Nuclear Physics Experiments for NSM: abundance pattern

- Neutron capture cross-section $\sigma_{(n,\gamma)}$
- β-decay half-lives $T_{1/2}$
- Neutron emission probabilities P_{xn}

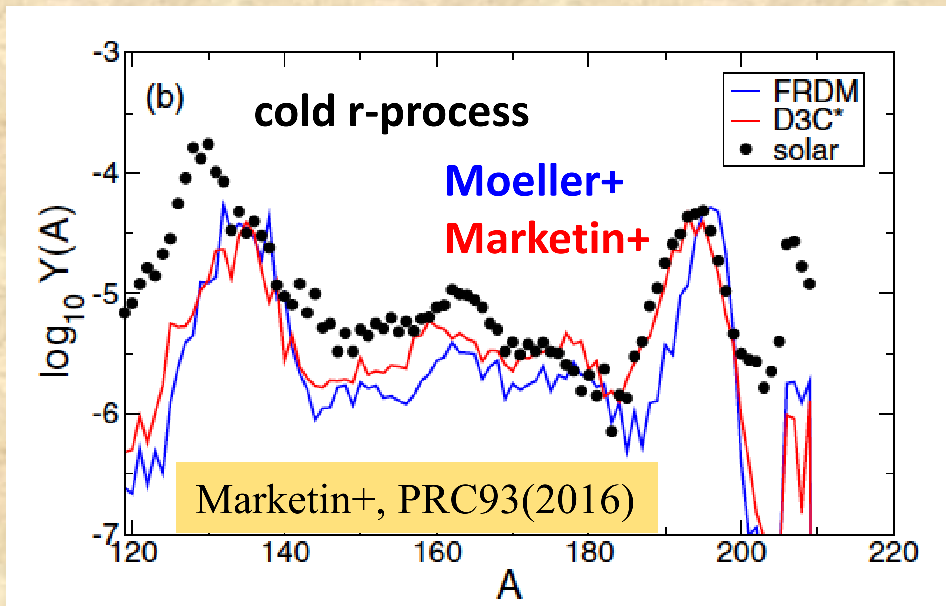
- Total absorption γ-ray spectroscopy: indirect information
- β-delayed neutron measurements: direct information

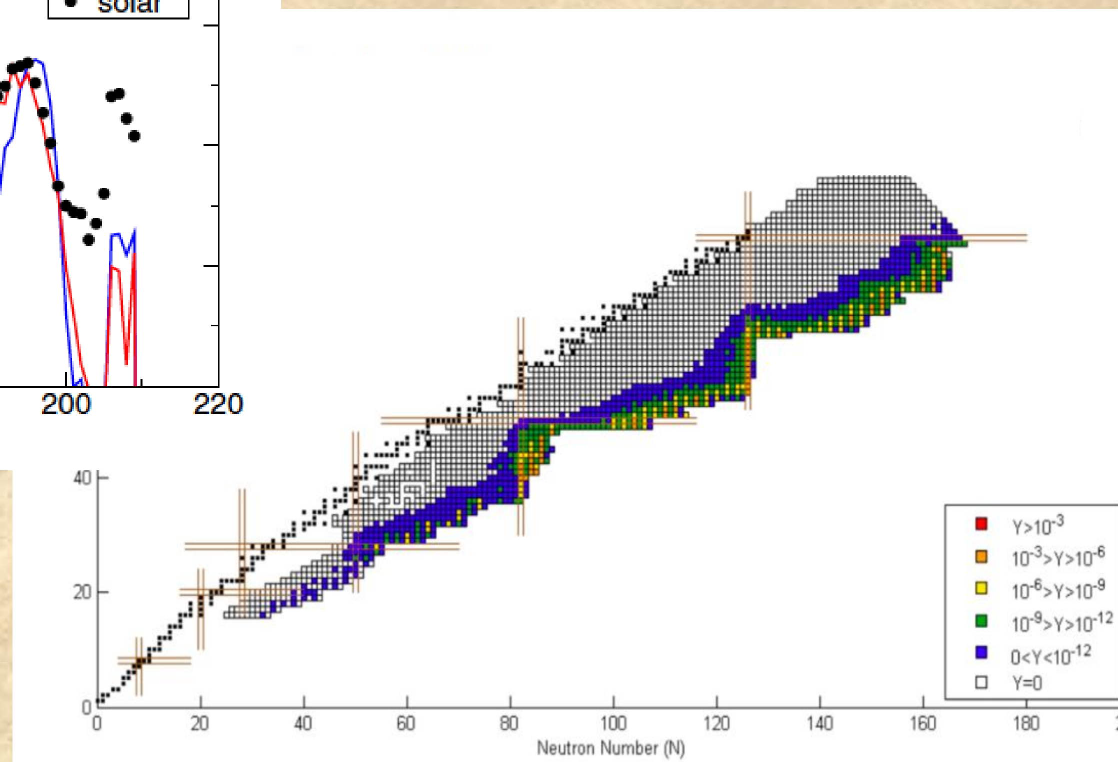
Abundance pattern: result of the interplay between **(n,γ)**, (γ,n), **β-decay** and fission

Difficulty of accessing the nuclei involved:

- to observe their decay
- to use as target for reactions

➔ Need of (uncertain) theoretical estimates





Neutron capture cross sections determination

Theoretical estimates:

- Hauser-Feshbach calculations of CN channel
- Contribution of direct channel is significant (Goriely, 1998)

Measurements:

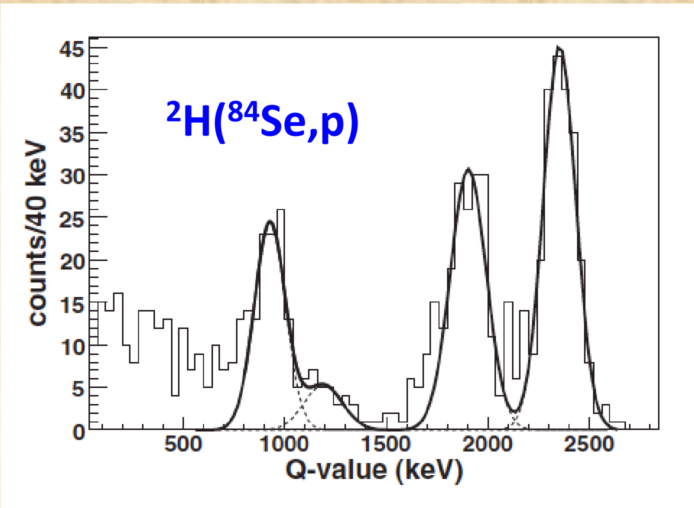
- Direct A(n,γ)B measurement (neutron ToF facilities): limited to stable or long lived isotopes
- Surrogate reactions (see Escher+,2012, for a review):
  - use of a reaction C(a,bγ)B that populates states “similar” to those in the capture reaction
  - needs correction for differences in (J,π) population
  - need radioactive beams in inverse kinematic to reach neutron-rich nuclei: can test the direct (Thomas+,2007) and CN components (Cizewski,2015, proposal)

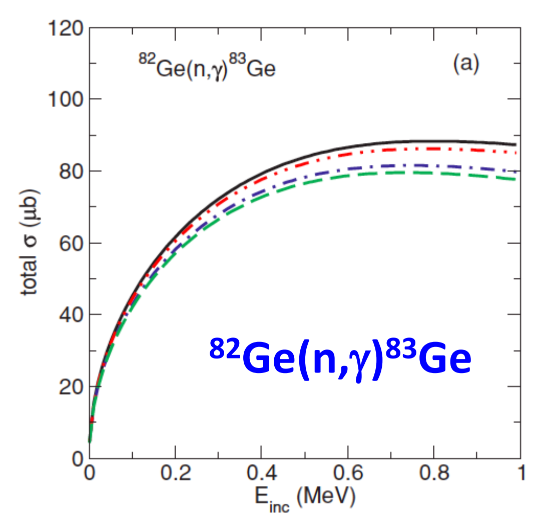
Thomas+,2007

Experiment at ORNL

$^{2}H(^{82}\mathbf{Ge},p)$, $^{2}H(^{84}Se,p)$:

CD_2 target, p detected, spectroscopic factors extracted



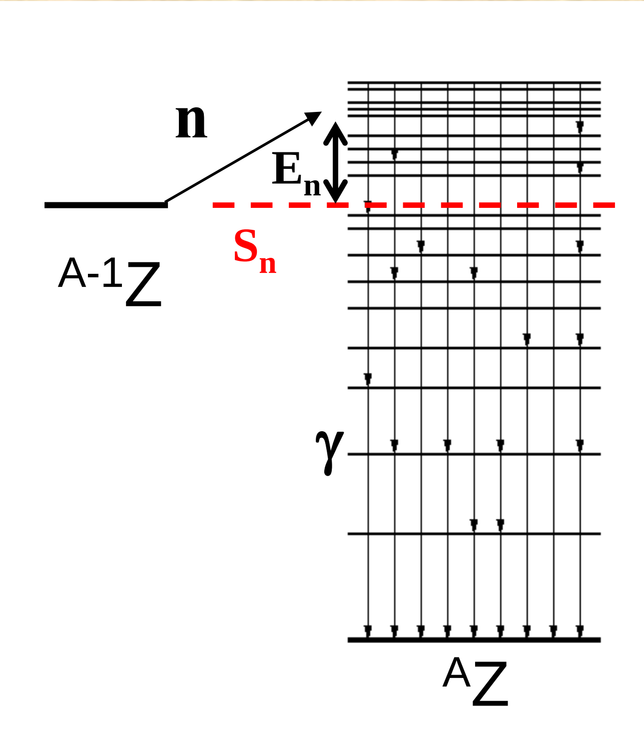


+6n

- More recently: use of β-decay as a “surrogate” reaction that provides information to improve theoretical estimates
  - γ/n competition in β-delayed neutron emitters
  - The β-Oslo method
- Future: Use a neutron target (reactor core, neutron guide) and recirculating radioactive beam (Reifarth-Litvinov,2014)

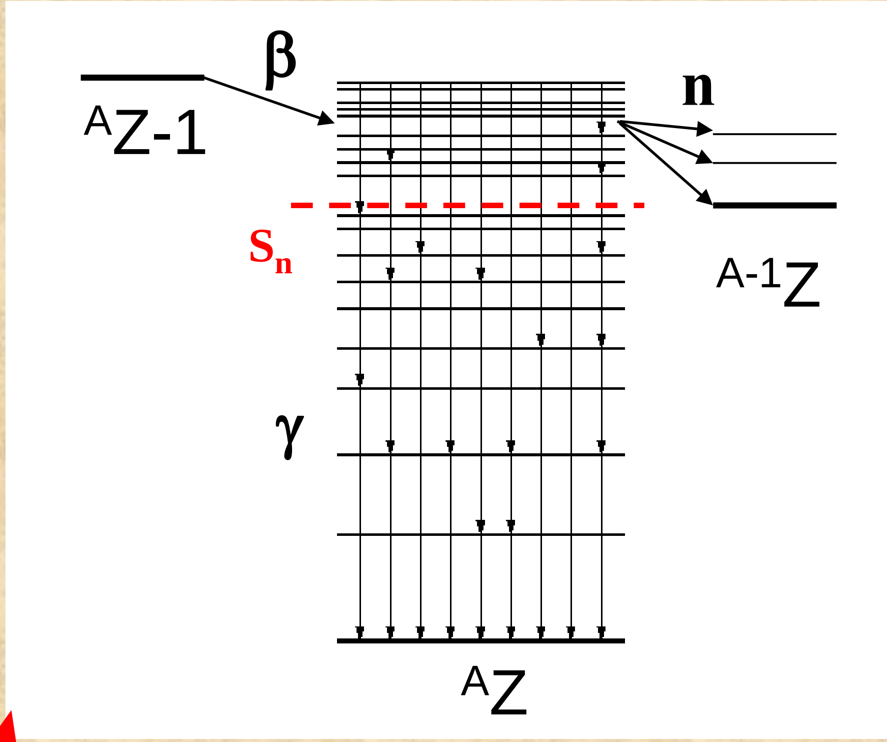
Analogy between (n,γ) and βn

Radiative neutron capture:



$$\sigma_\gamma(E_n) = \frac{4\pi}{k^2} g_J \frac{\Gamma_\gamma \Gamma_n}{\Gamma_\gamma + \Gamma_n} F(E_n)$$

Beta delayed neutron emission:



$$I_{\beta\gamma}(E_x) = \frac{\Gamma_\gamma}{\Gamma_\gamma + \Gamma_n} T_{1/2} f(Q_\beta - E_x) S_\beta(E_x)$$

