Nuclear data for reactor applications

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TASTES, 2018

Beta decay data for reactor applications

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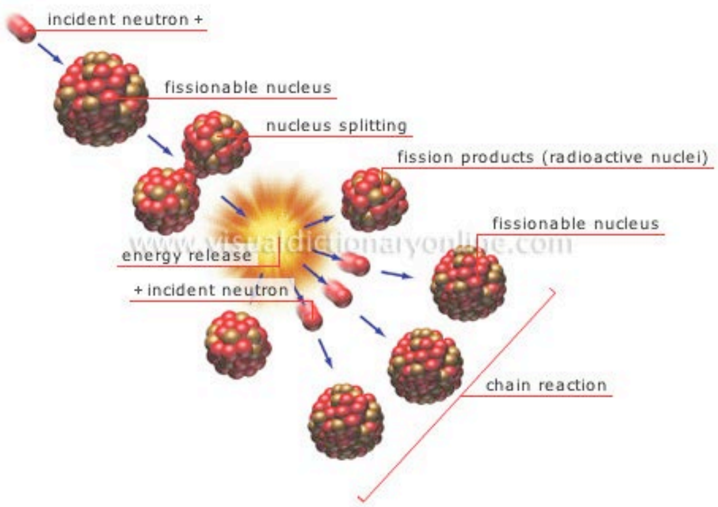
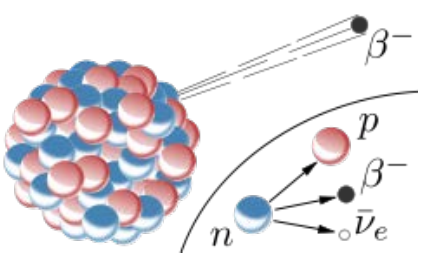
Outline

- Relevance of beta decay in fission
- Decay heat
- How decay heat is measured and calculated
- Why TAS measurements are important
- Examples and other implications of our measurements

Fission process energy balance and beta decay



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



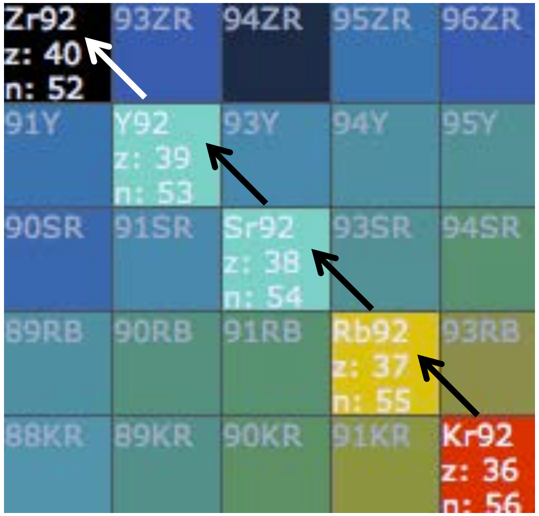
Energy released in the fission of ^{235}U	
Energy distribution	MeV
Kinetic energy light fission fragment	100.0
Kinetic energy heavy fission fragment	66.2
Prompt neutrons	4.8
Prompt gamma rays	8.0
Beta energy of fission fragments	7.0
Gamma energy of fission fragments	7.2
Subtotal	192.9
Energy taken by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

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

Example of elementary fission

$$n + {}^{235}U \rightarrow {}^{236}U \rightarrow {}^{92}Kr + {}^{141}Ba + 3n$$

4 decays

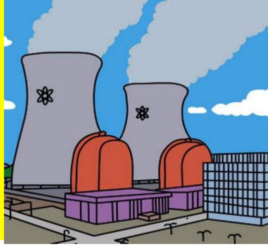


3 decays

${}^{236}U$	$Z/N = 92/144 = 0.64$
$SN(Z=40)$	$Z/N = 40/52 = 0.77$
${}^{92}Kr$	$Z/N = 36/56 = 0.64$
$SN(Z=59)$	$Z/N = 59/82 = 0.72$
${}^{141}Ba$	$Z/N = 56/85 = 0.66$

Fision products will have a neutron excess compared with stable nuclei around Z=50. So they will decay beta minus towards stability

1. Problem: decay heat



"Definition": Energy released when you turn off the reactor. It is mainly related to the decay of the fission products, not including the part taken away by the neutrinos (obviously).

This is the dominant part, but there are additional sources (decay of actinides produced by succesive neutron captures, fission induced by delayed neutrons and reactions induced by spontaneus fission, etc.)

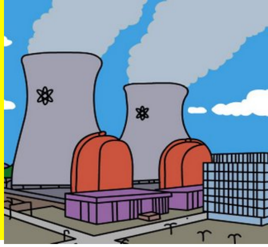
The total can be divided in an electromagnetic component (EM,gamma part), ligth particle component (LP,beta part) and heavy particle part (alphas, spont. fission products, etc). This division is of interest for dosimetry (charge particles get contained).

$$\overline{E}_{LP} = \overline{E}_{\beta-} + \overline{E}_{\beta+} + \overline{E}_{e-} + \cdots$$

$$\overline{E}_{EM} = \overline{E}_{\gamma} + \overline{E}_{x-ray} + \overline{E}_{anni.rad.} + \cdots$$

$$\overline{E}_{HP} = \overline{E}_{\alpha} + \overline{E}_{SF} + \overline{E}_{p} + \overline{E}_{n} + \cdots$$

Decay heat: how to measure it ?



Calorimetric techniques

Direct measurement of the heat released after irradiation inside a calorimeter.

Gives the total power in a single measurement

Important in these measurements is the time constant of the calorimeter. Limitation at short cooling times (quick response, short time constant). Low sensitivity at long cooling times.

Massive absorber needed (γ,implies large thermal capacity, slow termal response). Some corrections might be needed because the gamma radiation might not be fully contained

Radiometric measurements

Gamma and beta components can be measured separately, which provides additional information (not only relevant for DH, but also important for dosimetry applications). Separate components can be checked, and compared with summation calculations

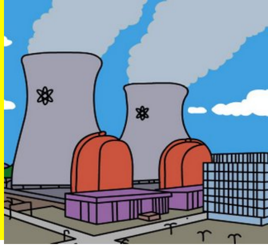
Very important in these measurements is to avoid "cross-contamination" in the measurements (gamma radiation on the measured beta spectra and vice versa)

Smaller samples can be used

Unfolding techniques have to be applied

All require the measurement of the number of fissions of the sample, and corrections to obtain f(t)

Decay heat: calorimetric measurements



Calorimetric technique examples (see V. Schrock, Prog. Nucl. En. **3**, p 125)

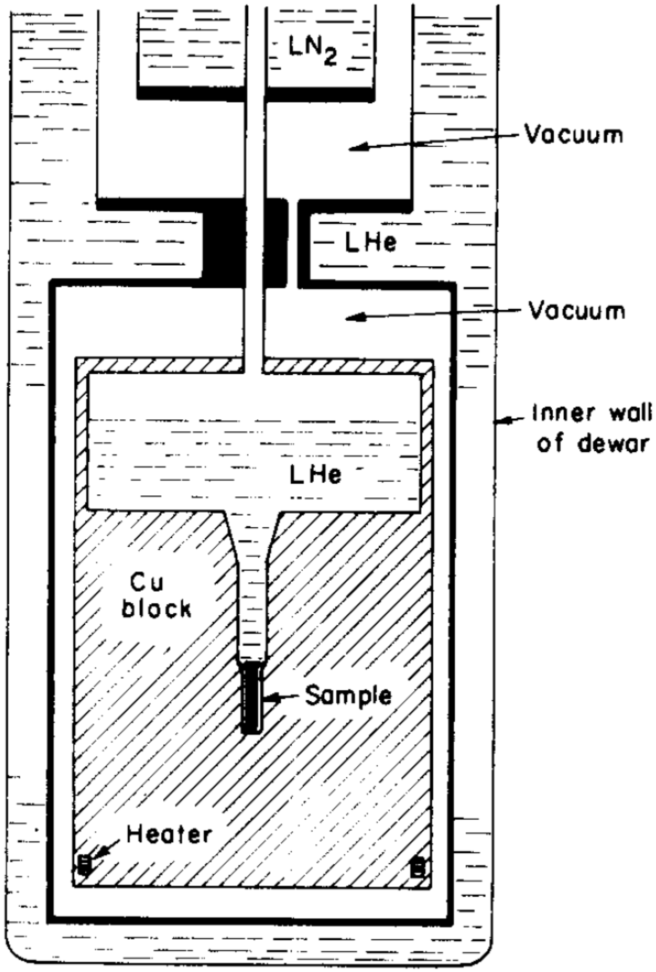


Fig. 3. LASL boil-off calorimeter. Yarnell and Bendt[62].

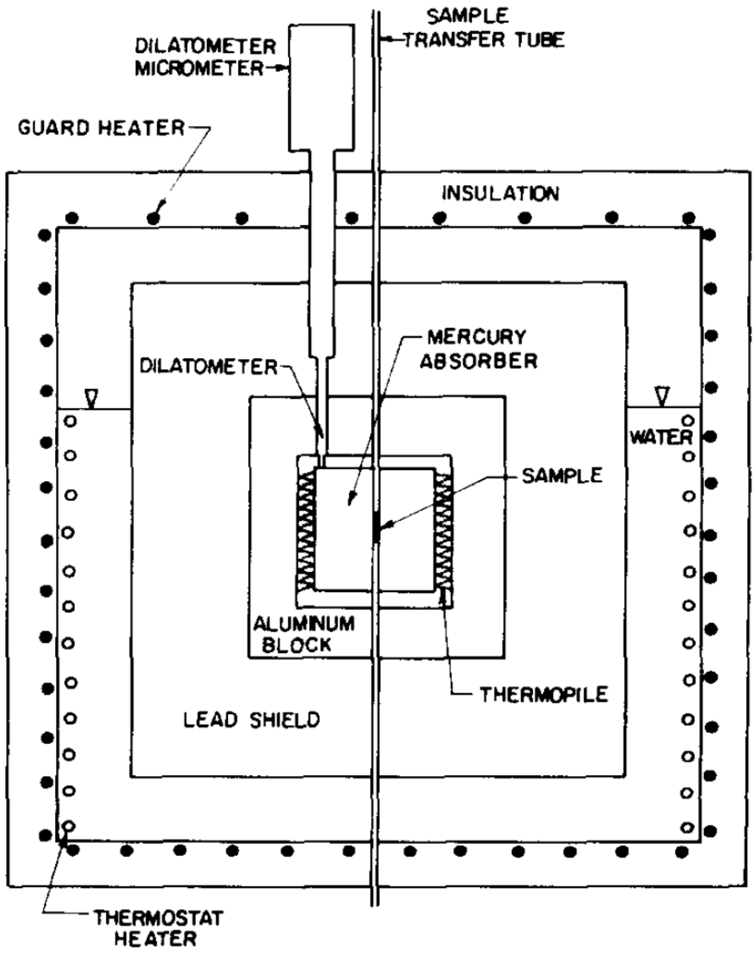
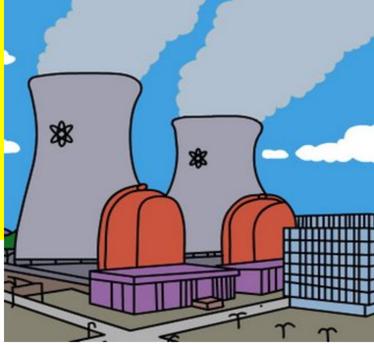


Fig. 7. Berkeley calorimeter. Schrock *et al.*[64]

Decay heat: radiometric measurements



Gamma and beta measurements

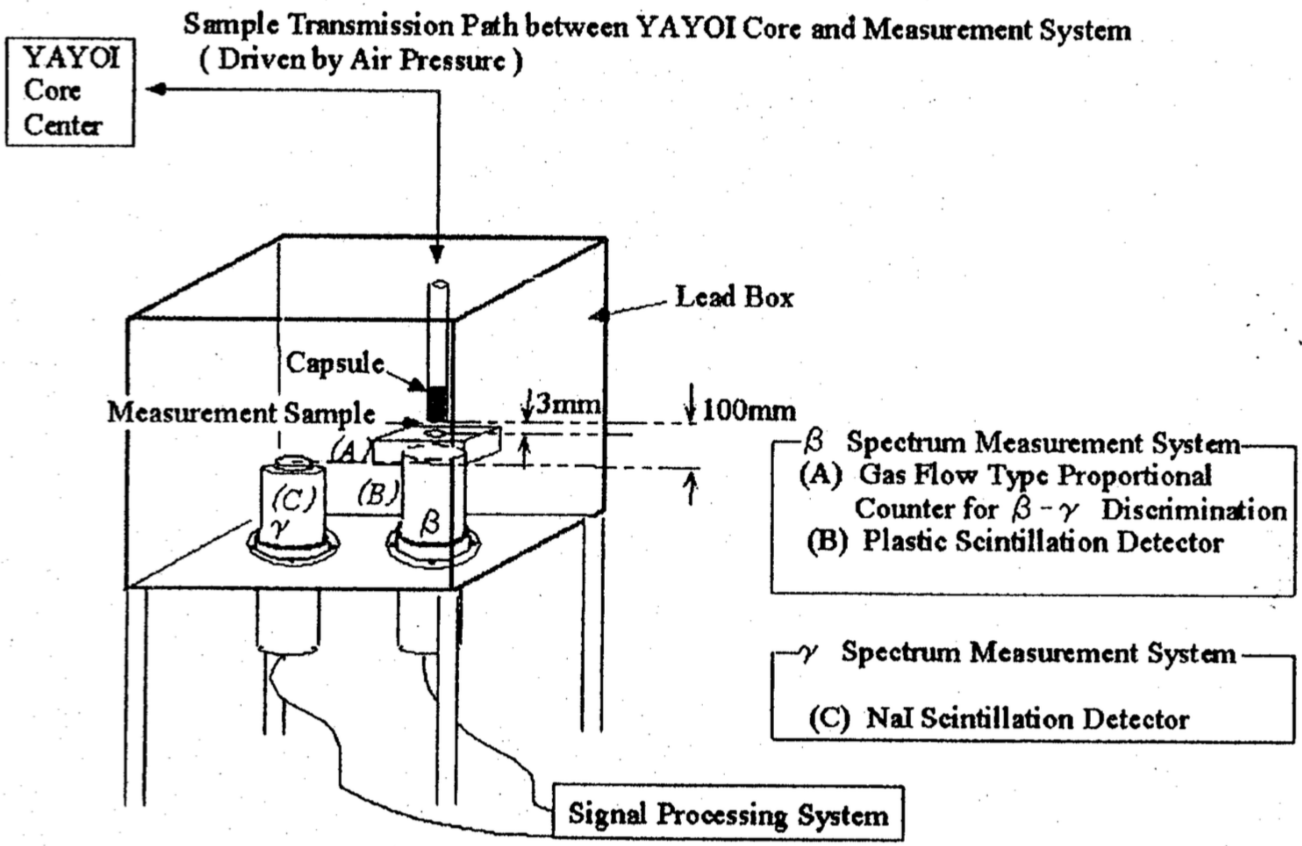


Fig.2 Conceptual View of Decay Heat Measurement System

Basic requirements

Beta measurements

Reduction of summing and gamma penetration (DE-E)

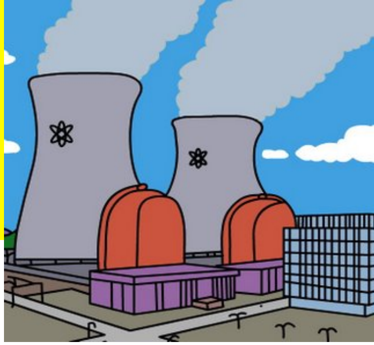
Proper calibration

Gamma measurements

Proper response function calculation for the deconvolution of the data.

Ohkawachi et al., Journal of Nucl. Sc. and Technology, Suppl 2, p. 493

Decay heat: if you can not measure, then how to determine it ?



- Try to predict or calculate in the best way
  - Statistical method (the first solution)

    Way and Wigner, Phys. Rev. 73 (1948) 1318

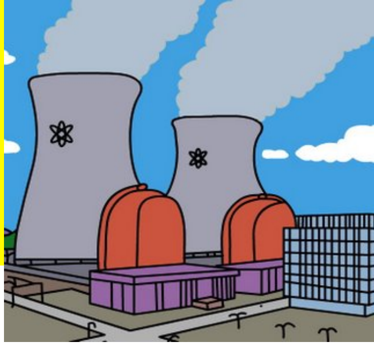
$$B(t) = 1.26 t^{-1.2} MeV/s$$

$$\Gamma(t) = 1.40 t^{-1.2} MeV/s$$

    later, Griffin, Phys. Rev. 134 (1964) B817

  - Summation calculations (next slide)

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)

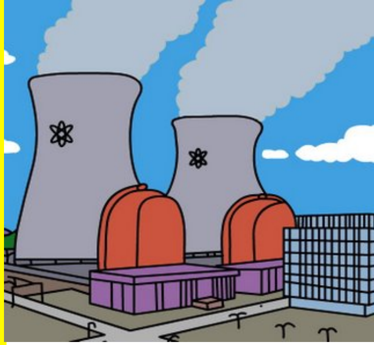
λ_i Decay constant of the nucleus i $\lambda = \frac{\ln(2)}{T_{1/2}}$

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)

The inventory of nuclides:

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



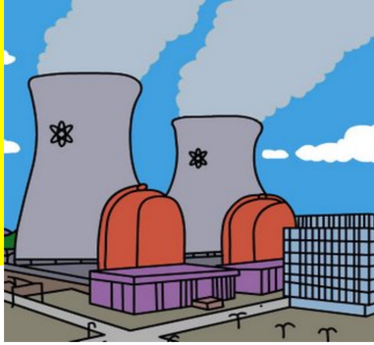
Solve a linear system of coupled first order differential equations

$$\frac{dN_i}{dt} = -(\lambda_i + \sigma_i \phi) N_i + \sum_j f_{j\to i} \lambda_j N_j$$

$$+ \sum_k \mu_{k\to i} \sigma_k \phi N_k + y_i F$$

N_i	Number of nuclides i
λ_i	decay constant i
σ_i	capture cross section i
ϕ	neutron flux
$f_{i\to j}$	branching ratio of j to i decay
$\mu_{k\to i}$	production rate of i per one neutron capture of k
y_i	fission yield of i
F	fission rate

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

N_i Number of nuclei i at the cooling time t

The topic of this talk is related basically to the determination of the mean energies released in the decay and their impact.

Question, how that is determined?

They are based in the data available from conventional nuclear structure databases (formulas later).

How the mean energies can be determined ?
1. direct measurements

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

Examples:

Rudstam et al.

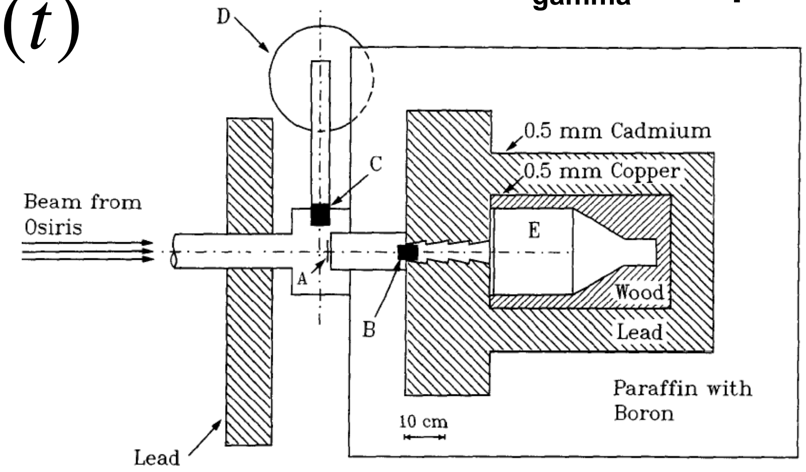
Atom. Dat. and Nucl. Dat. Tables 45, 239-320
89 mean gamma and 95 beta energies given for FP decays

Aleklett and Rudstam

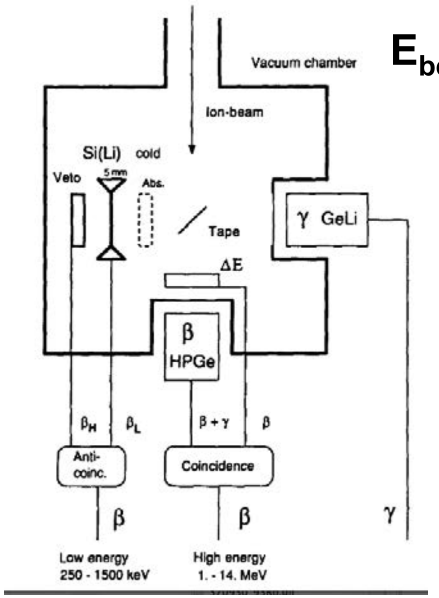
Nucl. Science and Eng. 80, 74-91(1990)
Mean beta energies given for 35+27 decays

Similar experimental problems to the radiometric measurements of the gamma and beta heat mentioned before: isolate the components, responses, etc.

