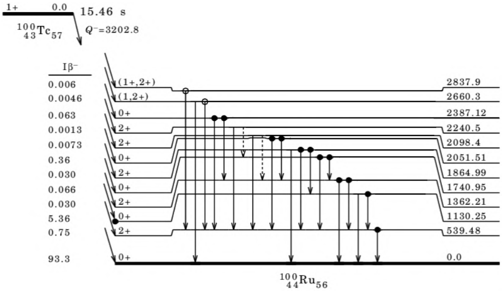
Beta-decay measurements with Total Absorption gamma-ray Spectroscopy at IGISOL

Víctor Guadilla

NARODOWA AGENCJA WYMIANY AKADEMICKIEJ

Zakład Fizyki Jądrowej
Uniwersytet Warszawski

Beta decay studies



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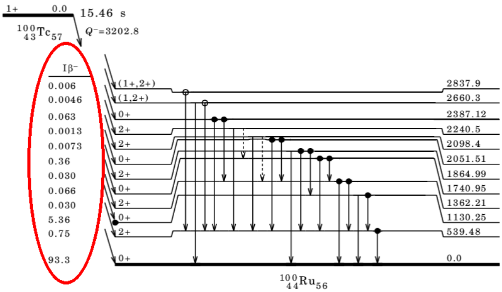

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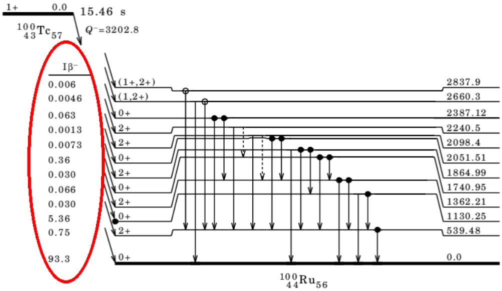


β-strength in the Fermi theory framework

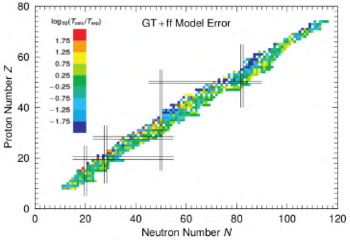
$$S_\beta(E_x) = \sum_{E_f \in \Delta E} \frac{\frac{1}{\Delta E} I_\beta(E_x)}{f(Q_\beta - Ex, Z) T_{1/2}} =$$

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

Validation of theoretical models

Comparison of **integral** quantities (P_n values, $T_{1/2}$)

P. Möller PRC 67 (2003) 055802



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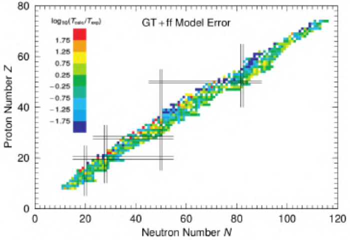
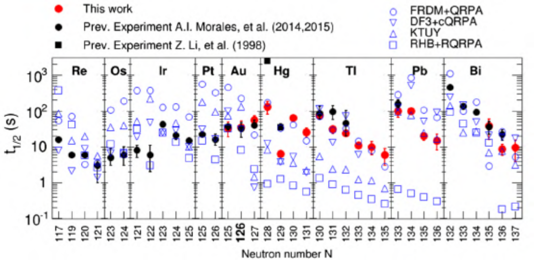


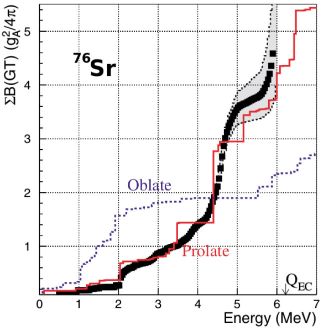


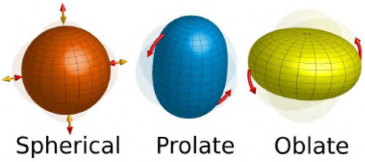
R. Caballero-Folch et al. PRL 117 (2016) 012501

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





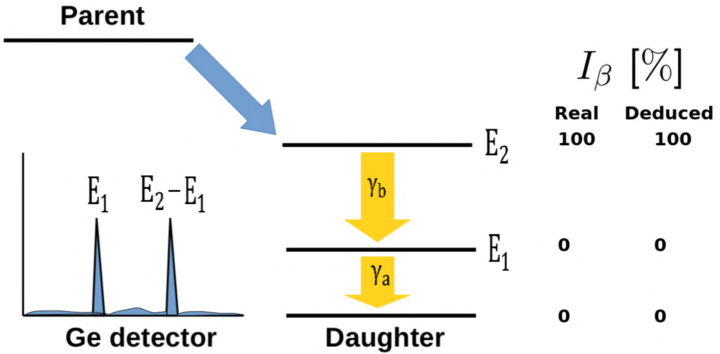
E. Nacher et al., PRL 92 (2004) 232501

QRPA calculations:

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

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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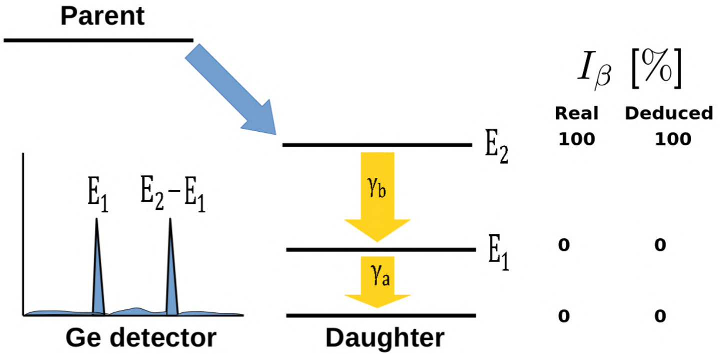

Low efficiency of HPGe detectors → what happens if we miss a γ-ray?