- But, it is difficult observe the γ-emission from states above S_n populated in β-decay: intensity fragmented over many cascades
- Only few γ-rays in a handful of isotopes have been observed in HPGe spectroscopy ➔ TAGS tecnique

Ingredients of Hauser-Feshbach statistical model calculations

PSF

$$\Gamma^{\gamma}_{J\pi\to J^d\pi^d} = \frac{1}{\rho(J,\pi,E_x)} \sum_{XL} \int_{E}^{E+\Delta E} E_\gamma^{2L+1} f_{XL}(E_\gamma)\, \rho(J^d,\pi^d,E_x - E_\gamma)\, dE_\gamma$$

NLD

$$\Gamma^{n}_{J\pi\to J^f\pi^f} = \frac{1}{2\pi\rho(J,\pi,E_x)} \sum_{l} \sum_{s=-1/2}^{+1/2} T^n_{J\pi\to J^f\pi^f}\left(E_x - S_n - E_x^f\right)$$

NTC

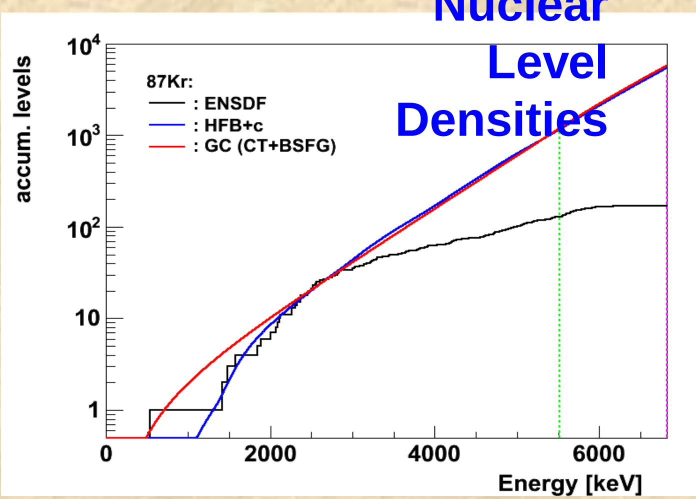
EM transitions:

$XL = E1, M1 \text{ or } E2$

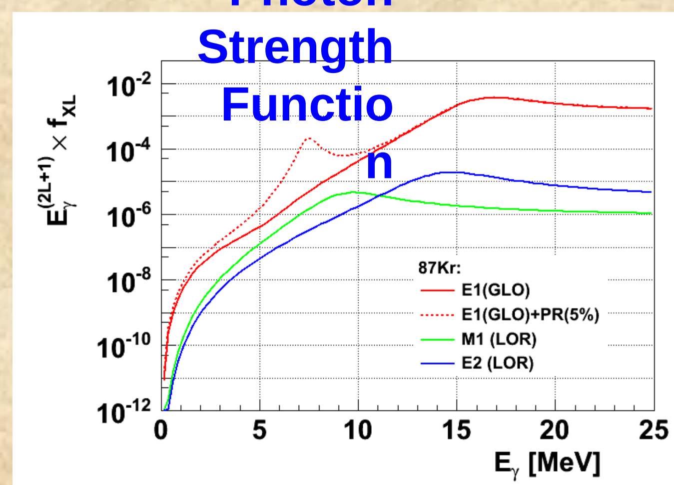
Neutron emission:

$\vec{J}^f = \vec{J} + \vec{l} + \vec{s}; \quad \pi^f = (-1)^l \pi$

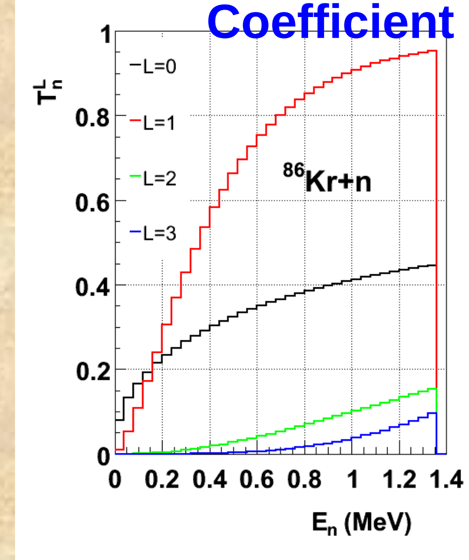
Nuclear Level Densities



Photon Strength Function



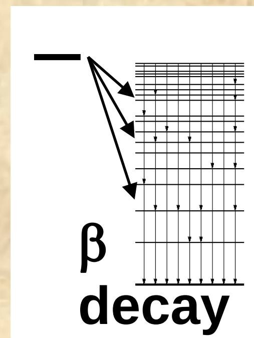
Neutron Transmission Coefficient



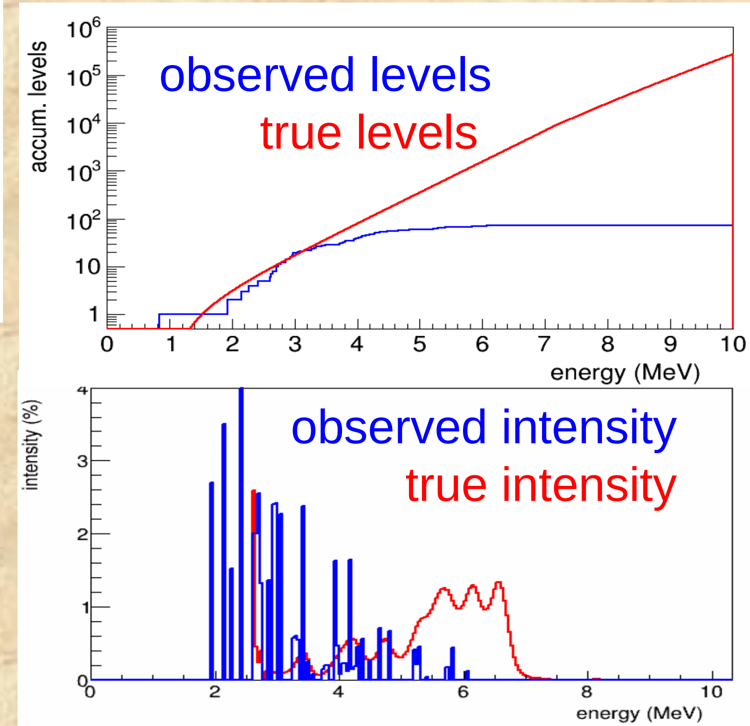
Goal: obtain information on PSF (and NLD)

Total Absorption Gamma-ray Spectroscopy Technique

Goal:
- Counting β-decays to a level from the γ-rays emitted

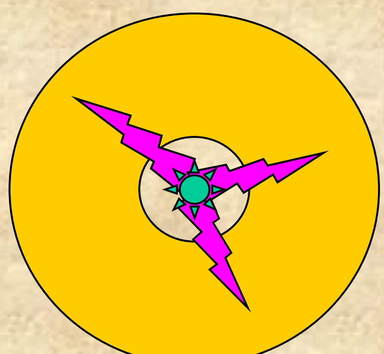


Problem:
- The limited efficiency of HPGe detectors together with the complex de-excitation path: ***Pandemonium effect***

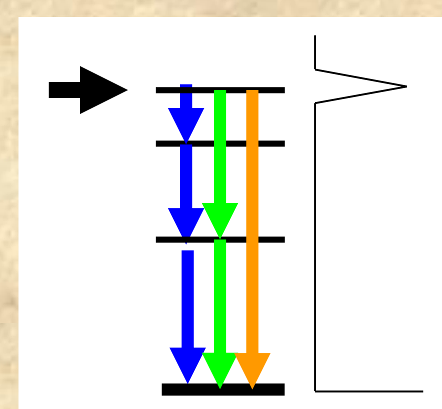


Solution:
- Measure the full γ-ray cascade with a calorimeter

Duke+,NPA151,1970



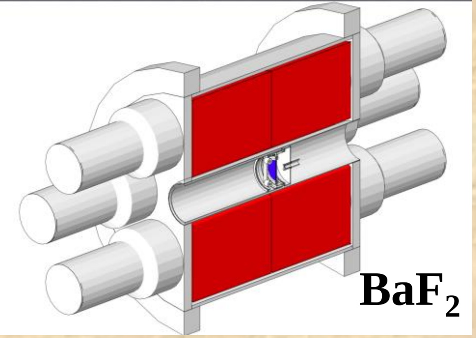
IDEAL TAS

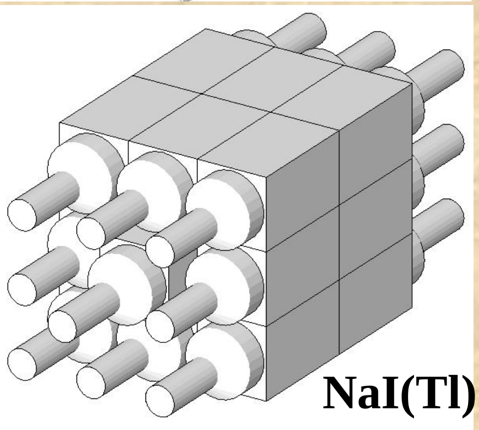


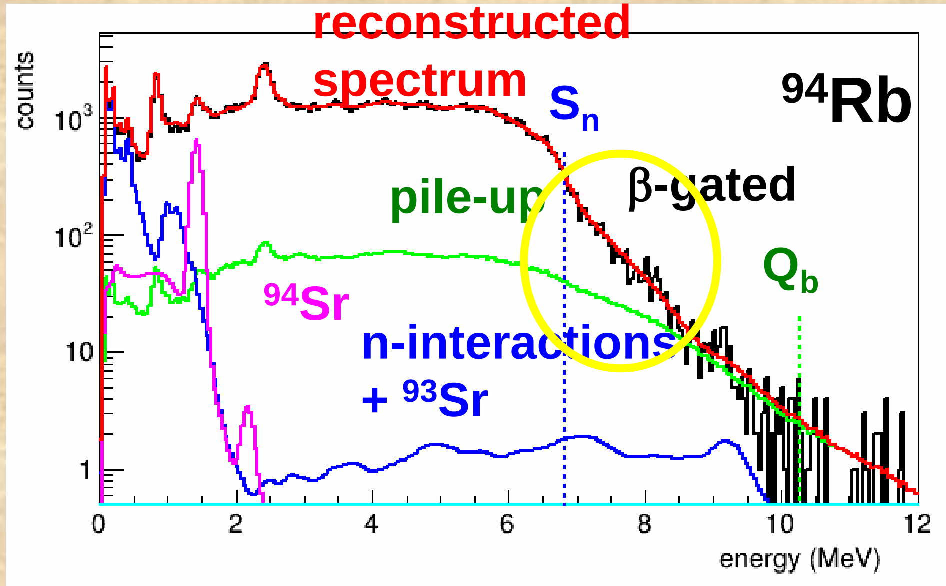
REAL TAS

Deconvolute the spectrum with a cascade dependent detector response (MC) constrained to reproduce several observables

Tain-Cano, 2007



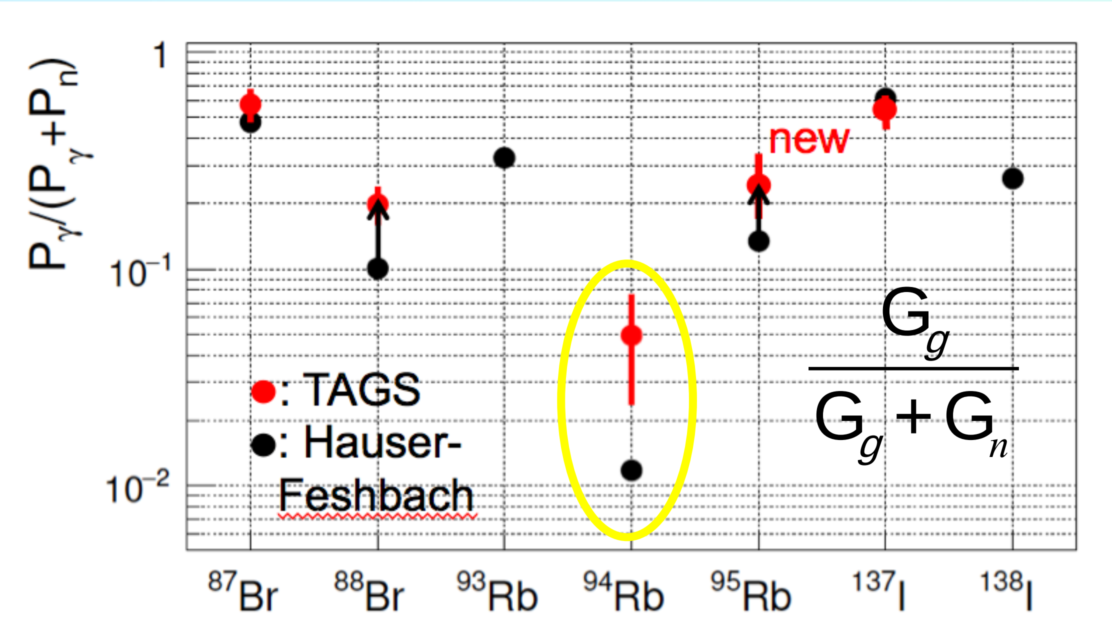




Experiments at IGISOL-JYFL

Tain+, 2015
Guadilla+, 2016
Valencia+, 2017

- In most of the cases $\Gamma\gamma/\Gamma n$ is quite large, due to neutron emission hindrance because of L mismatch



