Total absorption spectroscopy applications to neutrino physics

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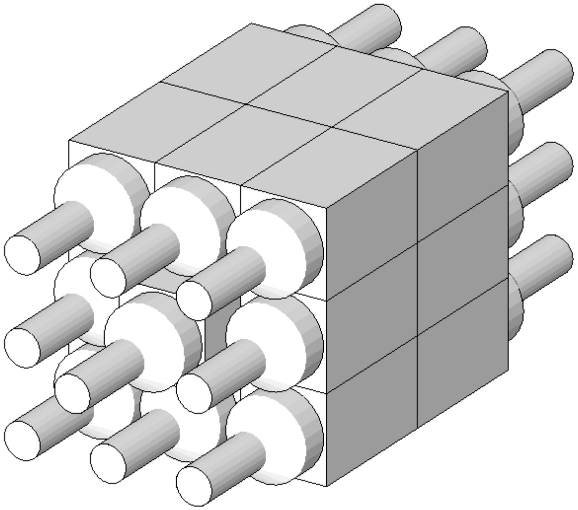
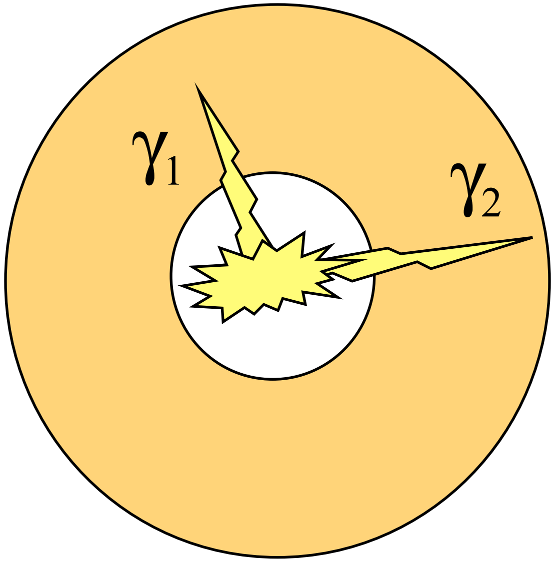
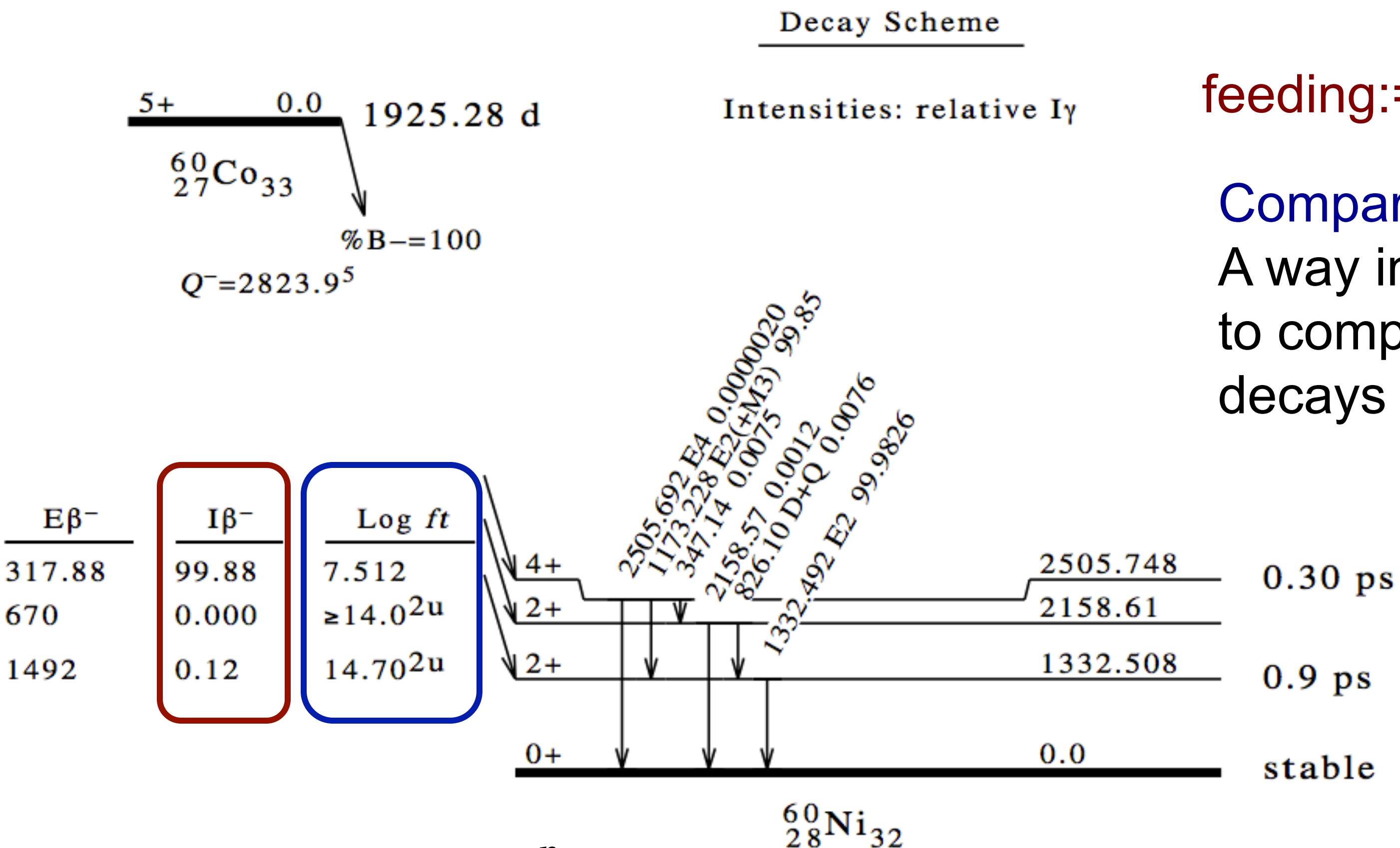




Erice, September 2017

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



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

Comparative half-life: ft

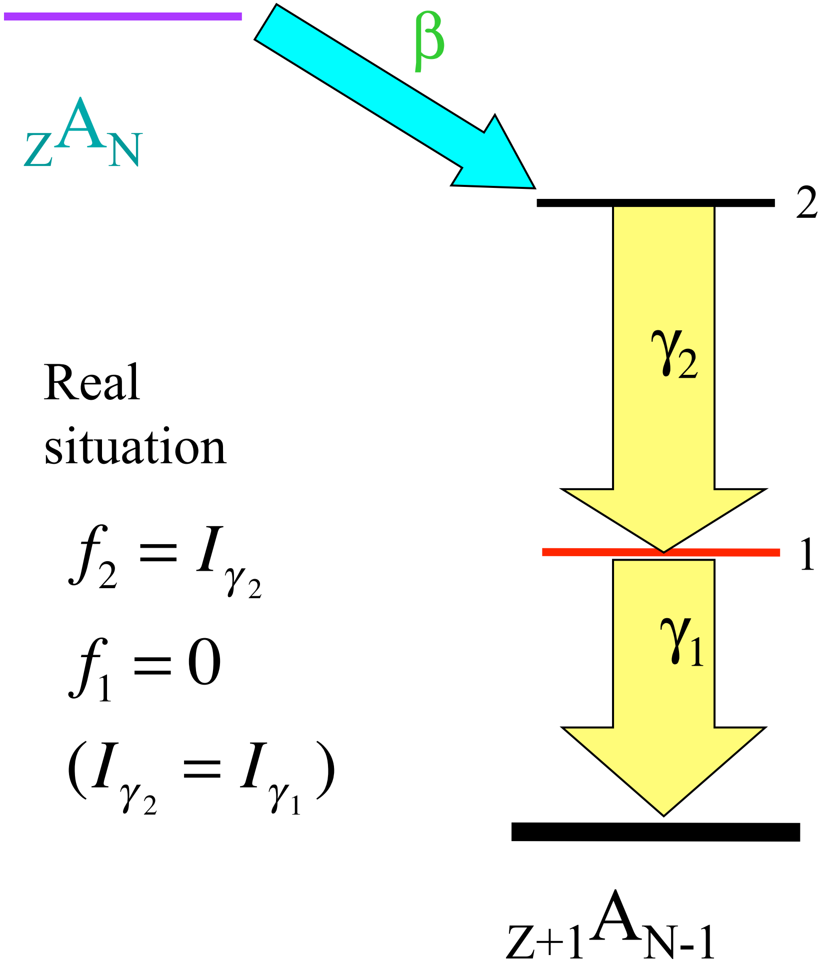
A way introduced by Fermi to compare the different decays (Q, Z')

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

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

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

The problem of measuring the β-feeding

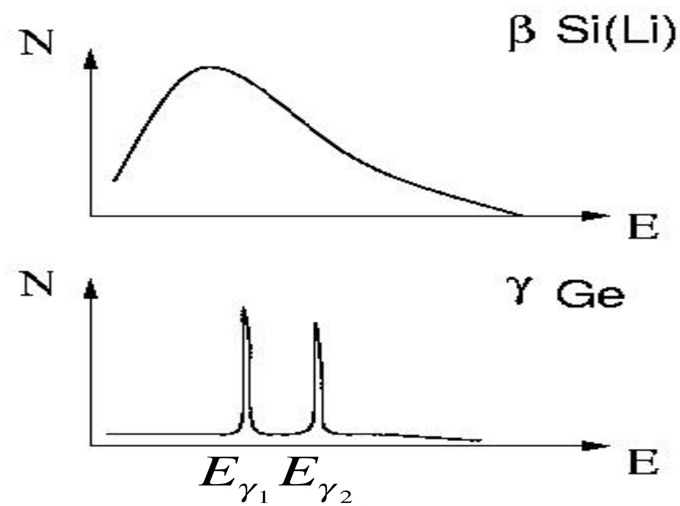


Real situation

$$f_2 = I_{\gamma_2}$$

$$f_1 = 0$$

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

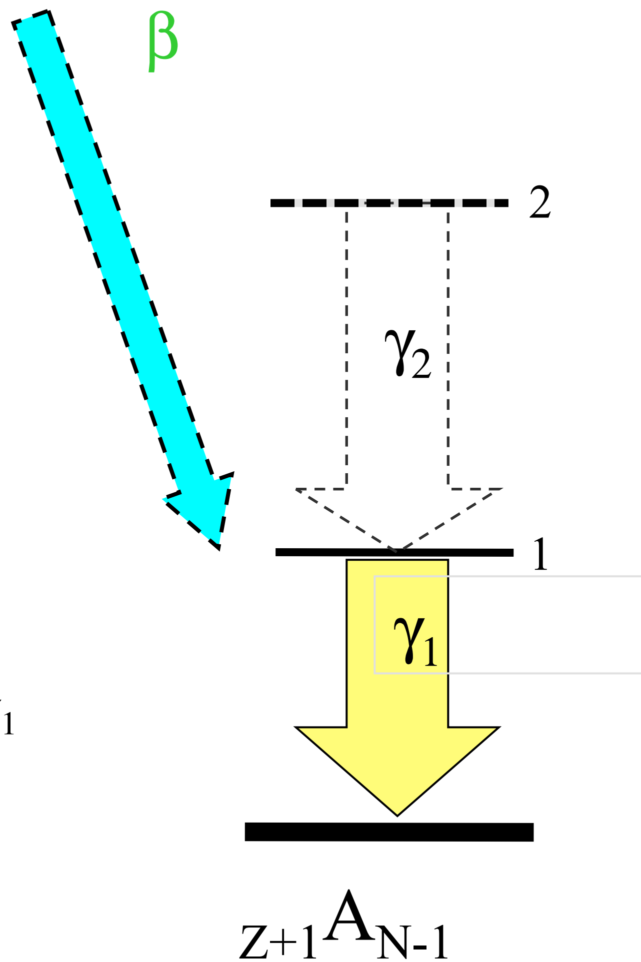


- Ge detectors are conventionally used to construct the level scheme populated in the decay

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

Experimental perspective: the problem of measuring the β- feeding

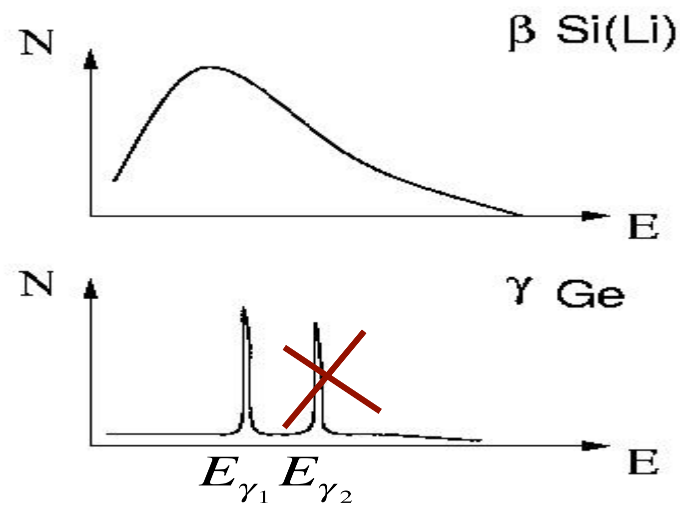
$_{Z}A_{N}$



Apparent situation

$$f_2 = 0$$

$$f_1 = I_{\gamma_1}$$



- What happens if we miss some intensity

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

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

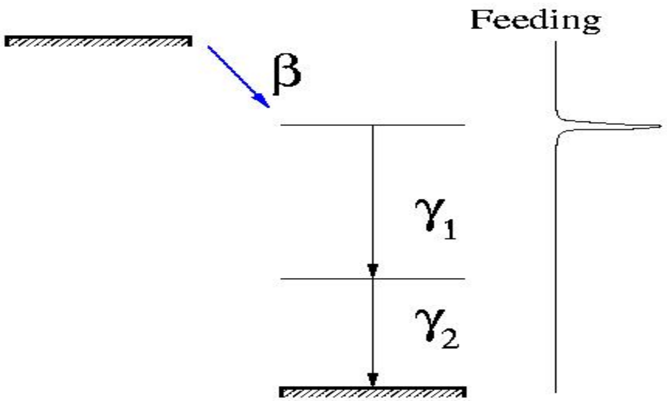
Pandemonium (The Capital of Hell)

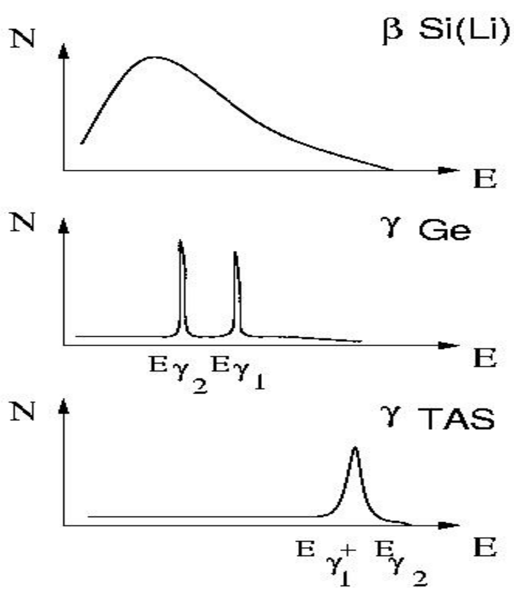
introduced by John Milton (XVII) in his epic poem Paradise Lost

John Martin (~ 1825), presently at Louvre

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

TAGS measurements





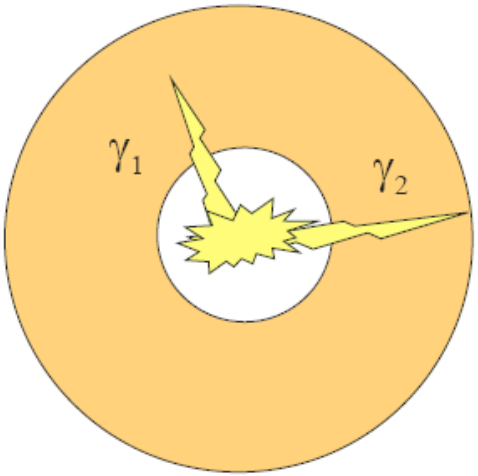
Since the gamma detection is the only reasonable way to solve the problem, we need a highly efficient device:

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!

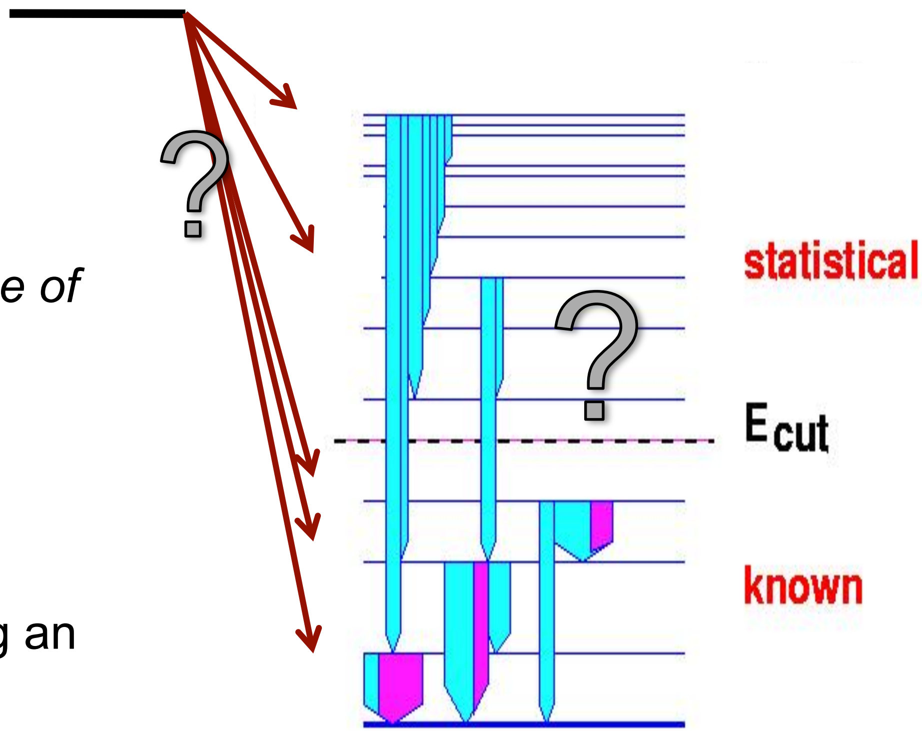
Big crystal, 4π



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

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:

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

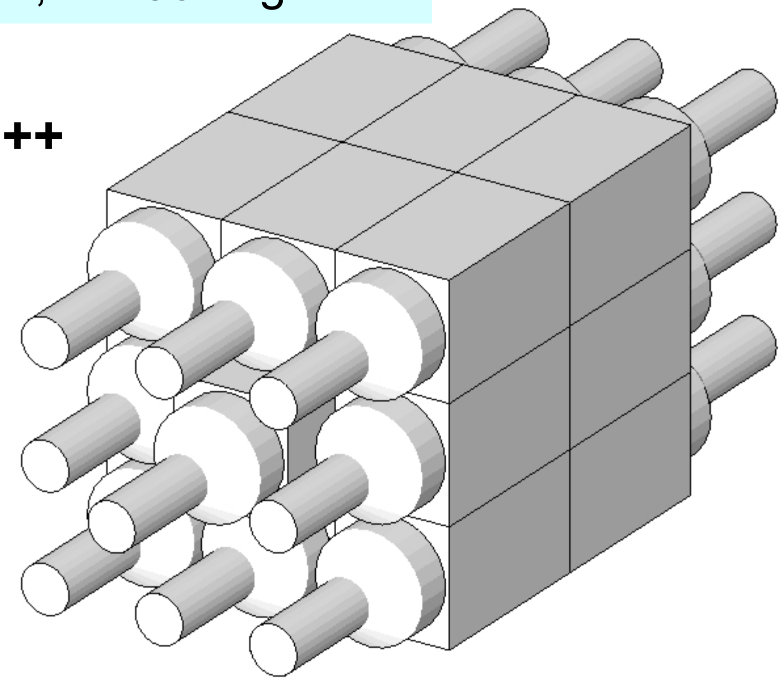
Mathematical formalization by Tain, Cano, et al.

