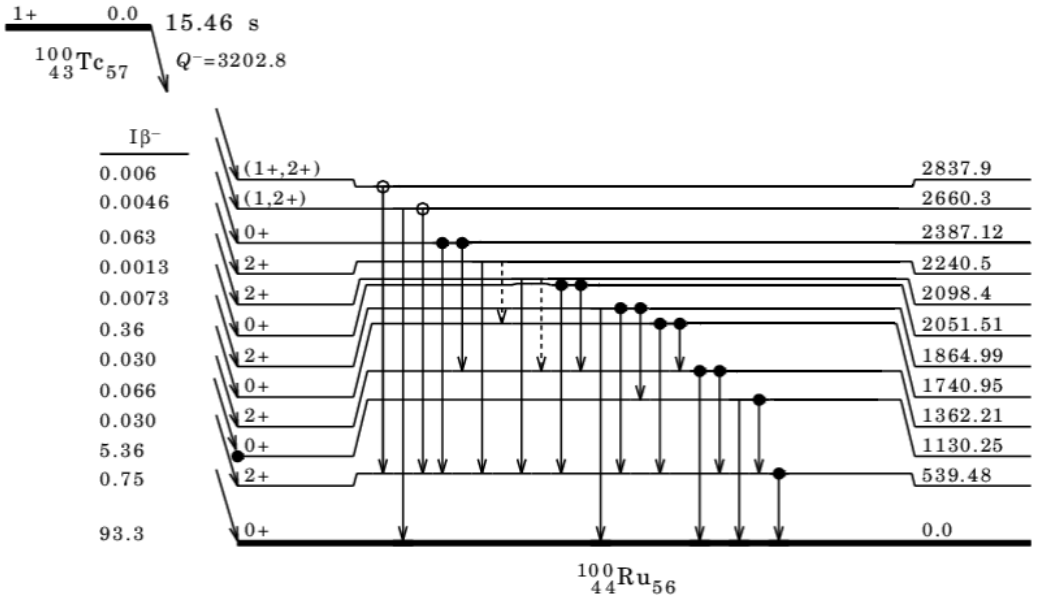
Nuclear astrophysics with TAGS

Víctor Guadilla

SEN group, Subatech

credit: Dana Berry and Erica Drezek, NASA/Goddard Space Flight Cente

β decay studies



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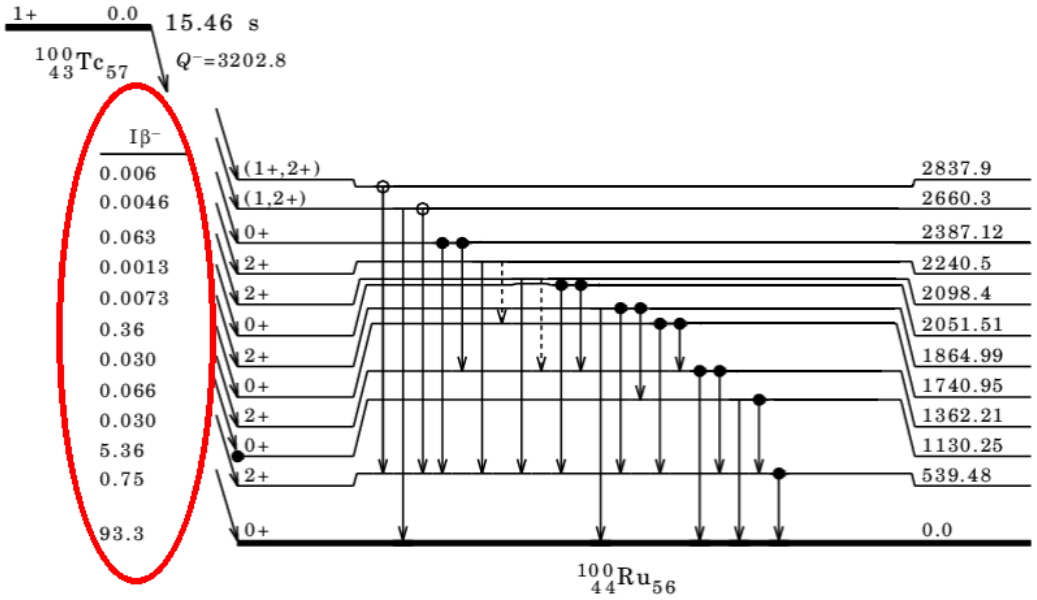

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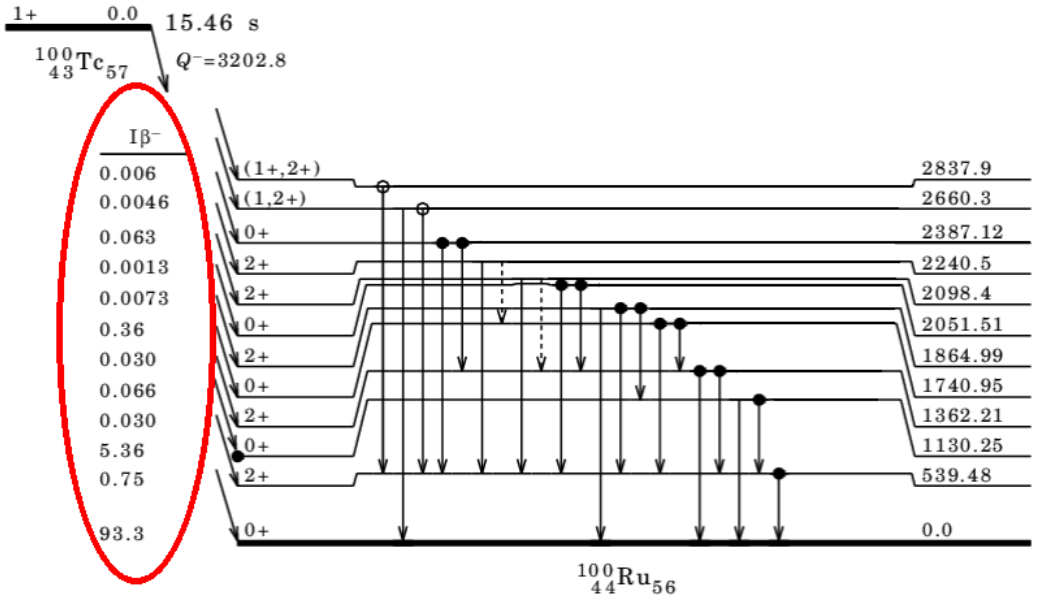


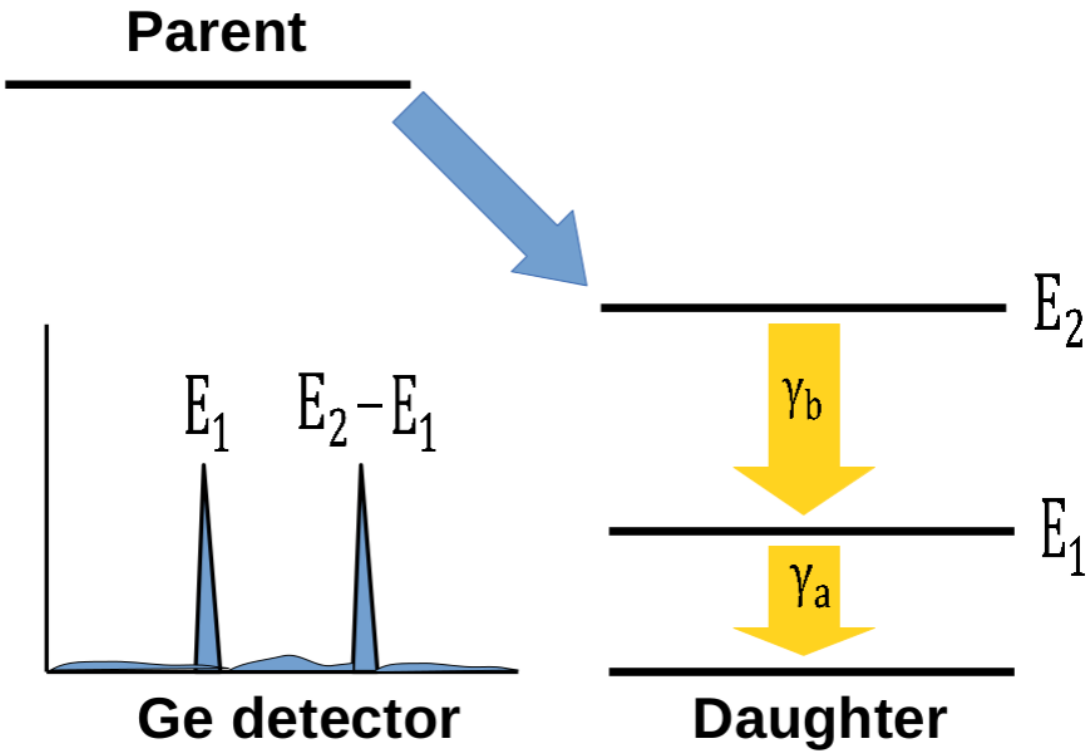
β-strength in the Fermi theory framework

$$S_\beta(E_x) = \sum_{E_f \in \Delta E} \frac{\frac{1}{\Delta E} I_\beta(E_x)}{f(Q_\beta - Ex, Z) T_{1/2}} =$$

$$= \frac{1}{6146 \pm 7} \left(\frac{g_A}{g_V}\right)^2 \sum_{E_f \in \Delta E} \frac{1}{\Delta E} B(GT)_{i \to f}$$

Determining I_β

I_β are often deduced from γ-intensity balance of the cascades that follow the β decay, using **HPGe detectors**:



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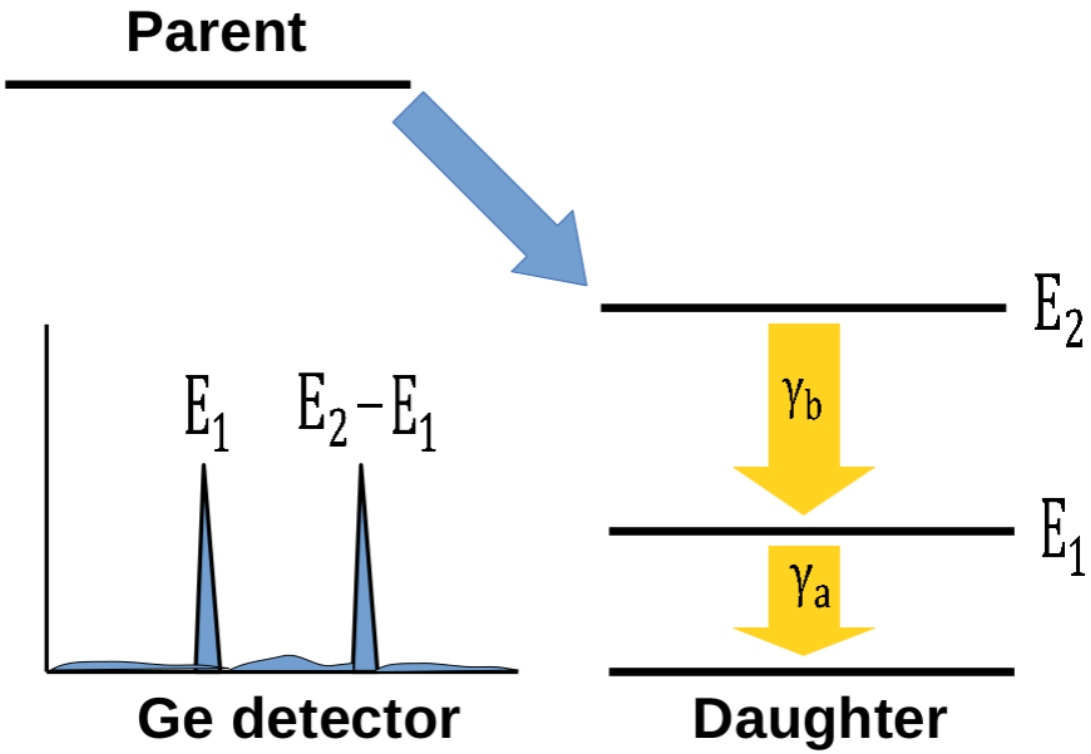

Low efficiency of HPGe detectors $\rightarrow$ what happens if we miss a γ-ray?