- For ^{94}**Rb**, although small it is much larger than HF estimate
- If due to $\Gamma\gamma$ it will imply a large increase (~20) of $\sigma_{(n,\gamma)}$

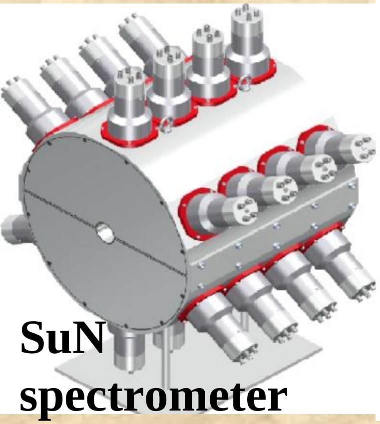
+6n

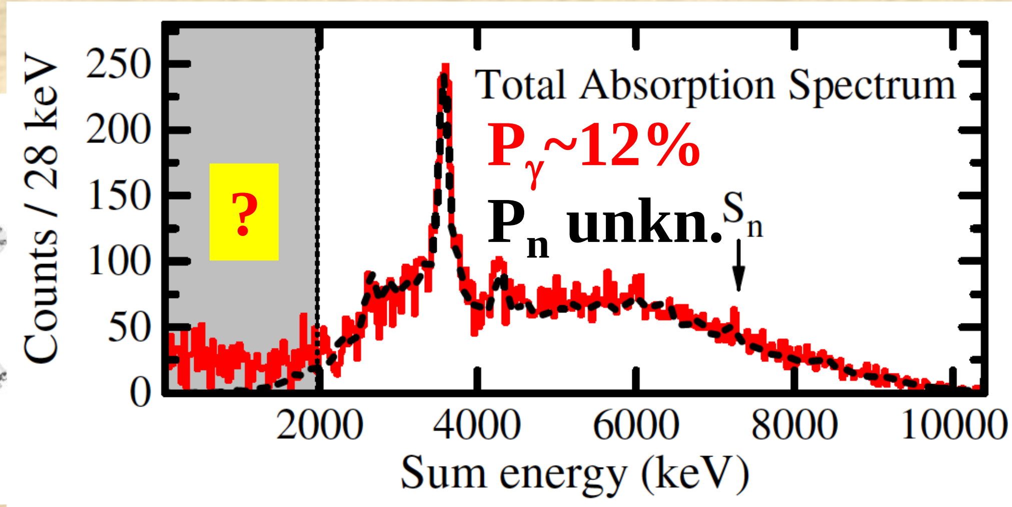
A. Spyrou+, 2016

^{70}Co (~100ms, 6,7^{-})

+6n

Experiment at NSCL





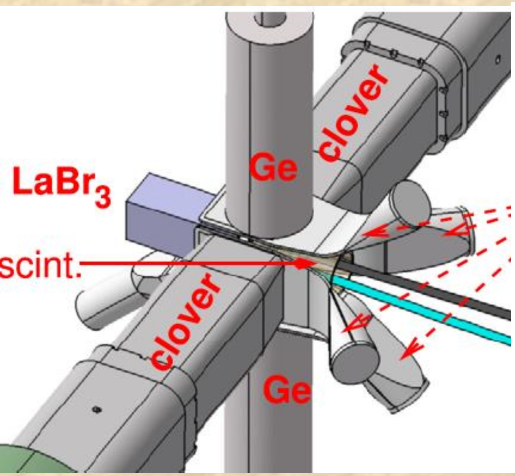
Large P_γ: hindrance of neutron emission due to small spectroscopic factor |<70Ni|69Ni+n>|^2

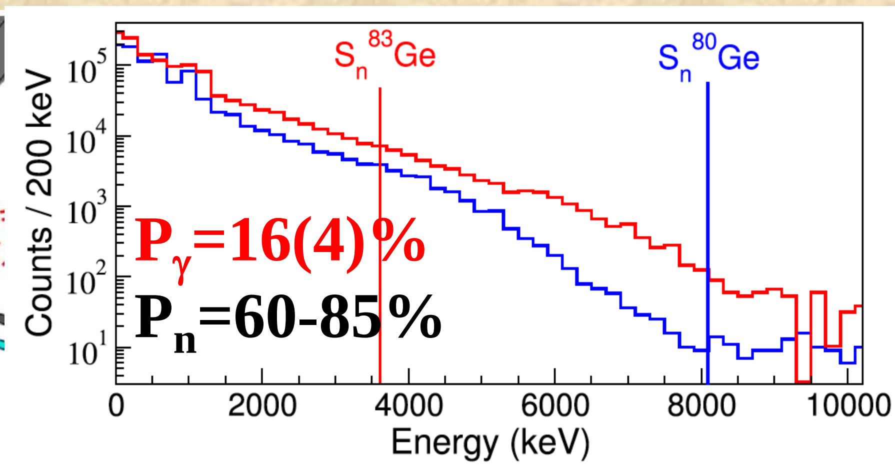
A. Gottardo+, 2017

^{83}Ga, 5/2^{-}

+12n

Experiment at IPNO





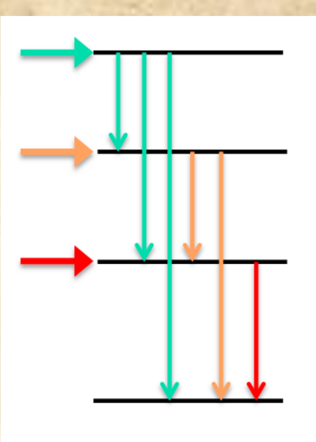
Large P_γ: enhancement of γ-emission due to Pigmy E1 resonance (PDR)

More experiments should be performed to asses this approach

The β-Oslo method

Spyrou+,2014

- The Oslo method (goal: obtain information on PSF and NLD):
  1) Measure single γ ray spectra in two-body or capture reactions varying E_x
  2) Determine γ-branchings as a function of E_x



Deconvolute γ spectra

$$S(E_x) = \sum_{E_\gamma} \beta(E_x, E_x - E_\gamma)\,\gamma(E_\gamma) \otimes S(E_x - E_\gamma)$$

  1) Extract NLD and PSF from the γ-branchings

$$\beta(E_x, E_x - E_\gamma) = \frac{T(E_\gamma)\,\rho(E_x - E_\gamma)}{\sum_{E_\gamma} T(E_\gamma)\,\rho(E_x - E_\gamma)}$$

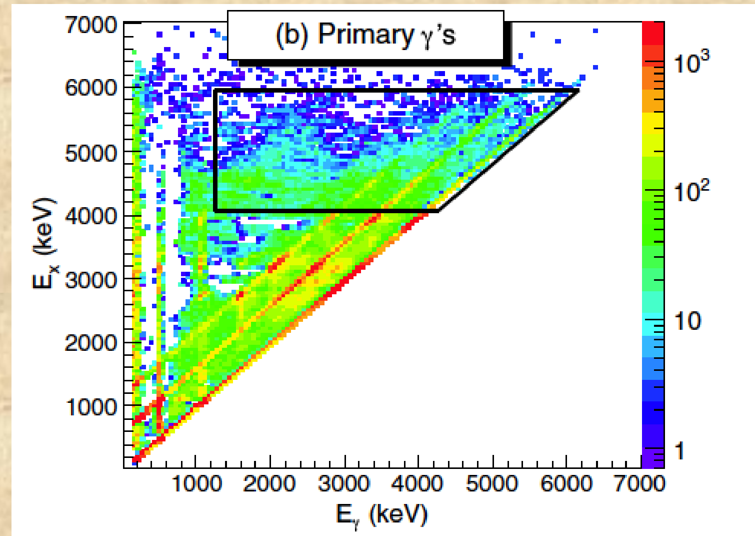
Solve a non-linear inverse problem

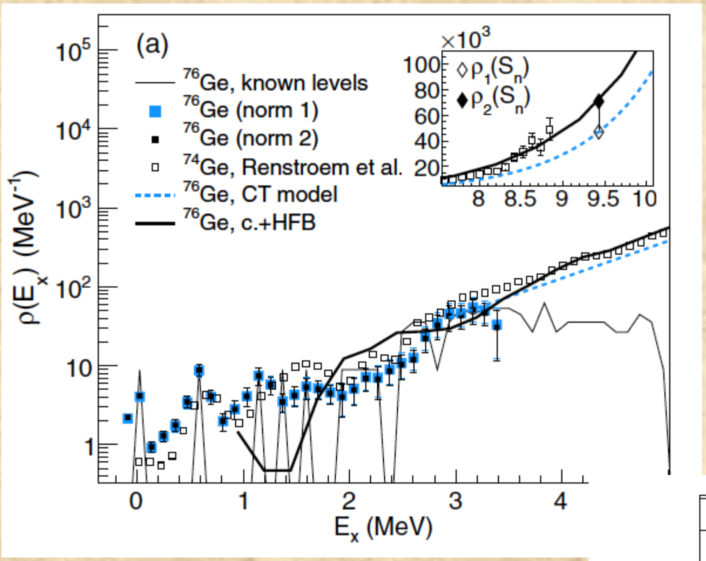
$$T_{XL}(E_\gamma) = 2\pi E_\gamma^{2L+1} f_{XL}(E_\gamma)$$

  1) The result is the shape of NLD and PSF (strongly correlated) not the absolute values. Need external normalization, typically from n capture reactions.

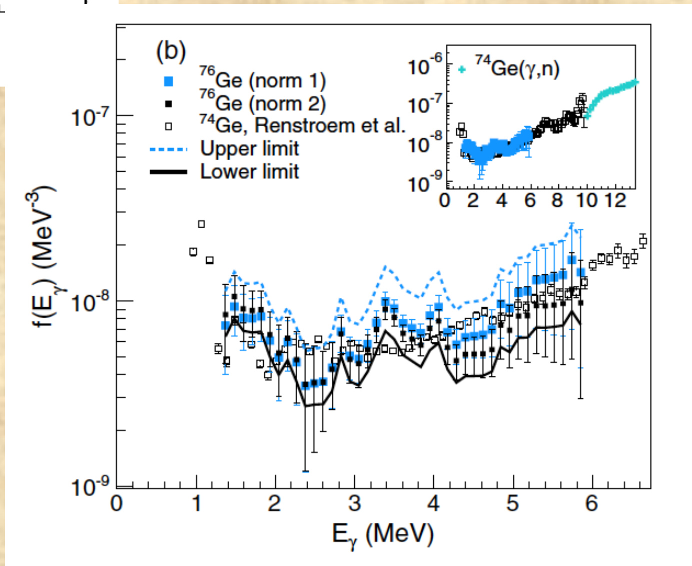
The β-Oslo method:

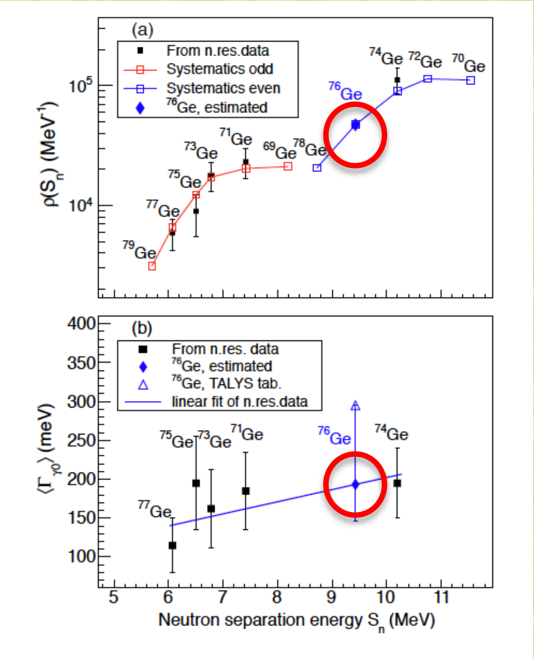
- Use of segmented TAS
- Equate E_x with total energy deposited E_{TAS} (approximation)
- Use systematics for normalization