DTAS detector for DESPEC

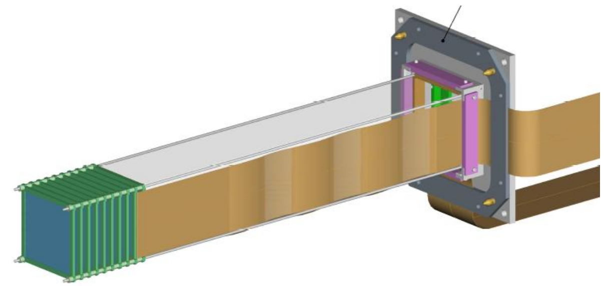
16 + (2) modules:
15 x15 x 25 cm^3 **NaI(Tl)**
+ 5” PMT (50% light col.)
V= 95 L, M= 351 kg

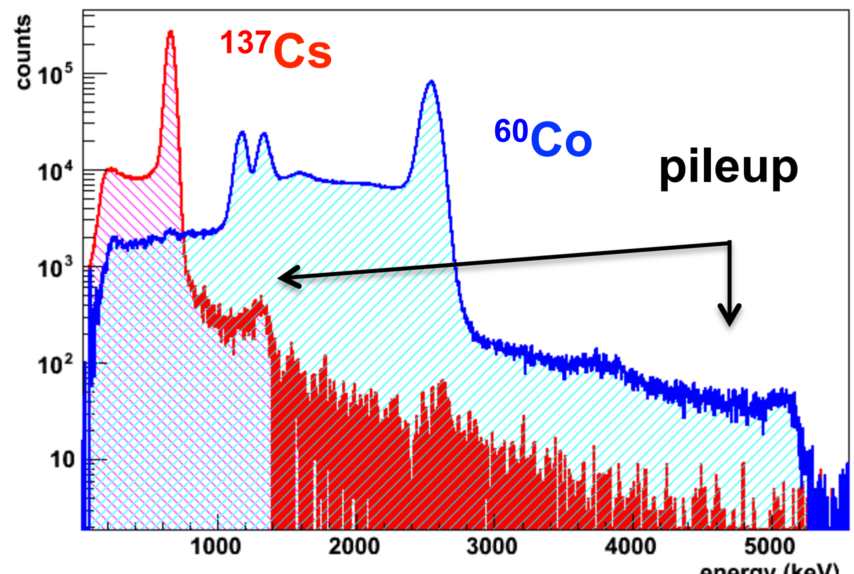
Tot eff ~90%

TAS++



Fast ions active stopper: AIDA (Stack of DSSSD)



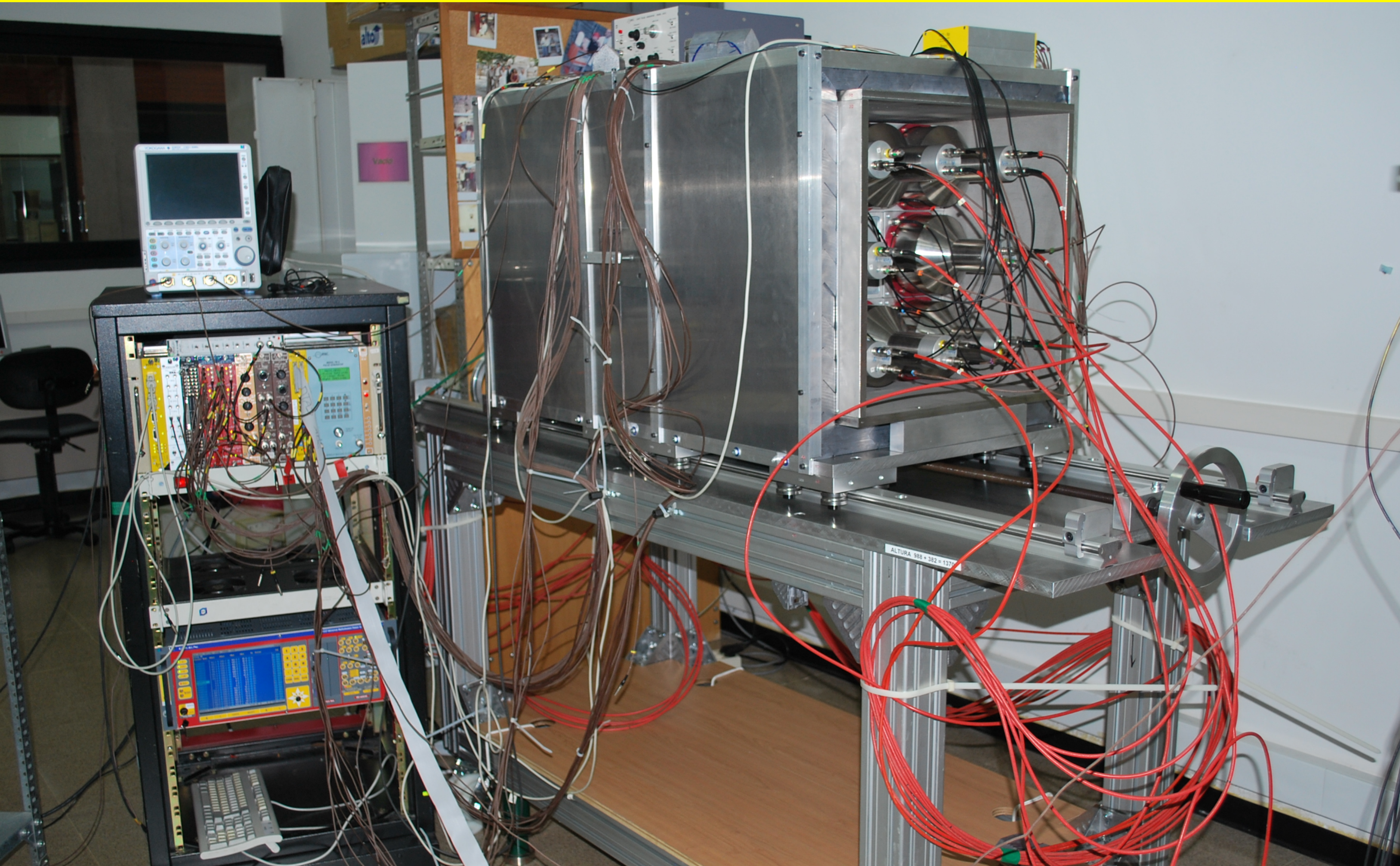


Convener: J. L. Tain (IFIC)
Funded by : 2 FPA and 1 AIC projects
(PIs: Tain, Algora)
TDR approved (01/2013)
Commissioning at IFIC (01/2014)
First experiments at JYFL (02-03/2014)

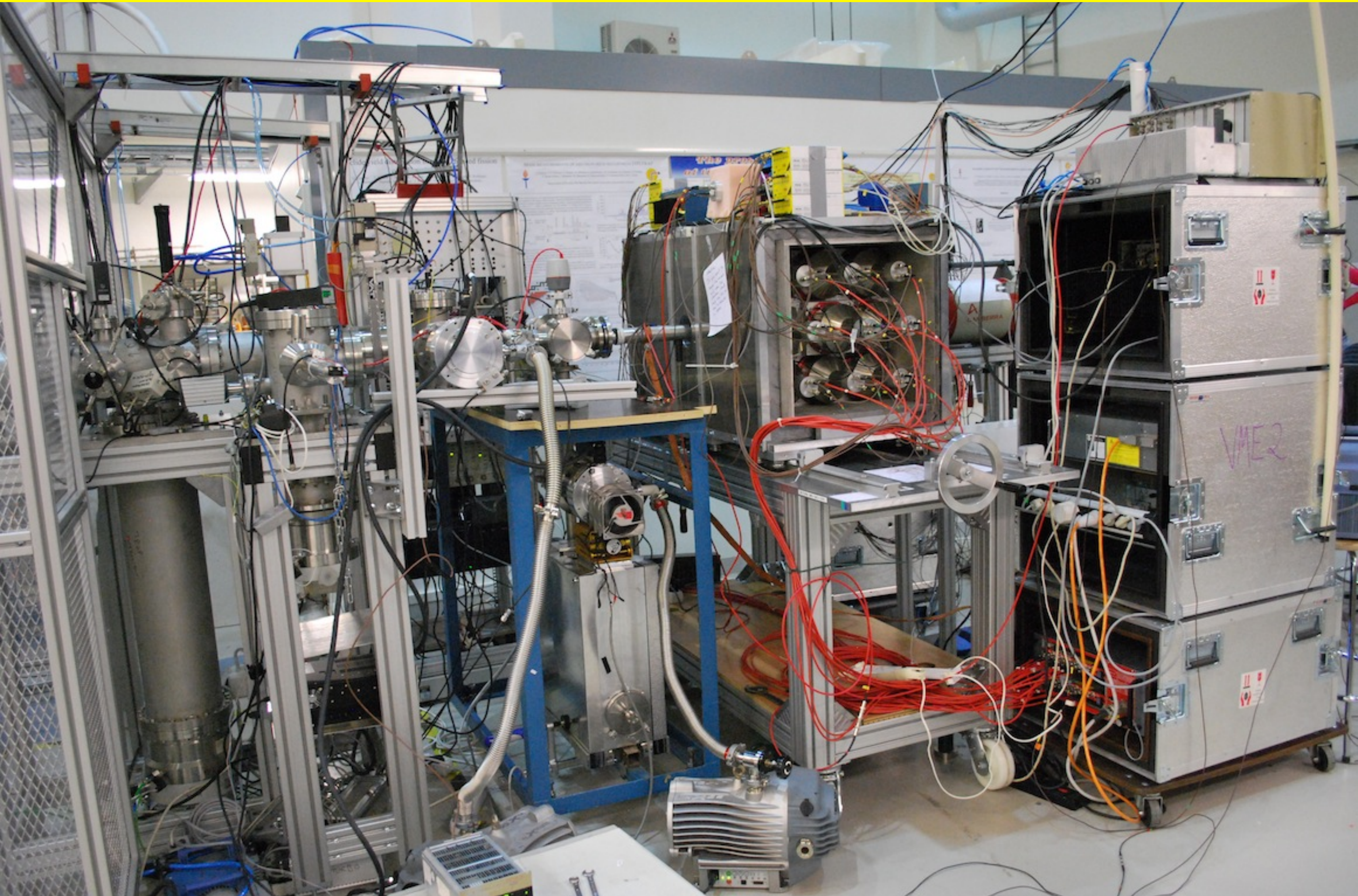
Starting point at IFIC

With some magic and juggling

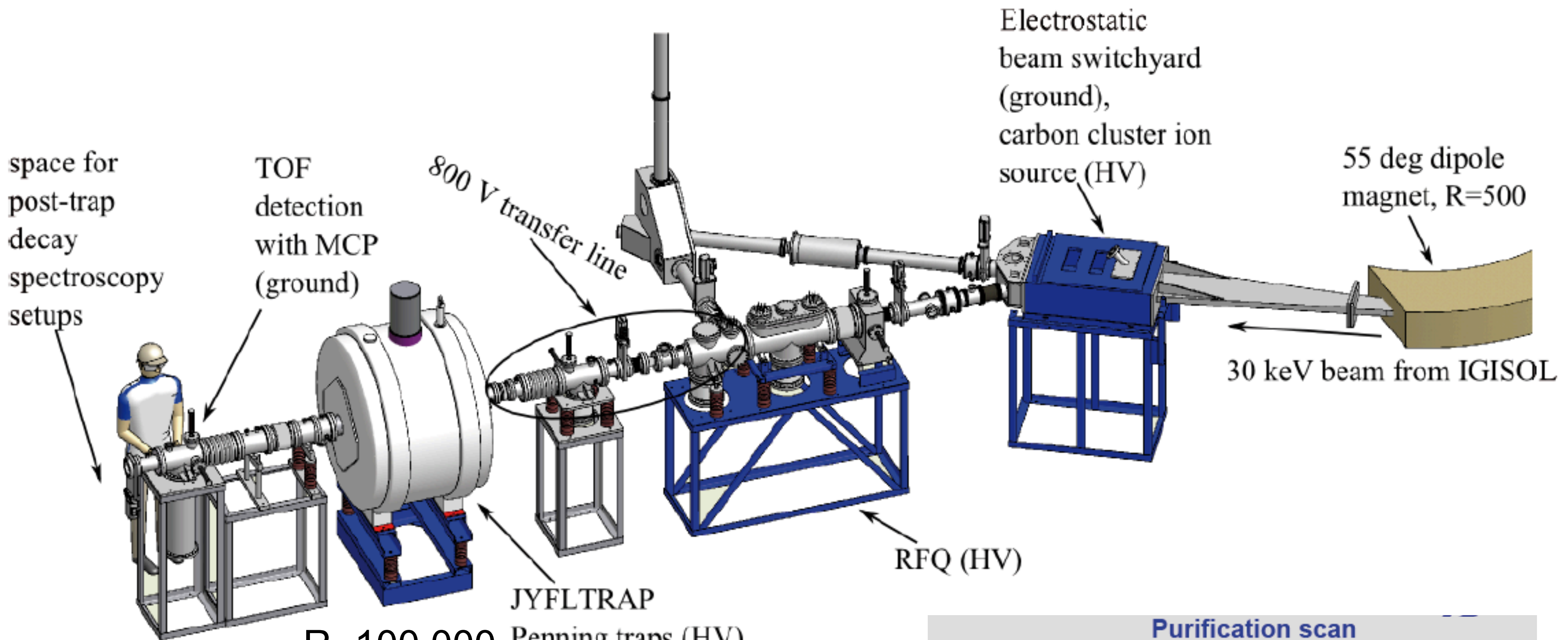
Commissioning at IFIC



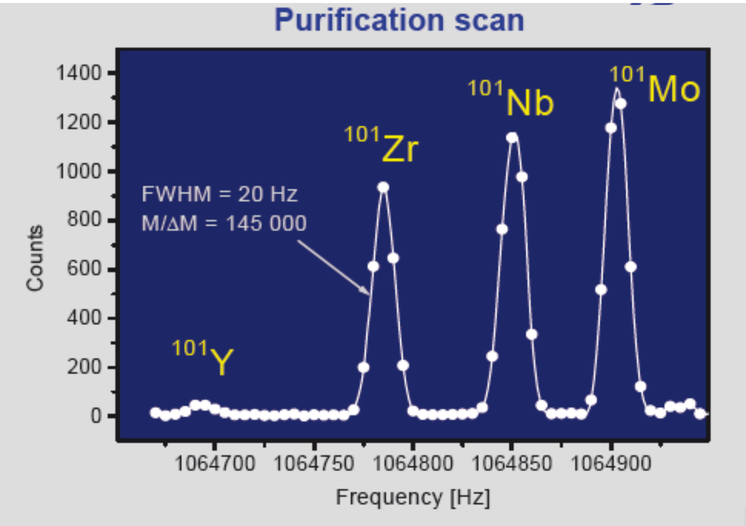
DTAS at Jyväskylä



Why JYFL?: IGISOL + a bonus



R~100 000



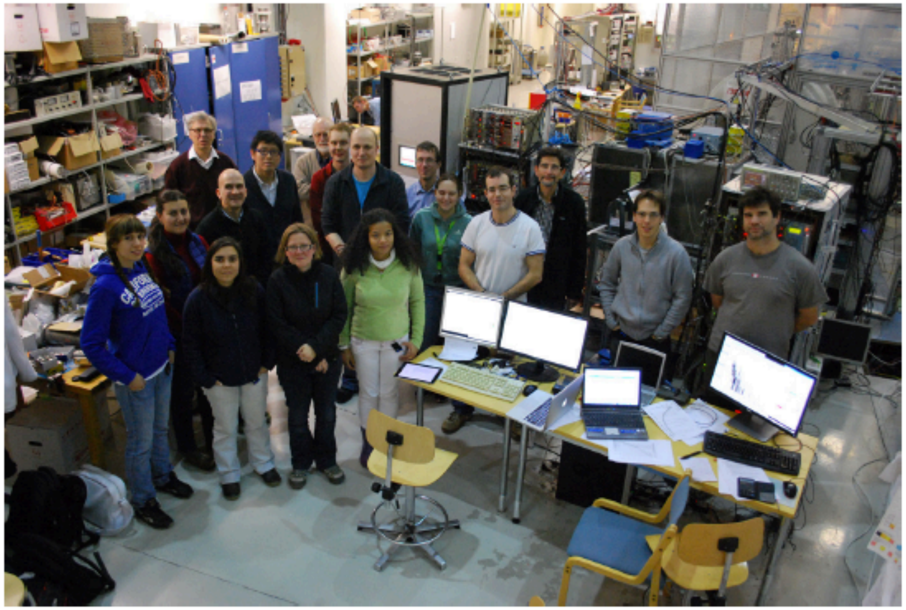
The main reasons are the chemical insensitivity (ion guide technique), high purity by means of purification of the beam using the JYFLTRAP and acceptable yields!