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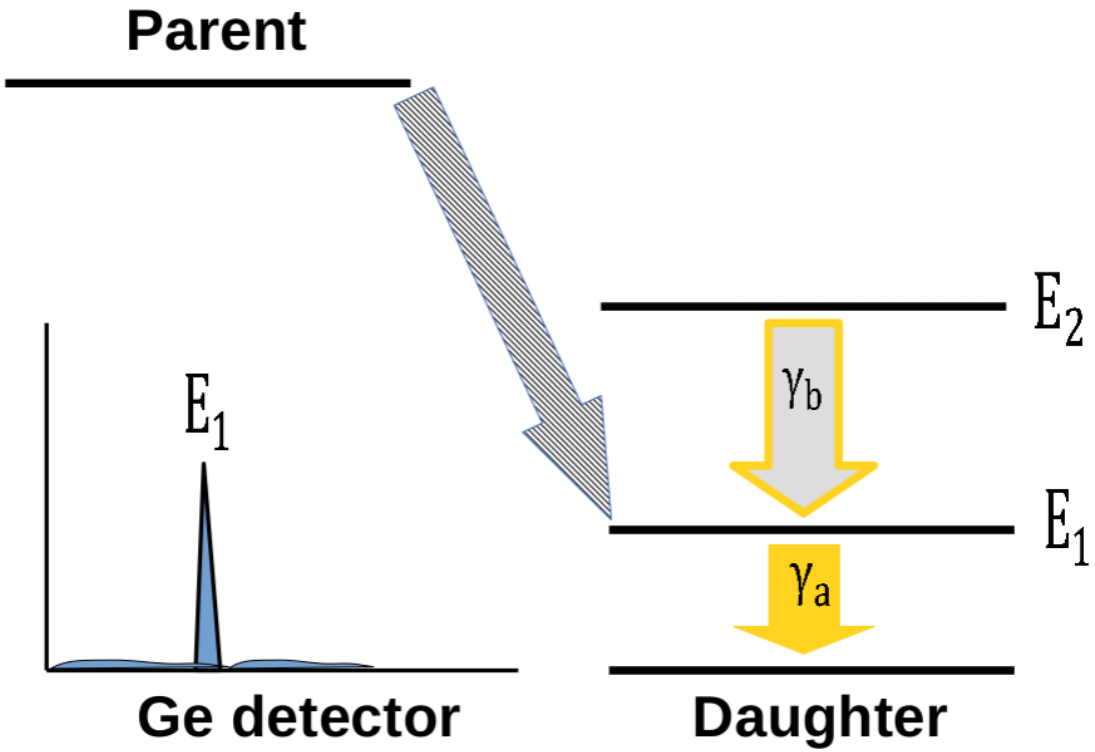
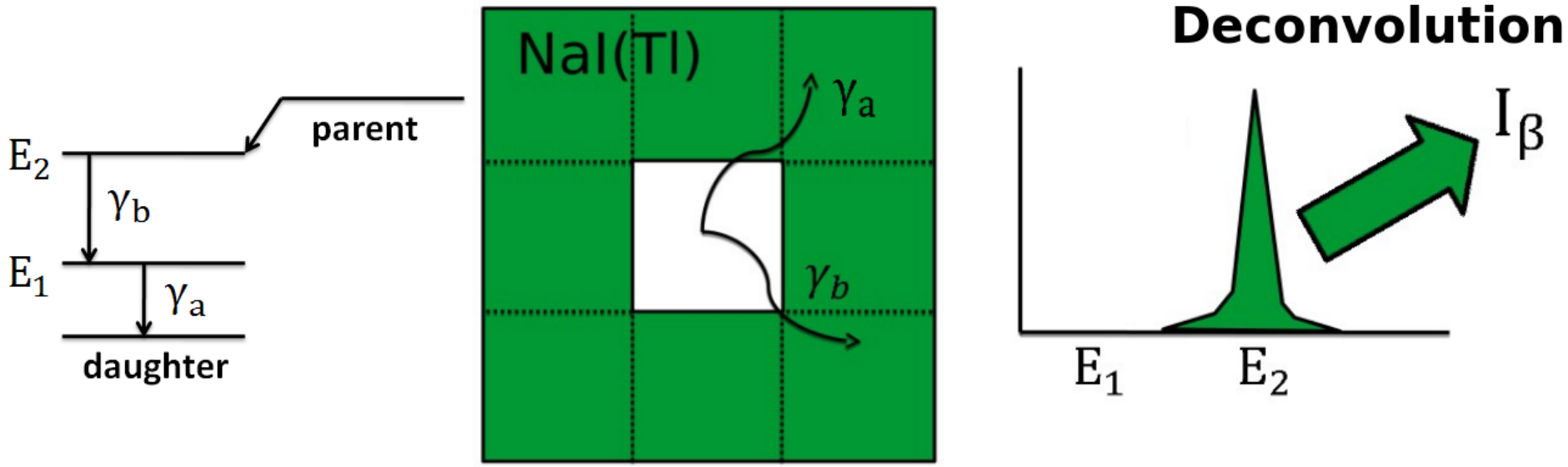


Low efficiency of HPGe detectors $\rightarrow$ what happens if we miss a γ-ray?

Pandemonium effect J.C. Hardy et al., PLB 71 (1977) 307

Total Absorption γ-Ray Spectroscopy (TAGS)

A **T**otal **A**bsorption **S**pectrometer (TAS) acts as a **calorimeter**, absorbing the full energy released in the β-decay process.



It requires:

Large scintillator crystals covering a solid angle of $\sim 4\pi$ in order to maximize the γ-ray detection **efficiency**.

Total Absorption γ-Ray Spectroscopy (TAGS)

Inverse problem:

$$d_i = \sum_{j=1}^{m} \boldsymbol{R_{ij}(B)} f_j$$

- $j \rightarrow$ levels, $i \rightarrow$ experimental bins
- f_j: $I_\beta(E)$ distribution
- d_i: experimental spectrum
- R_{ij}: response matrix of the detector
- B: branching ratio matrix (depends on the decay)

A deconvolution process to extract f_j

J.L. Tain and D. Cano-Ott NIMA 571 (2007) 728

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Expectation-Maximization (EM) algorithm

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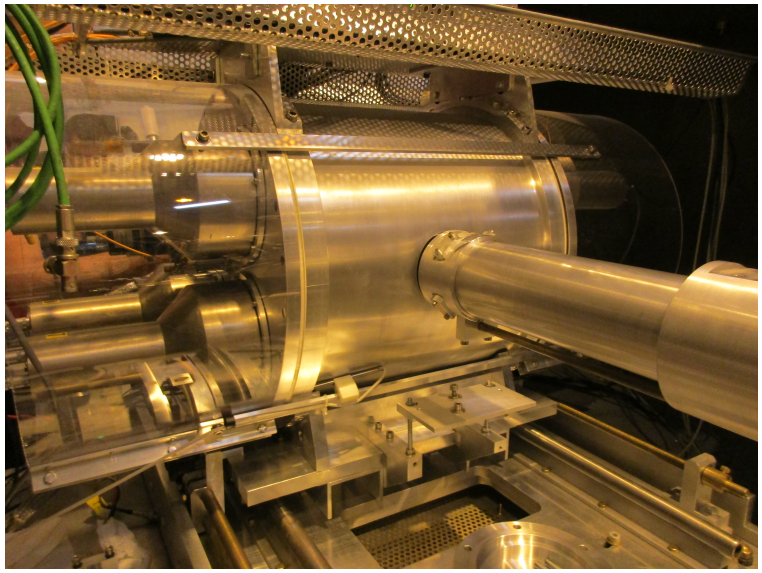
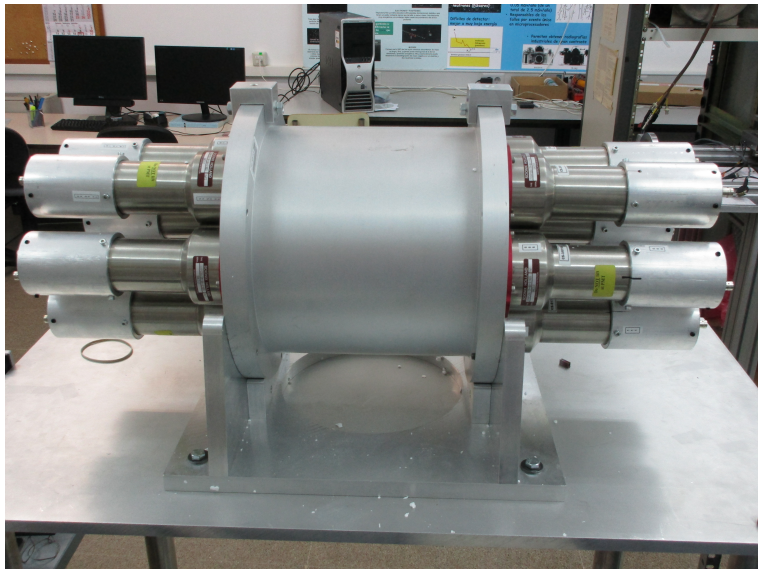
Examples of Total absorption γ-ray spectrometers I



Lucrecia



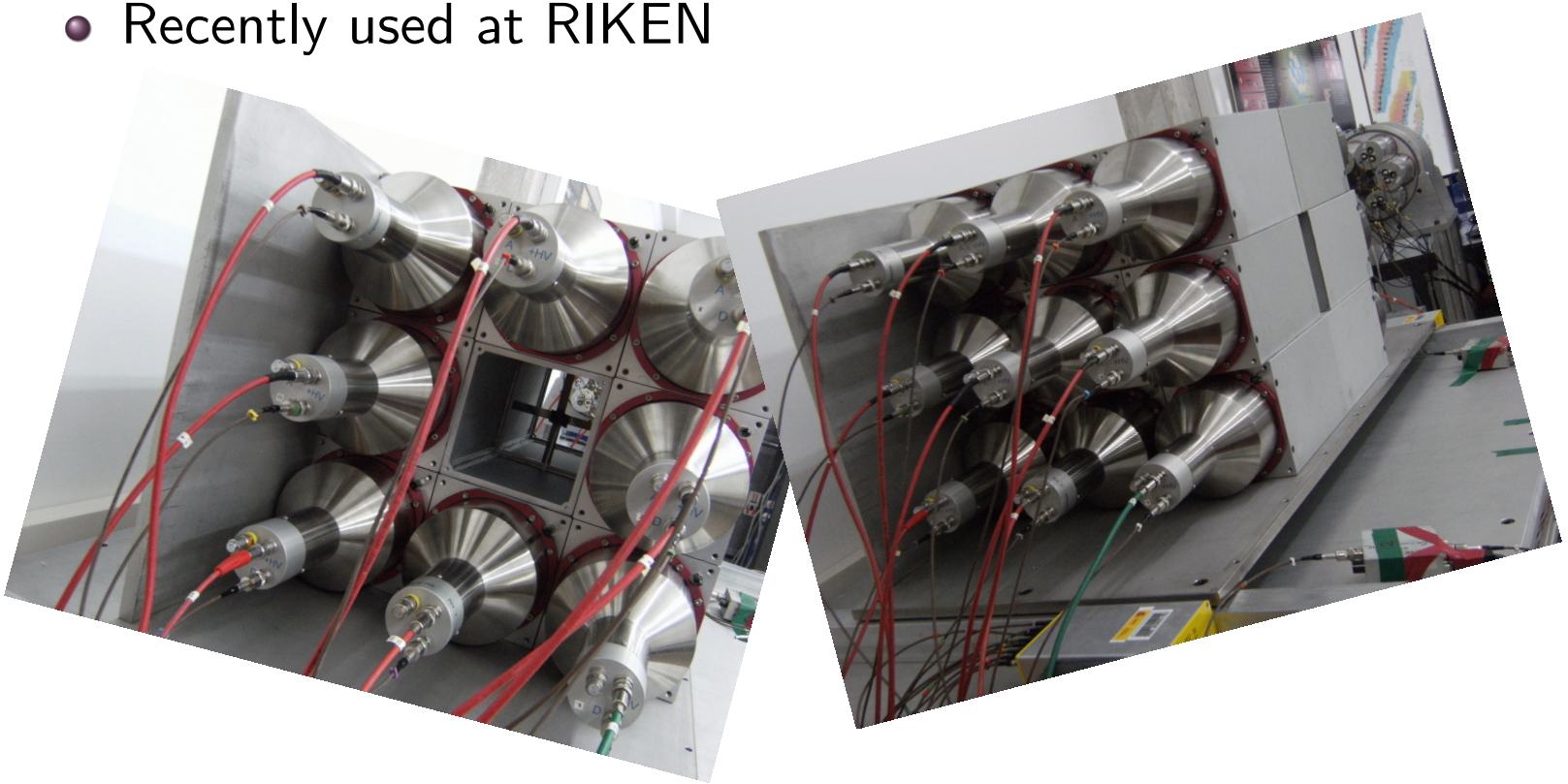
Rocinante

- **Lucrecia**: NaI(Tl) mono-crystal with cylindrical shape (38 cm diameter and 38 cm length). Permanent set-up at ISOLDE (CERN).
- **Rocinante**: cylindrical 12-fold segmented BaF_2 detector (25 cm external diameter and 25 cm length). Used in experiments at IGISOL (Jyväskylä).

Examples of Total absorption γ-ray spectrometers II

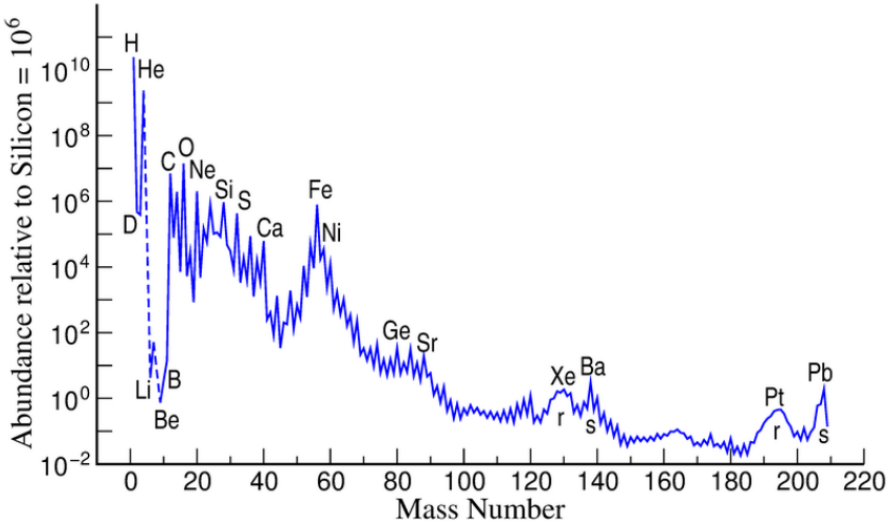
J.L. Tain et al., NIMA 803 (2015) 36

- 16-18 NaI(Tl) crystals of 150 mm $\times$ 150 mm $\times$ 250 mm
- Used in experiments at IGISOL (Jyväskylä)
- Recently used at RIKEN