E_{gamma} setup



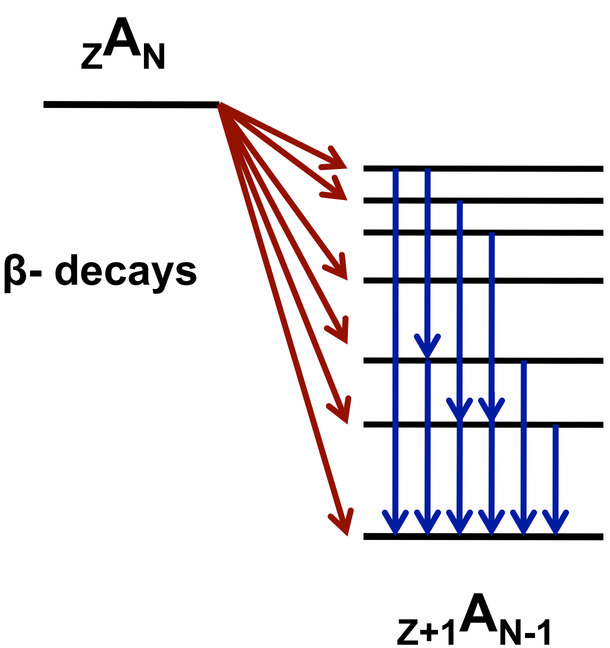
E_{beta} setup

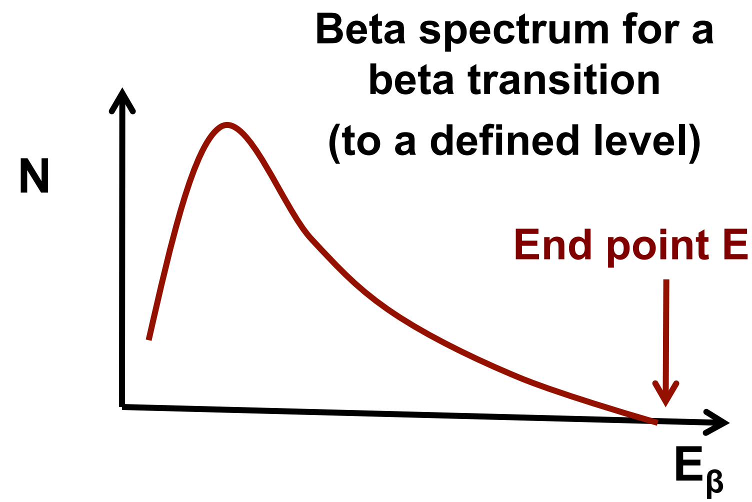


How the mean energies are determined ?
2. from databases

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

DATABASES:
feeding or beta decay prob. distributions

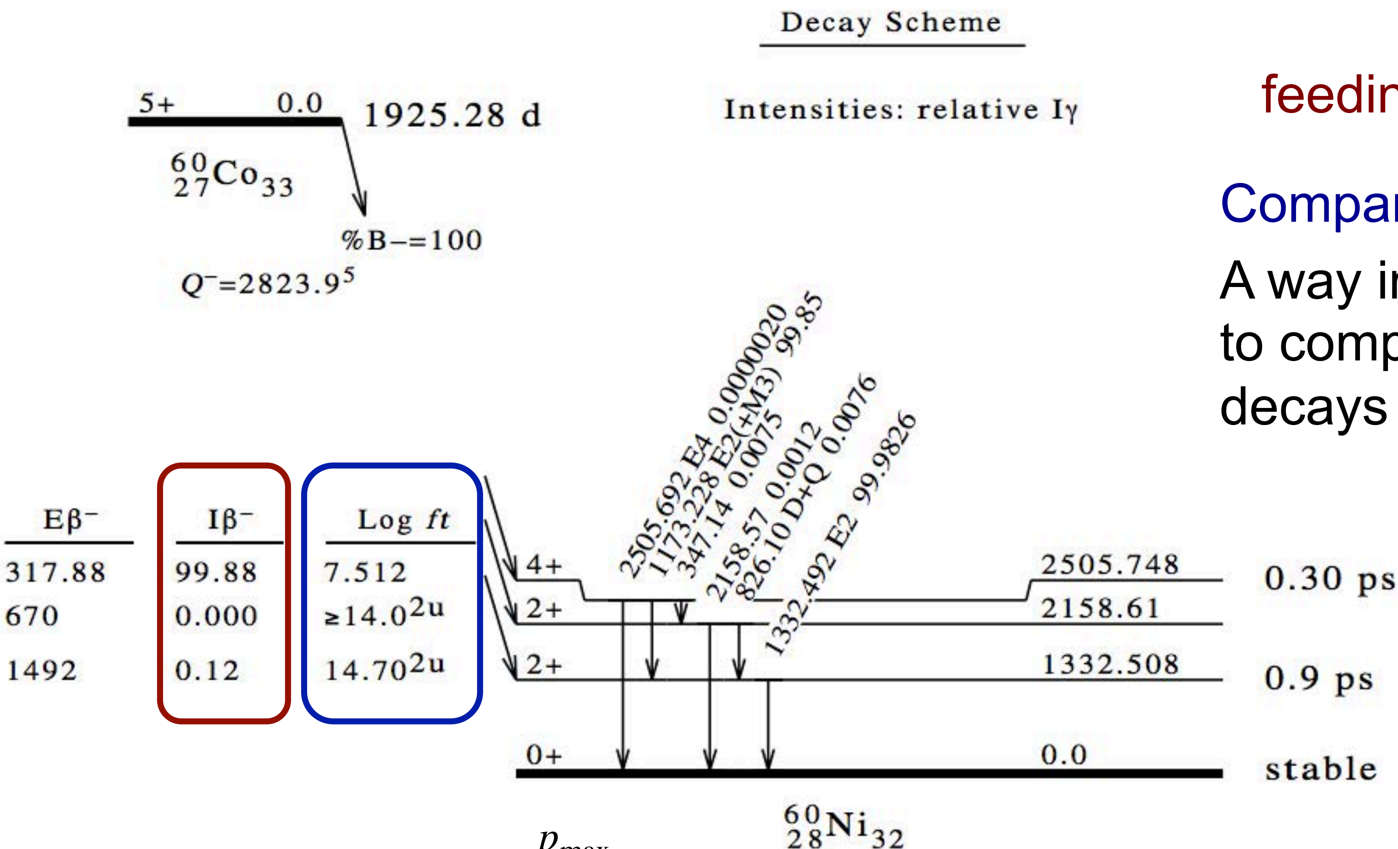




$$\bar{E}_\beta = \sum_i I_\beta(E_i)\langle E_{\beta,i}\rangle$$

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

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



feeding:=I_β = P_f*100

Comparative half-life: ft

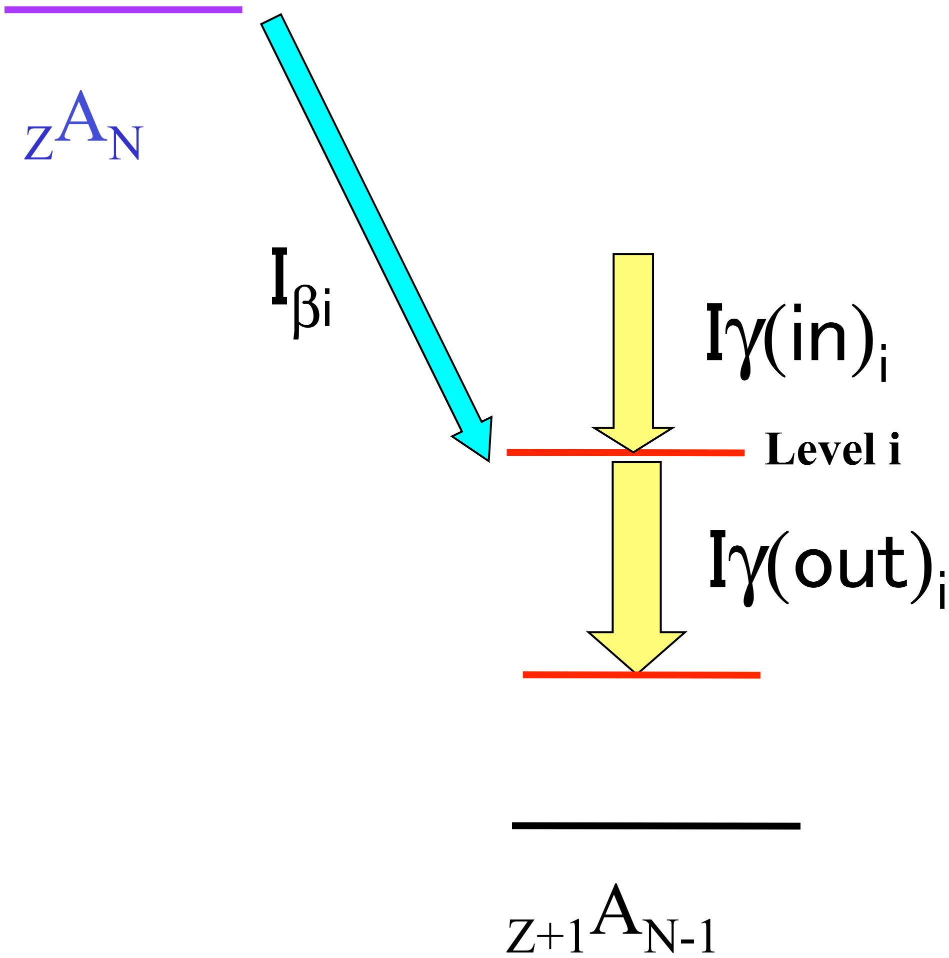
A way introduced by Fermi to compare the different decays (Q, Z')

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

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

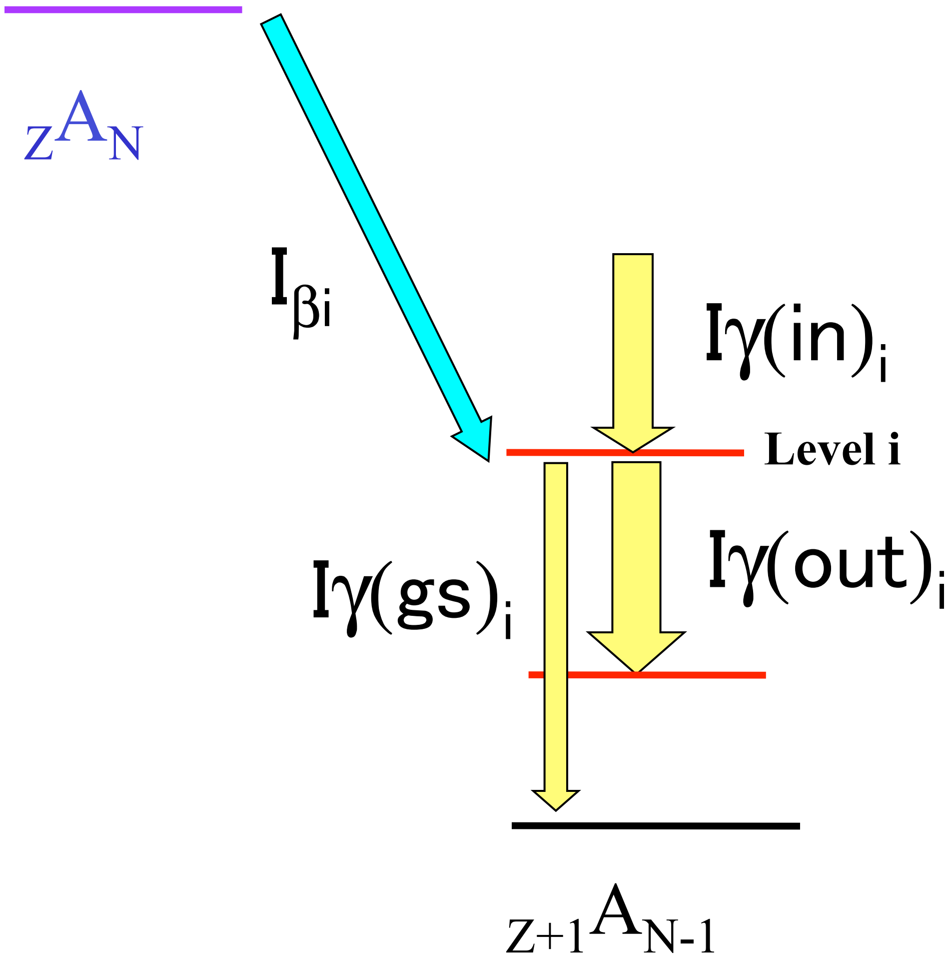
$$T_{1/2} = \frac{\ln(2)}{\lambda} = \tau \ln(2)$$

The intensity balance in a beta decay experiment



$$I_{\beta i} \sim \left(I\gamma(out)_i - I\gamma(in)_i\right)$$

The intensity balance in a beta decay experiment II



$$I_{\beta i} \sim (I\gamma(out)_i + I\gamma(gs)_i - I\gamma(in)_i)$$

$$100 = N(\sum_k I\gamma(gs)_k + I\beta(gs))$$

"Artificial" distinction between de-exiting gammas that go to the ground state and gammas that go to excited states. This is just to define properly the global normalization N required for the experiment.

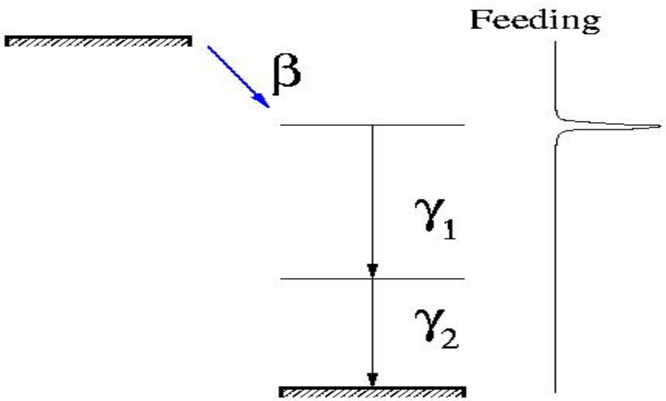
Pandemonium (The Capital of Hell)

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

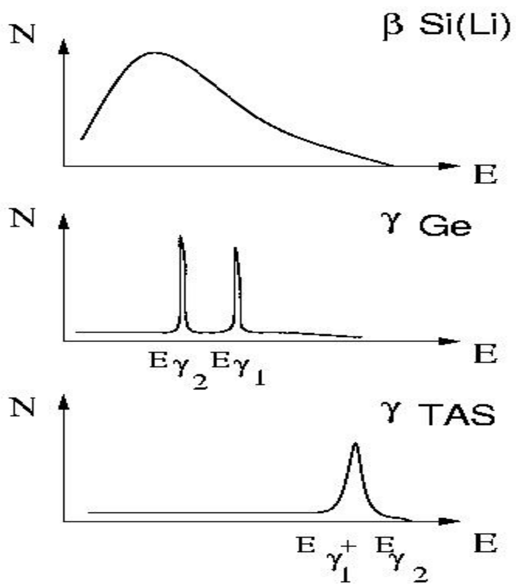
John Martin (~ 1825)

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

TAGS measurements



The decay seen by diff. detectors



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

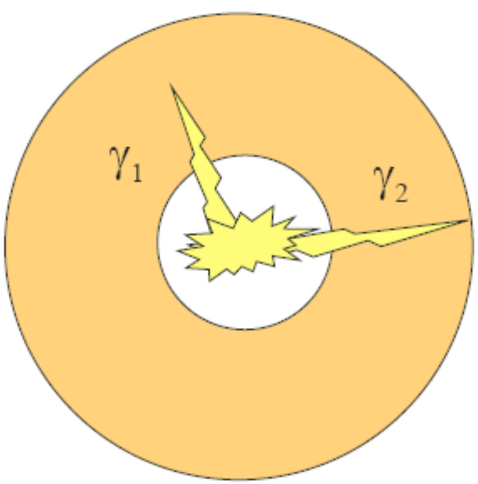
A TOTAL ABSORPTION SPECTROMETER

But we need 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!

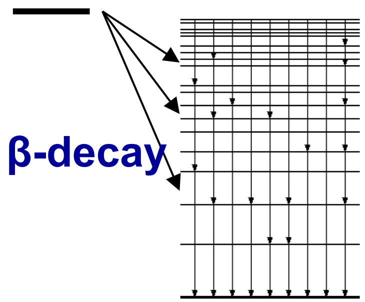
Big crystal, 4π

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



Analysis

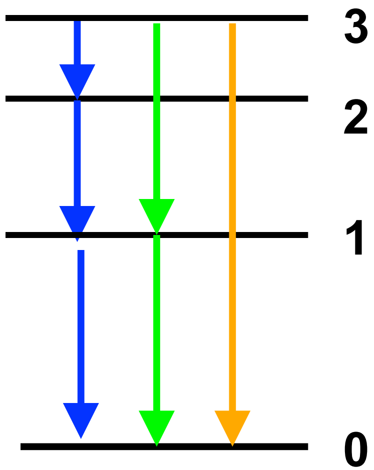
$$d_i = \sum_j R_{ij} f_j \quad or \quad \mathbf{d} = \mathbf{R} \cdot \mathbf{f}$$



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 $\mathbf{R}$ can be constructed by recursive convolution:

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

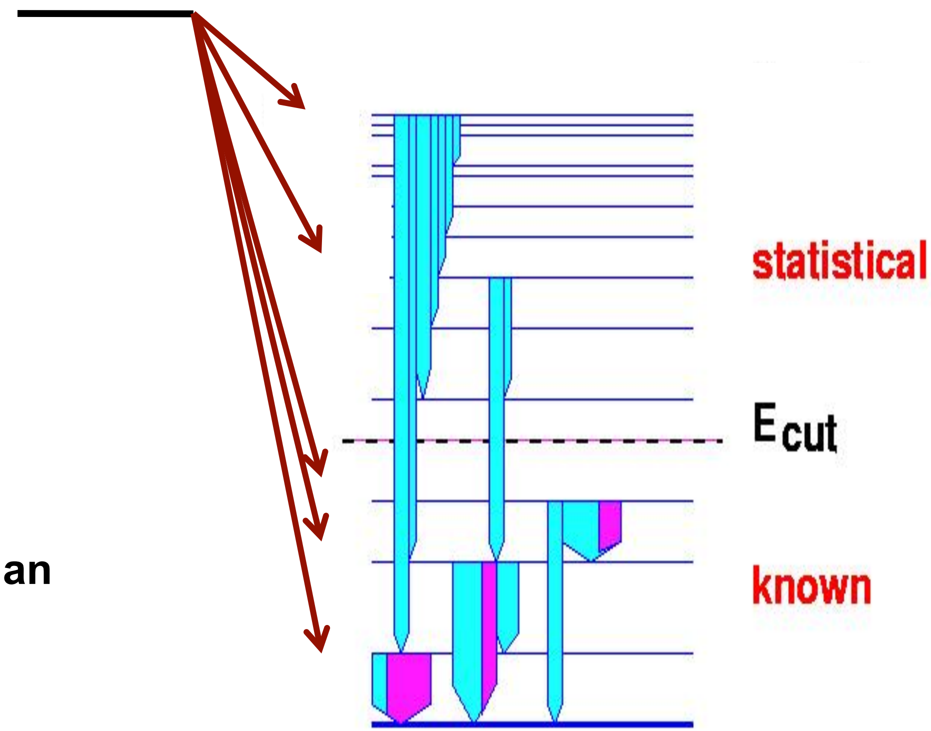


$\mathbf{g_{jk}}$: γ-response for *j* ➔ *k* transition
$\mathbf{R_k}$: response for level *k*
b_{jk}: branching ratio for *j* ➔ *k* transition

Mathematical formalization by Tain, Cano, et al.