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

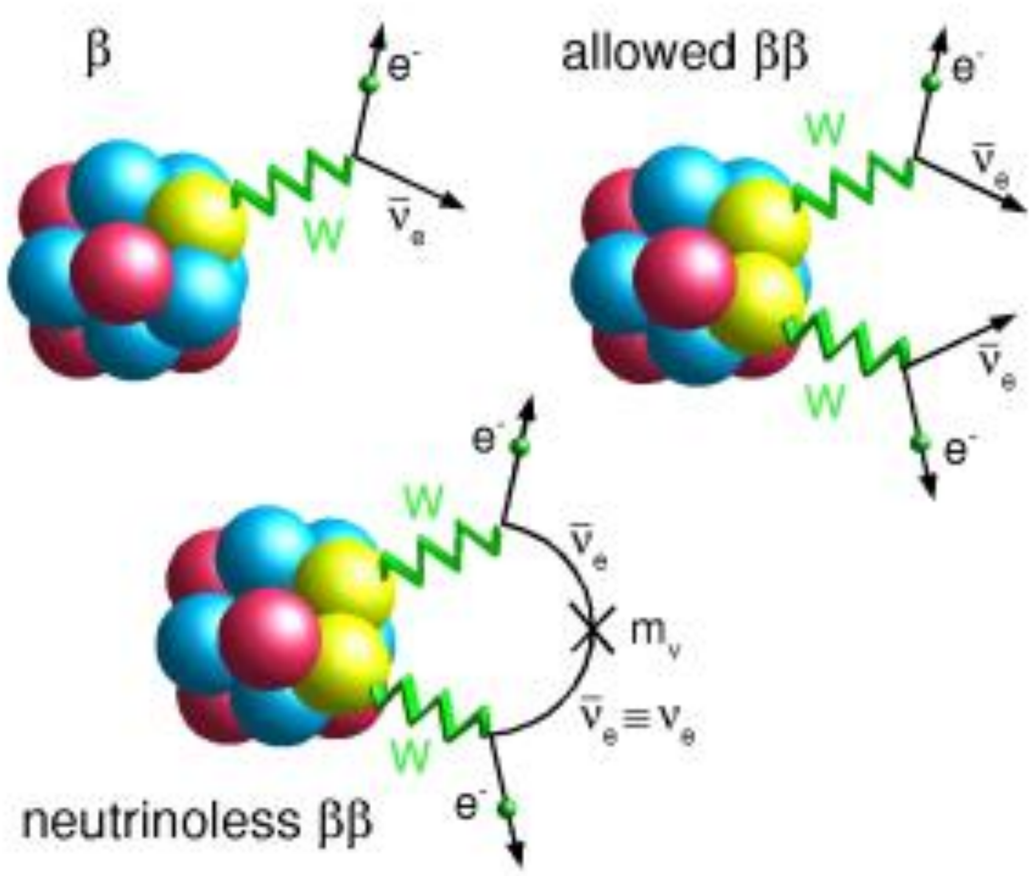


Members (current and old) of the IGISOL group along with some of our DTAS collaborators at a morning shift. JYFLTRAP can be seen in its high voltage cage in the background behind the TAS device and related electronics. In addition, the tape station from Strasbourg is in use. Unfortunately many people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

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.

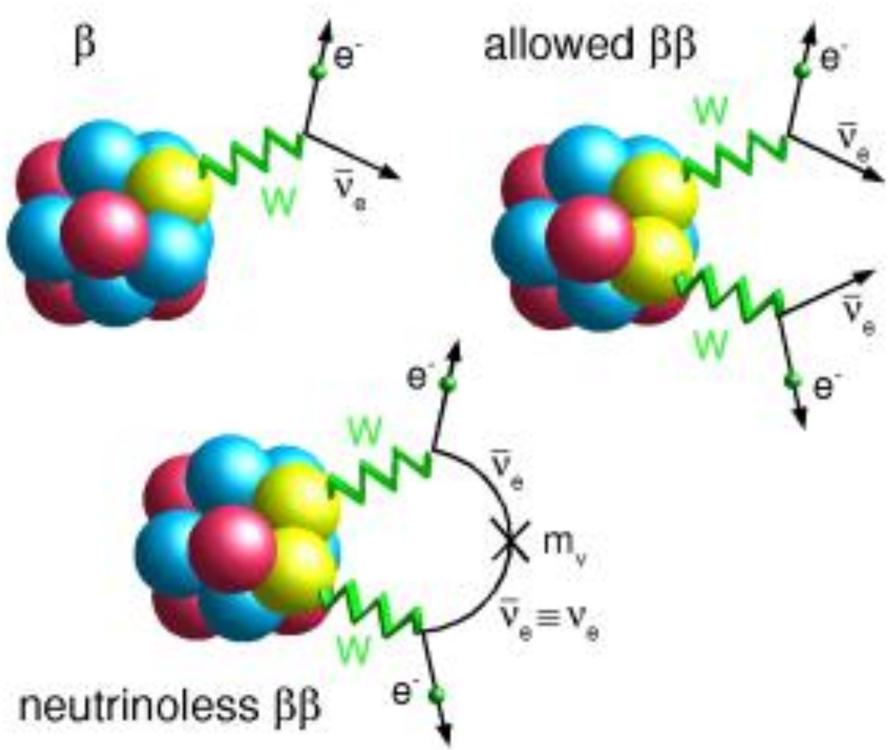
The coming year promises much activity and has already been a very busy time for the local group. Our colleagues from the UK saw in the first experiment of 2014 with collinear laser spectroscopy of fission fragments. Soon after, visitors from York and Aarhus, Denmark, utilized the new MCC30/15 cyclotron 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!

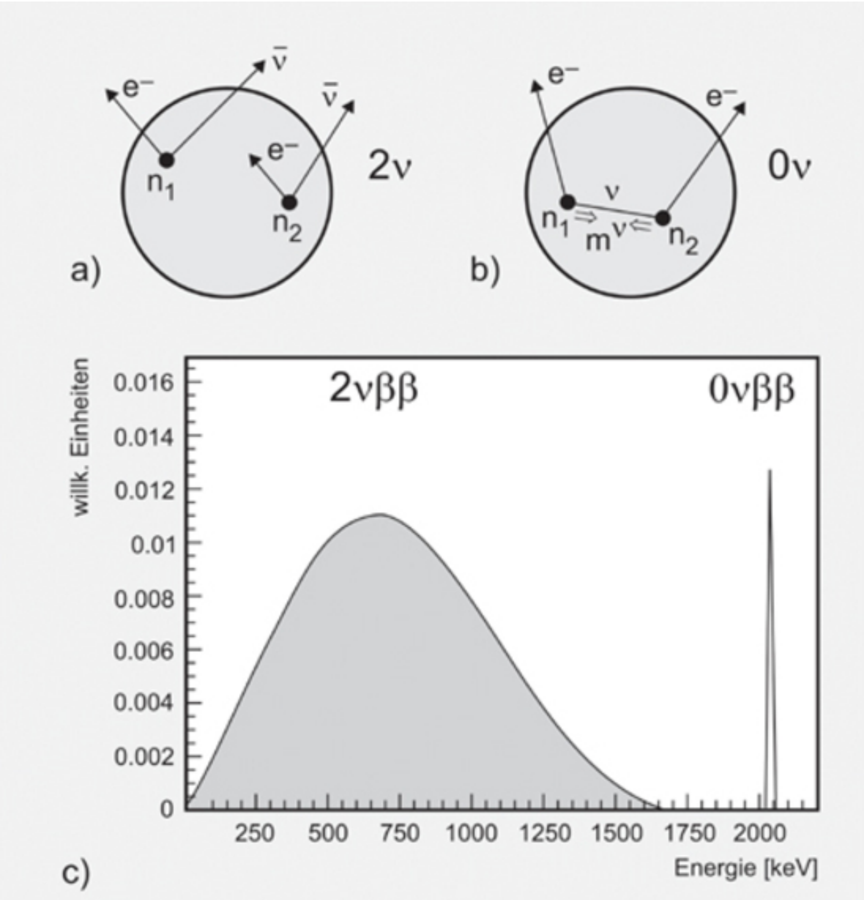
TAS and double beta decay ?
The I154 experiment
(spokespersons: Algora, Tain)



A few words about double beta decay

- It was first considered for study in a publication of Maria Goeppert-Mayer in 1935 (after Wigner)
- There are two possible types





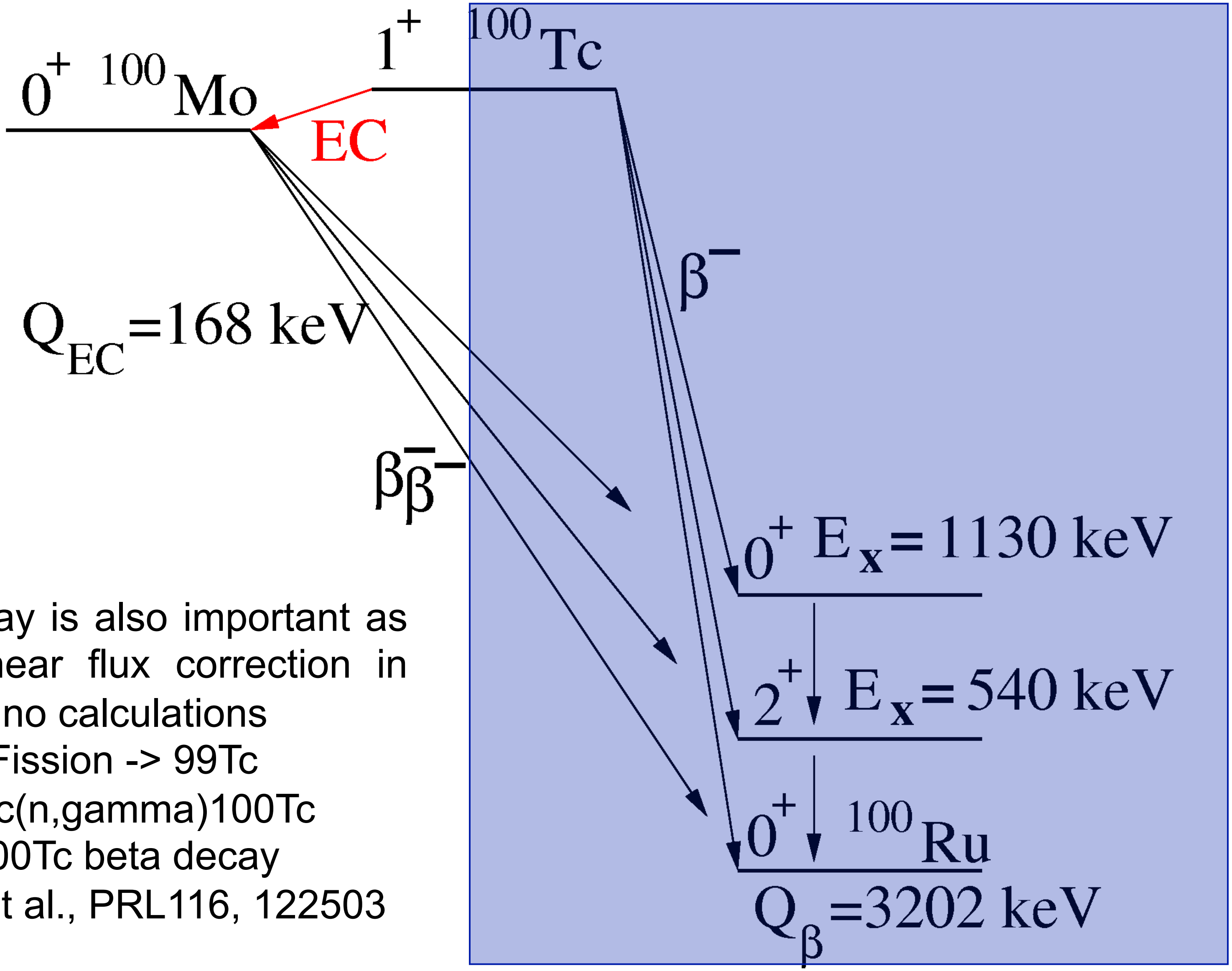
A few words about double beta decay

- The two neutrino emitting type is the rarest type of decays known (half lives of the order of 10^{18}-10^{20} y)
- The neutrino-less type has been searched for more than 75 years with ***no clear*** results. In case of positive detection it will have revolutionary impact in physics:
    - It will show that neutrinos are Majoranna particles (its own antiparticle). It violates lepton number conservation. **Implies physics beyond the Standard Model** and that the neutrino has mass. Can constrain the baryon asymmetry on the Universe.
    - It can help to determine **the effective neutrino mass and fix the mass scale**. This requires a proper knowledge of nuclear matrix elements

TAS: the relation with double beta decay

- Our technique is not appropriate for the study of double beta decay. But what we can do is to perform more modest experiments, in which we study single decays, but with high sensitivity
- It can be more relevant for cases with relatively high Q value of the (single) decay, but remember that we are studying cases close to stability
- Improve the knowledge of single beta decays that are important to fine tune the parameters in double beta decay calculations (in particular the particle-particle interaction strength for QRPA)

A = 100 double beta decay system



This decay is also important as a non-linear flux correction in antineutrino calculations

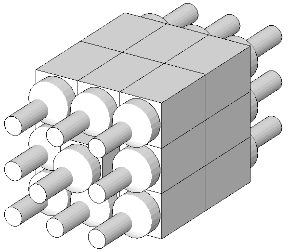
Fission -> 99Tc

99Tc(n,gamma)100Tc

100Tc beta decay

Huber et al., PRL116, 122503

Details of the experiment

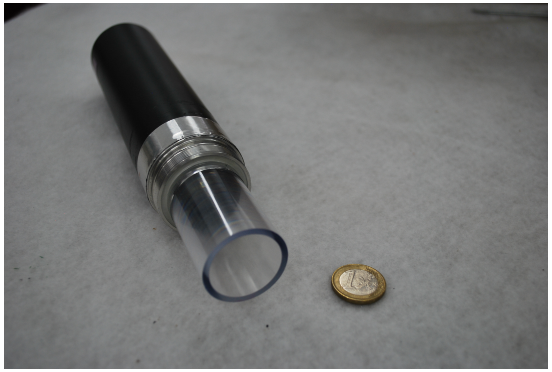


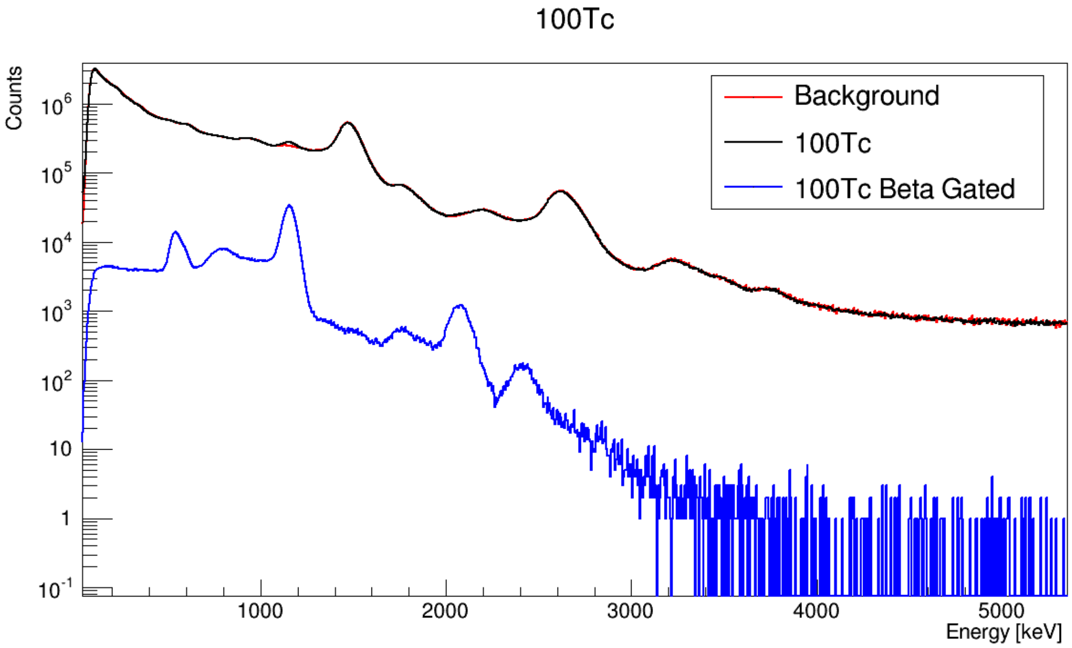
Reaction: $^{100}Mo(p,n)^{100}Tc$, Ep= 10 MeV

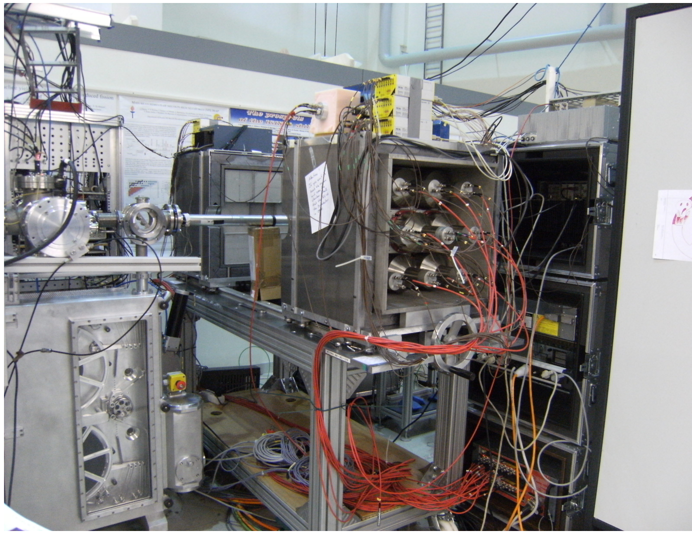
Target: 1.1mg/cm^2 97 %enriched target

Setup: IGISOL + JYFL trap for purification

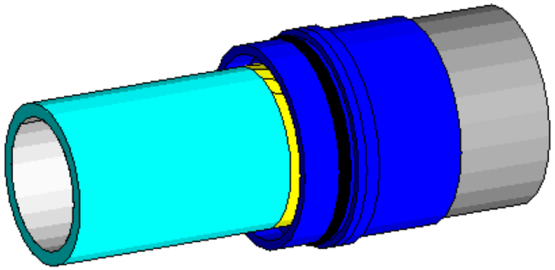
Rate: 400 ions/s (much less that expected)