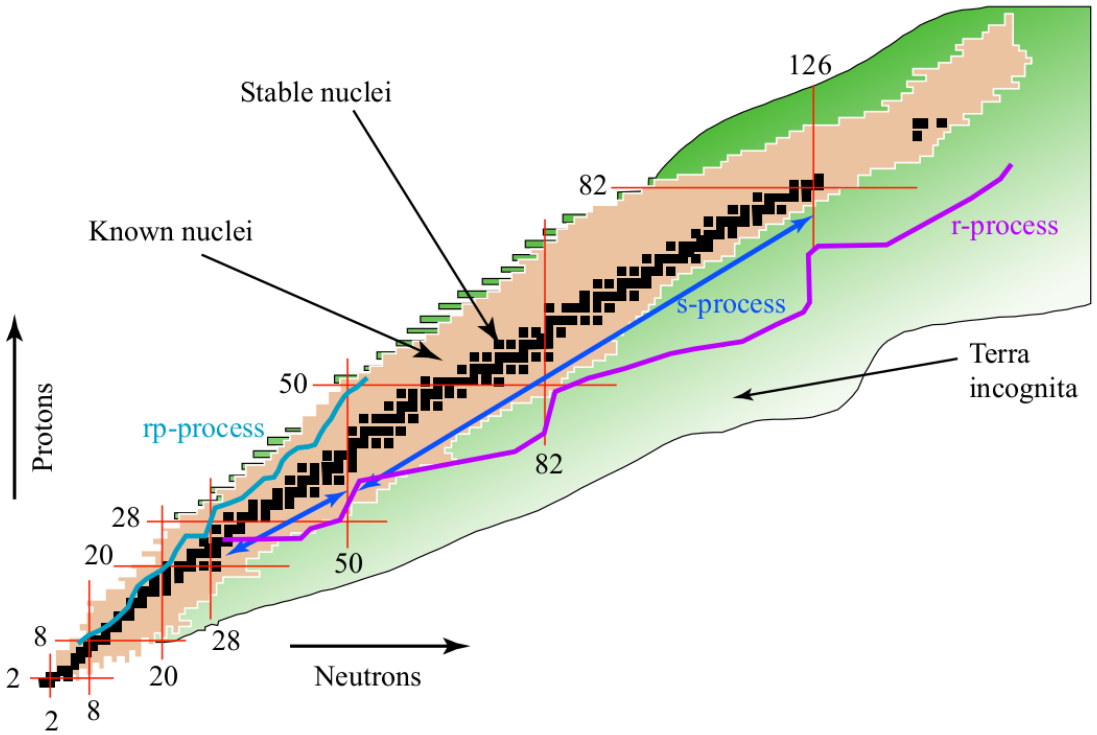
DTAS

Nucleosynthesis



← K. Lodders Ap. J. 591 1220 (2003)

from F. X. Timmes, Cococubed project →



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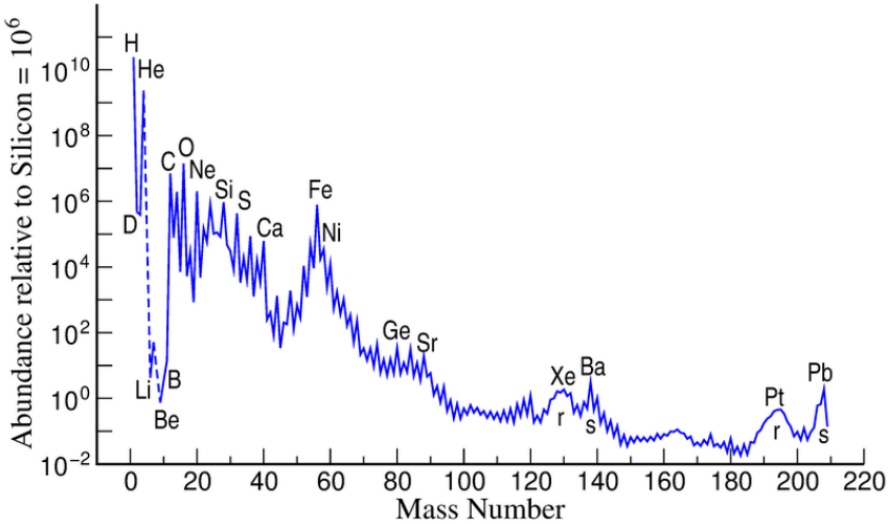

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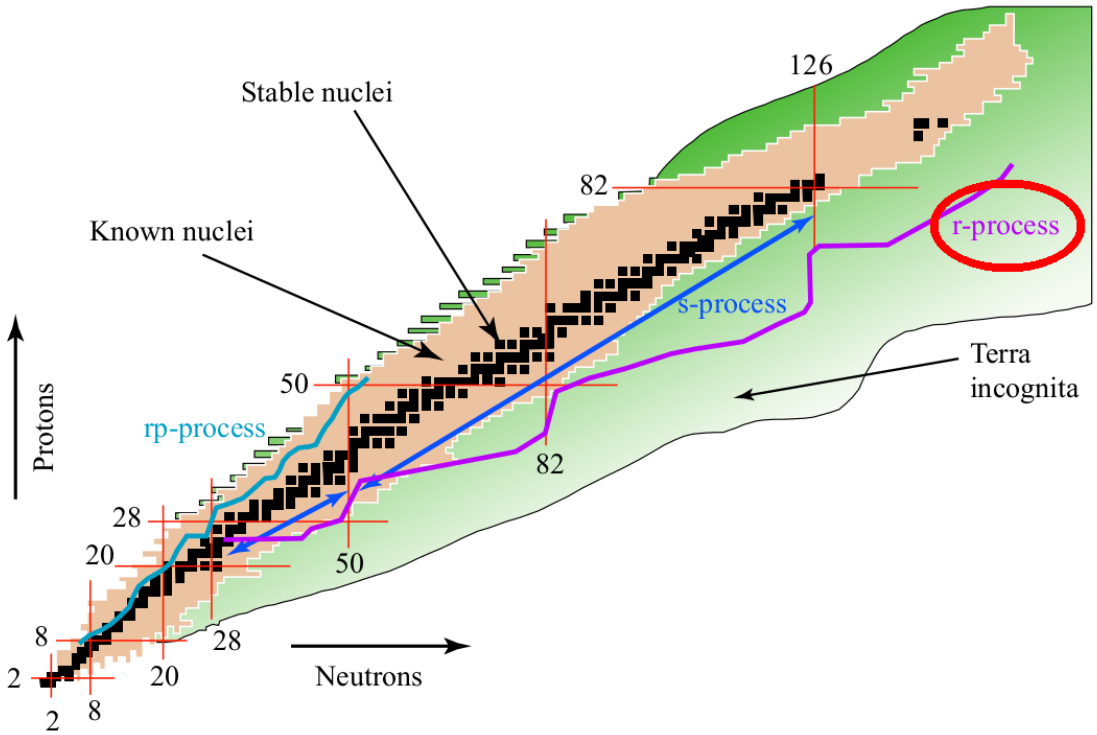

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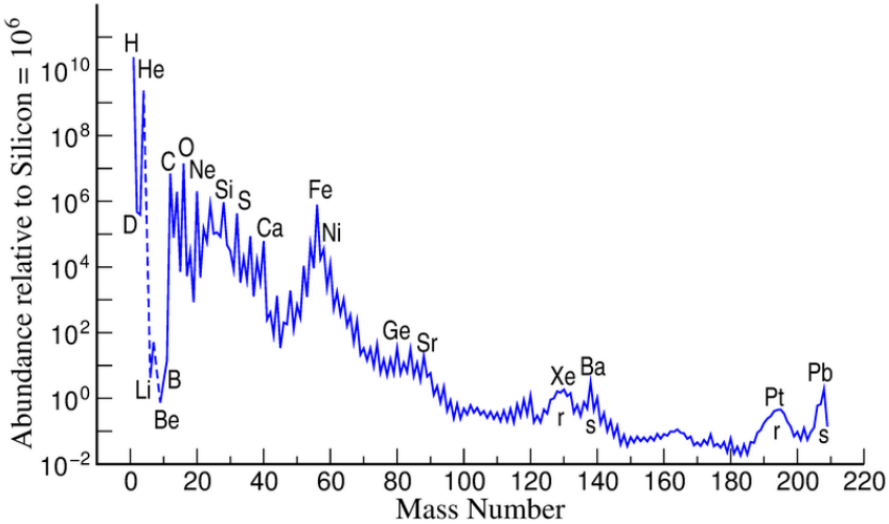

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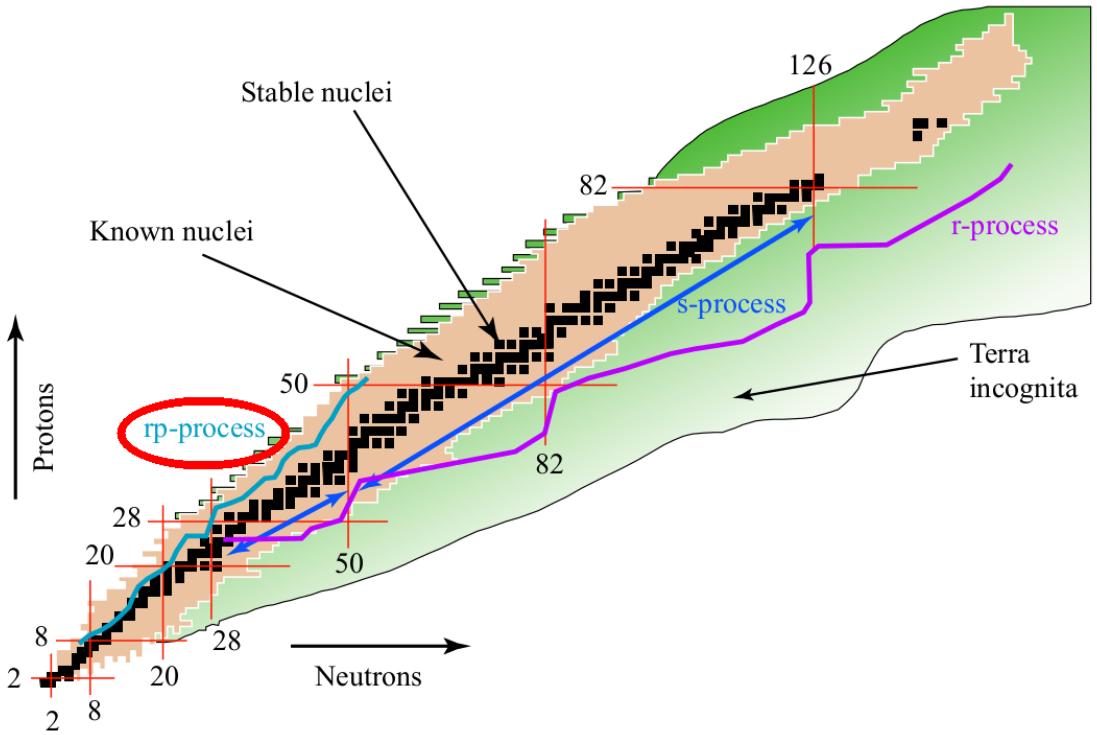

Reproduction of the experimental abundances

Ingredients of network calculations

$\downarrow$

For exotic neutron-rich and neutron-deficient nuclei:

- Nuclear masses
- Decay rates: β^- decay, EC/β^+ decay, p-decay, α-decay...
- Reaction rates: (n,γ), (p,γ), (α,γ)...
- Fission rates and yields

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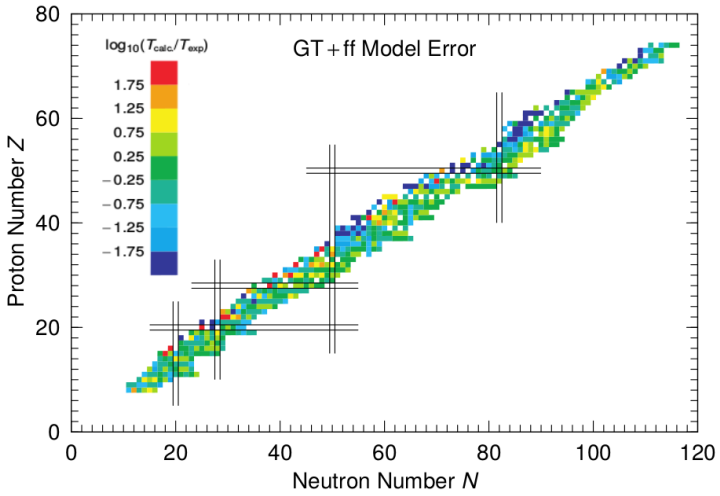
3. From systematics

Validation of theoretical models

Validation with **integral** quantities (P_n values, $T_{1/2}$)

P. Möller PRC 67, 055802 (2003)



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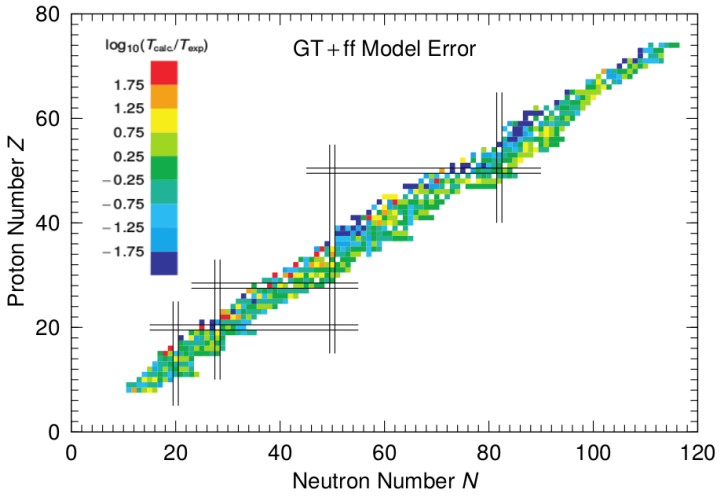
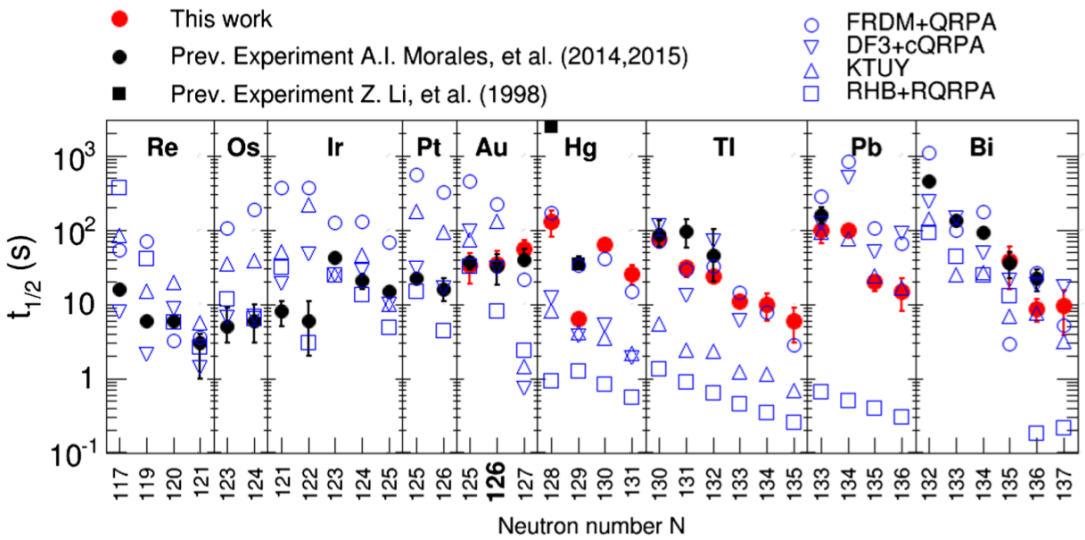


