Total absorption spectroscopy applications to reactor neutrino physics

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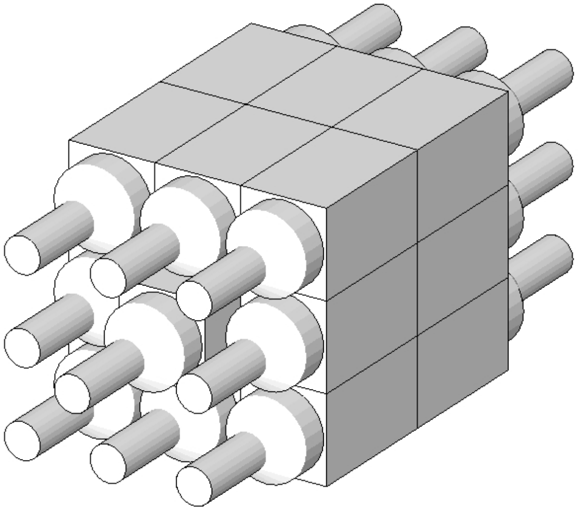
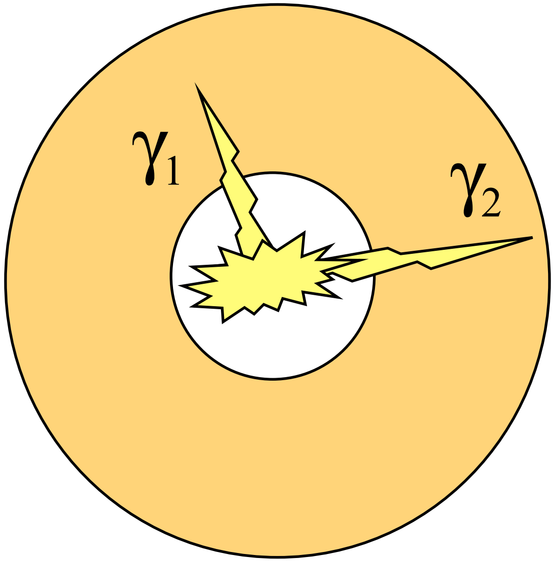
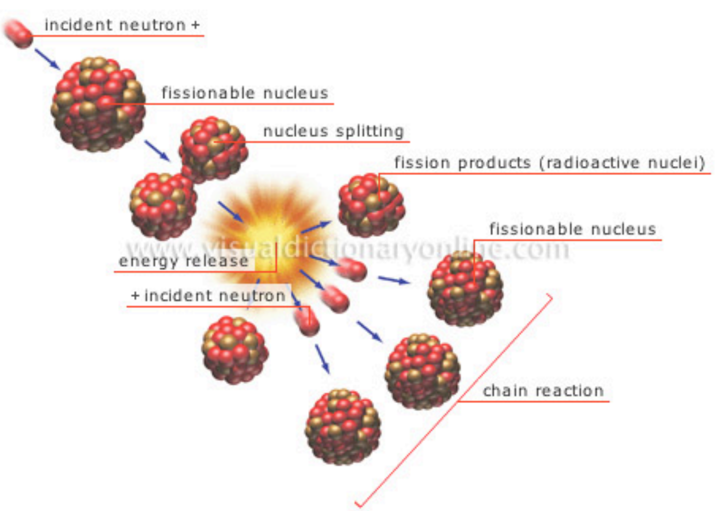




Solvay Workshop, Nov.-Dec. 2017

Fission process energy balance



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

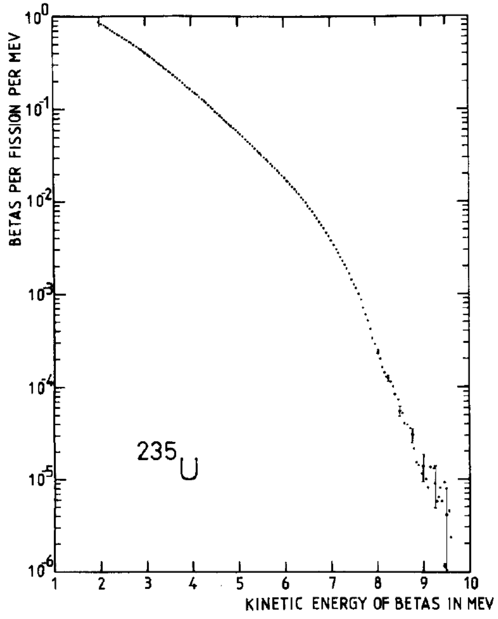
Each fission is approximately followed by 6 beta decays (sizable amount of energy)

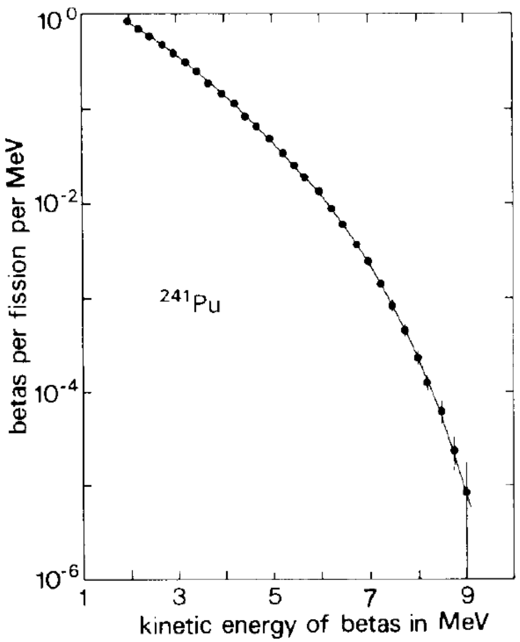
A reactor (1 GW thermal) produces 10^{20} v/s

Example of reactor neutrino oscillation experiment: Double Chooz, Θ_{13} (also: Daya Bay, Reno)

Determination of the primary antineutrino spectrum

• “Pure conversion procedure”: using the beta spectrum measured by Schreckenbach et al. from different fissile nuclides (^{235}U,$^{239,241}Pu$) and more recently ^{238}U (Haag et al.), which requires complex conversion procedures



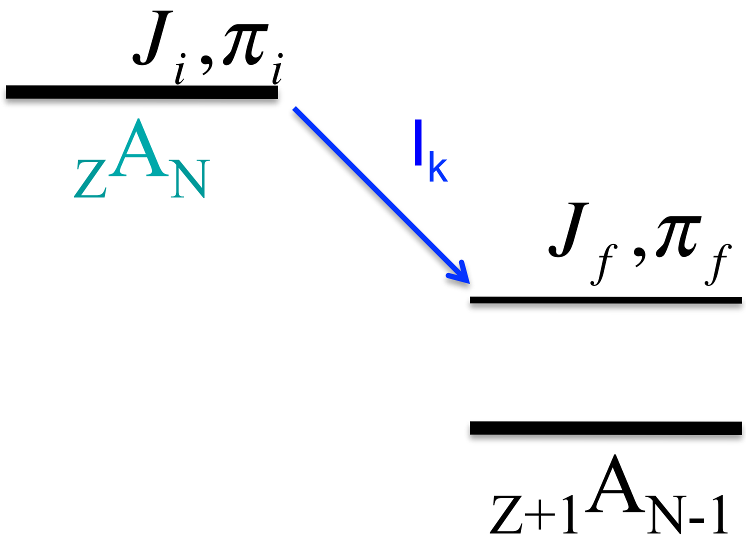


• “Pure” summation calculations (next slide), for many years the only posibility for ^{238}U

• “Mixed” solution (Huber-Mueller model)

Antineutrino and decay heat summation calculations

Beta decay (β^-)



Spectrum for each transition

$$J_i,\pi_i \rightarrow J_f,\pi_f$$

$$S(Q-E_k, J_i\pi_i, J_f\pi_f)$$

ν spectrum for the decay (n)

$$S_n(E)=\sum_k I_k S(Q-E_k, J_i\pi_i, J_f\pi_f)$$

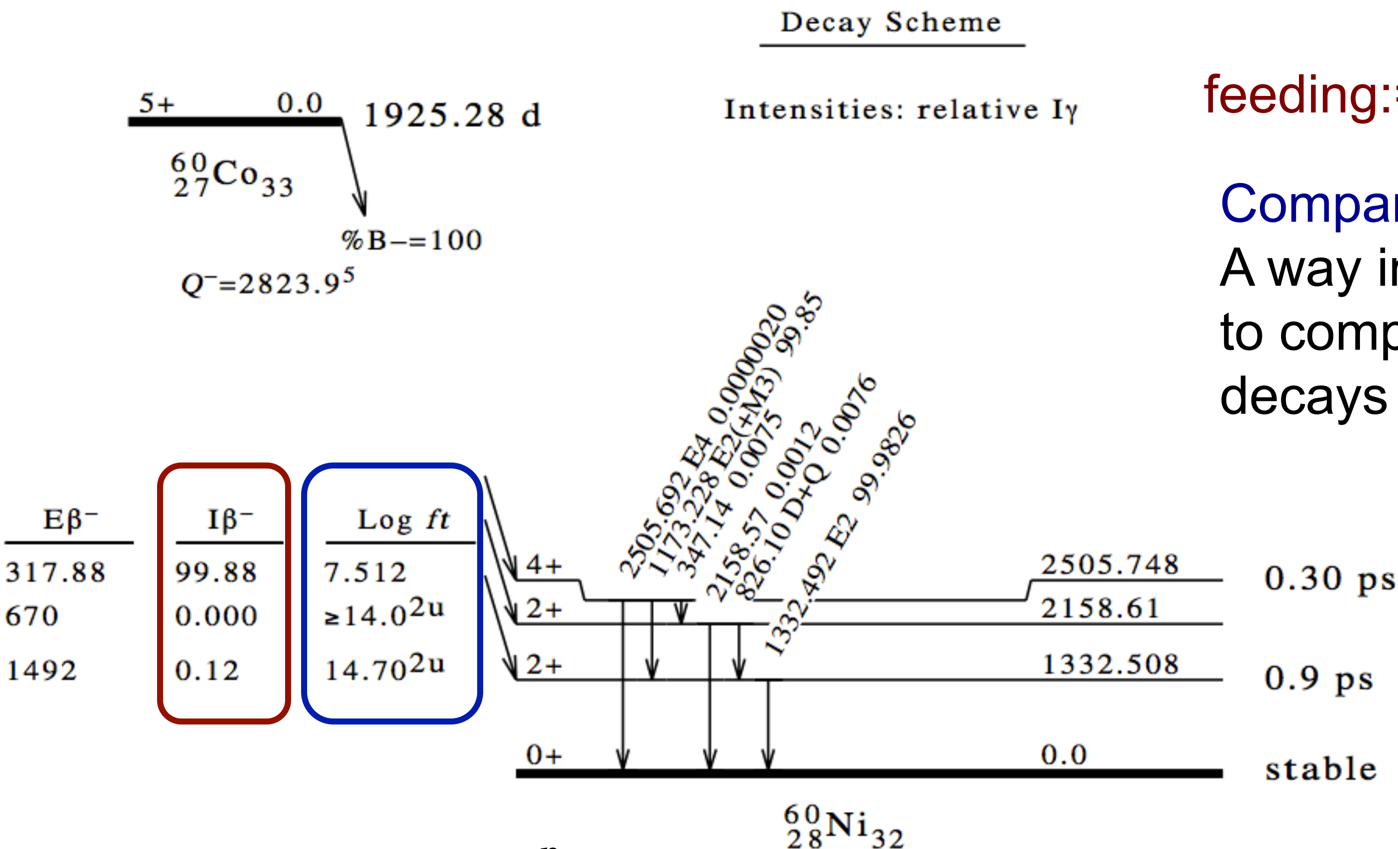
Anti-neutrino rate per fission (Vogel, 1981)

$$S(E)=\sum_n \lambda_n N_n S_n(E)/r=\sum_n CFY_n S_n(E)$$

Decay heat summation calculation

$$f(t)=\sum_i \overline{E_i}\lambda_i N_i(t)$$

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



feeding:=I_β = P_f*100

Comparative half-life: ft

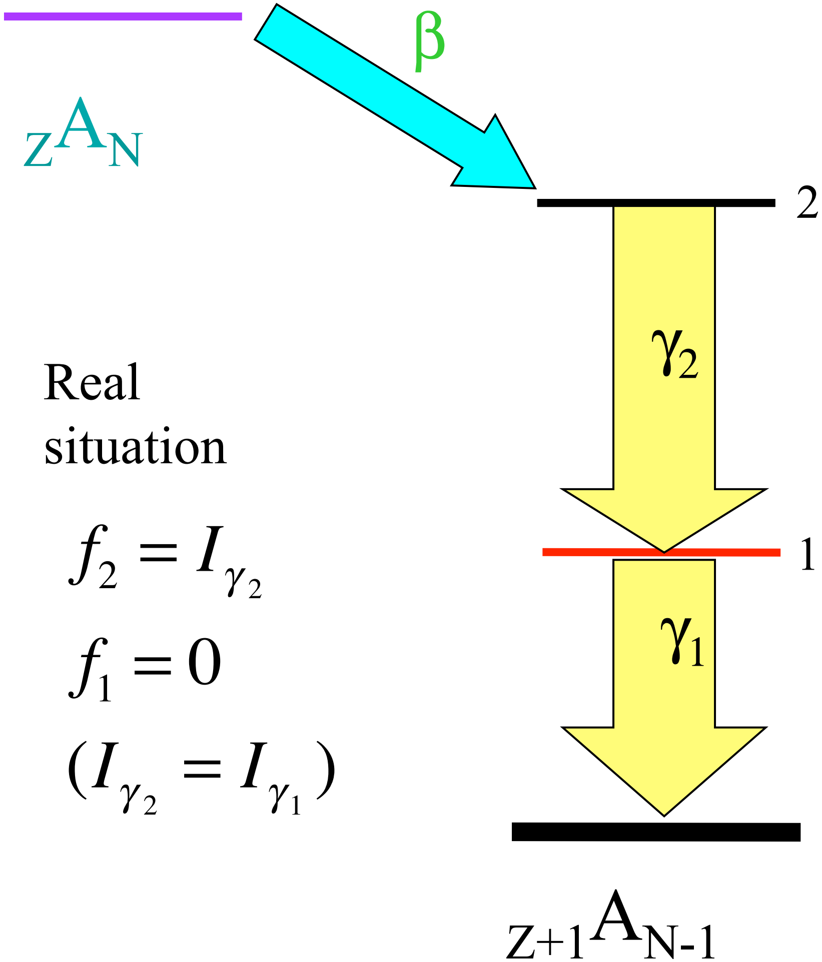
A way introduced by Fermi to compare the different decays (Q, Z')

$$f(Z',Q) = const \cdot \int_0^{p_{\max}} F(Z',p)p^2(Q-E_e)^2\,dp, \qquad t_f = \frac{T_{1/2}}{P_f}$$

$$ft_f = const' \frac{1}{\left|M_{if}\right|^2}$$

$$T_{1/2} = \frac{\ln(2)}{\lambda} = \tau \ln(2)$$

The problem of measuring the β-feeding

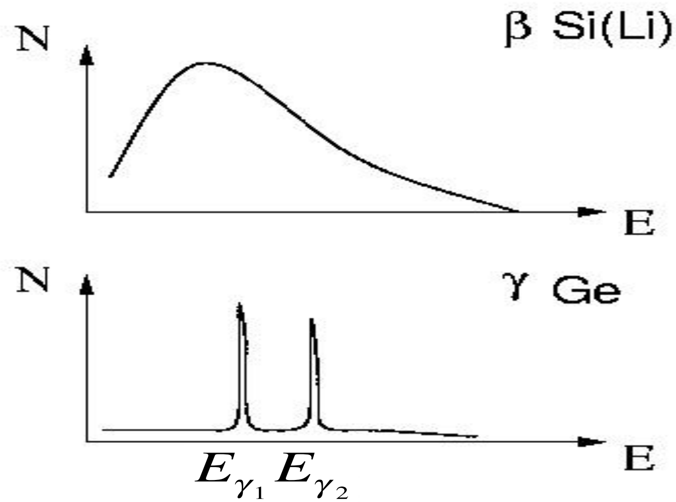


Real situation

$$f_2 = I_{\gamma_2}$$

$$f_1 = 0$$

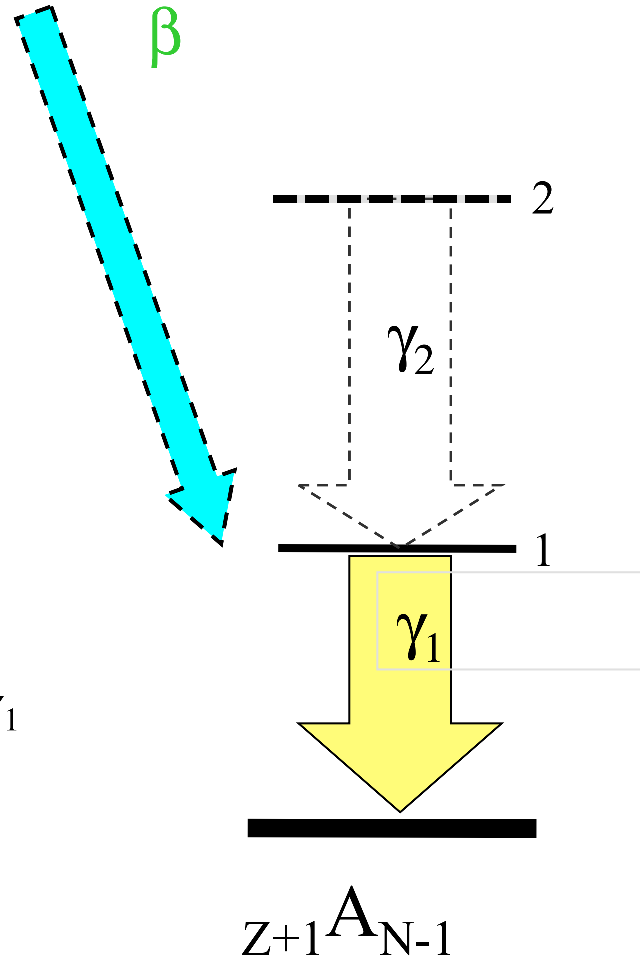
$$(I_{\gamma_2} = I_{\gamma_1})$$



- Ge detectors are conventionally used to construct the level scheme populated in the decay
- From the γ intensity balance we deduce the β-feeding

Experimental perspective: the problem of measuring the β- feeding

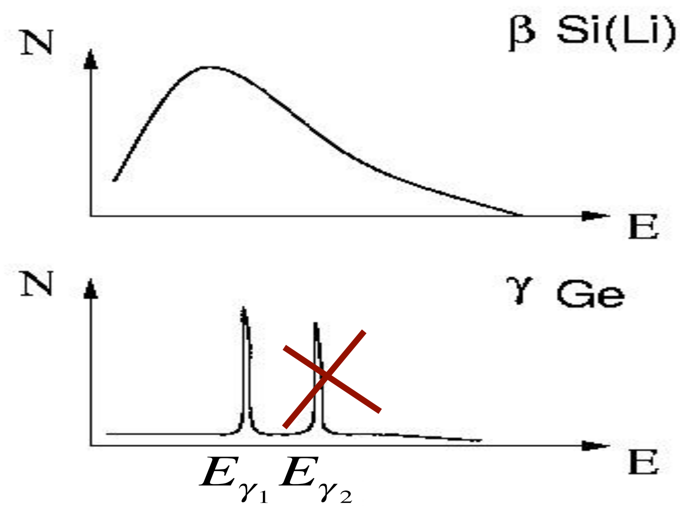
$_{Z}A_{N}$



Apparent situation

$$f_2 = 0$$

$$f_1 = I_{\gamma_1}$$



- What happens if we miss some intensity

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

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

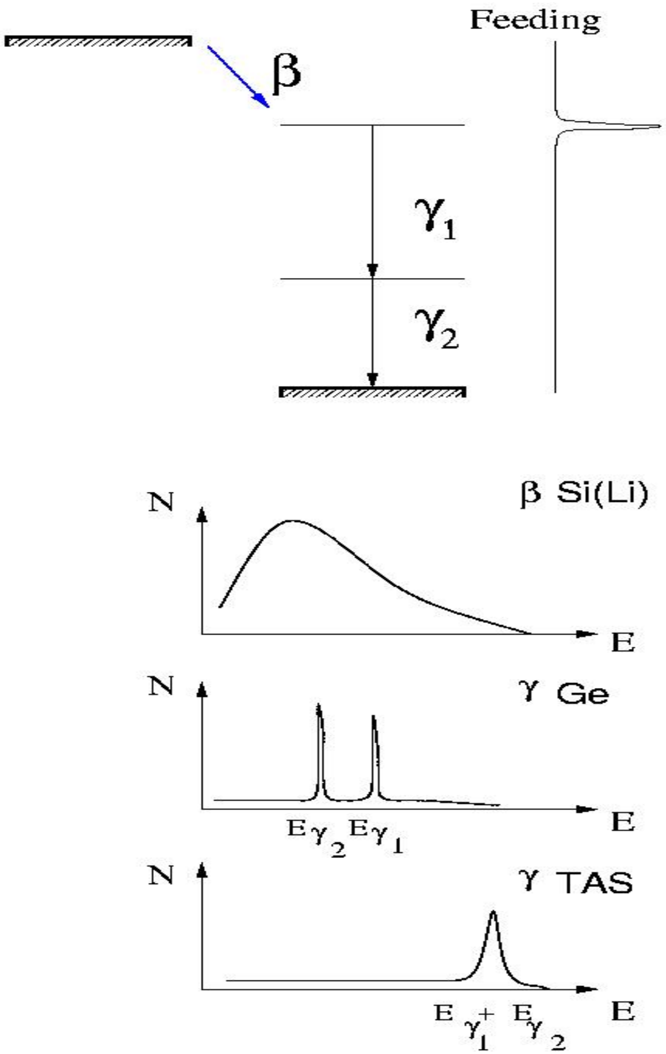
Pandemonium (The Capital of Hell)

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

John Martin (~ 1825), presently at Louvre

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:

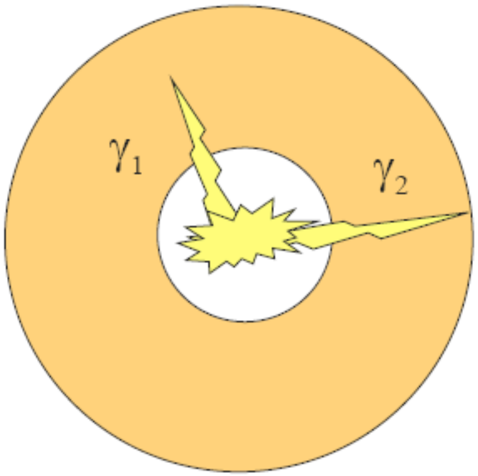
A TOTAL ABSORPTION SPECTROMETER

But if you built such a detector instead of detecting the individual gamma rays you can sum the energy deposited by the gamma cascades in the detector.