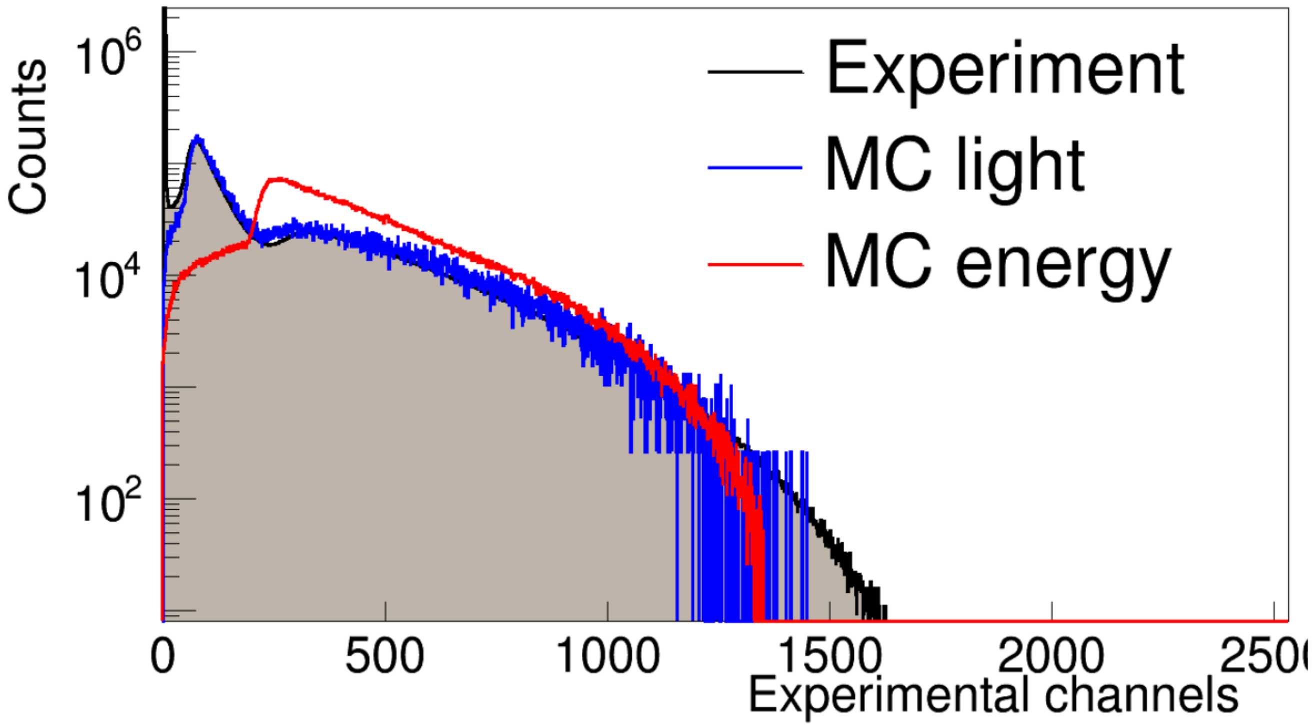




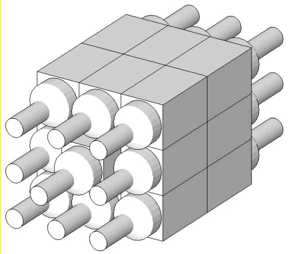
First step of the analysis: careful characterization of detectors

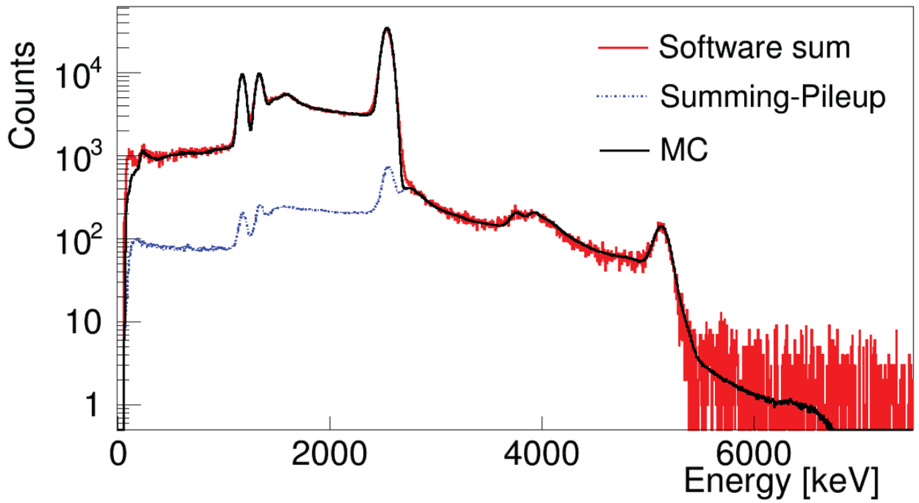


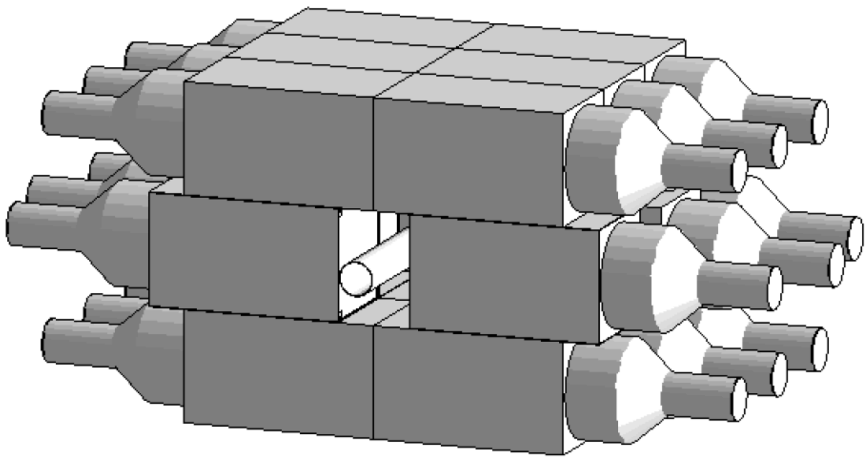
V. Guadilla et al., NIM 854(2017)134
V. Guadilla, PhD Thesis

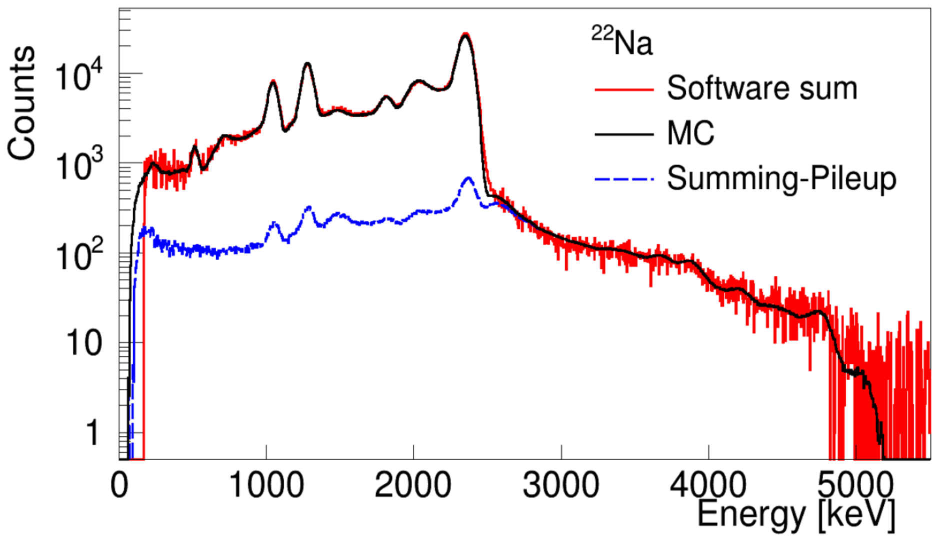


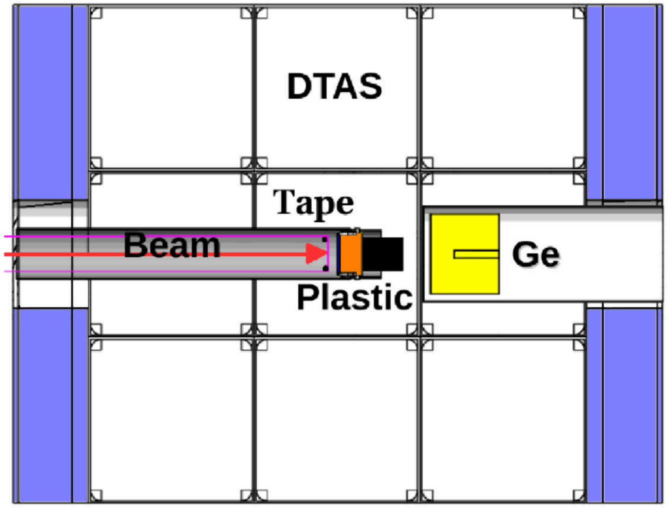
Details of the experiment



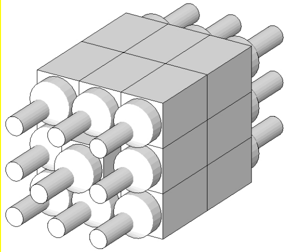


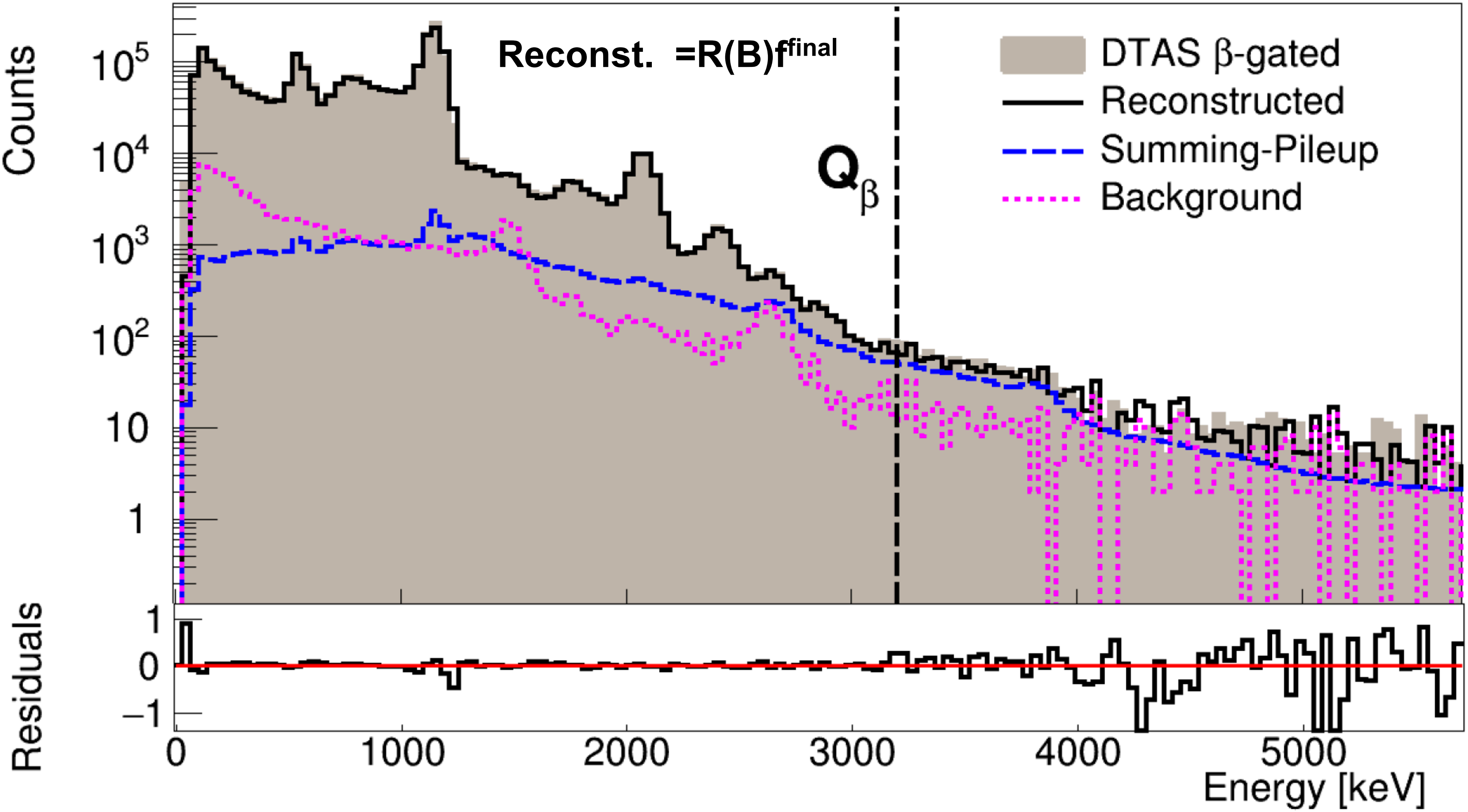






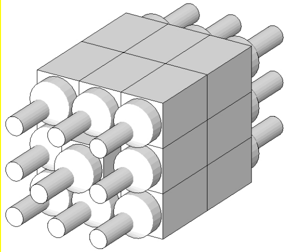
^{100}Tc decay

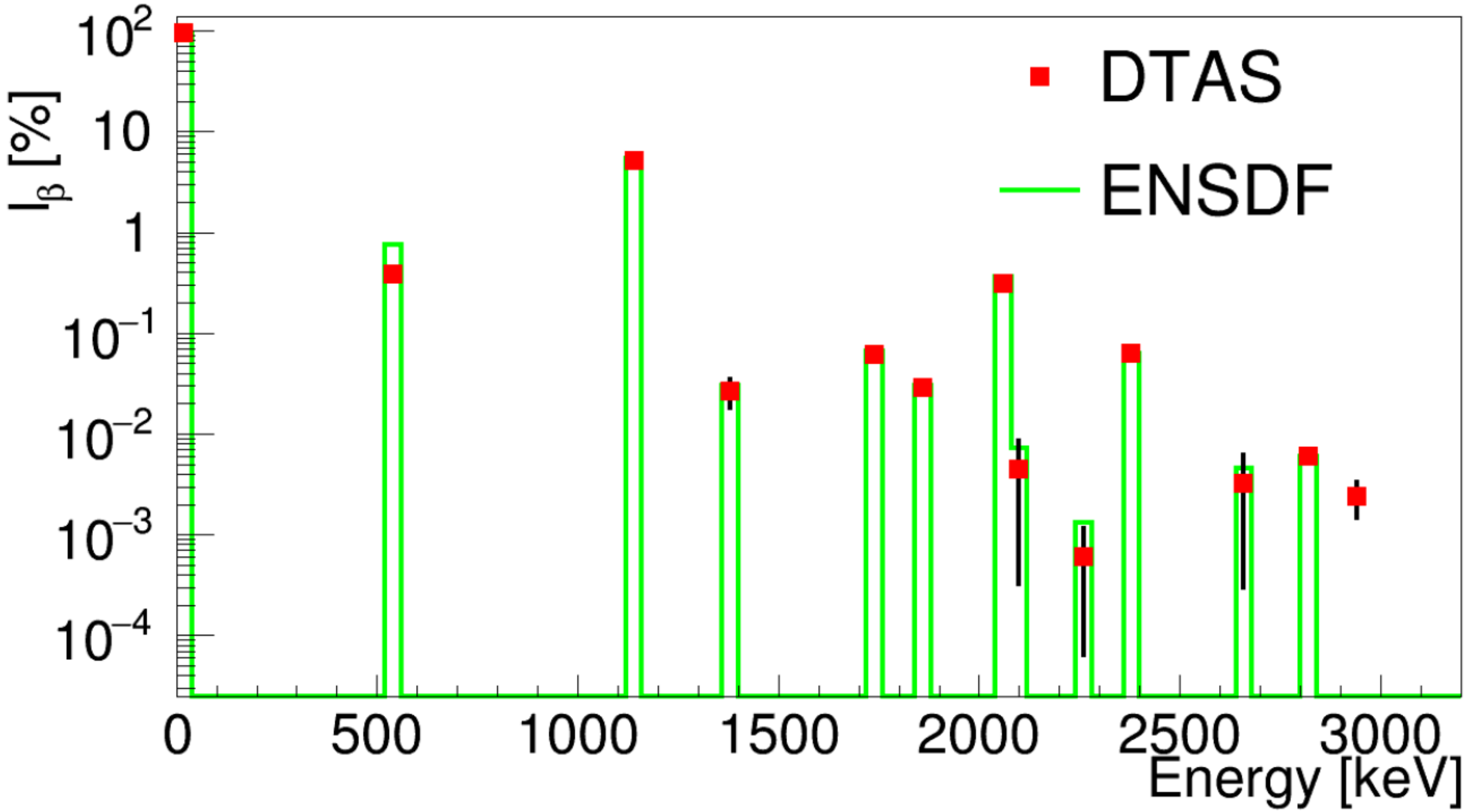




V. Guadilla et al., PRC 96, 014319 (2017)

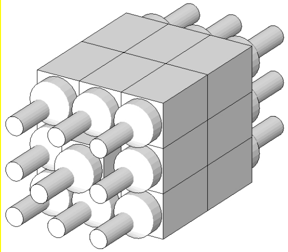
^{100}Tc decay





V. Guadilla et al., PRC 96, 014319 (2017)

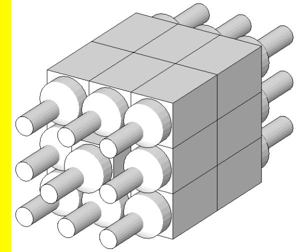
^{100}Tc decay results: dissapointing



Energy [MeV]	J^P	I_β ENSDF [%]	I_β DTAS [%]
0.000	$0^+_{g.s.}$	93.3(1[a])	93.9(5)
0.540	2^+_1	0.75(14)	0.39(5)
1.130	0^+_1	5.36(13)	5.20(40)
1.362	2^+_2	0.030(4)	0.026(8)
1.741	0^+_2	0.066(3)	0.062(6)
1.865	2^+_3	0.030(4)	0.029(3)
2.052	0^+_3	0.36(5)	0.31(2)
2.099	2^+_4	0.0073(7)	0.0045(40)
2.241	2^+_5	0.0013(7)	0.0006(5)
2.387	0^+_4	0.063(4)	0.062(6)
2.660	2^+_6	0.0046(10)	0.0032(30)
2.838	2^+_7	0.006(3)	0.006(1)
2.934	2^+_8	-	0.0024(9)

V. Guadilla et al., PRC 96, 014319 (2017)

^{100}Tc decay results: g_A "tension" not solved



Calculations by J. Suhonen, and O. Civitarese
To reproduce reasonably well the Log(ft) of the decay a g_A=0.4 was used (g_{pp}=0.7 for 100Tc, g_{pp}=1.0 for 100Ru) (same parametrization of P. Pirinen, J. Suhonen PRC91,054309