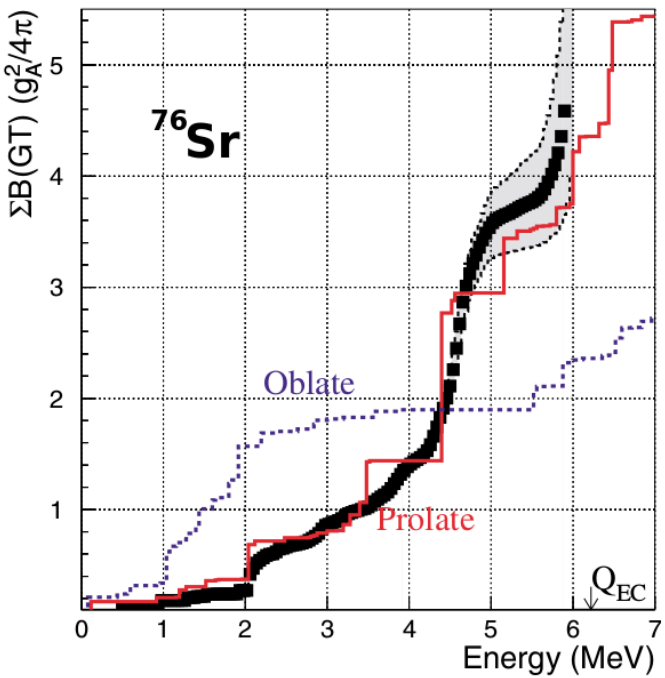


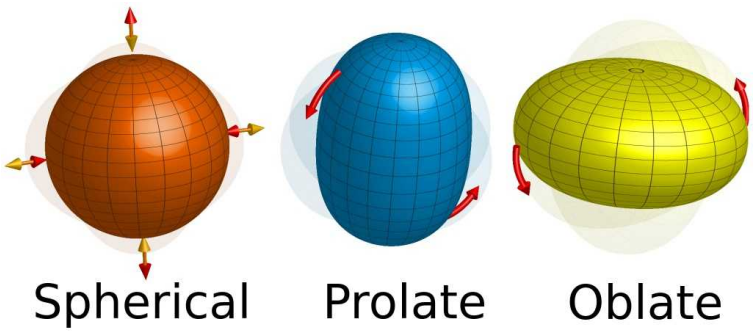
R. Caballero-Folch et al. PRL 117, 012501 (2016)

Problems to describe coherently the observed half-lives across N=126

Validation of theoretical models

Need of validating models with β **strength comparisons**: full information about the overlap of parent and daughter nuclear wave functions



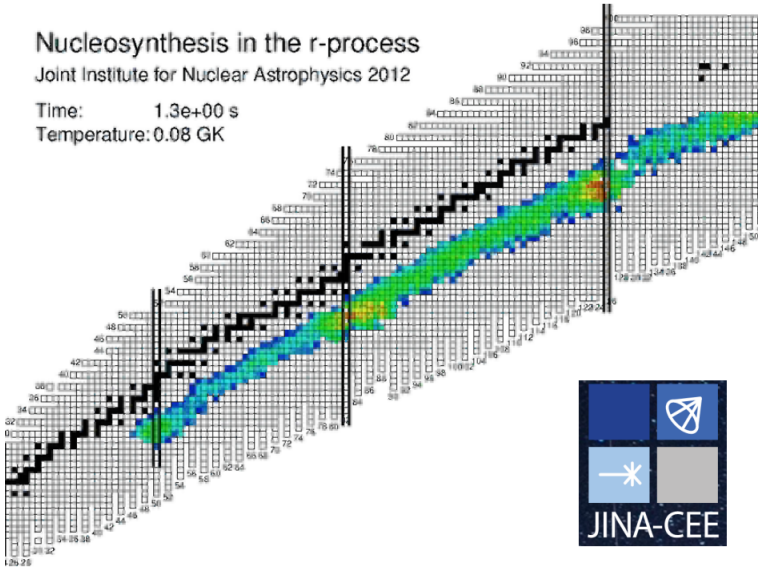


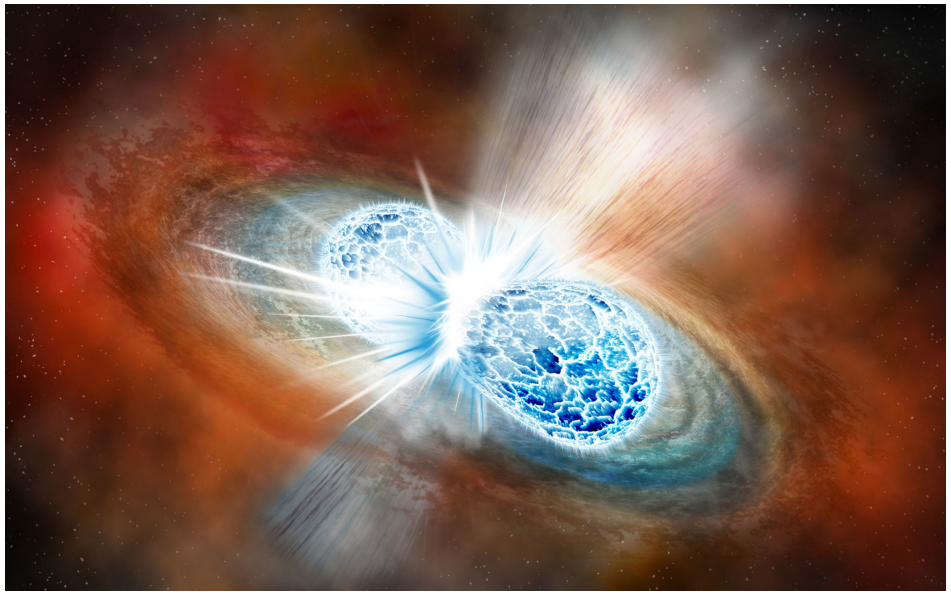
E. Nacher et al., PRL 92 (2004) 232501

QRPA calculations:

P. Sarriguren et al., PRC 89 (2014) 034311

r-process





- $N_n \sim 10^{20}$cm^{-3} and T$\geq$1GK
- Half of nuclei beyond iron
- Sites: Core Collapse Supernova, Neutron Star Mergers

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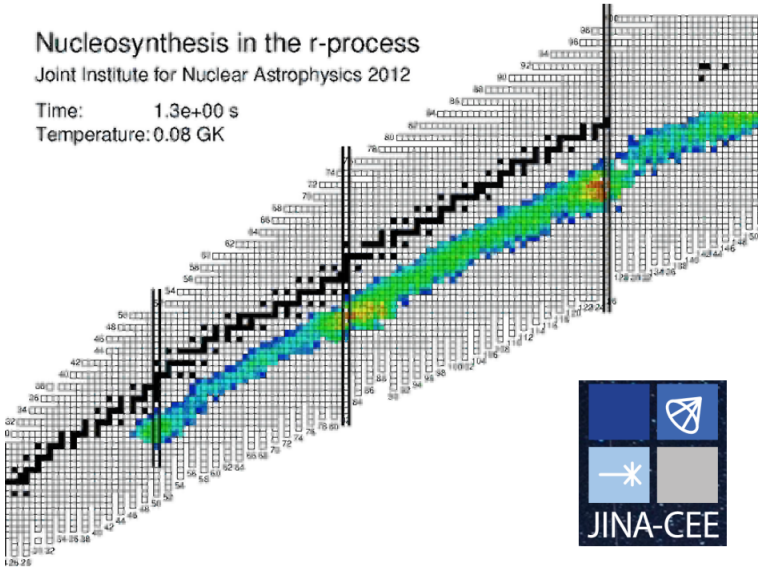

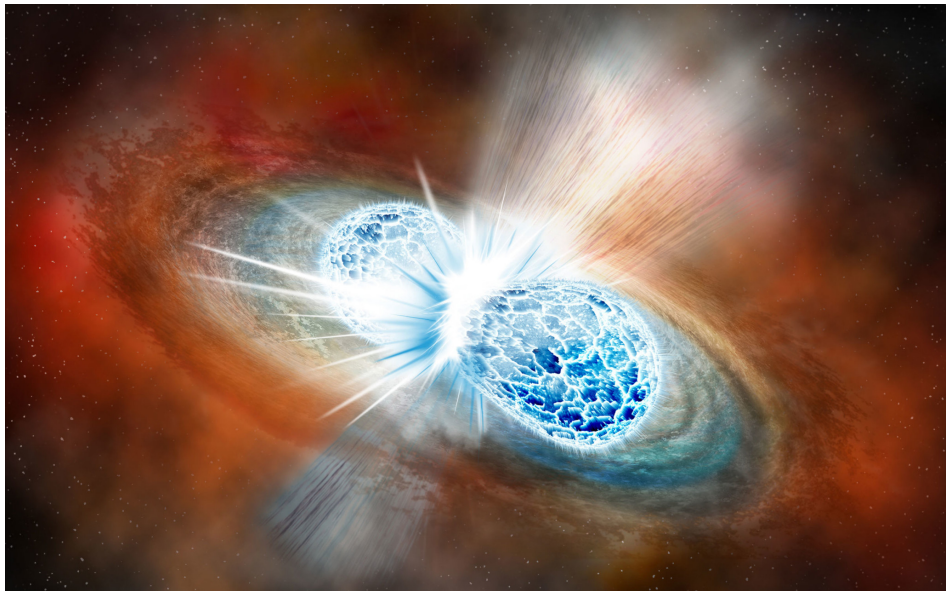

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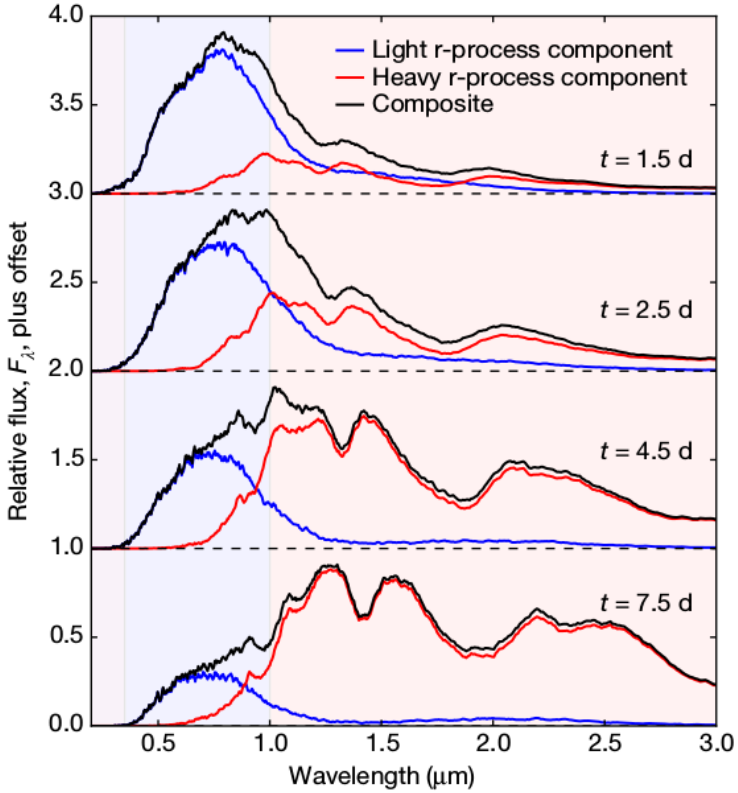
Neutron star mergers: GW170817

Kilonova

Electromagnetic signature of the r-process due to radioactive decay of r-process nuclei

Mon. Not. R. Astron. Soc. 406, 2650–2662 (2010)



Kasen et al, Nature 551, 80 (2017)

(n,γ) reactions

1. Hot r-process: β decay-(n,γ) competition during freeze out
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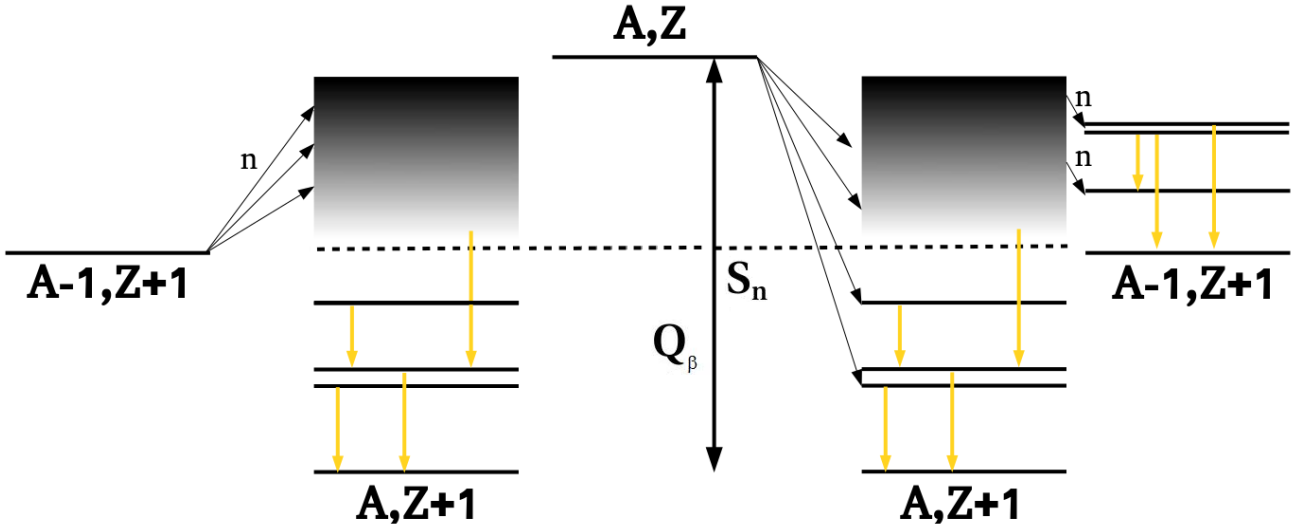
- Constrained with different indirect techniques
  A.C.Larsen et al., Prog. in Particle and Nuclear Physics 107 (2019)

Connection with β-delayed neutron emission



(n,γ) β decay

$$\sigma_{n\gamma} \propto \frac{\Gamma_\gamma \Gamma_n}{\Gamma_\gamma + \Gamma_n}$$

$$I_{\beta\gamma} \propto \frac{\Gamma_\gamma}{\Gamma_\gamma + \Gamma_n}$$

Difficulty to observe γ de-excitation from states above S_n

J.L. Tain et al., PRL 115 (2015) 062502

Some cases studied at IGISOL

Nuclide	Q_β [keV]	S_n in daughter [keV]	P_n [%]
^{87}Br	6818	5515.17	2.60
^{88}Br	8975	7053	6.58
^{94}Rb	10283	6831	10.5
^{95}Rb	9228	4345	8.7
^{137}I	6027	4025.56	7.14