A TAS is like a calorimeter!

Big crystal, 4π

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

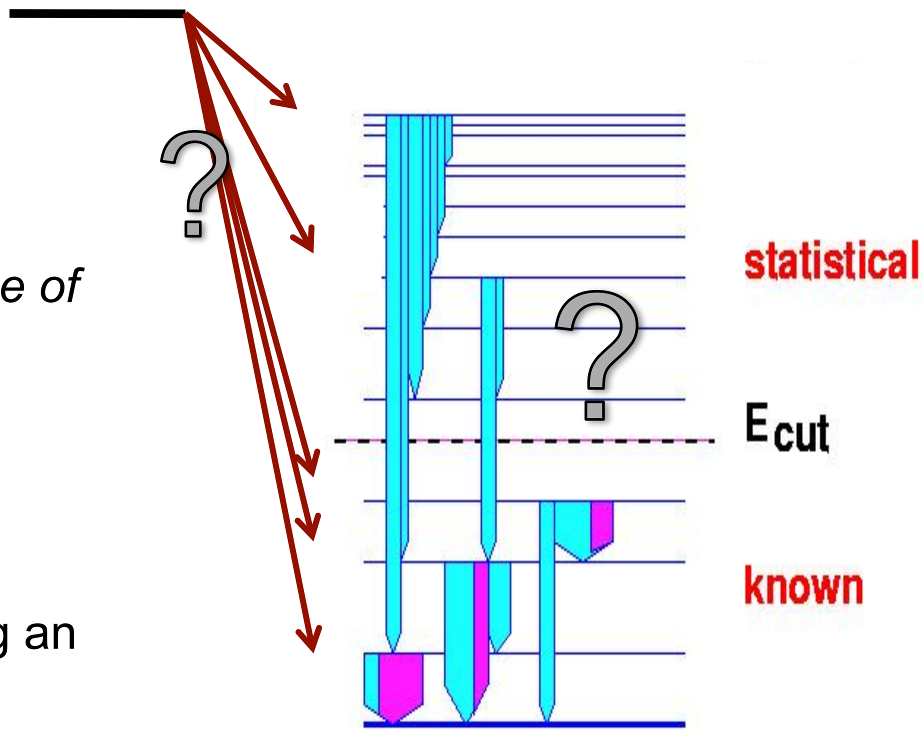


The complexity of the TAGS analysis: an ill posed problem

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

Primary question: f determination
but there is an incomplete knowledge of the level scheme populated

Steps:
1. Define B (branching ratio matrix)
2. Calculate R(B) (MC sim.)
3. Solve the equation d=R(B)f using an appropriate algorithm



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

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

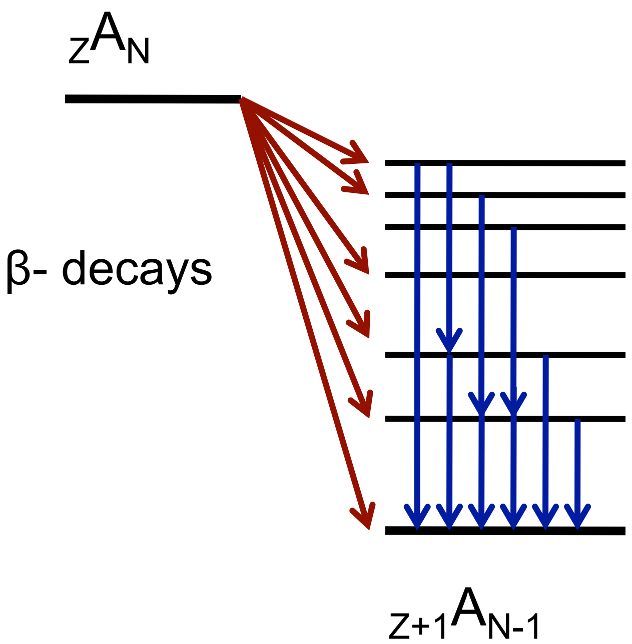
Algorithm:

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

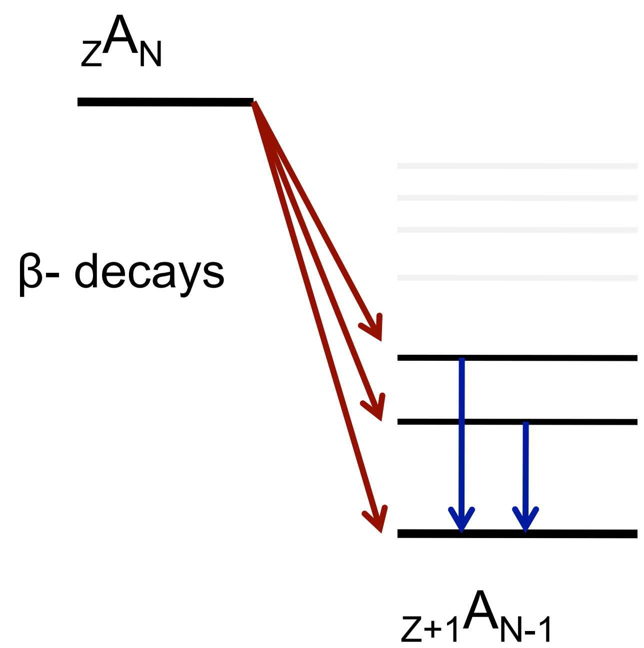
Mathematical formalization by Tain, Cano, et al.

Pandemonium and summation calculations

Real situation

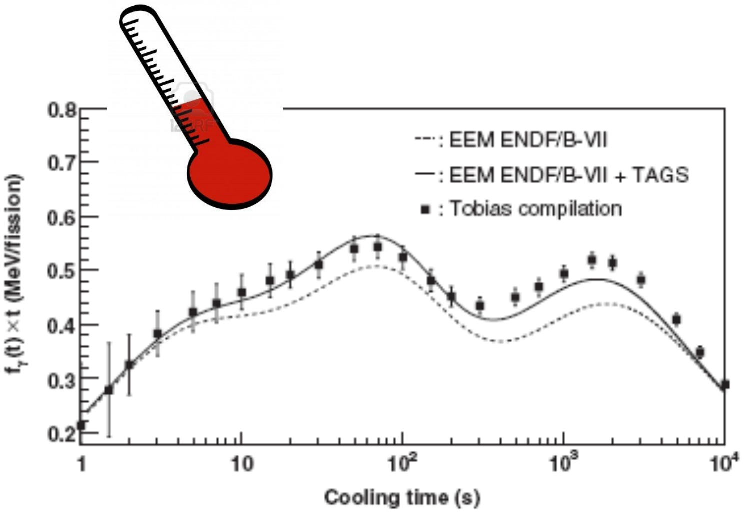


Pandemonium situation



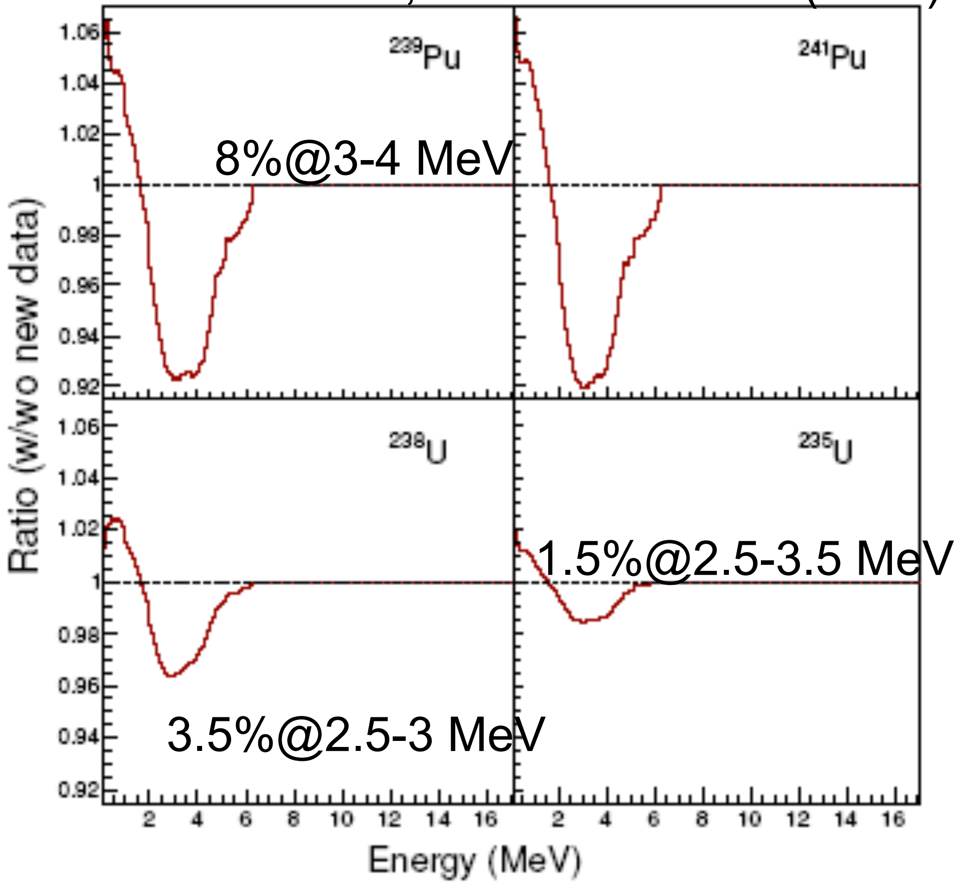
As a result of the Pandemonium, betas and neutrinos are estimated with higher energies from databases. This is why TAS data is very important

Impact of some of our earlier data



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

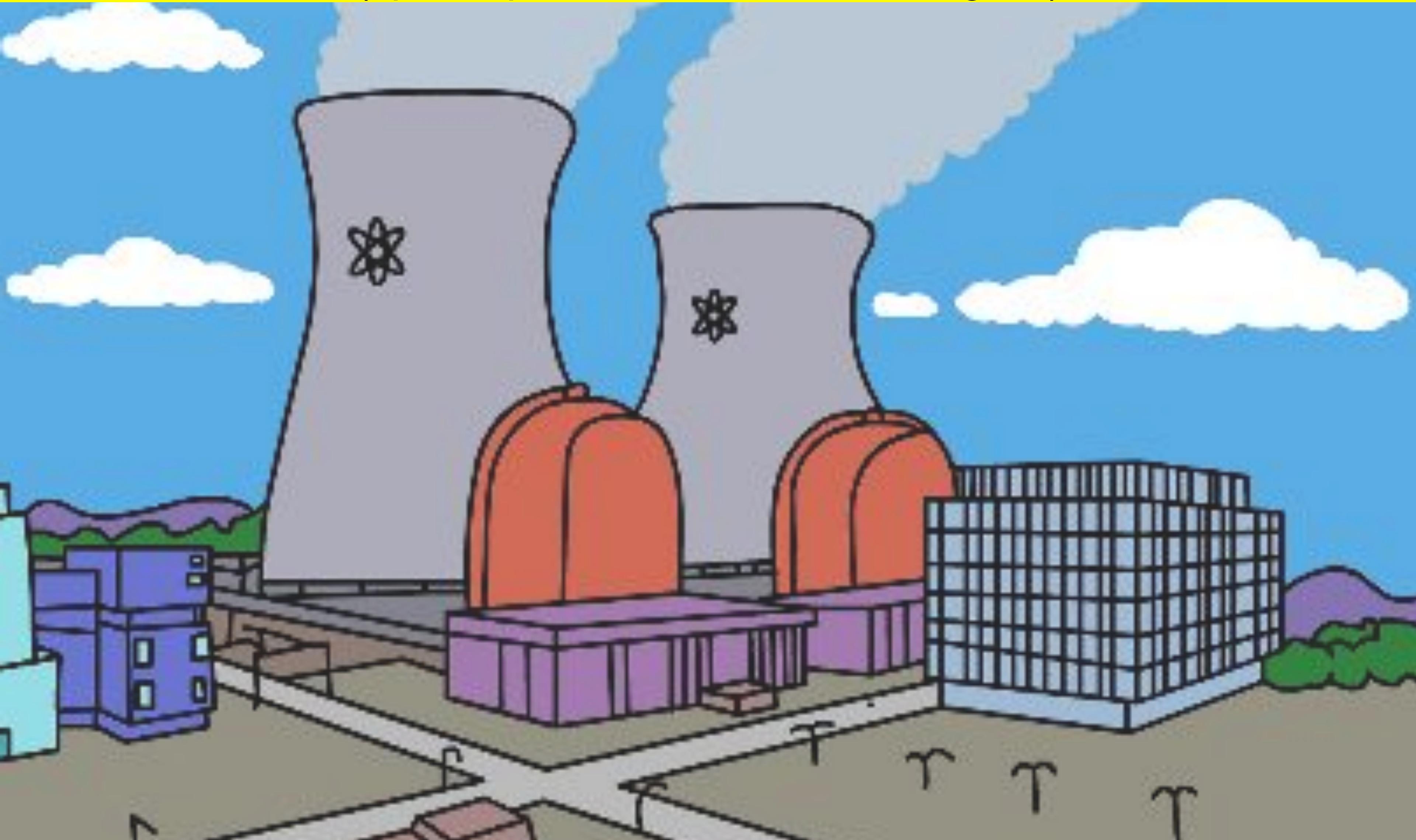
M. Fallot et al., PRL 109.202504 (2012)



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

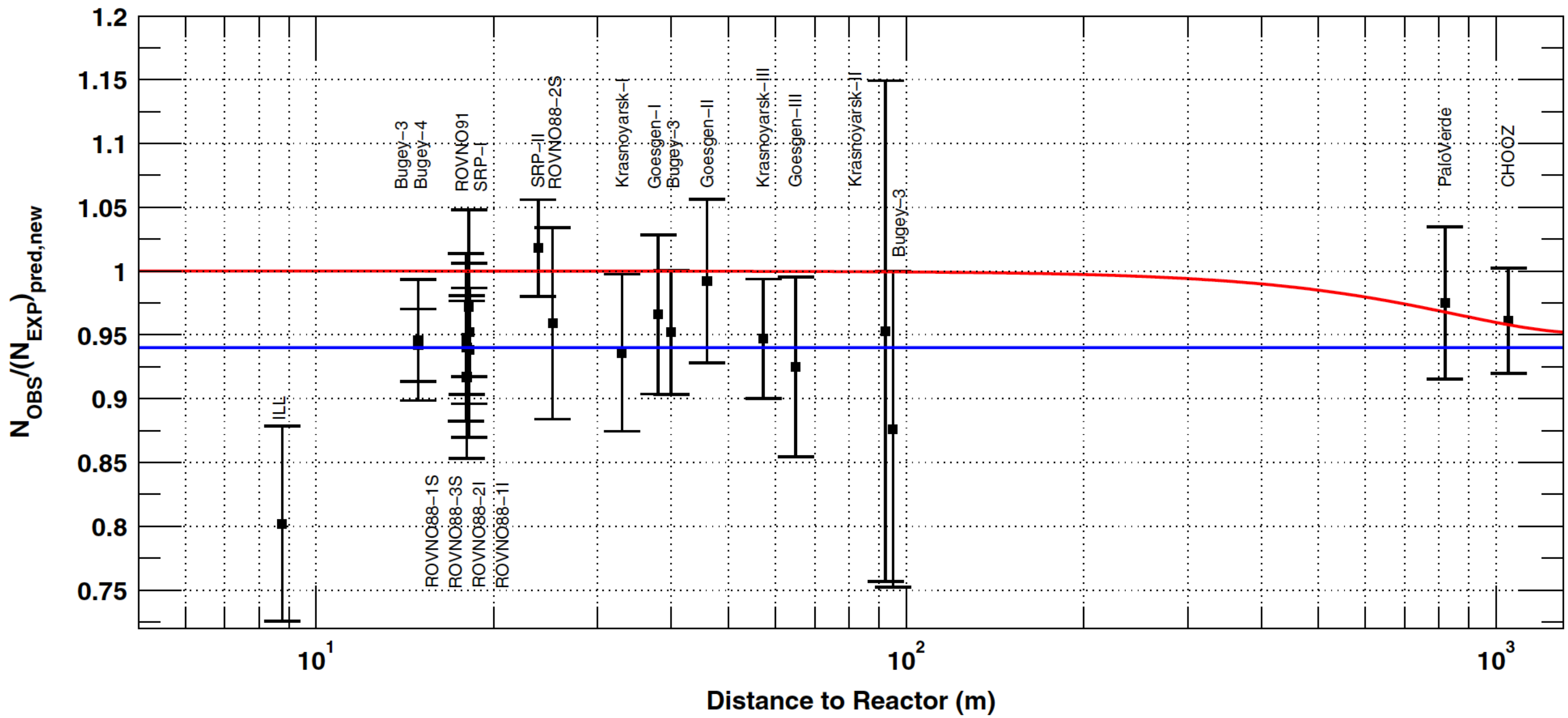
TAS and reactor neutrinos: I153 experiment (Univ. Jyväskylä)

(spokespersons: Fallot, Tain, Algora)



New questions: reactor anomaly ?