The complexity of the TAGS analysis: an ill posed problem

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



Steps:

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

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

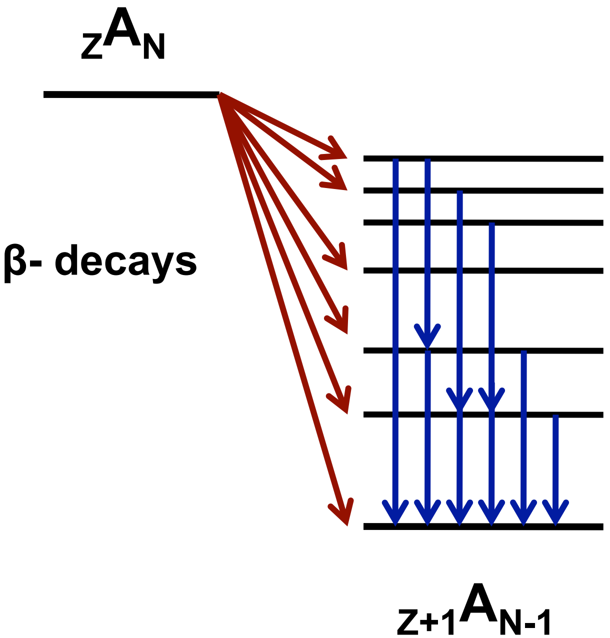
$$P(f_j \mid d_i) = \frac{P(d_i \mid f_j) P(f_j)}{\sum_j P(d_i \mid f_j) P(f_j)}$$

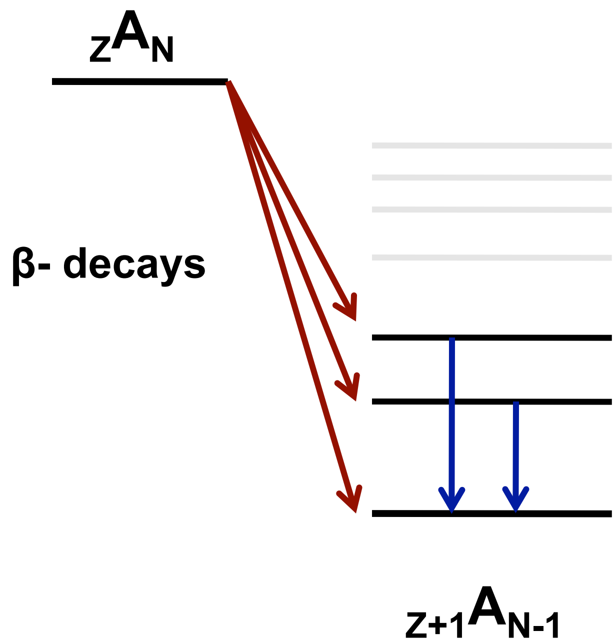
Algorithm:

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

Mean energies and Pandemonium

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





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

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

$\overline{E}_\beta$ overestimation

$\overline{E}_\gamma$ underestimation

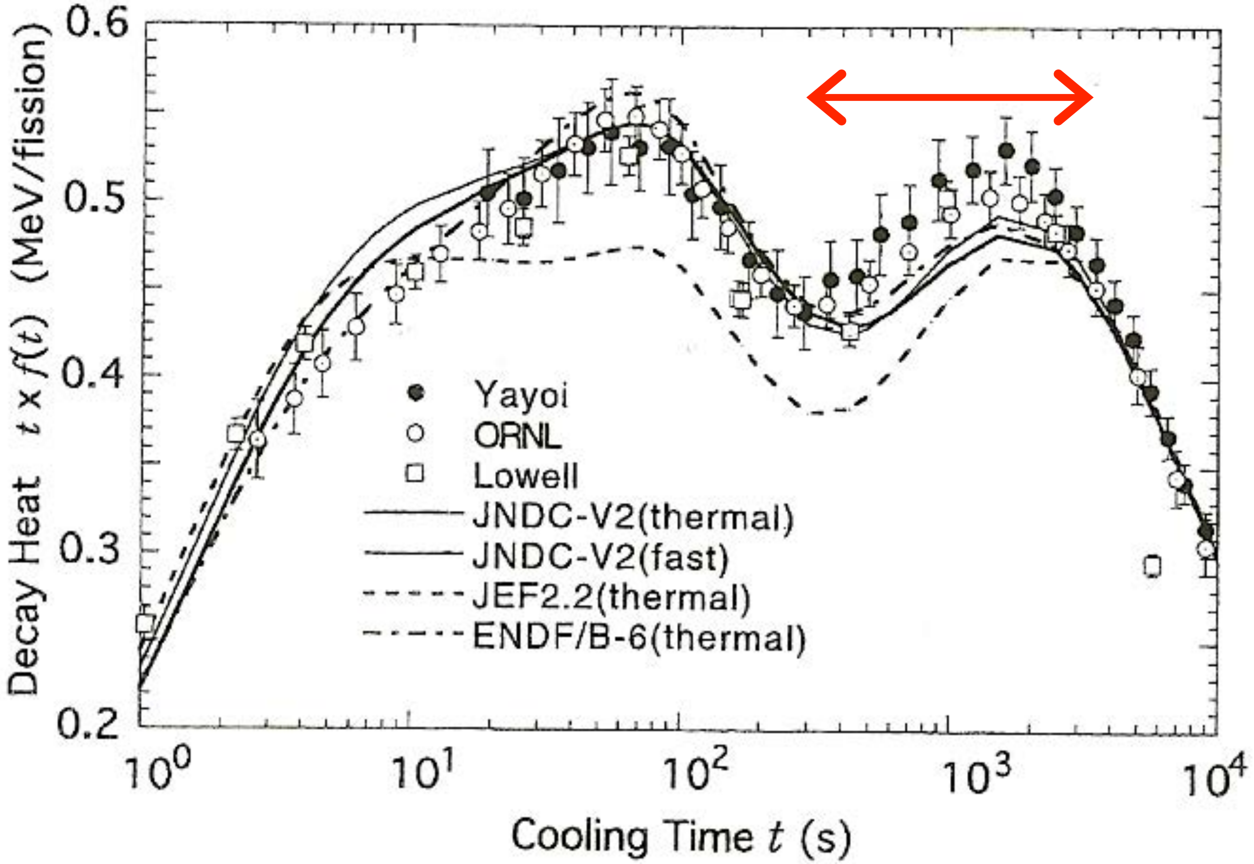
The beginning (for us) …

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.

Our favorite place for “polar” experiences

Published cases until know:

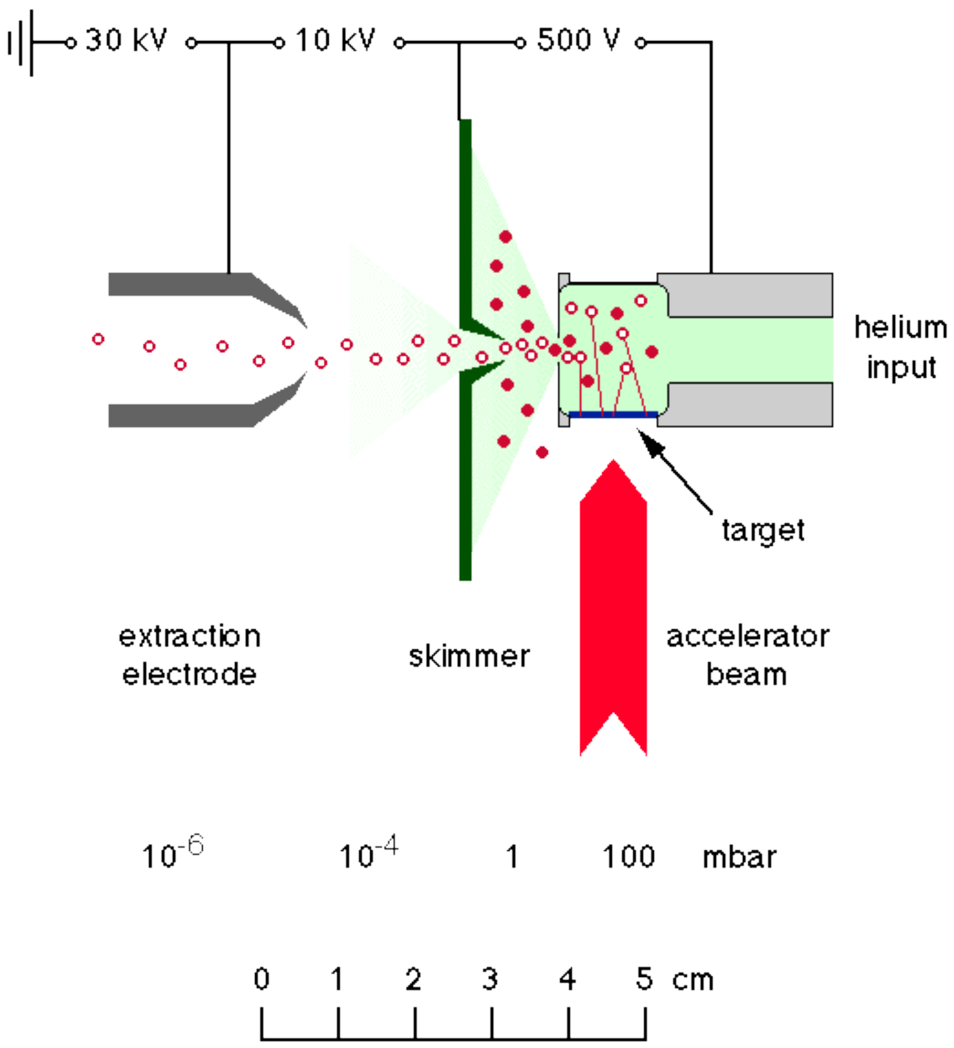
Yoshida’s work (^{102,104,105}Tc)

WPEC-25 (^{102,104,105,106,107}Tc, ^{105}Mo, ^{101}Nb)

More recently ^{87,88}Br, ^{92,94}Rb

Outgoing now: ^{100gs,m}Nb, ^{102gs,m}Nb

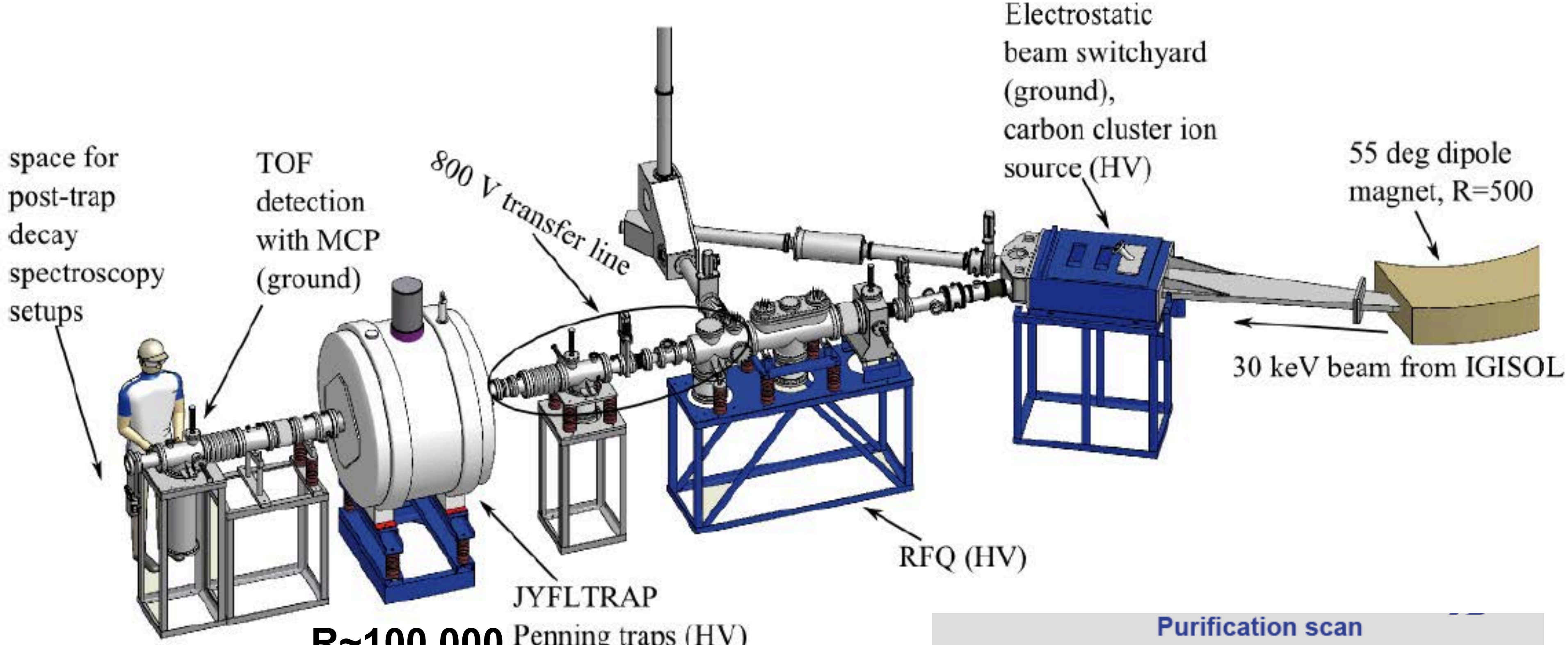
The ion guide technique



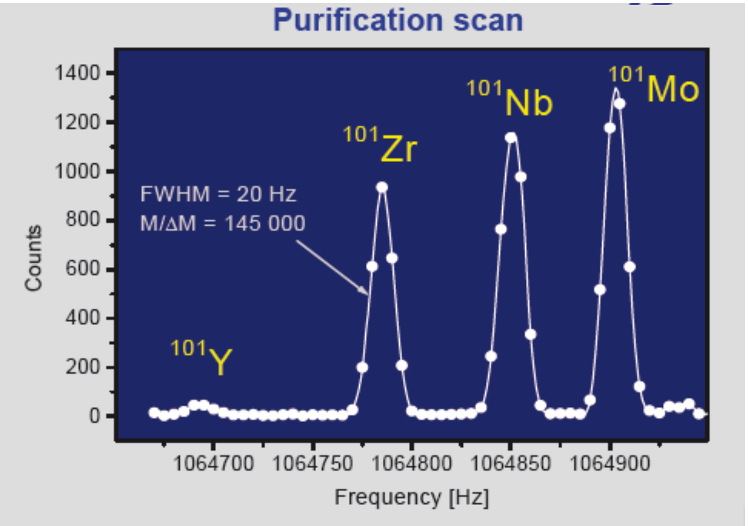
Generic ion guide: the nuclear reaction products are stopped in a gas and are transported through a differential pumping system into the accelerator stage of the mass separator.

The process is fast enough for the ions to survive as single charged ions. The system is chemically insensitive and very fast (sub-ms).

Why JYFL?: IGISOL + a bonus

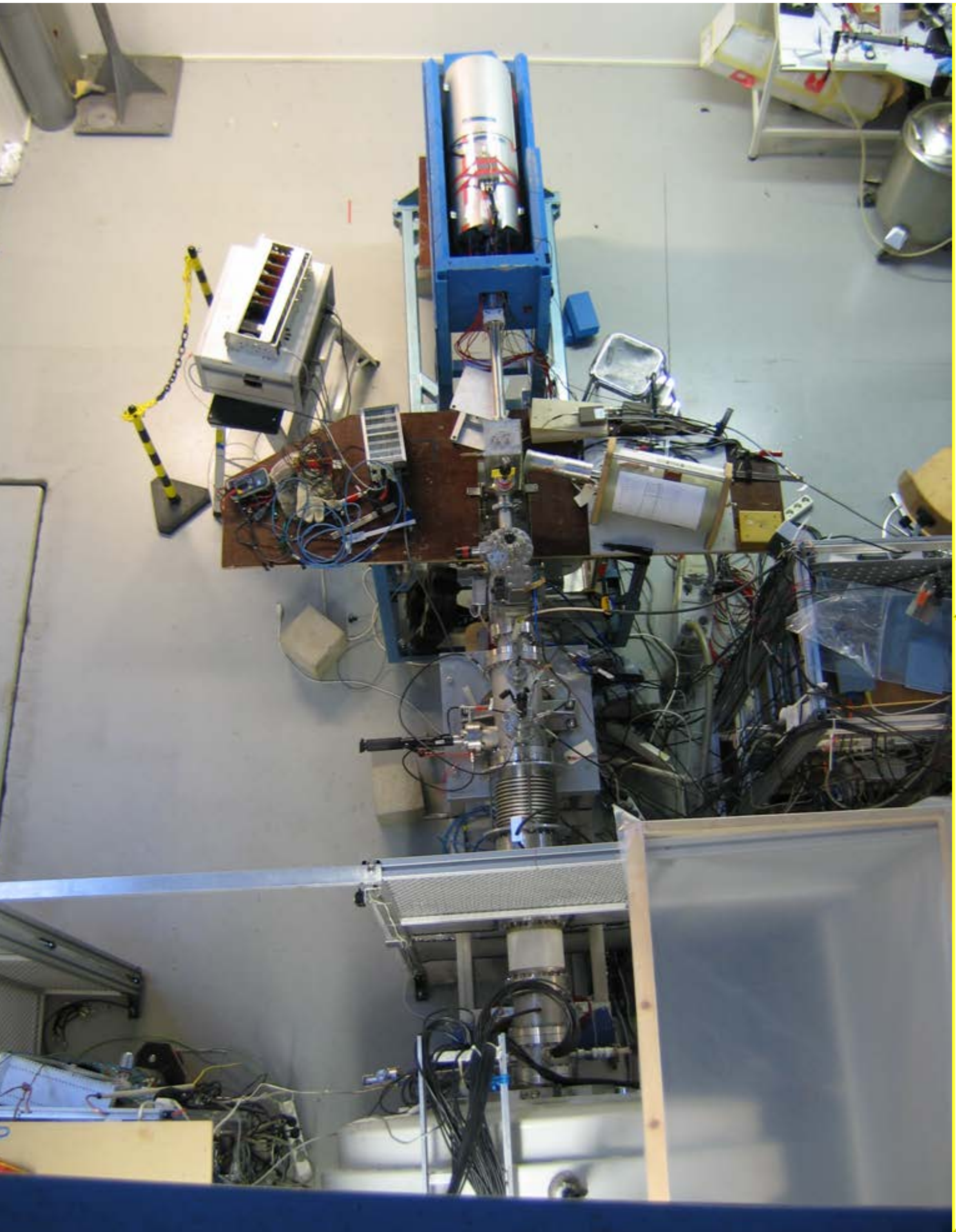


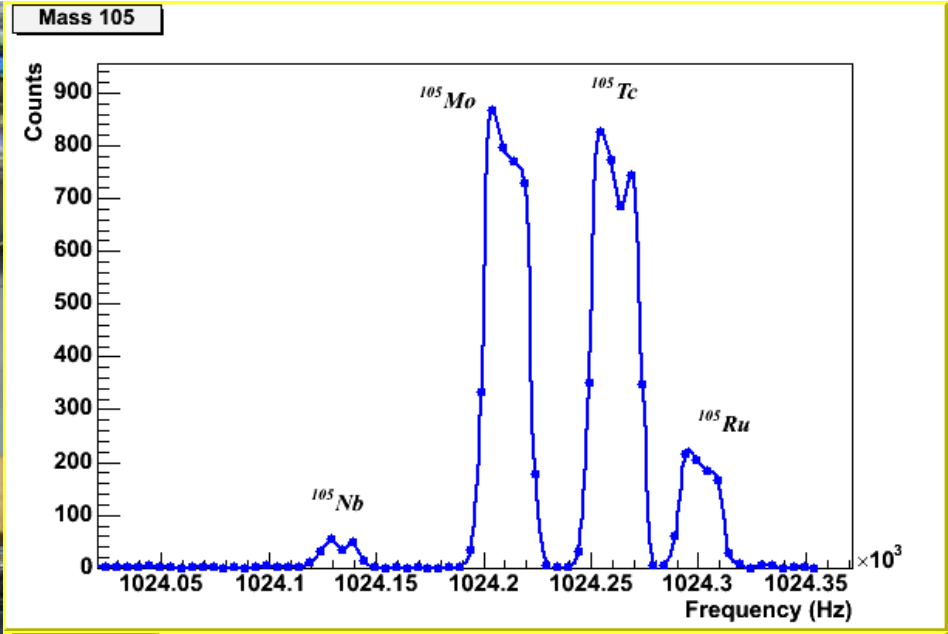
R~100 000

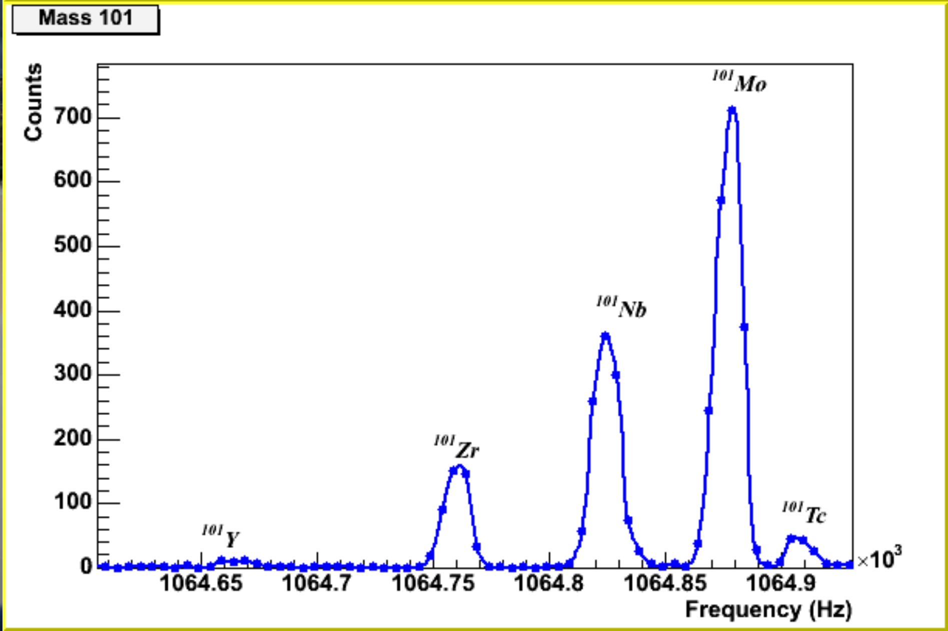


The main reasons are the chemical insensitivity (ion guide technique), high purity by means of purification of the beam using the JYFLTRAP and acceptable yields!

