Gamma-neutron competition above the neutron separation energy in beta-delayed neutron emitters

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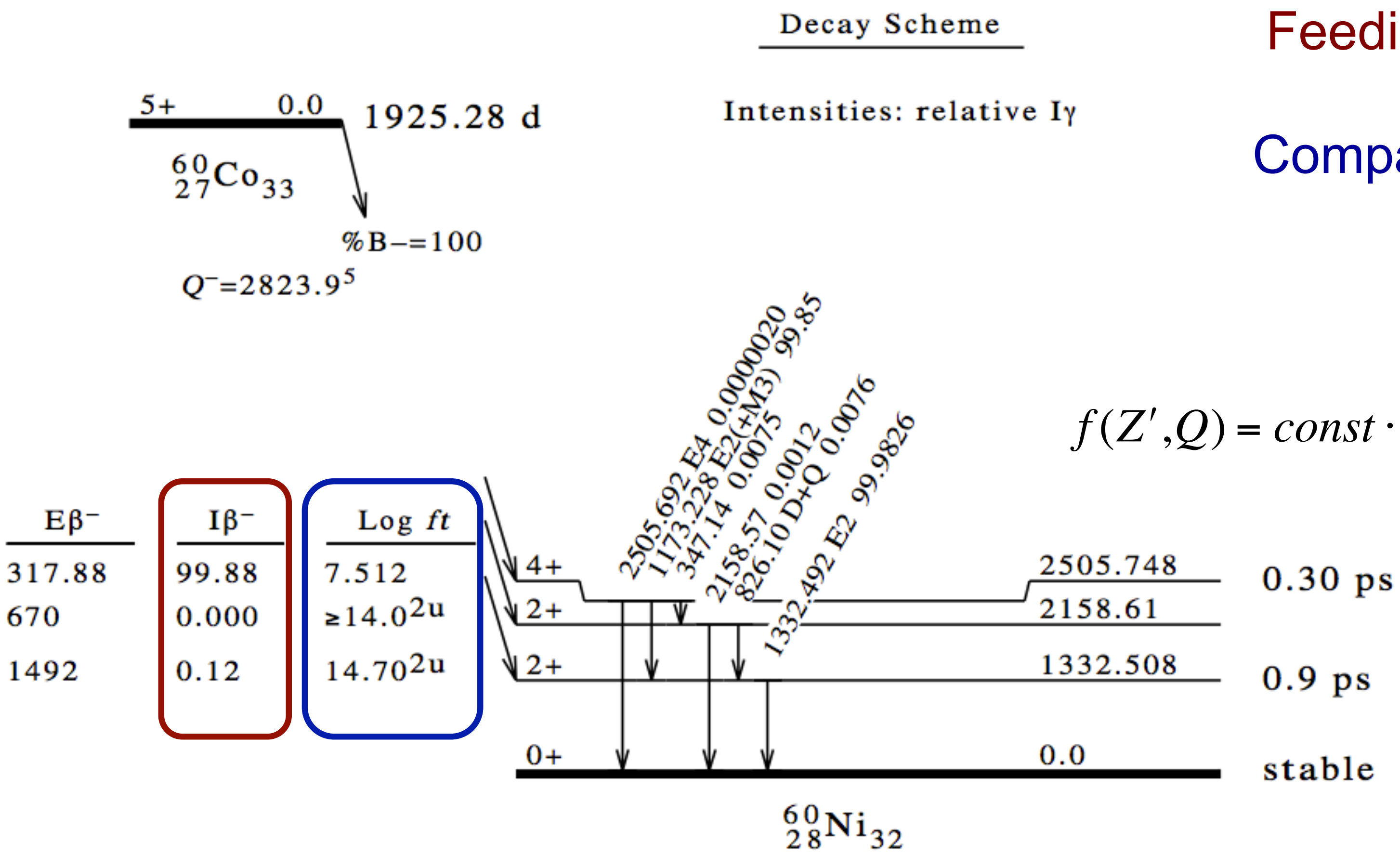
DISCLAIMER:

1. We are only users of Level Densities and Gamma Strength Functions, not experts
2. An slightly misleading title !, this will only be shown in the framework of a practical application at the very end.

“Practical” overview

- A few words (slides) about beta decay
- Why we use the total absorption technique in beta decay studies
- Why we need level densities and gamma strength functions for our analysis
- Why studying neutron-rich nuclei, applications
- Some nuclear structure aspects (as collateral effect)

Example: ^{60}Co decay from http://www.nndc.bnl.gov/



Feeding:=$I_\beta = P_f$*100

Comparative half-life: ft

$$t_f = \frac{T_{1/2}}{P_f}$$

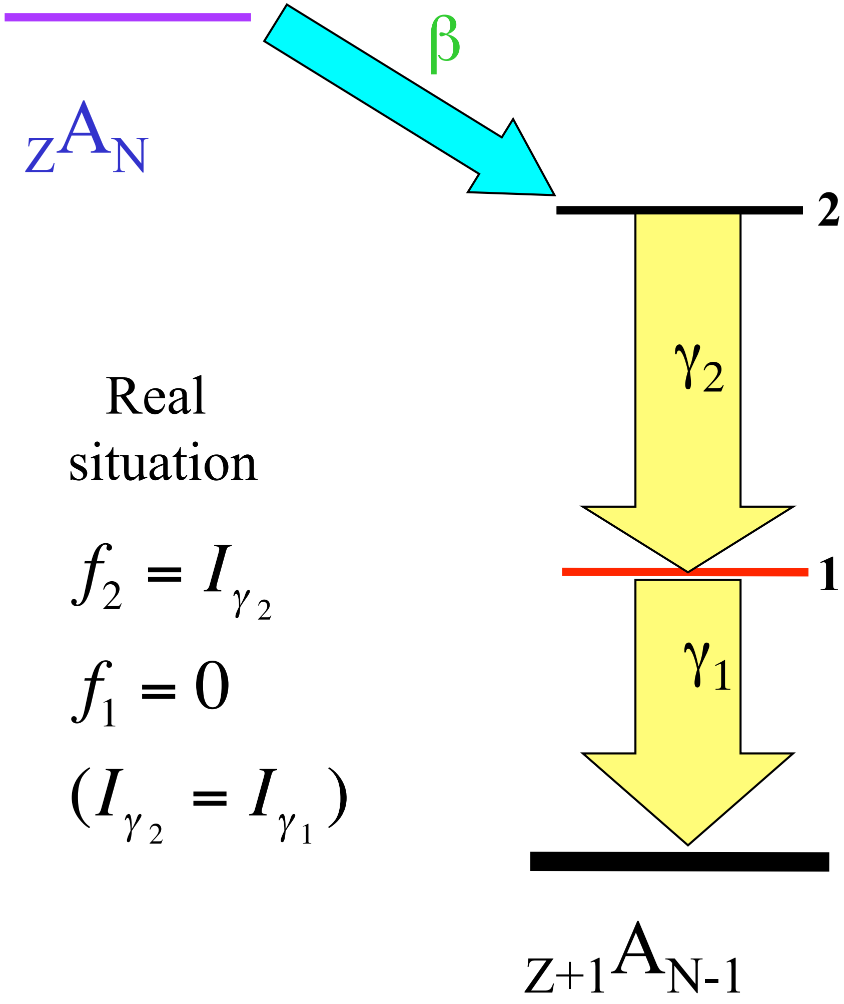
$$f(Z',Q) = const \cdot \int_0^{p_{\max}} F(Z',p)\,p^2 (Q - E_e)^2\,dp$$

$$ft_f = const' \frac{1}{|M_{if}|^2} = const' \frac{1}{B_{i\to f}}$$

$$B_{i\to f} = \frac{1}{2J_i + 1} \left| \langle \Psi_f | \tau^\pm \ or\ \sigma\tau^\pm | \Psi_i \rangle \right|^2$$

$$S_\beta(E) = \frac{P_\beta(E)}{f(Z', Q_\beta - E)\,T_{1/2}} = \frac{1}{ft(E)}$$

The problem of measuring the β- feeding

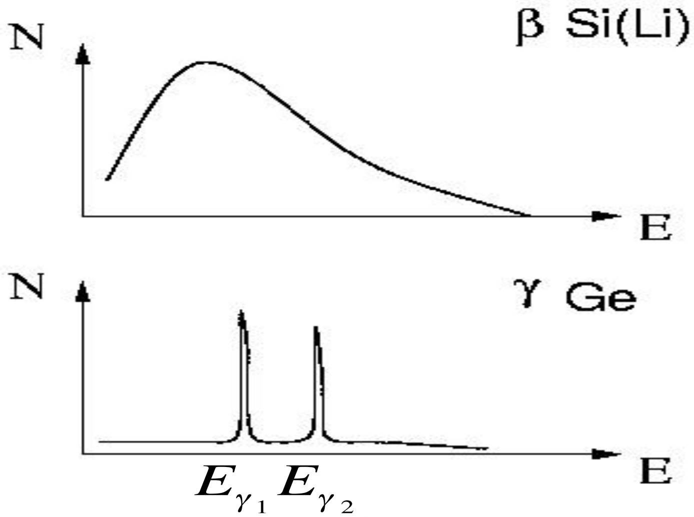


Real situation

$$f_2 = I_{\gamma_2}$$

$$f_1 = 0$$

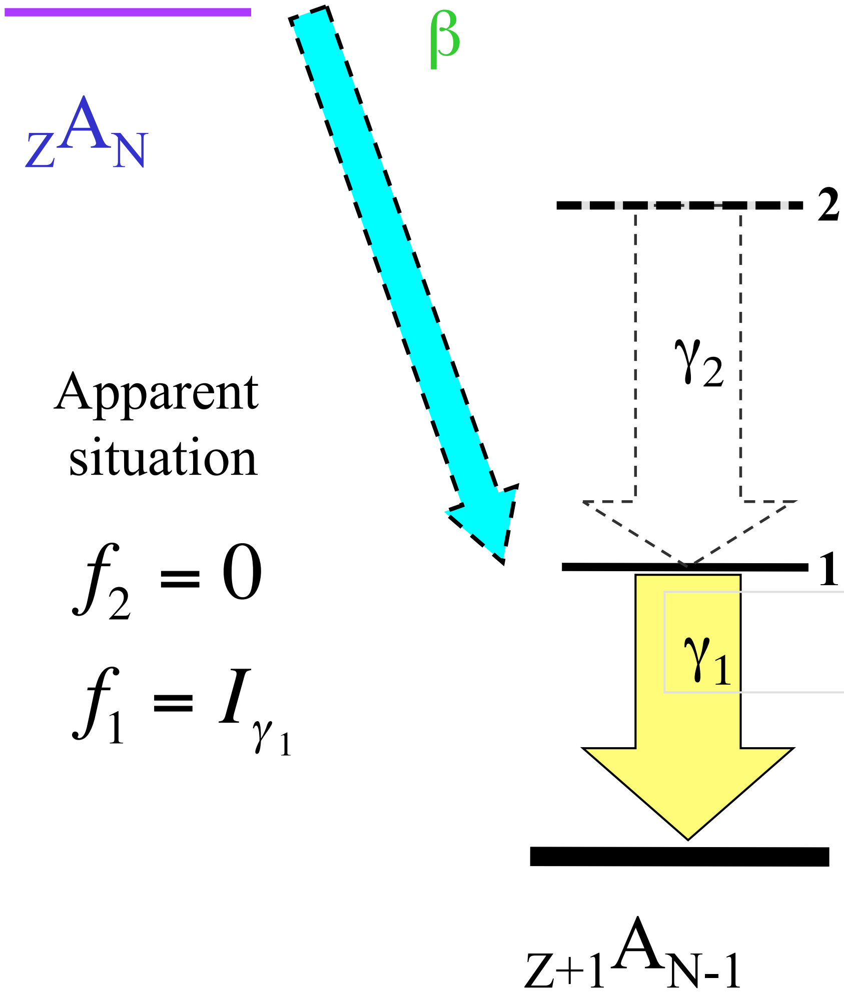
$$(I_{\gamma_2} = I_{\gamma_1})$$



- Ge detectors are conventionally used to construct the level scheme populated in the decay