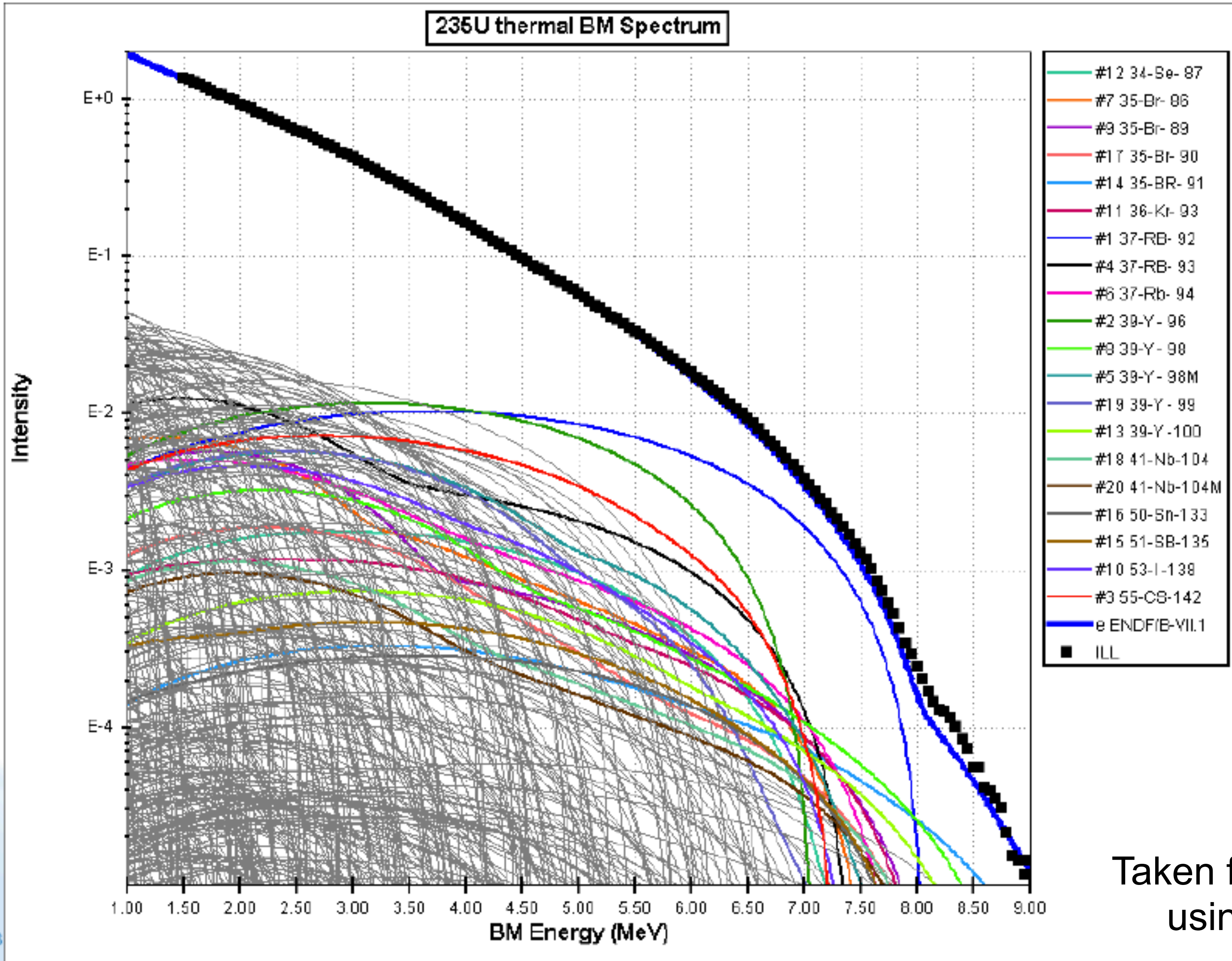
G. MENTION *et al.* PHYSICAL REVIEW D **83,** 073006 (2011)



Possible explanations:

- wrong conversion procedure, missing corrections?
- wrong reactor flux ?
- bias in all short base line experiments
- sterile neutrino ?, etc.

Role of individual decays



How to identify the main players

- Large cum. fission yields
- Large decay Q_{beta}
- Large beta feeding to gs

Taken from A. Sonzogni using ENDF VII.1

Identification of the main players

TABLE I. Main contributors to a standard PWR antineutrino energy spectrum computed with the MURE code coupled with the list of nuclear data given in Ref. [12], assuming that they have been emitted by ^{235}U (52%), ^{239}Pu (33%), ^{241}Pu (6%), and ^{238}U (8.7%) for a 450 day irradiation time and using the summation method described in Ref. [12].

	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%

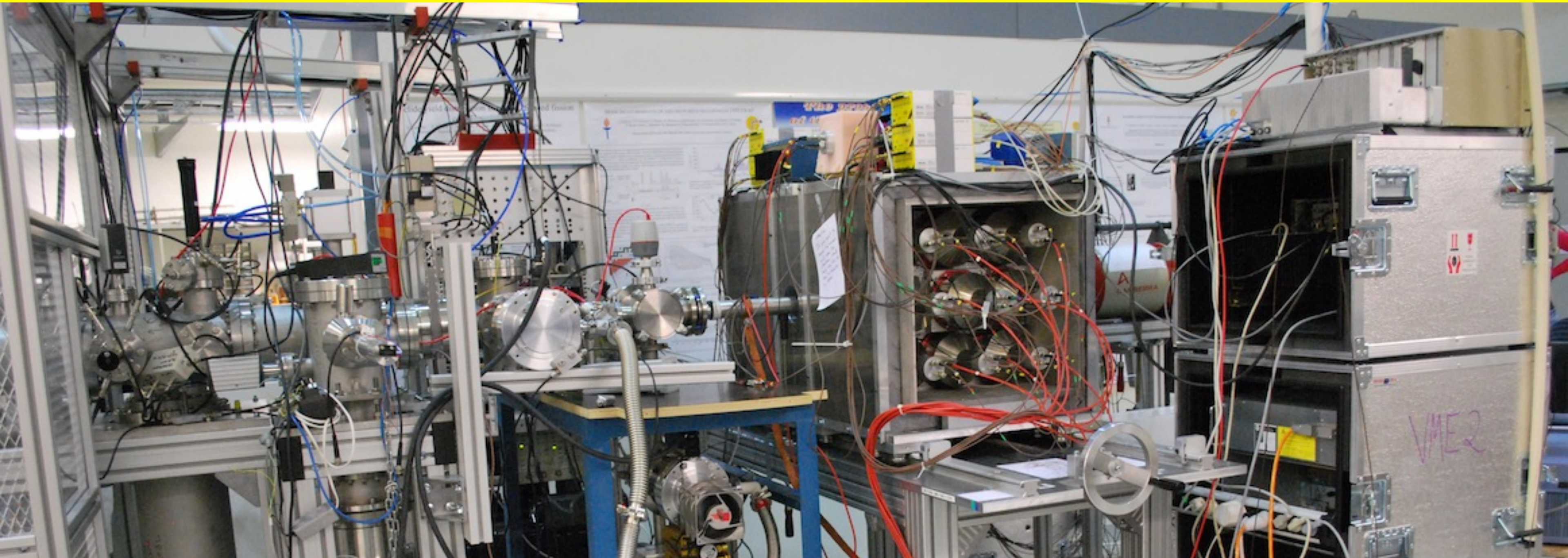
Table from Zakari-Issoufou et al. PRL 115.102503(2015)

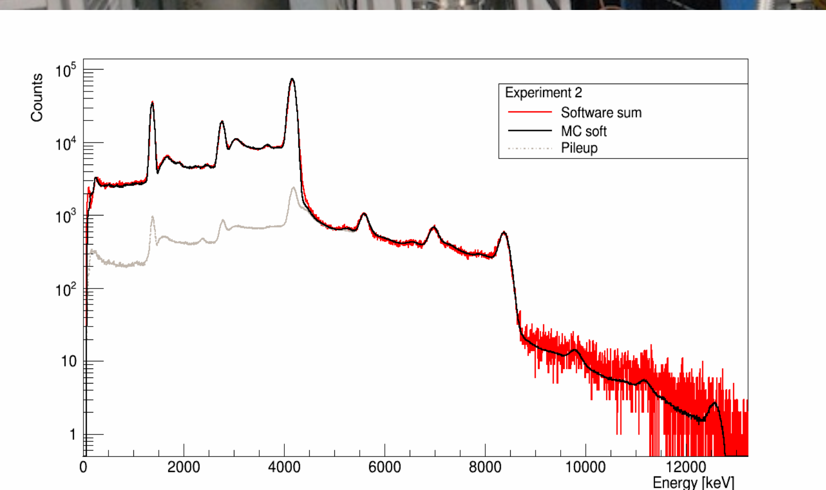
How to identify the main players

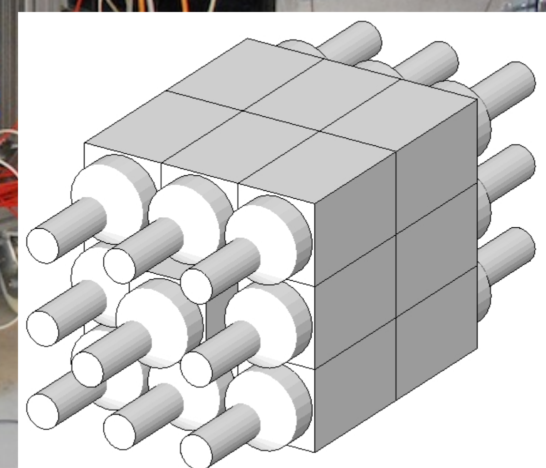
- Large cum. fission yields
- Large decay Q_{beta}
- Large beta feeding to gs

DTAS at Jyväskylä (Feb. 2014)

(collaboration with Subatech, spokespersons: Fallot, Tain, Algora)





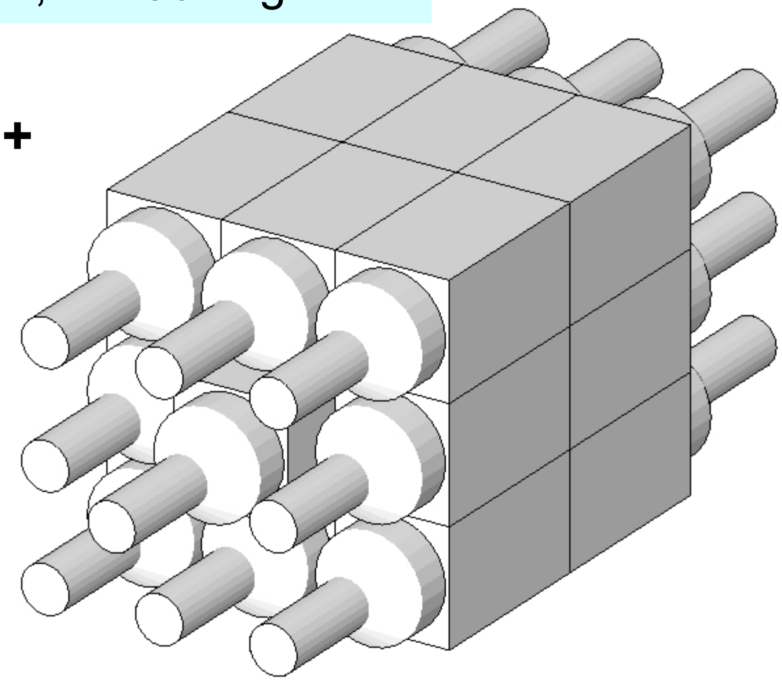


DTAS detector for DESPEC

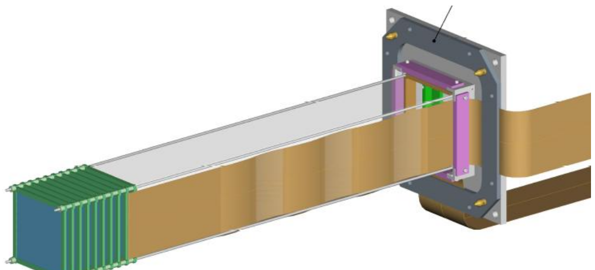
16 + (2) modules:
15 x15 x 25 cm^3 **NaI(Tl)**
+ 5" PMT (50% light col.)
V= 95 L, M= 351 kg

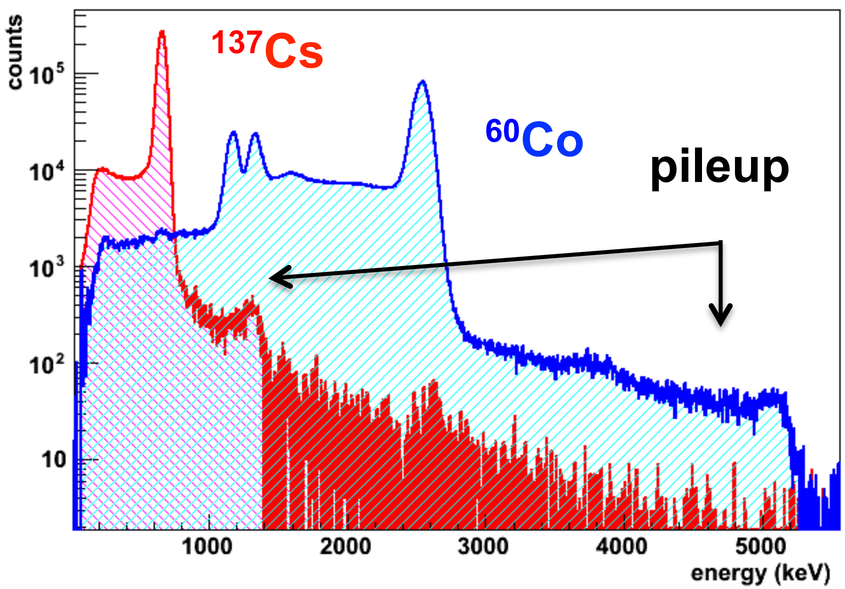
Tot eff ~90%

TAS+



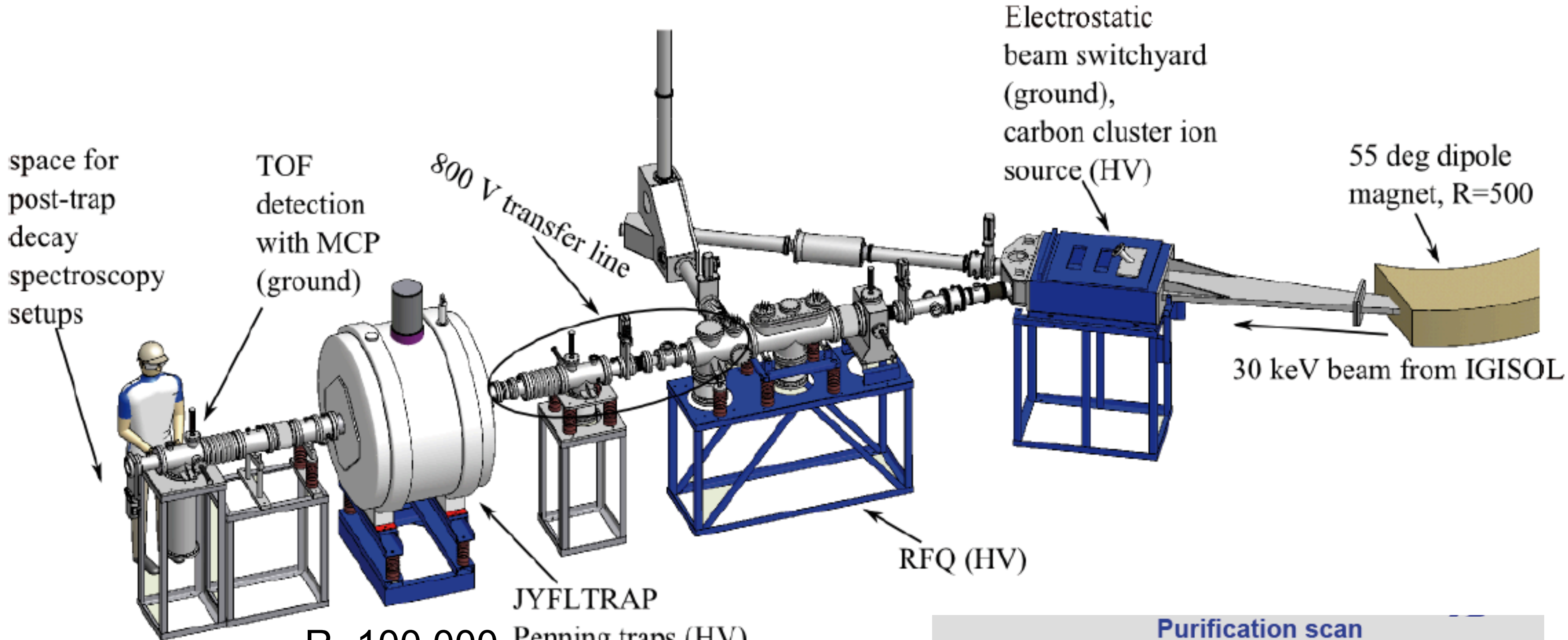
Fast ions active stopper: AIDA (Stack of DSSSD)





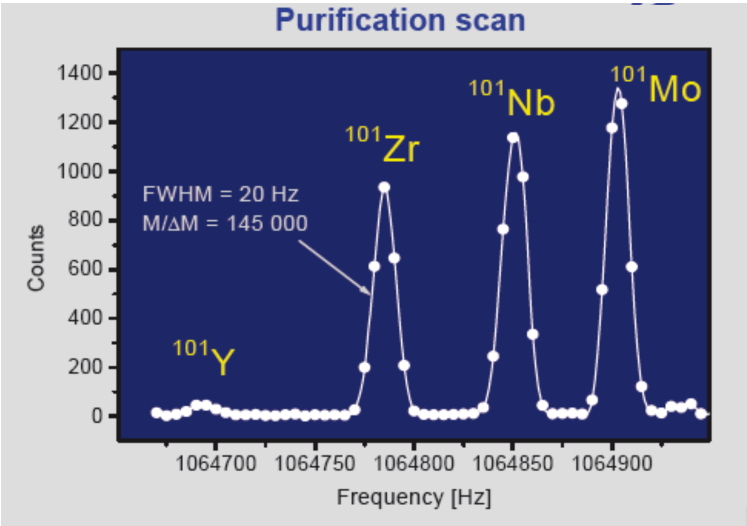
Convener: J. L. Tain (IFIC)
Funded by : 2 FPA and 1 AIC projects
(PIs: Tain, Algora)
TDR approved (01/2013)
Commissioning at IFIC (01/2014)
First experiments at JYFL (02-03/2014)

Why JYFL?: IGISOL + a bonus



R~100 000

The main reasons are the chemical insensitivity (ion guide technique), high purity by means of purification of the beam using the JYFLTRAP and acceptable yields!



JYFL Accelerator News

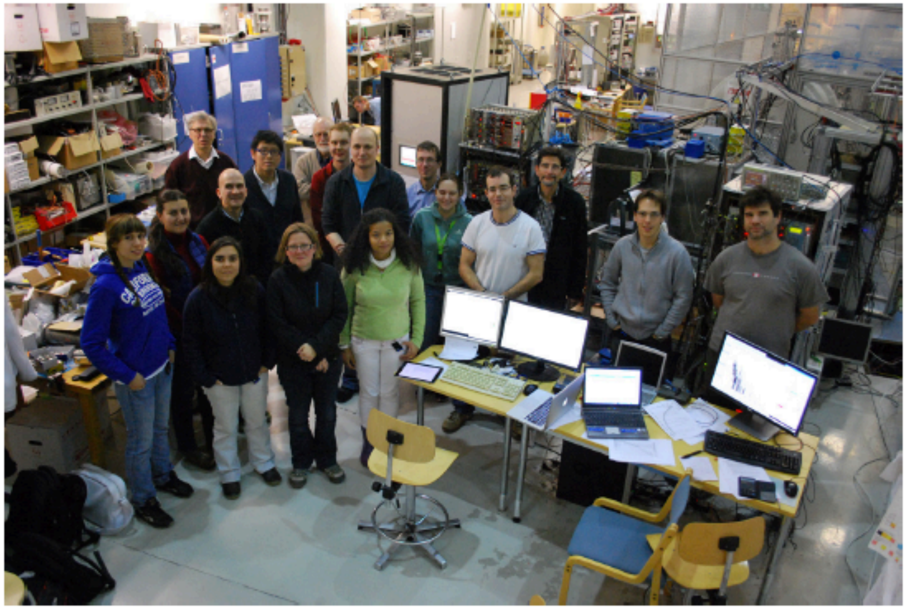
Accelerator Laboratory, Department of Physics
University of Jyväskylä, Finland

Volume 21, No. 1 February 2014

A new era of physics opportunities commences at IGISOL-4

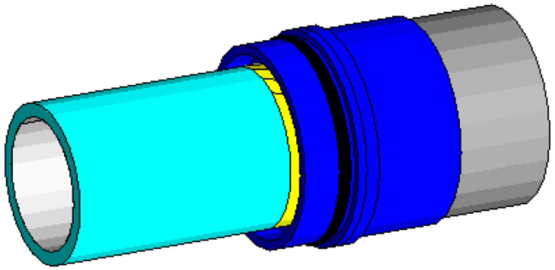
2013 marked an impressive year in the progress of the IGISOL-4 commissioning phase. In addition to test and development time, 40 days of cyclotron beam time were used for five PAC-approved experiments. One highlight was the visit by an external group of experimenters in November/December led Bertram Blank and his colleagues from Bordeaux. That run focused on measurements of beta-decay half-lives and branching ratios of mirror nuclei.

The coming year promises much activity and has already been a very busy time for the local group. Our colleagues from the UK saw in the first experiment of 2014 with collinear laser spectroscopy of fission fragments. Soon after, visitors from York and Aarhus, Denmark, utilized the new MCC30/15 cyclotron in a week of successful yield testing for the production of ^{12}N. In the past month, an impressive group of approximately 25 visitors mainly from Valencia in Spain, and Subatech, Nantes, in France arrived along with three tonnes of equipment. In two back-to-back experiments geared at measurements of the beta-decay strength of ^{100}Tc and a study of nuclei relevant for precise predictions of reactor neutrino spectra, JYFLTRAP has been used to provide high purity beams for a new total absorption gamma ray spectrometer (DTAS). The latter device consists of 18 NaI crystals and has been designed to be used by the DESPEC collaboration at NUSTAR, FAIR. IGISOL-4 is therefore finally back in business!

