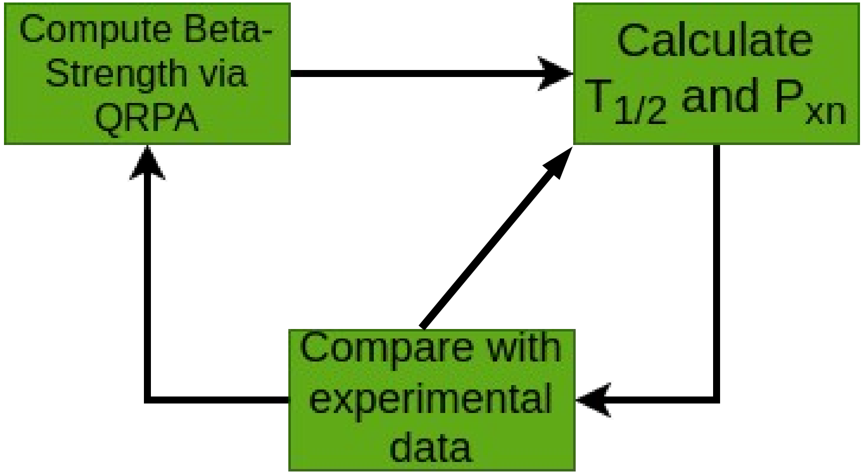


Nuclear structure calculations

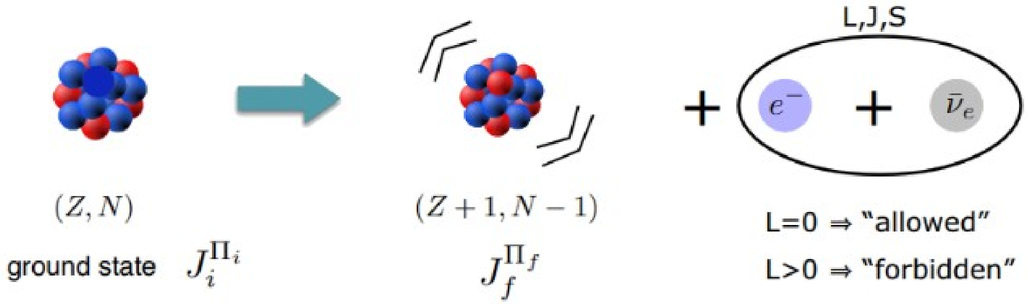
In collaboration with GSI Theoretical Nuclear Astrophysics Group.

1. Compute the β-Strength.
2. Calculate $T_{1/2}$ and P_{xn}.
3. Compared with the experimental data from REP-BRIKEN.

Diana Alvear Terrero



β-decay rates of r-process nuclei

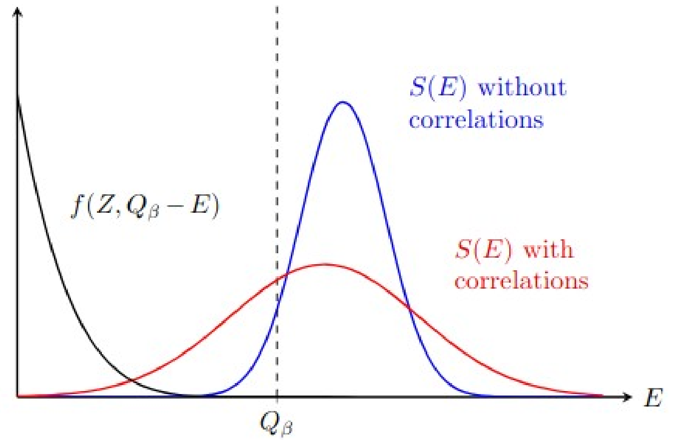


- Gamow-Teller (GT): $\Delta S = 1$
- First Forbidden: $L = 1, \Pi_i \neq \Pi_f$

- Allowed decays (GT):

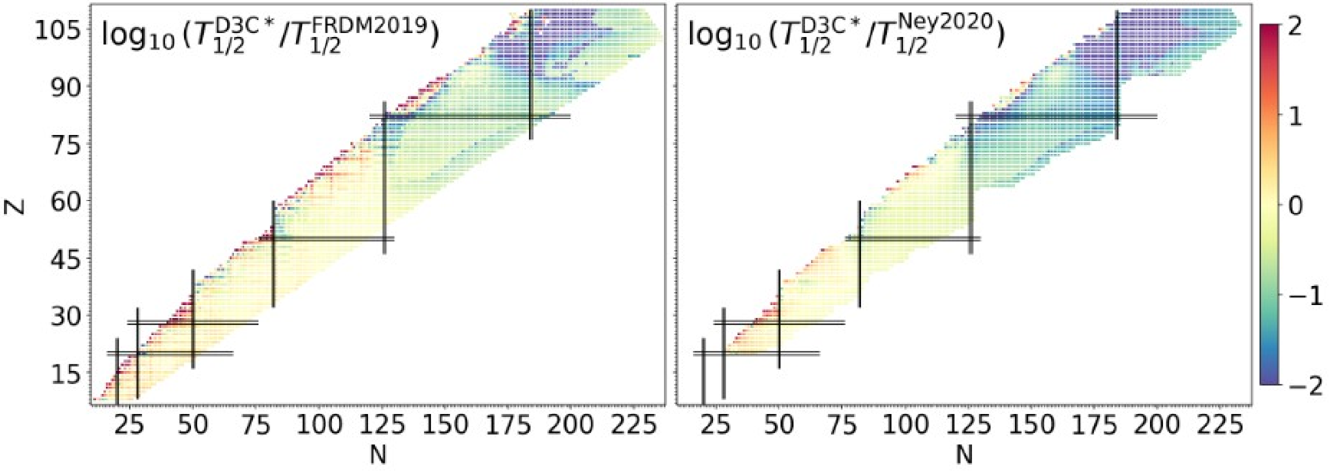
$$\lambda = \frac{\ln 2}{T_{1/2}} \propto \int^{Q_\beta} f(Z, Q_\beta - E) S(E) dE$$