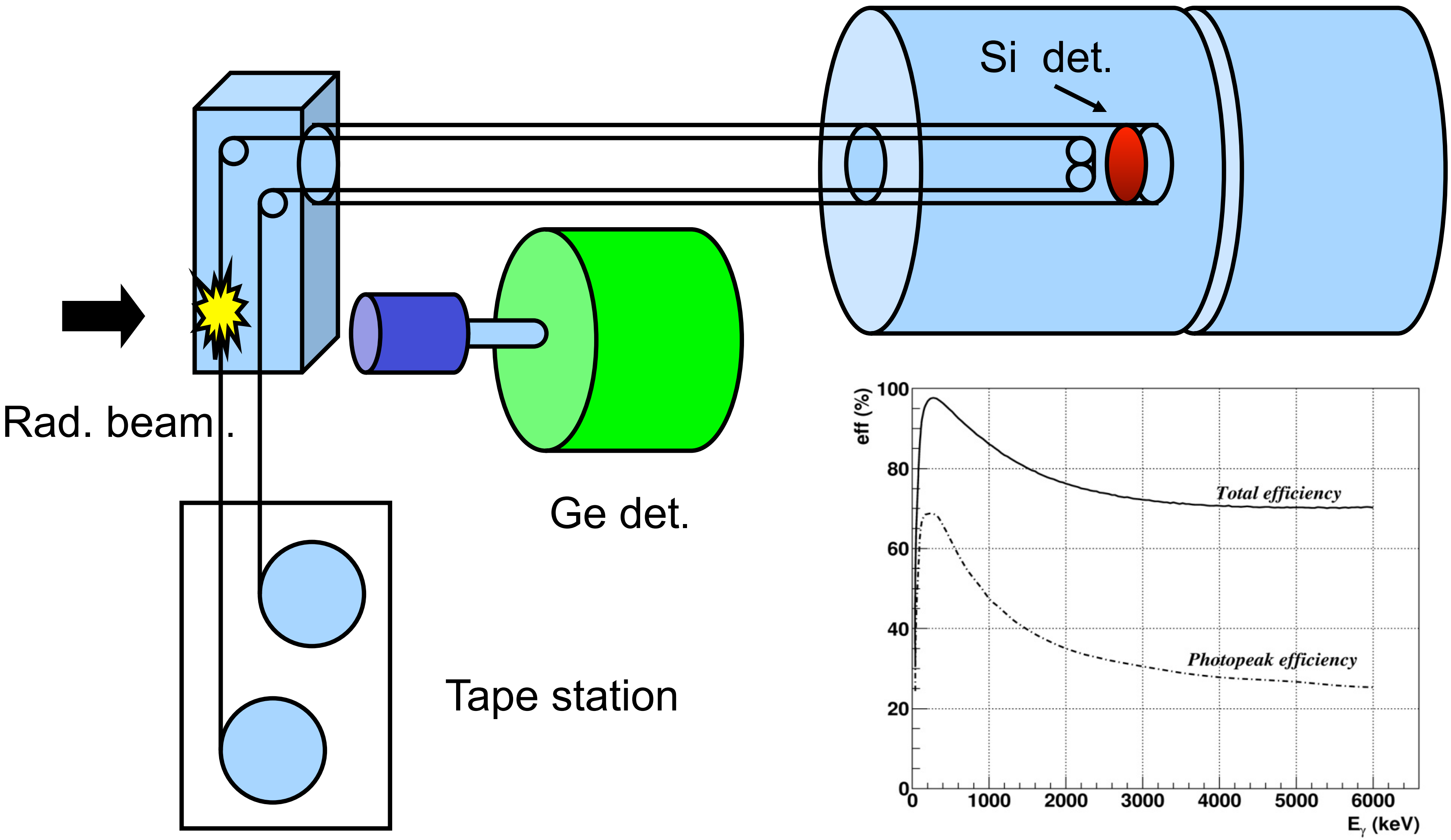
New feature: trap-assisted spectroscopy



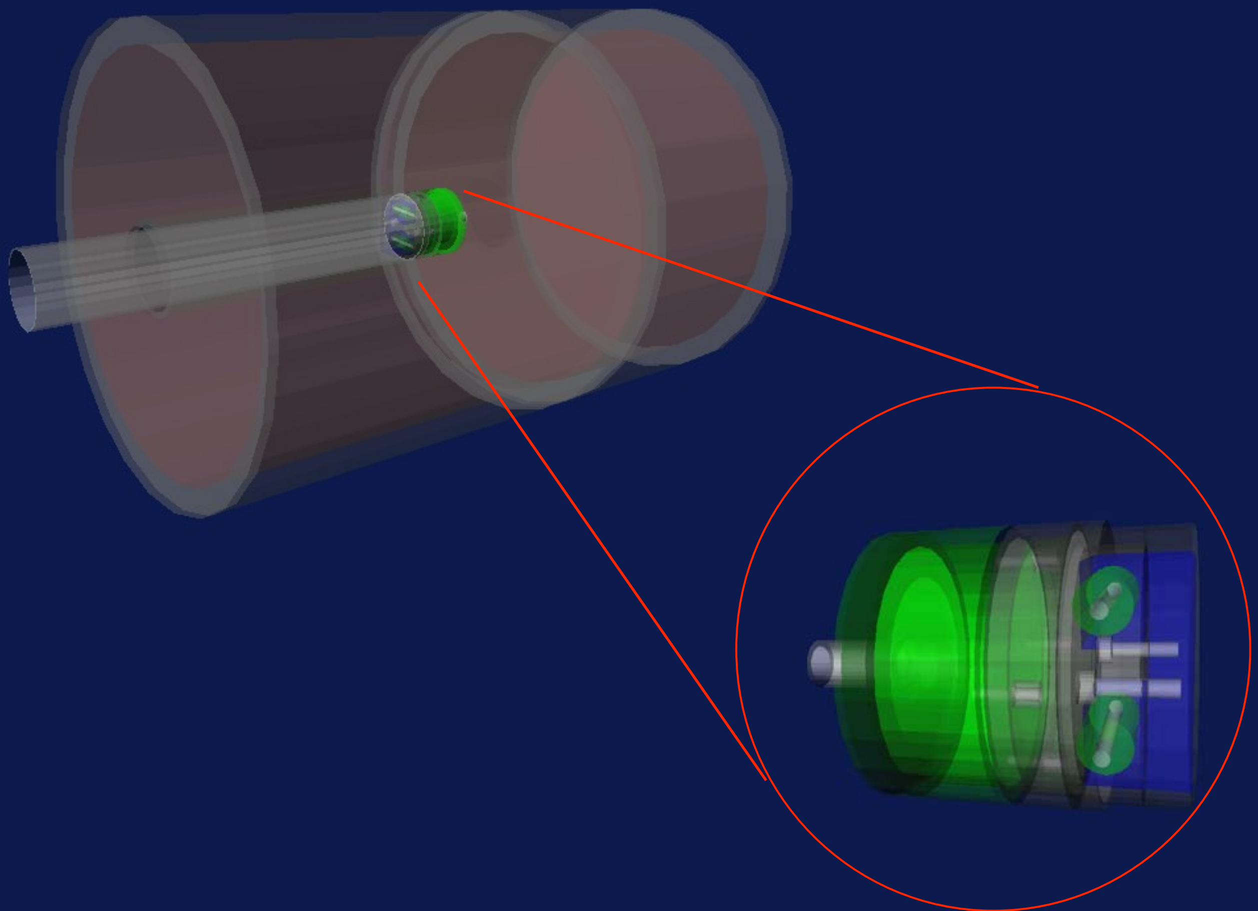




Experimental setup at Jyväskylä (I)



Monte Carlo simulations of the setup: geometry (Geant 4)



Analysis of ^{104}Tc

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

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

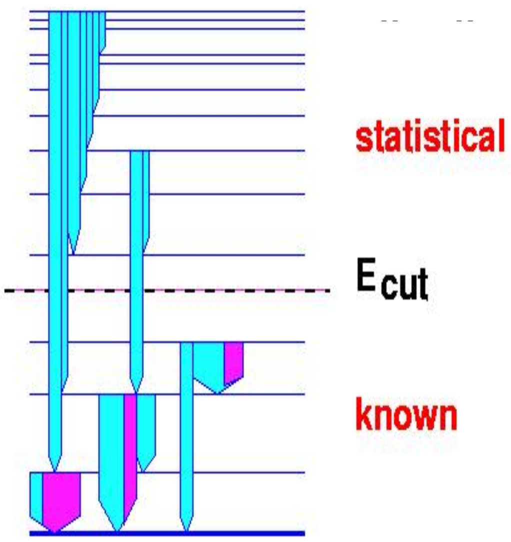
$$P(f_j | d_i) = \frac{P(d_i | f_j) P(f_j)}{\sum_j P(d_i | f_j) P(f_j)}$$

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

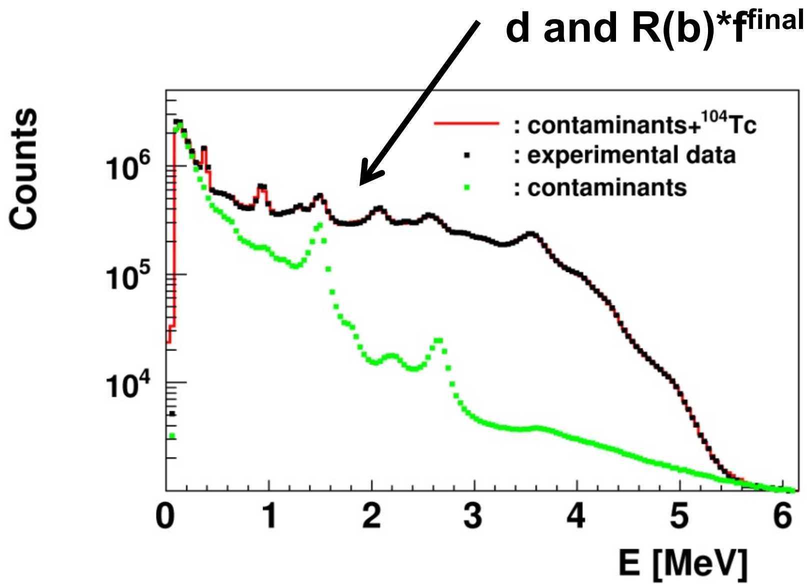
Tain et al. NIM A571 (2007) 719,728

Some details (d=R(B)f)
Known levels up to: 1515 keV excitation

From 1720 keV excitation up to the Q_β =5516(6) 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)



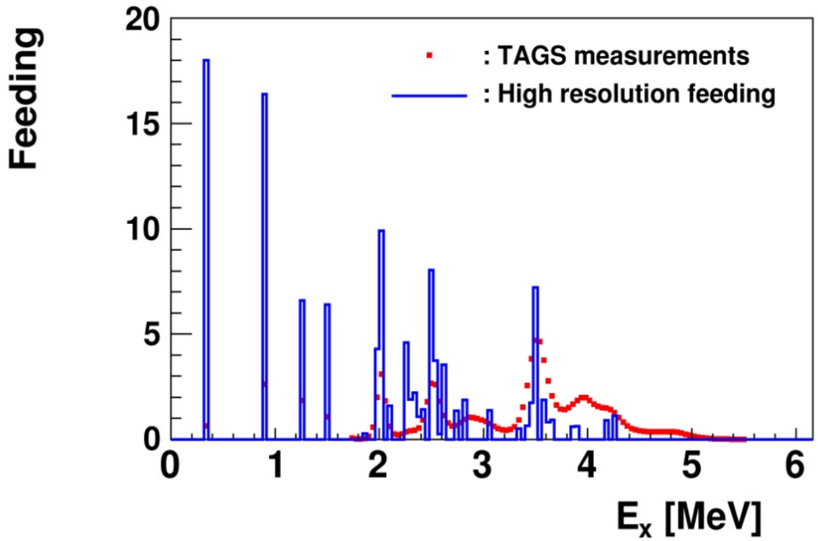
Results of the analysis for ^{104}Tc

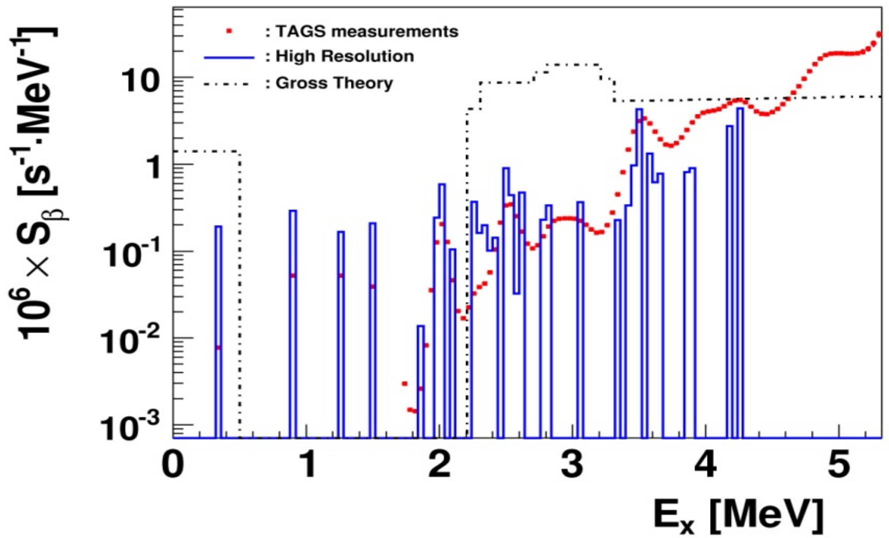


$T_{1/2}$ = 1098(18) s; Q_β= 5516(6) keV

E_β(TAGS) = 931 (10) keV
E_β(JEFF-3.1) = 1595 (75) keV
} ΔE_β = -664 keV

E_γ(TAGS) = 3229 (24) keV
E_γ(JEFF-3.1) = 1890 (31) keV
} ΔE_γ = 1339 keV





D. Jordan, PhD Thesis, Valencia, 2010

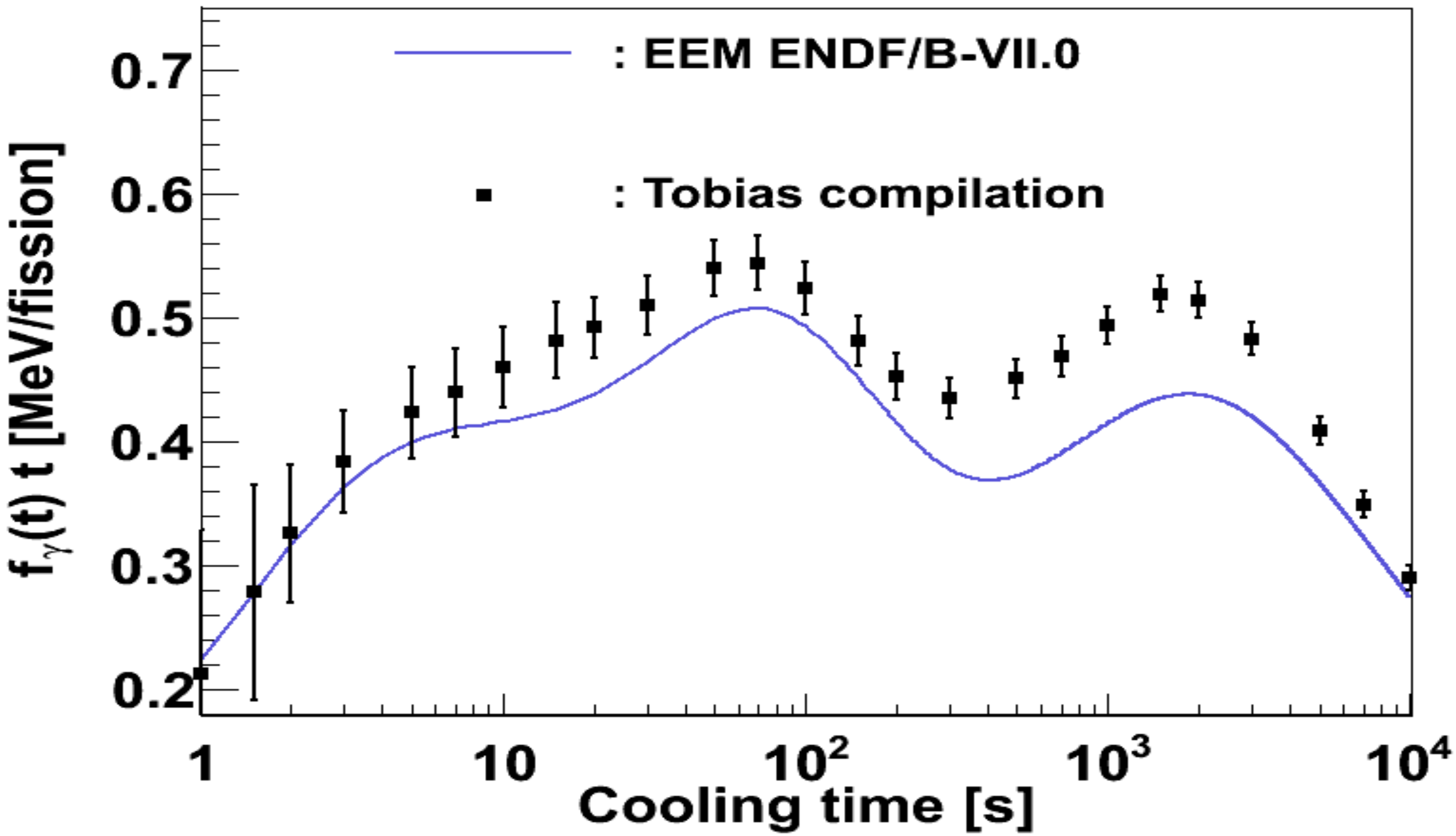
Some earlier results

Isotope	Energy type	TAGS [keV]	JEFF-3.1 [keV]	ENDF/B-VII [keV]	Difference [keV]
^{101}Nb (7.1 s)	beta	1797 (133)	1863 (307)	1966 (307)	-67/-169
	gamma	445 (279)	245 (22)	270 (22)	200/175
^{102}Tc (5.28 s)	beta	1935 (11)	1945 (16)	1945 (16)	-10
	gamma	106 (23)	81 (5)	81 (5)	25
^{104}Tc (1098 s)	beta	931 (10)	1595 (75)	1595 (75)	-664
	gamma	3229 (24)	1890 (31)	1890 (31)	1339
^{105}Tc (456 s)	beta	764 (81)	1310 (173)	1310 (205)	-546
	gamma	1825 (174)	668 (19)	665 (19)	1157/1160
^{105}Mo (35.6 s)	beta	1049 (44)	1922 (122)	1922 (122)	-873
	gamma	2407 (93)	551 (24)	552 (24)	1856/1855
^{106}Tc (35.6 s)	beta	1457 (30)	1943 (69)	1906 (67)	-486/-449
	gamma	3132 (70)	2191 (51)	2191 (51)	941
^{107}Tc (21.2 s)	beta	1263 (212)	2056 (254)	2054 (254)	-793/-791
	gamma	1822 (450)	515 (11)	515 (11)	1307

$$Q_\beta(^{102}Tc \rightarrow ^{102}Ru) = 4532 keV \qquad Q_\beta(^{101}Nb \rightarrow ^{101}Mo) = 4569 keV$$

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

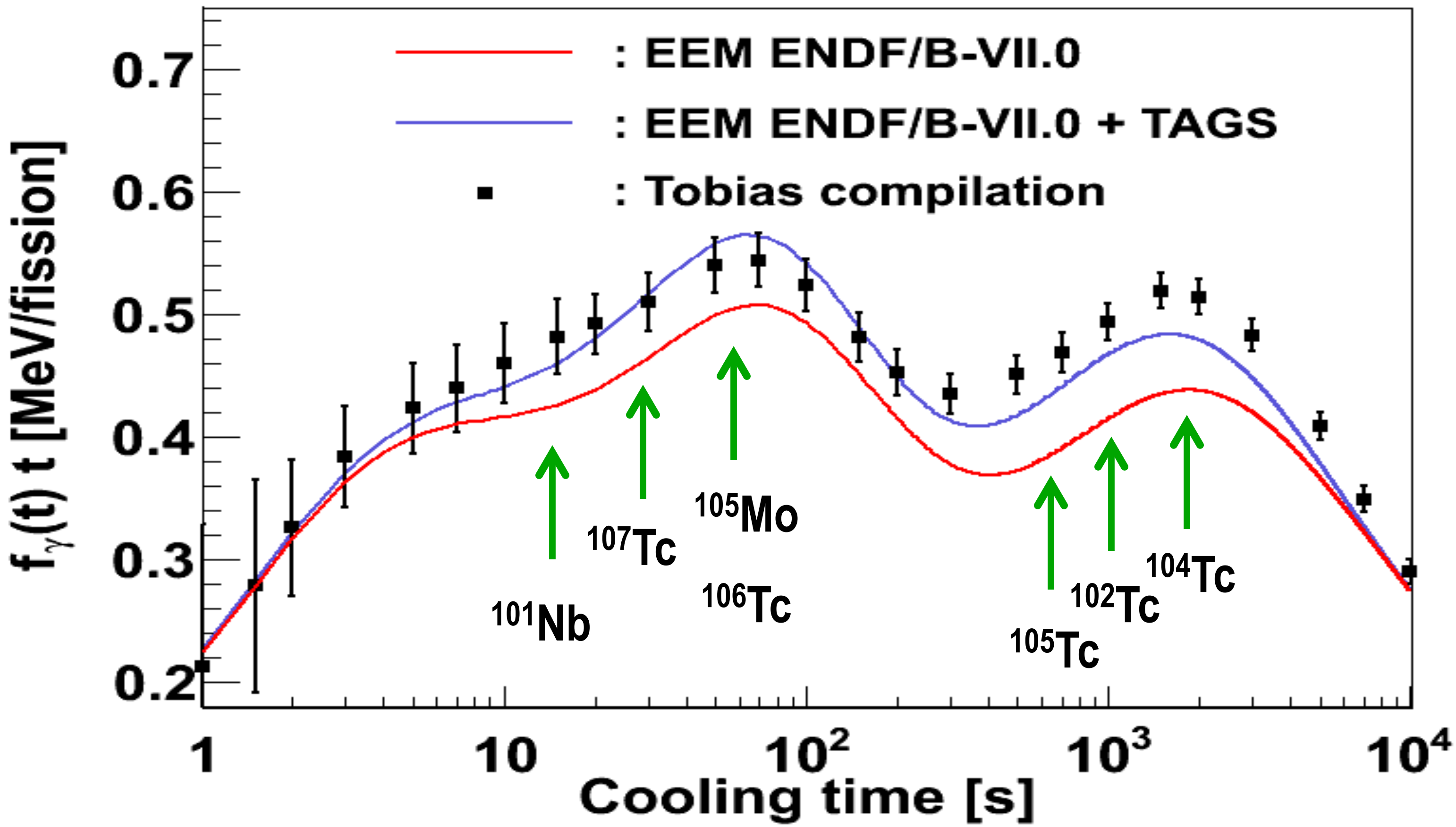
Motivated by Yoshida *et al.* (Journ. of Nucl. Sc. and Tech. 36 (1999) 135) and WPEC-25