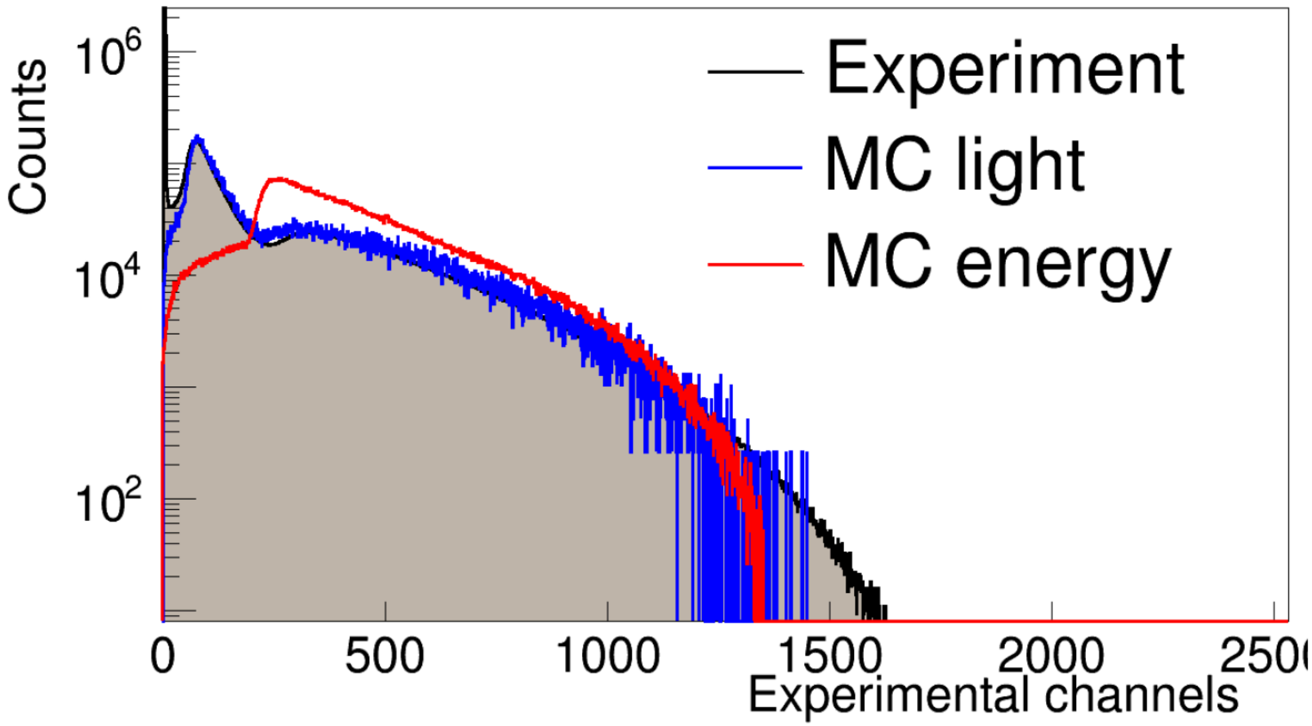


Members (current and old) of the IGISOL group along with some of our DTAS collaborators at a morning shift. JYFLTRAP can be seen in its high voltage cage in the background behind the TAS device and related electronics. In addition, the tape station from Strasbourg is in use. Unfortunately many people who have worked hard to realize the experiment, both local and visitors, are not present.

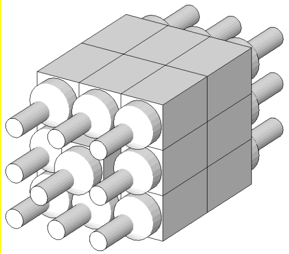
First step of the analysis: careful characterization of detectors

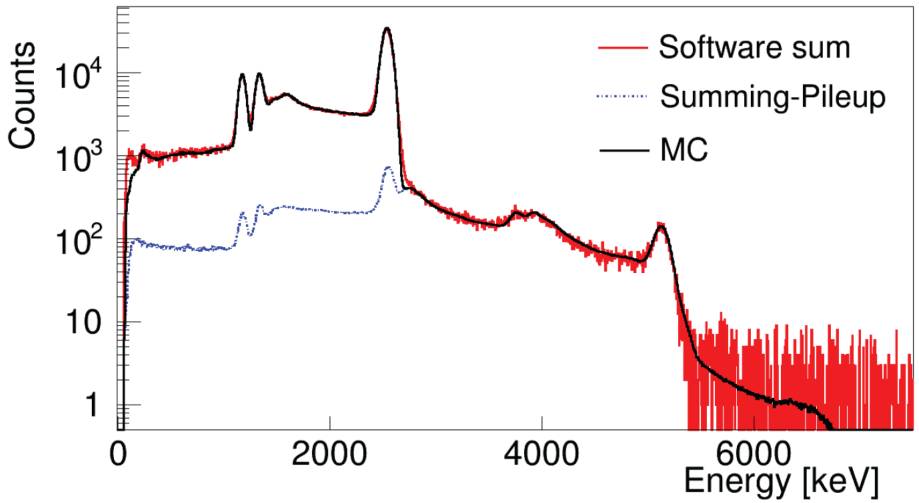


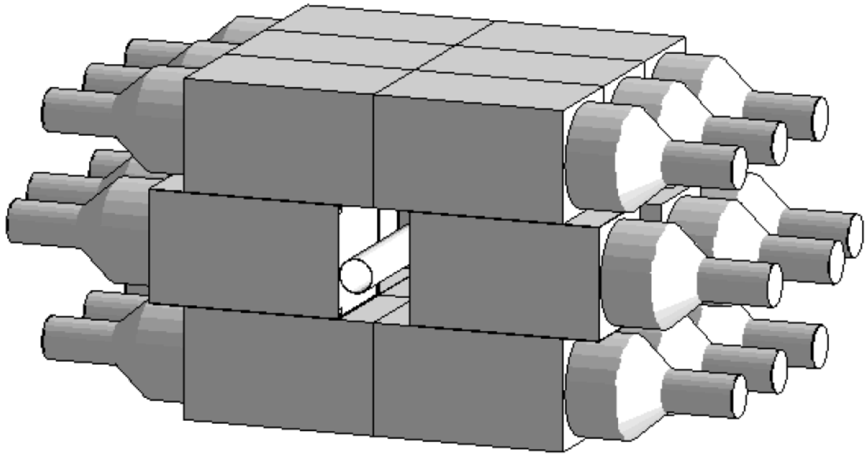
V. Guadilla et al., NIM 854(2017)134
V. Guadilla, PhD Thesis

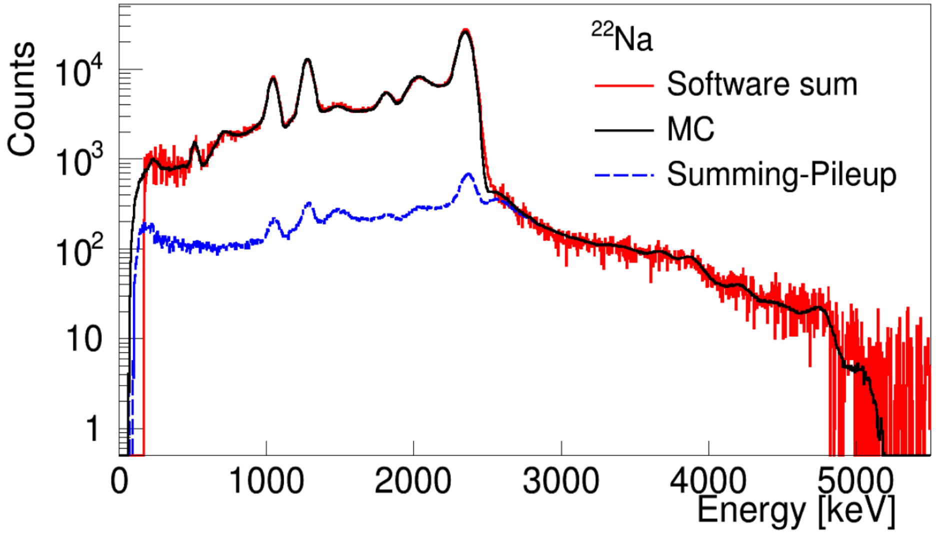


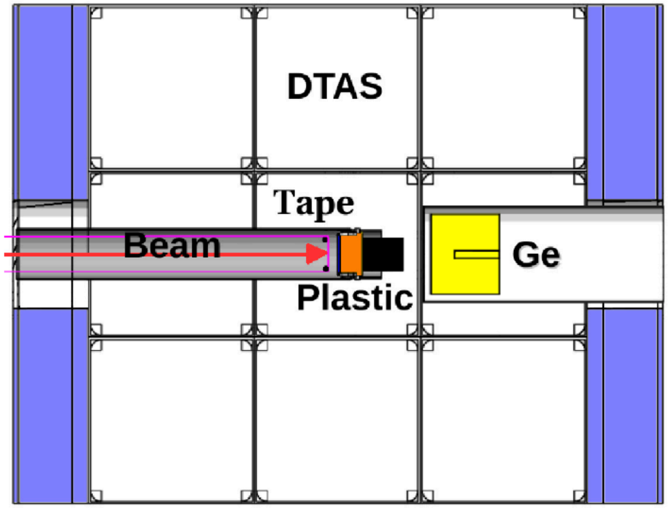
Details of the experiment



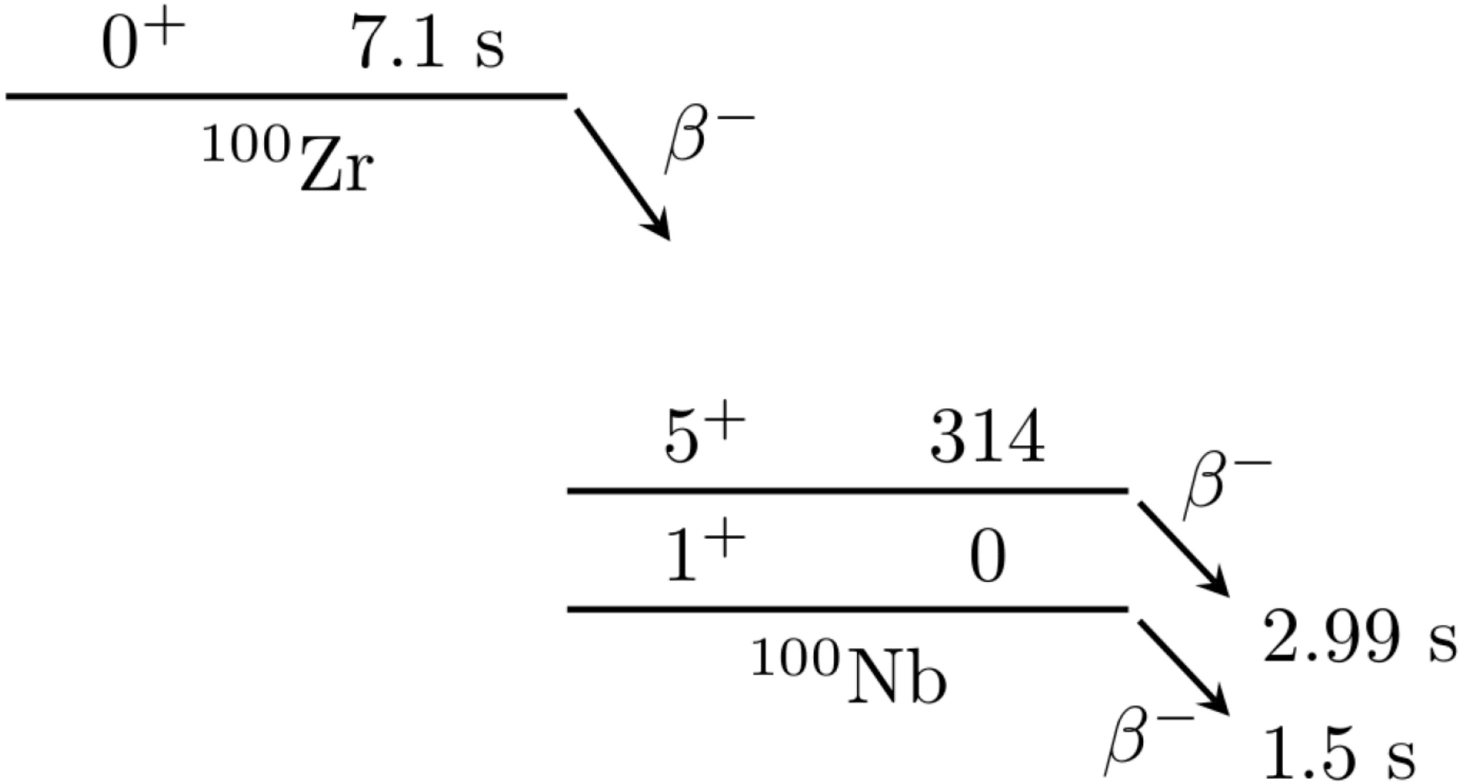






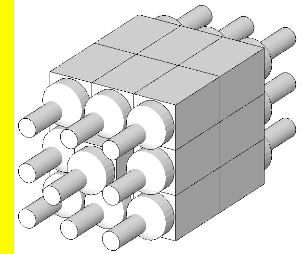


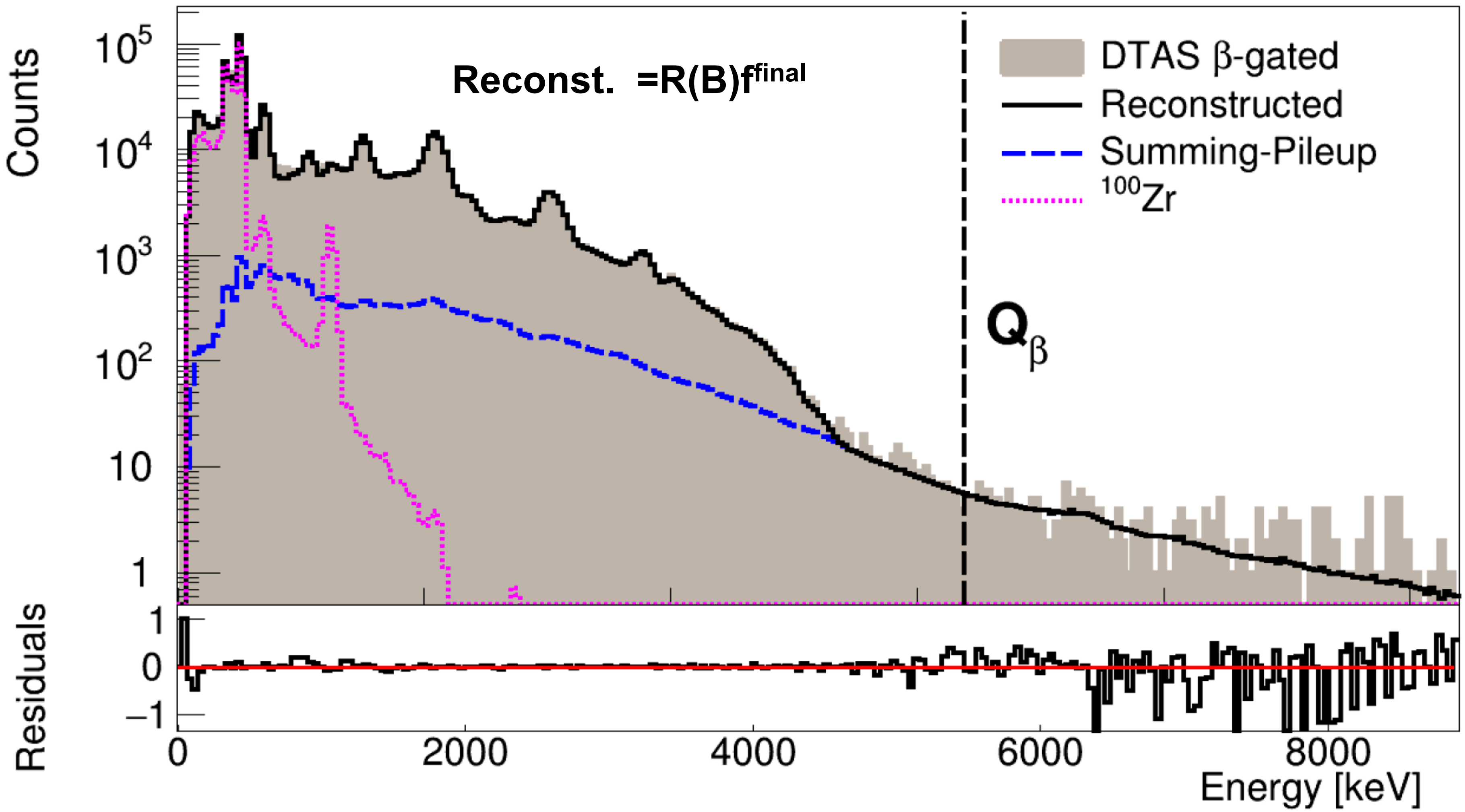
Example: 100Nb (from 14 relevant decays measured)



CFY of the order of 5% and ~1 % respectively (for both 235U and 239Pu)