- From the γ intensity balance we deduce the β-feeding

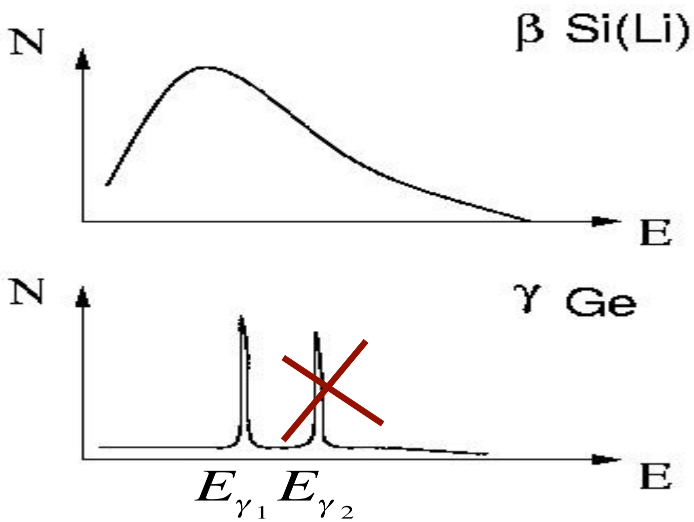
The problem of measuring the β- feeding



Apparent situation

$$f_2 = 0$$

$$f_1 = I_{\gamma_1}$$



- What happens if we miss some intensity

$$Single\ \gamma \sim \varepsilon$$

$$Coinc\ \gamma_1\gamma_2 \sim \varepsilon_1\varepsilon_2$$

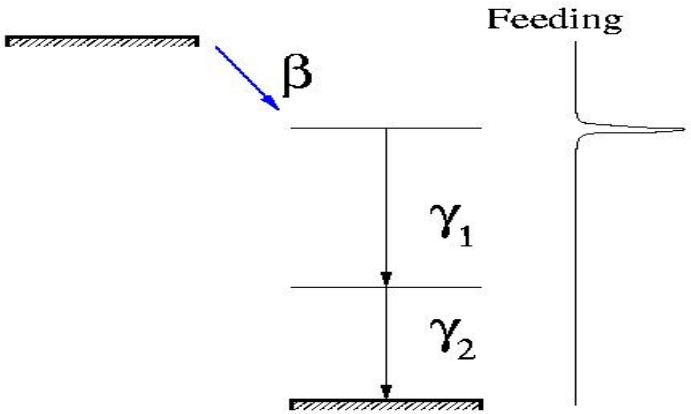
Pandemonium (The Capital of Hell)

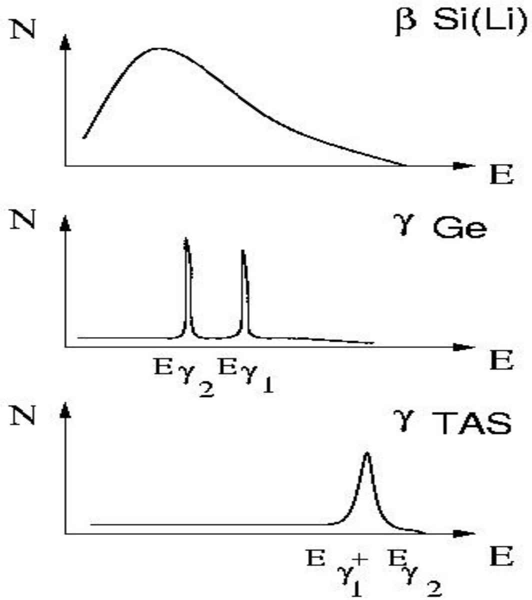
introduced by John Milton (XVII) in his epic poem Paradise Lost

John Martin (~ 1825)

Hardy et al., Phys. Lett. 71B (1977) 307

TAGS measurements





Since the gamma detection is the only reasonable way to solve the problem, we need a highly efficient device:

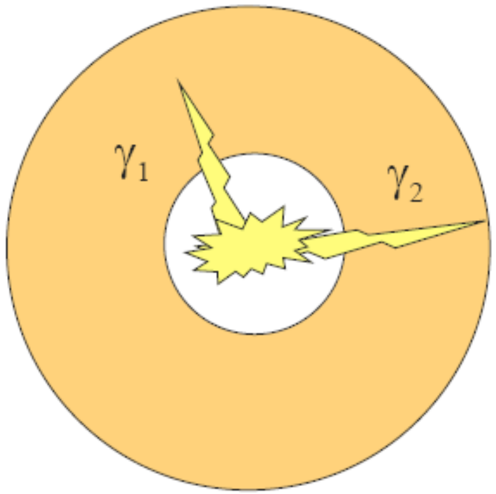
A TOTAL ABSORPTION SPECTROMETER

But there is a change in philosophy. Instead of detecting the individual gamma rays we sum the energy deposited by the gamma cascades in the detector.

A TAS is like a calorimeter!

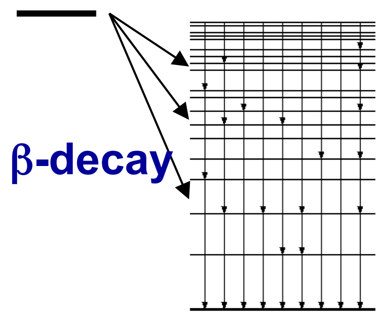
Big crystal, 4π

$$d = R(B) \cdot f$$



Analysis

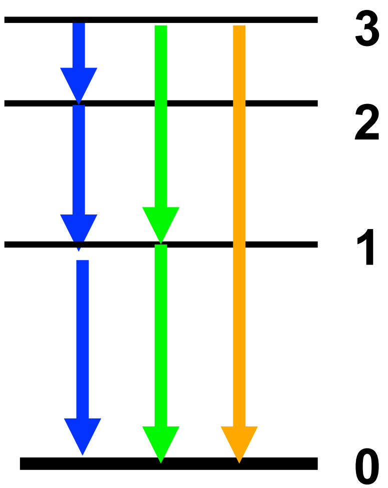
$$d_i = \sum_j R_{ij}(B) f_j \quad or \quad \mathbf{d} = \mathbf{R}(B)\cdot\mathbf{f}$$



R is the response function of the spectrometer, $\boldsymbol{R_{ij}}$ means the probability that feeding at a level ***j*** gives counts in data channel ***i*** *of the spectrum*

The response matrix **R** can be constructed by recursive convolution:

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



$\mathbf{g_{jk}}$: γ-response for $j \rightarrow k$ transition
$\mathbf{R_k}$: response for level k
b_{jk}: branching ratio for $j \rightarrow k$ transition

Mathematical formalization by Tain, Cano, et al.

Relation to level densities and gamma strength functions

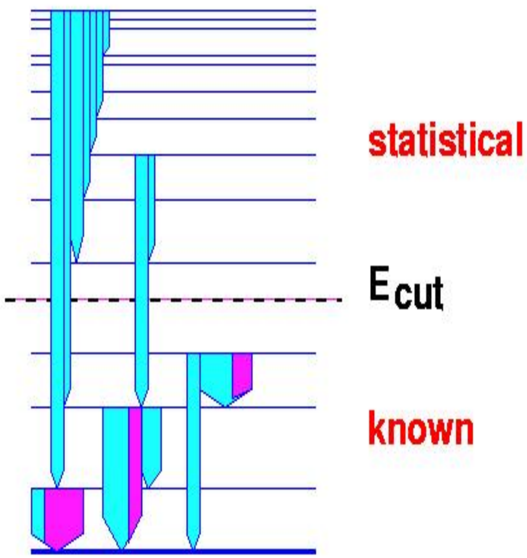
$$d_i = \sum_j R_{ij}(B) f_j$$

$$B \Rightarrow R(B)$$

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

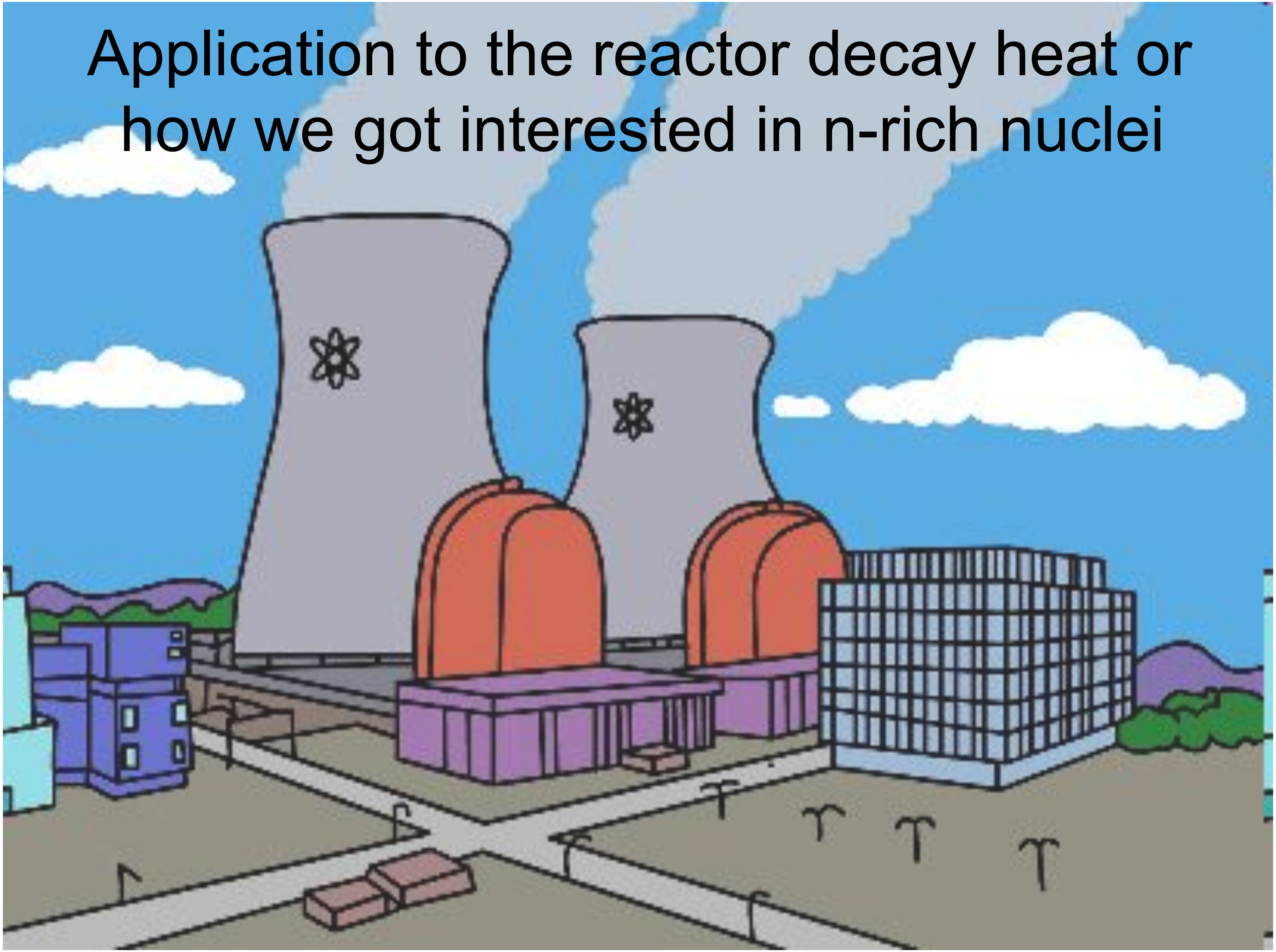
$\mathbf{g_{jk}}$: γ-response for $j \rightarrow k$ transition
$\mathbf{R_k}$: response for level k
b_{jk}: branching ratio for $j \rightarrow k$ transition

The treatment of the statistical region

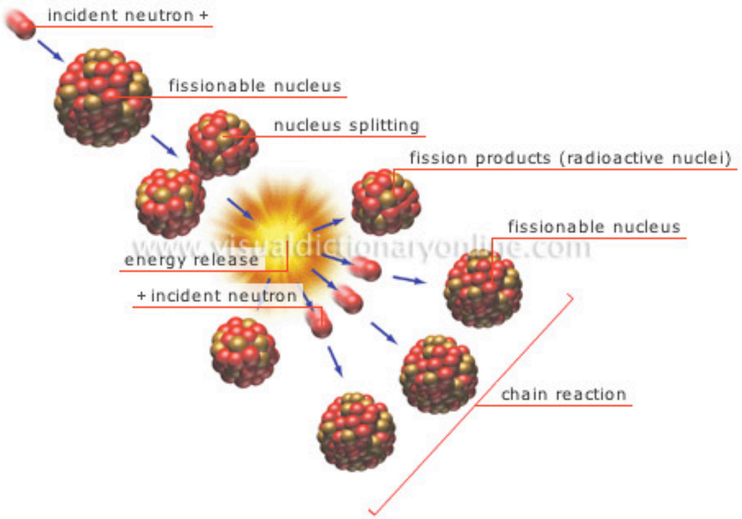


- We define energy bins from the cut energy up to the beta decay Q value
- The probability of finding levels in the bin (that satisfy beta decay selection rules) and that can be populated indirectly (gamma feeding from bins above) is determined by the level density
- The gamma branching interconnecting the binned part and its connection to the known part is determined by gamma strength functions (E1, M1, E2)