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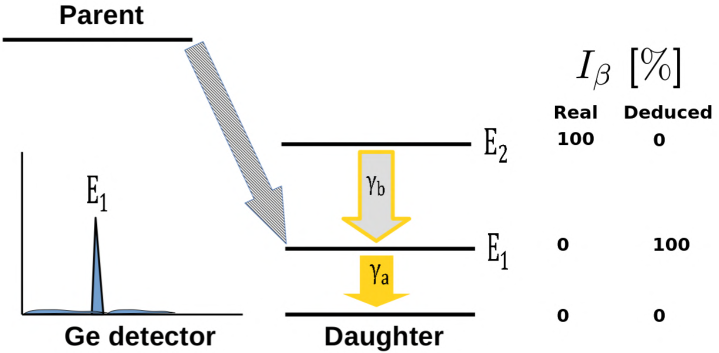
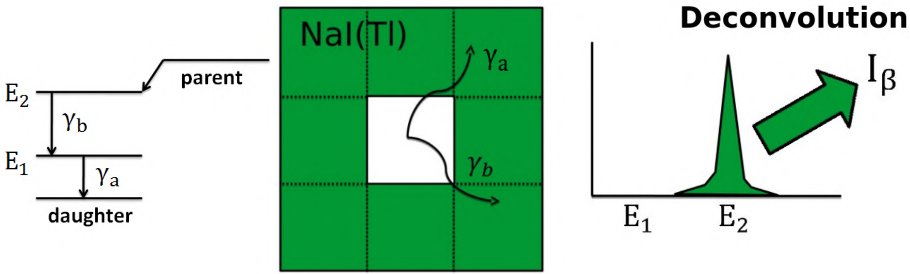


Low efficiency of HPGe detectors → what happens if we miss a γ-ray?

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:

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

- $j \rightarrow$ 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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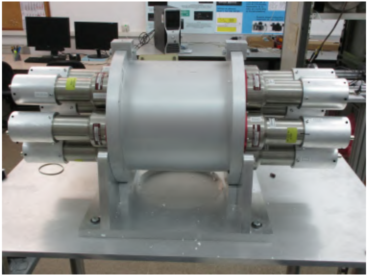
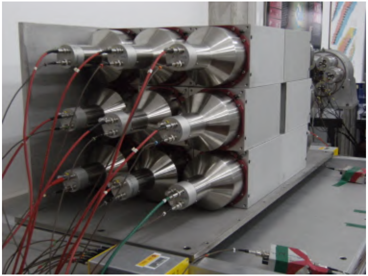
Examples of Total absorption γ-ray spectrometers



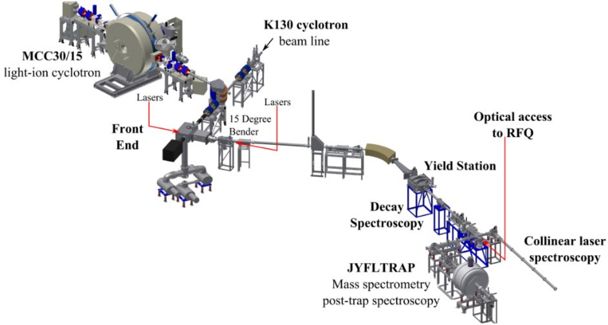
Rocinante



DTAS

- **Rocinante**: cylindrical 12-fold segmented BaF_2 detector (25 cm external diameter and 25 cm length). Used in experiments at IGISOL (Finland).
- **DTAS**: 16-18 NaI(Tl) crystals of 15 cm $\times$ 15 cm $\times$ 25 cm. Used in experiments at IGISOL (Finland). Recently used at RIKEN (Japan).

IGISOL-IV: Jyväskylä (Finland)



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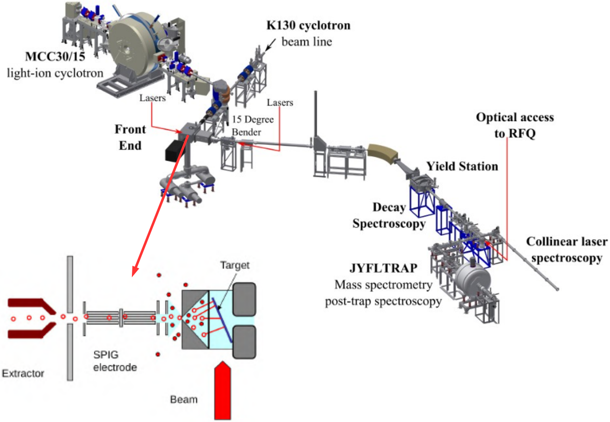

Fission Ion Guide

- Natural uranium target
- Refractory elements

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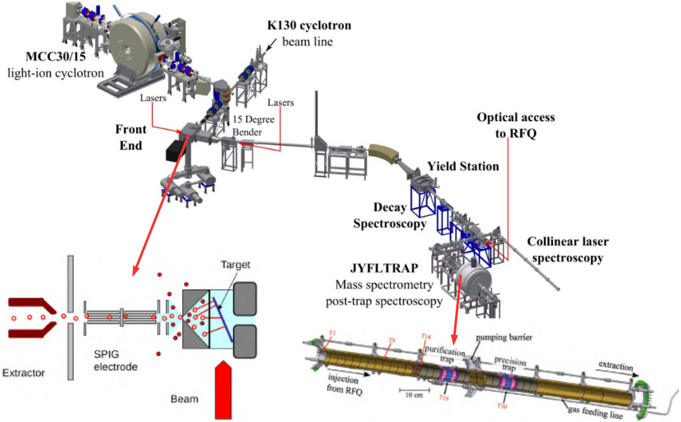


Fission Ion Guide

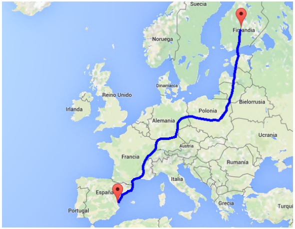
- Natural uranium target
- Refractory elements

JYFLTRAP Penning traps

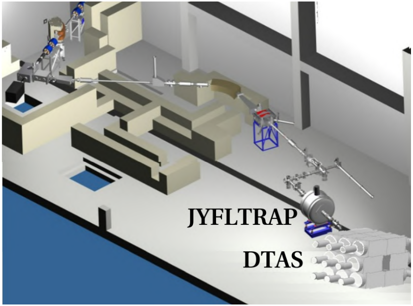
- Inside a 7 T solenoid
- $M/\Delta M \sim 10^{5-6}$

From Spain to Finland

More than 2 tones of equipment were transported from Valencia to Jyväskylä (Finland) in 2014



DTAS@IGISOL: campaign in 2014



- Proton induced fission ion-guide source
- Mass separator magnet
- Double Penning trap system to clean the beams
- Implantation at the centre of DTAS

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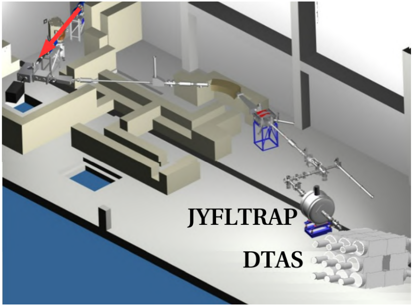