Experiment $t_{1/2}^{(2\nu)} = (7.1 \pm 0.4) \times 10^{18}$ yr

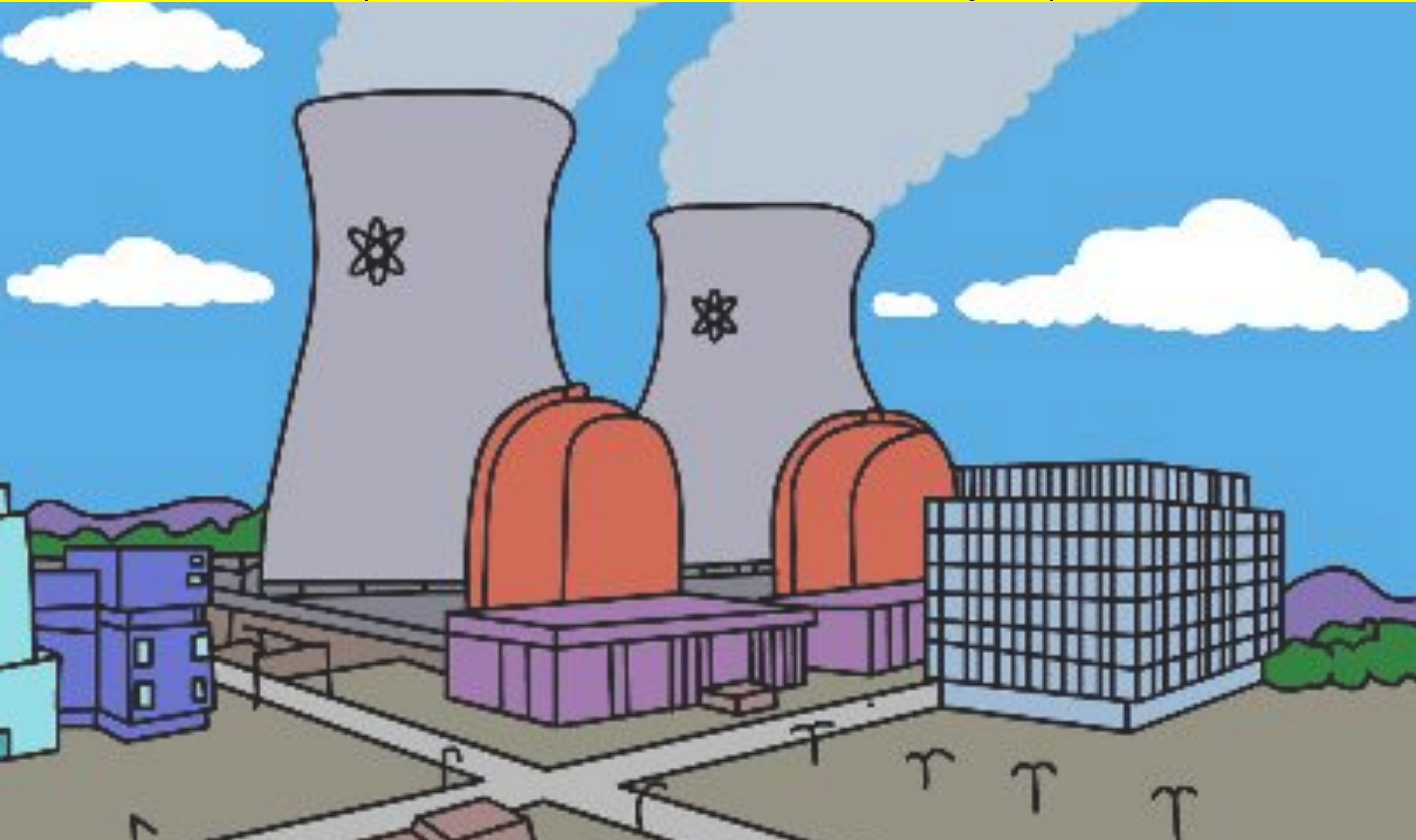
g_A=0.6 → $t_{1/2}^{(2\nu)} = 7.66 \times 10^{18}$ yr

g_A=0.4 → $t_{1/2}^{(2\nu)} \sim 3\times$ experiment

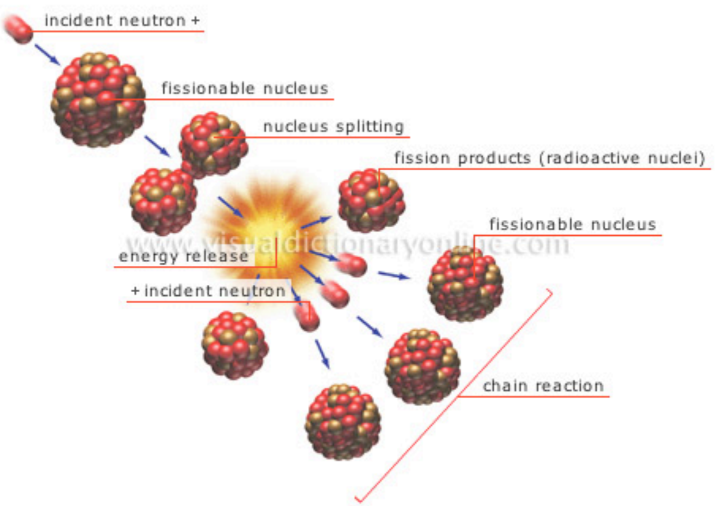
V. Guadilla et al., PRC 96, 014319 (2017)

TAS and reactor neutrinos: the I153 experiment

(spokespersons: Fallot, Tain, Algora)



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

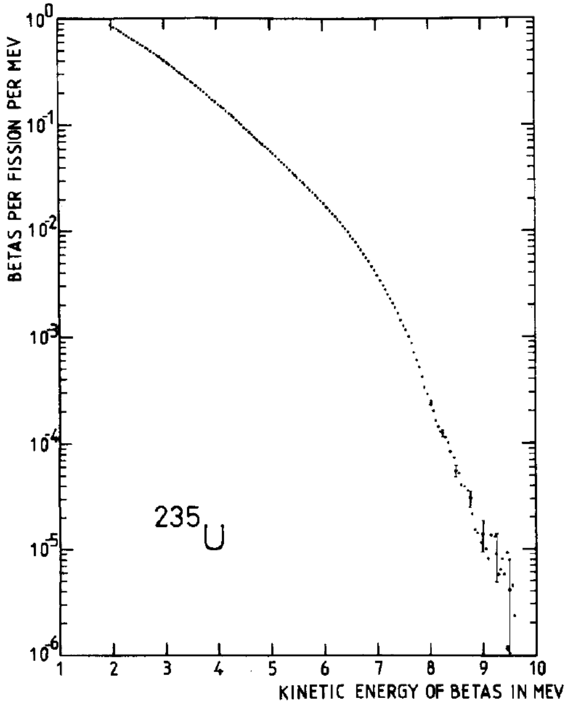
Each fission is approximately followed by 6 beta decays (sizable amount of energy)
A reactor produces 10^{20} v/s

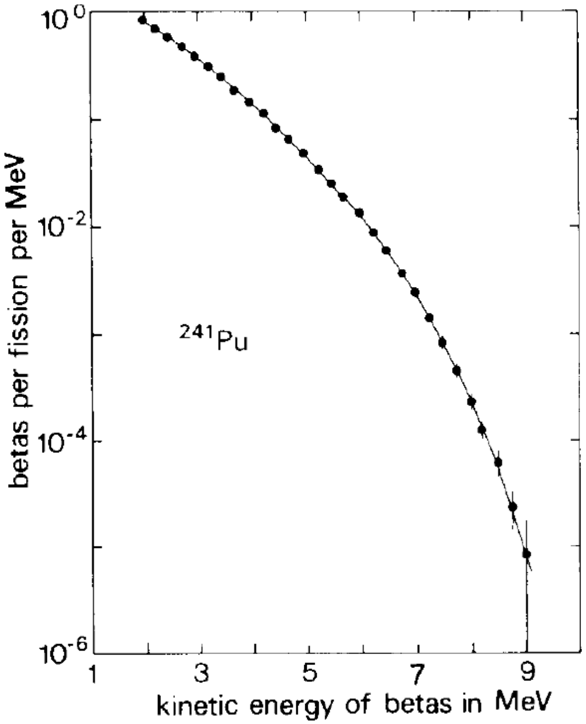
James, J. Nucl. Energy 23 (1969) 517

Example of reactor neutrino oscillation experiment: Double Chooz, Θ_{13}

Determination of the primary neutrino spectrum

•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

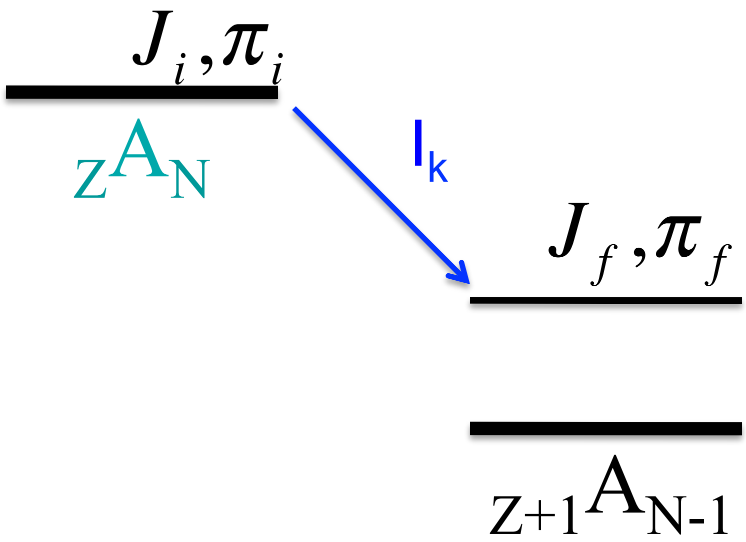




• “Pure” summation calculations (next slide), for many years the only posibility for ^{238}U

Neutrino and decay heat summation calculations

Beta decay (β^-)



Spectrum for each transition

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

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

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)

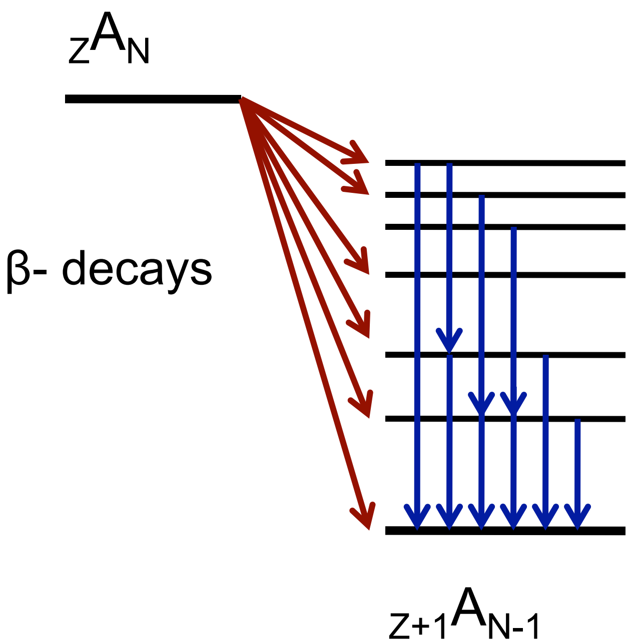
$$S(E) = \sum_n \lambda_n N_n S_n(E) / r = \sum_n CFY_n S_n(E)$$

Decay heat summation calculation

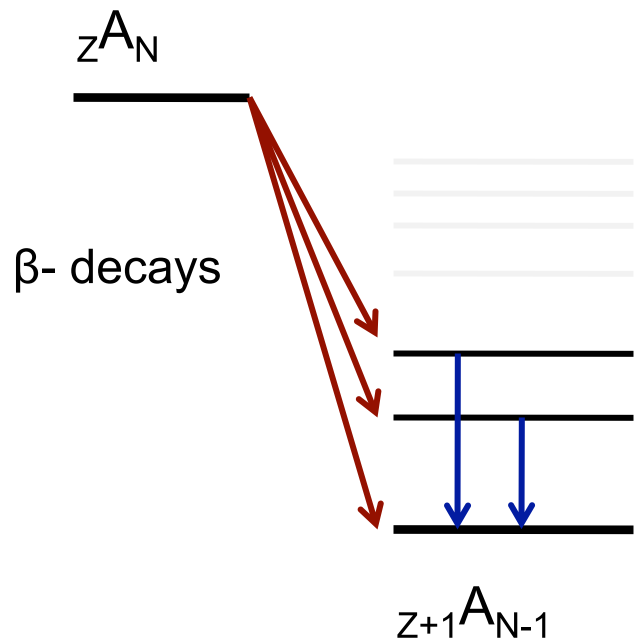
$$f(t) = \sum_i E_i \lambda_i N_i(t)$$

Pandemonium and summation calculations

Real situation

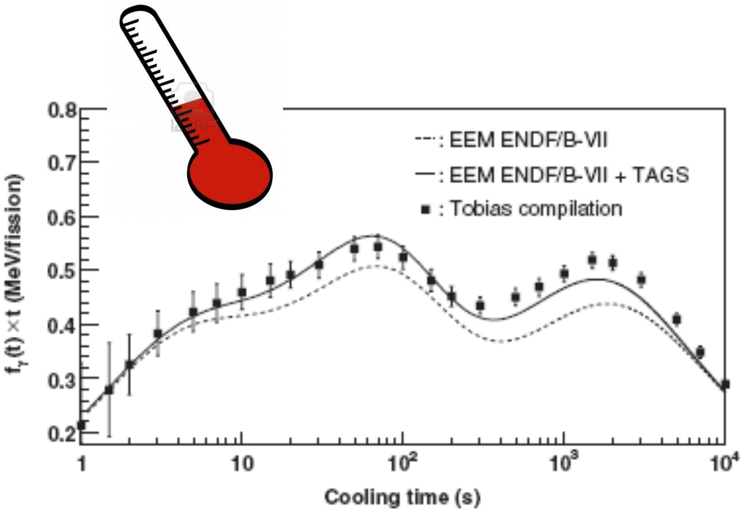


Pandemonium situation



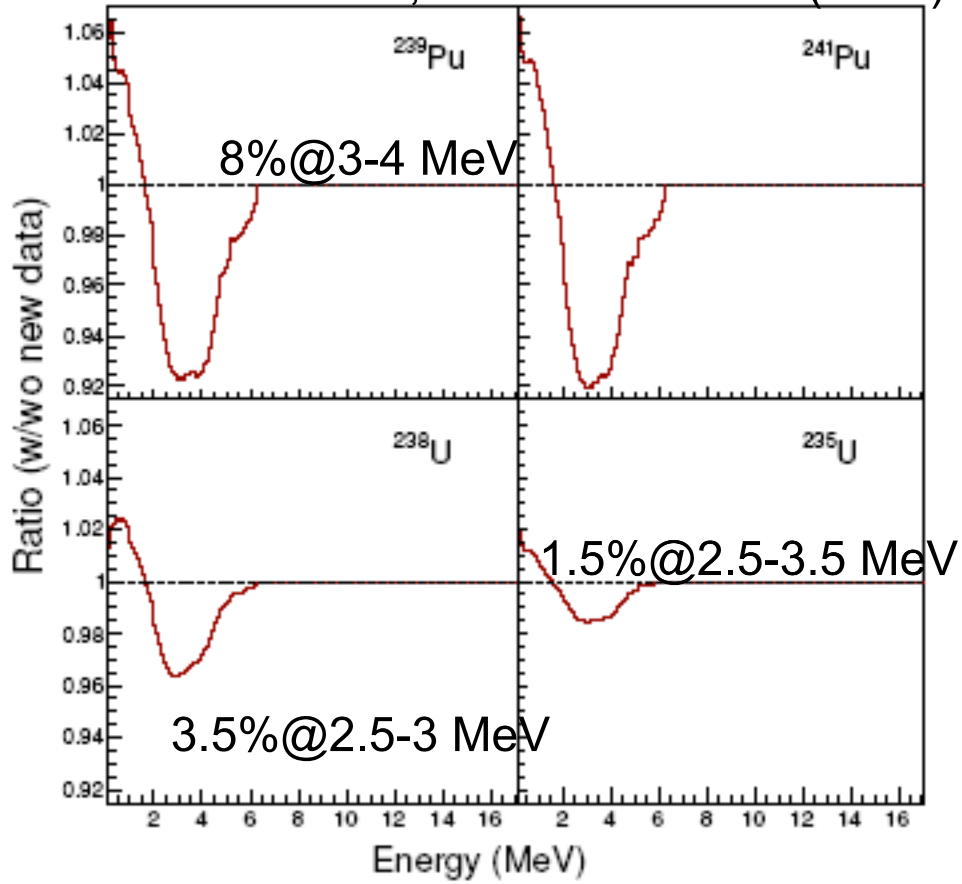
As a result of the Pandemonium, betas and neutrinos are estimated with higher energies from databases. This is why TAS data is very important

Impact of some of our earlier data



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

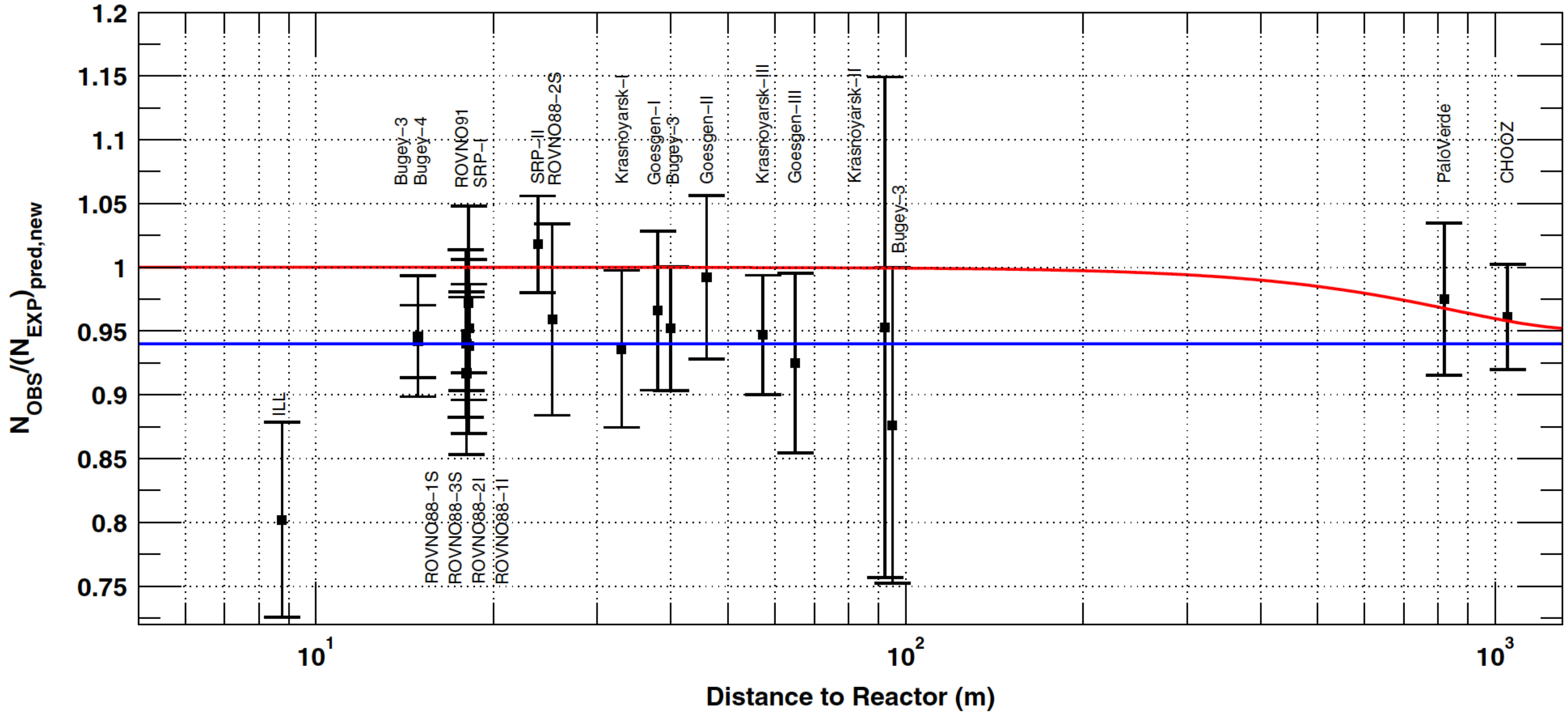
M. Fallot et al., PRL 109.202504 (2012)



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

New questions: reactor anomaly ?