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



Global β-decay calculations

- **FRDM** + gross theory for FF[1]
- relativistic spherical approach with **D3C***[2] and pairing correlations with D1S
- non-relativistic deformed approach with SKO' (**Ney 2020**)[3]

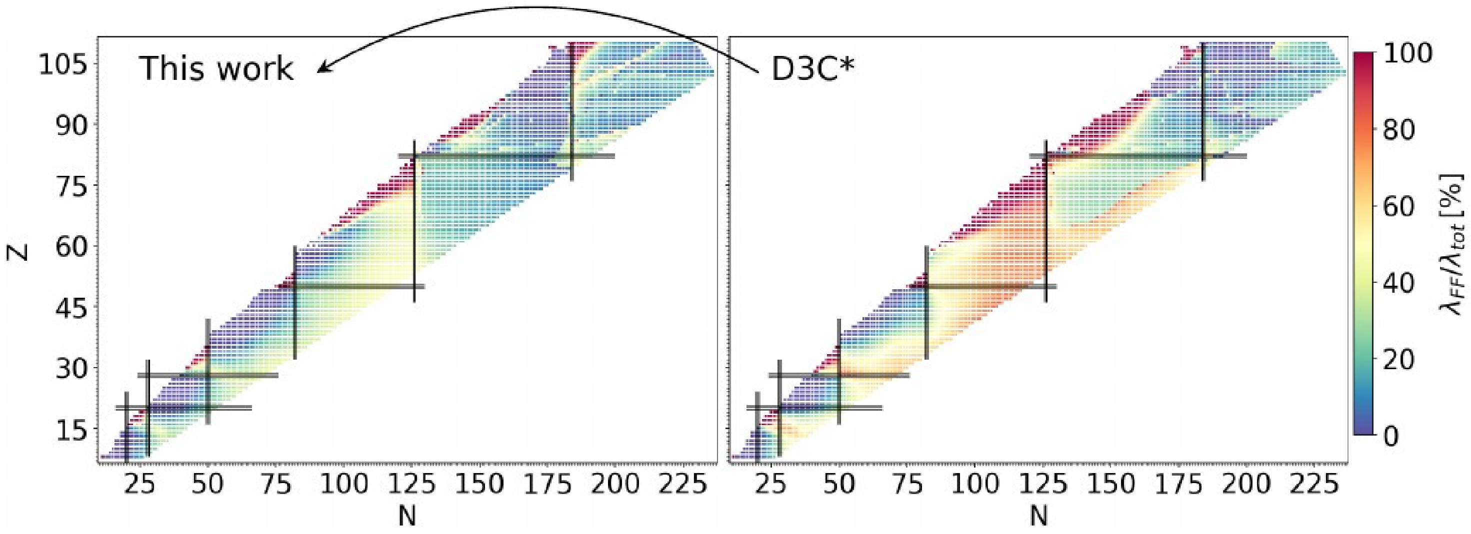


[1] P. Möller et al., Phys. Rev. C **67**, 055802 (2003), P. Möller et al., Atomic Data and Nuclear Data Tables **125**, 1–192 (2019).
[2] T. Marketin et al., Phys. Rev. C **93**, 025805 (2016), M. Eichler et al., The Astrophysical Journal **808**, 30 (2015).
[3] E. M. Ney et al., Phys. Rev. C **102**,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

Global β-decay calculations

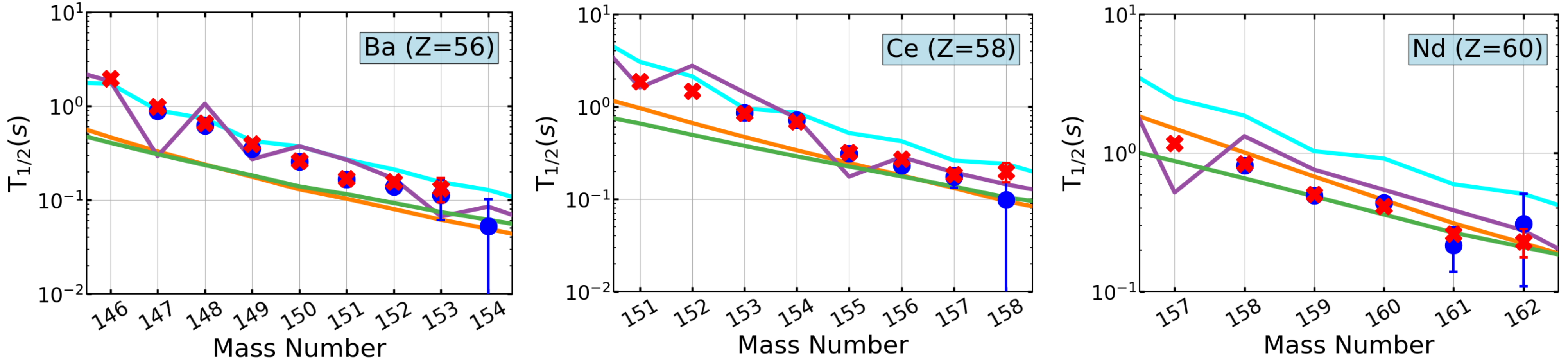
This work model uses the D3C* model but adds corrections[1] to the RHB+RQRPA code.