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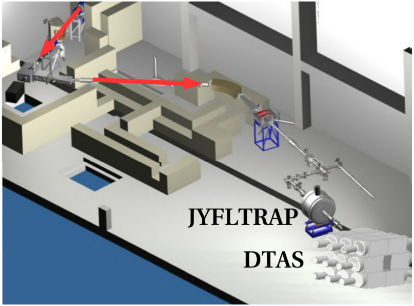

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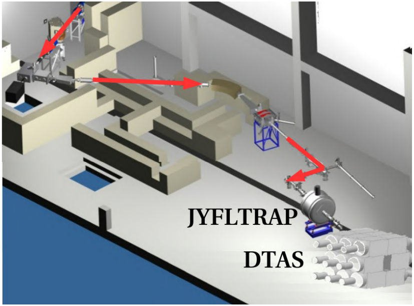

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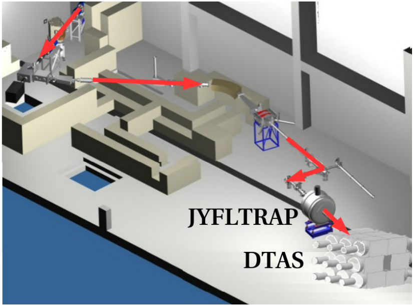

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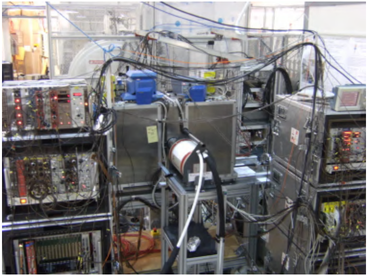
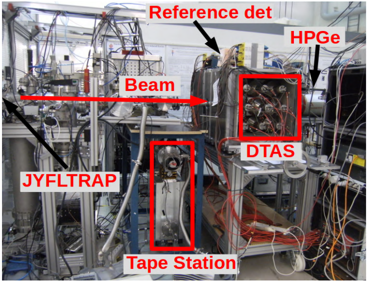
DTAS@IGISOL: set-up



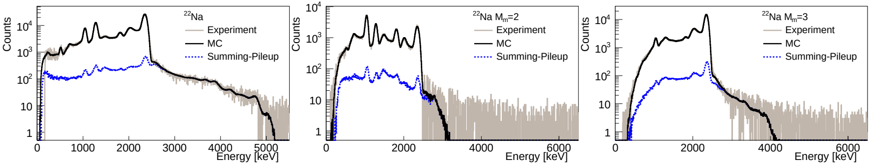


- DTAS: 18 NaI(TI) crystals
- Scintillator plastic β detector
- HPGe detector and Tape station
- MC characterization of the detectors

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

MC characterization: the path to R_{ij}

Segmentation can be useful to study different multiplicities:



M_m: number of modules with energy deposited in the event

V. Guadilla et al., NIMA 910 (2018) 79

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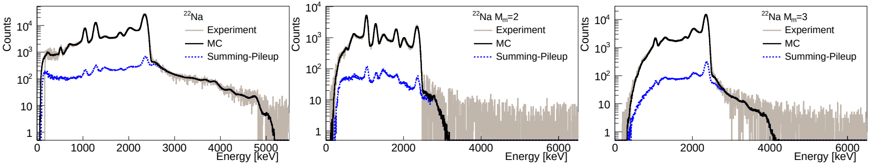

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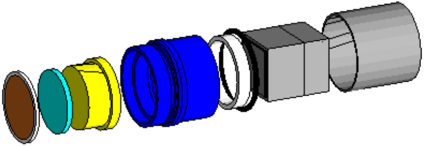

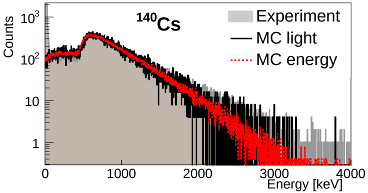

V. Guadilla et al., NIMA 854 (2017) 134

Connection with reactor physics

6 β decays/fission $\rightarrow 10^{21}\ \overline{\nu}_e$/s in a 1 GW reactor

$\overline{\nu}_e$ for fundamental physics and applications

- Neutrino oscillation experiments (Daya Bay, RENO, Double Chooz)
- Discrepancies experiment-calculations in **absolute flux** ("reactor anomaly") and **shape** ("bump")
- Antineutrino monitoring for non proliferation

Decay heat: energy due to the radioactive decay of fission products

- Design and safe operation of a reactor
- Evaluation of shielding requirements
- Safe management of radioactive waste products

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Reactor summation calculation method

Nuclear data approach

- $\overline{\nu}_e$ spectrum calculation:

$$S(E_{\overline{\nu}}) = \sum_i \left(A_i(t) \times \sum_j I_{ij} S_{ij}(E_{\overline{\nu}}) \right)$$

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- Decay heat calculation:

$$f(t) = \sum_i (\overline{E}_{\beta,i} + \overline{E}_{\gamma,i}) \lambda_i N_i(t) \rightarrow \begin{cases} \overline{E}_\gamma = \sum_i I_\beta(E_i) E_i \\ \overline{E}_\beta = \sum_i I_\beta(E_i) < E_{\beta i} > \end{cases}$$

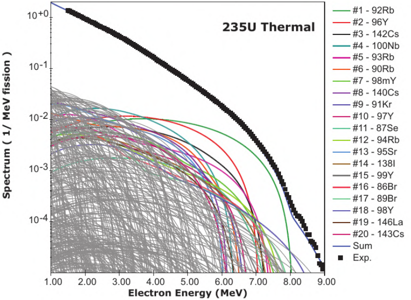
Reactor summation calculation method

- Strongly dependent on databases

  ↪ **non Pandemonium I_β needed: TAGS data!!**

- Evaluation of the main contributors:

	4–5 MeV	5–6 MeV	6–7 MeV	7–8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	...
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	...	...
^{93}Rb	2.34%	4.17%	6.78%	4.21%
^{98m}Y	2.43%	3.16%	4.57%	4.95%
^{135}Te	4.01%	3.58%	...	...
^{104m}Nb	0.72%	1.82%	4.15%	7.76%
^{90}Rb	1.90%	2.59%	1.40%	...
^{95}Sr	2.65%	2.96%	...	...
^{94}Rb	1.32%	2.06%	2.84%	3.96%

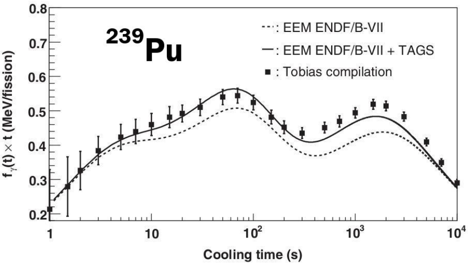


A.-A. Zakari-Issoufou et al., PRL (2015)　　A. A. Sonzogni PRC(R)(2015)