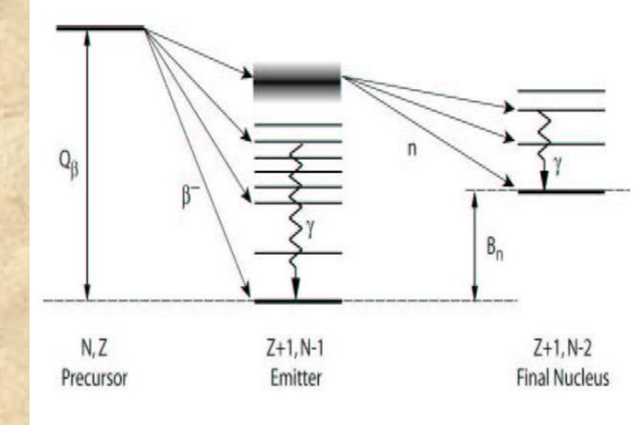
^{76}Ga(β)^{76}Ge





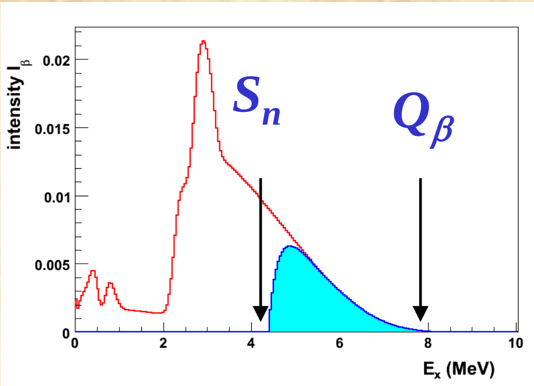
Experiment at NSCL

- For nuclei that are out of current experimental reach, **$T_{1/2}$ and P_n** for r-process network calculations are taken from **β-strength calculations**



$$\frac{1}{T_{1/2}} = \int_0^{Q_\beta} f\left(Q_\beta - E_x\right) S_\beta\left(E_x\right) dE_x$$

$$P_n = T_{1/2} \int_{S_n}^{Q_\beta} \frac{\Gamma^n}{\Gamma^n + \Gamma^g} f\left(Q_\beta - E_x\right) S_\beta\left(E_x\right) dE_x$$



β-strength (theory):

$$S_\beta^{th}\left(E_x\right) = \frac{1}{D}\frac{g_A^2}{g_V^2} B_{i\to f}$$

$$B_{i\to f} = \frac{1}{2J_i + 1}\left|\left\langle f \left\| M_{lp}^{\beta} \right\| i \right\rangle\right|^2$$

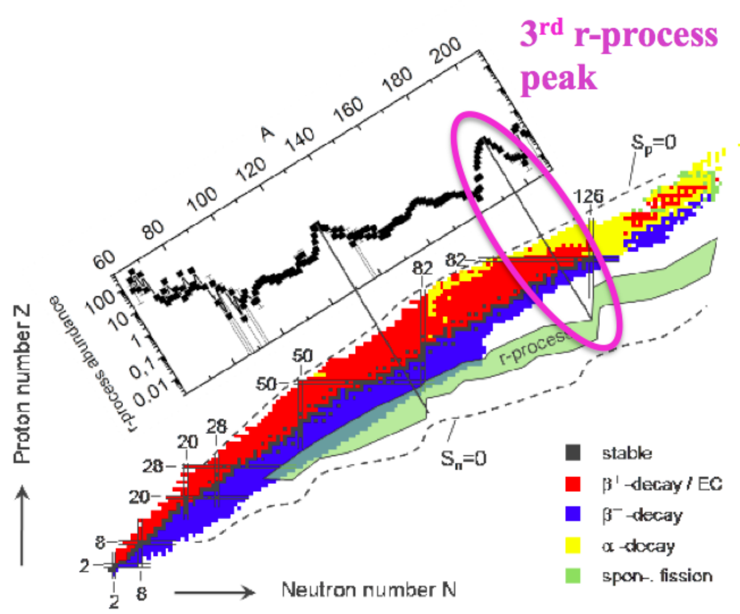
A TAS is a machine to measure β-strengths

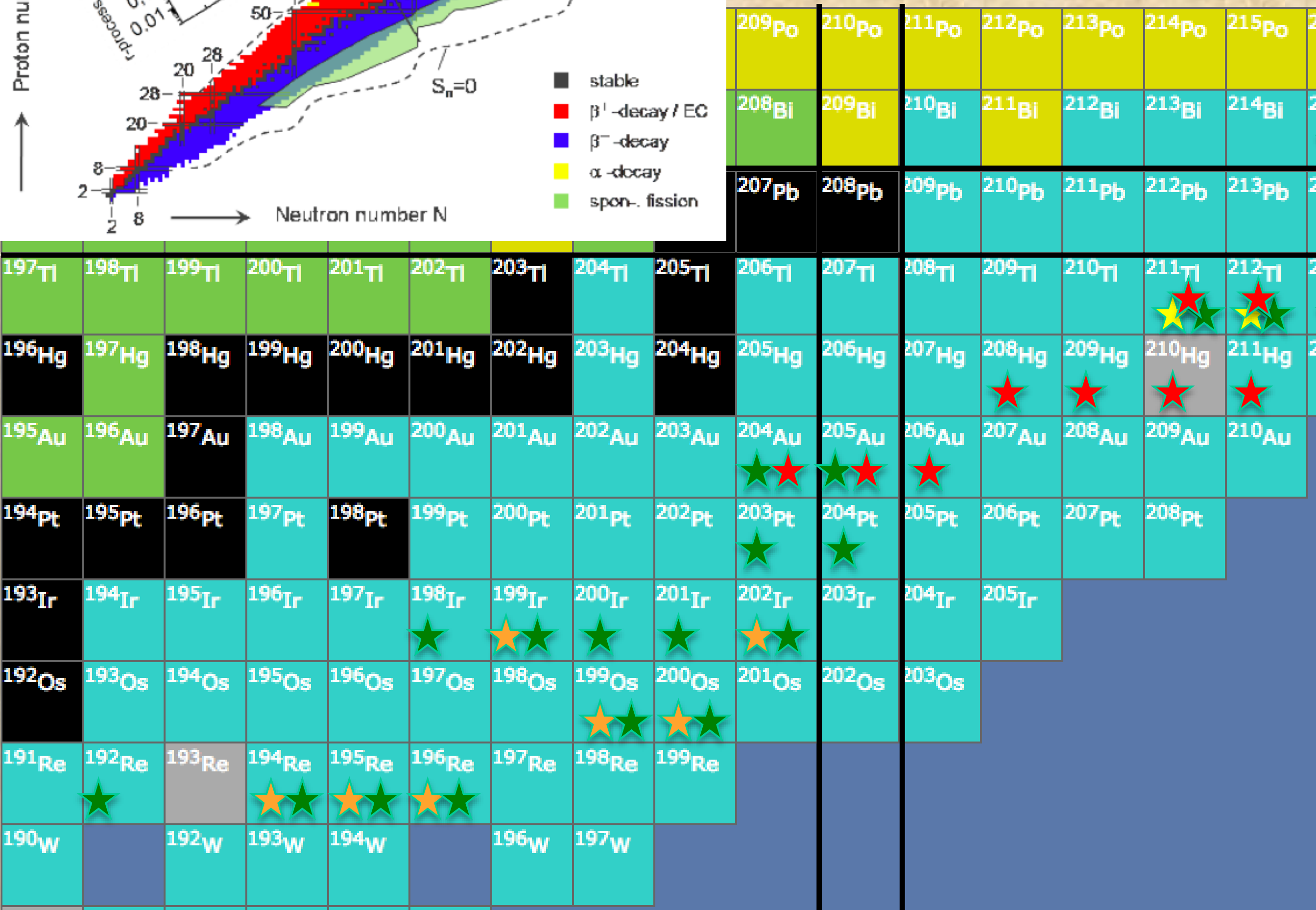
β-strength (experiment):

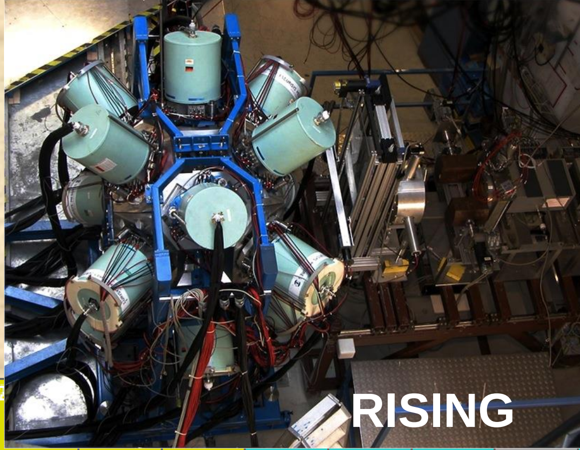
$$S_\beta^{\exp}\left(E_x\right) = \frac{1}{T_{1/2}} \frac{I_\beta\left(E_x\right)}{f\left(Q_\beta - E_x\right)}$$

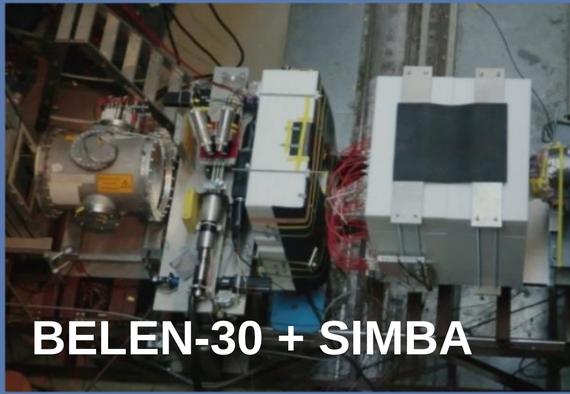
How good are these calculations?

3rd r-process peak region









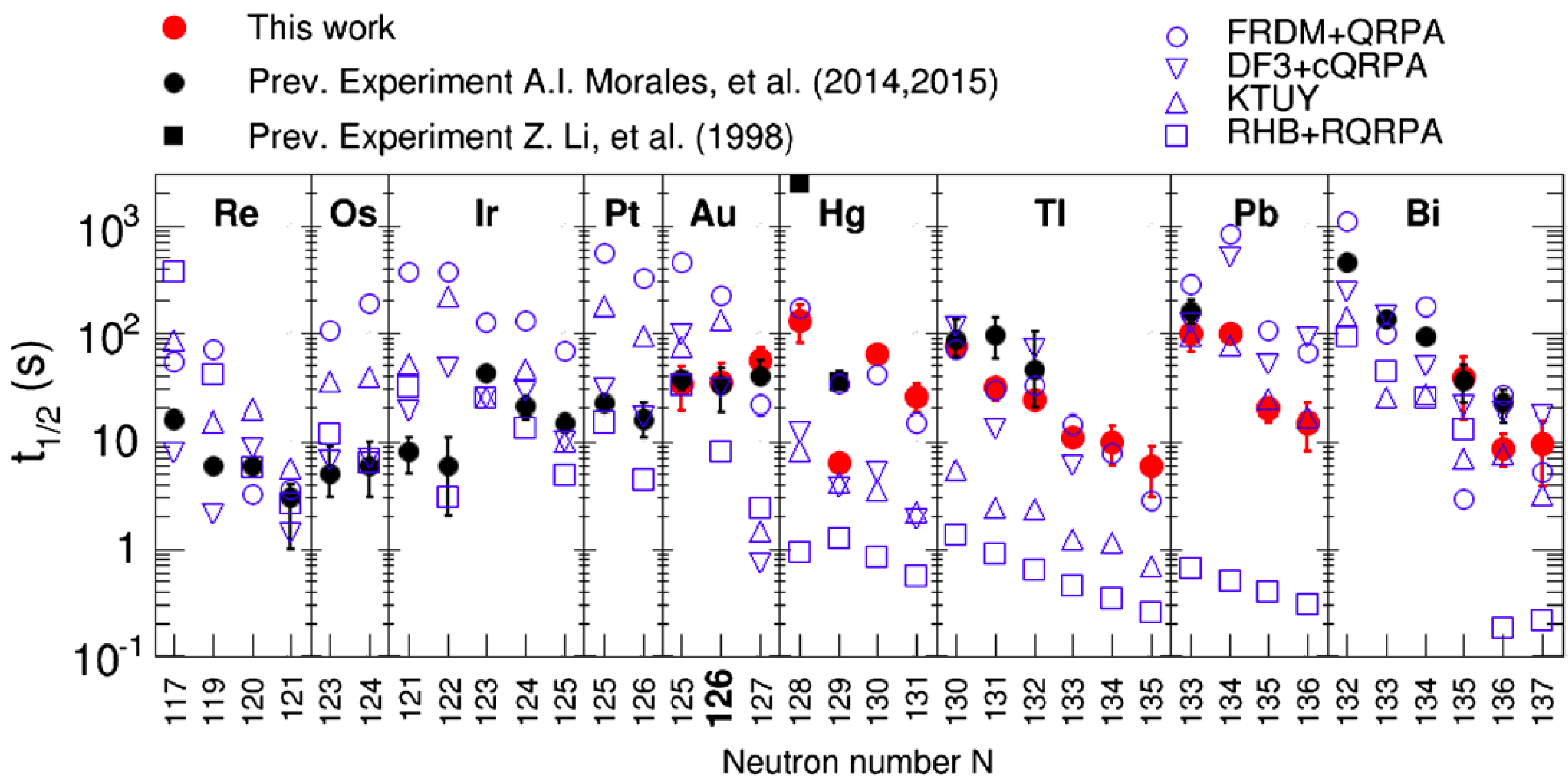
★ :Kurtukian+, NPA827(2009)