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

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



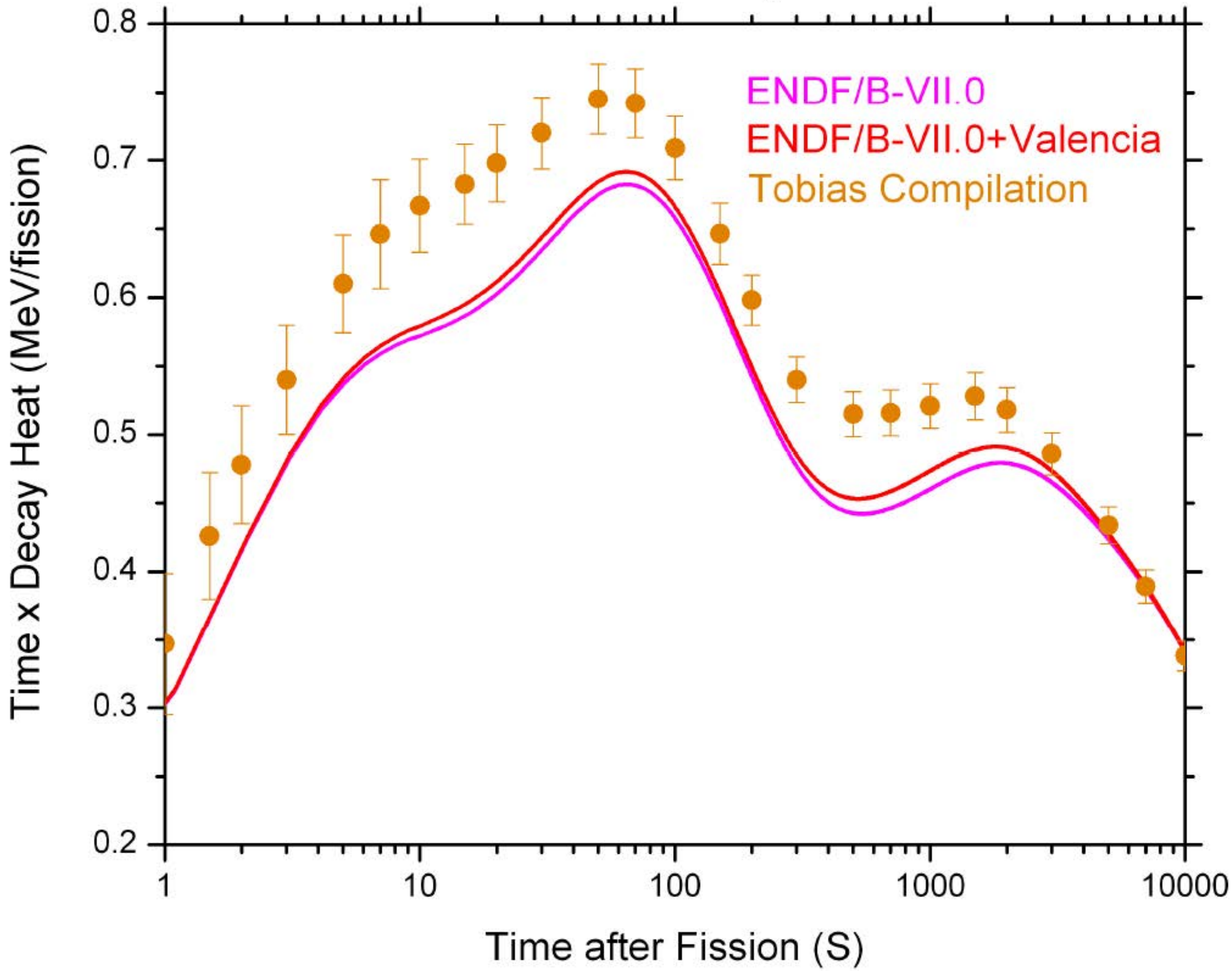
DH Courtesy A. Sonzogni

PhD Thes. D. Jordan , Algora, Jordan et al PRL 105, 202505

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

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

Impact of the results for ^{235}U



Why the results are better for ^{239}Pu than for ^{235}U

Isotope	^{235}U cum.fiss.yield	^{239}Pu cum. fiss yield
^{102}Tc	0.04284	0.06064
^{104}Tc	0.01876	0.06071
^{105}Tc	0.00943	0.05682
^{106}Tc	0.00410	0.03889
^{107}Tc	0.00139	0.02446
^{101}Nb	0.05051	0.05642
^{105}Mo	0.00829	0.04043
Total sum	0.13532	0.33837

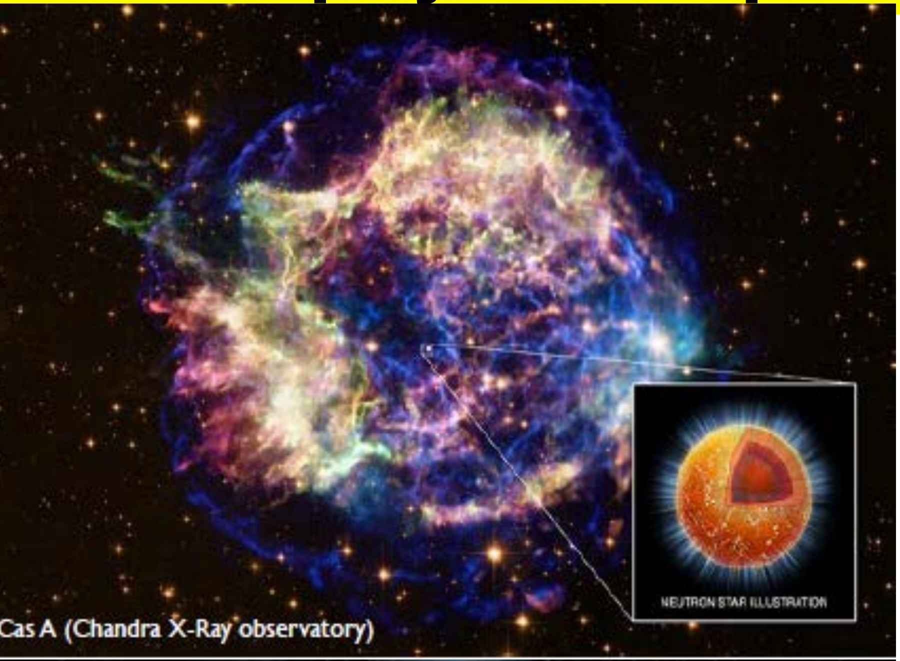
The cummulative yields of the studied nuclei “sample” 33.8 % of fission in ^{239}Pu. Compared to 13 % in ^{235}U. But ….

Courtesy of A. Sonzogni

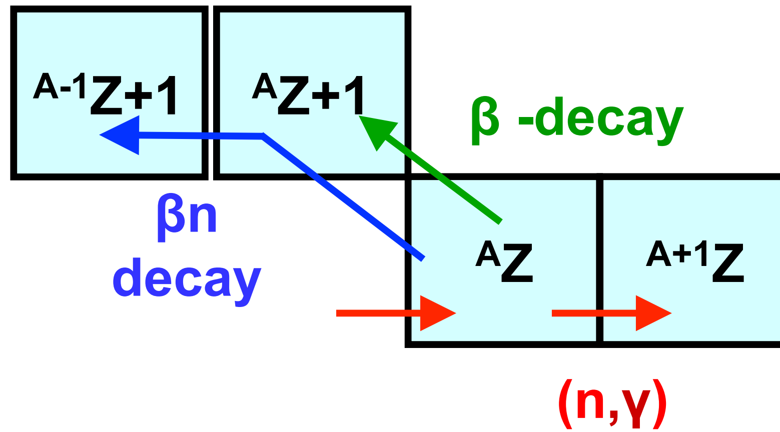
Side product: nuclear structure aspects, astrophysics

- **Test of nuclear models (difficult) that can be relevant for astrophysics and nuclear structure**
- **Region where shape effects may be important**
- **Triaxiality has been showed present in the Ru isotopes**
- **Role of FF component**
- **Etc.**

Astrophysics: r-process input from models



r-process: A short and very high neutron flux produces very neutron-rich nuclei in a short time, which then decay to stability.



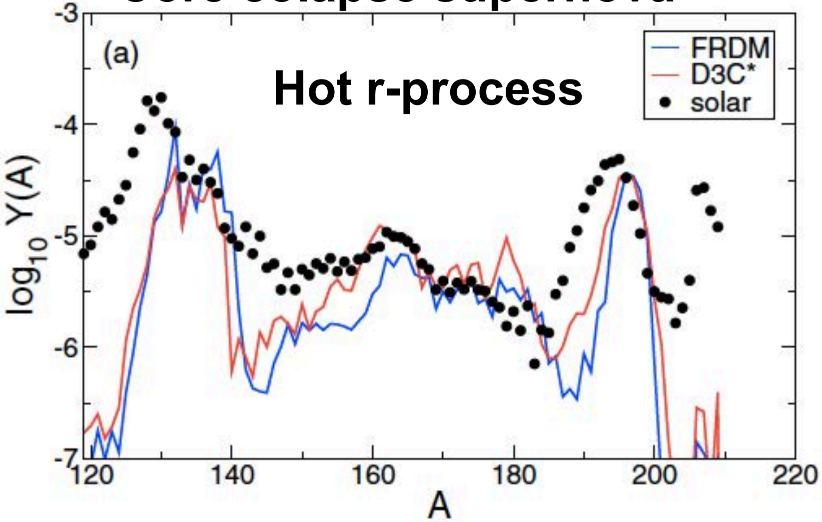
- **The β-decay half-life determines the speed of the process and shapes the abundance distribution**
- **The delayed neutron emission probability modifies the abundance distribution**

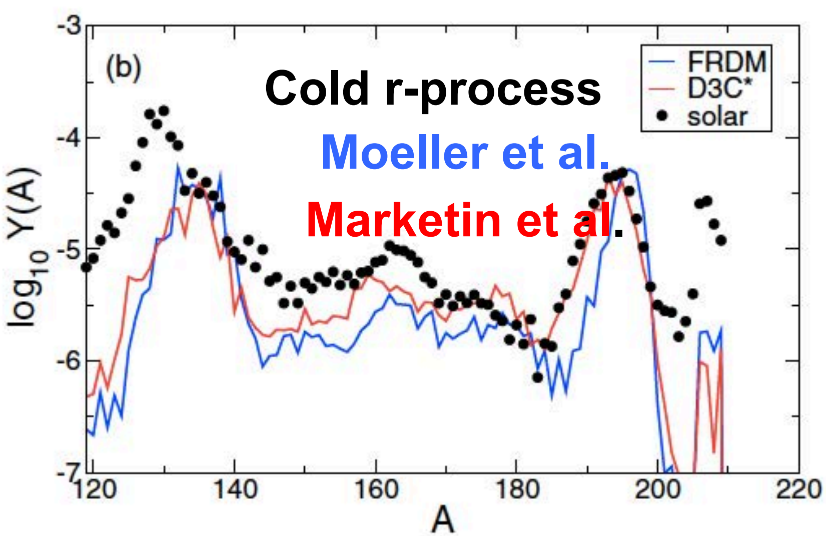
Input parameter effect: $T_{1/2}$, P_n

T1/2 impact

Marketin et al., PRC93.025805

Core colapse supernova

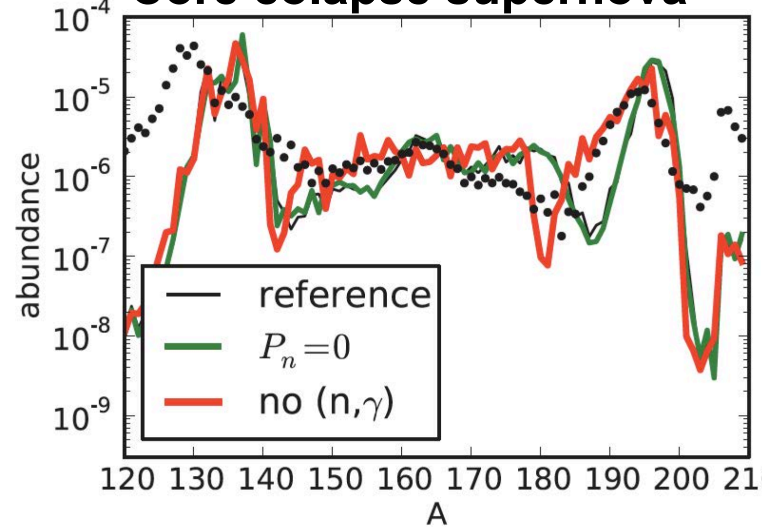


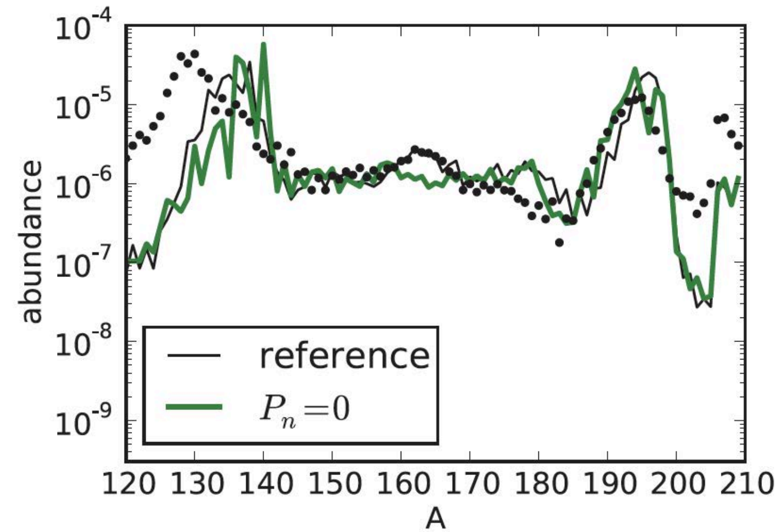


Pn impact

Arcones et al., PRC83.045809

Core colapse supernova



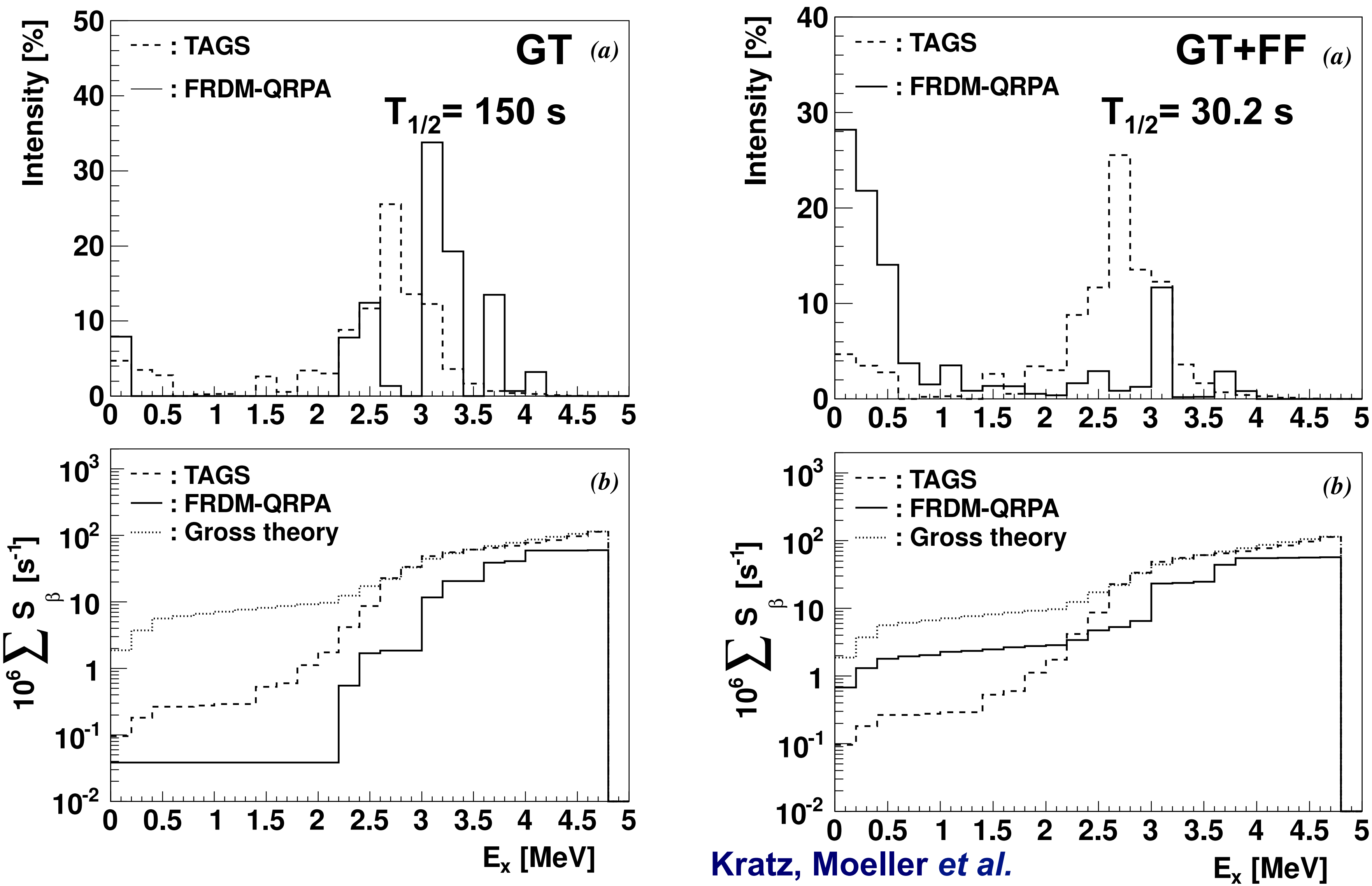


Preliminary look at half-lives results (experiment compared with Moeller, Marketin)

Decay	$T_{1/2}$ [s] Exp	$T_{1/2}$ [s] (GT)	$T_{1/2}$ [s] (GT+ff)	$T_{1/2}$ [s] (GT)	$T_{1/2}$ [s] (GT+ff)
$^{101}Nb \rightarrow ^{101}Mo$	7.1	9.9	8.3	8.92	8.87
$^{105}Mo \rightarrow ^{105}Tc$	35.6	150	30.2	3,71	3,75
$^{102}Tc \rightarrow ^{102}Ru$	5.3	6.72	6.69	_	_
$^{104}Tc \rightarrow ^{104}Ru$	1098	151	40.7	1375,14	1375,09
$^{105}Tc \rightarrow ^{105}Ru$	456	16920	162	99,64	99,51
$^{106}Tc \rightarrow ^{106}Ru$	35.6	64.8	17.9	23,13	23,03
$^{107}Tc \rightarrow ^{107}Ru$	21.2	135.6	29.7	8,29	8,22