Impact of TAGS data

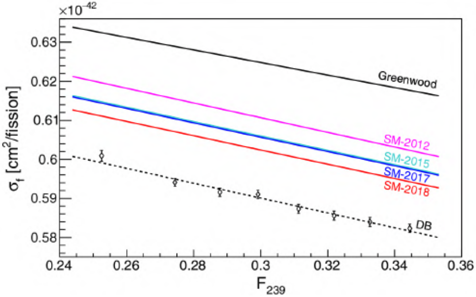
Valencia-Nantes-Surrey collaboration

Decay heat



A. Algora et al., PRL (2010)

Antineutrino



M. Estienne et al., PRL (2019)

Some important contributors with isomers

Parent nucleus	Q_β [keV]	Energy [keV]	Priority U/Pu	Priority Th/U	Priority $\overline{\nu}_e$
^{96gs}Y	7103	0	2	2	1
^{96m}Y		1140	-	1	-
^{98gs}Nb	4591	0	1	1	1
^{98m}Nb		84	-	-	-
^{100gs}Nb	6396	0	1	1	1
^{100m}Nb		313	-	1	-
^{102gs}Nb	7262	0	2	2	1
^{102m}Nb		94	-	1	-

(priorities from IAEA Report INDC(NDS) 0676 (2015))

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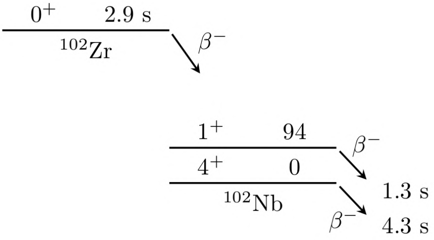
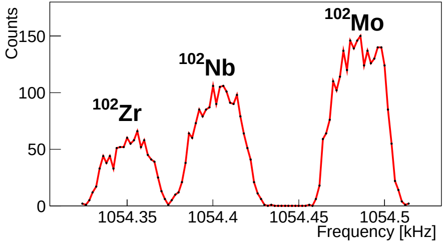
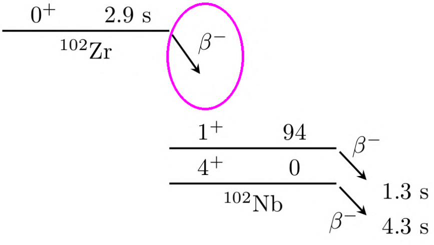
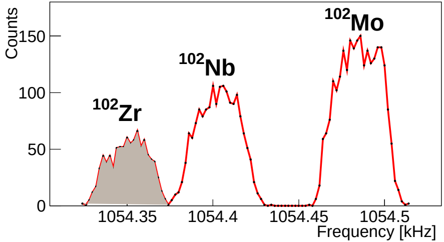
Disentanglement of the decaying states: A=102