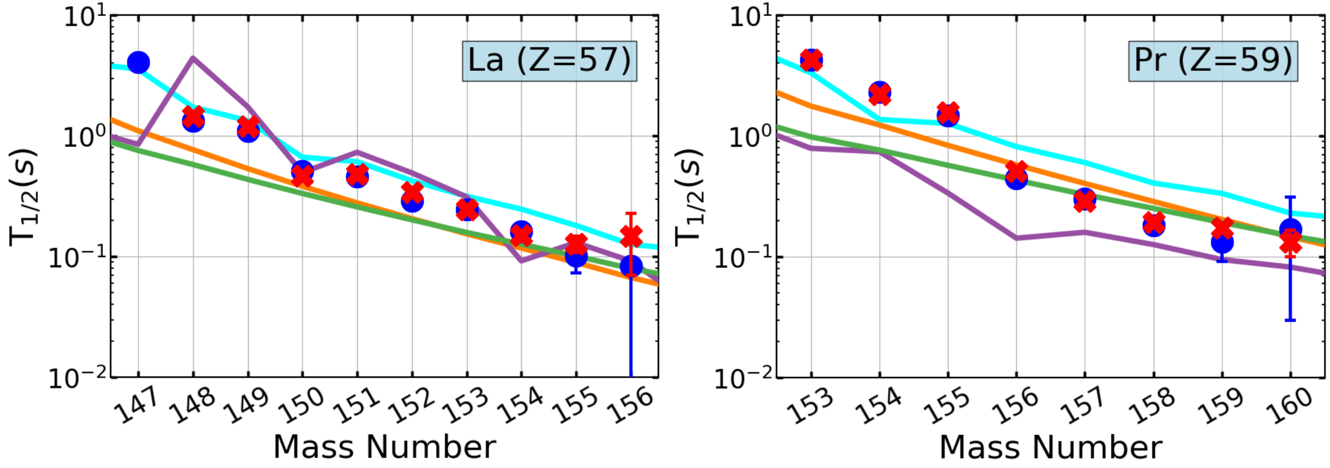
This varies FF contributions significantly



[1] C.E.P Robin and G. Martinez-Pinedo, arXiv:20403.17115 (2024)

$T_{1/2}$ for the REP





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

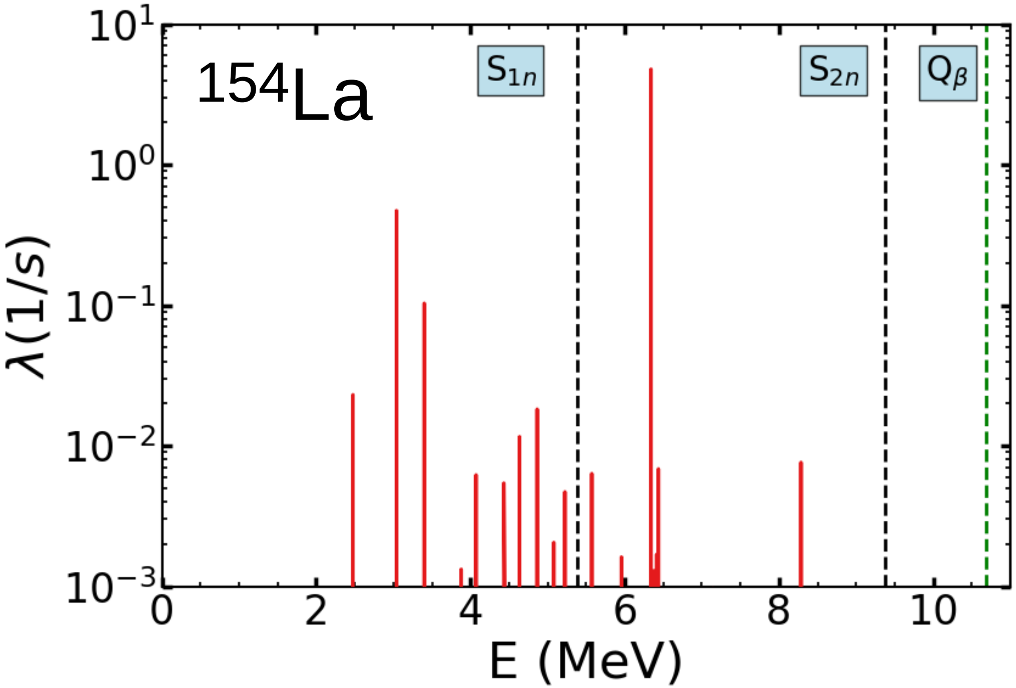
Calcution of the P_{xn}

Cut off method: If the neutron emission is energetically possible, it will take place.