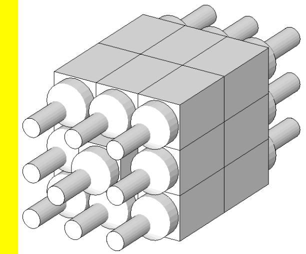
$^{100gs}Nb$

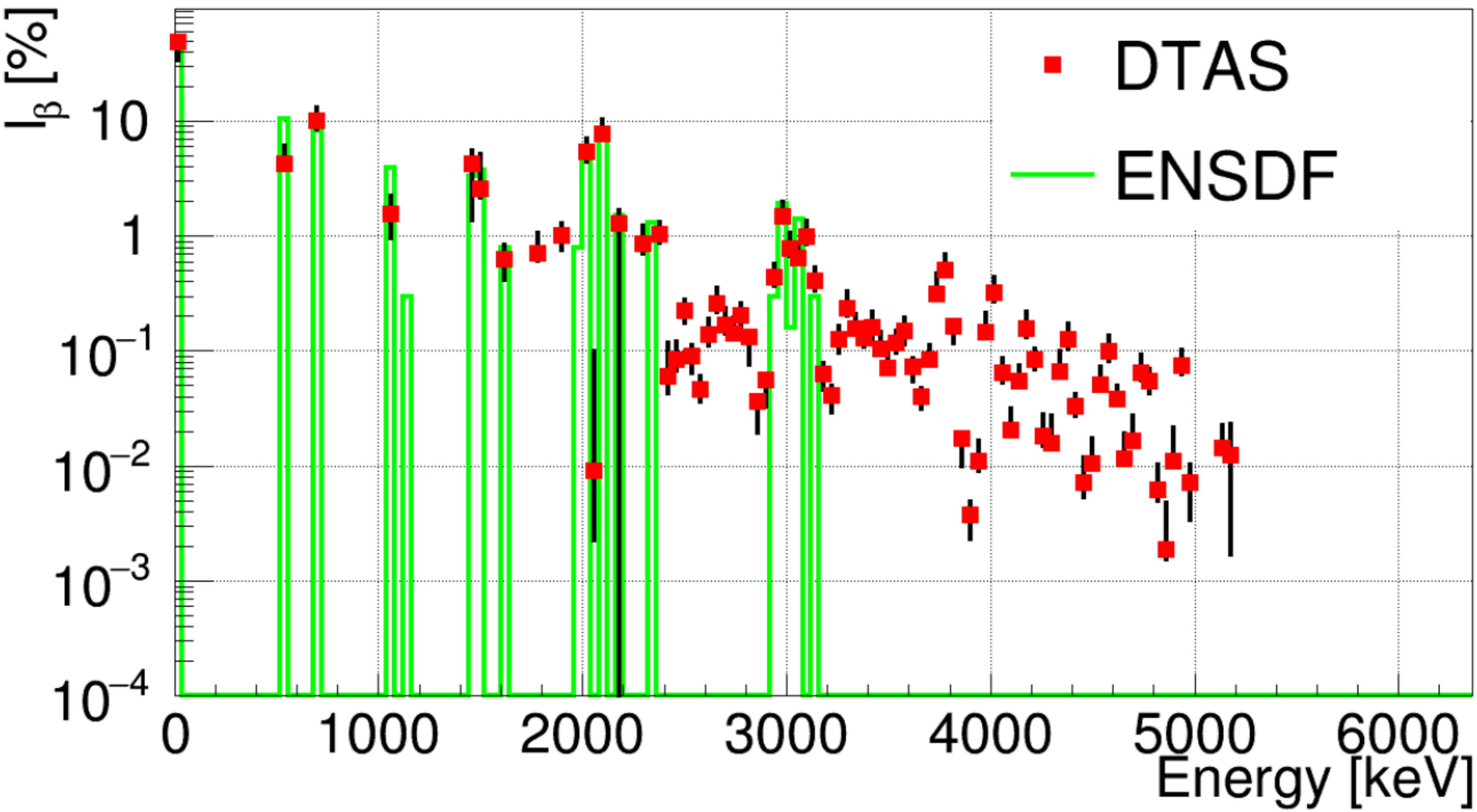




V. Guadilla et al., PhD thesis, 2017

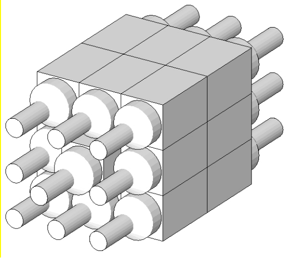
^{100gs}Nb

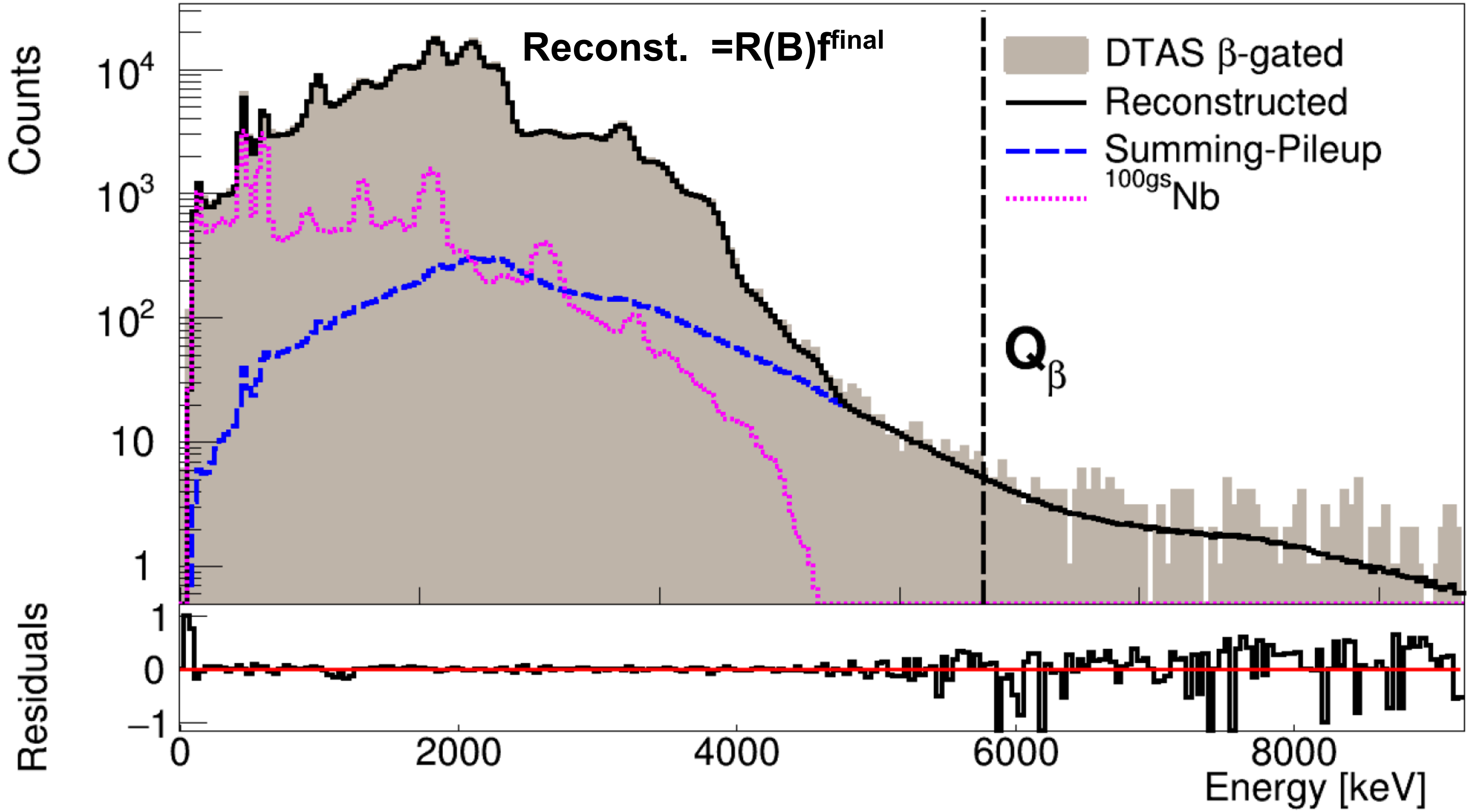




V. Guadilla et al., PhD thesis, 2017

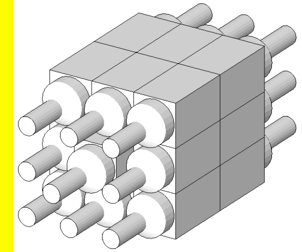
^{100m}Nb

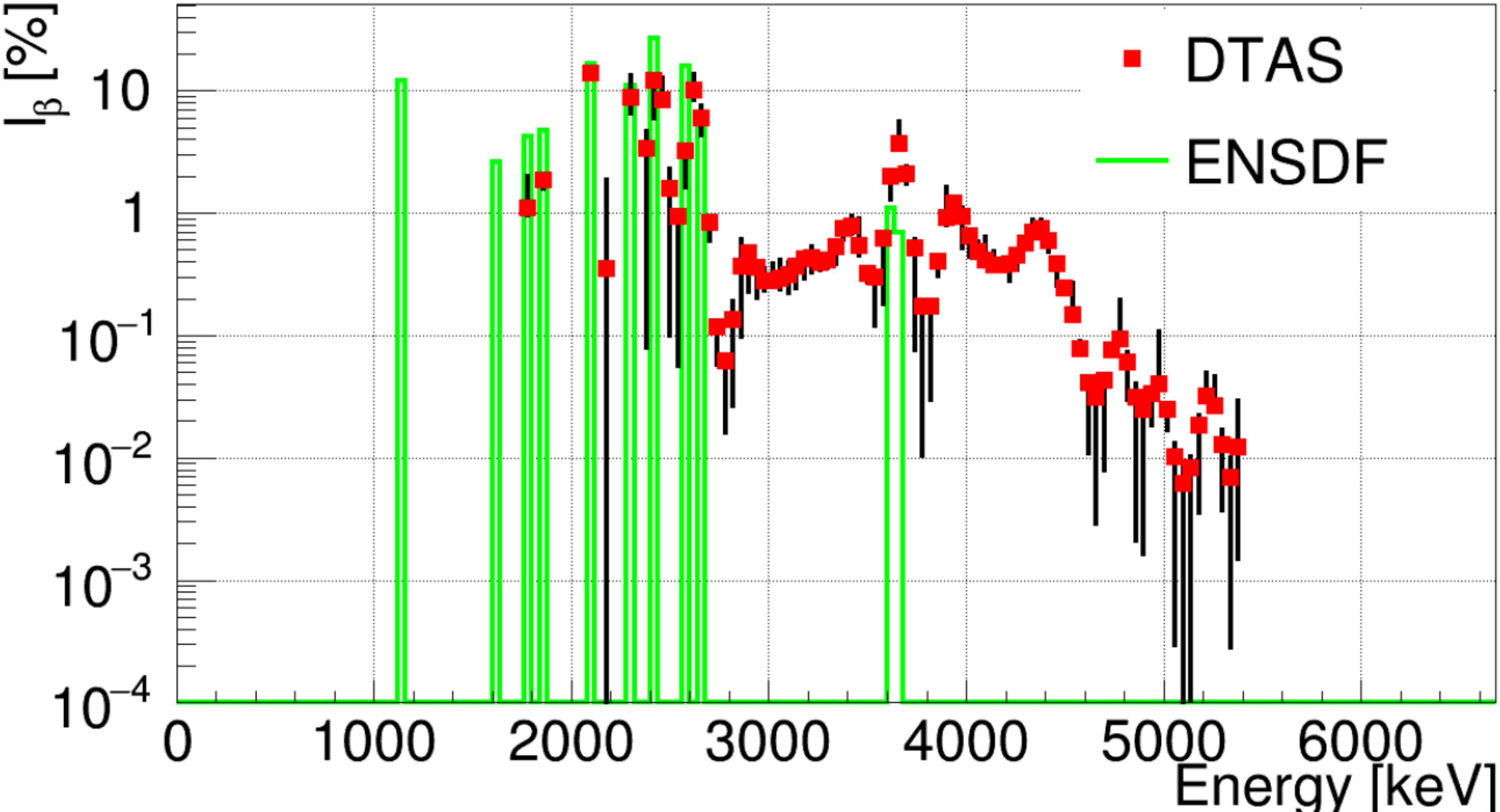




V. Guadilla et al., PhD thesis, 2017

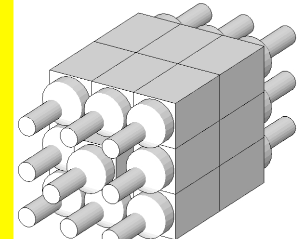
^{100m}Nb





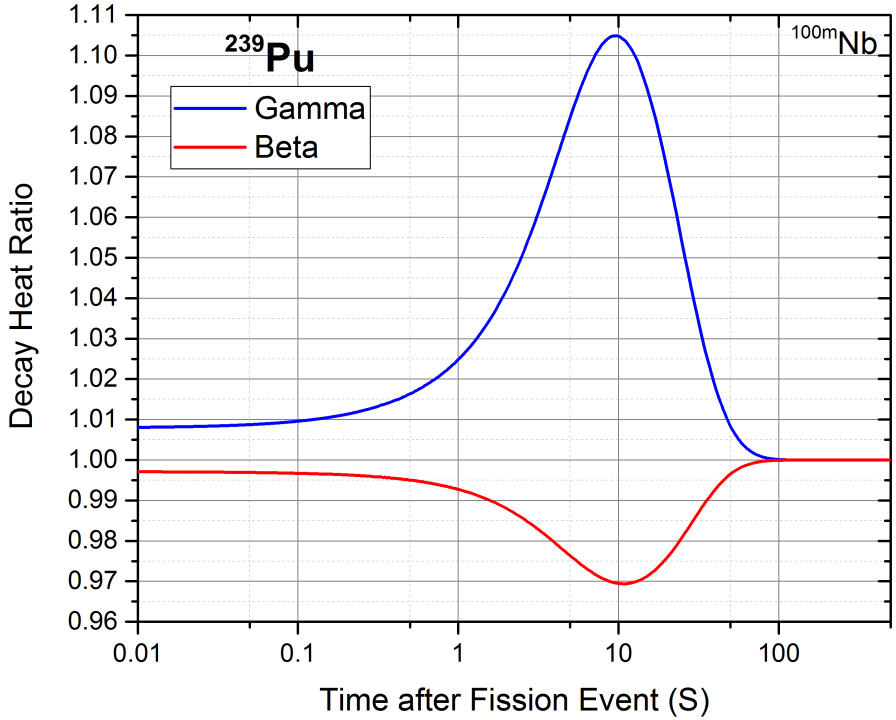
V. Guadilla et al., PhD thesis, 2017

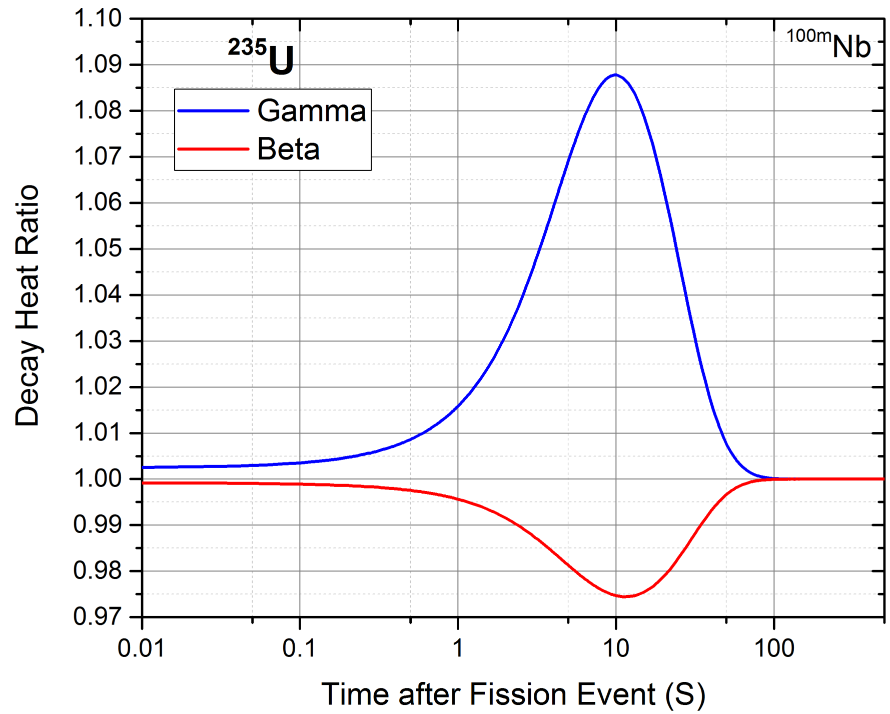
Impact on the decay heat (preliminary)



Decay heat summation calculation

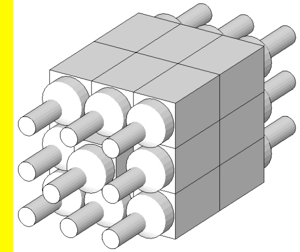
$$f(t) = \sum_i E_i \lambda_i N_i(t)$$





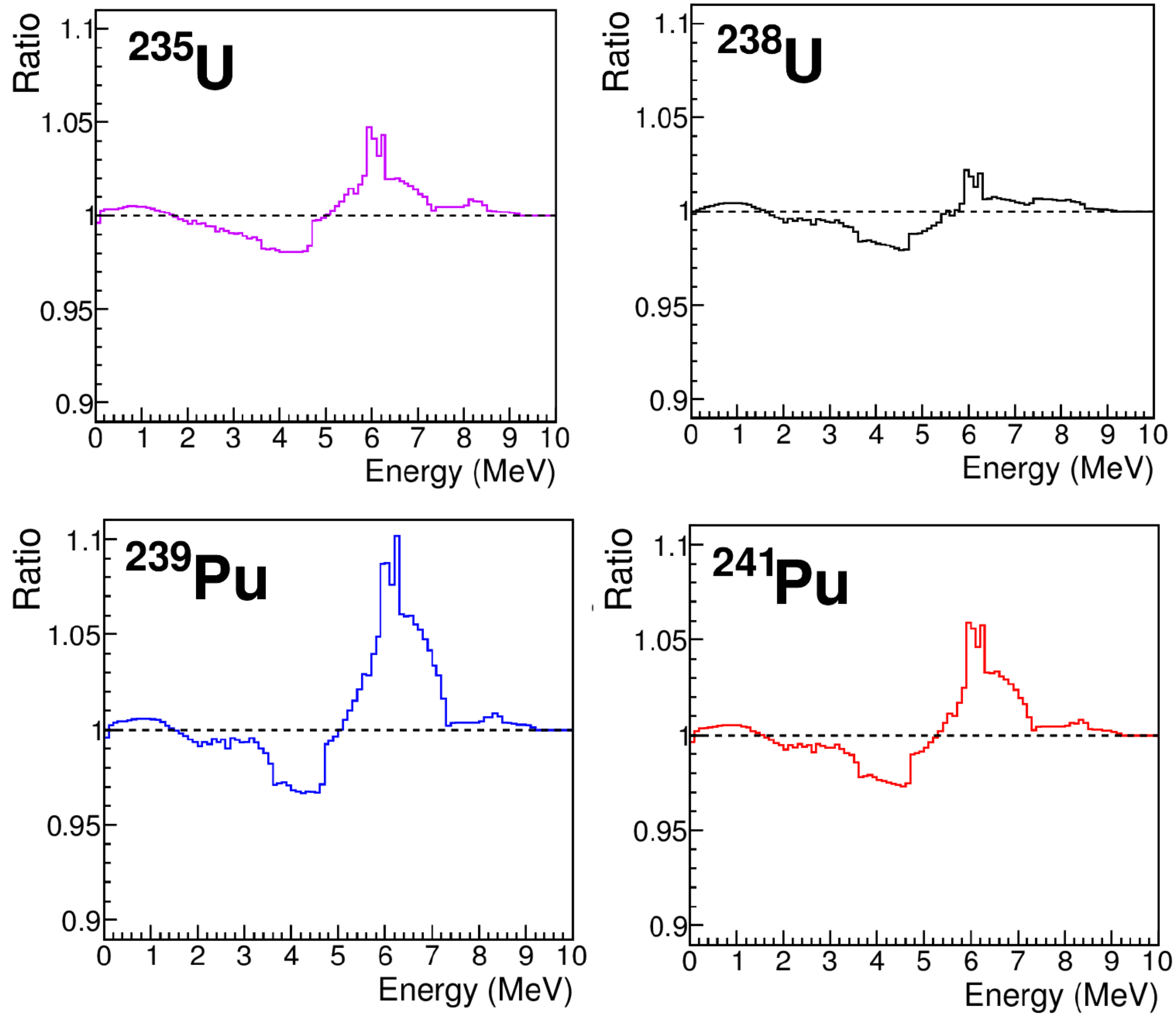
Impact of 8 new decays,
Some with decaying isomers

Impact on the neutrino summation calc. (preliminary)



Neutrino summation calculation
Courtesy of M. Fallot, M. Estienne et al,
PhD thesis of V. Guadilla

Impact of 8 new decays, some with decaying isomers, Still some to be analyzed by the Nantes group



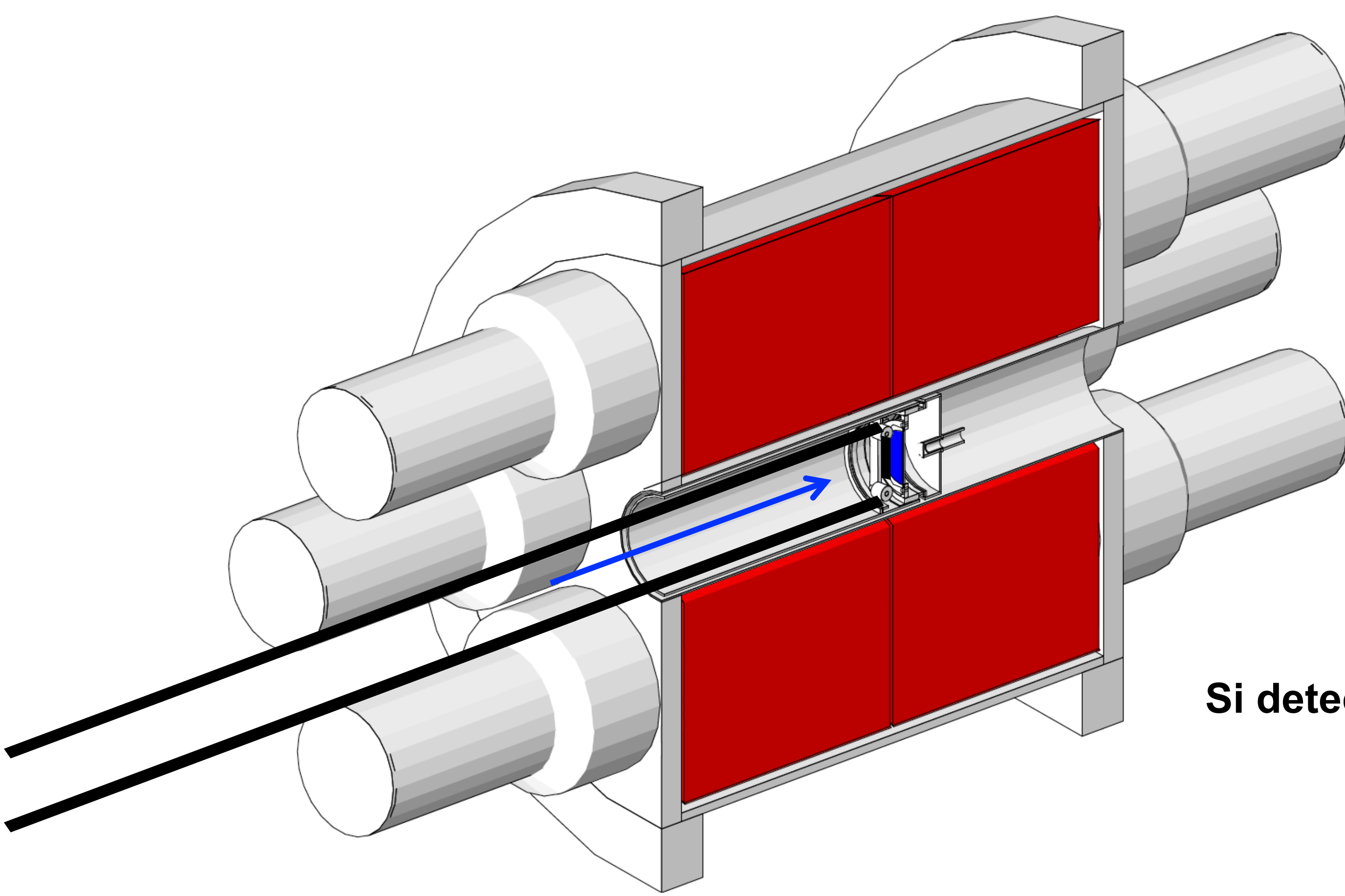
Other groups are also working in the topic, see for example Rasco et al. PRL117.092501

VTAS in Jyväskylä (November 2009)