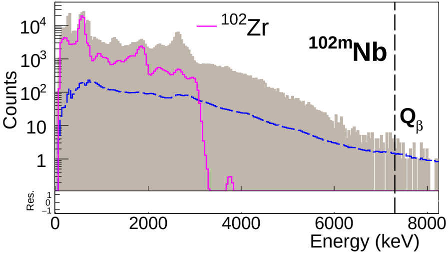




Disentanglement of the decaying states: A=102

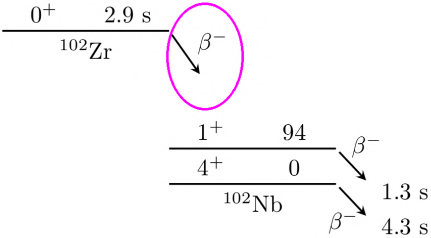


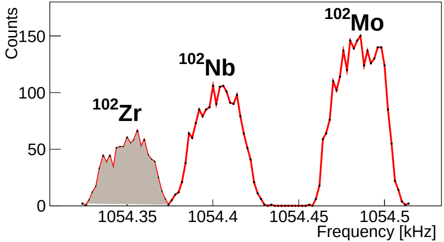


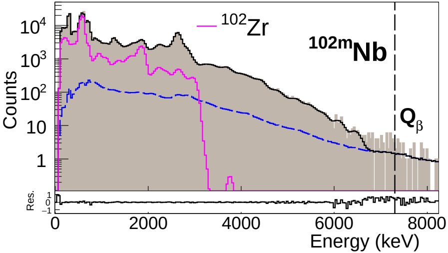


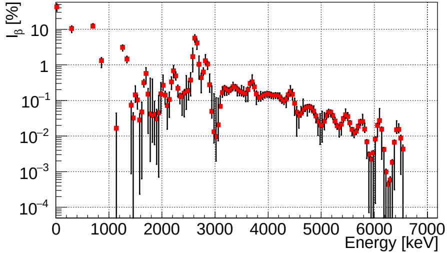
^{102}Zr + ^{102m}Nb

Disentanglement of the decaying states: A=102



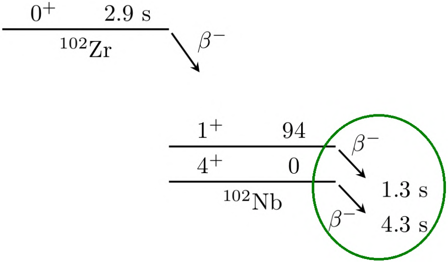


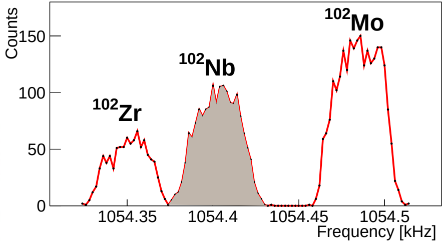


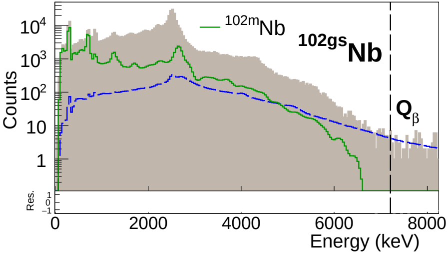


Reconstructed spectrum

Disentanglement of the decaying states: A=102







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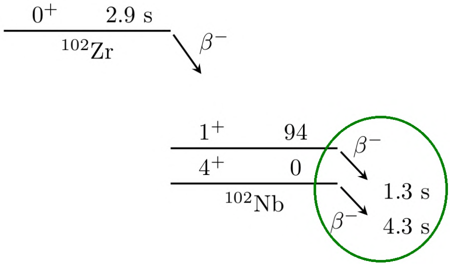
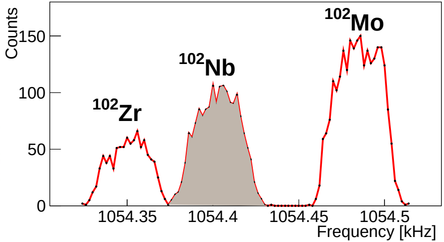
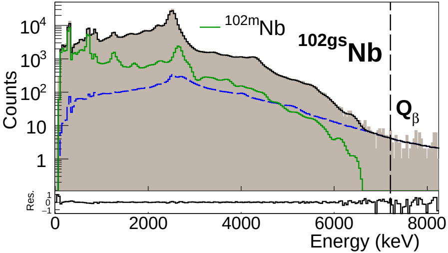
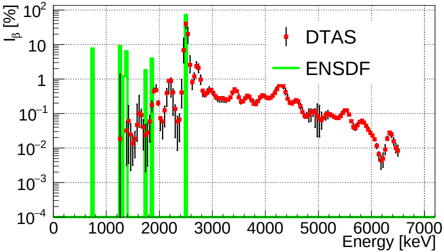
Disentanglement of the decaying states: A=102







Reconstructed spectrum



TAGS results

- Previously undetected beta intensity found in the decays of ^{100gs,100m102gs}Nb
- Beta intensity of ^{102m}Nb determined for the first time

Decay	$\overline{E}_\gamma$ [keV]			$\overline{E}_\beta$ [keV]		
	TAGS	ENDF	JEFF	TAGS	ENDF	JEFF
^{100gs}Nb	959(275)	708(37)	708	2414(133)	2539(213)	2484(209)
^{100m}Nb	2763(27)	2213(69)	2056	1706(13)	1999(198)	2039
^{102gs}Nb	2764(57)	2094(97)	2094	1948(27)	2300(169)	2276(169)
^{102m}Nb	1023(170)	-	-	2829(82)	-	-

Pandemonium: $\overline{E}_\beta$ overestimated while $\overline{E}_\gamma$ underestimated

V. Guadilla et al. PRL 122, 042502, 2019
V. Guadilla et al. PRC 100, 024311, 2019

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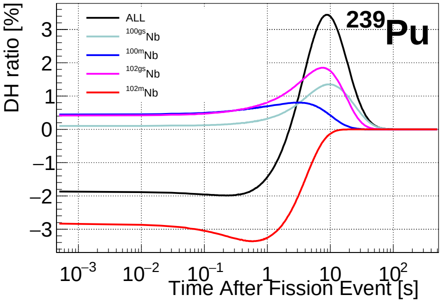
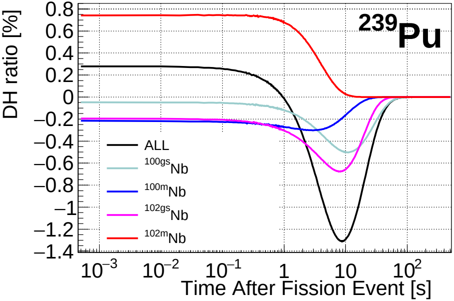
Impact on reactor summation calculations I

Decay heat ratio computed wrt the reference ENDF/B-VII.1 database:

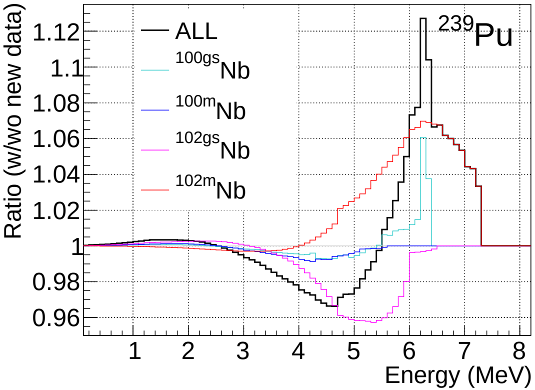


Gamma component



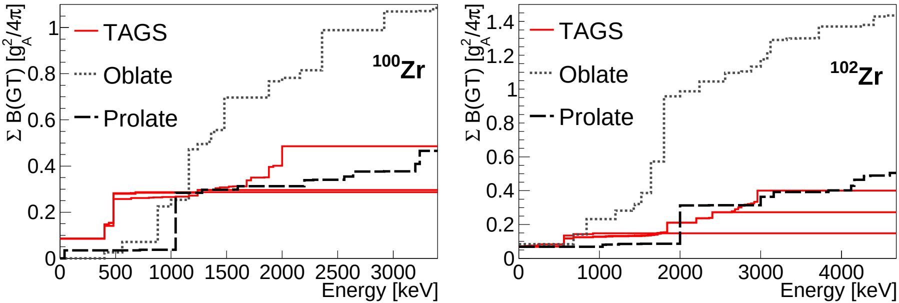
Beta component

Impact on reactor summation calculations II



Significant in the region of the reactor antineutrino shape distortion: for the **first time** the discrepancy between the summation calculations and the measured antineutrino spectra is **reduced**

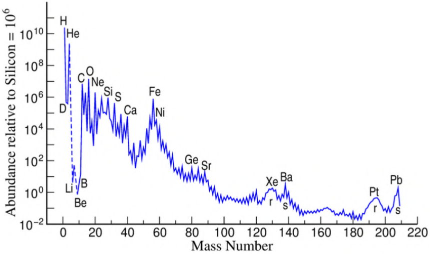
Addendum: shape of Zr isotopes



Comparison with proton-neutron QRPA calculations:

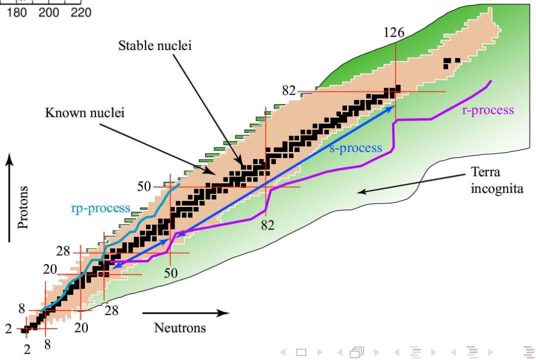
P. Sarriguren and J. Pereira, PRC 81 (2010) 064314
P. Sarriguren, A. Algora, and J. Pereira, PRC 89 (2014) 034311