$$P_{xn} = \frac{\sum_{i,E_i=S_{xn}}^{\min(Q_\beta, S_{(x+1)n})} \lambda_i}{\sum_i \lambda_i}.$$

The P_{xn} calculations depends on:

1. The Rate distribution.
2. Nuclear data (Q_{beta} and S_{xn})



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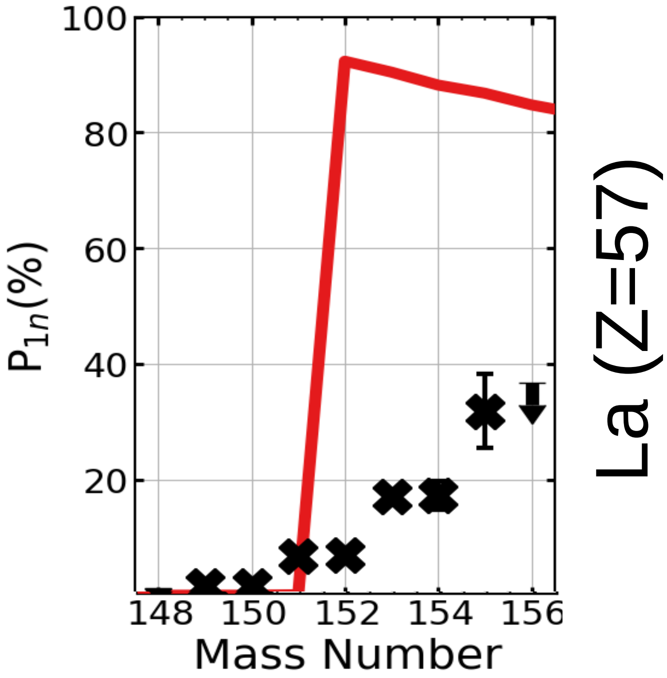
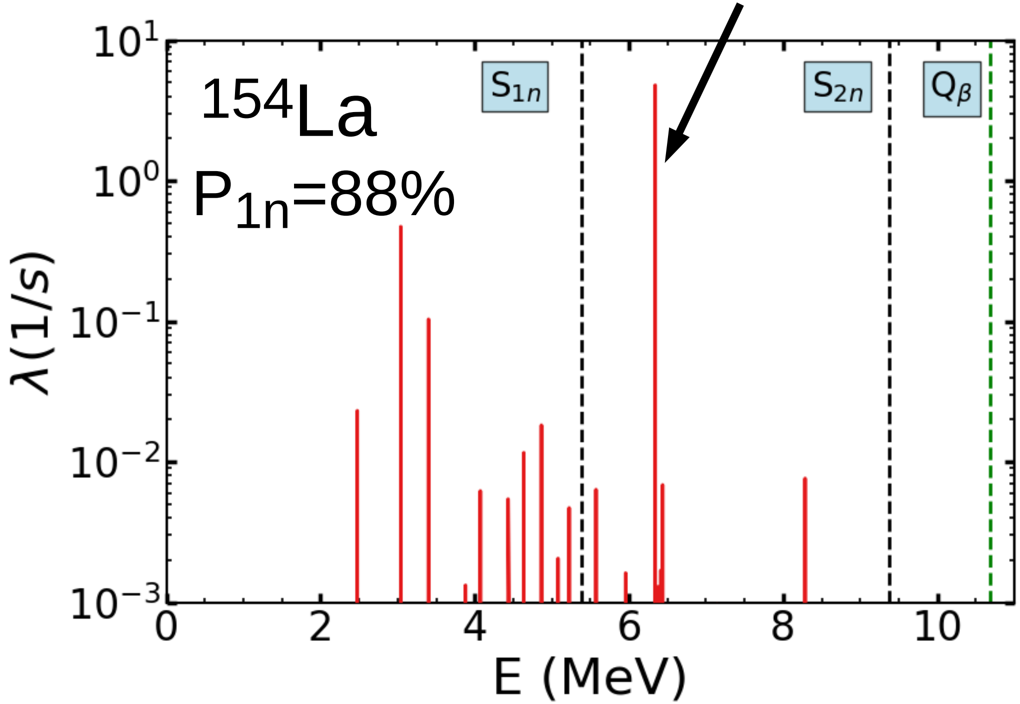
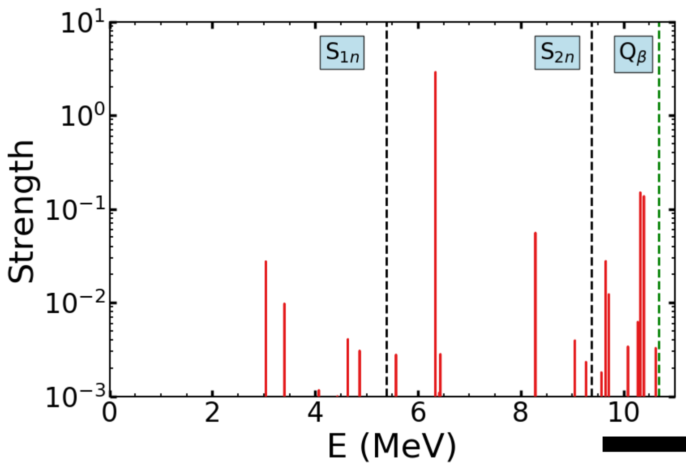