★ :Benzoni+, PLB715(2012)

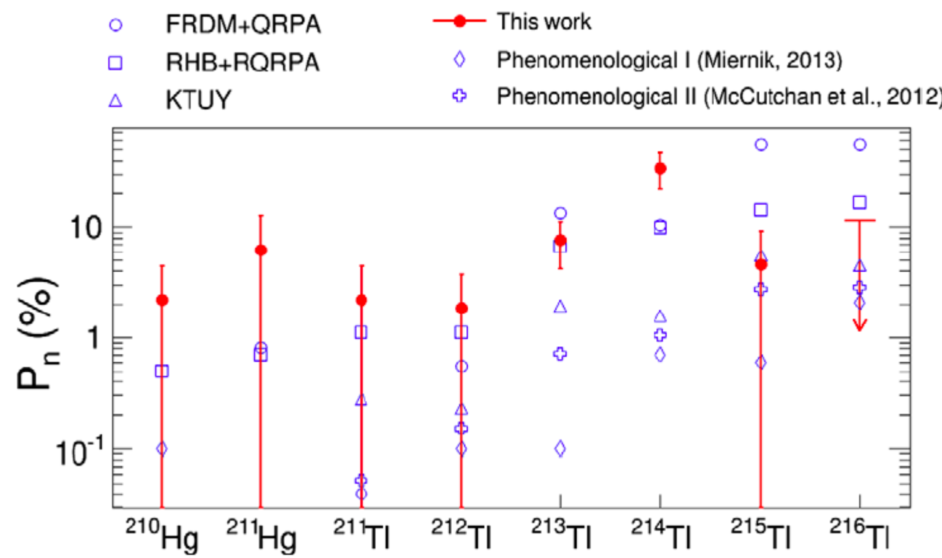
★ :Morales+, PRL113(2014)

★ :Caballero+, PRL117(2016)

Experiments at GSI-FRS



Caballero+, PRL117(2016)

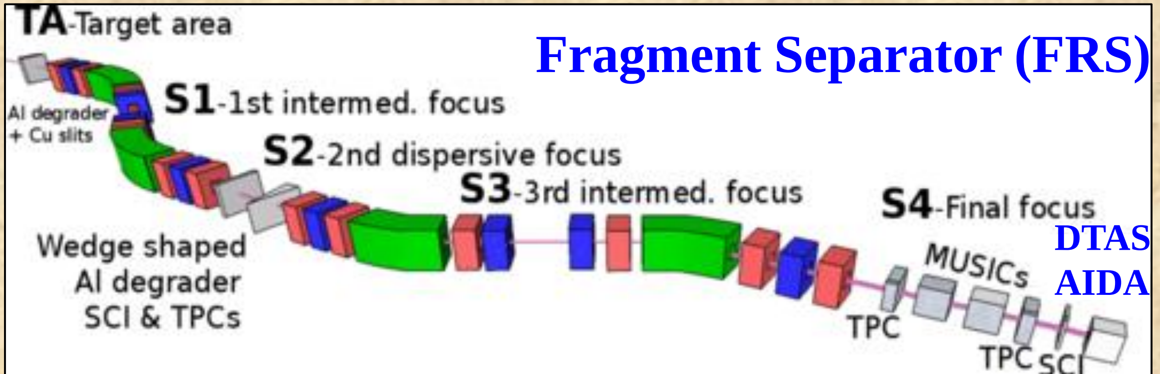


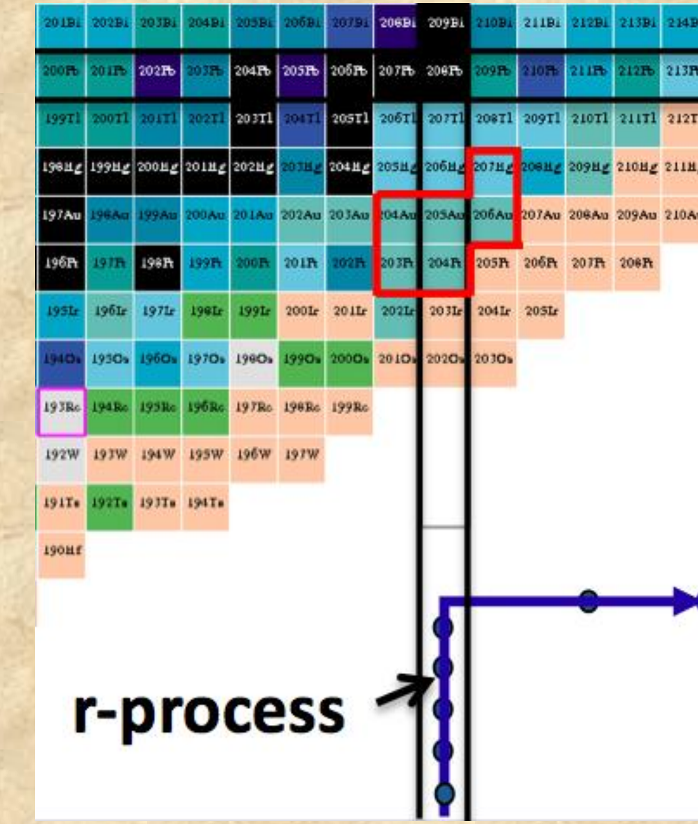
Experiment vs. Theory

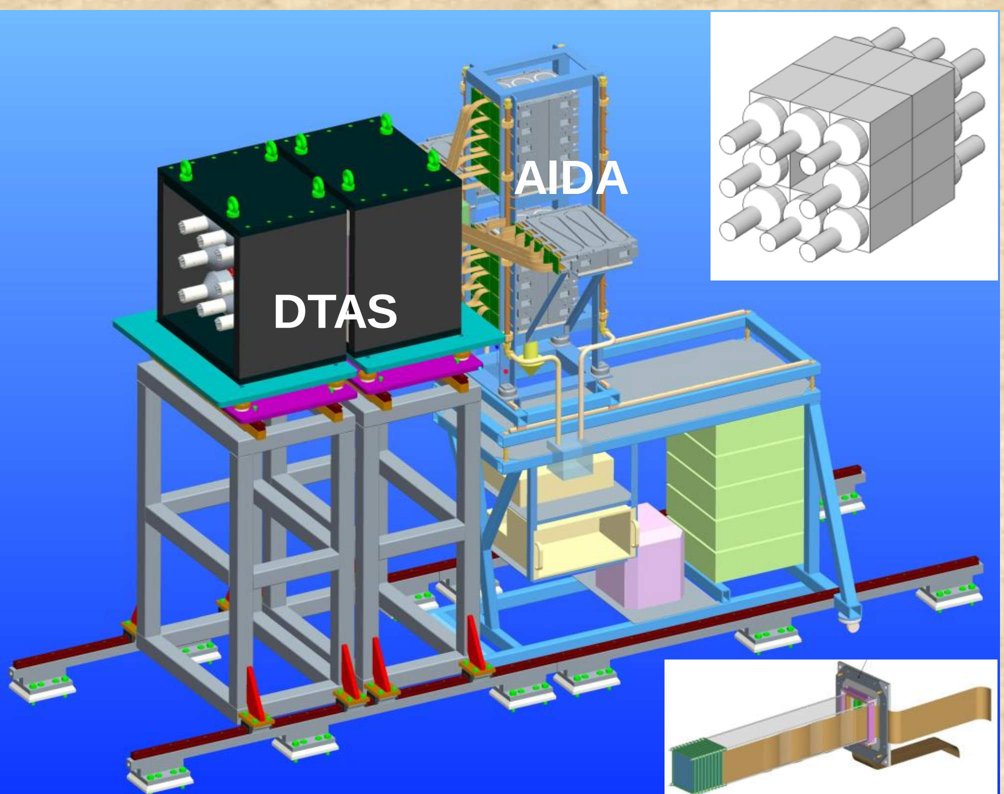
A determination of the β-strength can shed light on the situation

The experiment that can be performed now at GSI-FAIR with the FRS

Beam: ^{208}Pb (1GeV/u, 3 × 10^{8}pps)



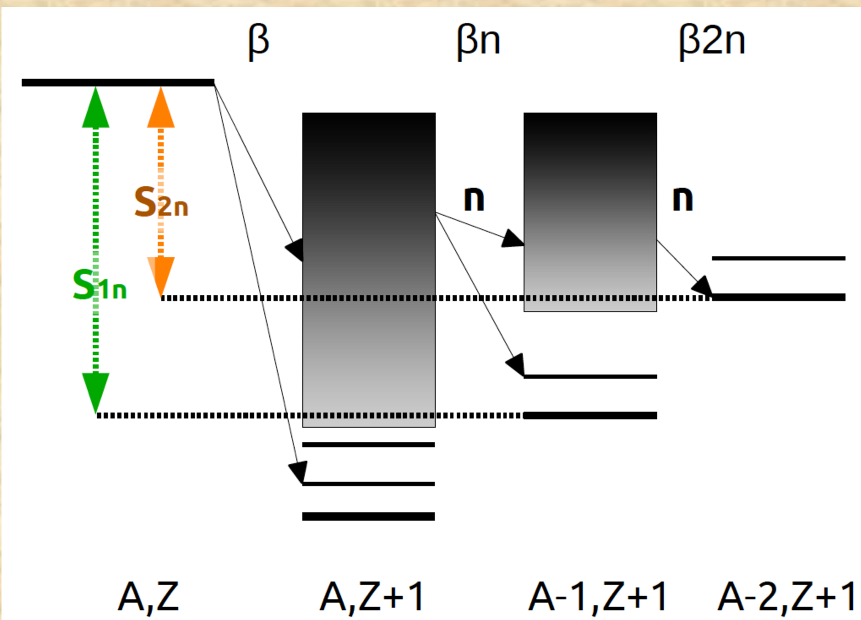




In the future we can move closer to the r-process path

β-delayed neutron decay

- The dominant decay mode of most nuclei formed along the r-process path is β-delayed neutron emission
- Every xn emission in the decay chain reduces the final mass to A-x
- The emitted neutrons (together with fission neutrons) reactivate the capture reactions after neutron exhaustion