Reproduction of the experimental abundances

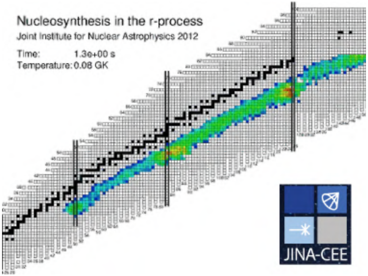


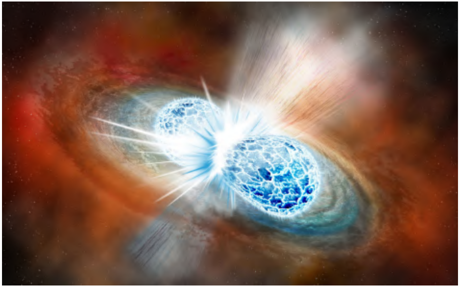
← K. Lodders Ap. J. 591 1220 (2003)

F. X. Timmes (Cococubed project) →



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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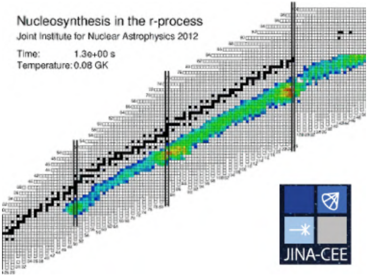

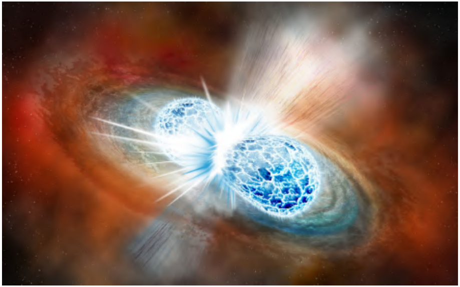

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(n,γ) reactions

1. Hot r-process: β decay-(n,γ) competition during freeze out
2. Cold r-process: equilibrium β decay-(n,γ) not reached

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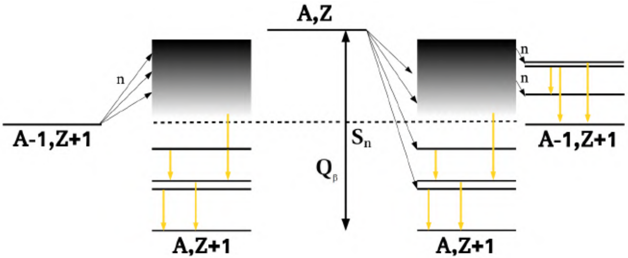
- Constrained with different indirect techniques
  A.C.Larsen et al., Prog. in Particle and Nuclear Physics 107 (2019)

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-rays from states above S$_n$

Some cases studied at IGISOL

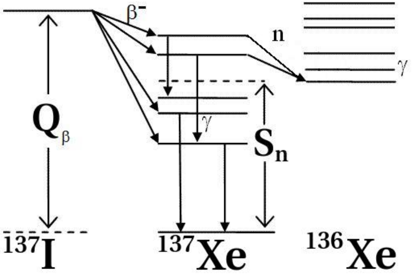
Nuclide	Q_β [keV]	S$_n$ in daughter [keV]	P$_n$ [%]
^{87}Br	6818	5515.17	2.60
^{88}Br	8975	7053	6.58
^{94}Rb	10283	6831	10.5
^{95}Rb	9228	4345	8.7
^{137}I	6027	4025.56	7.14

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., PRC 100 (2019) 044305

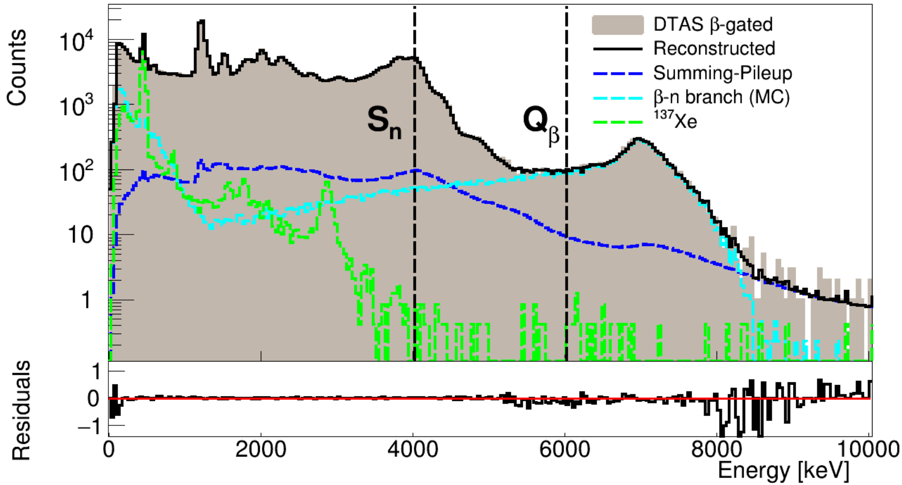
β-delayed neutron emission: ^{137}I

- 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...) → MC



V. Guadilla et al., PRC 100 (2019) 044305

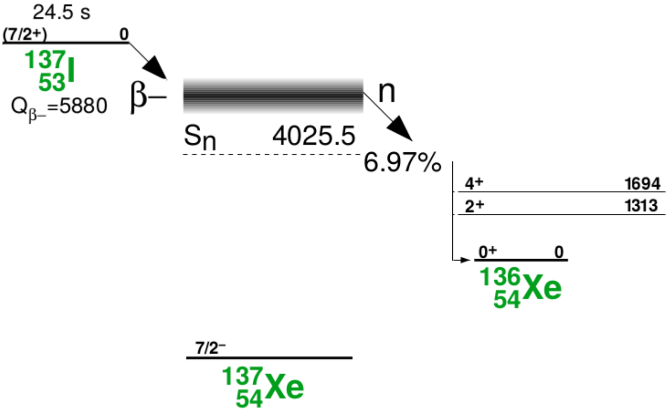
^{137}I: analysis



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

γ emission above S_n

Nucleus	P_γ ENSDF [%]	P_γ DTAS [%]	P_n [%]
^{137}I	2.76	$8.88^{+1.96}_{-1.53}$	7.14(23)



V. Guadilla et al., PRC 100 (2019) 044305

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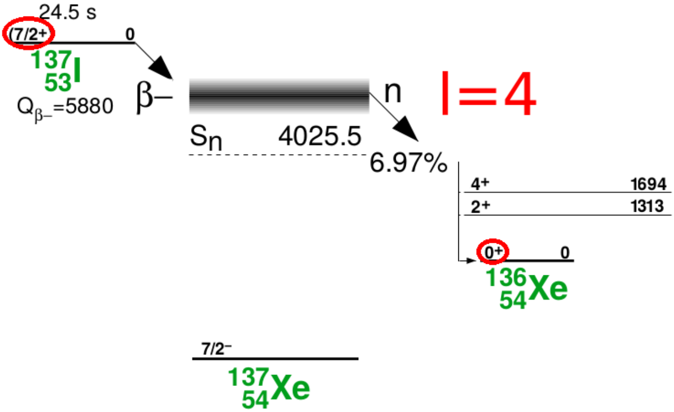