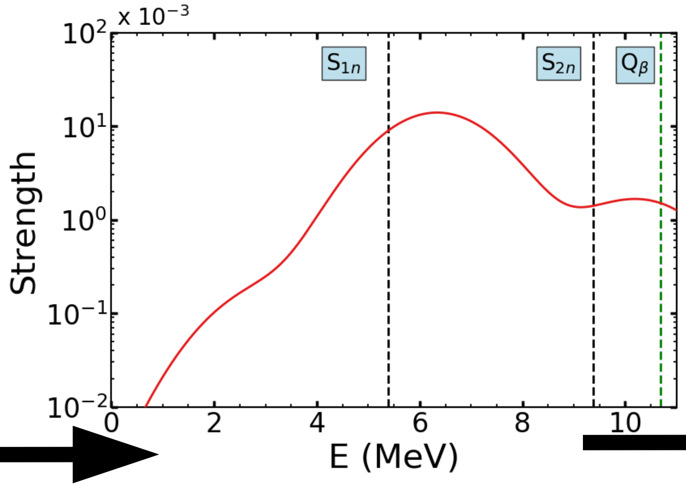
Heavily dependent on the most intense level.

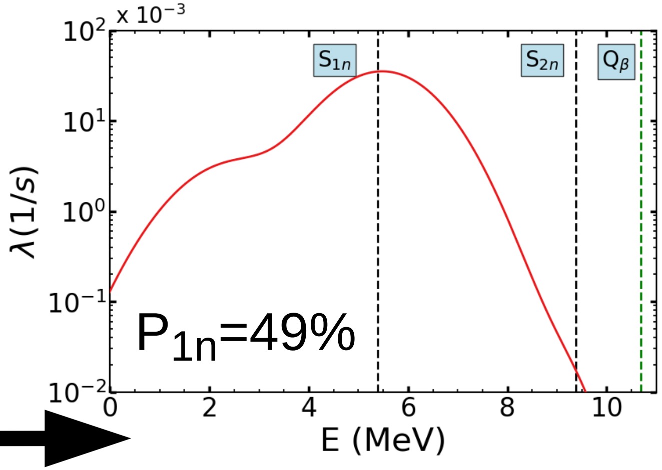


Calcution of the P_{xn}

The QRPA calculations offers single discrete levels. As in reality the strength is a continous distribution, we must apply gausian distribution of certain width (σ) on each energy level of the Strength.







Gaussian distribution

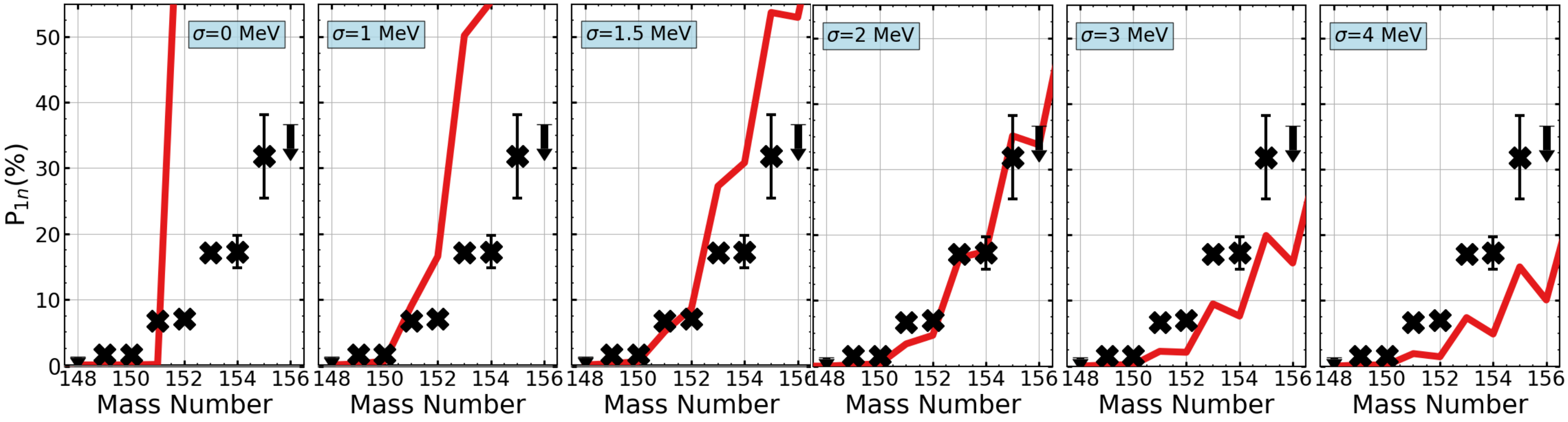
$$C(W) = k + kaW + kb/W + kcW^2.$$

$$\lambda = \frac{\ln 2}{K} \int_0^{p_0} p_e^2 (W_0 - W)^2 F(Z,W) C(W) dp_e,$$

Calcution of the P_{xn}

The QRPA calculations offers single discrete levels. As in reality the strength is a continous distribution, we must apply gausian distribution of certain width (σ) on each energy level of the Strength.