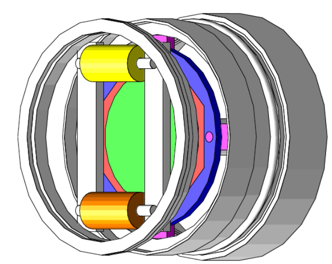
$^{86,87,88}Br$, $^{91,92,93,94}Rb$

Z	89Y STABLE 100%	90Y 64.053 H β-: 100.00%	91Y 58.51 D β-: 100.00%	92Y 3.54 H β-: 100.00%	93Y 10.18 H β-: 100.00%	94Y 18.7 M β-: 100.00%	95Y 10.3 M β-: 100.00%	96Y 5.34 S β-: 100.00%	97Y 3.75 S β-: 100.00% β-n: 0.06%
38	88Sr STABLE 82.58%	89Sr 50.53 D β-: 100.00%	90Sr 28.90 Y β-: 100.00%	91Sr 9.63 H β-: 100.00%	92Sr 2.66 H β-: 100.00%	93Sr 7.43 M β-: 100.00%	94Sr 75.3 S β-: 100.00%	95Sr 23.90 S β-: 100.00%	96Sr 1.07 S β-: 100.00%
37	87Rb 4.81E+10 Y 27.83% β-: 100.00%	88Rb 17.773 M β-: 100.00%	89Rb 15.15 M β-: 100.00%	90Rb 158 S β-: 100.00%	91Rb 58.4 S β-: 100.00%	92Rb 4.492 S β-: 100.00% β-n: 0.01%	93Rb 5.84 S β-: 100.00% β-n: 1.39%	94Rb 2.702 S β-: 100.00% β-n: 10.50%	95Rb 377.7 MS β-: 100.00% β-n: 8.70%
36	86Kr STABLE 17.279%	87Kr 76.3 M β-: 100.00%	88Kr 2.84 H β-: 100.00%	89Kr 3.15 M β-: 100.00%	90Kr 32.32 S β-: 100.00%	91Kr 8.57 S β-: 100.00%	92Kr 1.840 S β-: 100.00% β-n: 0.03%	93Kr 1.286 S β-: 100.00% β-n: 1.95%	94Kr 212 MS β-: 100.00% β-n: 1.11%
35	85Br 2.90 M β-: 100.00%	86Br 55.1 S β-: 100.00%	87Br 55.65 S β-: 100.00% β-n: 2.60%	88Br 16.29 S β-: 100.00% β-n: 6.58%	89Br 4.40 S β-: 100.00% β-n: 13.80%	90Br 1.91 S β-: 100.00% β-n: 25.20%	91Br 0.541 S β-: 100.00% β-n: 20.00%	92Br 0.343 S β-: 100.00% β-n: 33.10%	93Br 102 MS β-: 100.00% β-n: 68.00%
	50	51	52	53	54	55	56	57	N

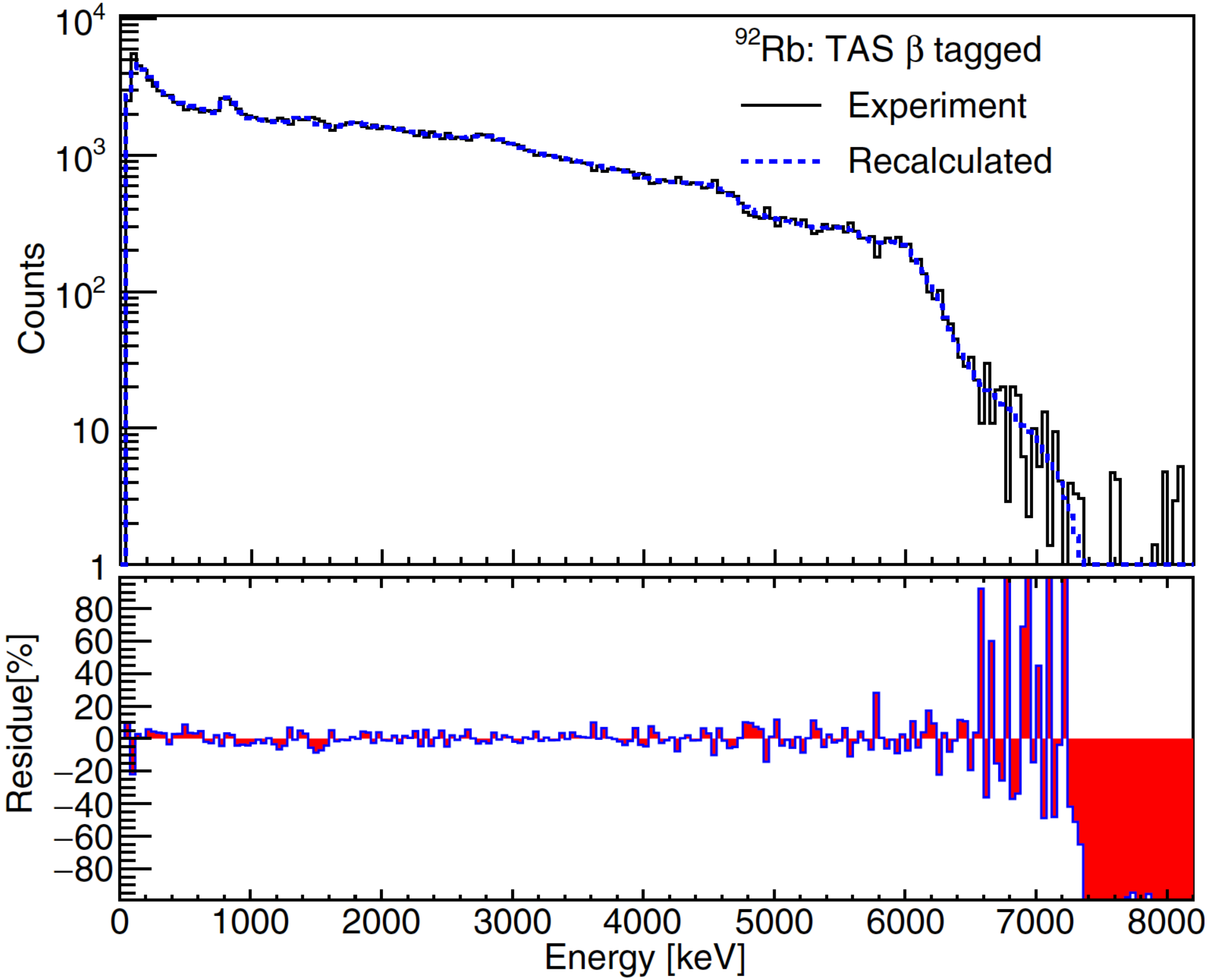
VTAS in Jyväskylä (November 2009)
^{86,87,88}Br, ^{91,92,93,94}Rb



Si detector endcup



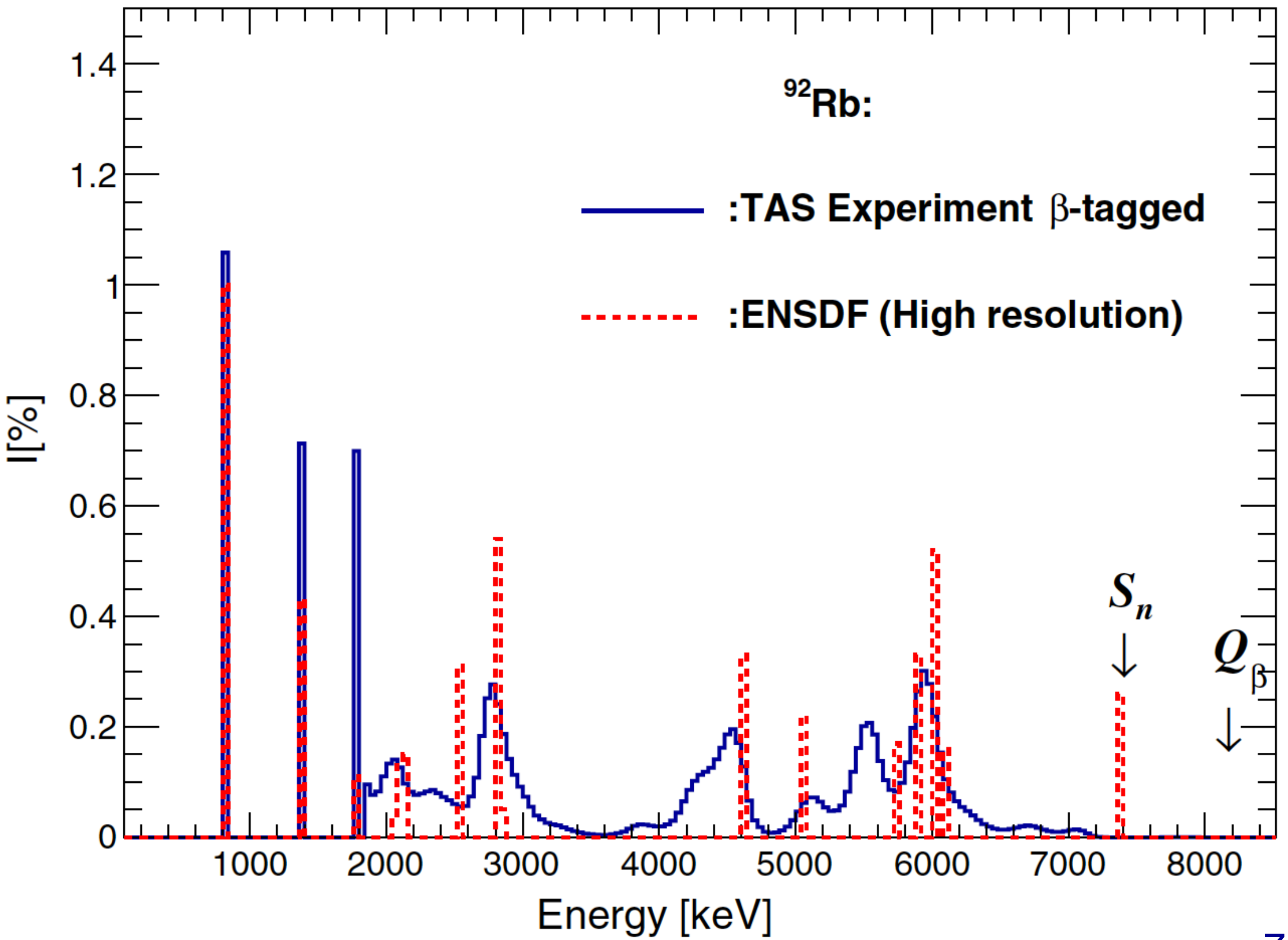
92Rb: TAS measurement, 2009 exp. Analized by the Nantes group



Zakari-Issoufou et al.
PRL 115.102503(2015)

Another recent measurement by Rasco et al.
PRL 117.092501 (2016)
(Oak Ridge group)

92Rb: star case



Gs to gs feeding Evolution

94(+6−20)(<2000)
Olson et al.

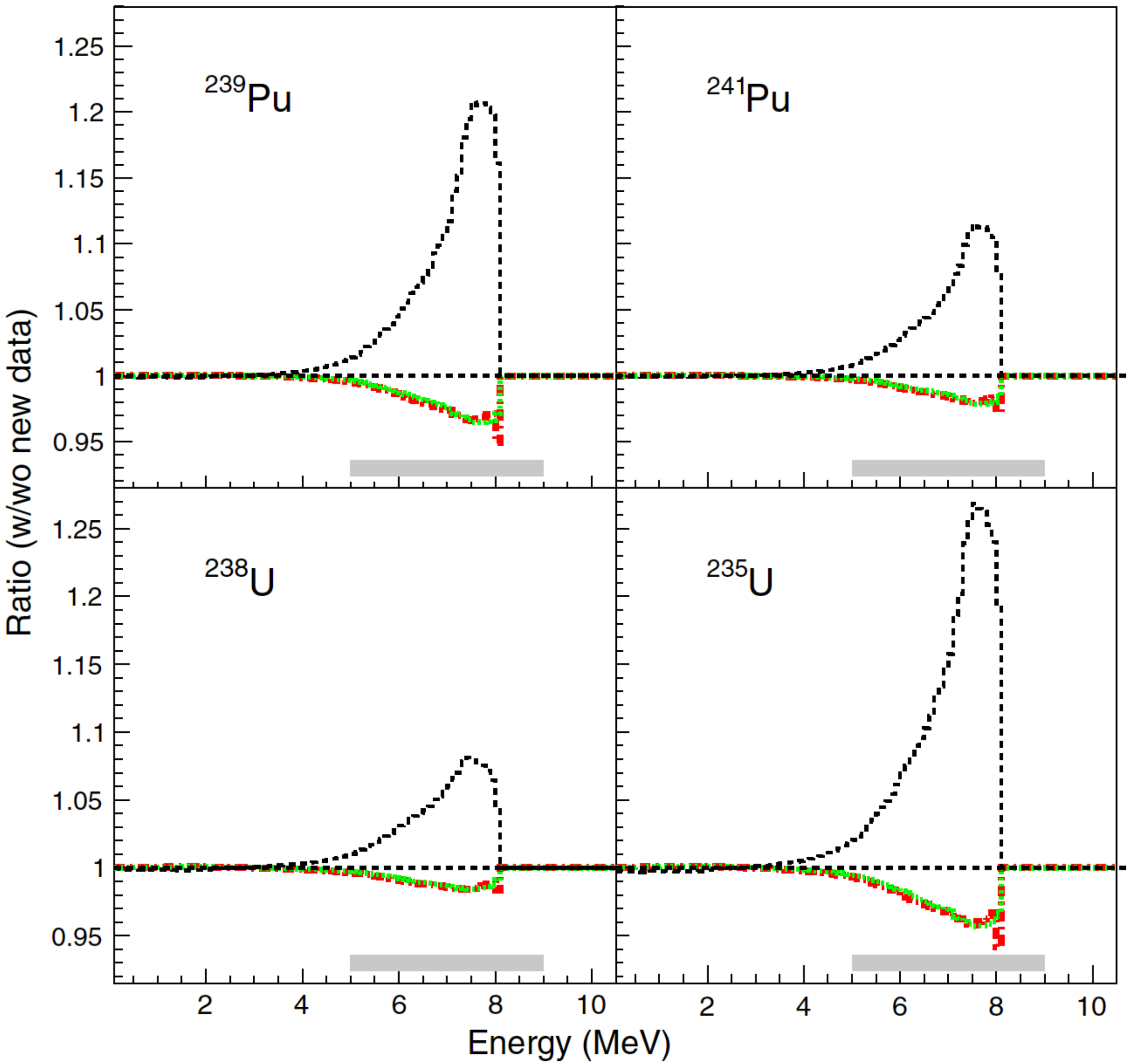
51(18) % (<2012)
NDS 2000

95.2(7) % (2012)
NDS 2012
G. Lhersonneau (PRC74 (2006)017308)

87.5(2.5)% (2015)
TAS result

Zakari-Issoufou et al.
PRL 115.102503(2015)

92Rb: comparison of the impact with respect to earlier used gs feeding values



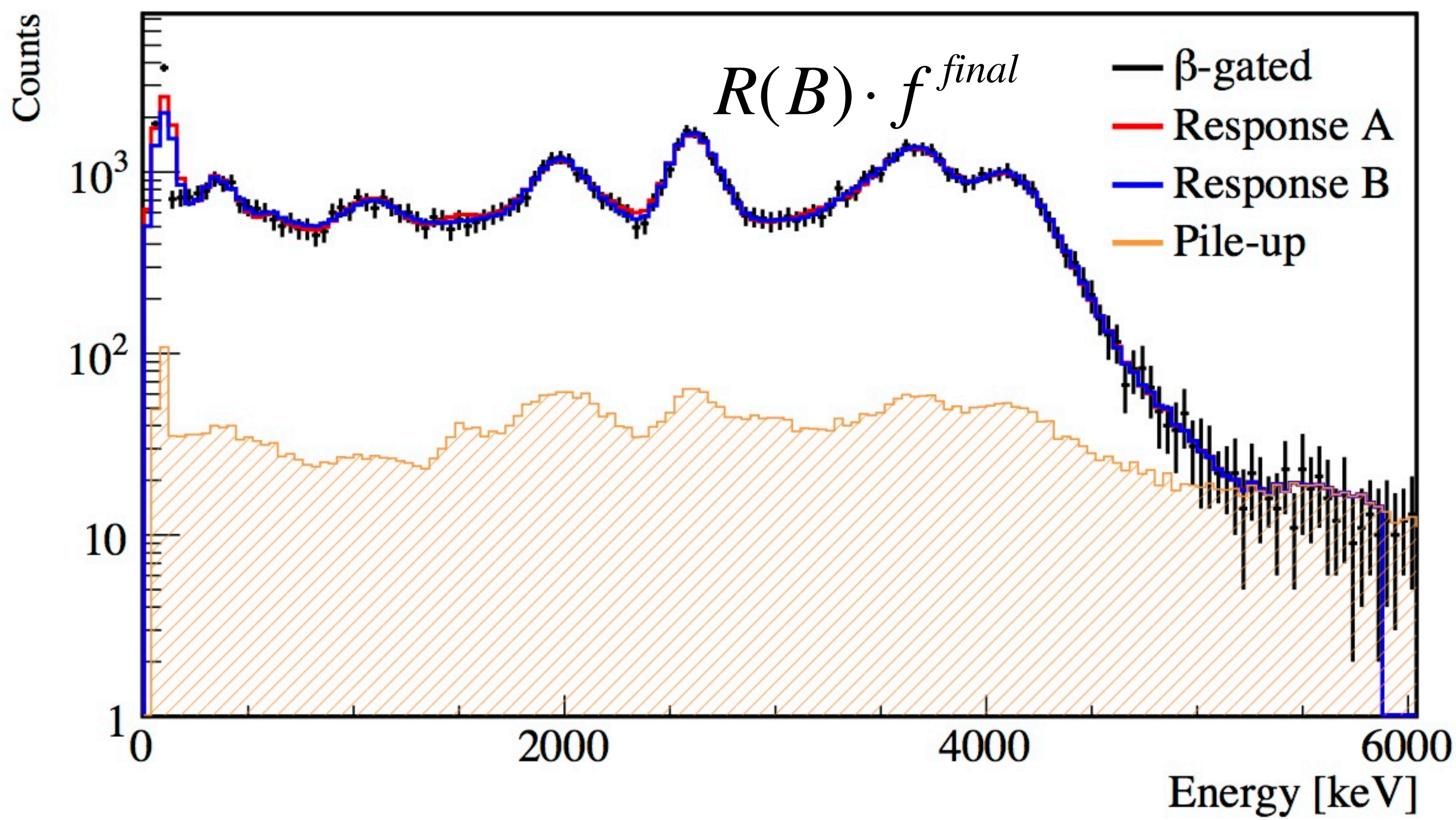
92Rb impact
Zakari-Issoufou et al.
PRL 115.102503(2015)

Black: with respect to the value used in D. A. Dwyer et al. PRL 114,012502

Green: with respect to A. A. Sonzogni et al. PRC 91, 011301(R)

Red: with respect to M. Fallot et al., PRL 109, 202504

One case of interest: 91Rb
(not from the high priority list for decay heat)



Measured by Greenwood, and used by Rudstam as calibration point for his mean gamma energy measurements, assuming that it does not suffer from *Pandemonium*

S. Rice, A. Algora, J. L.Tain et al, PRC 96, 014320 (2017)
S. Rice, PhD thesis (Univ. Surrey)

Rudstam et al publication

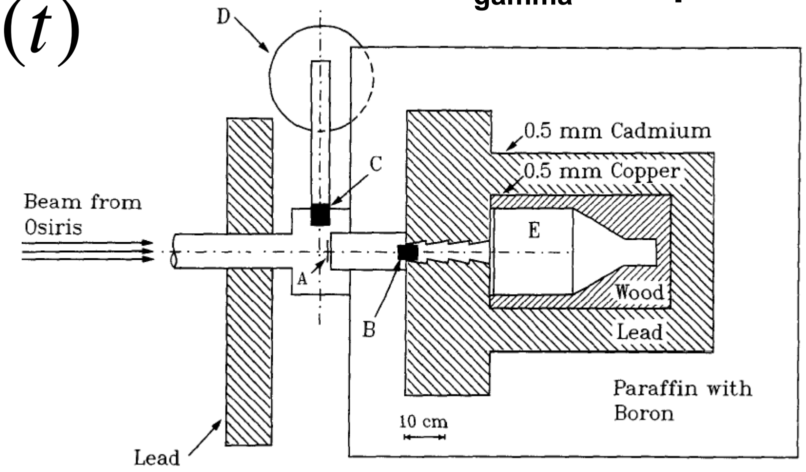
$$f(t) = \sum_i \overline{E_i} \lambda_i N_i(t)$$

Rudstam et al.