2009 $\longleftrightarrow$ Rocinante

J.L. Tain et al., PRL 115 (2015) 062502

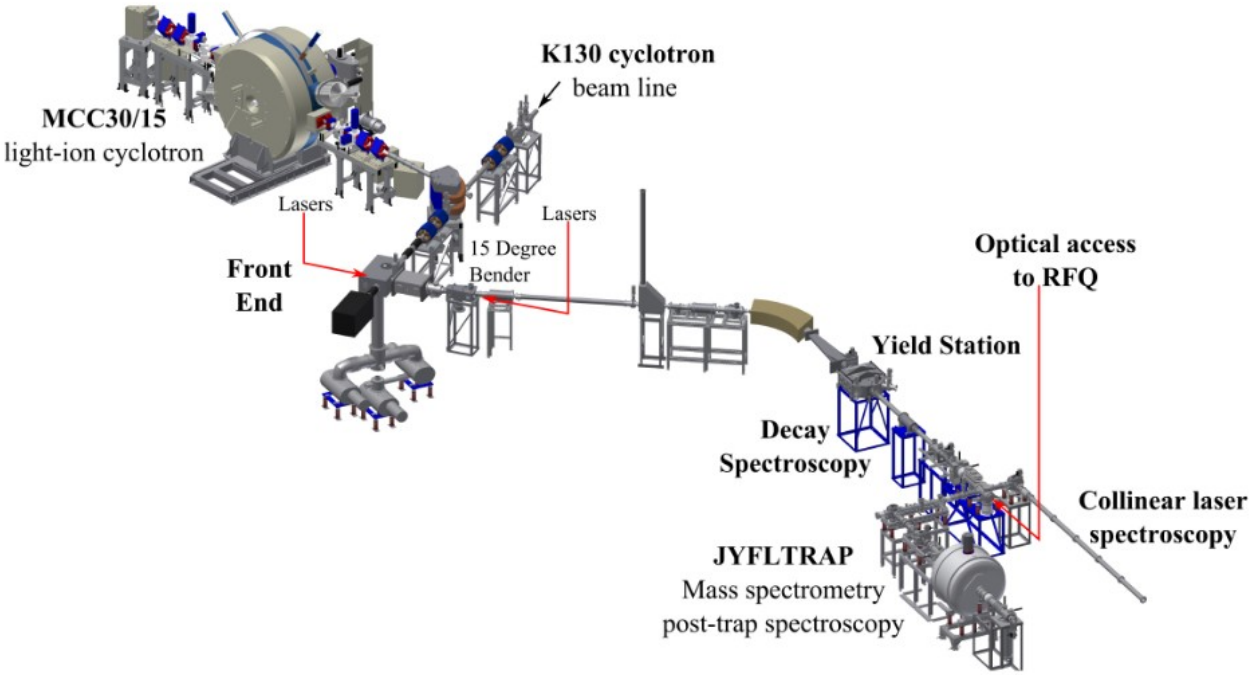
E. Valencia et al., PRC 95 (2017) 024320

2014 $\longleftrightarrow$ DTAS

V. Guadilla et al., NIMB 376 (2016) 334

V. Guadilla et al. (2019)

IGISOL-IV: Jyväskylä (Finland)



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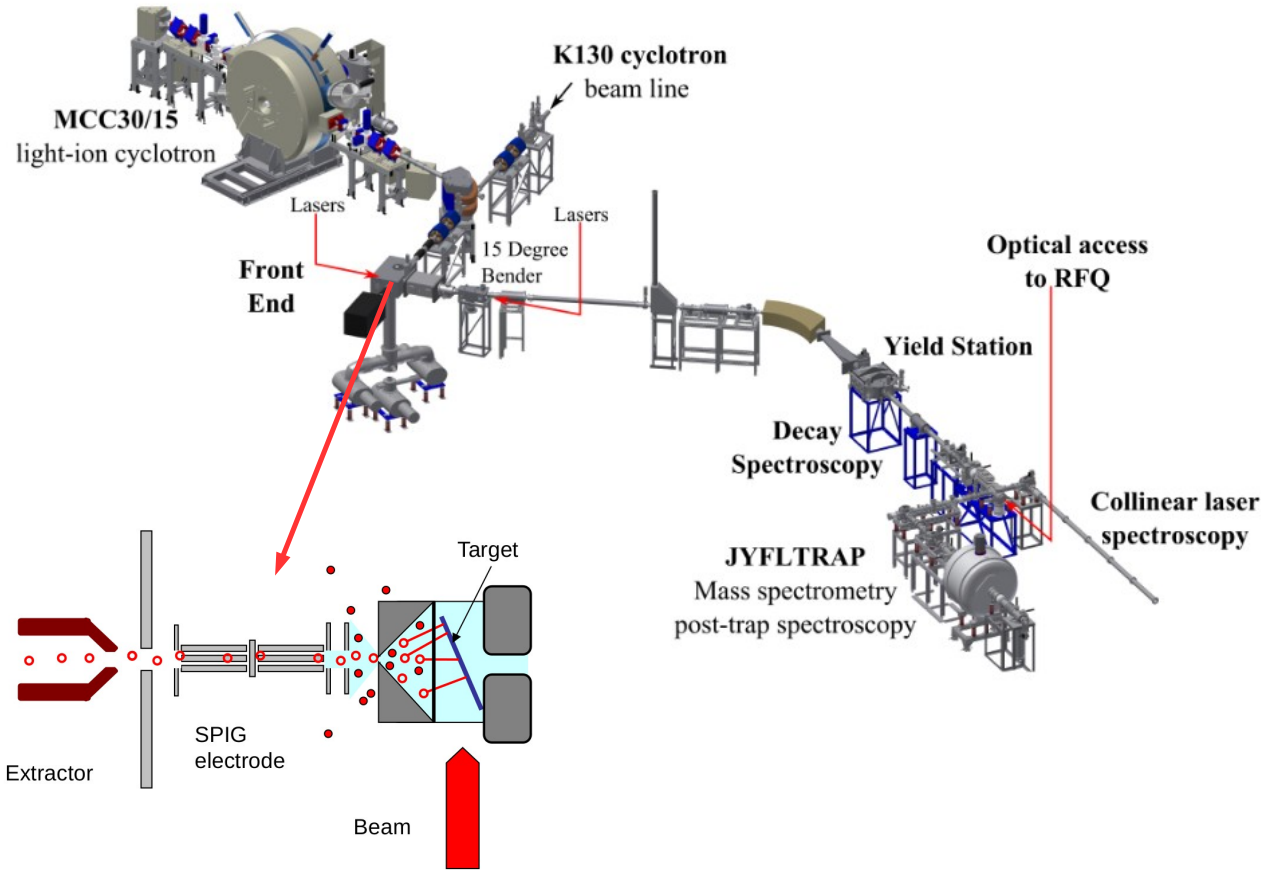

Fission Ion Guide

- Natural uranium target
- Refractory elements

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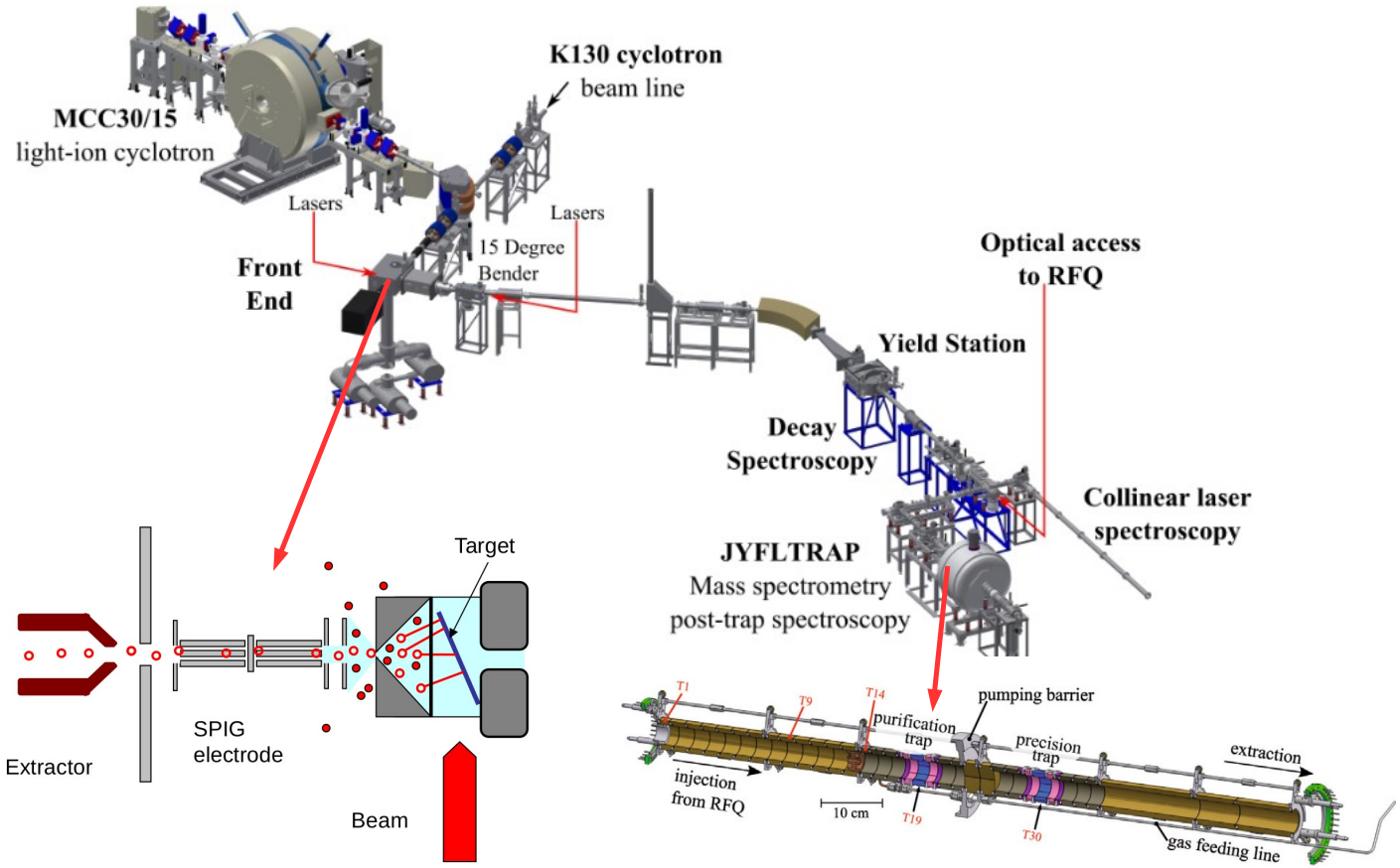


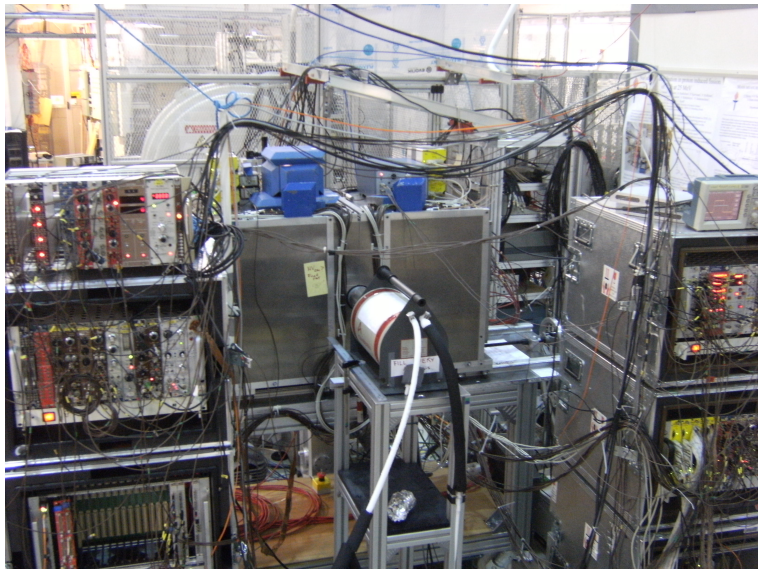
Fission Ion Guide

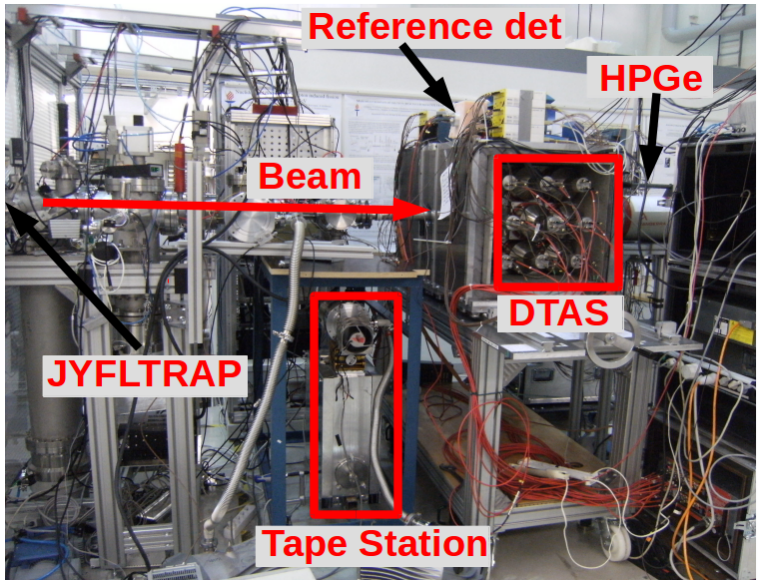
- Natural uranium target
- Refractory elements

JYFLTRAP Penning traps

- Inside a 7 T solenoid
- $M/\Delta M \sim 10^{5-6}$

DTAS@IGISOL: set-up



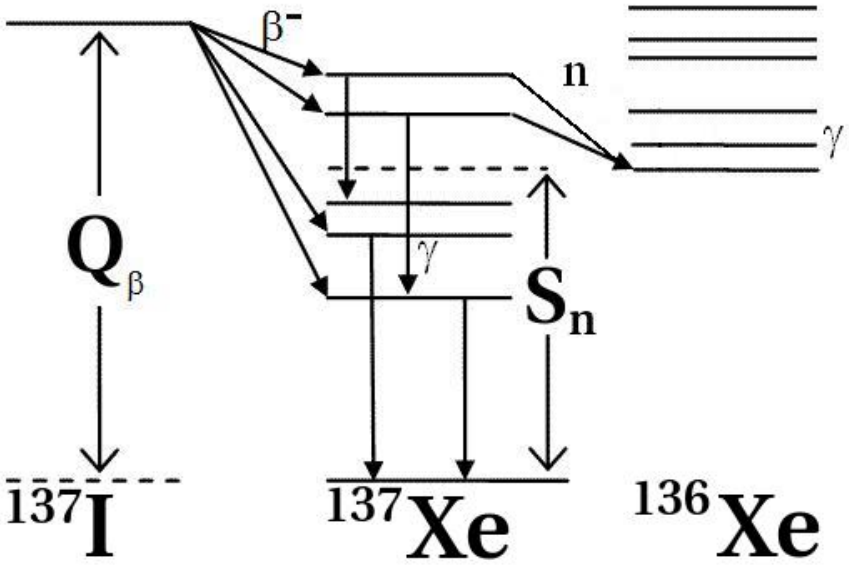


- Scintillator plastic β detector
- HPGe detector
- Tape station
- MC characterization of the detectors