Application to the reactor decay heat or how we got interested in n-rich nuclei



Fission process energy balance

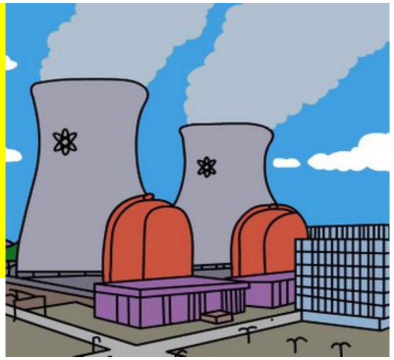


Each fission is approximately followed by 6 beta decays (sizable amount of energy)

Energy released in the fission of ^{235}U	
Energy distribution	MeV
Kinetic energy light fission fragment	100.0
Kinetic energy heavy fission fragment	66.2
Prompt neutrons	4.8
Prompt gamma rays	8.0
Beta energy of fission fragments	7.0
Gamma energy of fission fragments	7.2
Subtotal	192.9
Energy taken by the neutrinos	9.6
Total	202.7

James, J. Nucl. Energy 23 (1969) 517

Decay heat: summation calculations



$$f(t) = \sum_i E_i \lambda_i N_i(t)$$

E_i Decay energy of the nucleus i (gamma, beta or both)

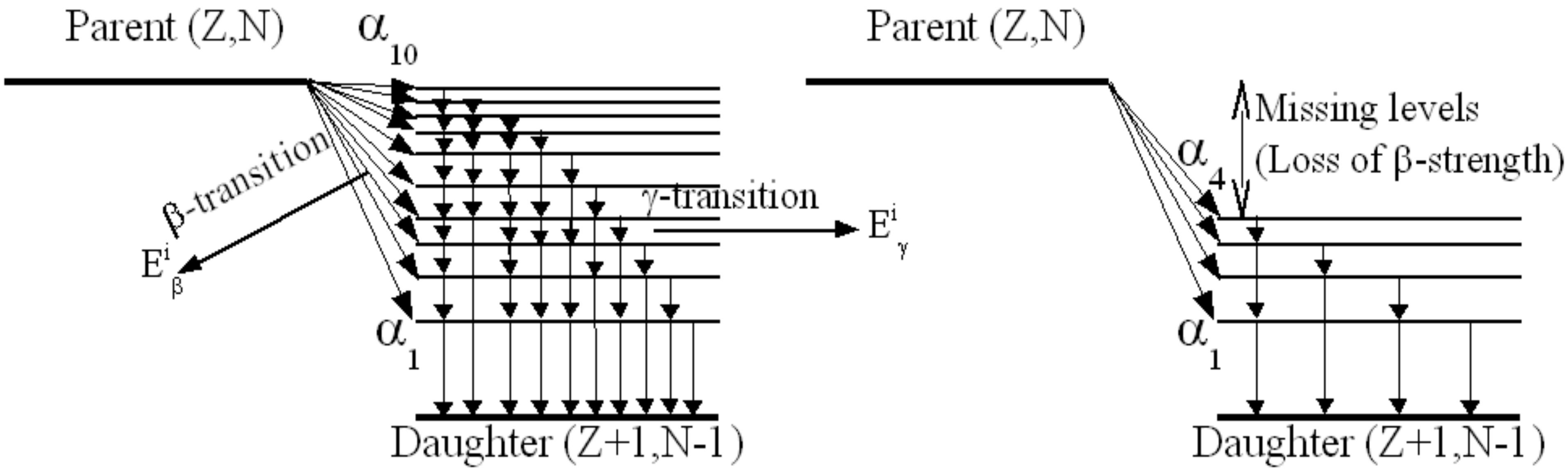
λ_i Decay constant of the nucleus i $\lambda = \frac{\ln(2)}{T_{1/2}}$

N_i Number of nuclei i at the cooling time t

Requirements for the calculations: large databases that contain all the required information (half-lives, mean γ- and β-energies released in the decay, n-capture cross sections, fission yields, this last information is needed to calculate the inventory of nuclides)

Pandemonium and decay heat: what happens with the mean energies ?

$$f(t) = \sum_i E_i \lambda_i N_i(t)$$



$$\overline{E}_\beta = \sum_i I_\beta(E_i)\langle E_{\beta,i}\rangle$$

$$\overline{E}_\gamma = \sum_i I_\beta(E_i) E_i$$

$\overline{E}_\beta$ overestimation

$\overline{E}_\gamma$ underestimation

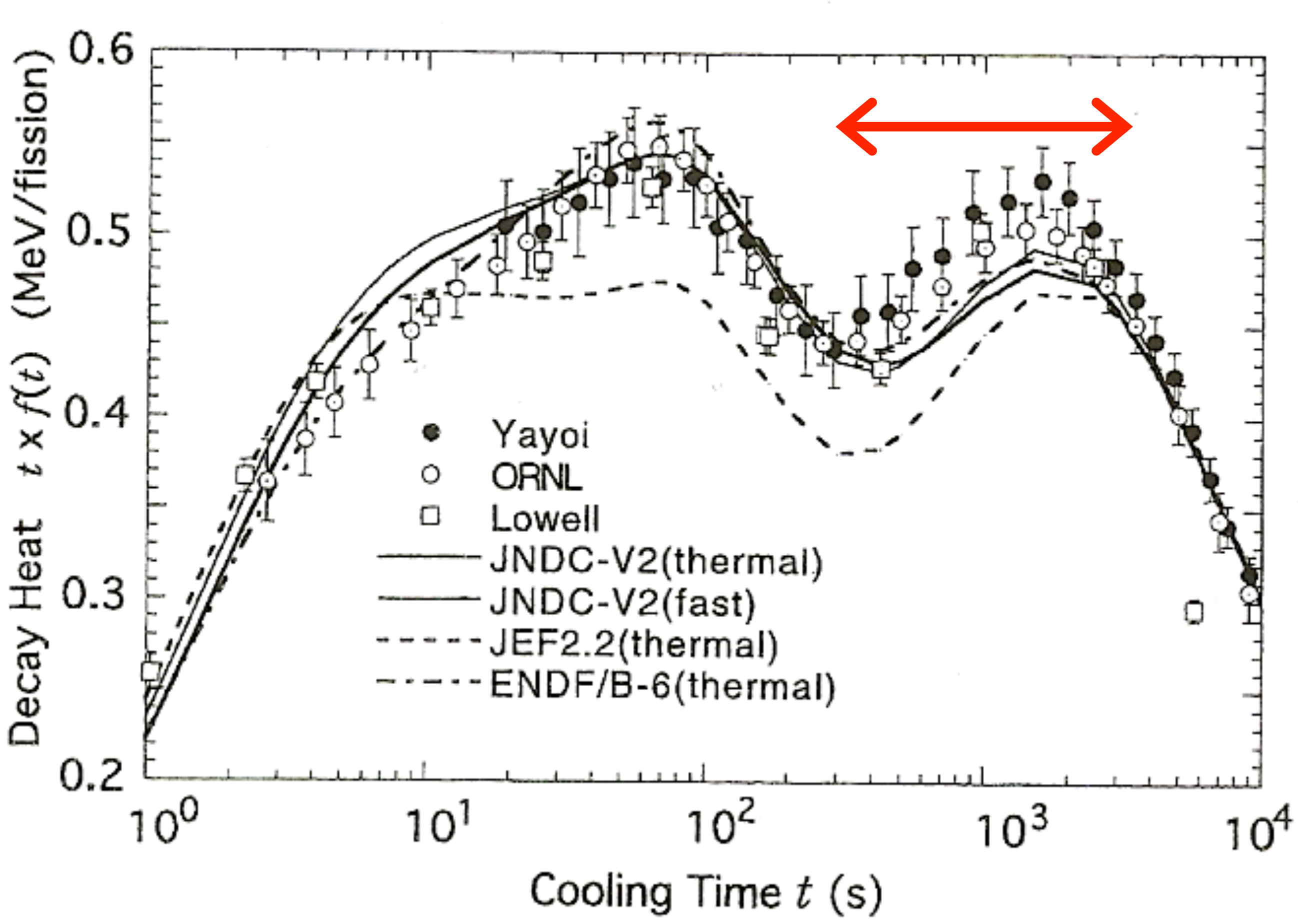
The beginning …

We got interested in the topic after the work of Yoshida and co-workers (Journ. of Nucl. Sc. and Tech. 36 (1999) 135)

^{239}Pu example (similar situation for ^{235,238}U)

Detective work: identification of some nuclei that could be blamed for the anomaly ^{102,104,105}Tc

^{239}Pu example (γ component)

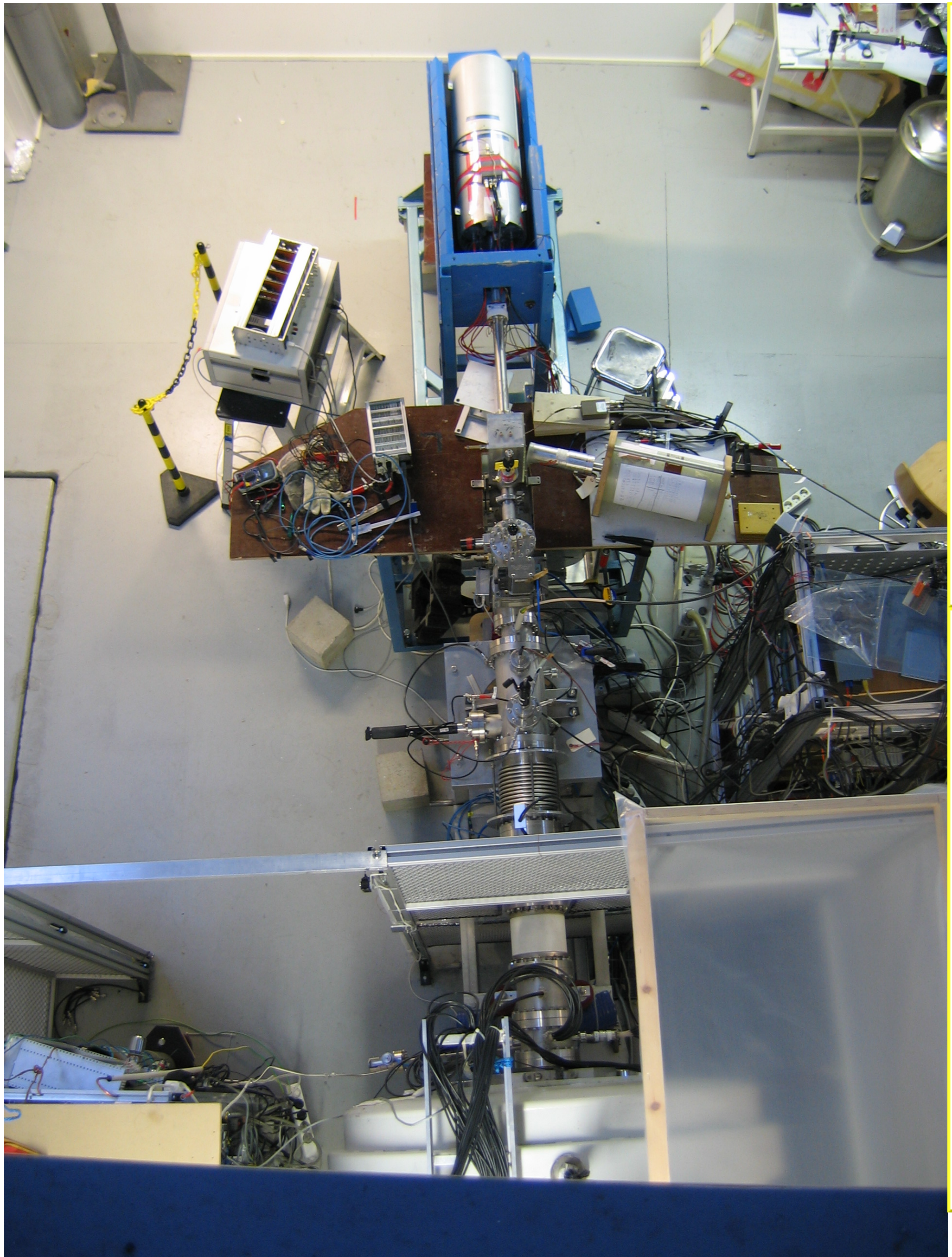


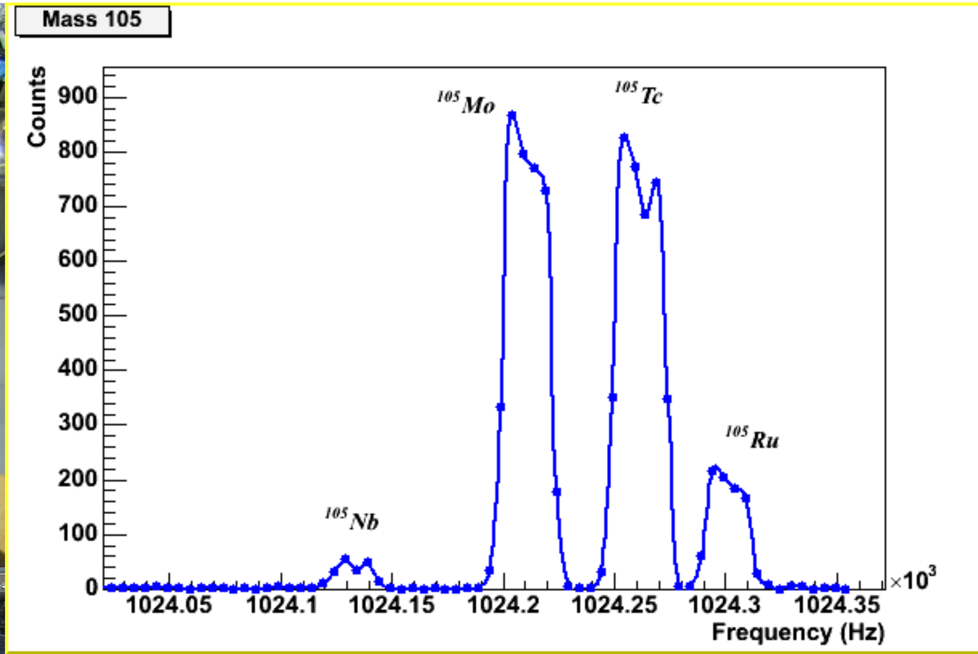
The “famous” list
WPEC-25 (IAEA working group)