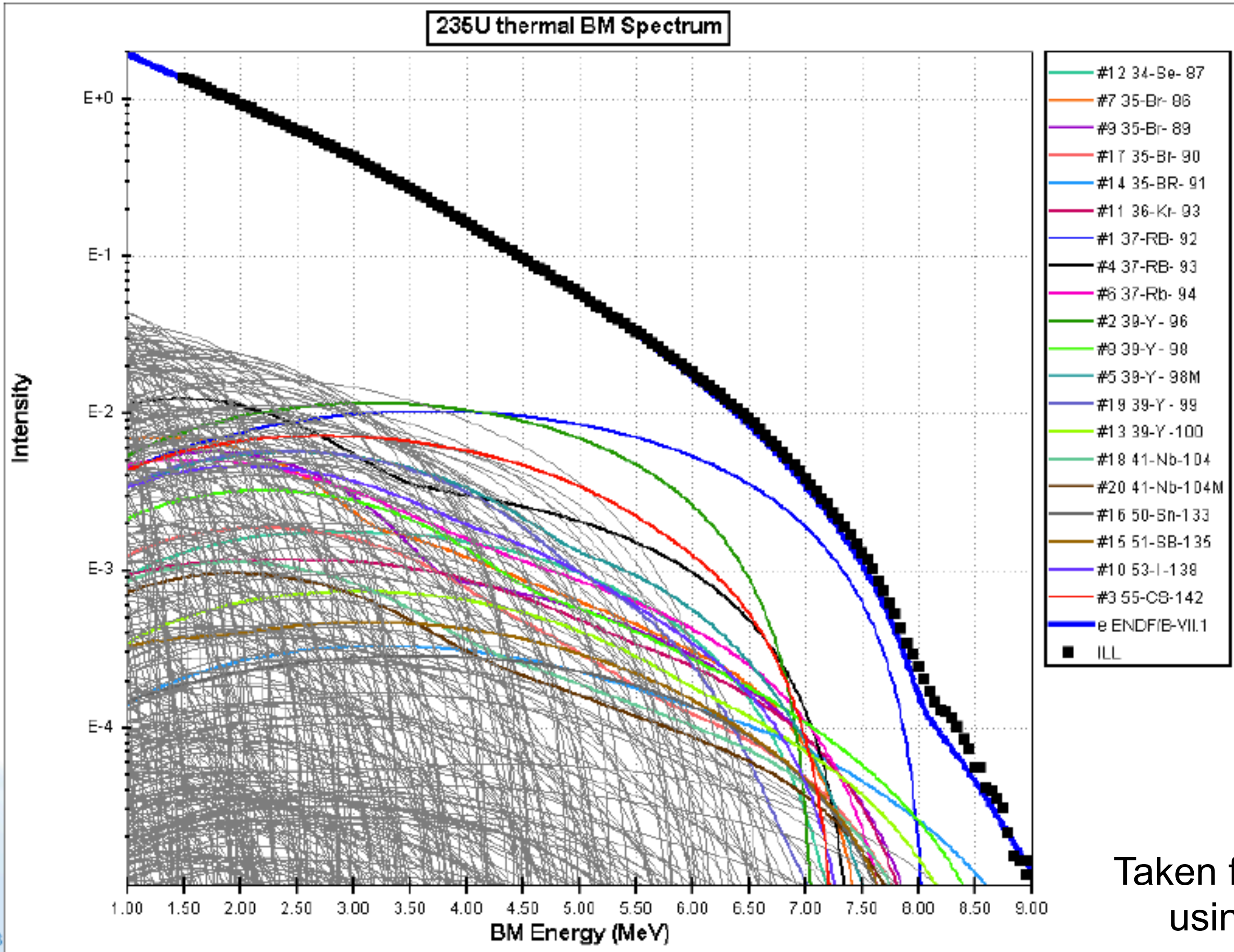
G. MENTION *et al.* PHYSICAL REVIEW D **83,** 073006 (2011)



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

92Rb: star case, nuclea data matters

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].

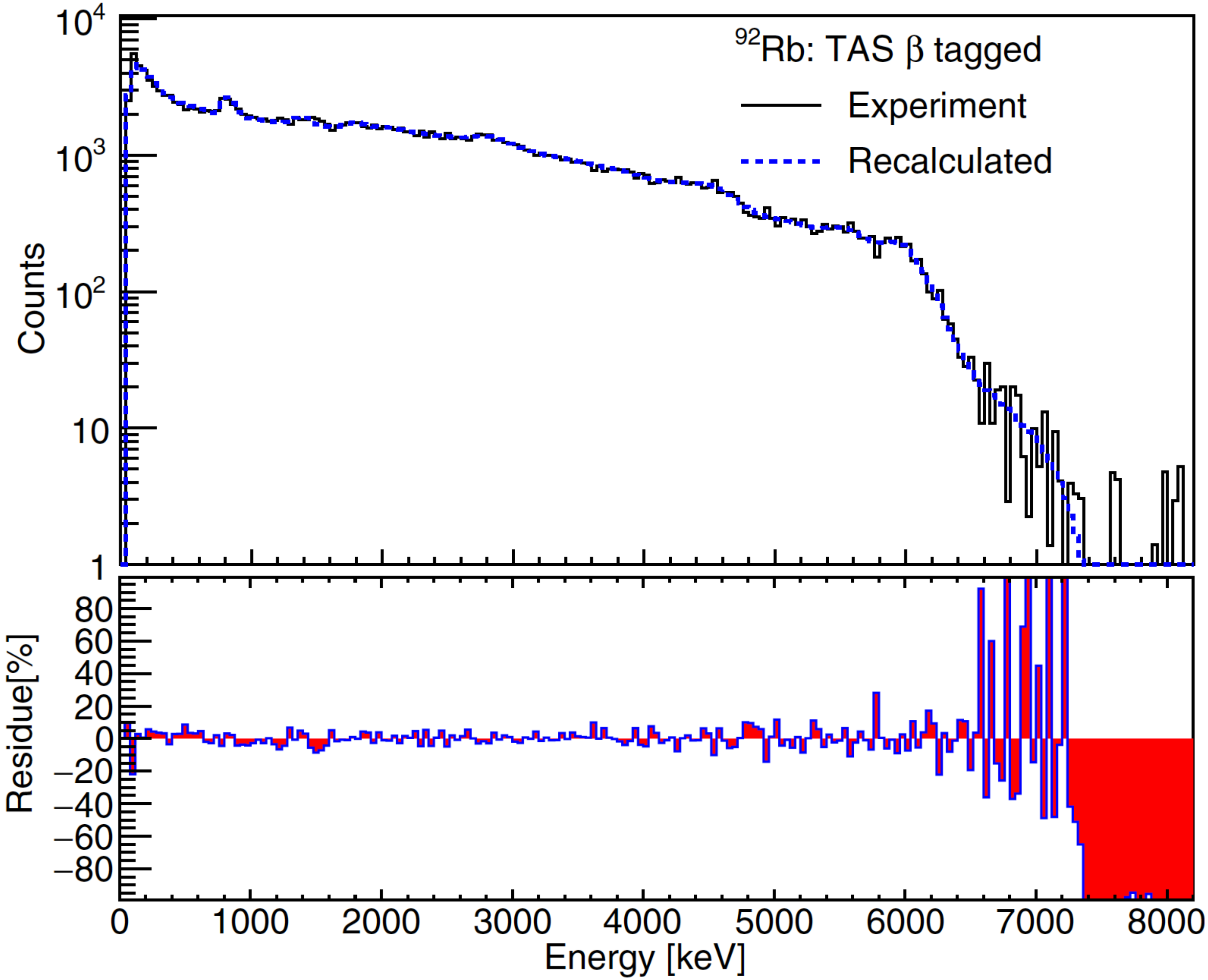
	4–5 MeV	5–6 MeV	6–7 MeV	7–8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	...
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	...	...
^{93}Rb	2.34%	4.17%	6.78%	4.21%
^{98m}Y	2.43%	3.16%	4.57%	4.95%
^{135}Te	4.01%	3.58%	...	...
^{104m}Nb	0.72%	1.82%	4.15%	7.76%
^{90}Rb	1.90%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

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)
New experiment ????

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

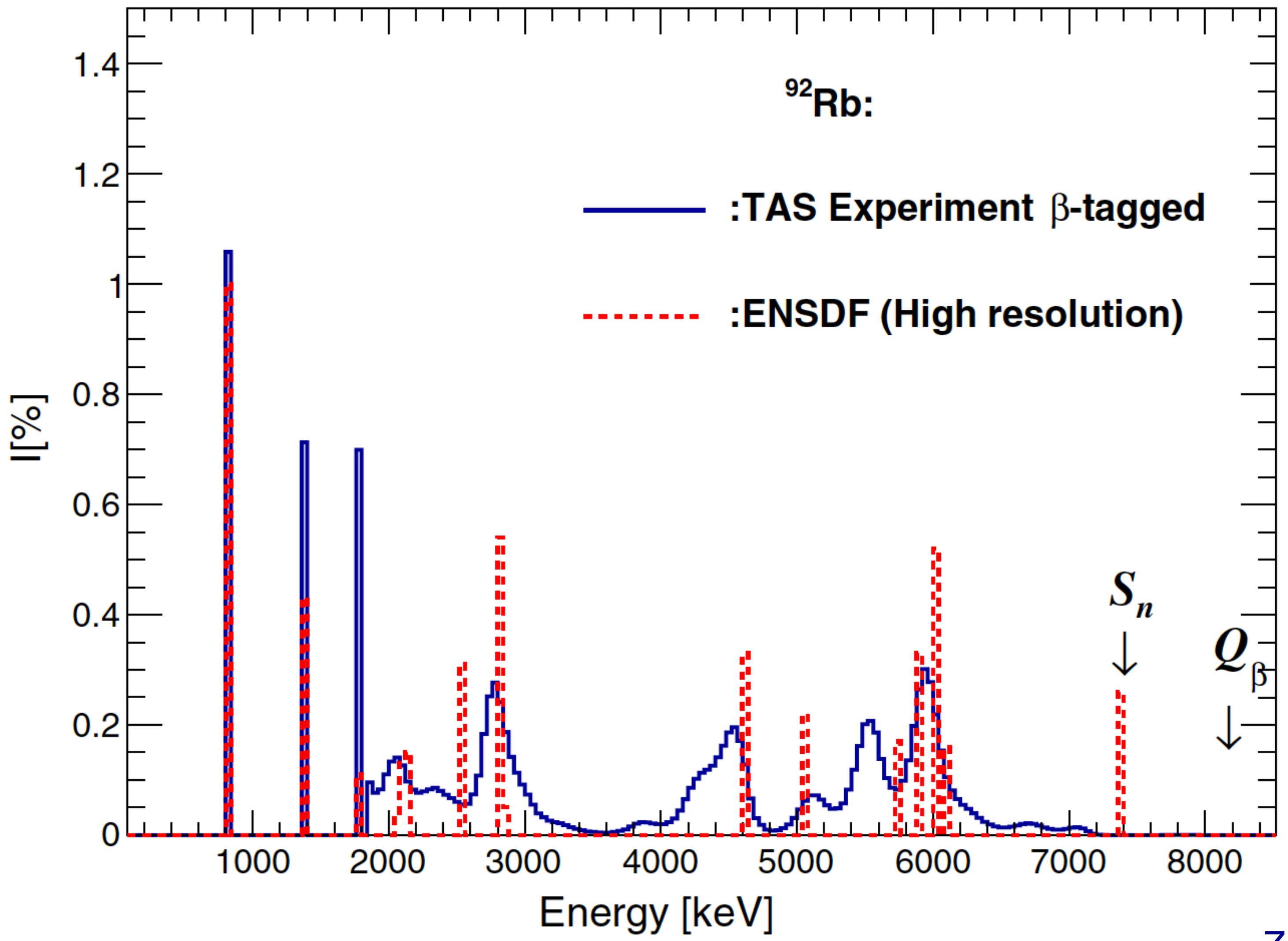
92Rb: TAS measurement, 2010 exp. Analized by the Nantes group



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

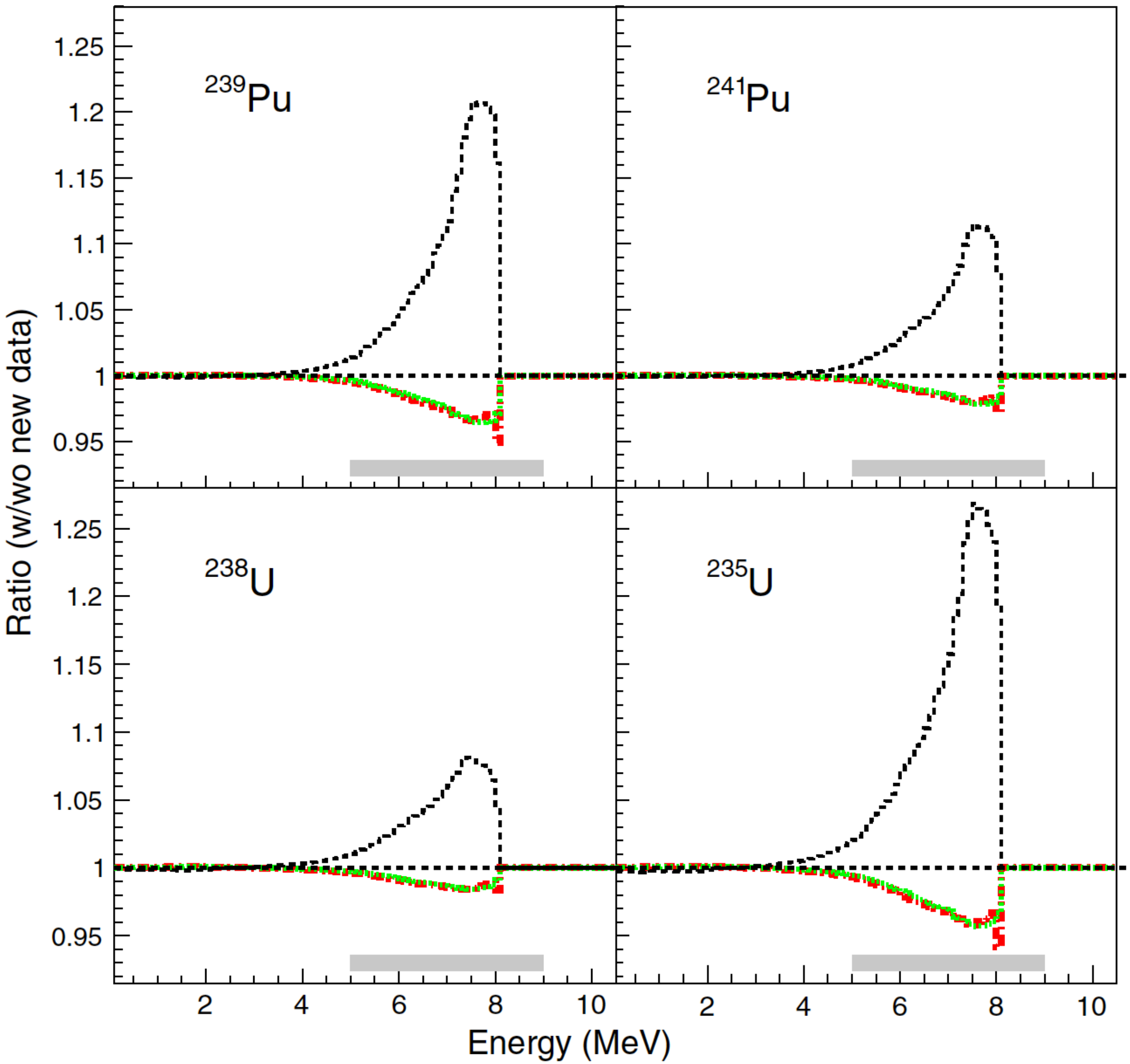


Gs to gs feeding Evolution

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)