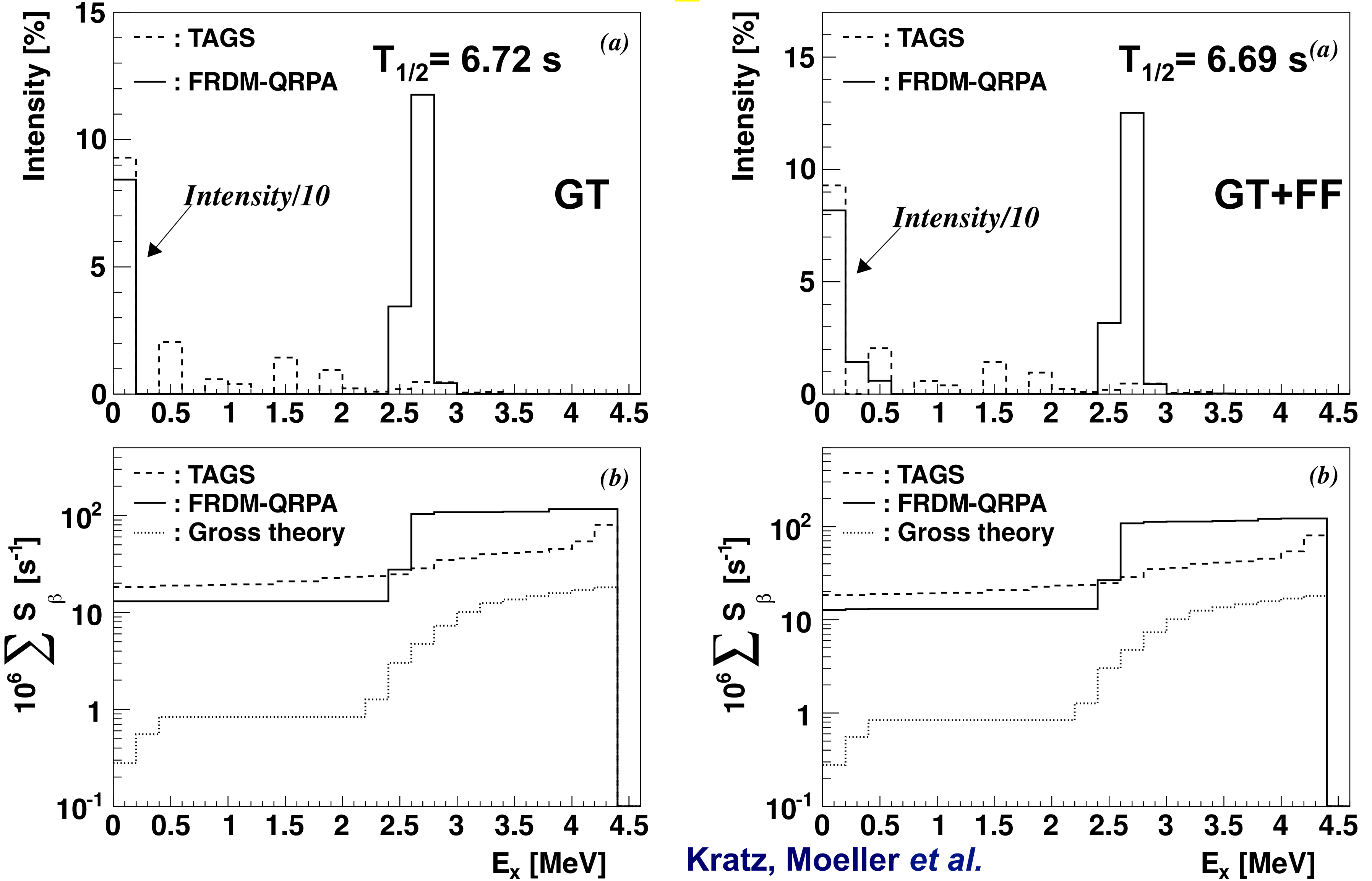
Kratz, Moeller *et al.* **Marketin *et al.***

Nuclear structure ^{105}Mo: FRDM-QRPA calculations; $T_{1/2}(exp) = 35.6$ s



Kratz, Moeller *et al.*

Nuclear structure ^{102}Tc: FRDM-QRPA calculations; $T_{1/2}$(exp) = 5.3 s

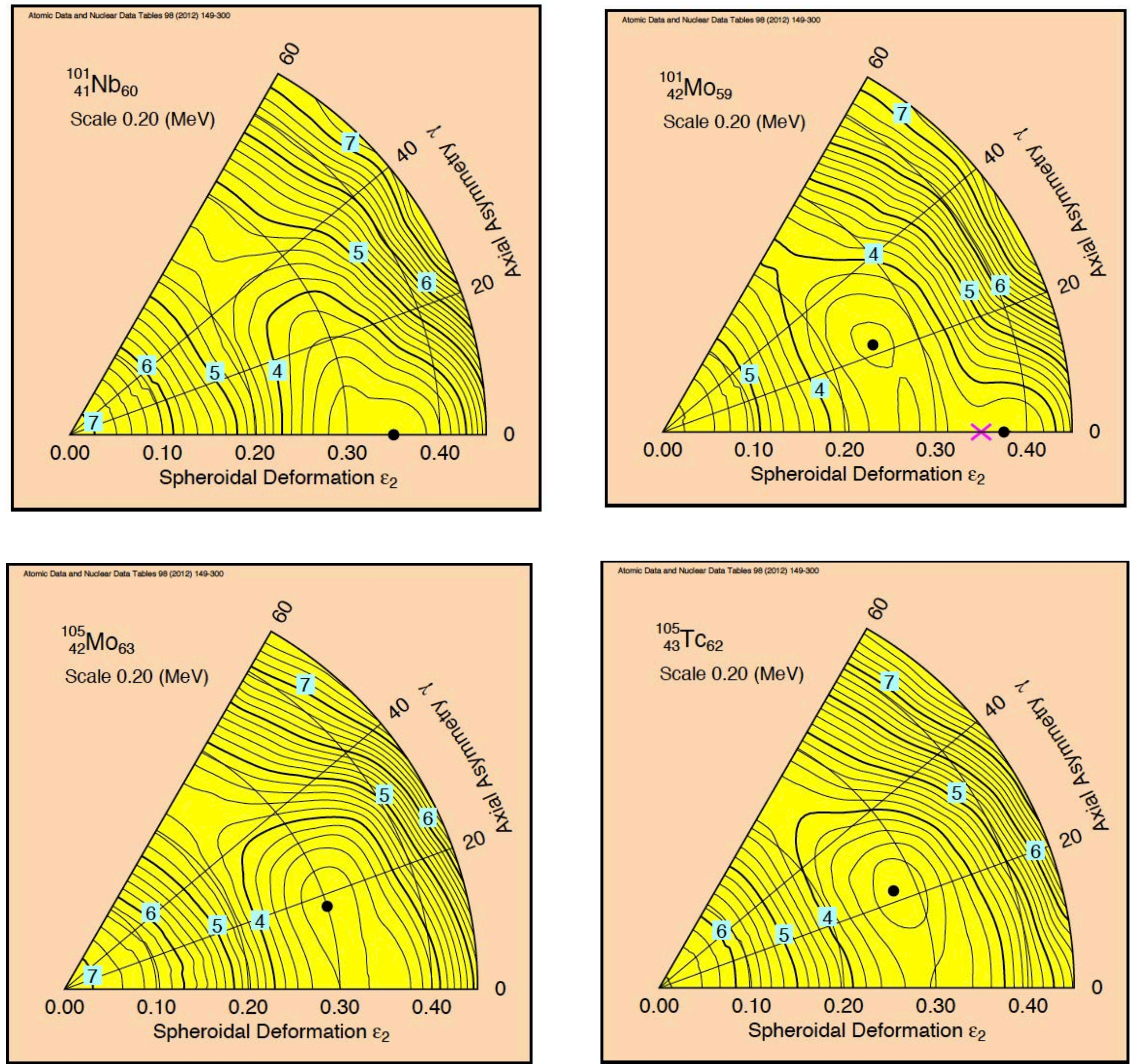


Kratz, Moeller *et al.*

Deformation related problem?

$^{101}Nb \rightarrow {}^{101}Mo$

$^{105}Mo \rightarrow {}^{105}Tc$

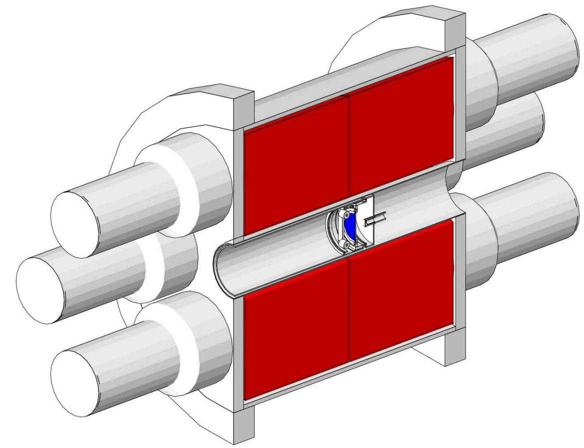


FRDM Model

“Recently” performed measurements

VTAS run (November 2009)

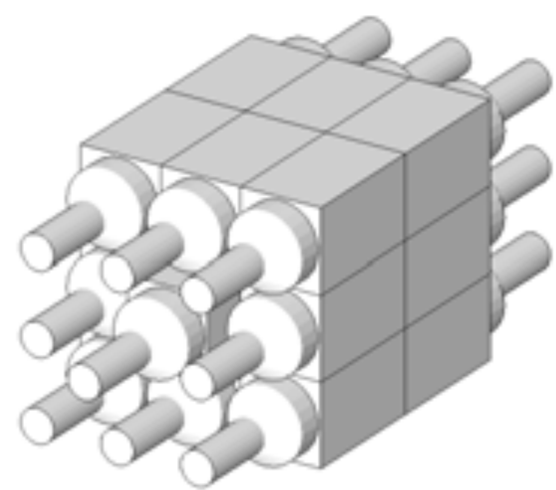
Measurement of beta delayed neutron emitters cases of high priority for decay heat. The idea was to measure the same nuclides using different techniques and different setups(TAS, Pn, neutron spectrum meas.). In this run we also measured some cases of interest for neutrino physics. All analyses finished, some results are already published and in preparation. BaF2 detector



DTAS run (December 2014)

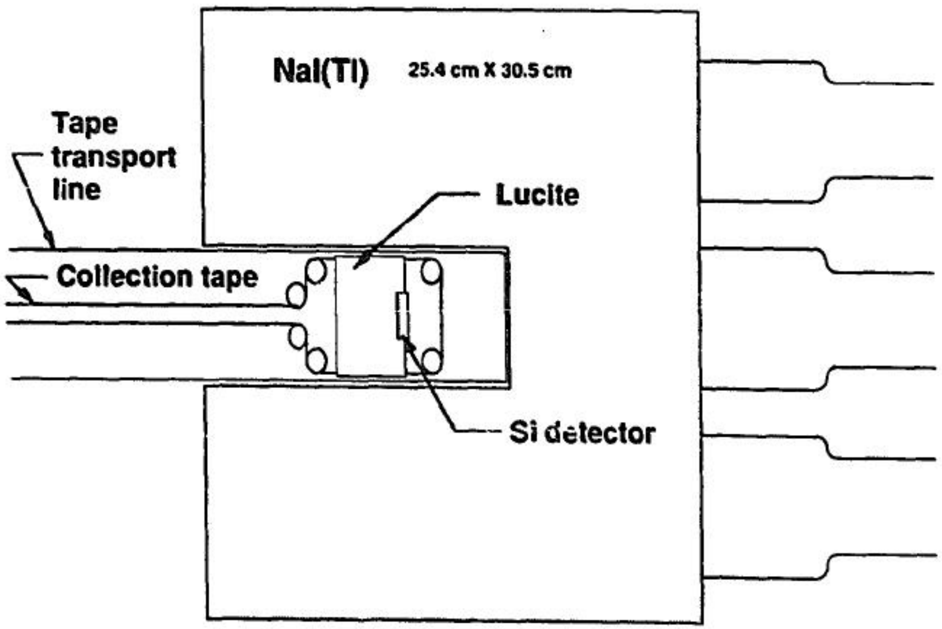
Primary goal: measurement of nuclei of high interest for the prediction of the neutrino spectrum in reactors. Priority list defined by the Nantes group. Common proposal.

NaI detector developed for FAIR.



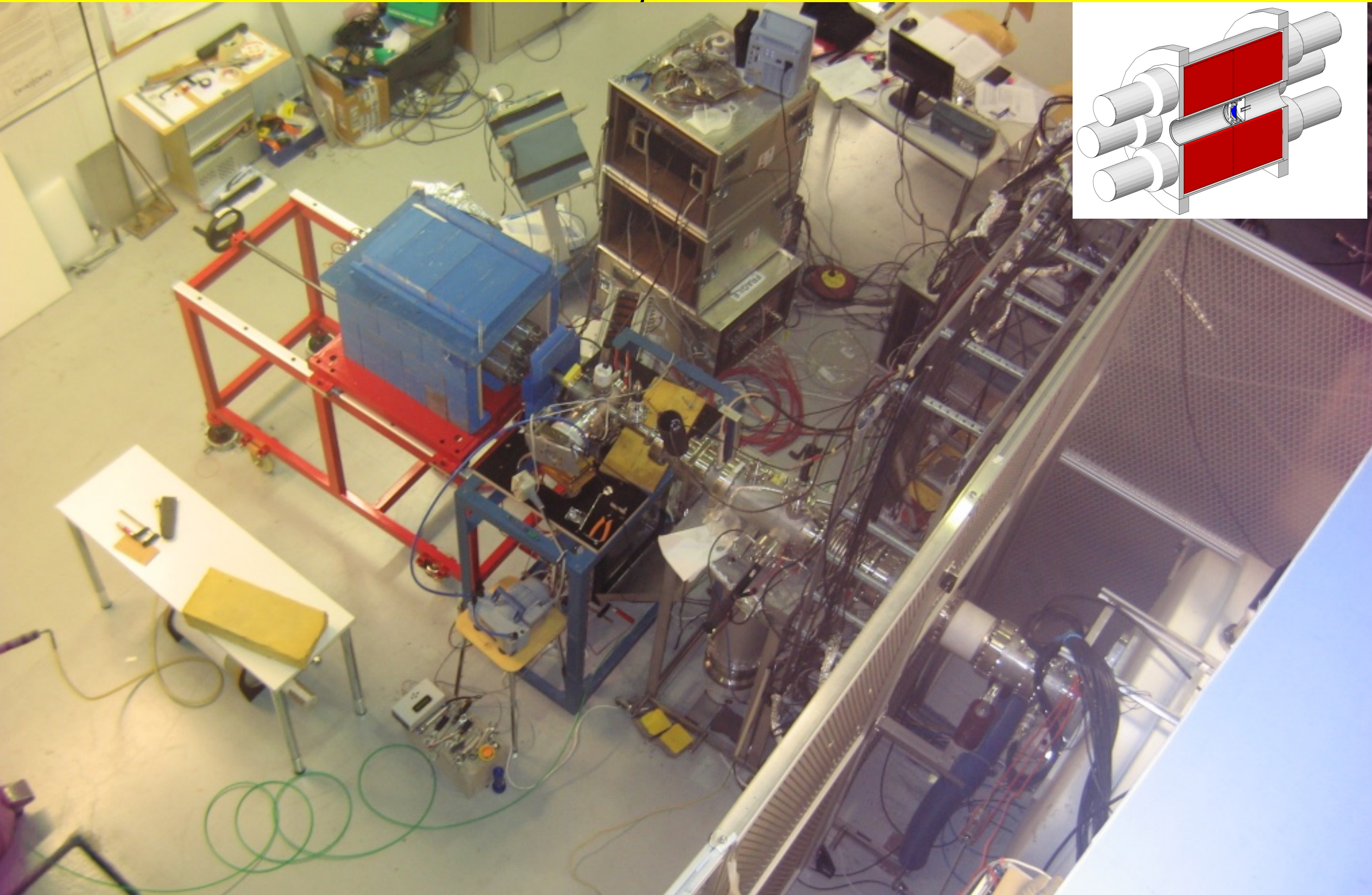
Work in the past: Greenwood TAGS work

Greenwood et al. (see NIM A 390 (1997) 95)
~50 decays studied using the total absorption technique at the INEL ISOL facility



- Sources obtained from ^{252}Cf and the ISOL technique
- Isotopic separation by proper choice of meas/coll. time
- Analysis method: no deconvolution (forward solution) levels introduced by hand until the spectrum is reproduced
- Background and pileup taken into account

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



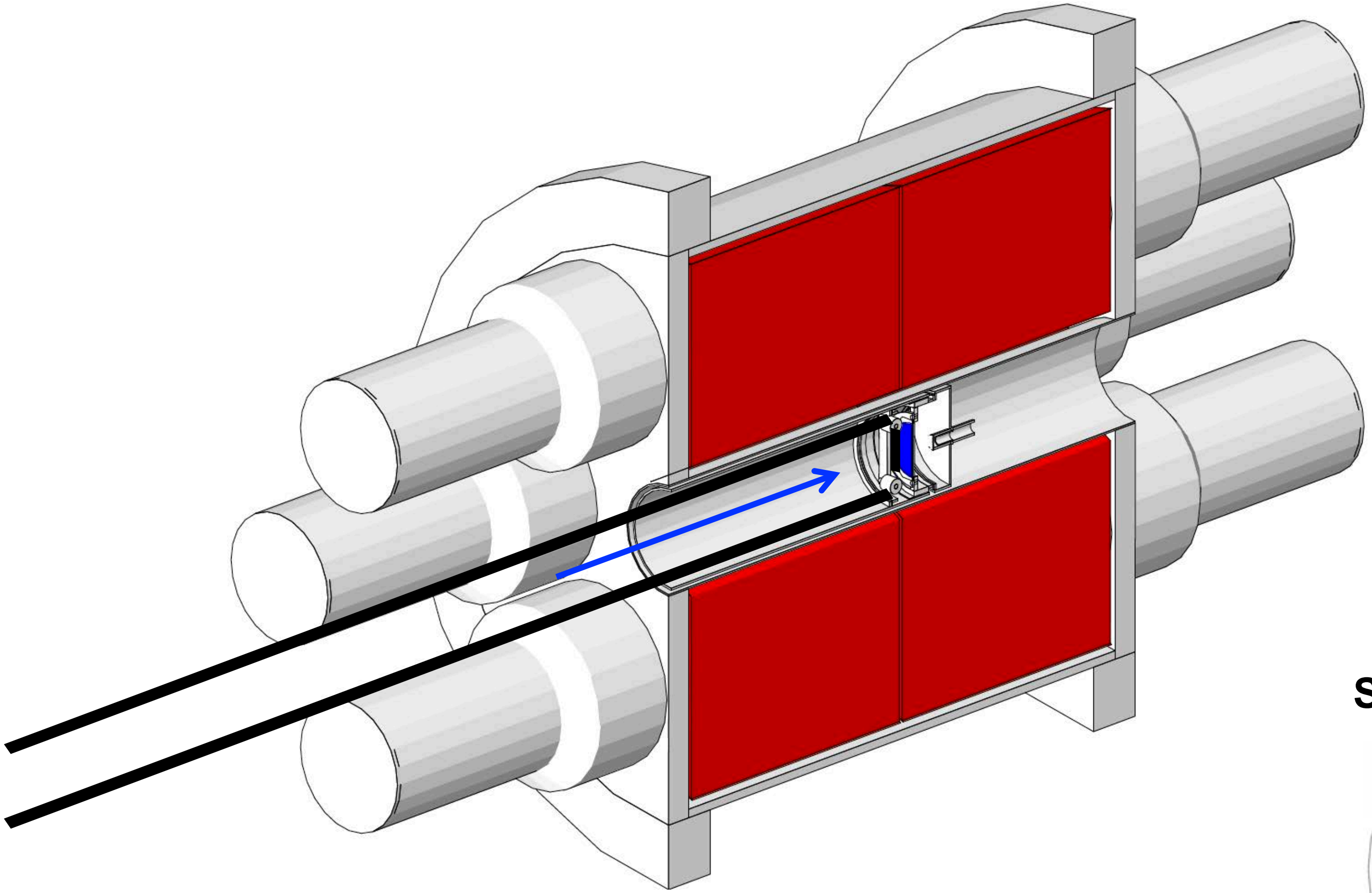
VTAS in Jyväskylä (November 2009)

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

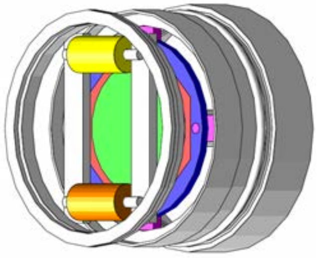
Z	50	51	52	53	54	55	56	57	N
	89Y STABLE 100%	90Y 64.053 H β-: 100.00%	91Y 58.51 D β-: 100.00%	92Y 3.54 H β-: 100.00%	93Y 10.18 H β-: 100.00%	94Y 18.7 M β-: 100.00%	95Y 10.3 M β-: 100.00%	96Y 5.34 S β-: 100.00%	97Y 3.75 S β-: 100.00% β-n: 0.06%
38	88Sr STABLE 82.58%	89Sr 50.53 D β-: 100.00%	90Sr 28.90 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%

VTAS in Jyväskylä (November 2009)