P_{xn}: x-neutron emission probability

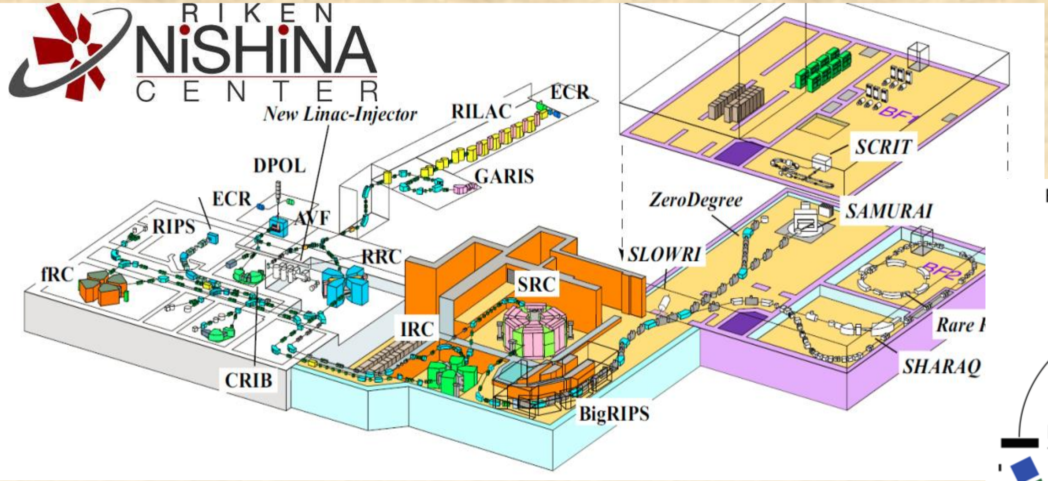
$$P_n = \sum_x P_{xn}$$

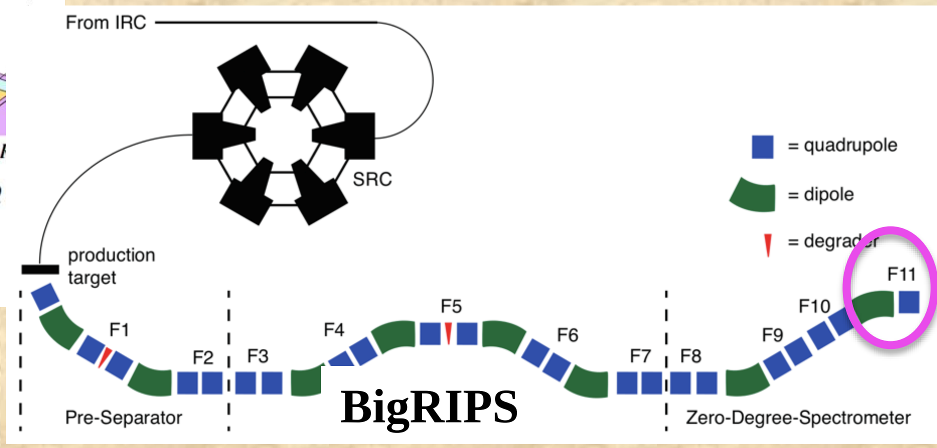
$$\langle n \rangle = \sum_x x P_{xn}$$

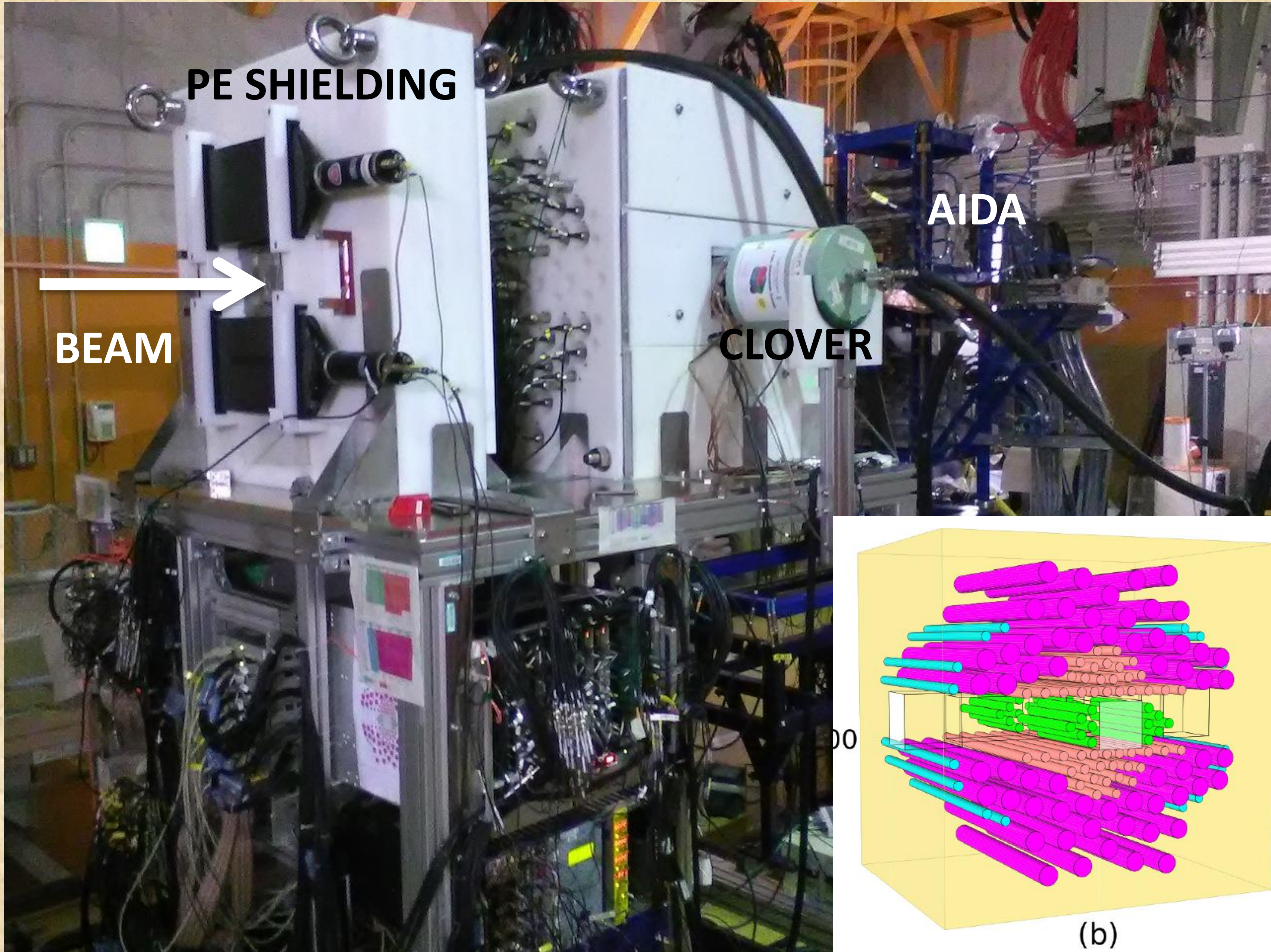
Current theoretical estimates use crude approximations to distribute the β-strength in the xn channels

The BRIKEN project

- Measurement of P_{xn} and $T_{1/2}$ of the most exotic neutron-rich nuclei currently accessible
- The RIBF high intensity radioactive beams
- The BigRIPS+ZeroDegree spectrometer
- The largest ^{3}He moderated neutron counter
- The AIDA implant/decay detector

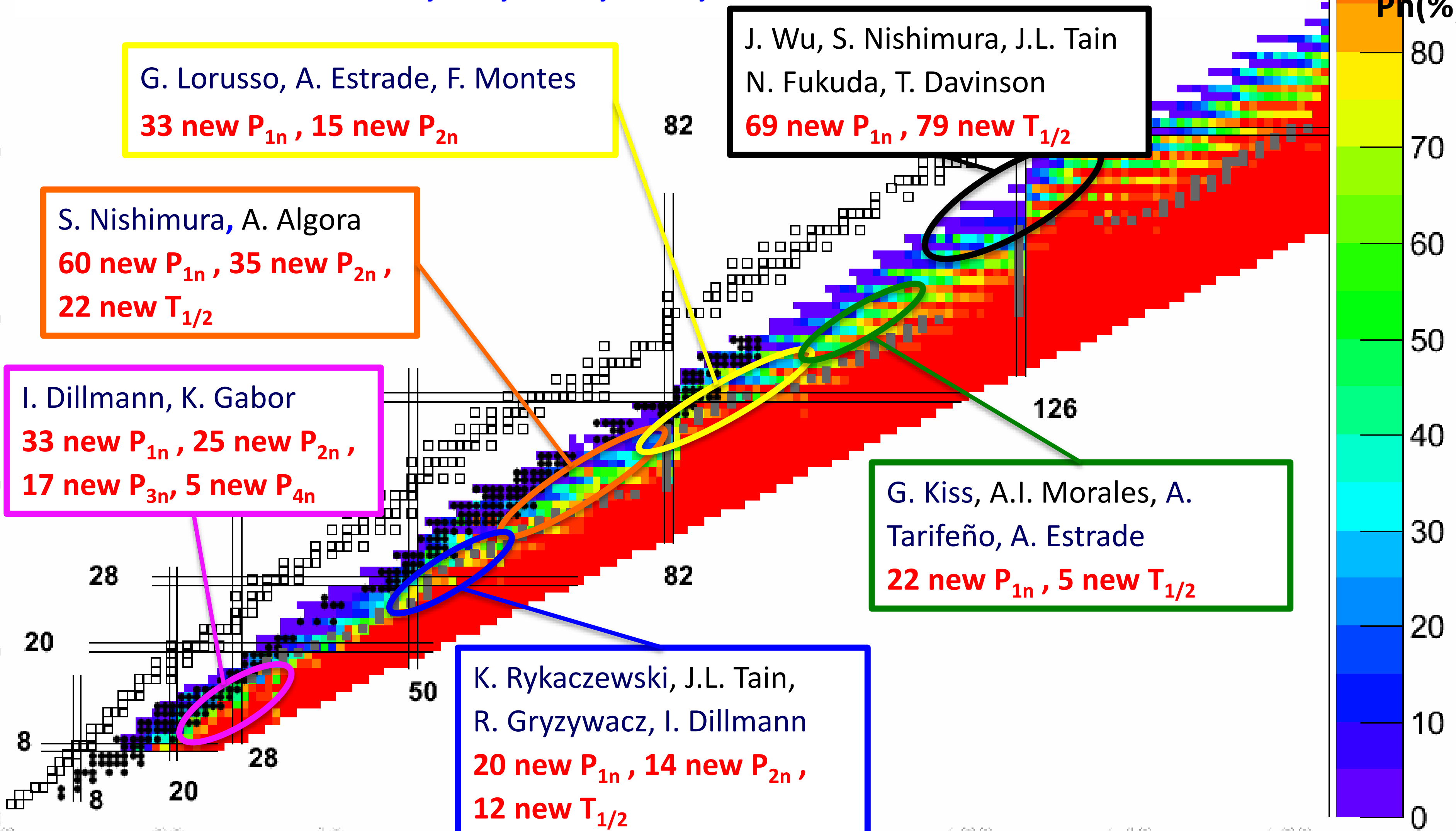




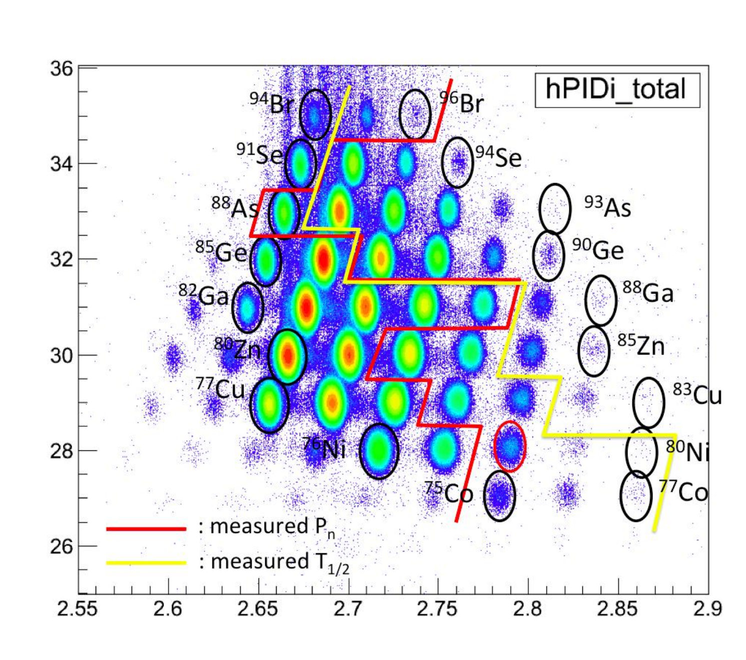

PE SHIELDING
BEAM
CLOVER
AIDA
(b)