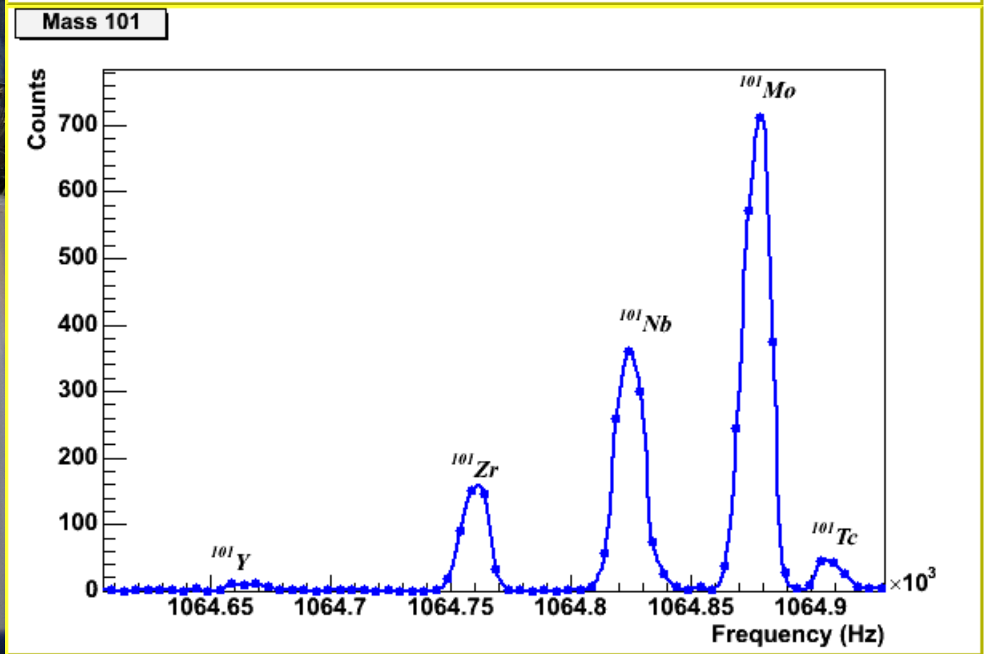
Radionuclide	Priority	Radionuclide	Priority	Radionuclide	Priority
35-Br-86	1	41-Nb-99	1	52-Te-135	2
35-Br-87	1	41-Nb-100	1	53-I-136	1
35-Br-88	1	41-Nb-101	1	53-I-136m	1
36-Kr-89	1	41-Nb-102	2	53-I-137	1
36-Kr-90	1	42-Mo-103	1	54-Xe-137	1
37-Rb-90m	2	42-Mo-105	1	54-Xe-139	1
37-Rb-92	2	43-Tc-102	1	54-Xe-140	1
38-Sr-89	2	43-Tc-103	1	55-Cs-142	3
38-Sr-97	2	43-Tc-104	1	56-Ba-145	2
39-Y-96	2	43-Tc-105	1	57-La-143	2
40-Zr-99	3	43-Tc-106	1	57-La-145	2
40-Zr-100	2	43-Tc-107	2		
41-Nb-98	1	51-Sb-132	1		

37 nuclides, of which 23 were given first priority, reports by A. Nichols.

New feature: IGISOL + trap-assisted spectroscopy

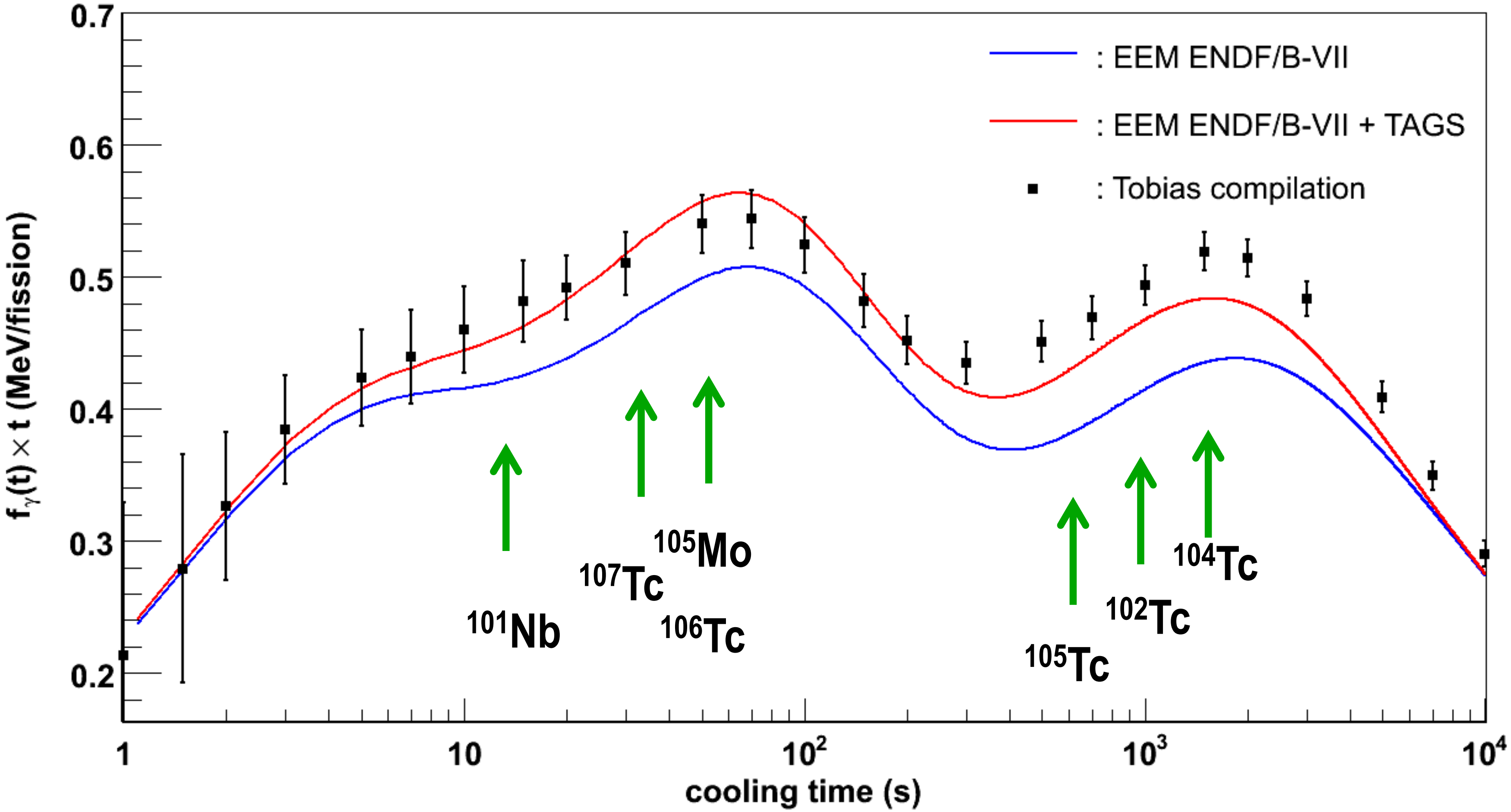






Impact of the results for ^{239}Pu: electromagnetic component

Motivated by Yoshida *et al.* (Journ. of Nucl. Sc. and Tech. 36 (1999) 135) and WPEC-25



Algora, Jordan, Tain, et al. Phys. Rev. Letts. 105, 202505,

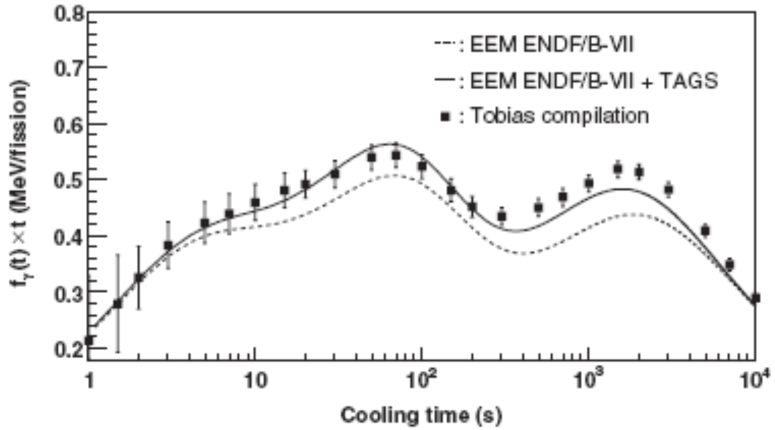
PhD Thesis D. Jordan,

K. P. Rykaczewsky, Physics 3, 94 (2011)

DH Courtesy A. Sonzogni

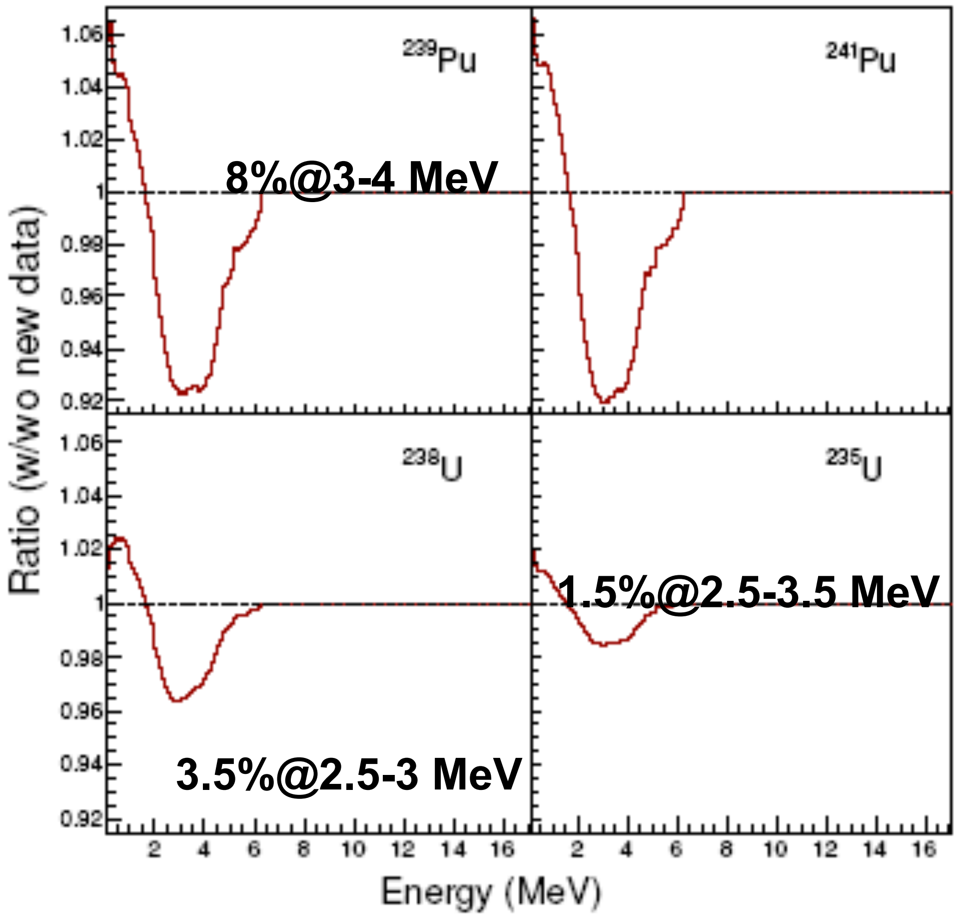
Results also confirmed by R. W. Mills using JEFF 3.1