V. Guadilla et al., PRC 100 (2019) 044305

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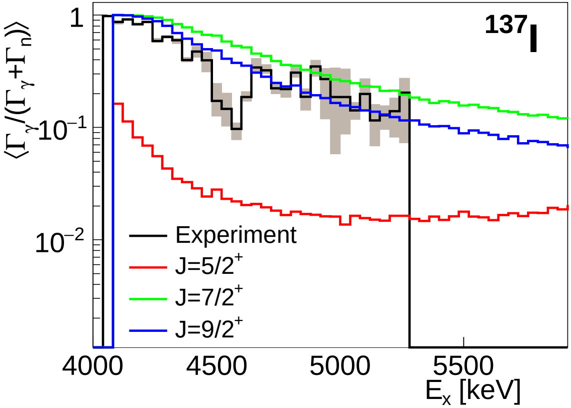
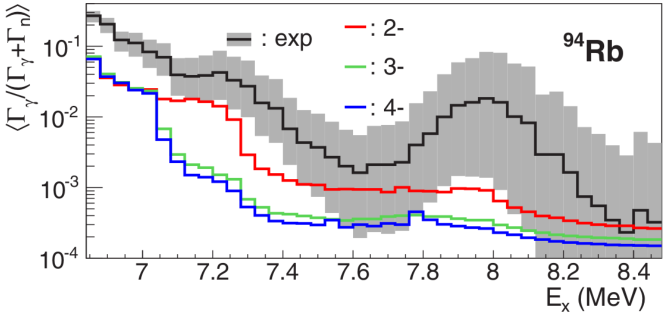


V. Guadilla et al., PRC 100 (2019) 044305

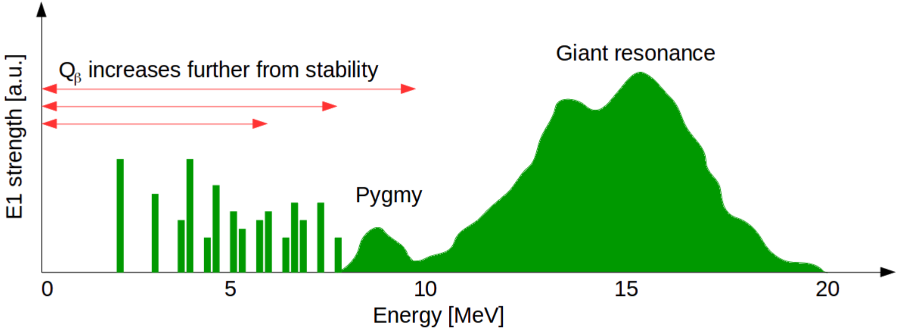
γ emission above S_n

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

Collective modes inside Q_β?

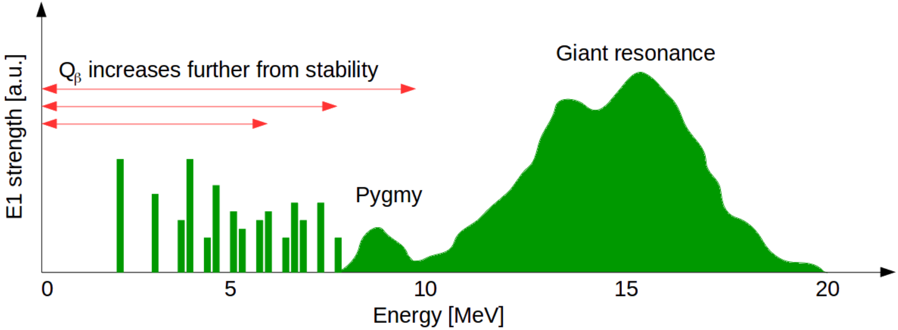


β decay window covering low-lying collective states

Advantages:

- Complementary to: $(p,p^{'})$, $(\gamma,\gamma^{'})$, $(\alpha,\alpha^{'}\gamma)$
- Studies for exotic nuclei not accessible with other techniques
- Background free data

Collective modes inside Q_β?

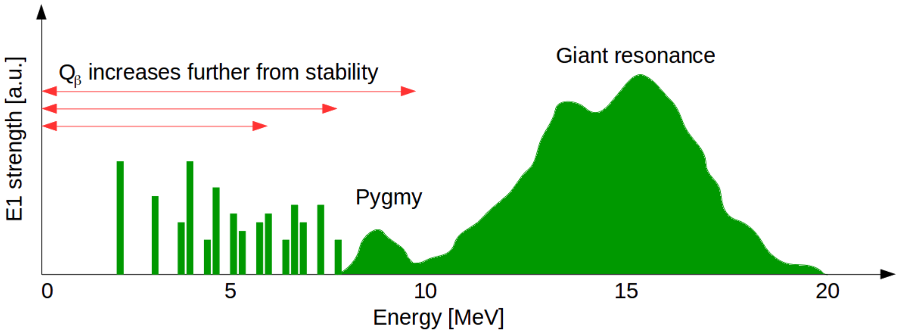


β decay window covering low-lying collective states

Disadvantages:

- Different states are populated
- Theoretical interpretation needed
- Sensitivity to γ-rays de-exciting levels at high excitation energy?

Collective modes inside Q_β?



β decay window covering low-lying collective states

γ-rays de-exciting levels above S_n:

J. L. Tain et al., PRL (2015)
A. Spyrou et al., PRL (2016)
V. Vaquero et al., PRL (2017)
A. Gottardo et al., PLB (2017)
B. C. Rasco et al. PRC (2017)
S. Lyons et al., PRC (2019)
M. Piersa et al., PRC (2019)
V. Guadilla et al., PRC (2019)

Collective modes inside Q_β?

PRL **116,** 132501 (2016) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2016

Investigating the Pygmy Dipole Resonance Using β Decay

M. Scheck,[1,2,*] S. Mishev,[3,4] V. Yu. Ponomarev,[5] R. Chapman,[1,2] L. P. Gaffney,[1,2] E. T. Gregor,[1,2] N. Pietralla,[5] P. Spagnoletti,[1,2] D. Savran,[6] and G. S. Simpson[1,2]

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[6]*ExtreMe Matter Institute EMMI and Research Division, GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany*

(Received 30 October 2015; published 30 March 2016)

In this contribution it is explored whether γ-ray spectroscopy following β decay with high Q values from mother nuclei with low ground-state spin can be exploited as a probe for the pygmy dipole resonance. The suitability of this approach is demonstrated by a comparison between data from photon scattering, ^{136}Xe(γ,γ'), and ^{136}I $[J_0^\pi = (1^-)] \rightarrow {}^{136}$Xe* β-decay data. It is demonstrated that β decay populates 1^- levels associated with the pygmy dipole resonance, but only a fraction of those. The complementary insight into the wave functions probed by β decay is elucidated by calculations within the quasiparticle phonon model. It is demonstrated that β decay dominantly populates complex configurations, which are only weakly excited in inelastic scattering experiments.