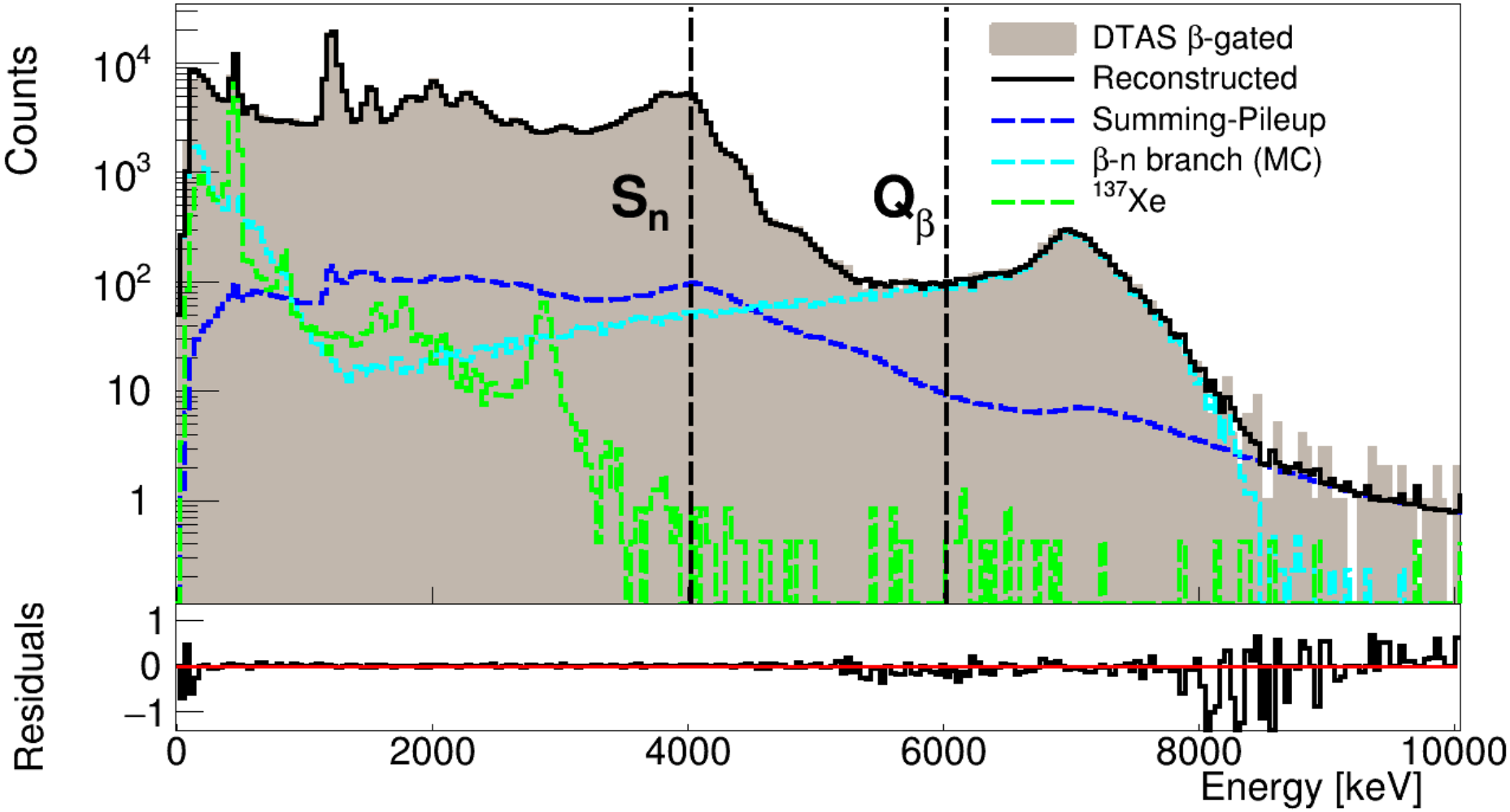
V. Guadilla et al., NIMB 376 (2016) 334
V. Guadilla et al., NIMA 910 (2018) 79

β-delayed neutron emission: ^{137}I

- Q_β=6027 keV and S_n=4025 keV
- P_n=7.14% and $T_{1/2}$=24.5 s
- Neutrons interact with DTAS (inelastic, capture...) $\rightarrow$ MC



^{137}I: analysis

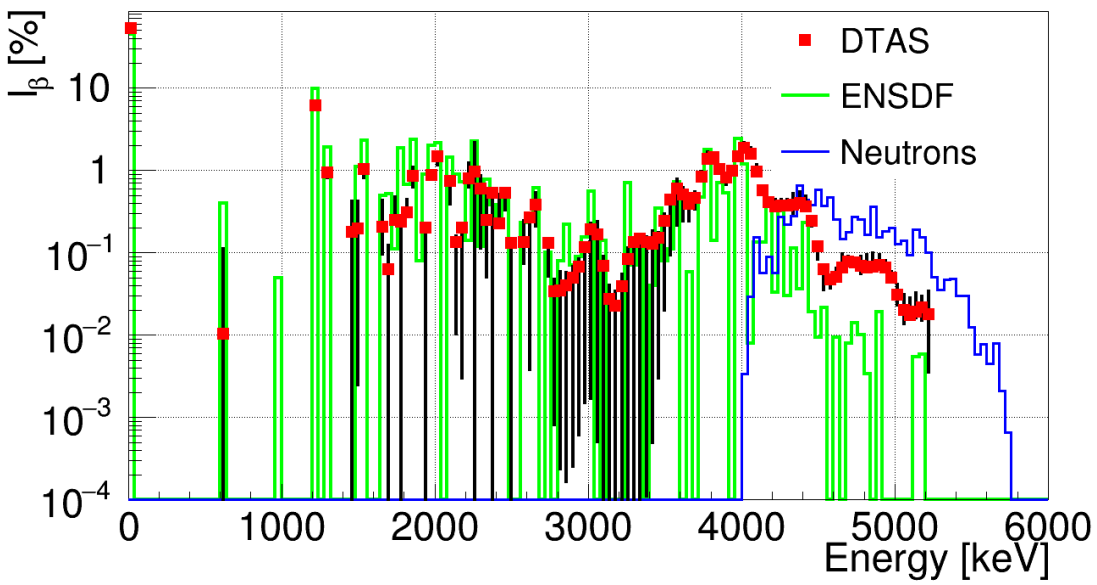


Reconstructed $\rightarrow \sum_{j=1}^{m} \boldsymbol{R_{ij}(B)} f_{j\,(final)}$

^{137}I: analysis

Envelope of solutions compatible with data:

- Daughter normalization
- β-n normalization
- Summing-pileup normalization
- Known level scheme
- Deconvolution algorithm
- β detector efficiency
- β-gated **vs**. singles **vs.** neutron veto



- Branching ratio variations: parameters of level density, γ-strength function, spin-parity values of known level scheme, better reproduction of known γ-intensities etc.

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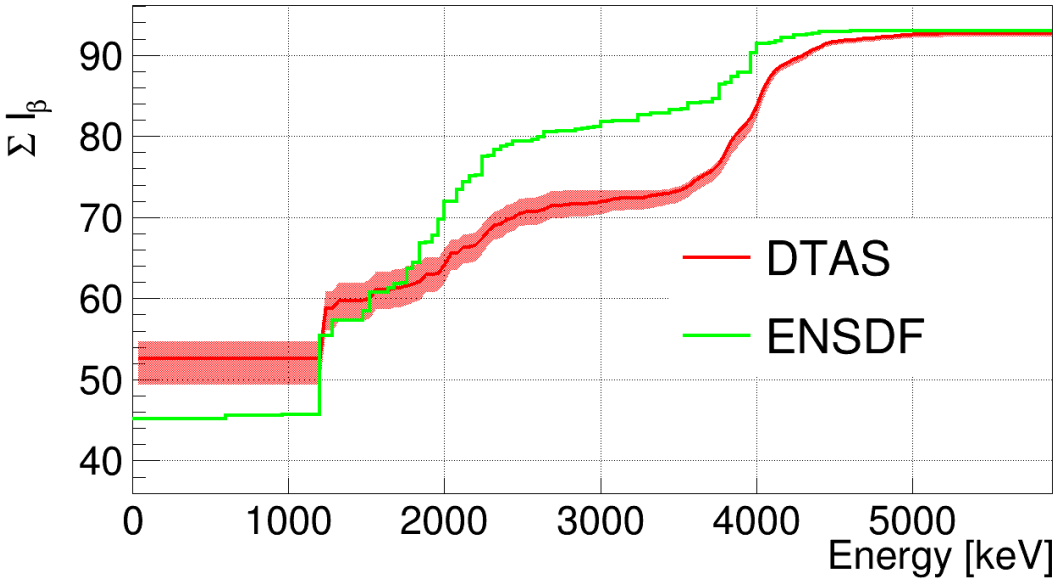

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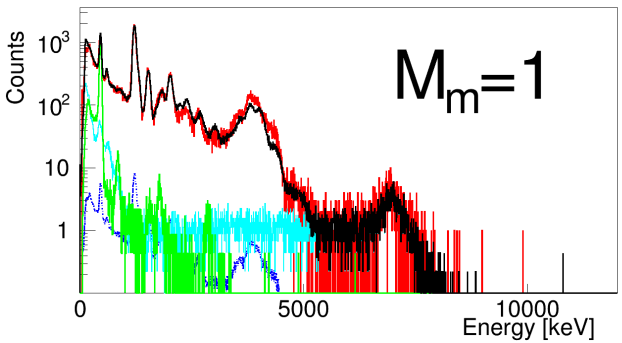
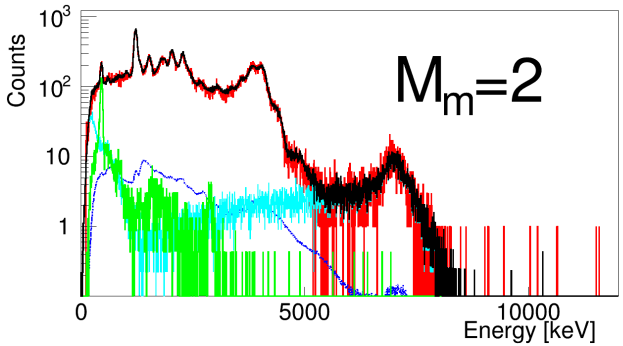
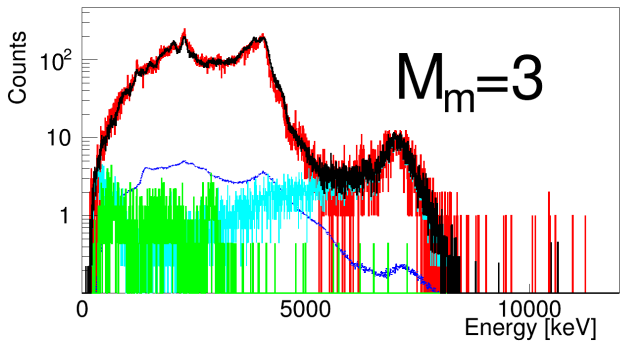
^{137}I: multiplicities

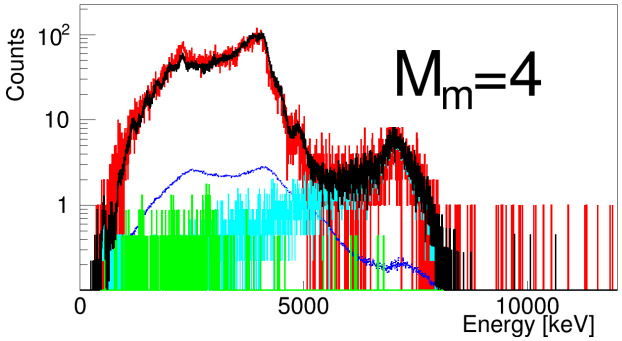


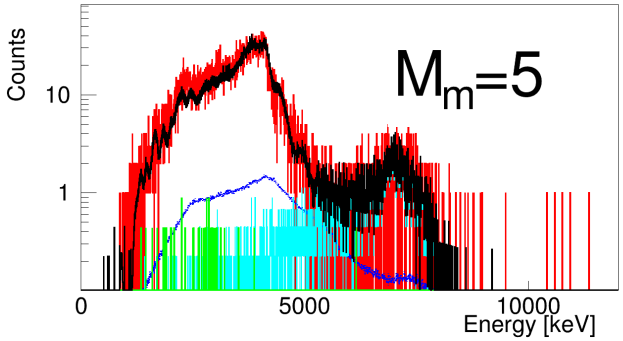


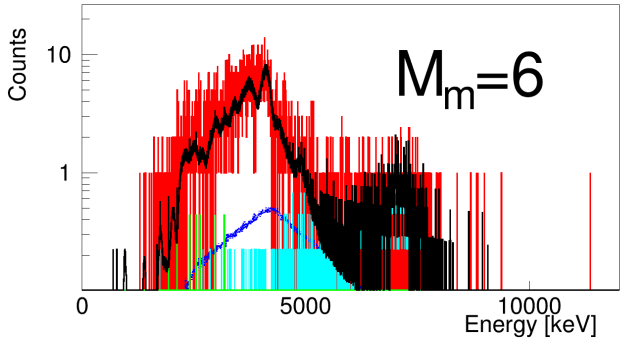


β gated
MC analysis
Summing-Pileup
MC neutrons
^{137}Xe

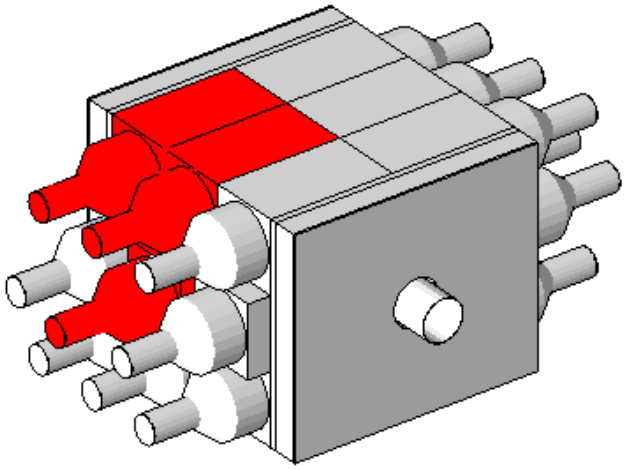
MC with event generator
↪ Input: $\mathbf{I}_\beta$ of the analysis +
branching ratio matrix