Some additional impact of our data



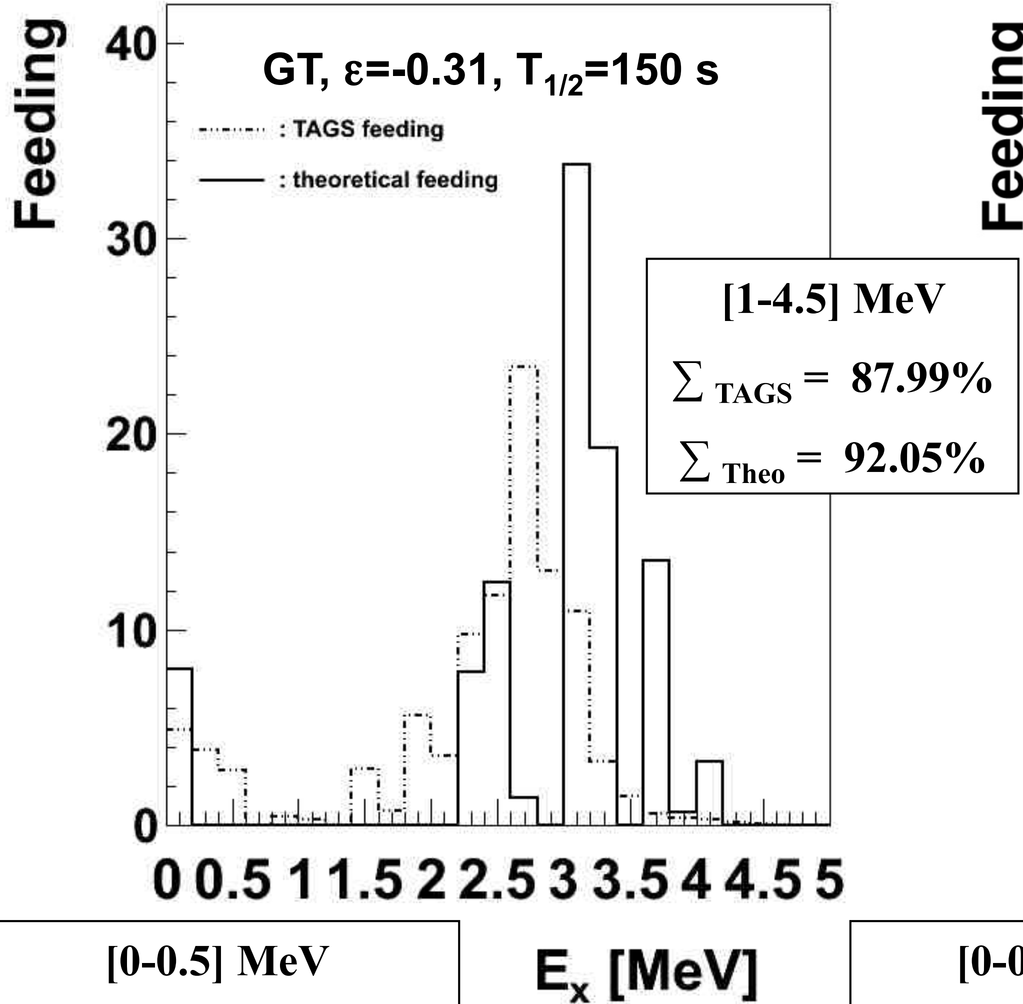
Algora et al., PRL 105, 202501, 2010
Dolores Jordan, PhD thesis

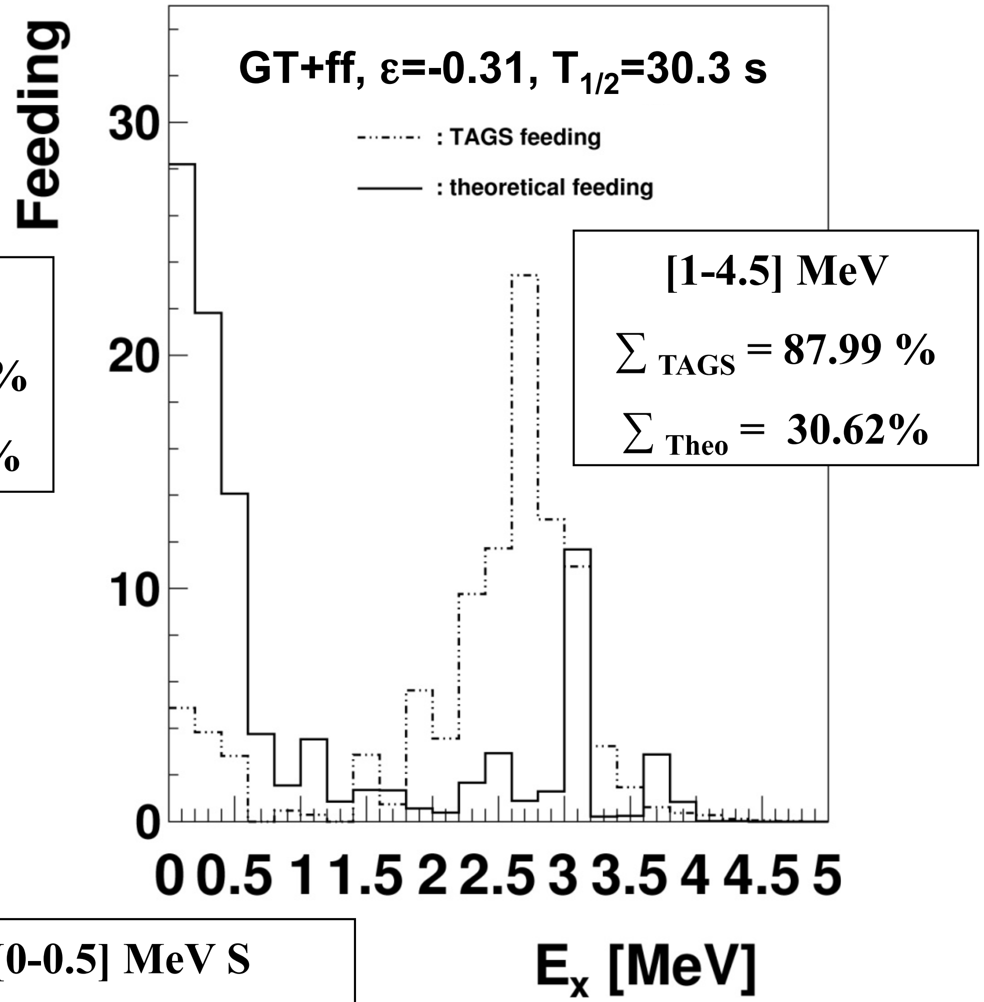
M. Fallot et al., PRL 109.202504



Ratio between 2 antineutrino spectra built with and without the ^{102,104,105,106,107}Tc, ^{105}Mo, ^{101}Nb TAS data

Results of QRPA calculations
^{105}Mo, $T_{1/2}$(exp) = 35.6 s





[0-0.5] MeV

$\sum_{TAGS}$ = 11.51%

$\sum_{Theo}$ = 7.94%

[0-0.5] MeV S

$\sum_{TAGS}$ = 11.51%

$\sum_{Theo}$ = 67.84 %

Kratz *et al.*

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36-Kr-89	1	41-Nb-102	2	53-I-137	1
36-Kr-90	1	42-Mo-103	1	54-Xe-137	1
37-Rb-90m	2	42-Mo-105	1	54-Xe-139	1
37-Rb-92	2	43-Tc-102	1	54-Xe-140	1
38-Sr-89	2	43-Tc-103	1	55-Cs-142	3
38-Sr-97	2	43-Tc-104	1	56-Ba-145	2
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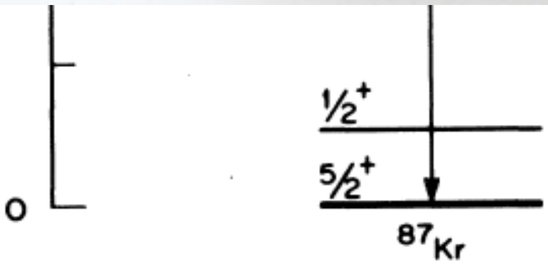
40-Zr-100	2	43-Tc-107	2		
41-Nb-98	1	51-Sb-132	1		

37 nuclides, of which 23 were given first priority, reports by A. Nichols.

Motivation of recently analyzed cases: ^{87}Br,^{88}Br



- Priority one in the IAEA list
- Moderate fission yields
- Pandemonium cases ?, 87Br is one of the best studied nucleus from high resolution
- Interest from the structure point of view: vicinity of n closed shell
- Competition between gamma and neutron emission above the Sn value

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

$$P_n = \frac{\int_{S_n}^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)\frac{\Gamma^n}{\Gamma^n+\Gamma^\gamma}\,dE_x}{\int_0^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)\,dE_x}$$

Analysis of ^{87}Br

$$d = R(B) \cdot f$$

Expectation Maximization (EM) method:
modify knowledge on causes from effects

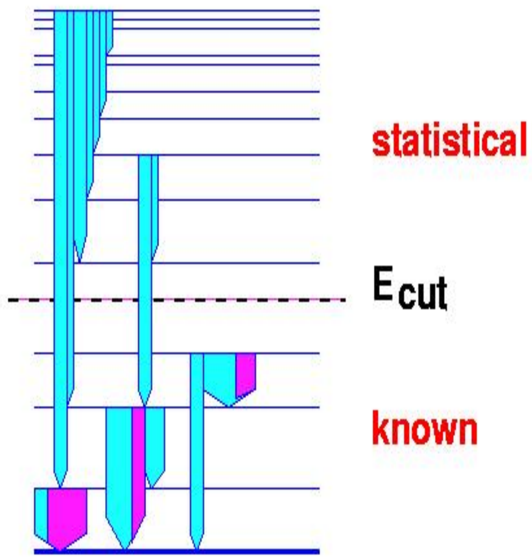
$$P(f_j | d_i) = \frac{P(d_i | f_j) P(f_j)}{\sum_j P(d_i | f_j) P(f_j)}$$