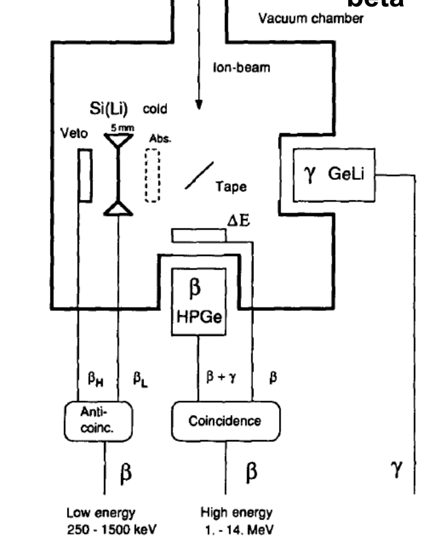
Atom. Dat. and Nucl. Dat. Tables 45, (1990)
89 mean gamma and 95 beta energies gi
for FP decays

It has a particular interest for neutrino physics. Apart from the mean gamma and beta energies it provides beta spectra measured by Tengblad et al.
This spectra was used to deduce antineutrino spectra

E_{gamma} setup

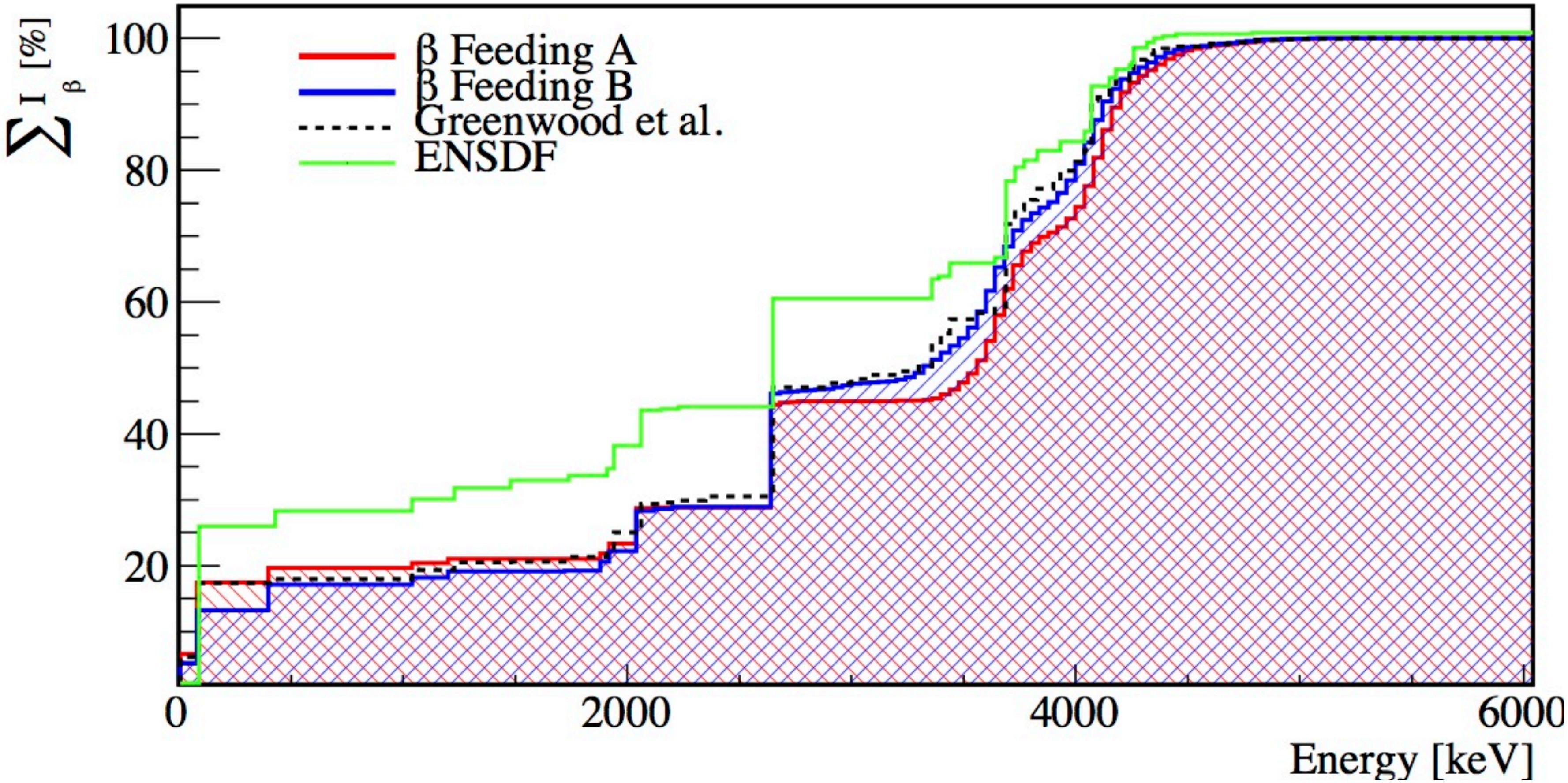


E_{beta} setup



Consistency check: $Q_\beta \approx \overline{E_\gamma} + \overline{E_\beta} + \overline{E_\nu}$

91Rb: accumulated feeding



S. Rice, A. Algora, J. L.Tain et al, PRC 96, 014320 (2017)
S. Rice, PhD thesis

Rudstam data set normalization point (91Rb)

ATOMIC DATA AND NUCLEAR DATA TABLES **45**, 239–320 (1990)

BETA AND GAMMA SPECTRA OF SHORT-LIVED FISSION PRODUCTS

G. RUDSTAM, P. I. JOHANSSON, O. TENGBLAD,* P. AAGAARD, and J. ERIKSEN

Studsvik Neutron Research Laboratory
S-61182 Nyköping, Sweden

Rb-91	345.4	8.3±0.4	200	2304±6	17±1	2321±6	1.43±0.02	Used for normali-zation

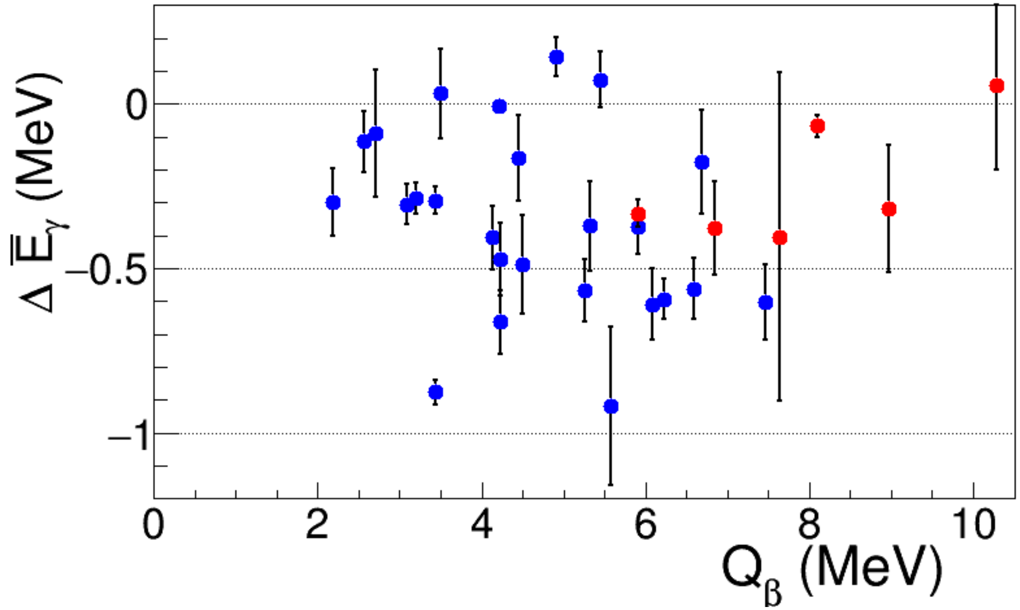
$$\overline{E_\gamma^R} = 2335 keV$$ Used value by Rudstam (from HR)

$$\overline{E_\gamma^T} = 2669(29) keV$$ (Valencia)

$$\overline{E_\gamma^T} = 2705(95) keV$$ (Greenwood)

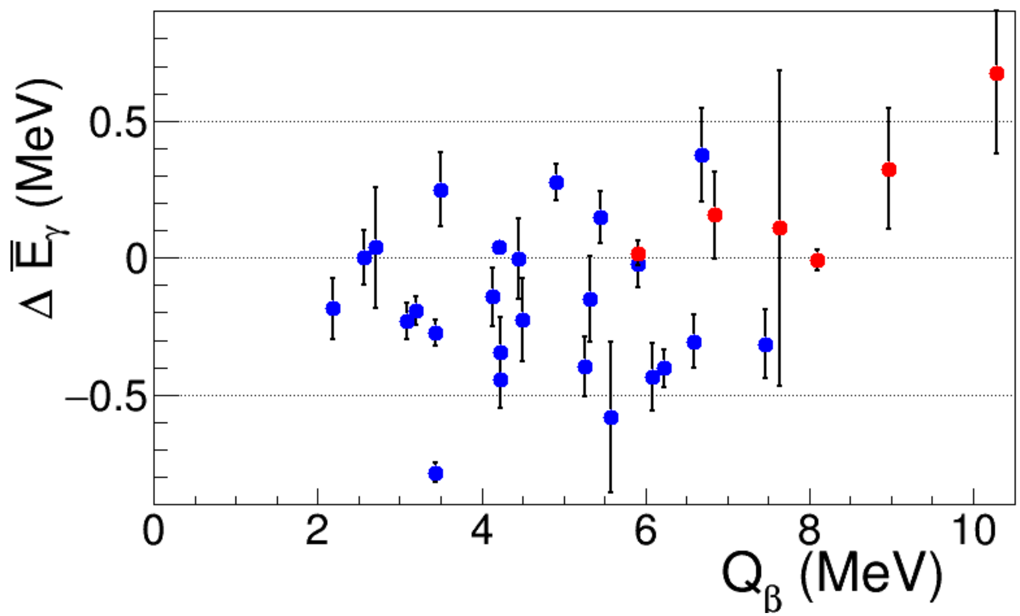
Since the absolute normalization was based on the 91Rb mean gamma energy, the data set needs to be renormalized !!!

TAGS (Greenwood & us) vs Rudstam
91Rb used as calibration



Systematic differences first pointed out by O. Bersillon in one of the WPEC25 meetings

$$\langle \overline{E_R} - \overline{E_T} \rangle_{\gamma} = -360 keV$$

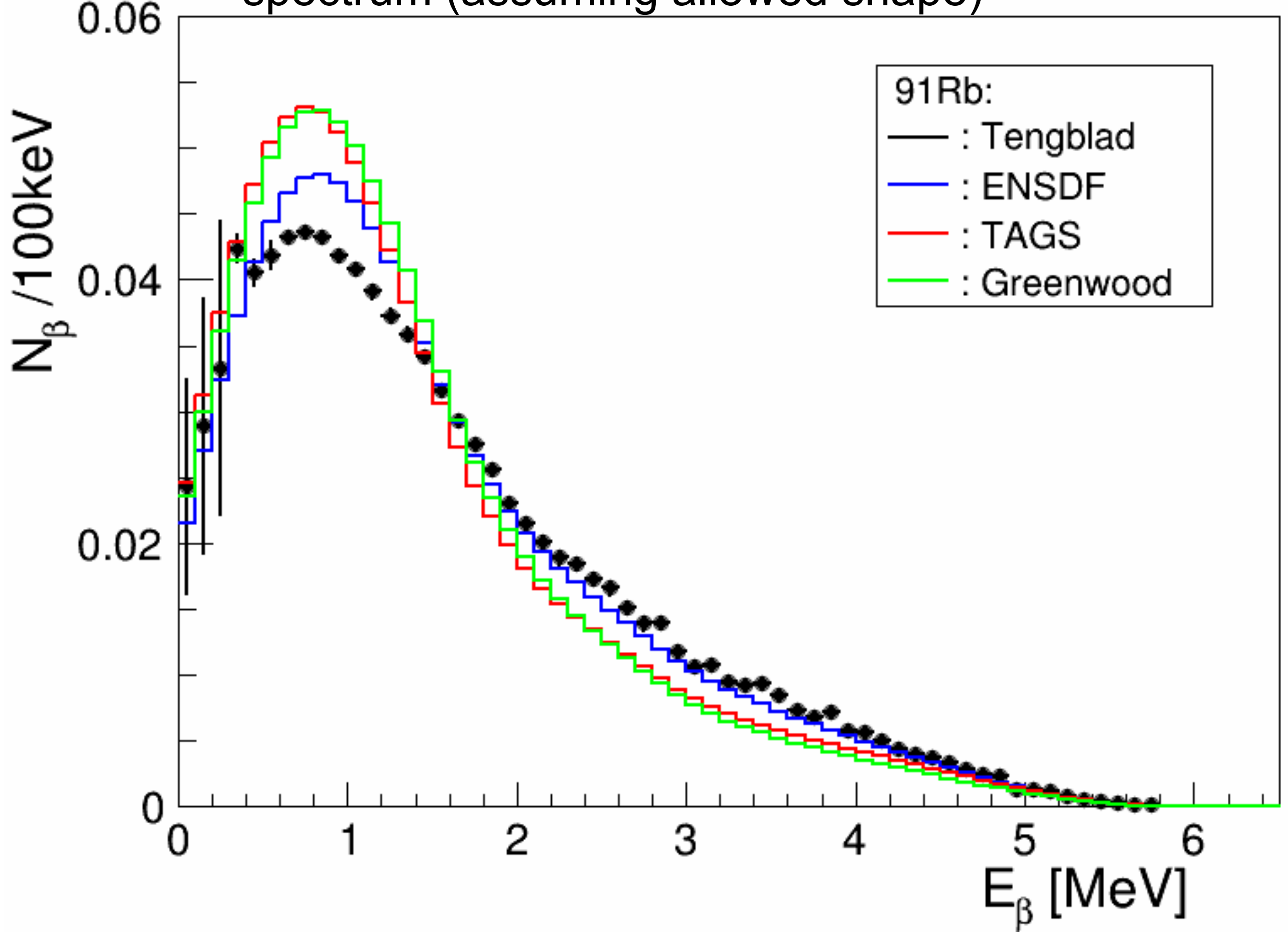


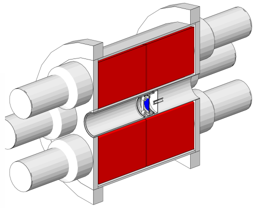
$$\langle \overline{E_R^*} - \overline{E_T} \rangle_{\gamma} = -185 keV$$

* After renormalization of mean energies of Rudstam with the new mean gamma value from TAGS analysis, the problem persist !!!

Another impact of the studied cases
Posibility of comparison with Tengblad data

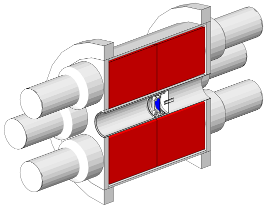
Comparison with the deduced beta spectrum (assuming allowed shape)

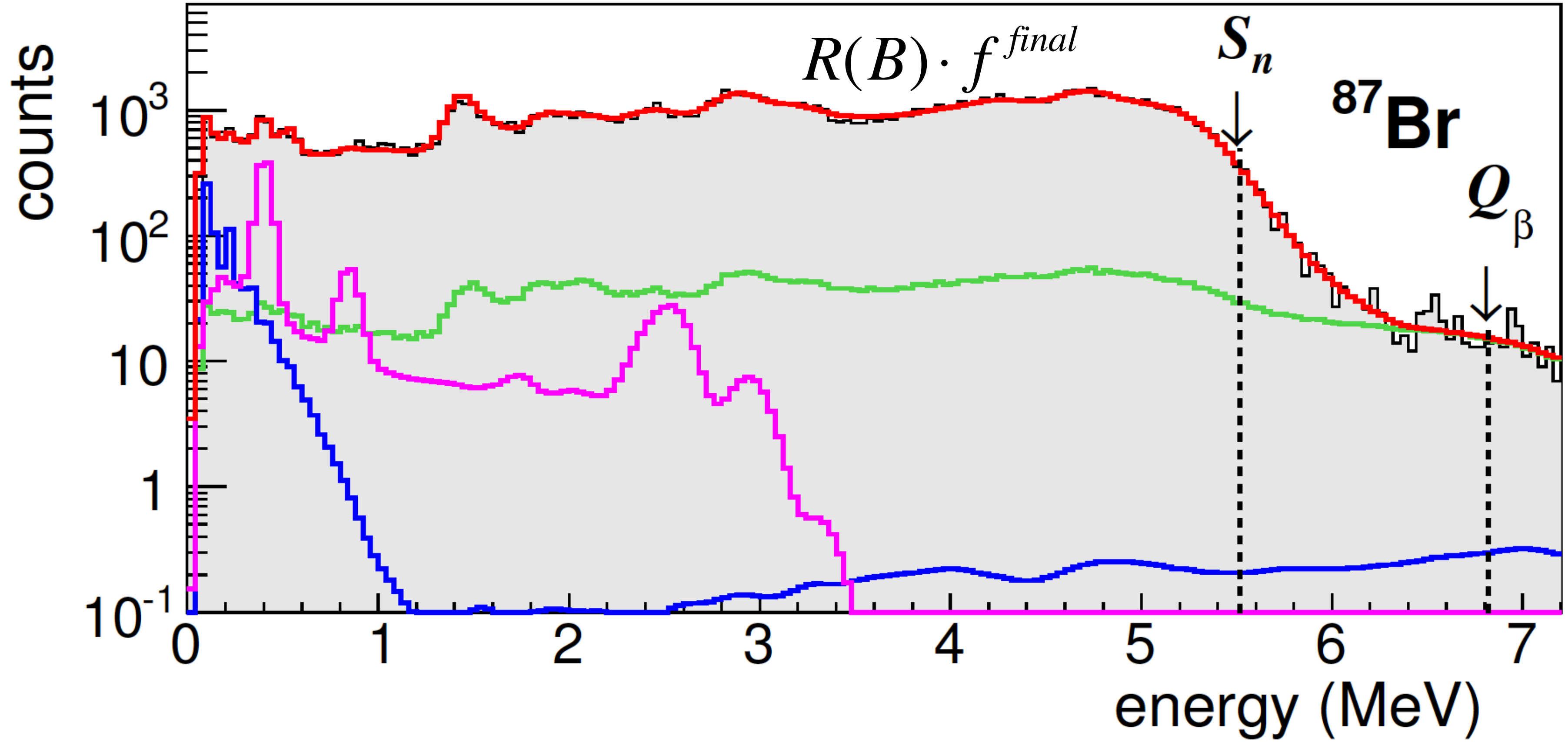




S. Rice, A. Algora, J. L.Tain et al, PRC 96, 014320 (2017)S. Rice, PhD thesis

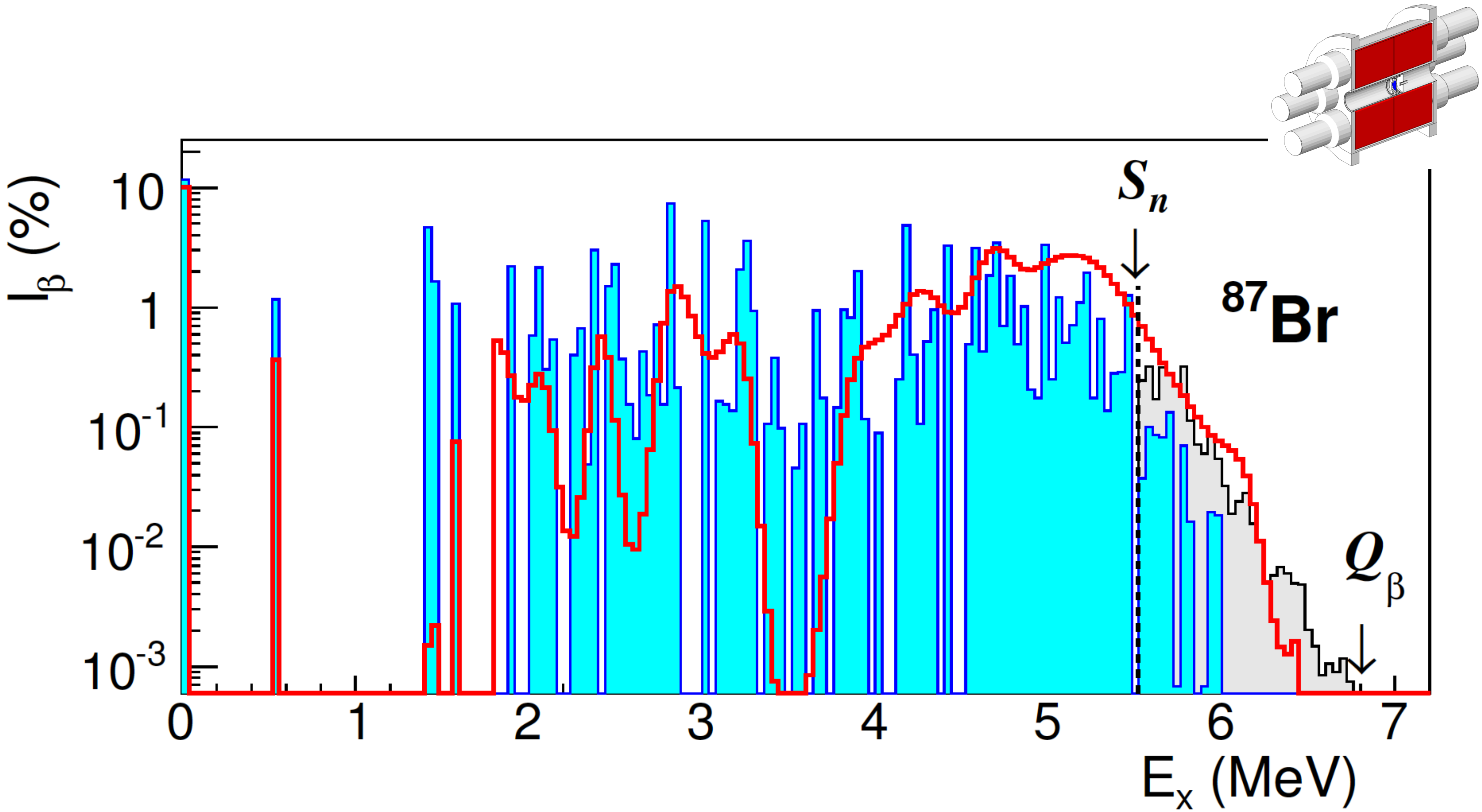
Beta delayed neutron emitters, example: ^{87}Br