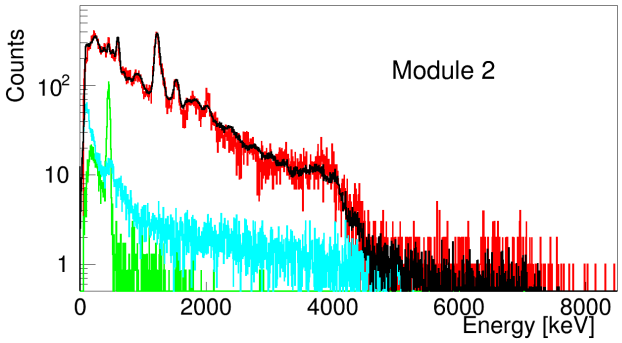
^{137}I: individual modules

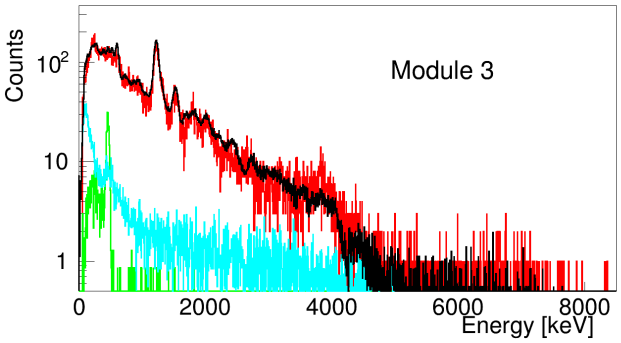


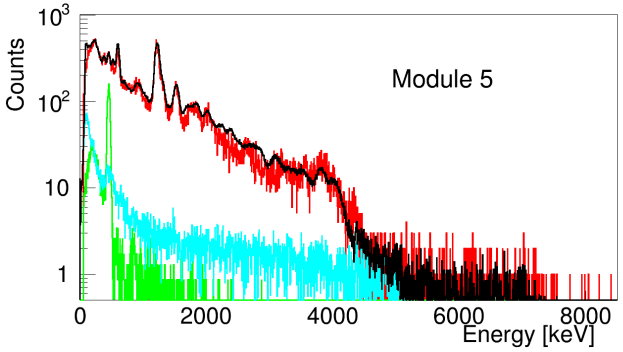
Three classes of modules geometrically equivalent

MC with event generator
$\hookrightarrow$ Input: $\mathbf{I}_\beta$ of the analysis
$+$ **branching ratio matrix**

β gated
MC analysis
MC neutrons
^{137}Xe

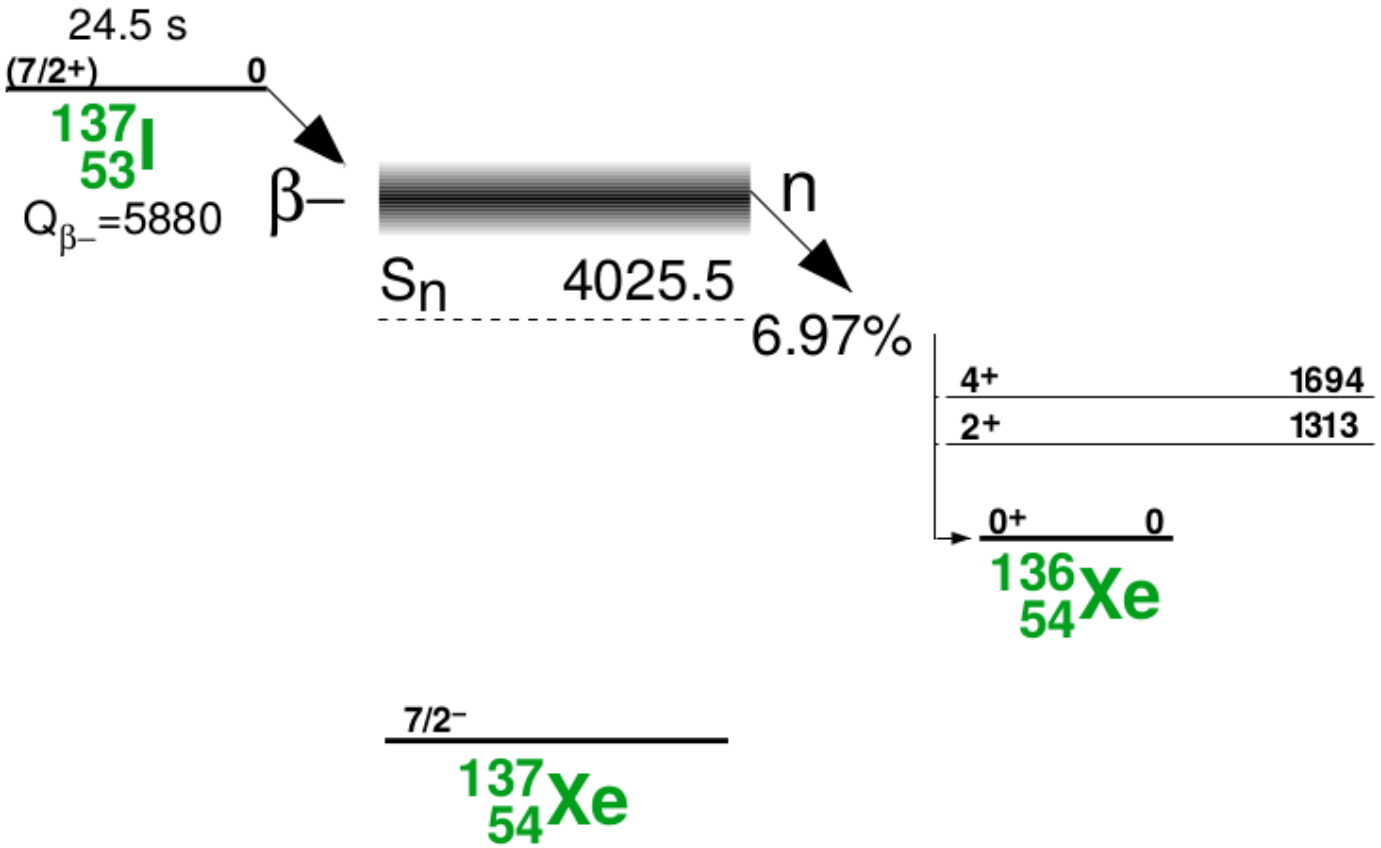






γ emission above S_n

Nucleus	P_γ ENSDF [%]	P_γ DTAS [%]	P_n [%]
^{137}I	2.76	$8.88^{+1.96}_{-1.53}$	7.33(38)



V. Guadilla et al.(2019)

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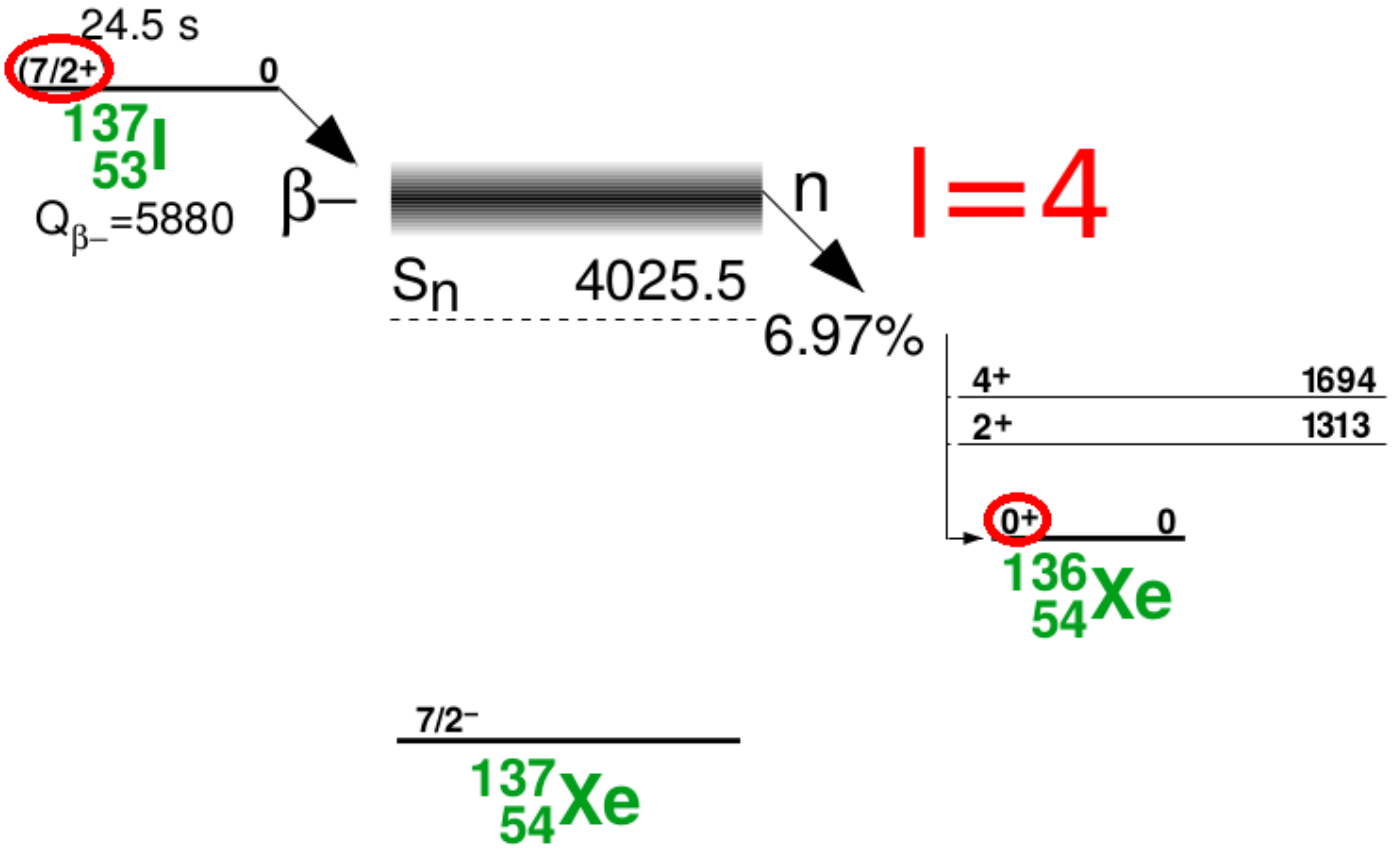

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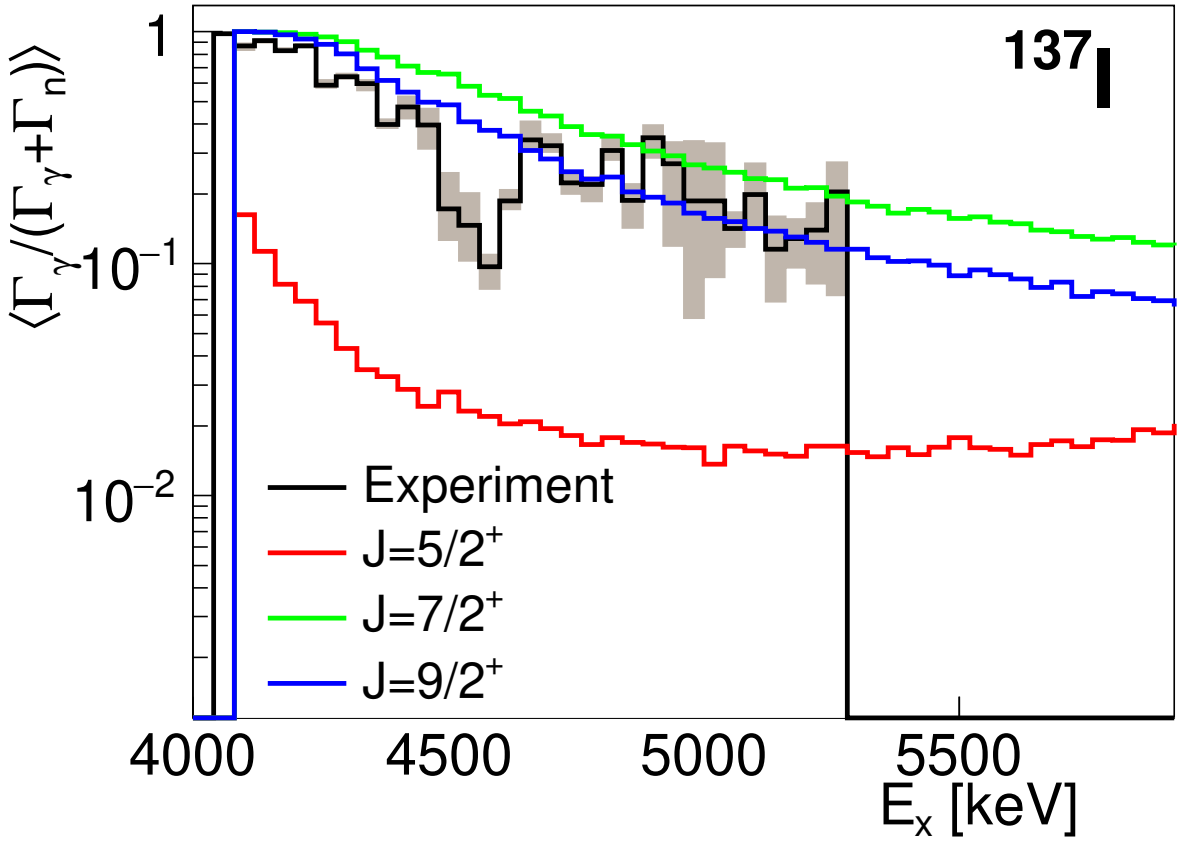
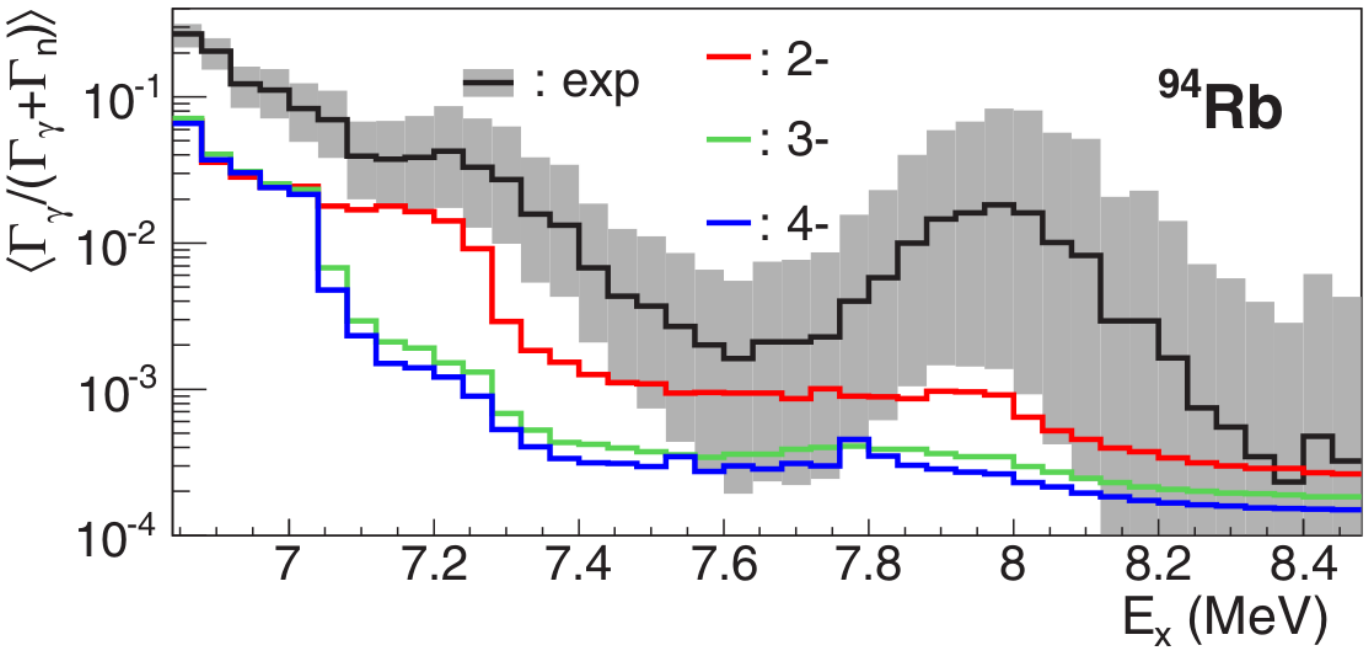