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

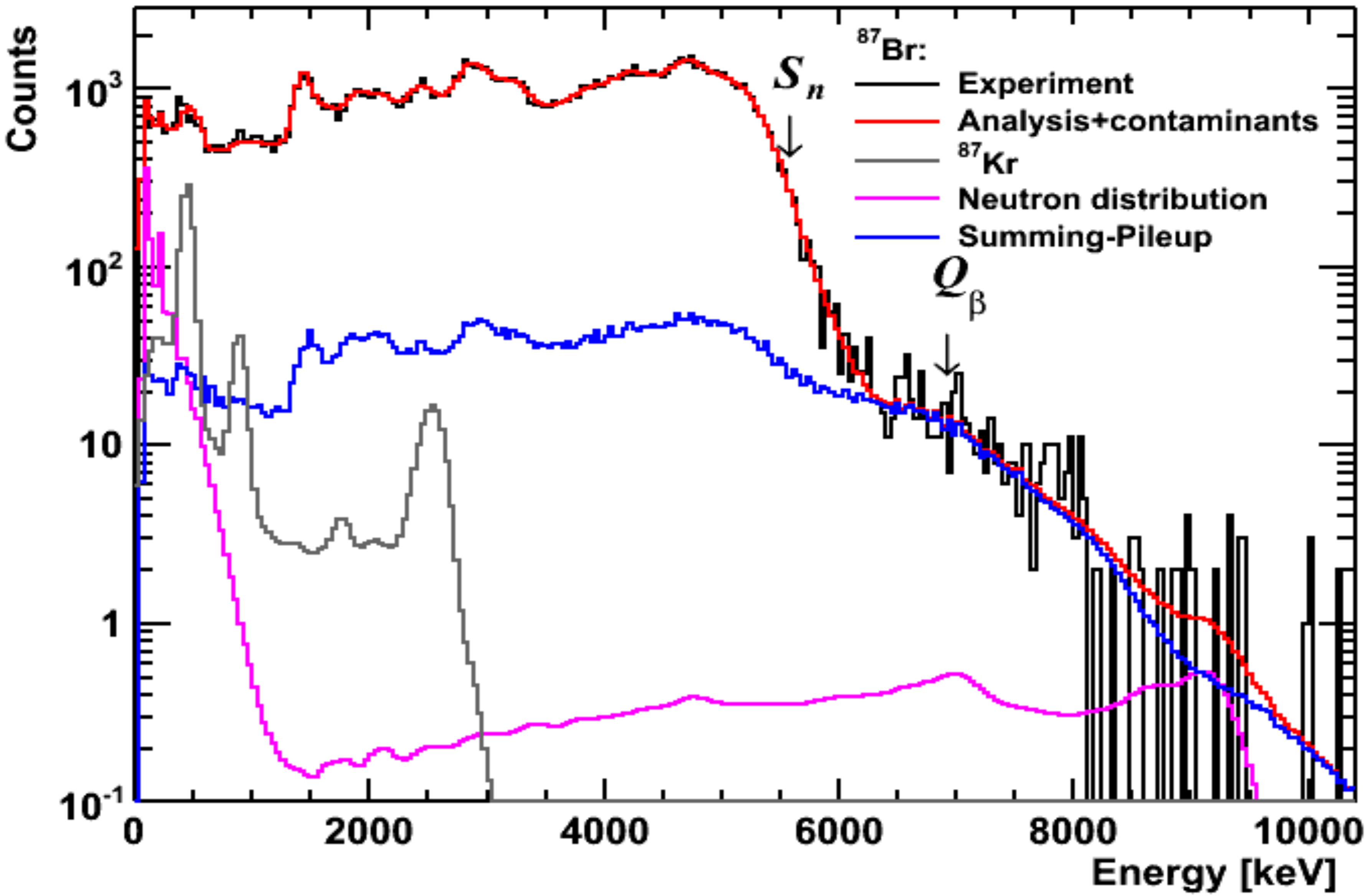
Tain et al. NIM A571 (2007) 719,728

Some details (d=R(B)f)
Known levels up to: 1520 keV excitation

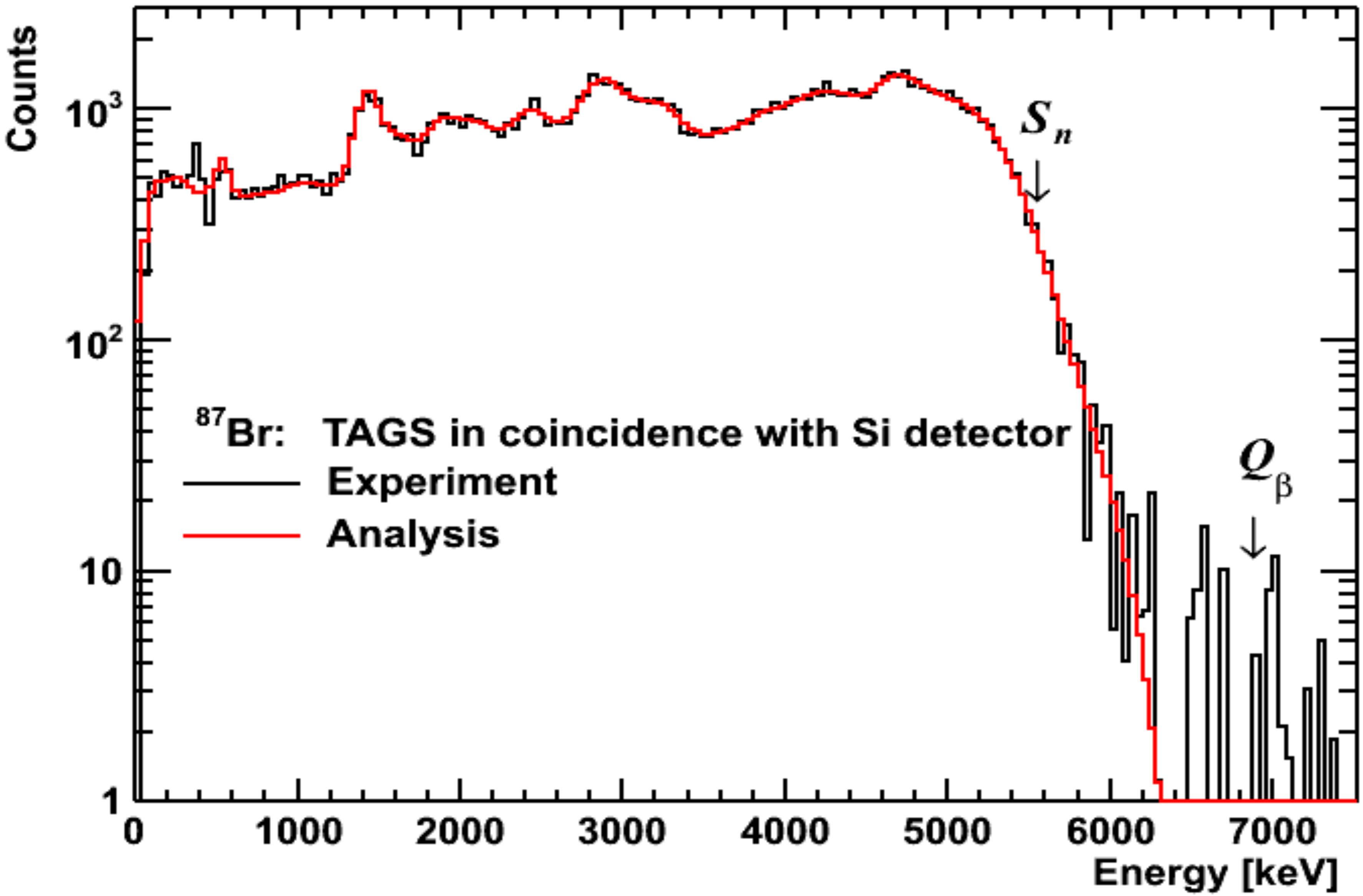
From 1520 keV excitation up to the Q_β =6852(18) value we use an statistical nuclear model to create the branching ratio matrix (Back Shifted Fermi formula for the level density & γ-ray strength functions)



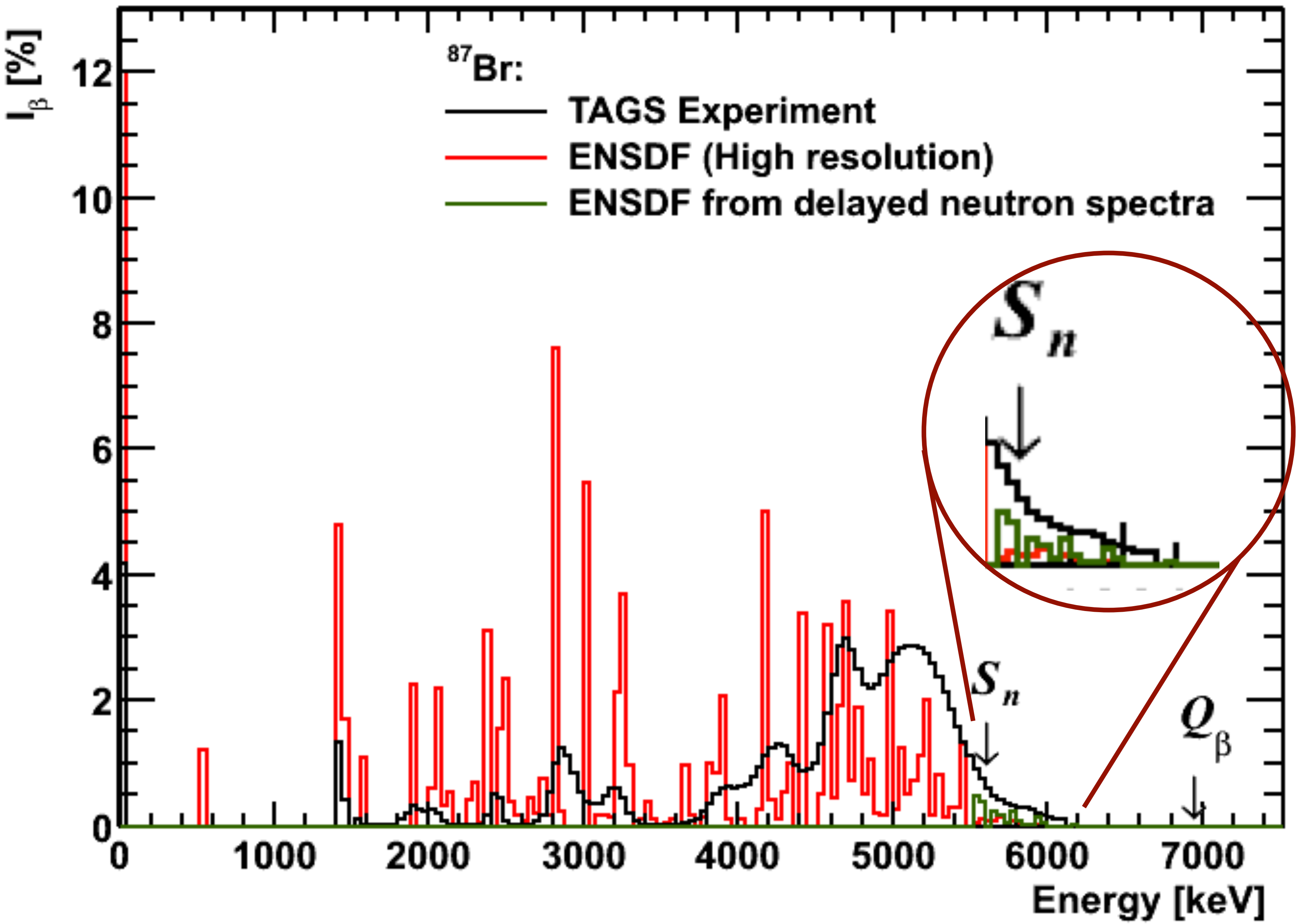
^{87}Br: meas. spectrum + contaminants + analysis



^{87}Br: clean spectrum + analysis



Deduced feedings from 87Br decay

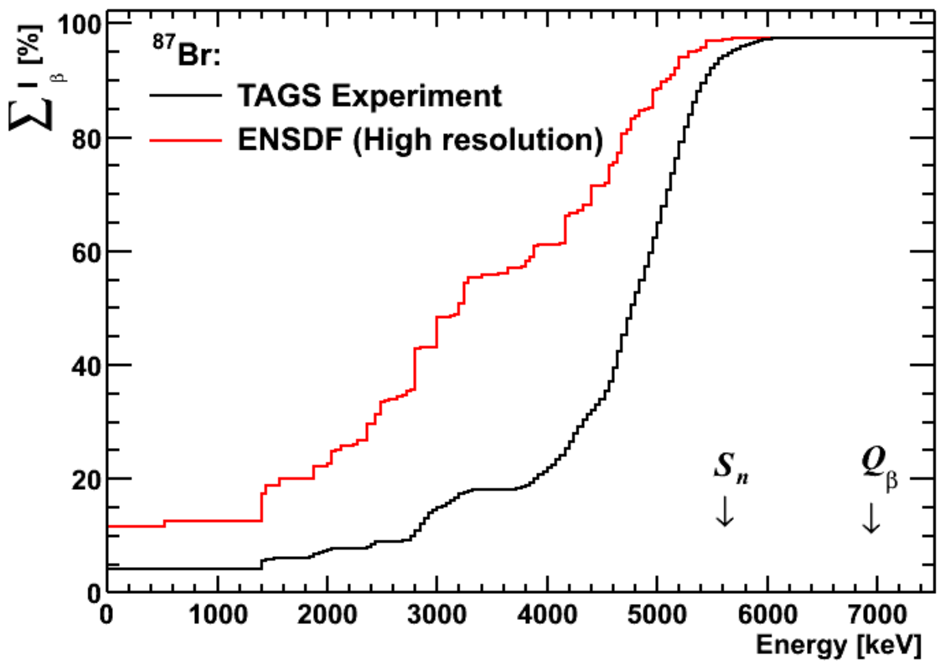


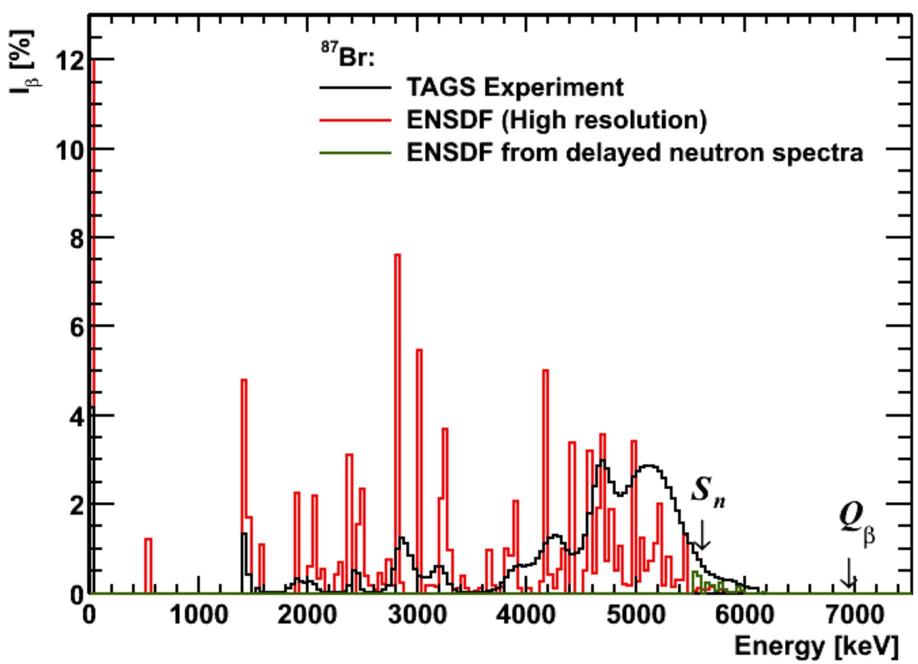
^{87}Br feedings and mean energies

	ENSDF	TAGS
$<E_\beta>$[keV]	1656(75)	1017(16)
$<E_\gamma>$ [keV]	3345(35)	4242(30)
% above Sn	0.58	< 5.4 %