Population of 1^- states in β decay associated with Pygmy modes?

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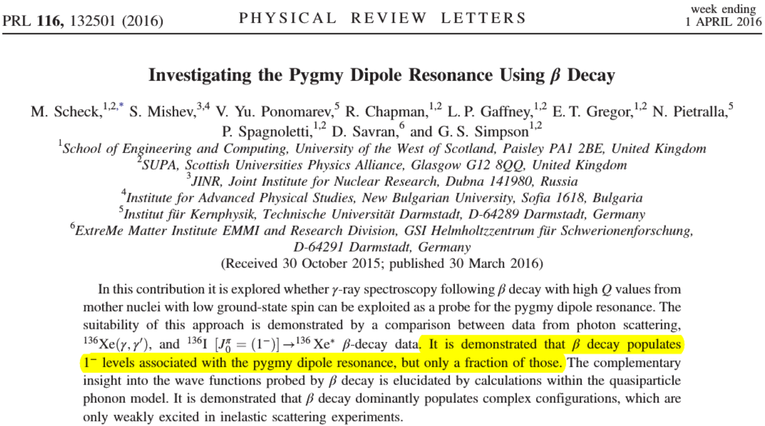
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$$^{96gs}\text{Y}\ (0^-) \rightarrow {}^{96}\text{Zr}\ (1^-)$$

Decay of ^{96gs}Y

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- Possibility to study multiplicities thanks to segmentation
- Statistical model for unknown level scheme (high excitation energies)
- Nice control of MC simulations

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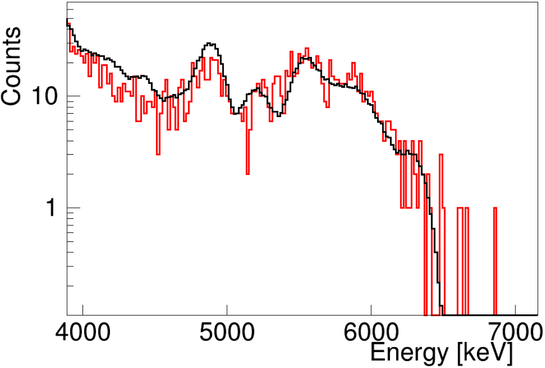

Experiment vs **MC simulation**

- M_m=1 gated TAGS spectrum
- 1^- levels in ^{96}Zr (ENSDF)

V. Guadilla et al. in preparation

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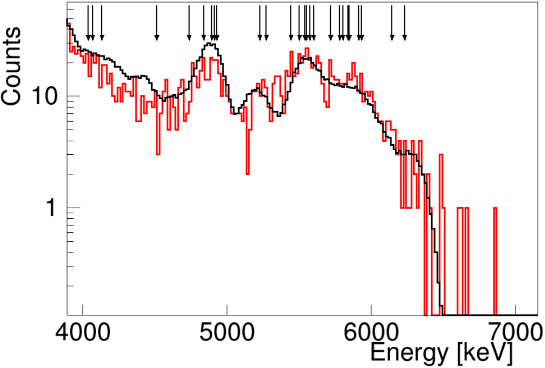

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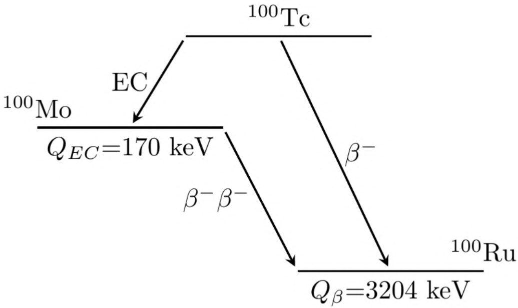
V. Guadilla et al. in preparation

Double β decay: ^{100}Tc

Improvements of the theoretical calculations for the system:



QRPA models may use information of single EC/β decays as constraints

$$\Downarrow$$
$$g_A,\ g_{pp}$$

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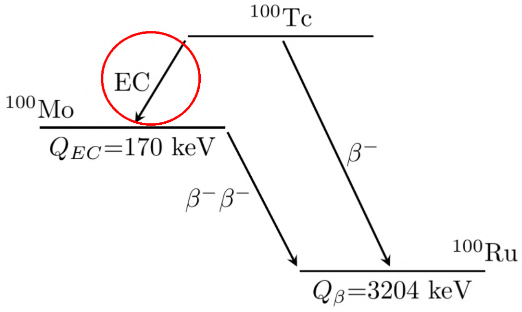

S.K.L. Sjue et al., PRC 78 (2008) 064317

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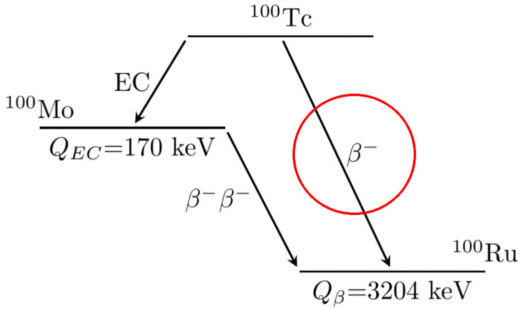

^{100}Mo(p,n)^{100}Tc: V. Guadilla et al., PRC 96 (2017) 014319

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QRPA double β decay calculations

Jouni Suhonen and Osvaldo Civitarese

pnQRPA for ^{100}Tc wave functions
g_{ph} fixed by systematics, g_{pp}=0.7 and g_A=0.4

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from P. Pirinen and J. Suhonen, PRC 91, 054309 (2015)

Conflict with g_A

- $T_{1/2}^{(2\nu)}$=(7.1±0.4)×10^{18} yr → experiment
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- $T_{1/2}^{(2\nu)} \sim 3\times$ experiment → $g_A = 0.4$

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↪ Best reproduction of TAGS results!!

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- **Sensitivit**y to I_β followed by γ de-excitation above S_n
- **Future** TAGS experiments at IGISOL:

I241: 10 days beam time
I248: 10 days beam time

DTAS first experiments collaborators

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Thank you very much for your attention!

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