La (Z=57)



Other methods to compute P_{xn}

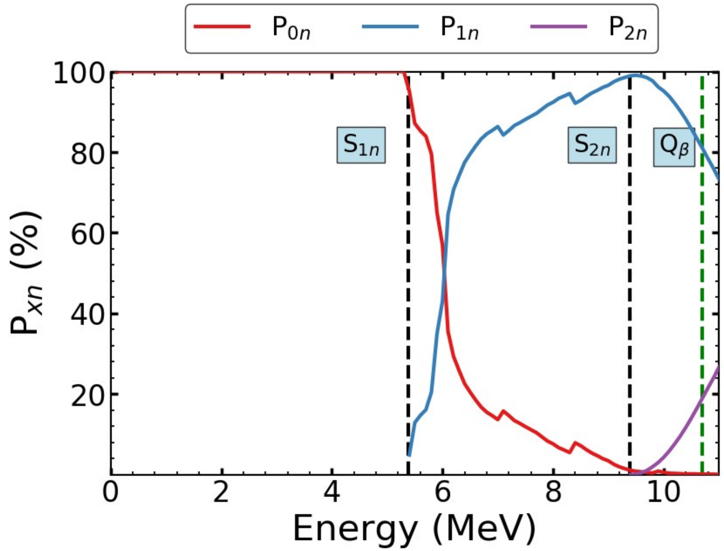
Cut off method:

1. If the neutron emission is energetically possible, it will take place.
2. By definition offers an upper limit.

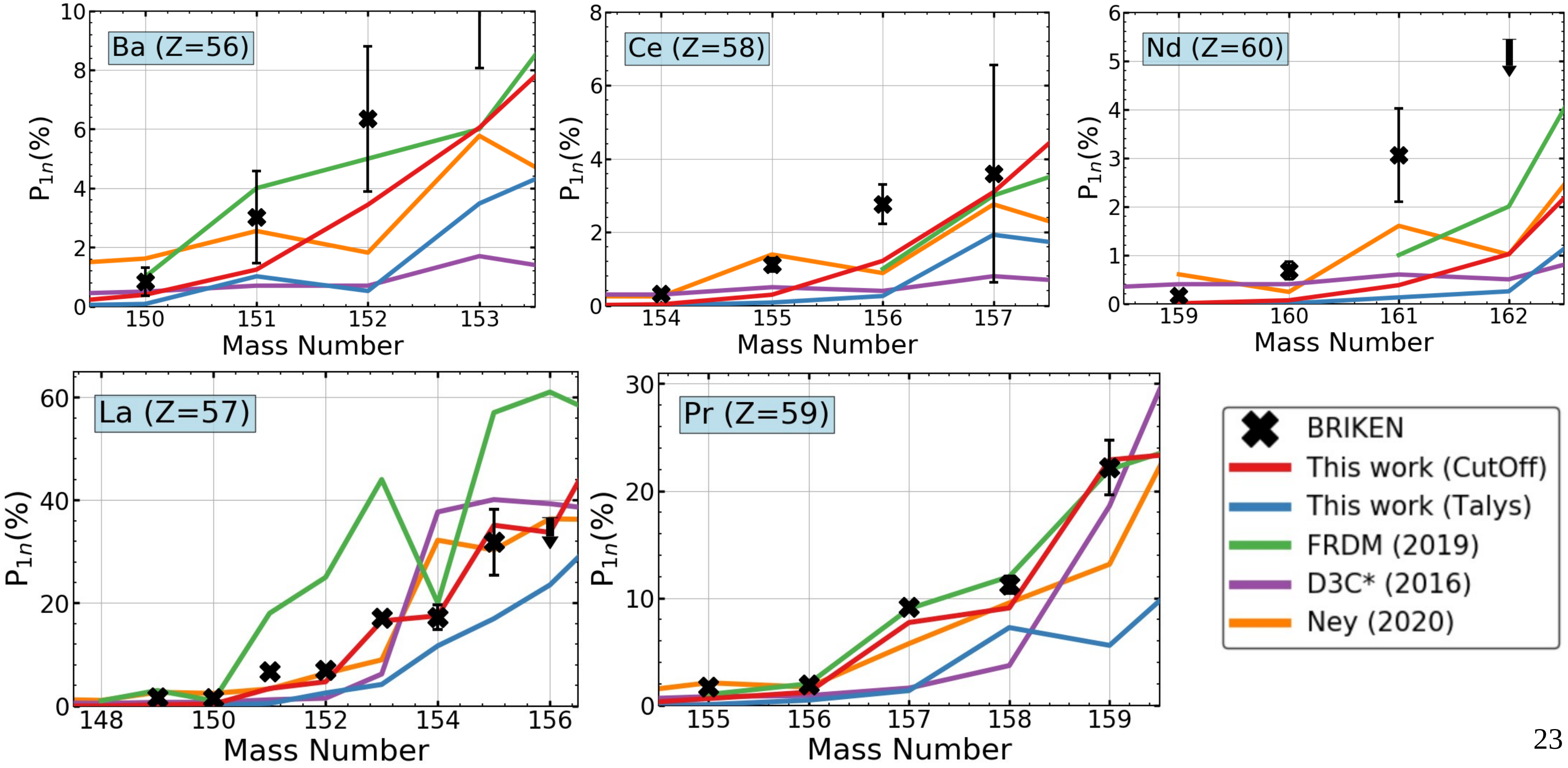
$$P_{xn} = \frac{\sum_{i, E_i = S_{xn}}^{\min(Q_\beta, S_{(x+1)n})} \lambda_i}{\sum_i \lambda_i}.$$