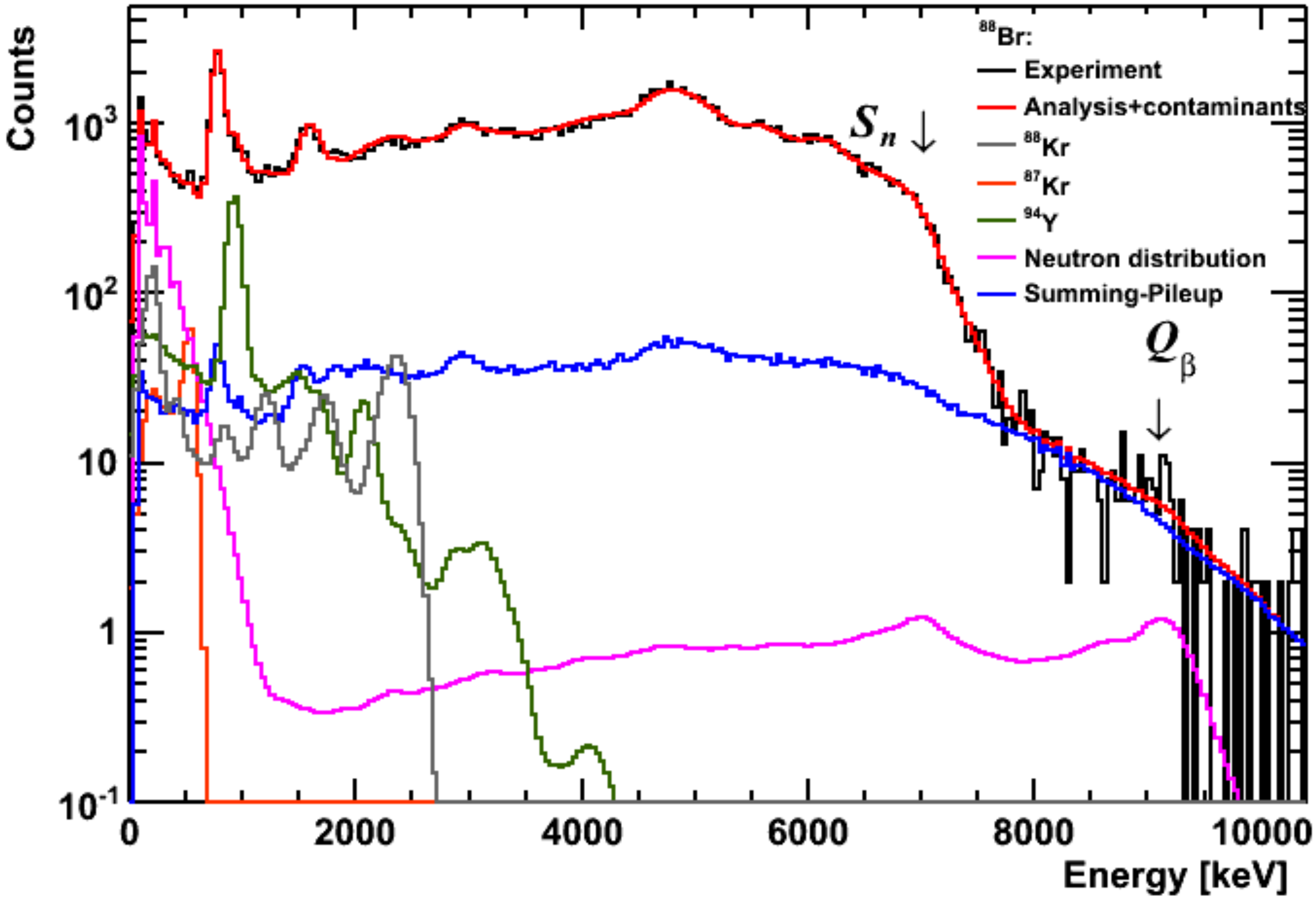
Q_β=6817(5) keV
Sn= 5515.4(8)
$T_{1/2}$=55.65(13) s
Pn (^{87}Br) = 2.52(7)%
Cum fiss. (^{235}U) =0.02
Cum fiss.(^{239}Pu) =0.005

Nuh et al. I_{gam}/I_n~0.9

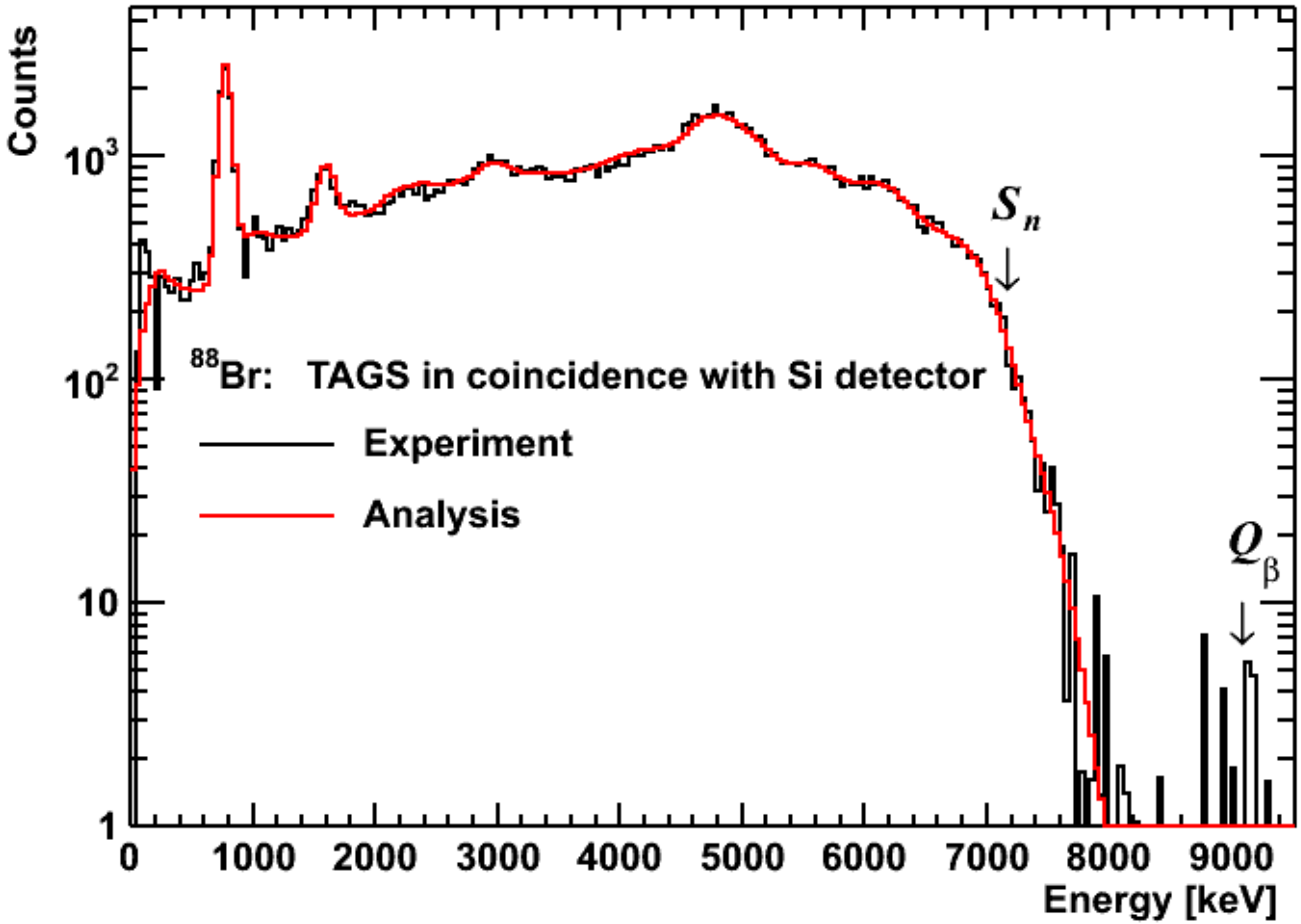




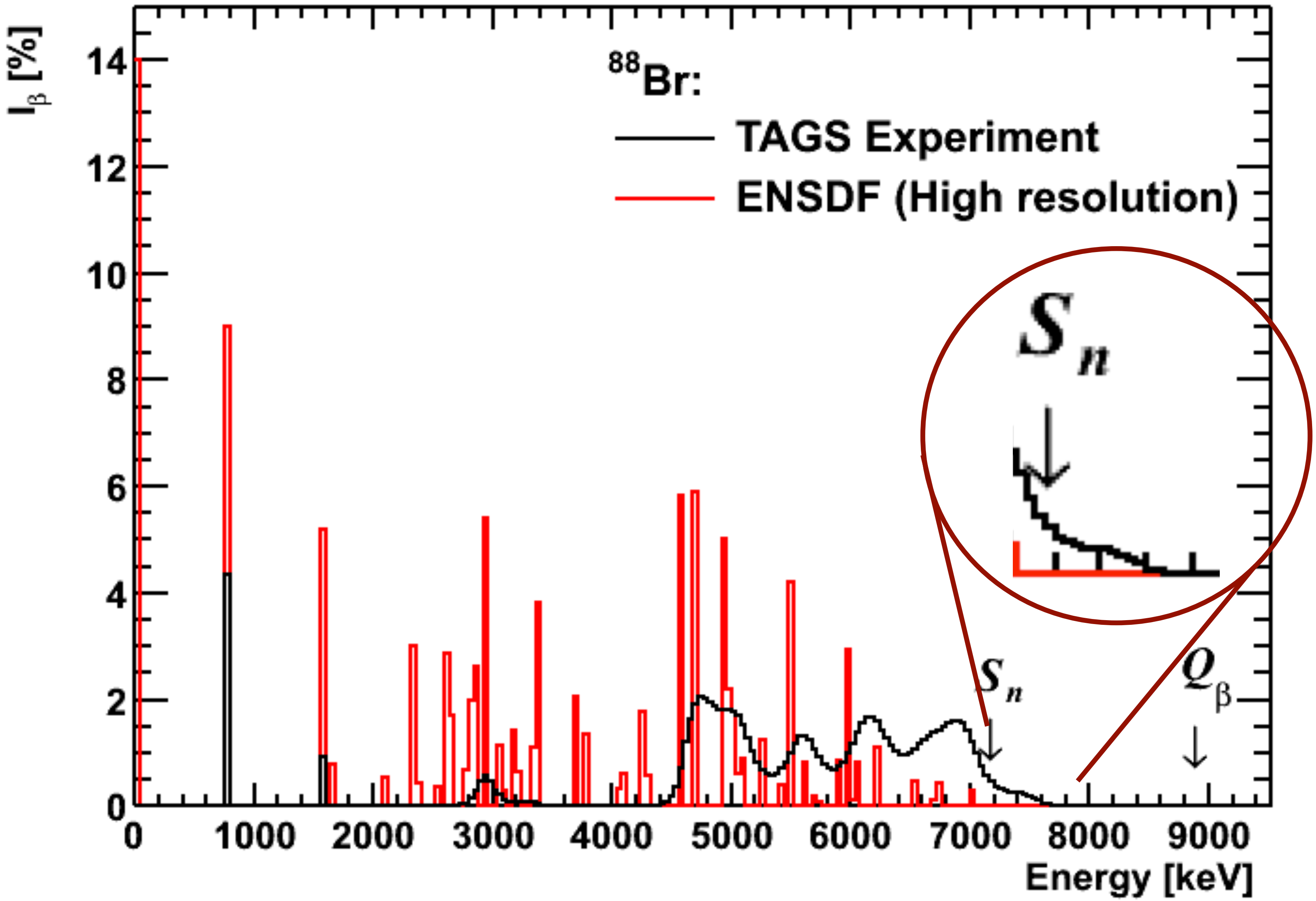
^{88}Br: meas. spectrum + contaminants + analysis