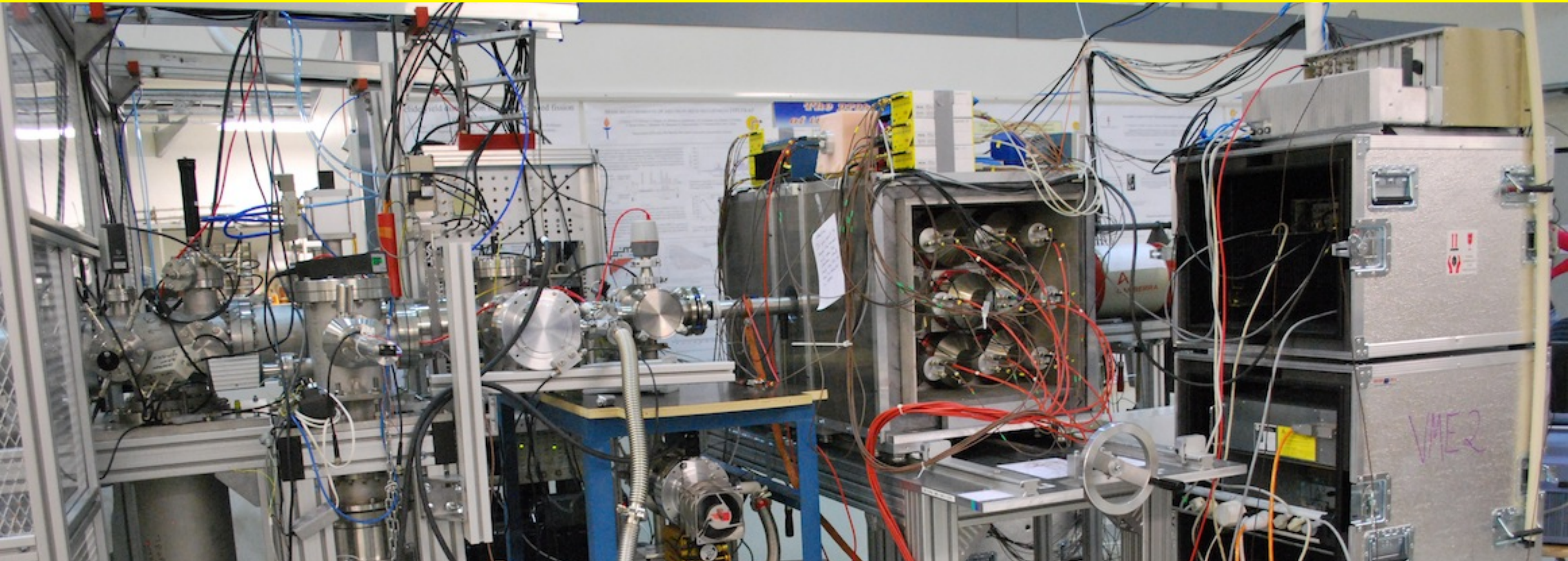
Black: with respect to the value used in D. A. Dwyer et al. PRL 114,012502

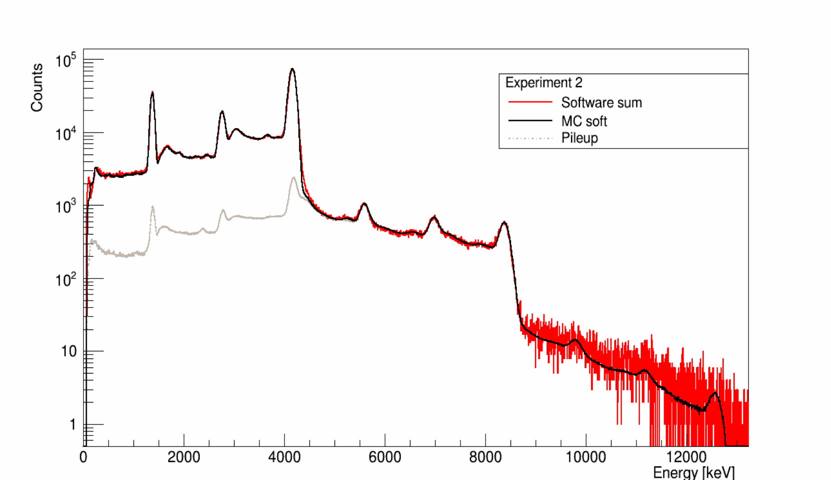
Green: with respect to A. A. Sonzogni et al. PRC 91, 011301(R)

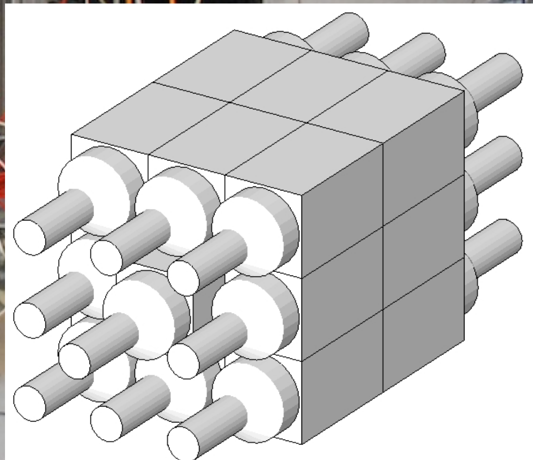
Red: with respect to M. Fallot et al., PRL 109, 202504

DTAS at Jyväskylä (Feb. 2014)

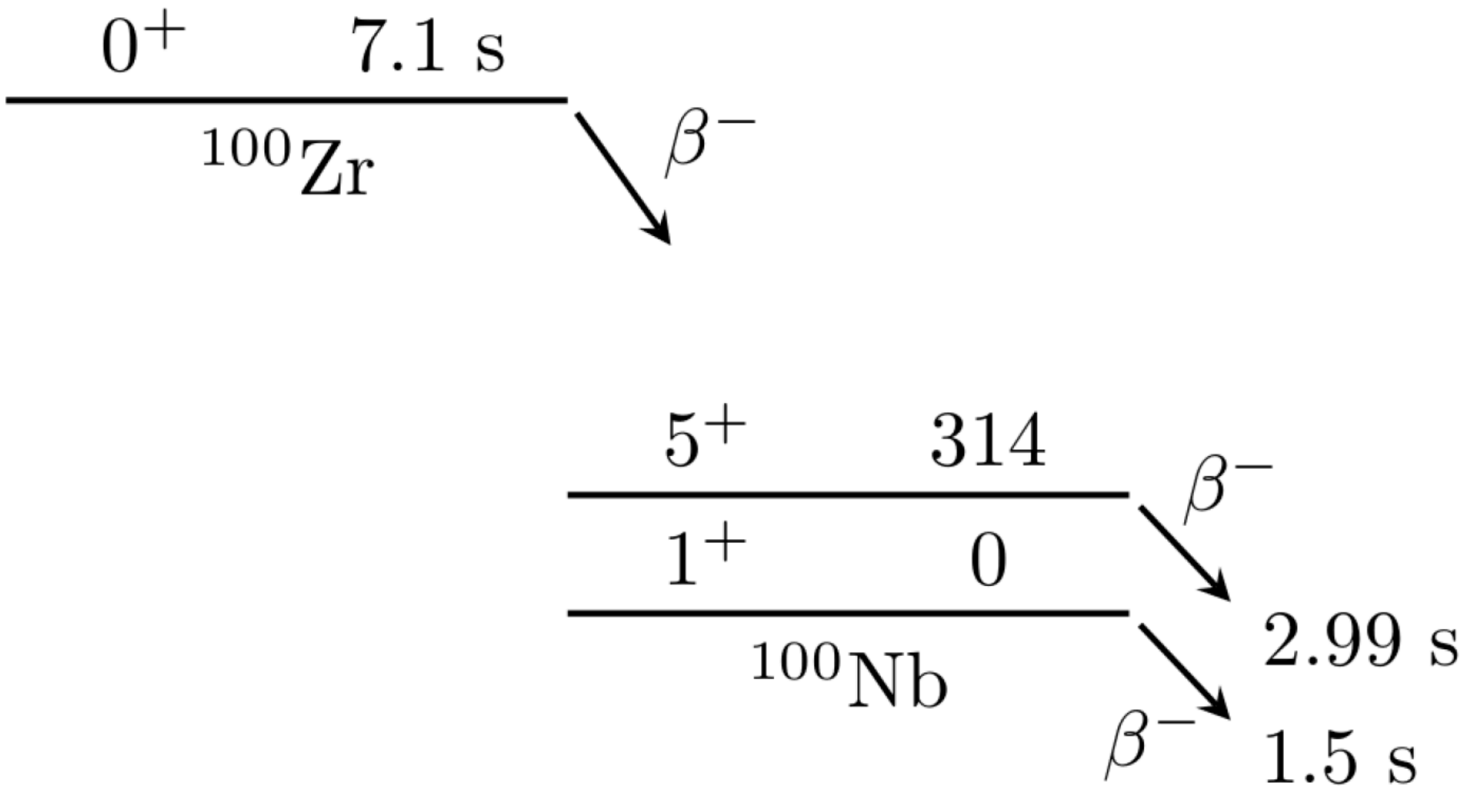
(collaboration with Subatech, spokespersons: Fallot, Tain, Algora)





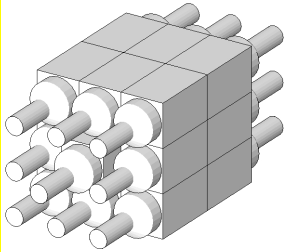


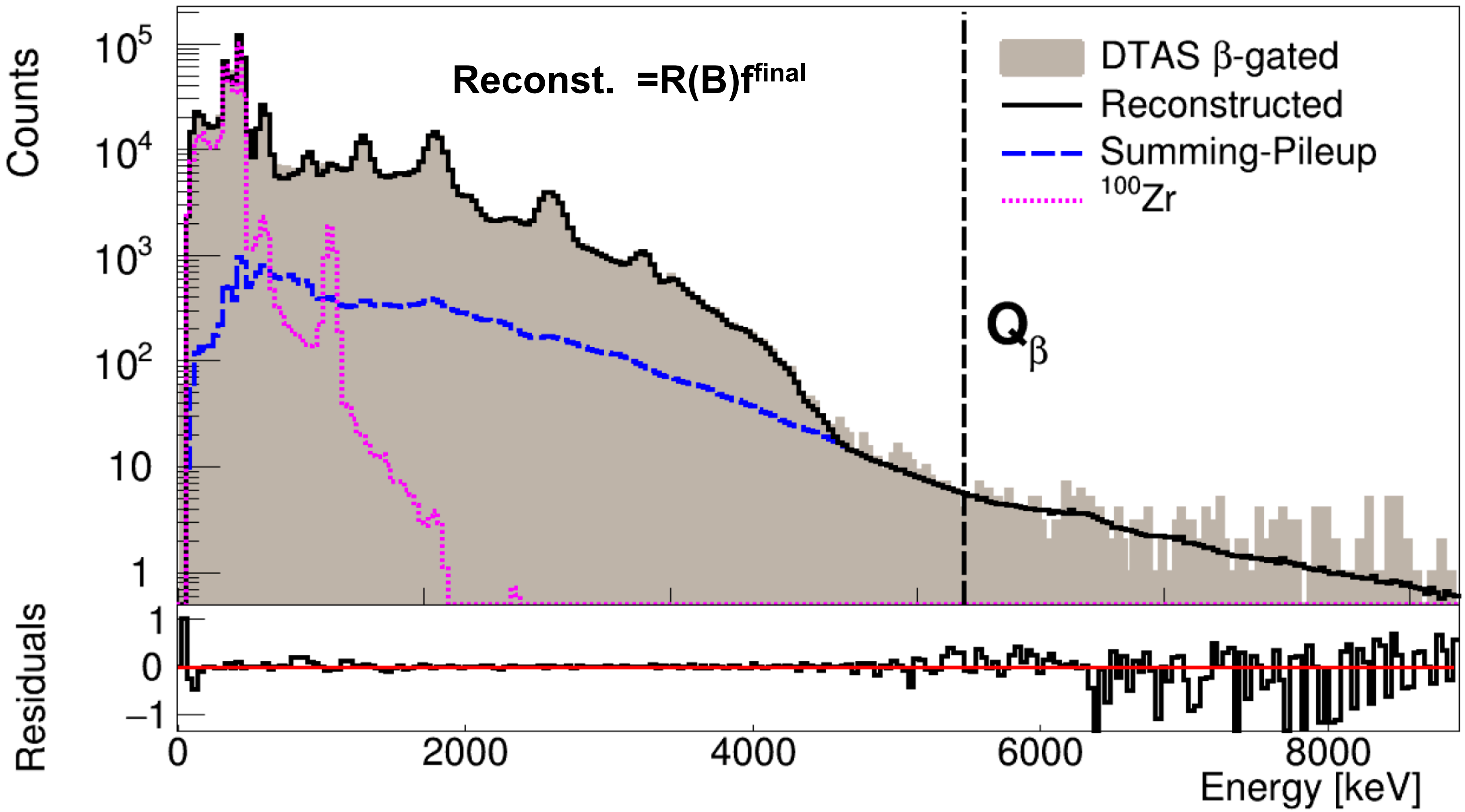
Example: 100Nb
(from 14 relevant decays measured)



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

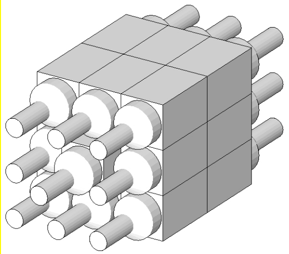
$^{100gs}Nb$

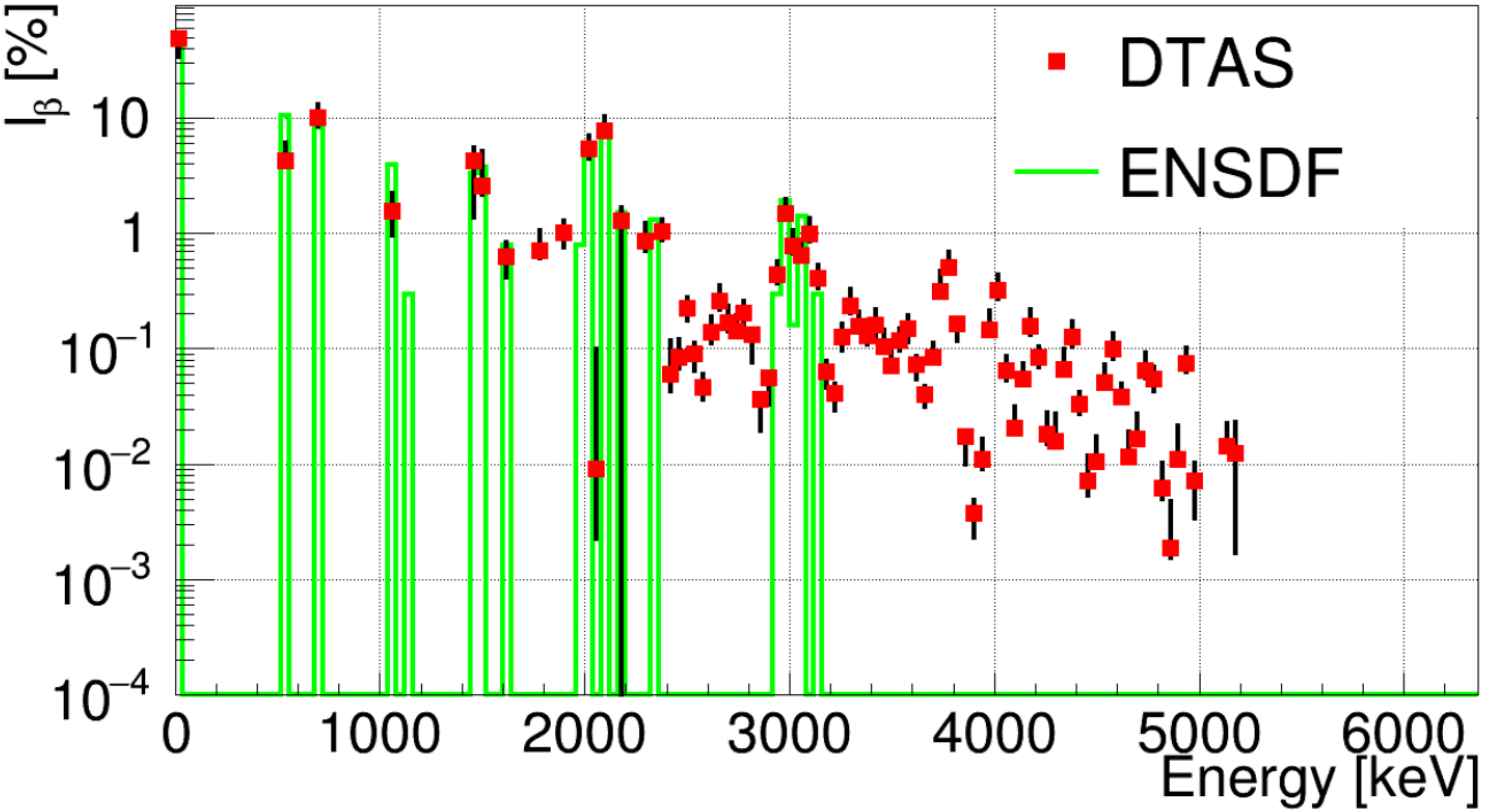




V. Guadilla et al., PhD thesis

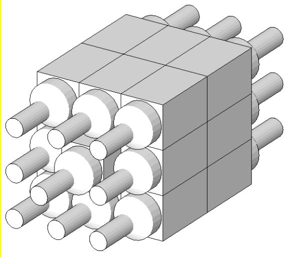
$^{100gs}Nb$

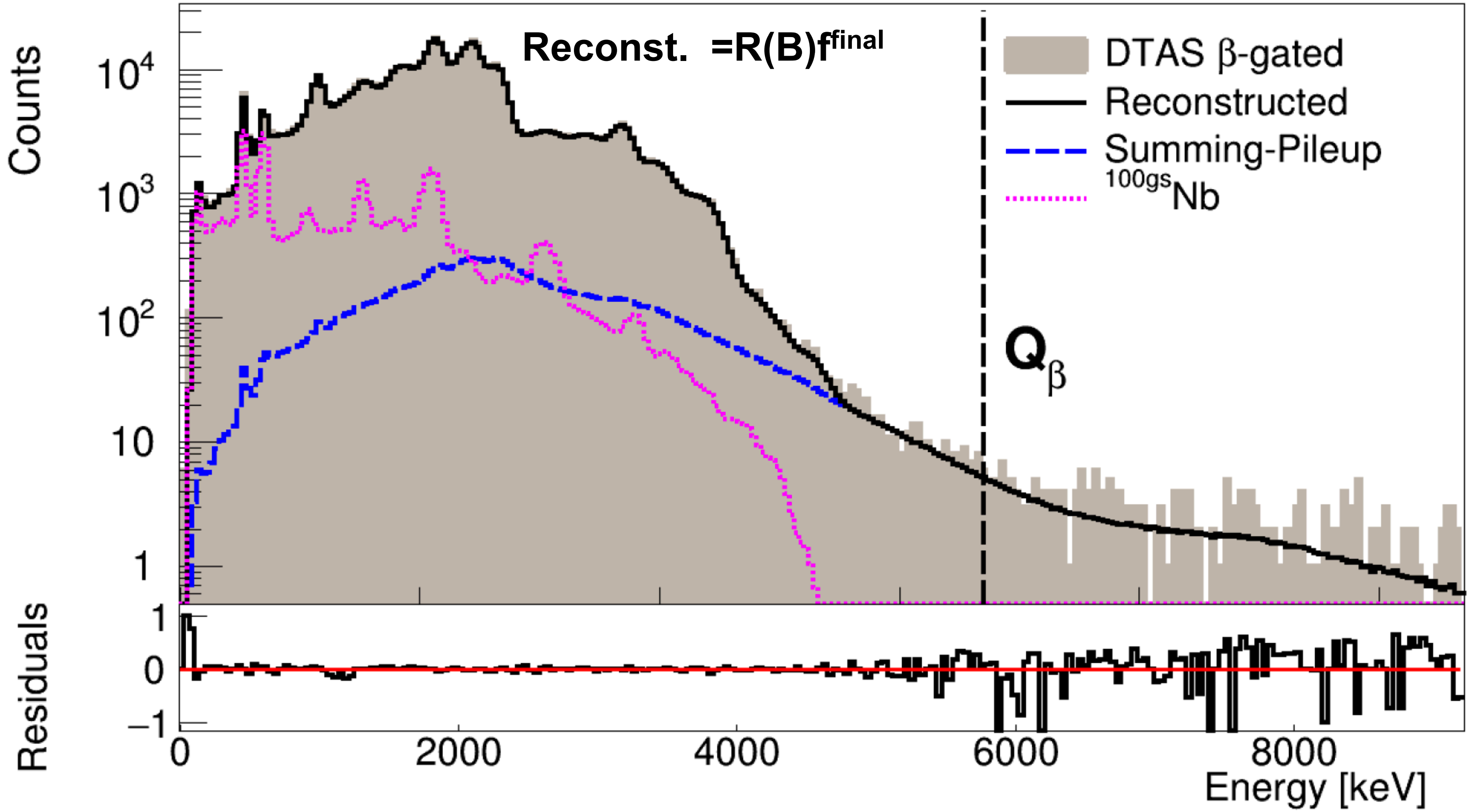




DTAS
ENSDF
Iβ [%]
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
0
1000
2000
3000
4000
5000
6000
Energy [keV]