E. Valencia, JL Tain, A. Algora et al, PRC95, 024320 (2017)
Tain et al. PRL 115, 062502

Beta delayed neutron emitters, example: 87Br

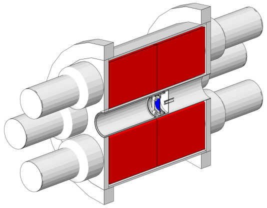


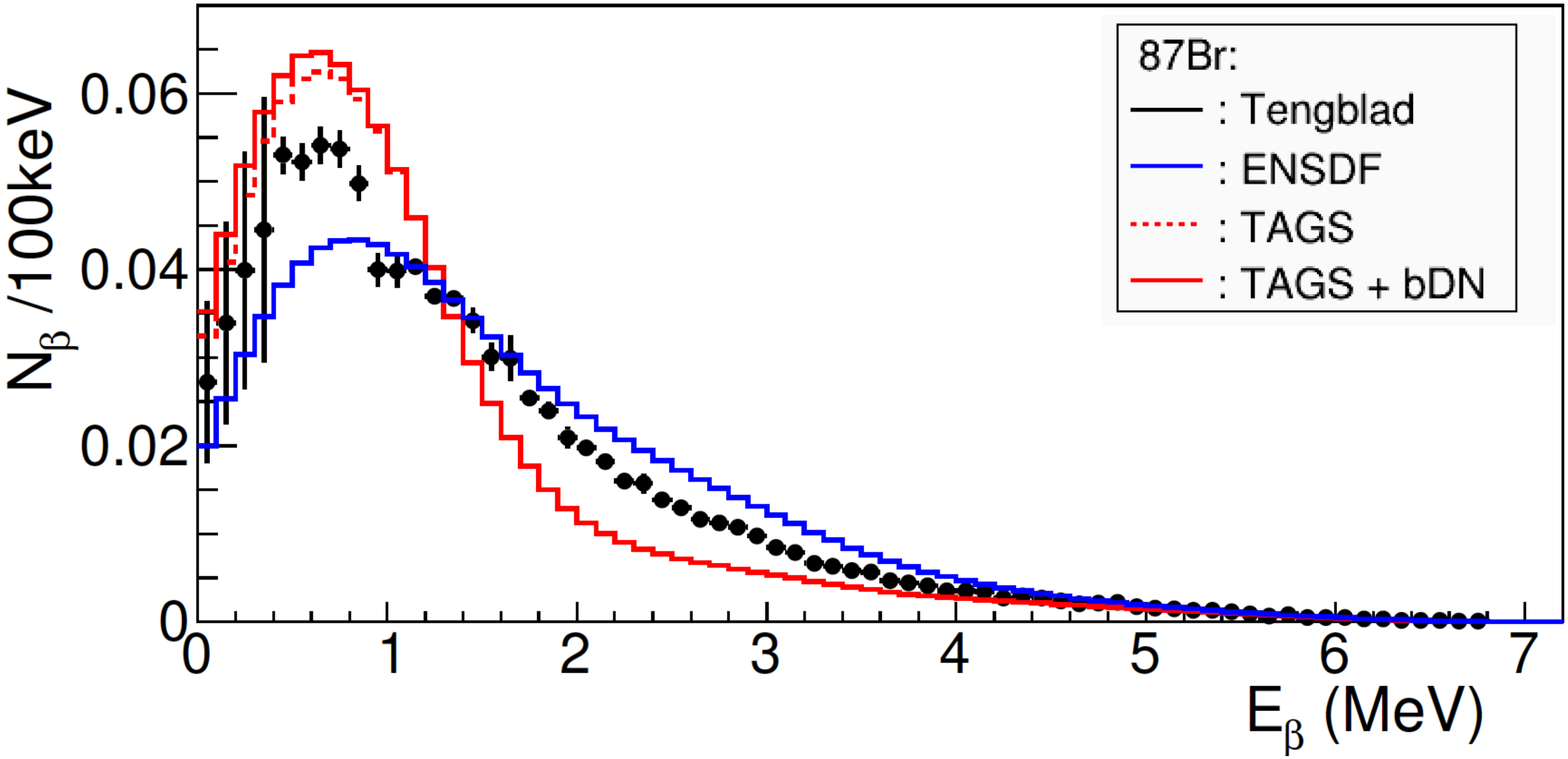
E. Valencia, JL Tain, A. Algora et al, PRC95, 024320 (2017)
Tain et al. PRL 115, 062502

Pγ=3.50 (+49-40) %
Pn=2.60 (4) %

Impact of the studied (bdn) cases
Posibility of comparison with Tengblad data

Comparison with the deduced beta spectrum (allowed shape)





E. Valencia, JL Tain, A. Algora et al, PRC95, 024320 (2017)

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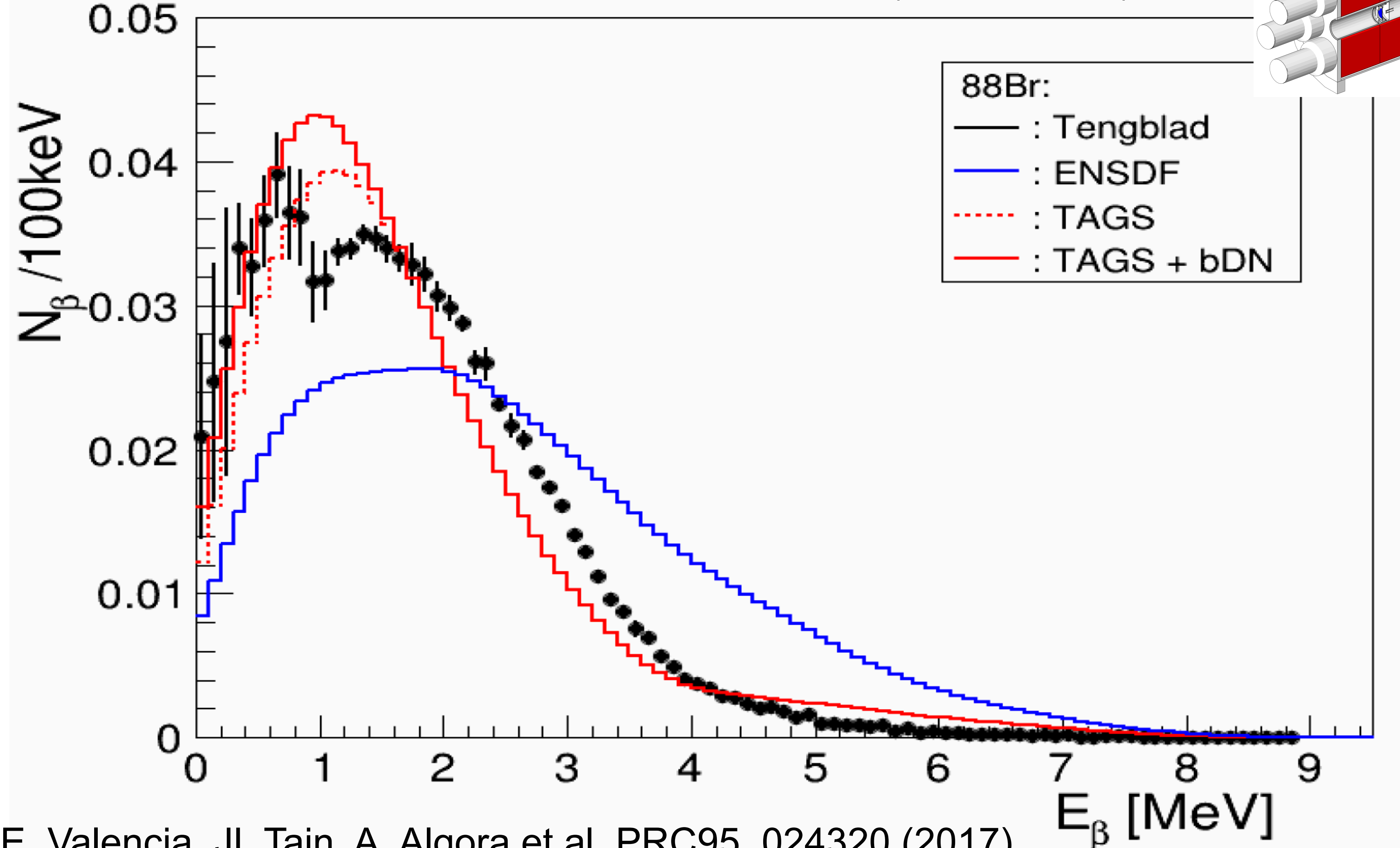
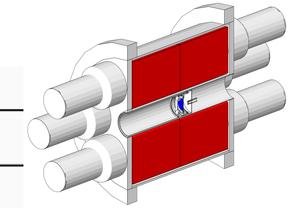




E. Valencia, JL Tain, A. Algora et al, PRC95, 024320 (2017)

Impact of the studied (bdn) cases in the calculated antineutrino spectrum

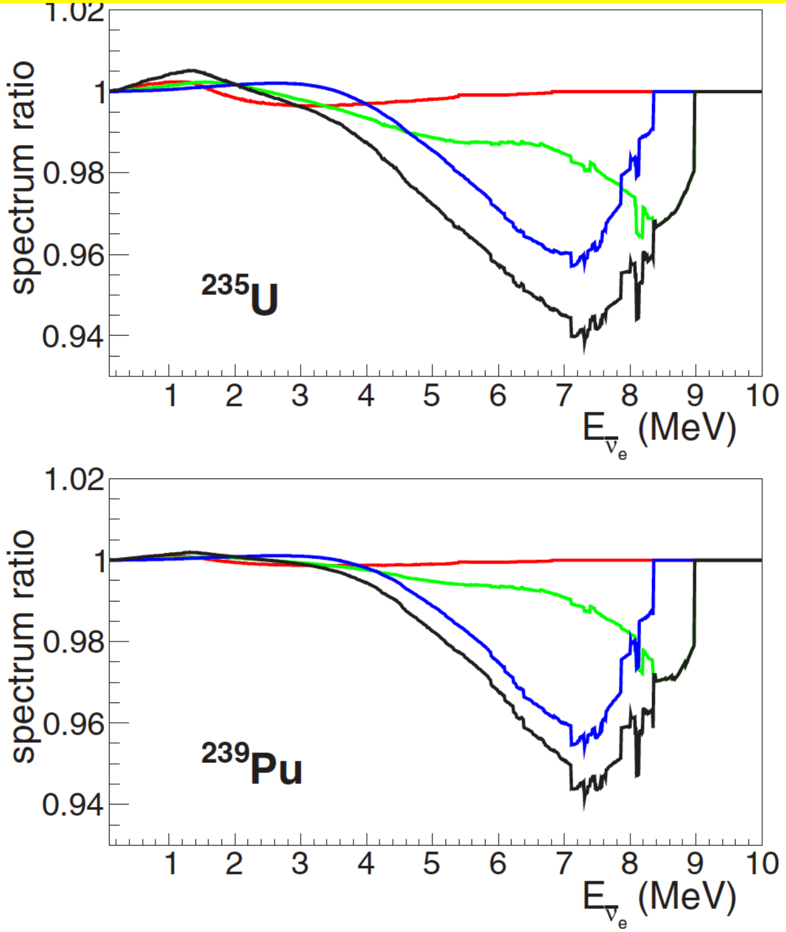


FIG. 10. Ratio of antineutrino spectra as a function of energy calculated for ^{235}U and ^{239}Pu when our TAGS data replace high-resolution data. Red: ^{87}Br; green: ^{88}Br; blue: ^{94}Rb; black: all three isotopes.

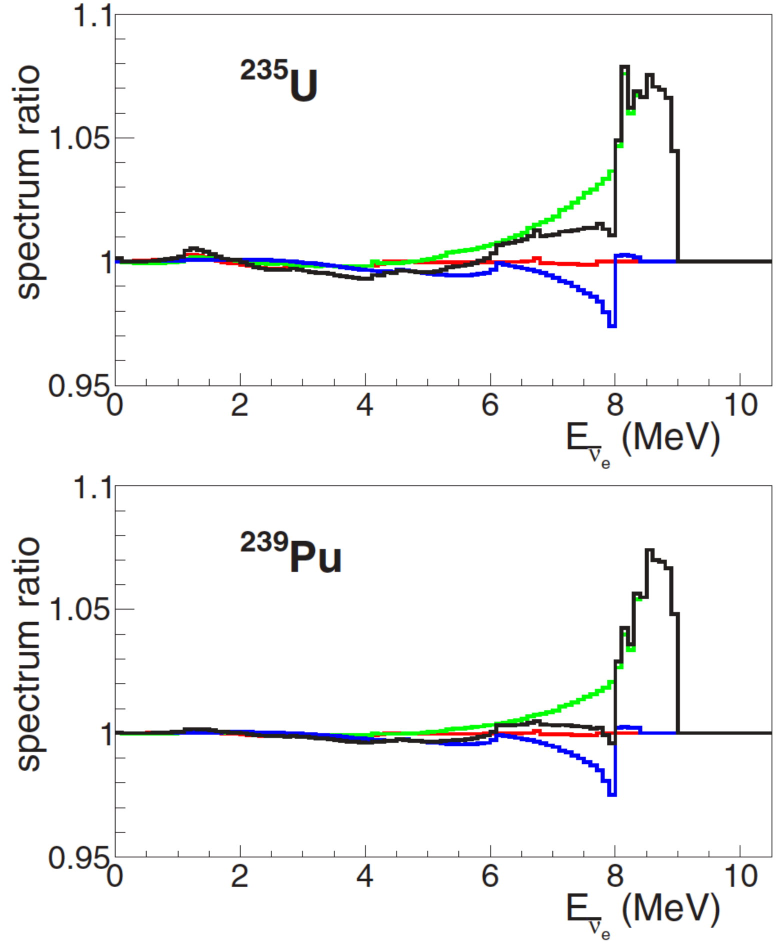


FIG. 11. Ratio of antineutrino spectra as a function of energy calculated for ^{235}U and ^{239}Pu when our TAGS data replace the data of Tengblad *et al.* Red: ^{87}Br; green: ^{88}Br; blue: ^{94}Rb; black: all three isotopes.

E. Valencia, JL Tain, A. Algora et al, PRC95, 024320 (2017)

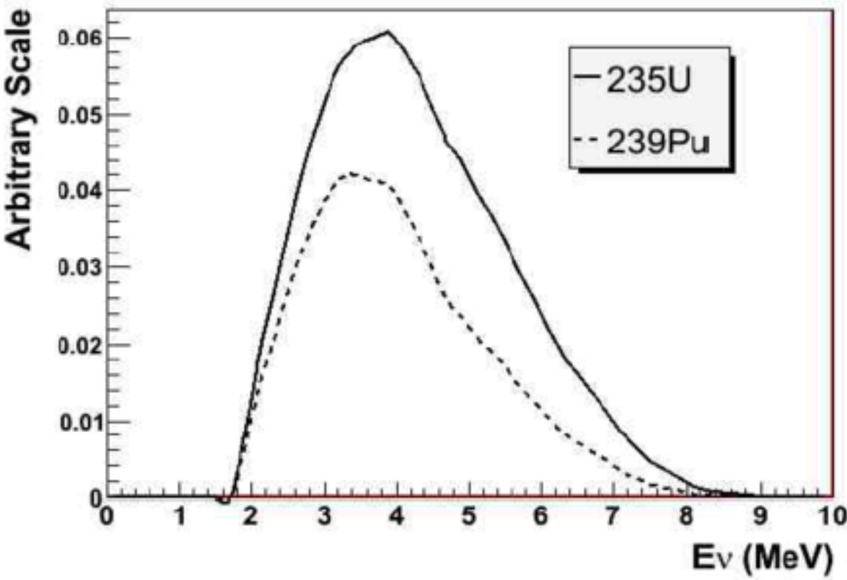
Another application: prediction of the neutrino spectrum from reactors for non-proliferation

	235U	239Pu
Released E per fission	201.7 MeV	210.0 MeV
Mean neutrino E	2.94 MeV	2.84 MeV
Neutrinos/fission >1.8 MeV	1.92	1.45
Aver. Int. cross section	$3.2\times10^{-43}cm^2$	$2.8\times10^{-43}cm^2$

$\bar{\nu} + p \rightarrow e^+ + n$ (threshold 1.8 MeV)

- Relevance for non-proliferation studies (working group of the IAEA). Neutrino flux can not be shielded. Study to determine fuel composition and power monitoring. Non-intrusive and remote method.

- Study of some Rb, Sr, Y, Nb, I and Cs (IGISOL, trap assisted TAS) (Fallot, Tain, Algora)



Summary

- I hope that I have shown that the TAS technique can contribute to the improvement of nuclear data for neutrino applications, in particular for summation calculations
- There are still several cases to be analized among the top contributors to the neutrino spectrum, but we are working on that.

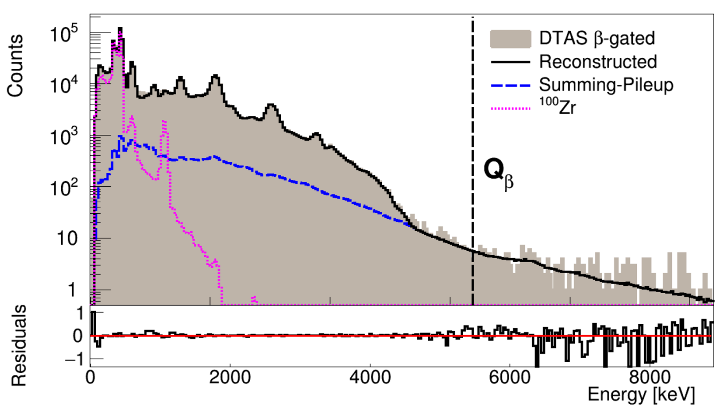
THANK YOU

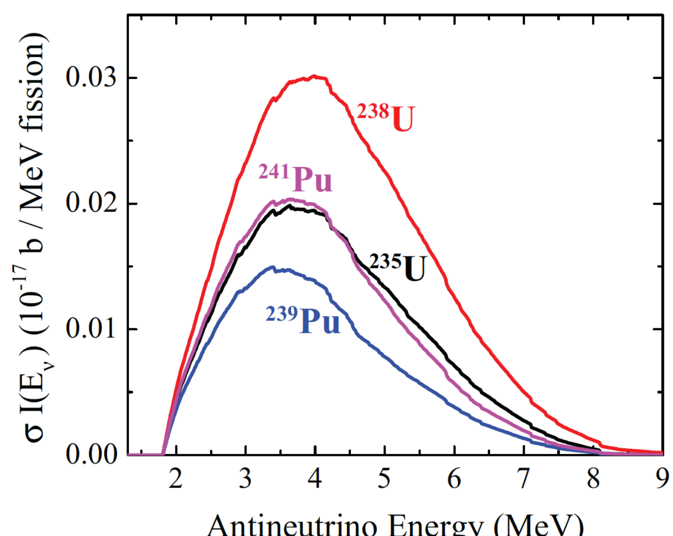
V. Guadilla, J. L. Tain, J. Agramunt, M. Fallot, A. Porta, L. Le Meur, J. A. Briz, T. Eronen, M. Estienne, L. M. Fraile, E. Ganioglu, W. Gelletly, D. Gorelov, J. Hakala, Z. Issoufou, A. Jokinen, M. D. Jordan, V. Kolkinen, J. Koponen, T. Martinez, A. Montaner, I. Moore, E. Nácher, S. Orrigo, H. Penttilä, I. Pohjalainen, J. Reinikainen, M. Reponen, S. Rinta-Antila, B. Rubio, T. Shiba, A. A. Sonzogni, E. Valencia, V. Vedia, A. Voss, A. Algora

Analogy: providing the stones to build the temple

Cave die Cusa

Selinunte, Sicily





Accumulated feeding for beta delayed neutron cases