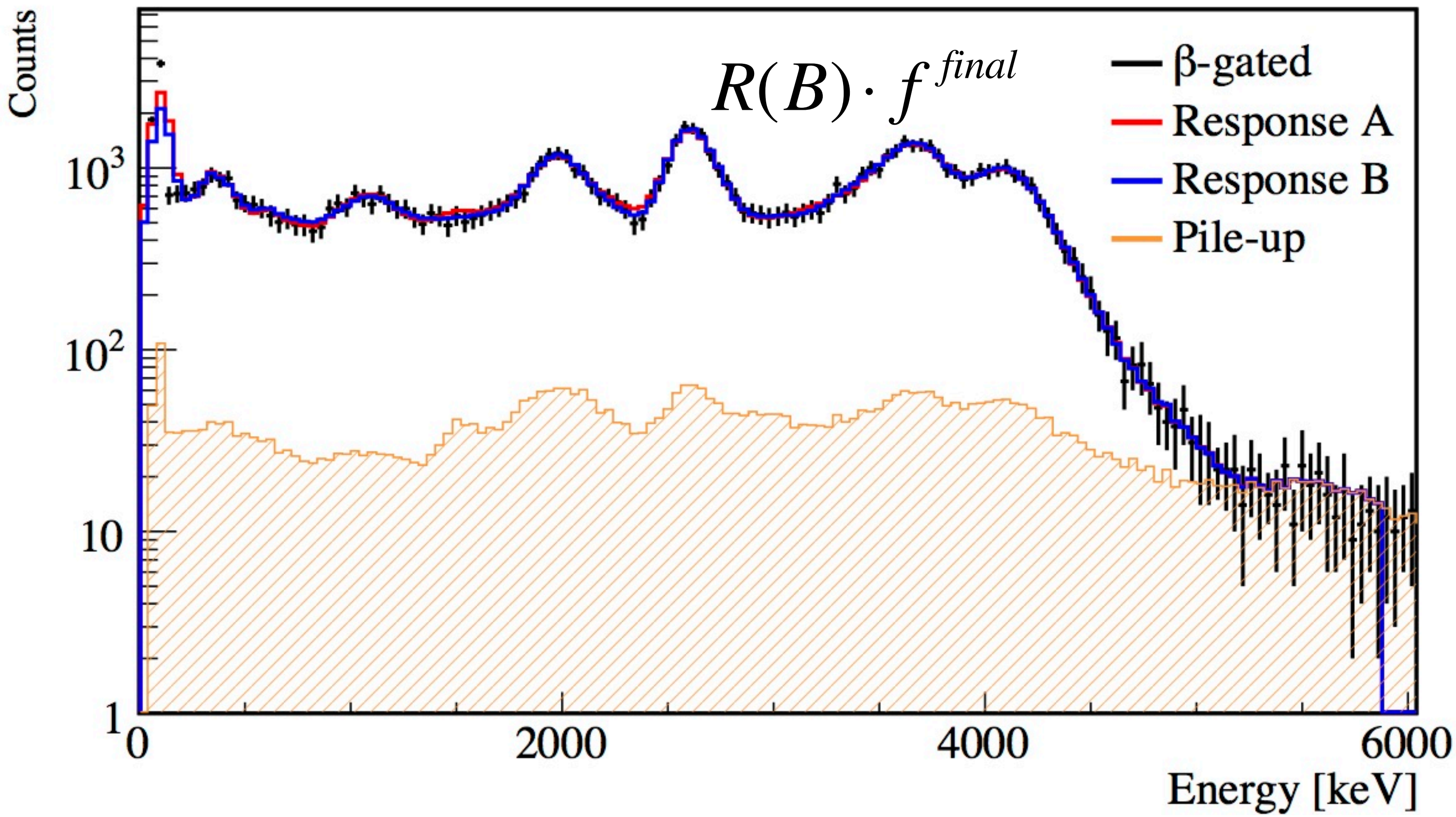
^{86,87,88}Br, ^{91,92,93,94}Rb



Si detector endcup



One case of interest (not from the list): 91Rb

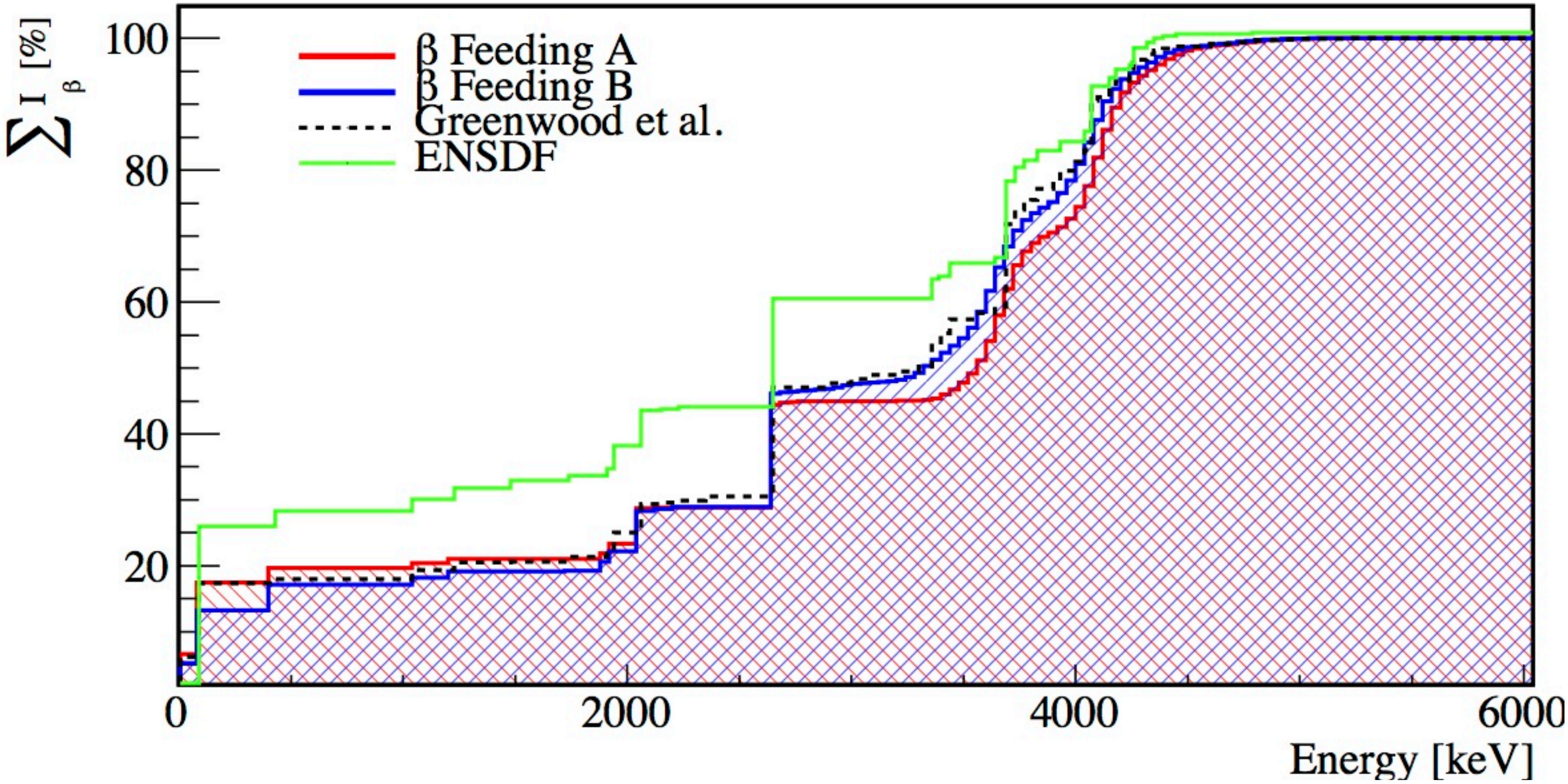


Measured by Greenwood, and used by Rudstam as calibration point for his mean gamma energy measurements, assuming that it does not suffer from *Pandemonium*

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

S. Rice, PhD thesis (Univ. Surrey)

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

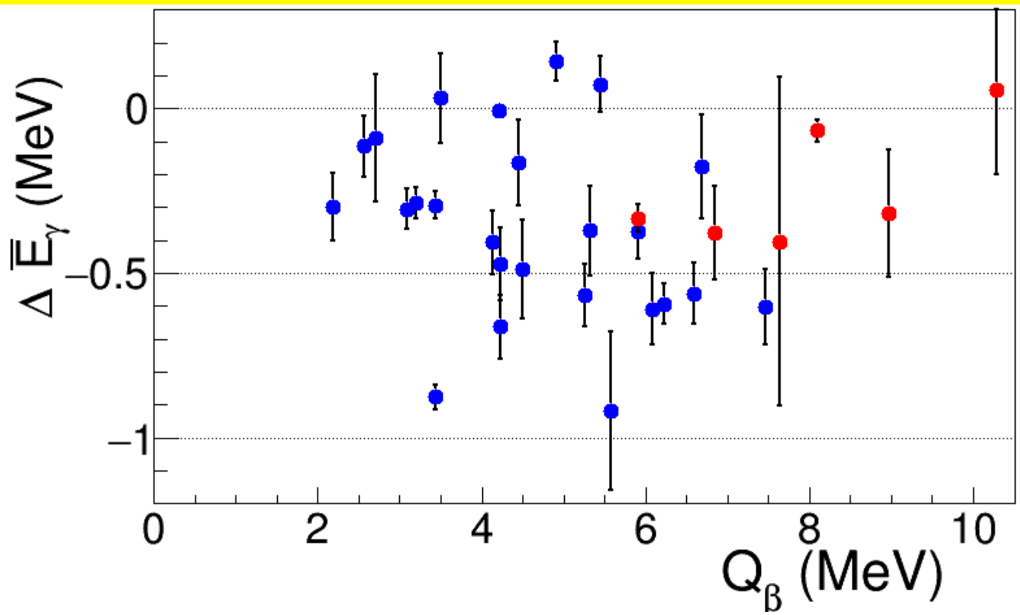
$$\overline{E_\gamma^R} = 2335 keV$$ Used value by Rudstam (from HR)

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

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

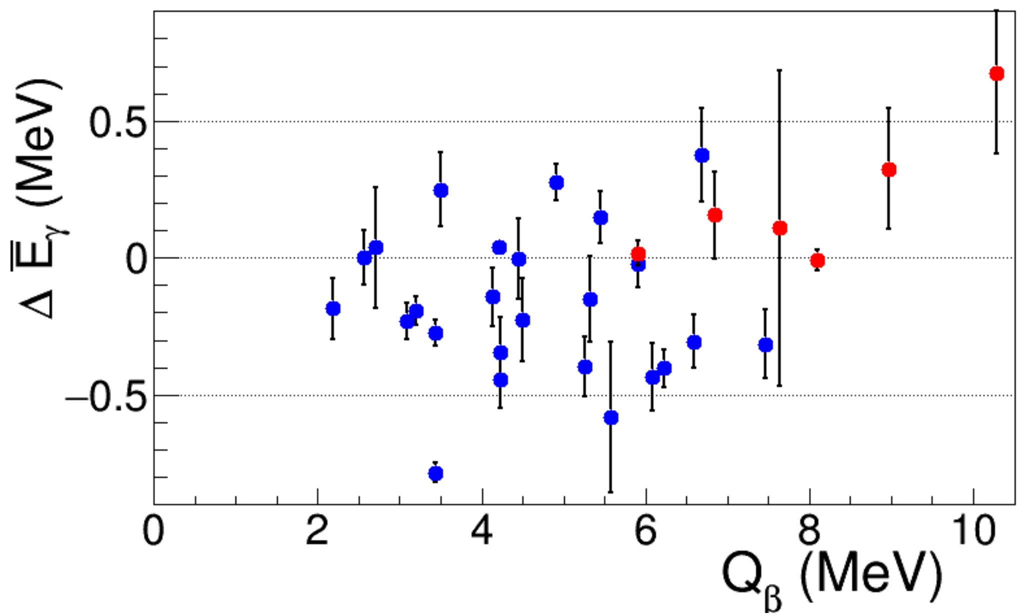
Since the absolute normalization was based on the 91Rb mean gamma energy, the data set needs to be renormalized !!!

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



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

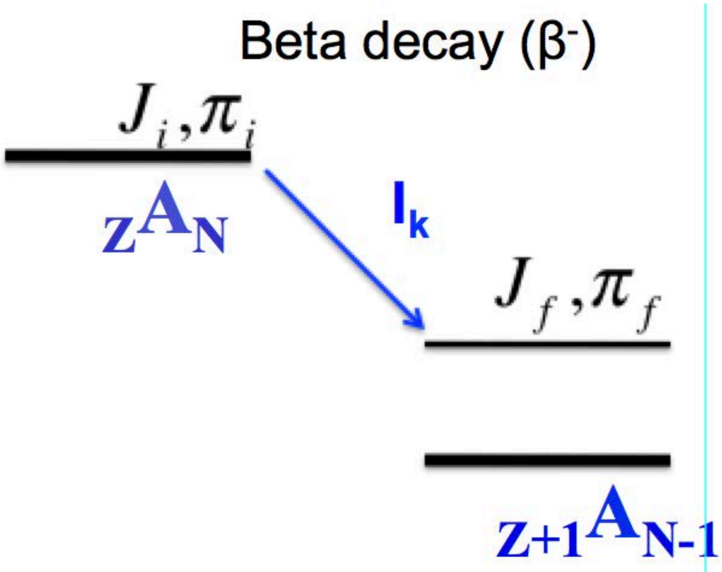
$$\langle \overline{E_R} - \overline{E_T} \rangle_\gamma = -360 keV$$



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

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

Deduced beta spectrum for comparisons (allowed shape)



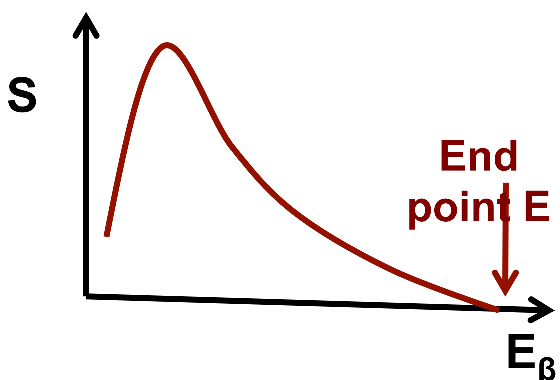
Spectrum for each transition

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

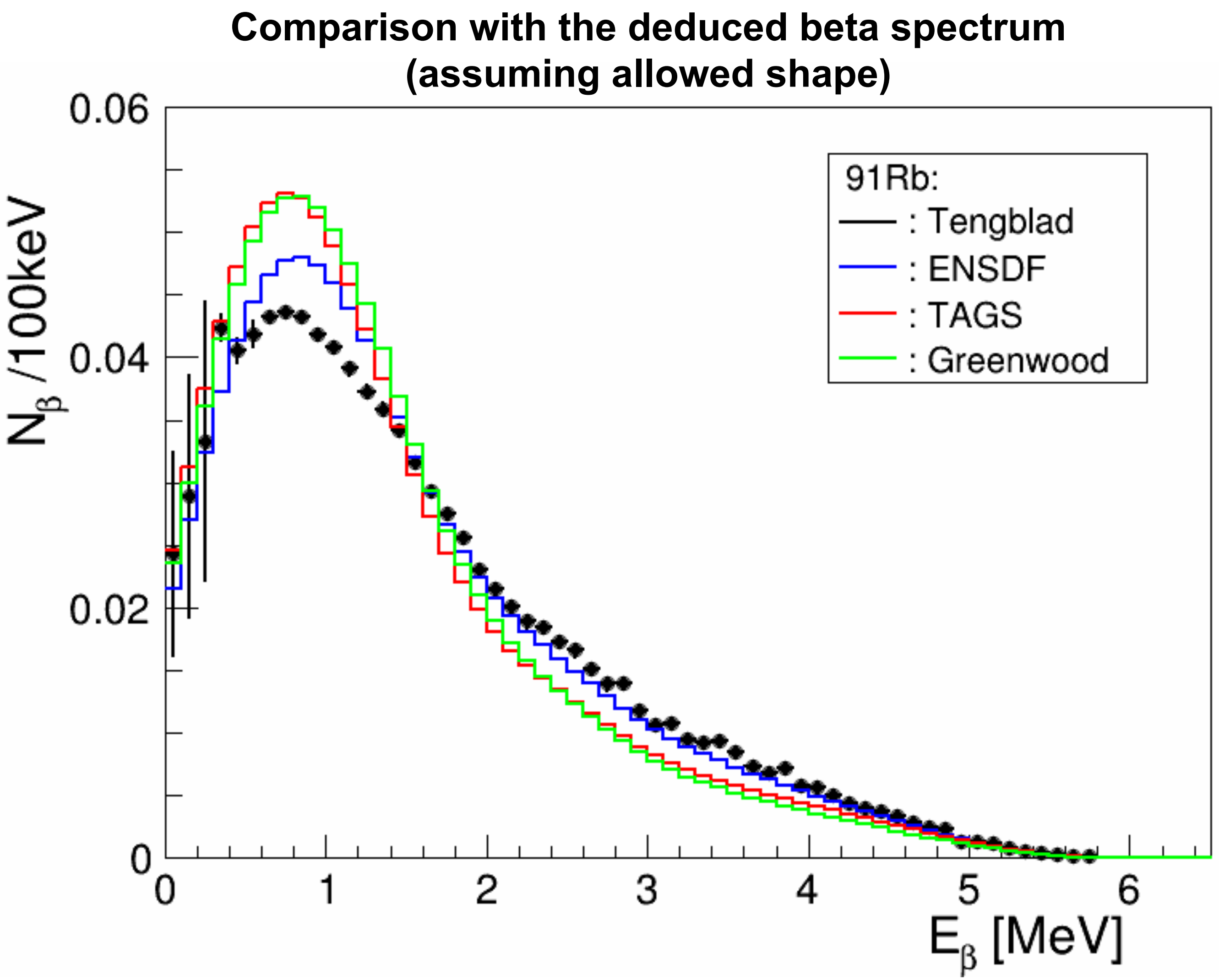
$$S(Q - E_k, J_i\pi_i, J_f\pi_f)$$

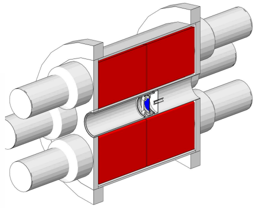
Spectrum for the decay (n)

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



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





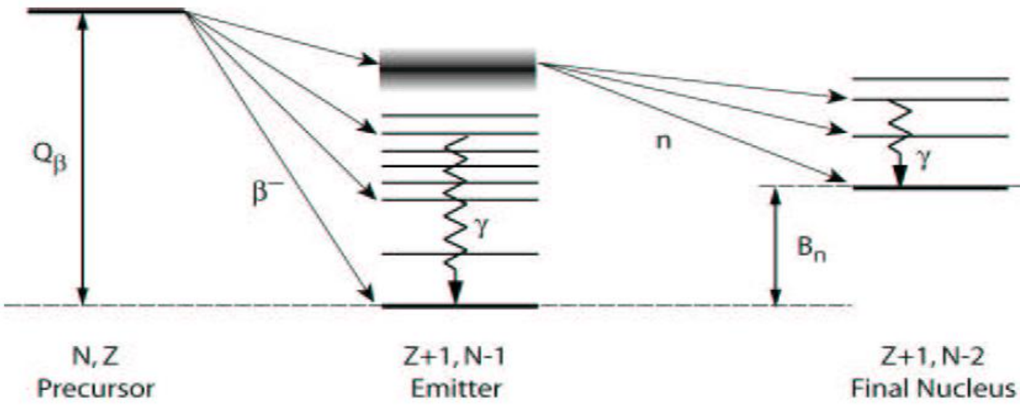
S. Rice, A. Algora, J. L.Tain et al, PRC 96, 014320 (2017),S. Rice, PhD thesis

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

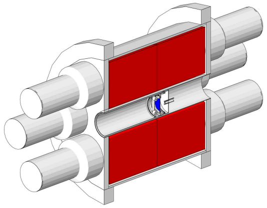
- Priority one in the IAEA list (decay heat)
- Moderate fission yields
- Pandemonium cases ?
- Interest from the structure point of view: vicinity of N=50 closed shell
- Competition between gamma and neutron emission above the Sn value

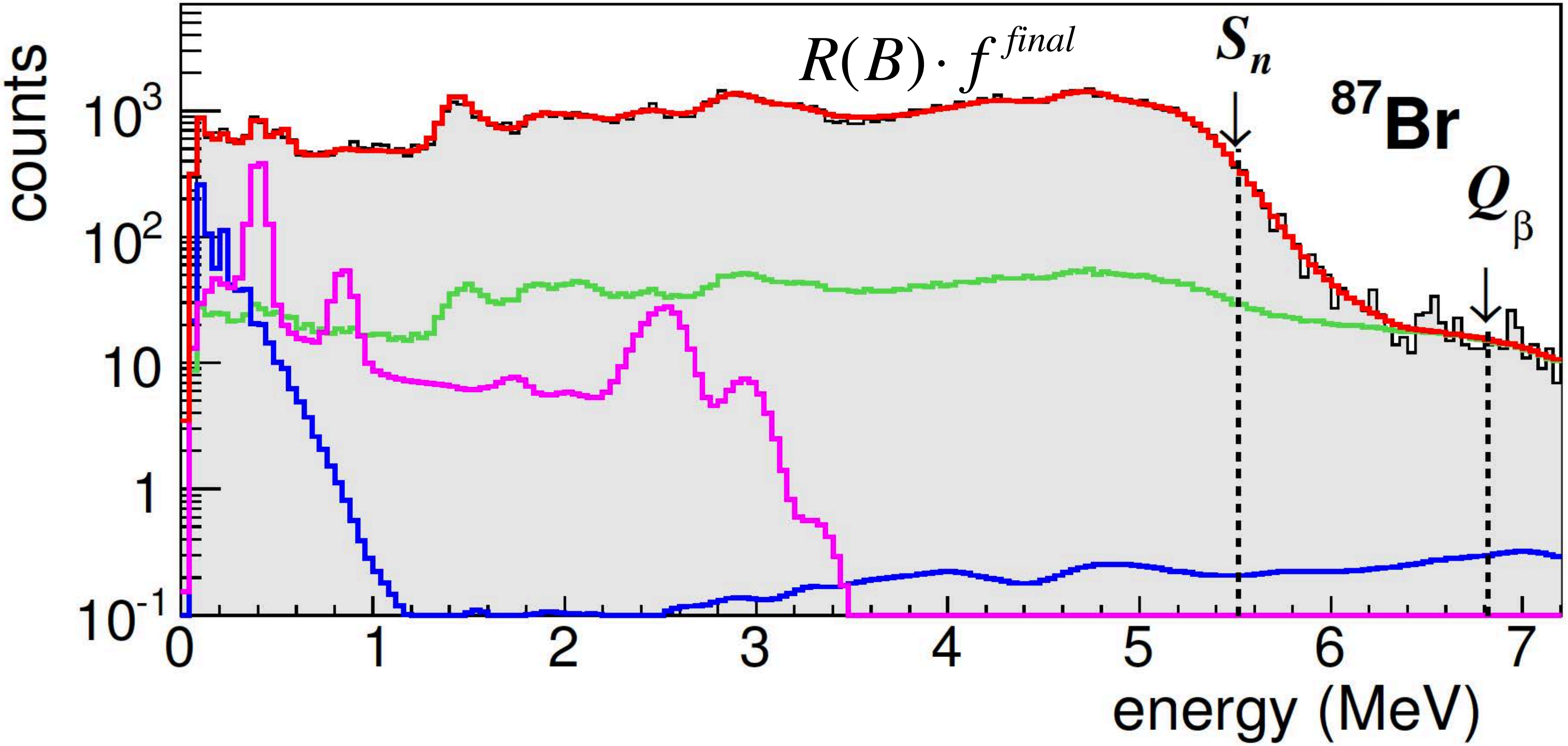
$$\frac{1}{T_{1/2}} = \int_0^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)\,dE_x$$