^{88}Br: clean spectrum + analysis



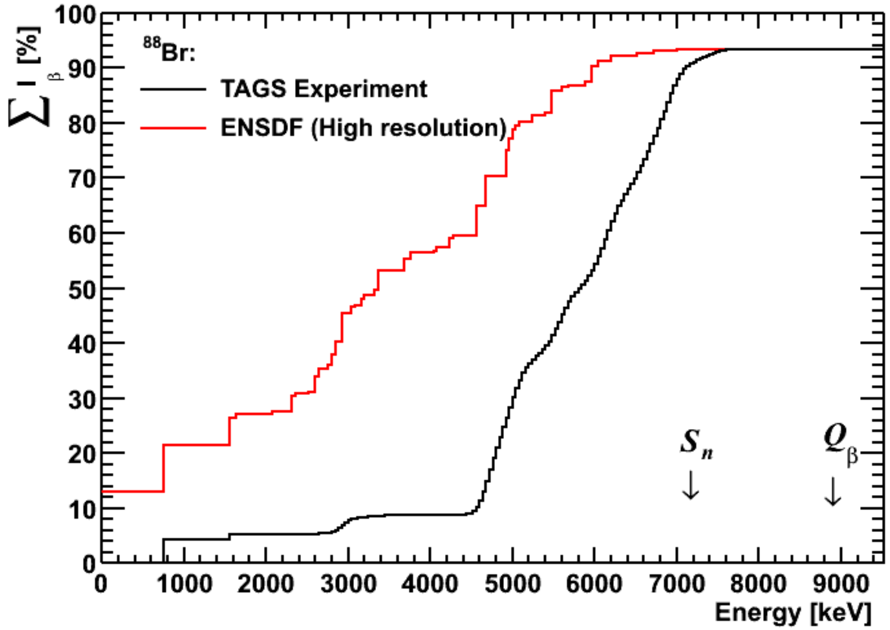
Deduced feedings from ^{88}Br decay

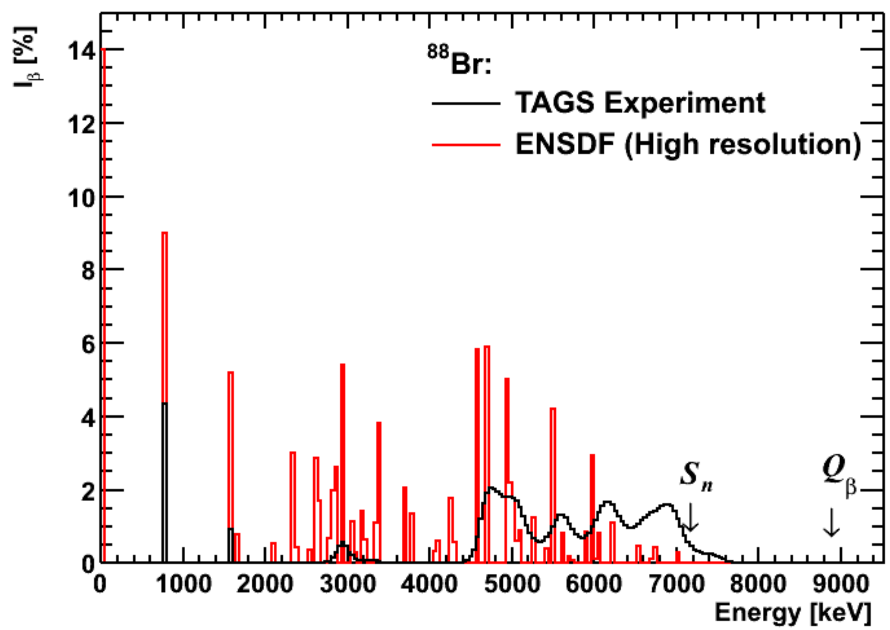


^{88}Br feeding and mean energies

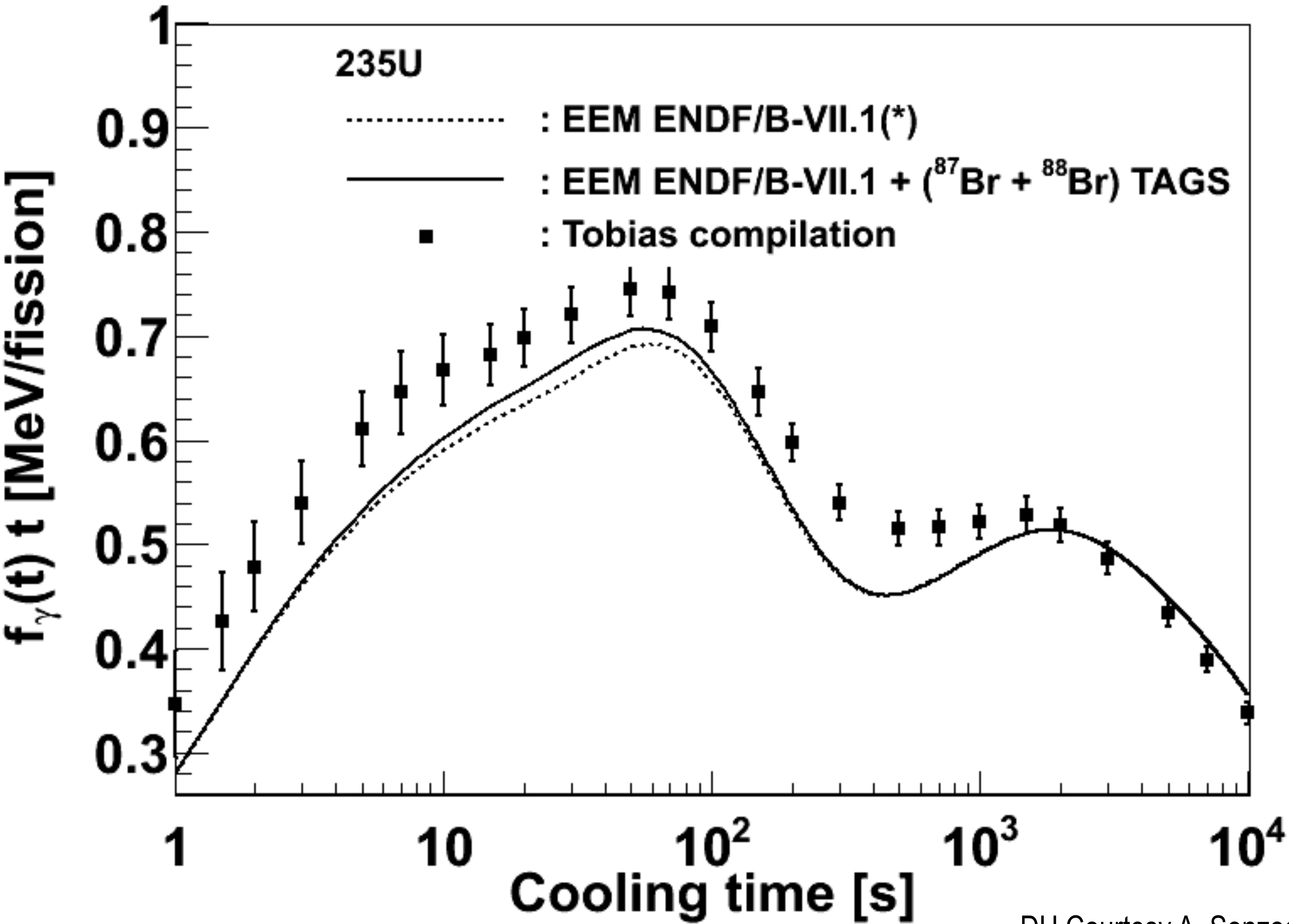
	ENSDF	TAGS
$\langle E_\beta \rangle$[keV]	2392(300)	1427(20)
$\langle E_\gamma \rangle$[keV]	3134(58)	5090(30)
% above Sn	0.0 %	< 3.2 %

Q_β=8975(5) keV
Sn= 7054(13) keV
$T_{1/2}$=16.29(6) s
Pn (^{88}Br) = 6.58(18)%
Cum fiss. (^{235}U) =0.018
Cum fiss.(^{239}Pu) =0.007





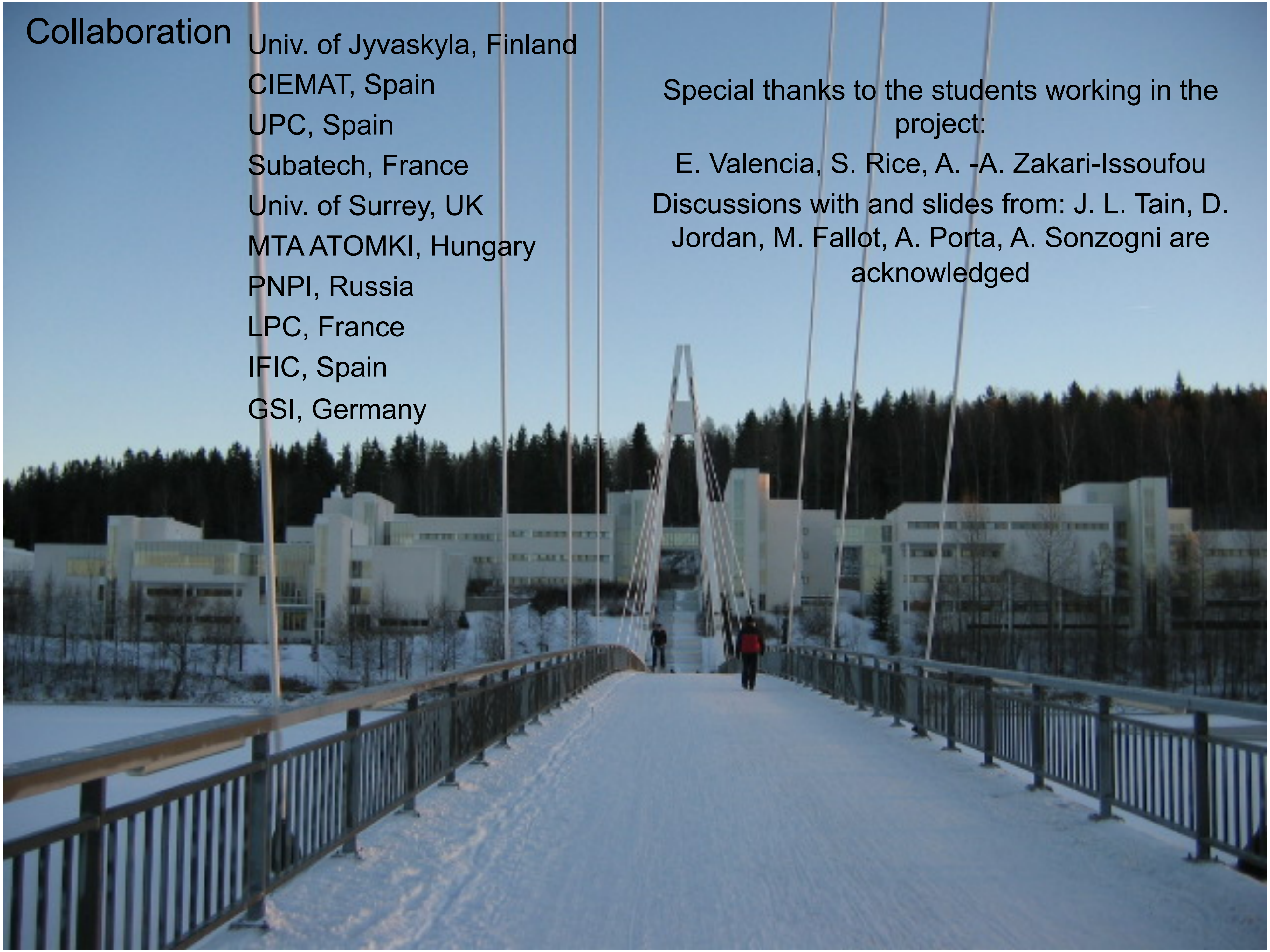
Impact of the results for ^{235}U



DH Courtesy A. Sonzogni

Conclusions

- The recently analyzed beta decay cases from the IAEA high priority list were presented (87,88Br)
- These nuclei show a moderate beta delayed neutron emission and competition between gamma and neutron emission above the Sn of the daughter. Both decays suffered from the Pandemonium effect.
- An open question is why we suffered from the gamma strength functions in the case of 87Br. Not typical situation.
- Those measurements will also have an impact in nuclear structure (as our earlier measurements) and in neutrino physics.



Collaboration

Univ. of Jyvaskyla, Finland
CIEMAT, Spain
UPC, Spain
Subatech, France
Univ. of Surrey, UK
MTA ATOMKI, Hungary
PNPI, Russia
LPC, France
IFIC, Spain
GSI, Germany

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