Statistical HF method:

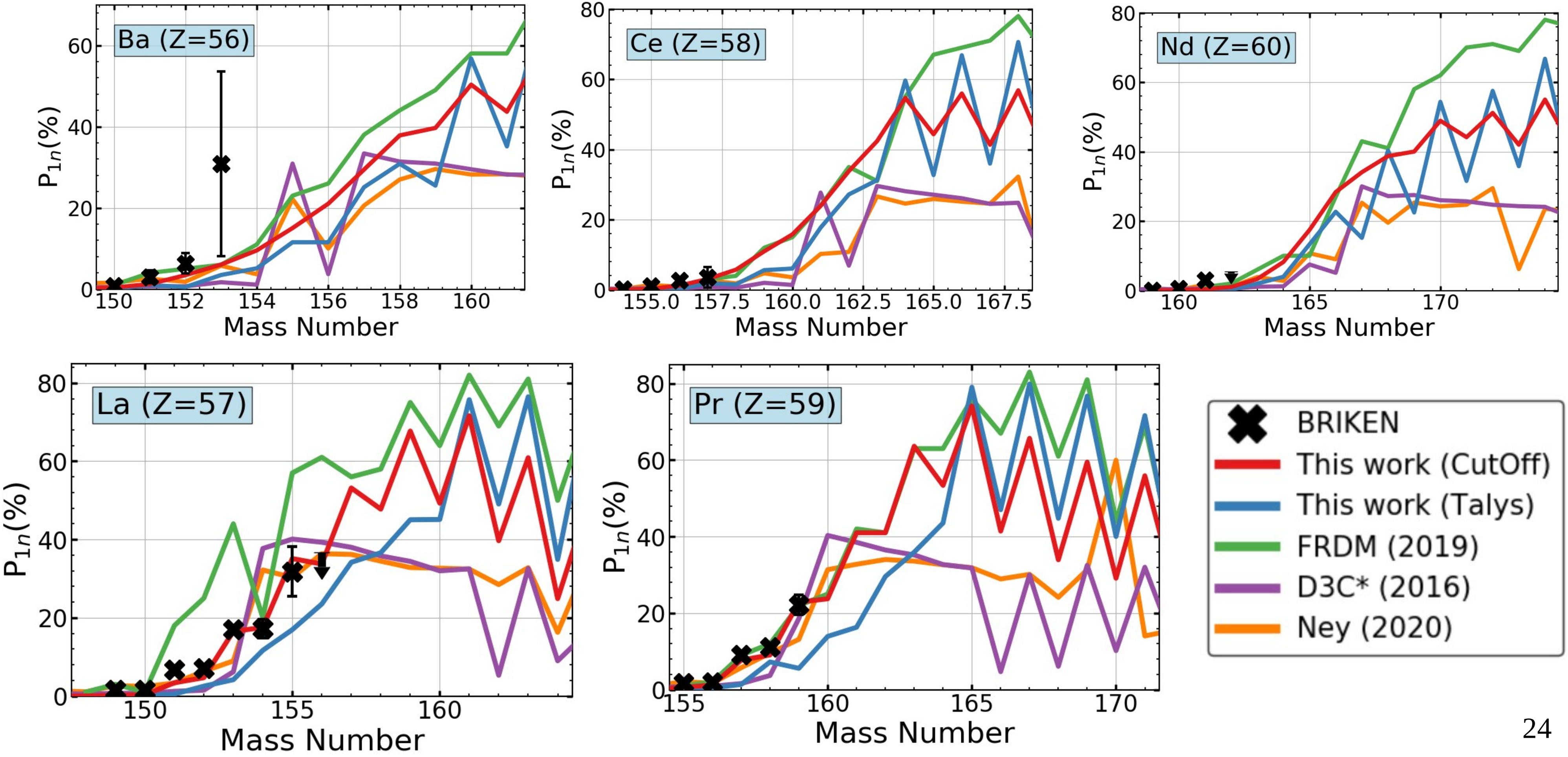
1. If neutron emission is energetically possible, there will be a probability of it occurring.
2. We employ TALYS.