BRIKEN goal: astrophysics (r-process) and nuclear structure

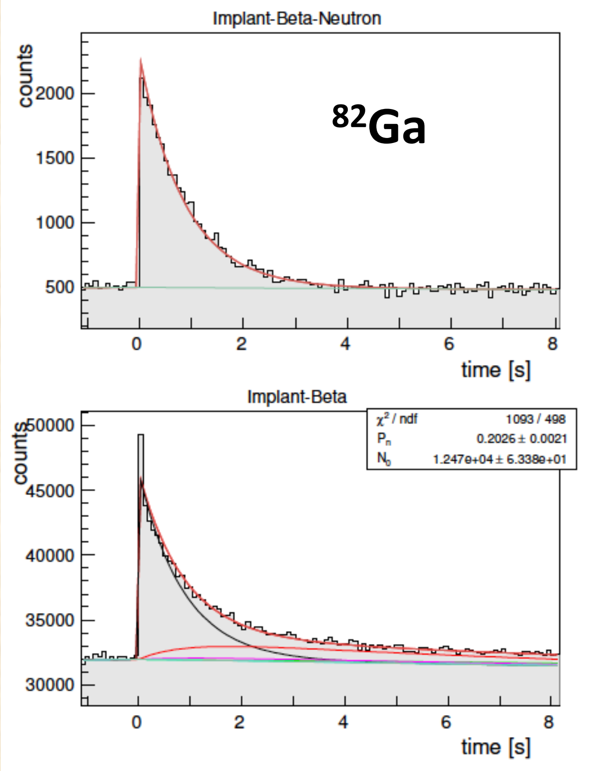
Six proposals accepted until now to measure $T_{1/2}$, P_{xn} of nuclei around A~20, 80, 110, 130, 150 and 200



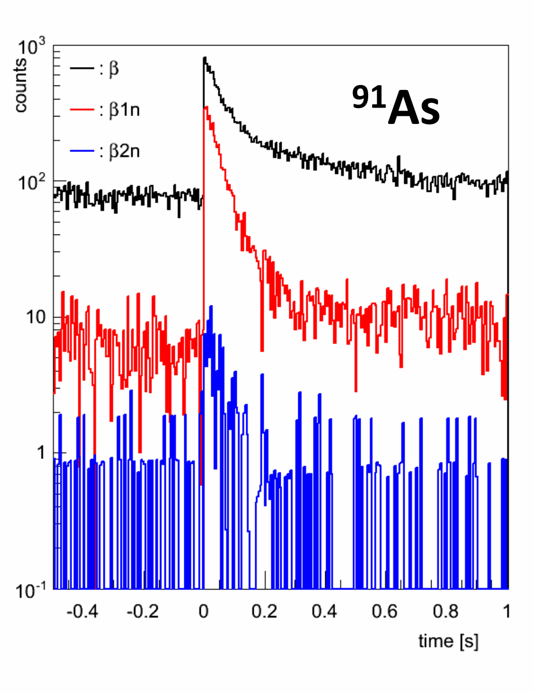
- Commissioning and first experiments done
- Performing according expectations
- Analysis in progress



Ion identification plot for RIBF127 (A~80)



A test case



An exotic case

Other approaches to the measurement of P_{xn} for exotic nuclei are possible: storage rings, mrTOF, …

Summary:

- Direct measurement of (n,γ) cross sections for the r-process is still very challenging and we must resort to indirect methods for the time being
- A sizeable improvement on $T_{1/2}$ and P_{xn} data base has been done (see Nishimura talk) or is ongoing (exception: 3rd r-process peak region)

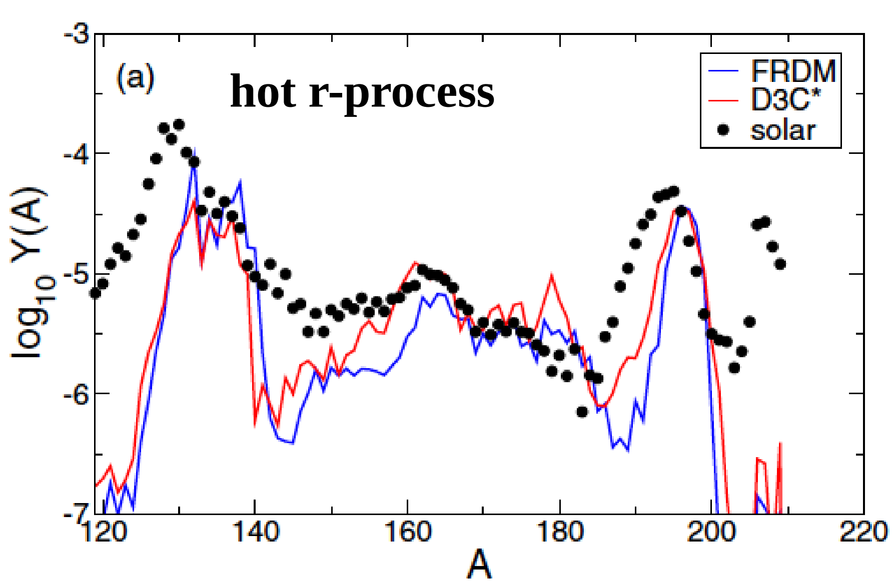
Questions:

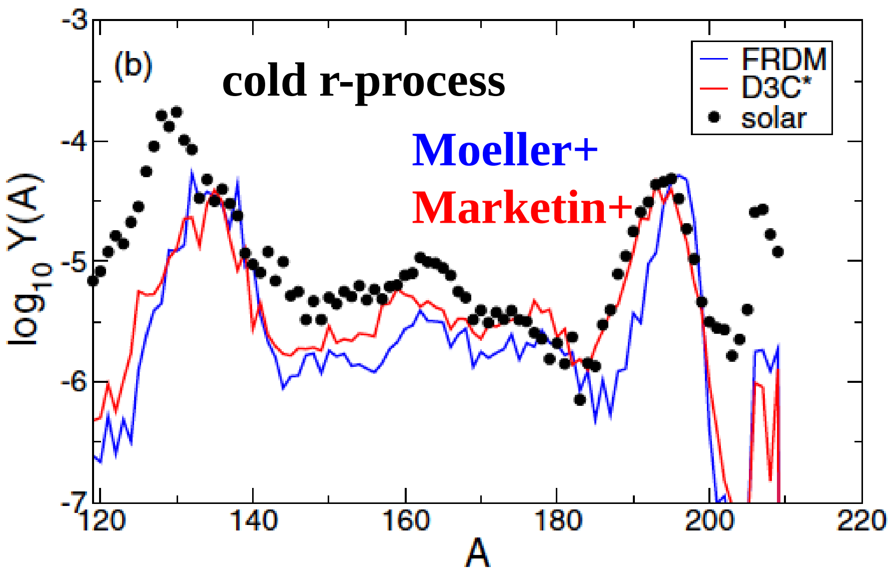
- What improvements can we expect from the upgrades or coming facilities?
- What improvements should be done in instrumentation?
- Other experimental methods?
- Where should we concentrate the efforts?

Backup

Impact of $T_{1/2}$

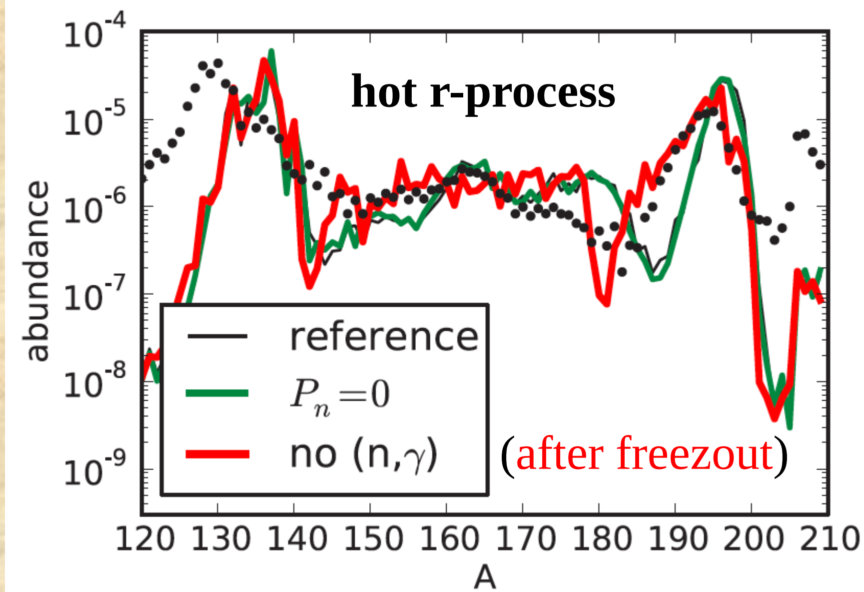
Marketin+, PRC93(2016)025805

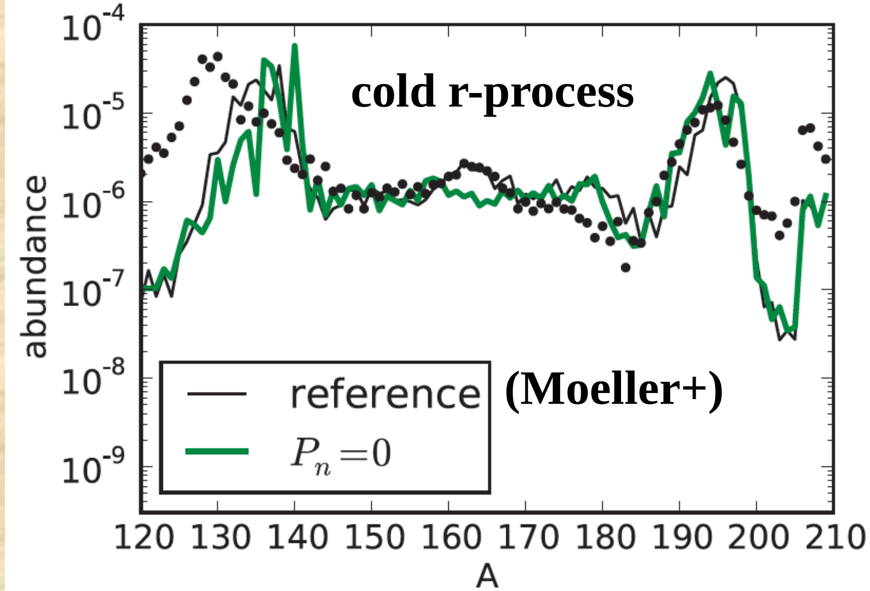




Impact of P_n

Arcones+, PRC83(2011)045809



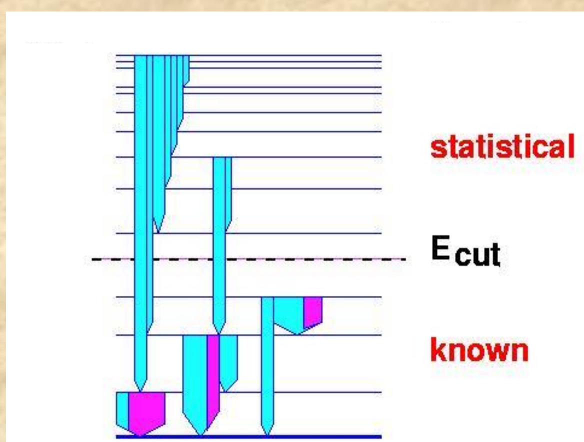


The TAGS analysis in a nutshell

1) Reduce the analysis to a **linear inverse problem** taking the b.r. as parameters:

$$d_i = \sum_j R_{ij}(\mathbf{b}) \times f_j$$

2) Make a reasonable choice of b.r. matrix: we use the **nuclear statistical model (NLD & PSF)** plus **known level-scheme**



bined continuum

discrete

3) Construct the spectrometer response using **MC simulations**:

$$\mathbf{r_j} = \sum_{k=0}^{j-1} b_{jk} g_{\mathbf{jk}} \otimes \mathbf{r_k}$$

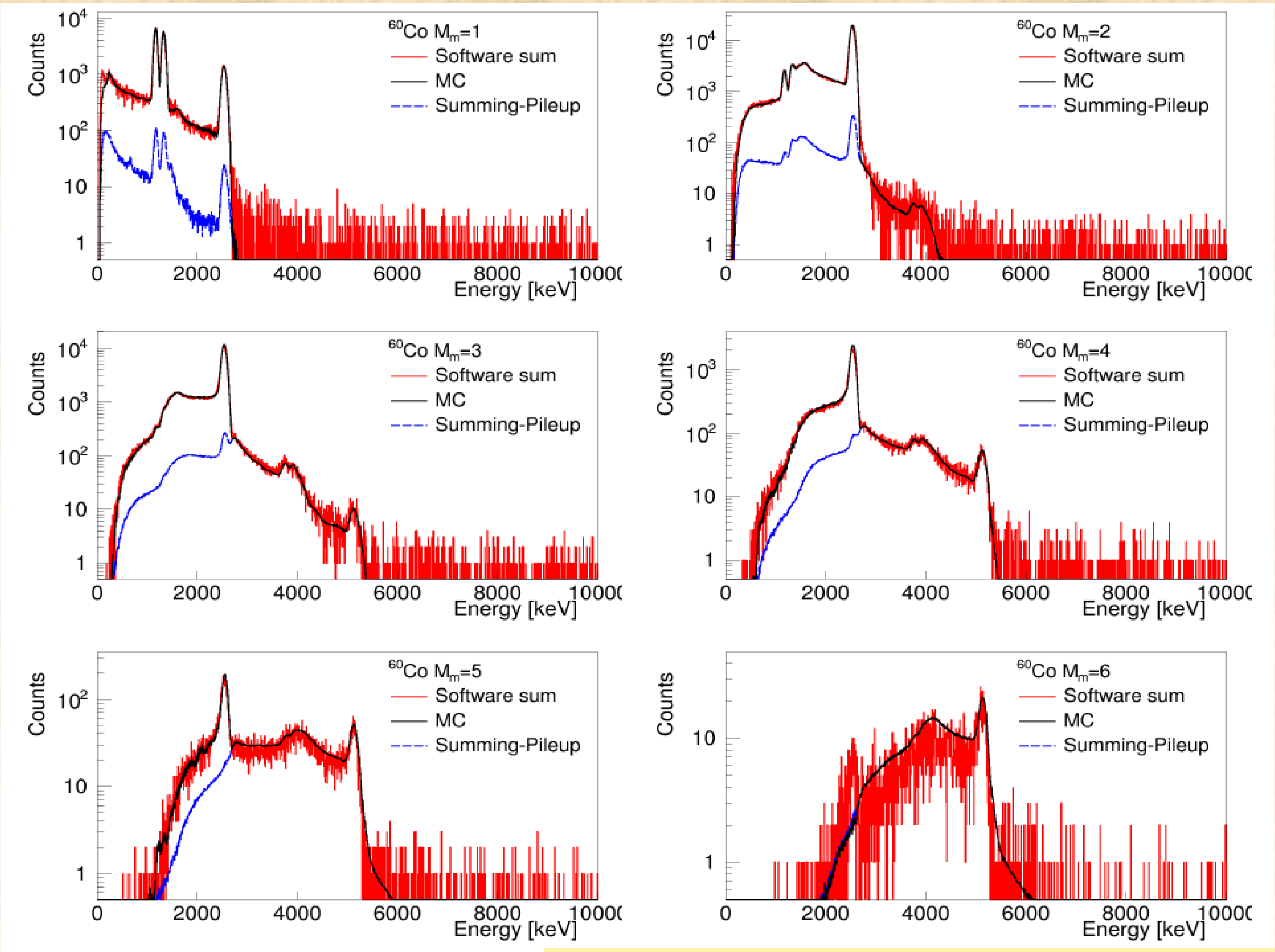
$$\mathbf{R_j} = b_j \otimes \mathbf{r_j}$$

4) Needs **careful calibration of the simulation** using known sources

Cano+, NIMA430(1999)p333, Tain-Cano, NIMA571(2007)p728, NIMA571(2007)p719, Guadilla+, NIMA submitted

The new segmented TAS: multiplicity distributions

^{60}Co



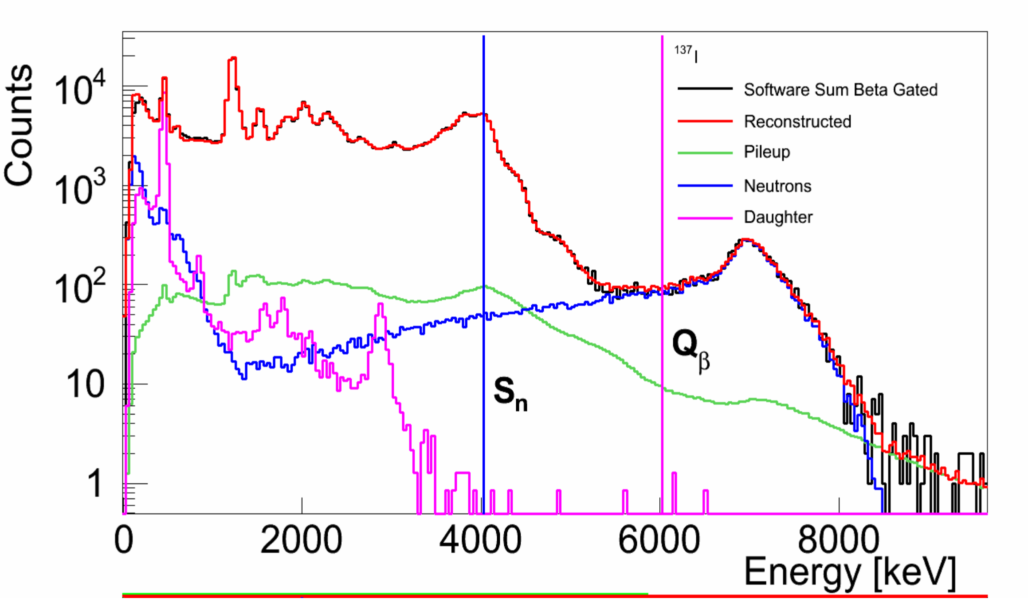
V. Guadilla, PhD Thesis, NIMA submitted

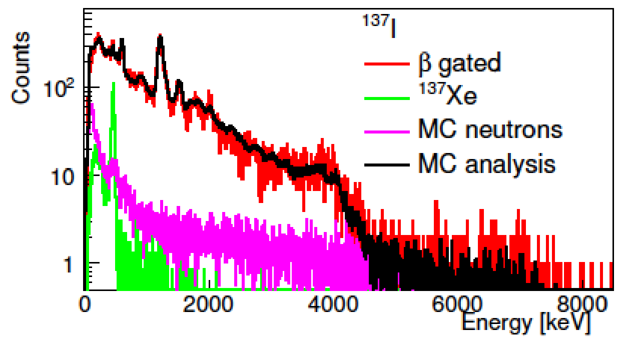
Known sources: more restrictive verification of Geant4 response simulation and of summing-pileup calculation

5) Apply any suitable (**deconvolution**) algorithm to obtain I_β (normalized f_j): we use primarily the EM method

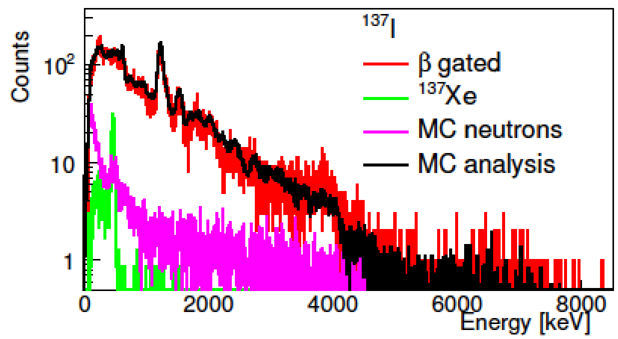
$$f_j^{(s+1)} = \frac{1}{\sum_i R_{ij}} \sum_i \frac{R_{ij} f_j^{(s)}}{\sum_k R_{ik} f_k^{(s)}} d_i$$

6) Compare reconstructed spectra (I_β & brm) with measured spectra: a) **sum energy**, b) **single-crystal energy**, c) **sum energy gated with crystal multiplicity**

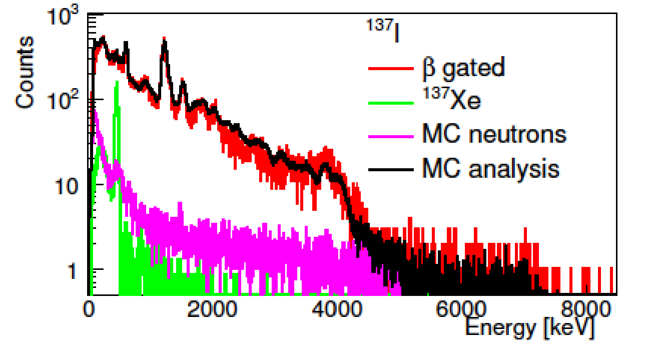




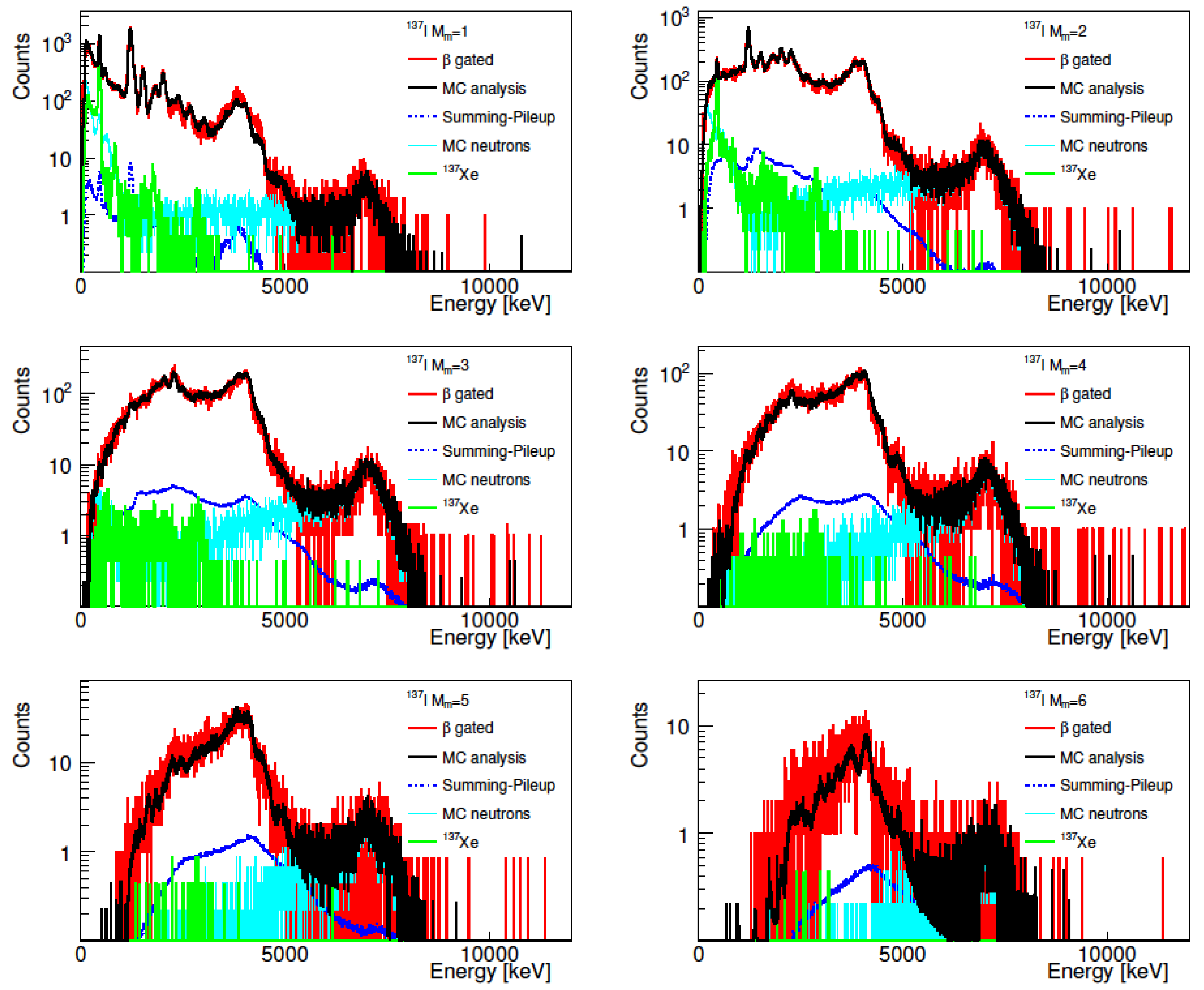
Module 2



Module 3



Module 5



^{137}I M_m=1
^{137}I M_m=2
^{137}I M_m=3
^{137}I M_m=4
^{137}I M_m=5
^{137}I M_m=6
β gated
MC analysis
Summing-Pileup
MC neutrons
^{137}Xe
Counts
Energy [keV]
0
5000
10000
1
10
10^2
10^3