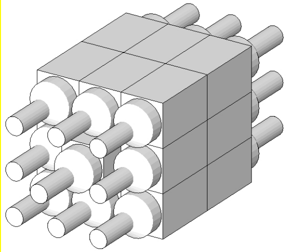
^{100m}Nb

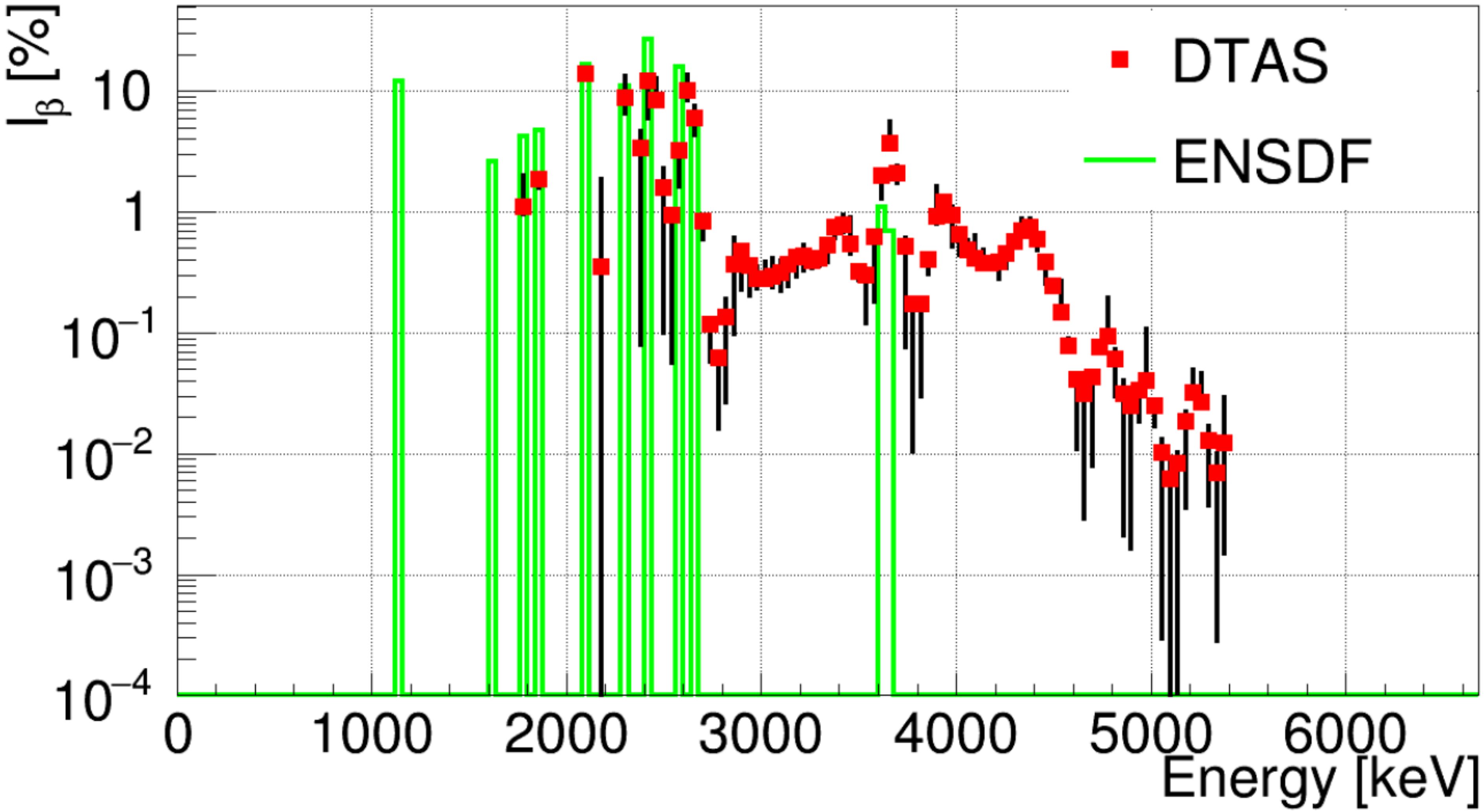




V. Guadilla et al., PhD thesis

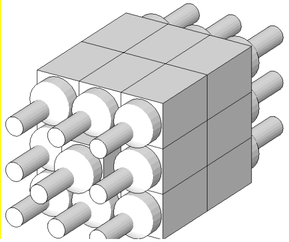
^{100m}Nb





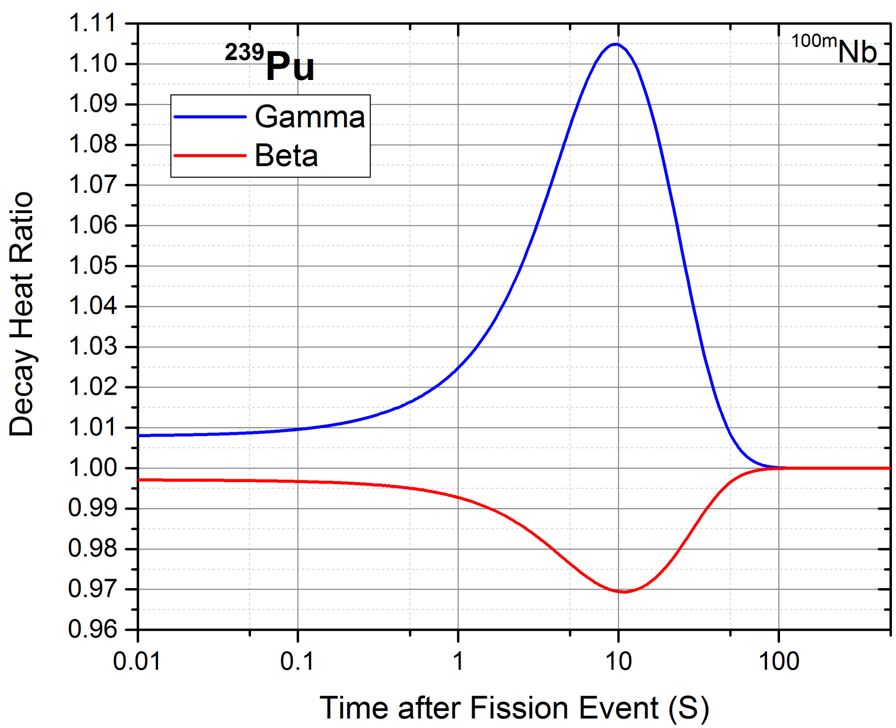
I_β [%]
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1000
2000
3000
4000
5000
6000
Energy [keV]
DTAS
ENSDF

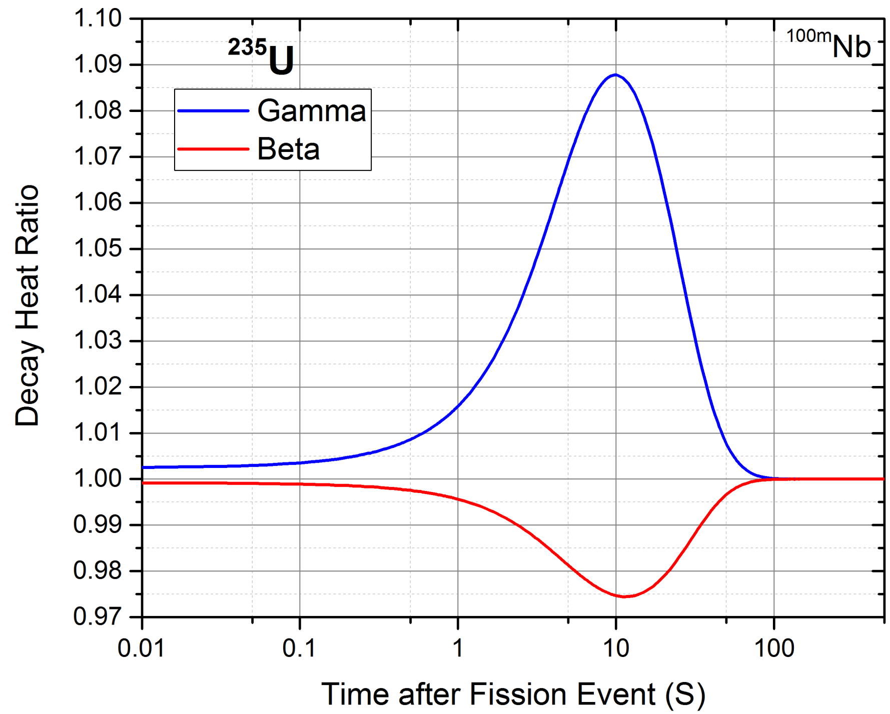
Impact on the decay heat (preliminary)



Decay heat summation calculation

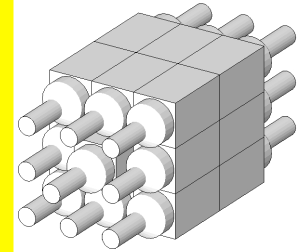
$$f(t) = \sum_i E_i \lambda_i N_i(t)$$





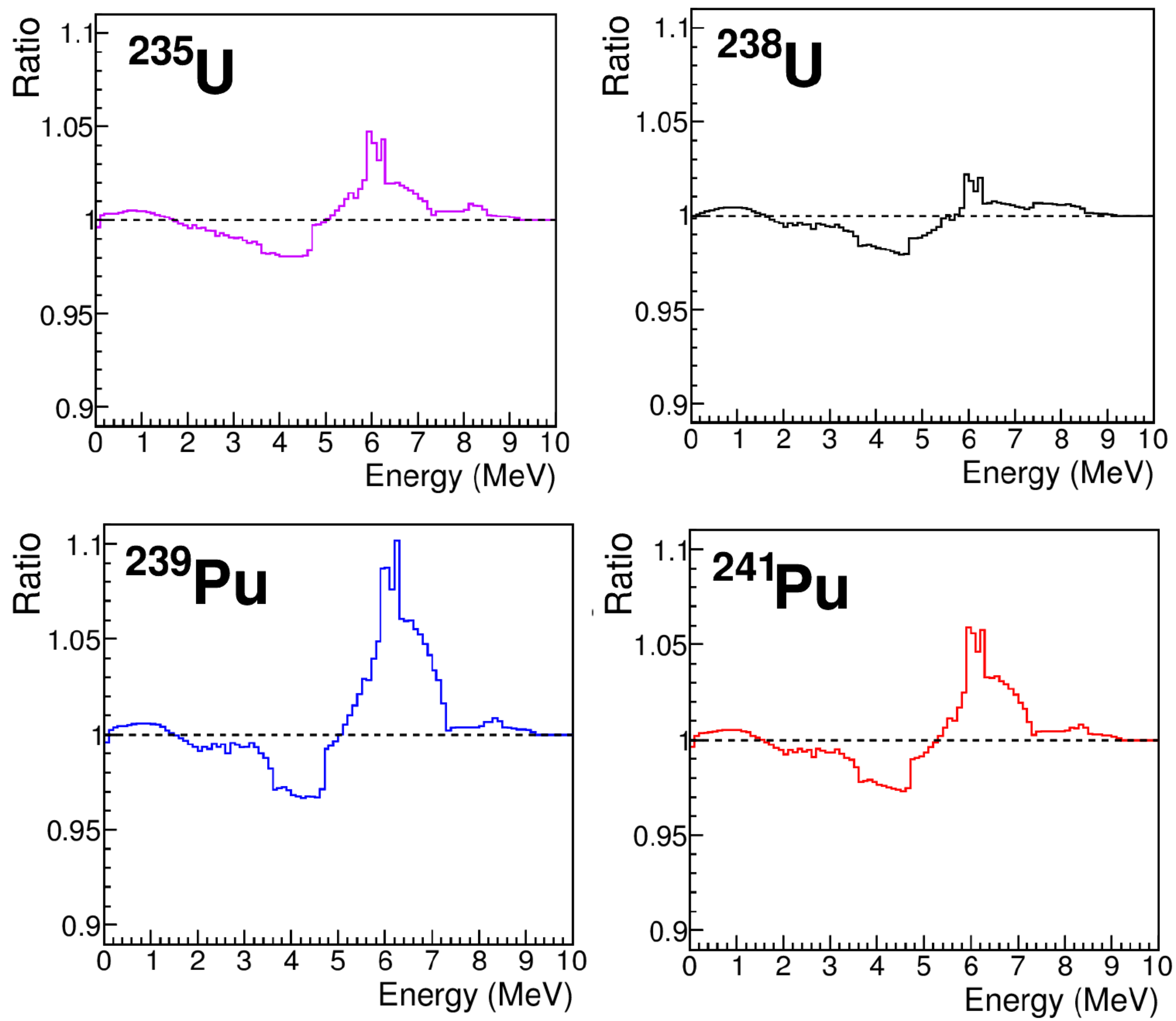
Impact of 8 new decays,
Some with decaying isomers

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

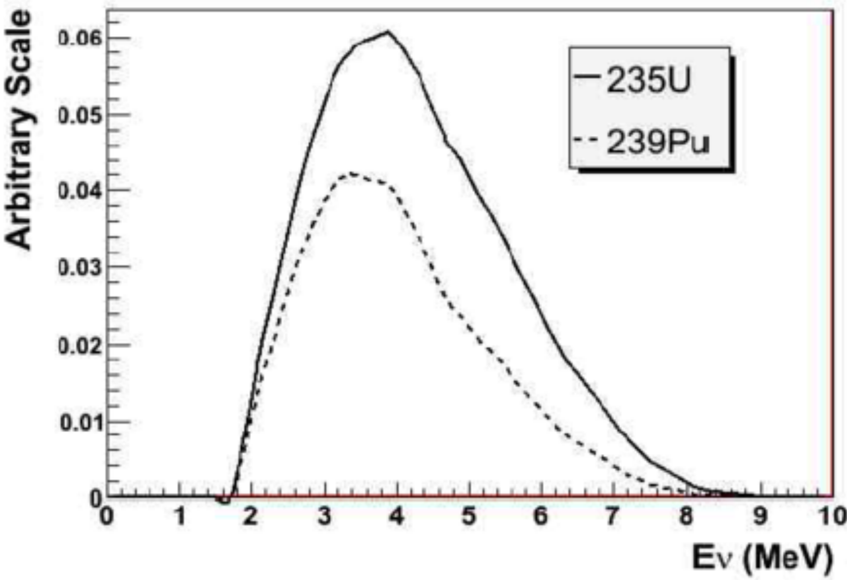
Another application: prediction of the neutrino spectrum from reactors for non-proliferation

	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	$3.2 \times 10^{-43} cm^2$	$2.8 \times 10^{-43} cm^2$

$$\bar{\nu} + p \rightarrow e^{+} + n$$ (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.

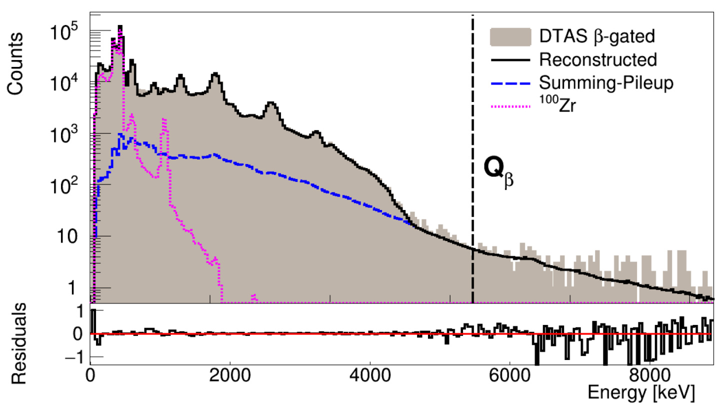
•Study of some Rb, Sr, Y, Nb, I and Cs (IGISOL, trap assisted TAS) (Fallot, Tain, Algora)

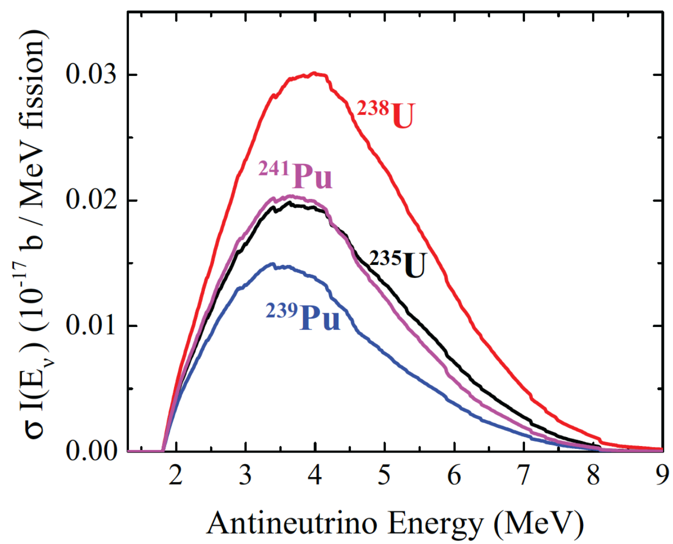


Summary

- 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.

Analogy: providing the stones to build the temple





THANK YOU

V. Guadilla, J. L. Tain, J. Agramunt, M. Fallot, A. Porta, 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