P_{1n} for REP-BRIKEN



P_{1n} for REP

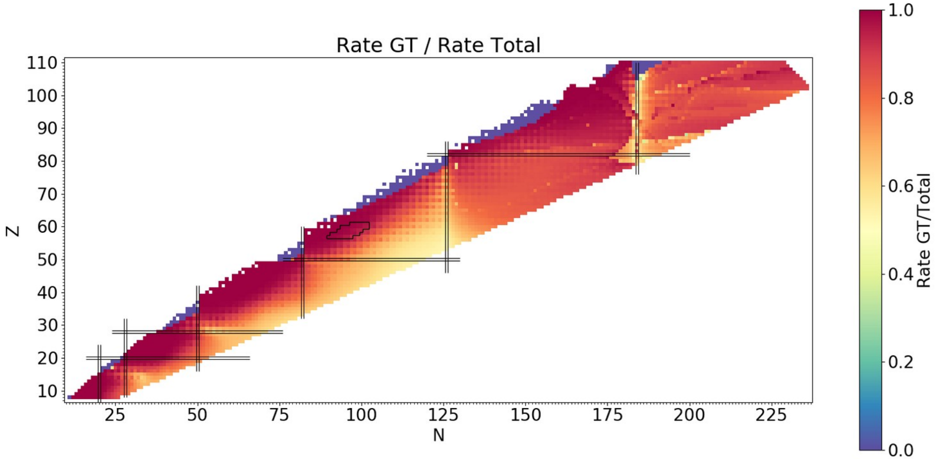

Ba (Z=56)
Ce (Z=58)
Nd (Z=60)
La (Z=57)
Pr (Z=59)
P1n(%)
Mass Number
BRIKEN
This work (CutOff)
This work (Talys)
FRDM (2019)
D3C* (2016)
Ney (2020)

Talys Spin-Parity

We do not have a detailed description of these excited states but we can assume that all are populated by GT.

The other required information is the initial state from which the parent nucleus decayed. We can assume it was the ground state.

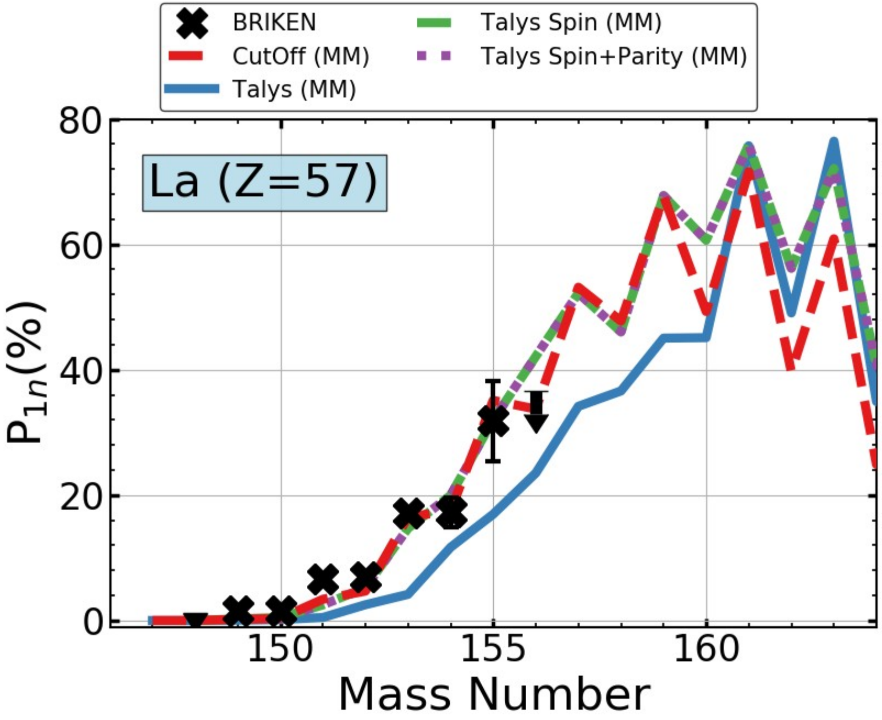
Most of our nuclei present a λ distribution with 90% GT



Example: Talys Spin-Parity

Ground state spin taken from JINA.

Assuming all decays are GT.



Experimental

140La	3-
141La	(7/2+)
142La	2-
143La	(7/2)+
144La	3-
145La	(5/2+)
146La	(2-)
147La	(5/2+)
148La	(2-)
149La	(3/2-)
150La	(3+)

JINA ReacLib

151La	1/2-
152La	3+
153La	1/2-
154La	2+
155La	1/2-
156La	0+
157La	1/2-
158La	4+
159La	1/2-
160La	3+
161La	1/2-
162La	3+
163La	1/2-
164La	4+
165La	1/2-
166La	1+
167La	5/2-

Explore:
Level Densities
γ-Strength function
Optical model

Conclusions and outlook

- We performed high-precision measurements of beta-decay properties for dozens of very neutron-rich REP isotopes.
- Nuclear structure calculations using a global QRPA model offered consistent results.
- Future work:
  - Explore the impact of different parameters on the TALYS calculations for the P_{xn} values.
  - Combine the new experimental data from BRIKEN with updated nuclear structure calculations to perform r-process nuclear reaction network calculations.

Acknowledgments

This work has been supported by the Spanish Ministerio de Economía y Competitividad under Grants nos. FPA2014-52823-C2-1-P, FPA2014-52823-C2-2-P, FPA2017-83946-C2-1-P, FPA2017-83946-C2-2-P and grants from Ministerio de Ciencia e Innovacion nos PID2019-104714GB-C21, PID2019-104714GB-C22 and PID2022-138297NB-C22. Also supported by SANDA project funded under H2020-EURATOM-1.1 Grant No. 847552.