V. Guadilla et al.(2019)

γ emission above S_n

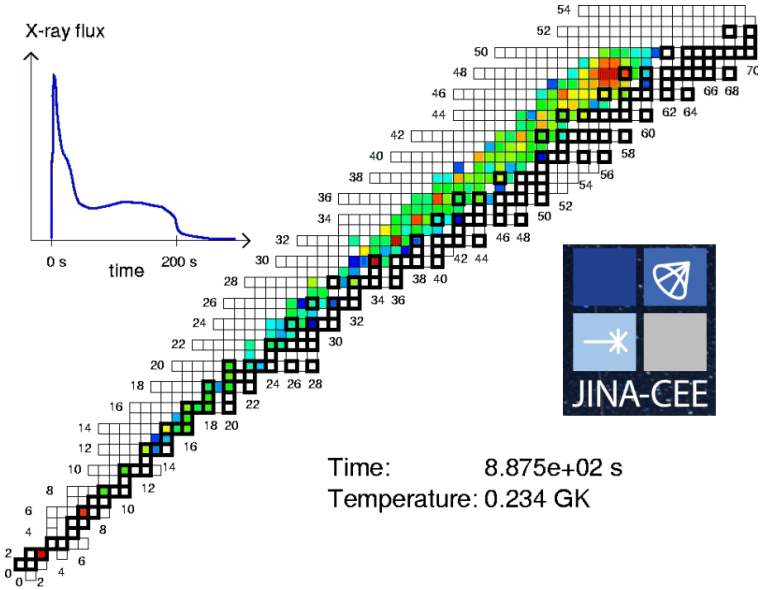
Enhanced γ-branching in ^{94}Rb with respect to H-F $\Rightarrow$ increase in the photon strength function $\Rightarrow$ similar increase in the (n,γ) cross section

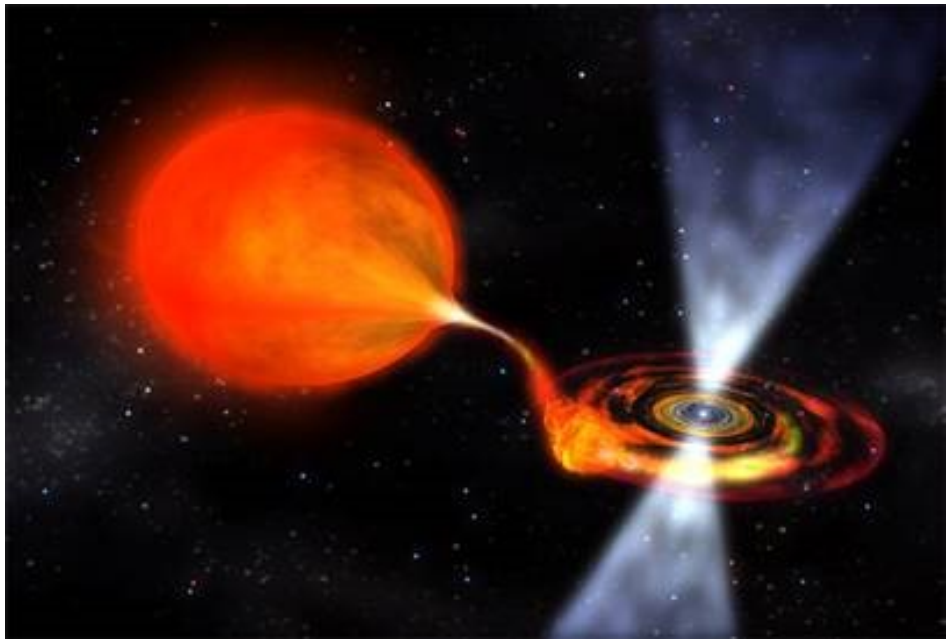


J.L. Tain et al., PRL 115 (2015) 062502
E. Valencia et al., PRC 95 (2017) 024320

X-ray bursts: intense x-ray emission

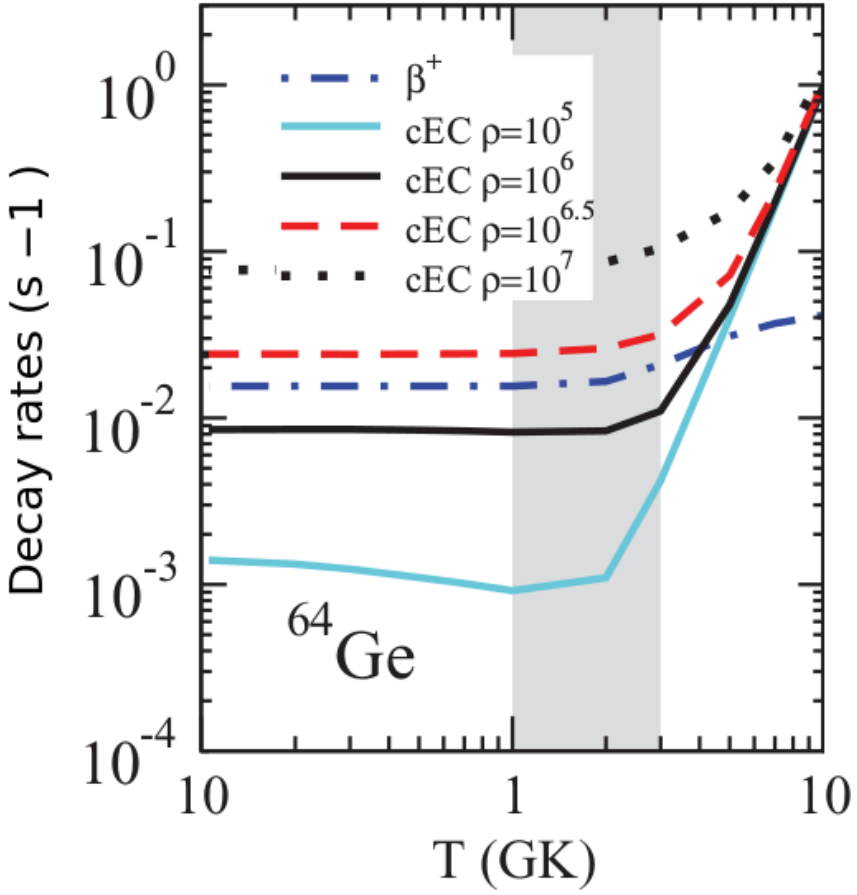
- Type I: instabilities in the accretion disk (binary system: neutron star + main sequence or red giant star)
- T_{peak} = 1-3 GK and $\rho = 10^6$-10^7 g/cm^3
- Light curves with a large variety of shapes
- Fast rise (1-10 s), peak luminosity of 10^{38} erg s^{-1} + slower decline
- When β-decay competes with proton capture $\Rightarrow$ waiting points





The role of electron capture

- Electron capture to weak-decay rates was traditionally neglected in model calculations of Type I X-ray bursts
- cEC process plays an important role in the weak-decay rates of nuclei close to the proton drip-line in XRB calculations.

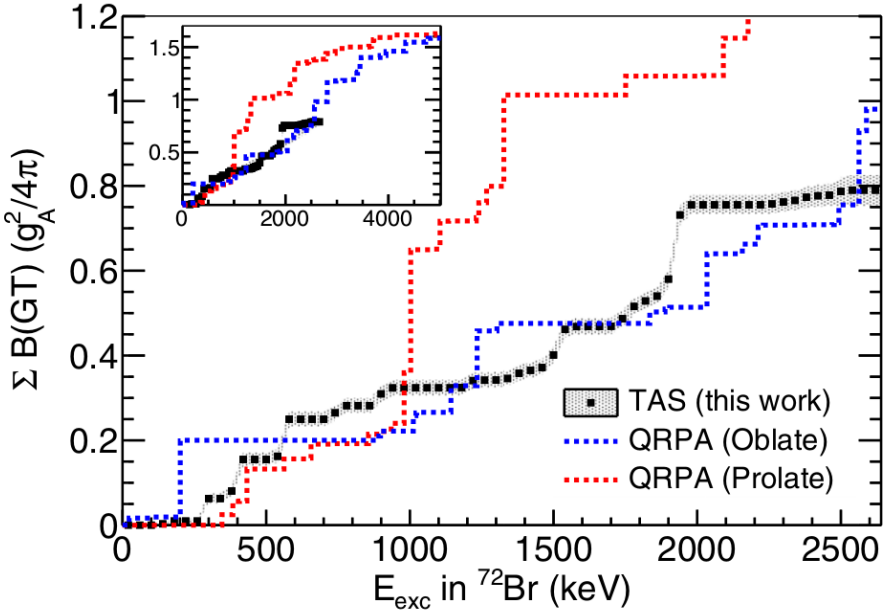


P. Sarriguren, PRC 83 (2011) 025801

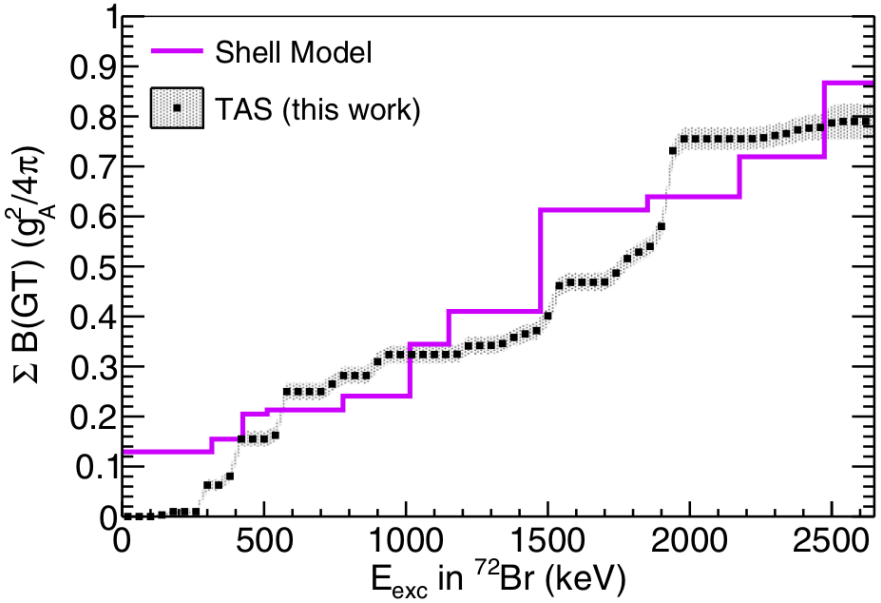
Waiting points and TAGS@ISOLDE: ^{72}Kr, ^{76}Sr

^{76}Sr: E. Nacher et al., PRL 92 (2004) 232501

^{72}Sr: J.A. Briz et al., PRC 92 (2015) 054326:



QRPA

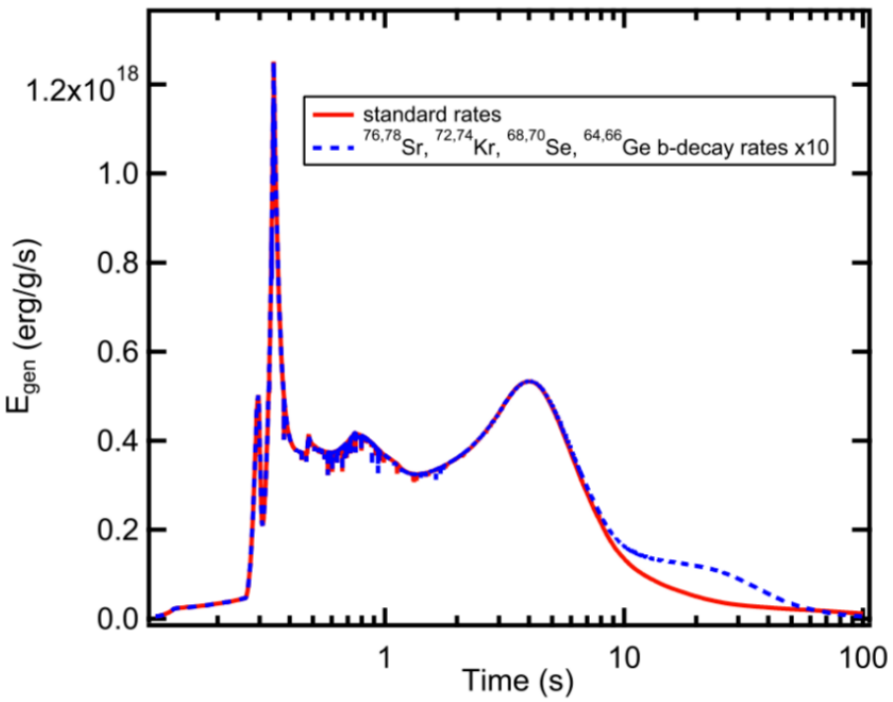


Shell Model

also beyond-mean-field: A. Petrovici a and O. Andrei EPJA (2015) 51: 133

Waiting points and TAGS@ISOLDE: ^{64}Ge and ^{68}Se

- IS570: ^{64,66}Ge in May 2015: analysis ongoing
- ^{68,70}Se foreseen after the long shutdown of CERN



← A. Parikh calculation for the IS570 proposal

^{64}Ge and ^{68}Se: cEC-decay rates higher than the β^+ decay rates: factor 2
For their **N=Z+2 neighbours** factor 100

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- Important decays for the r-process and for the rp-process

Thank you very much for your attention!

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Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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