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



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

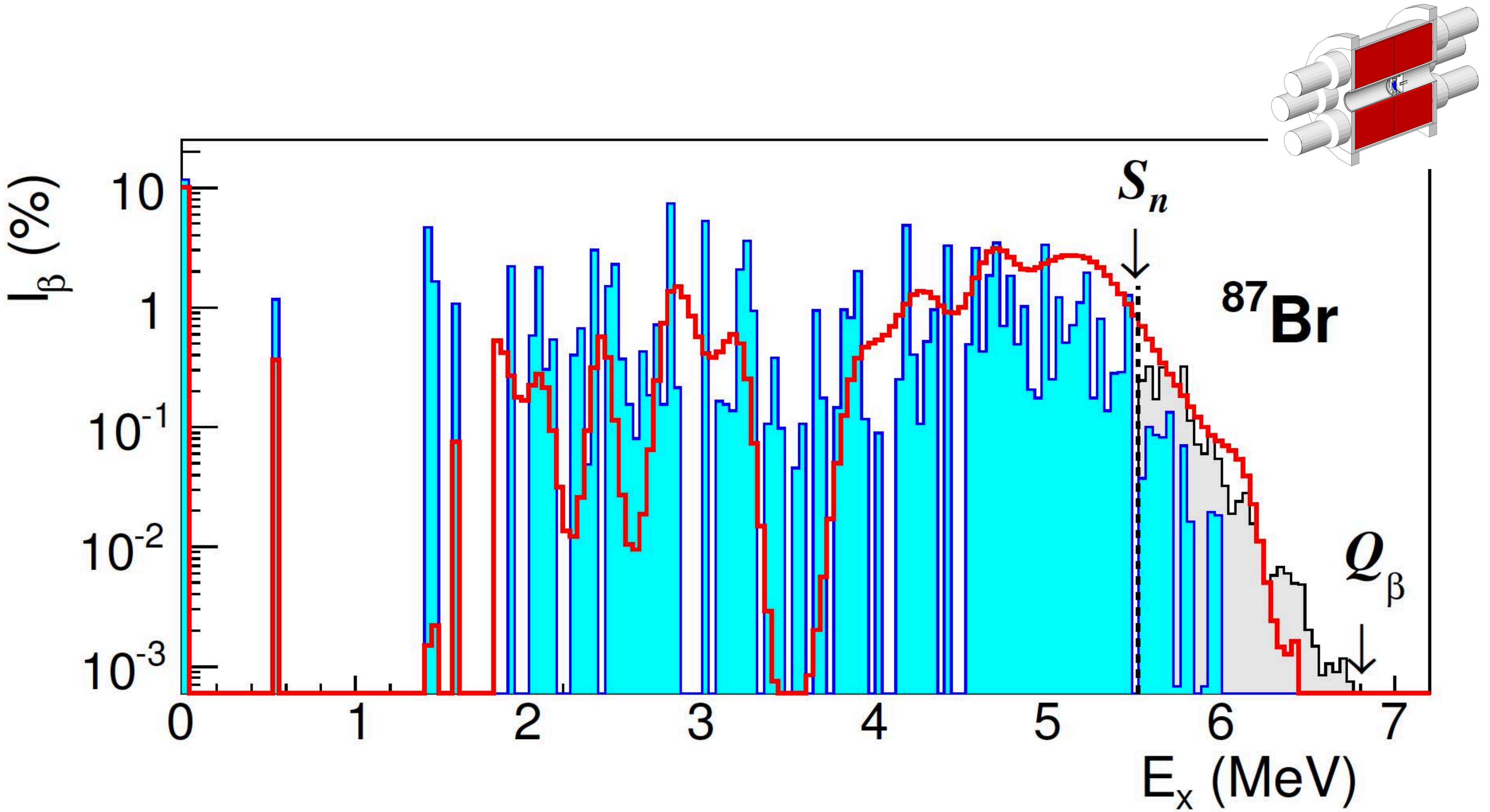




E. Valencia, et al, PRC95, 024320 (2017)

Tain et al. PRL 115, 062502

Beta delayed neutron emitters, example: 87Br

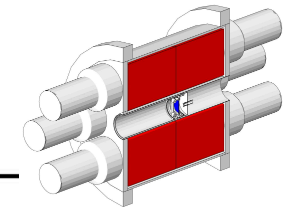


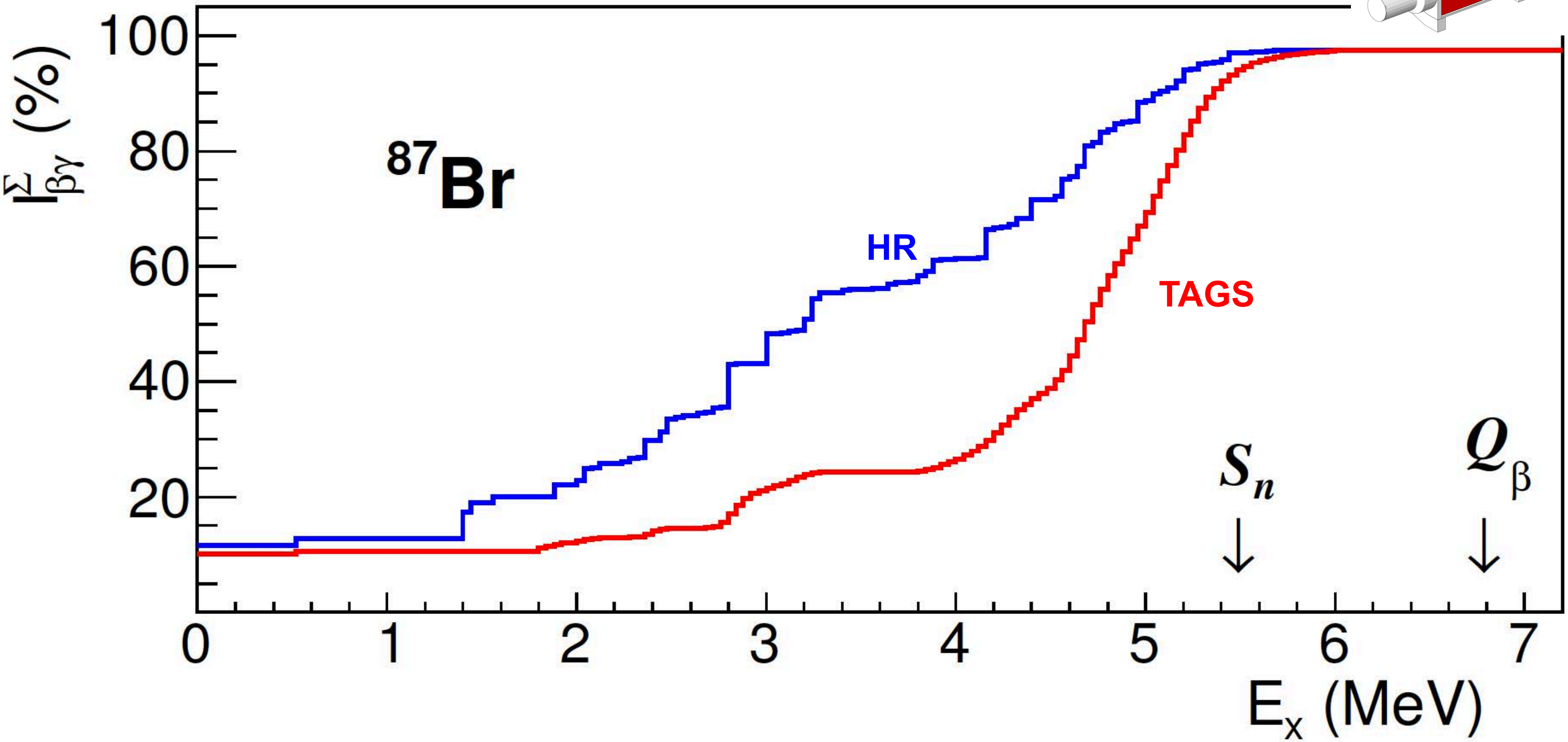
E. Valencia, et al, PRC95, 024320 (2017)
Tain et al. PRL 115, 062502

Pγ=3.50 (+49-40) %

Pn=2.60 (4) %

Beta delayed neutron emitters, example: 87Br



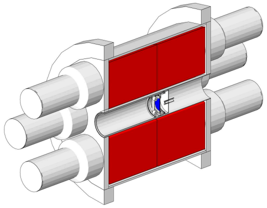


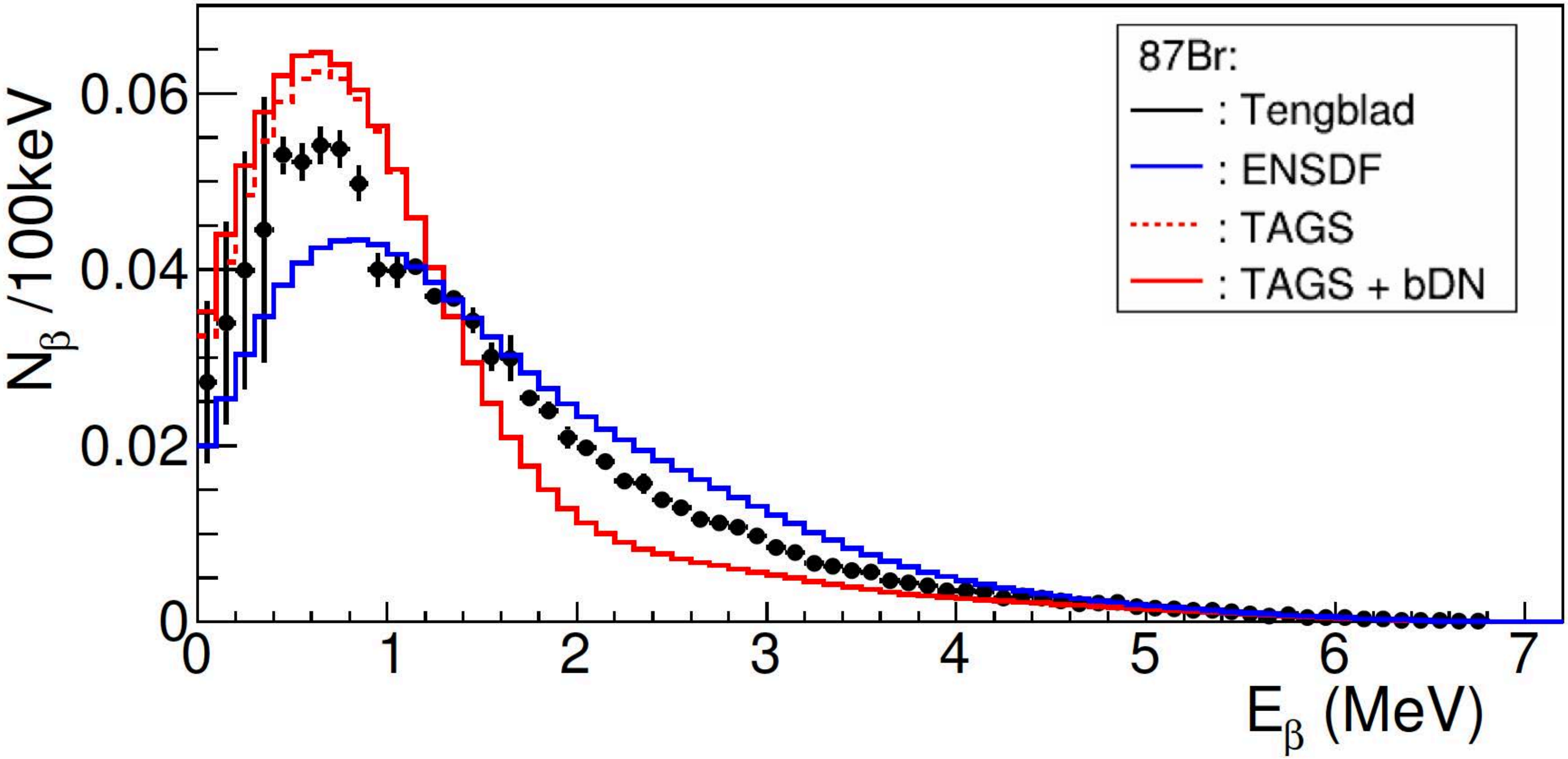
E. Valencia, et al, PRC95, 024320 (2017)

Tain et al. PRL 115, 062502

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

Comparison with the deduced beta spectrum (allowed shape)





E. Valencia, et al, PRC95, 024320 (2017)

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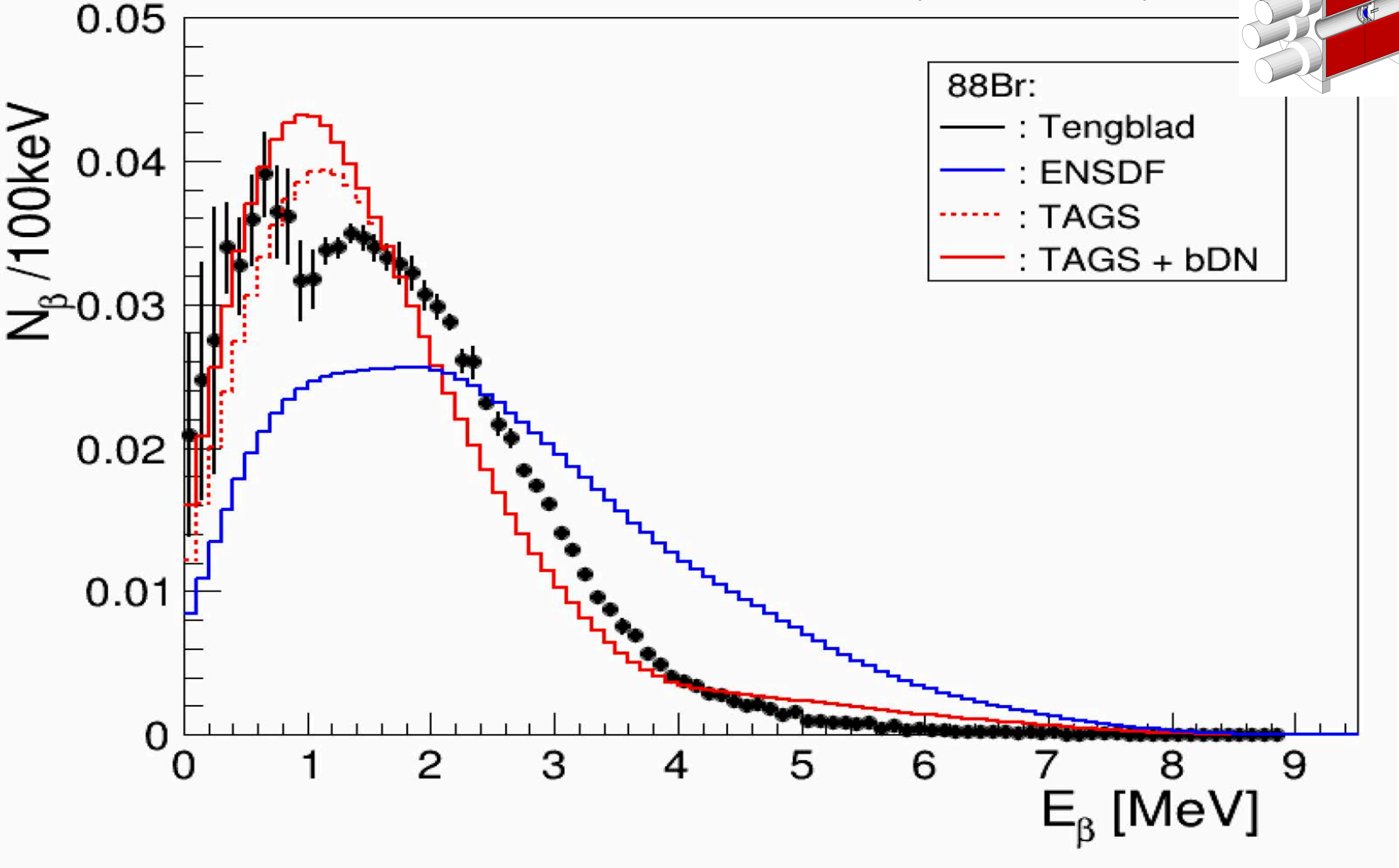
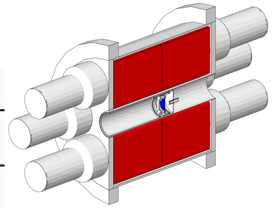
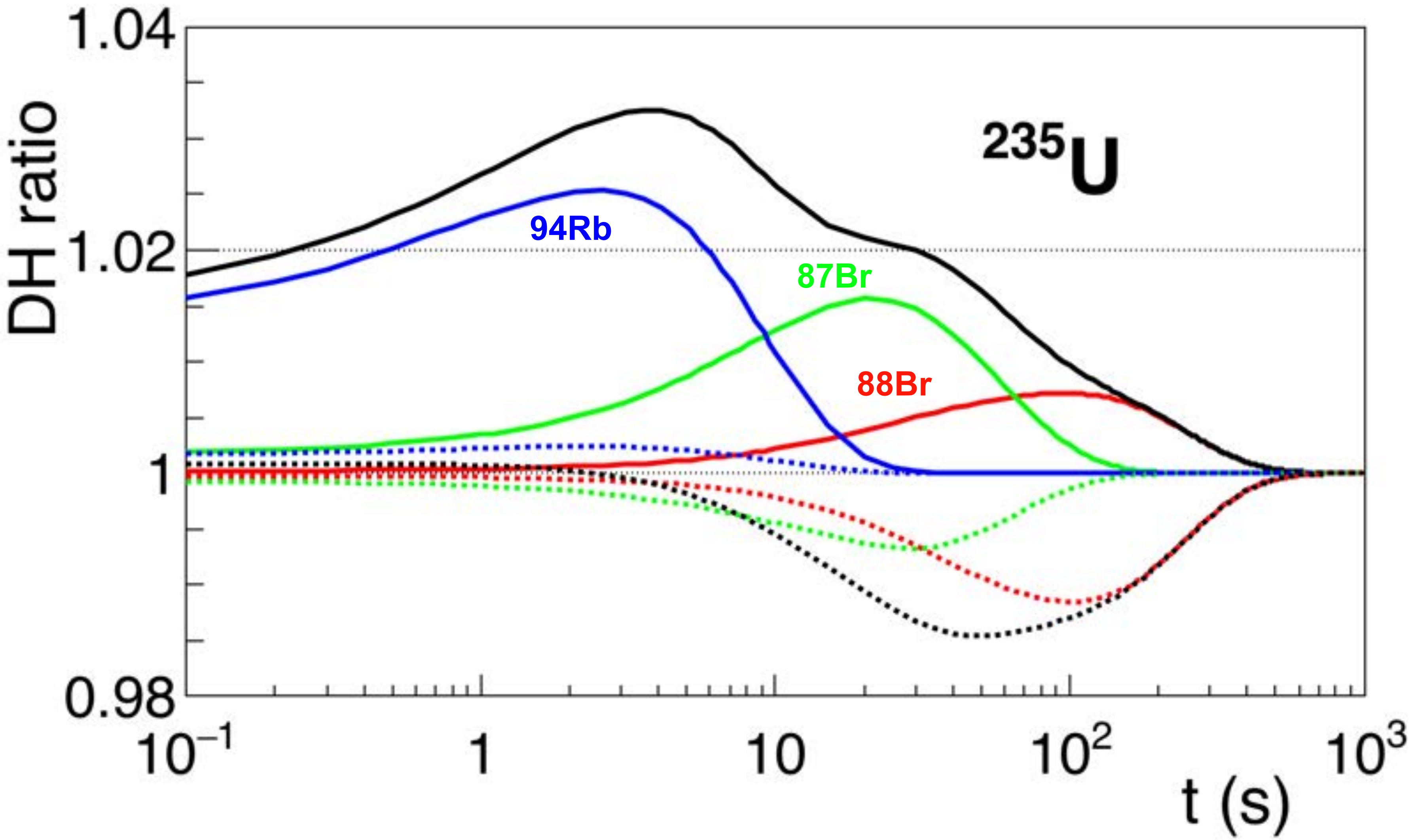
Comparison with the deduced beta spectrum (allowed shape)



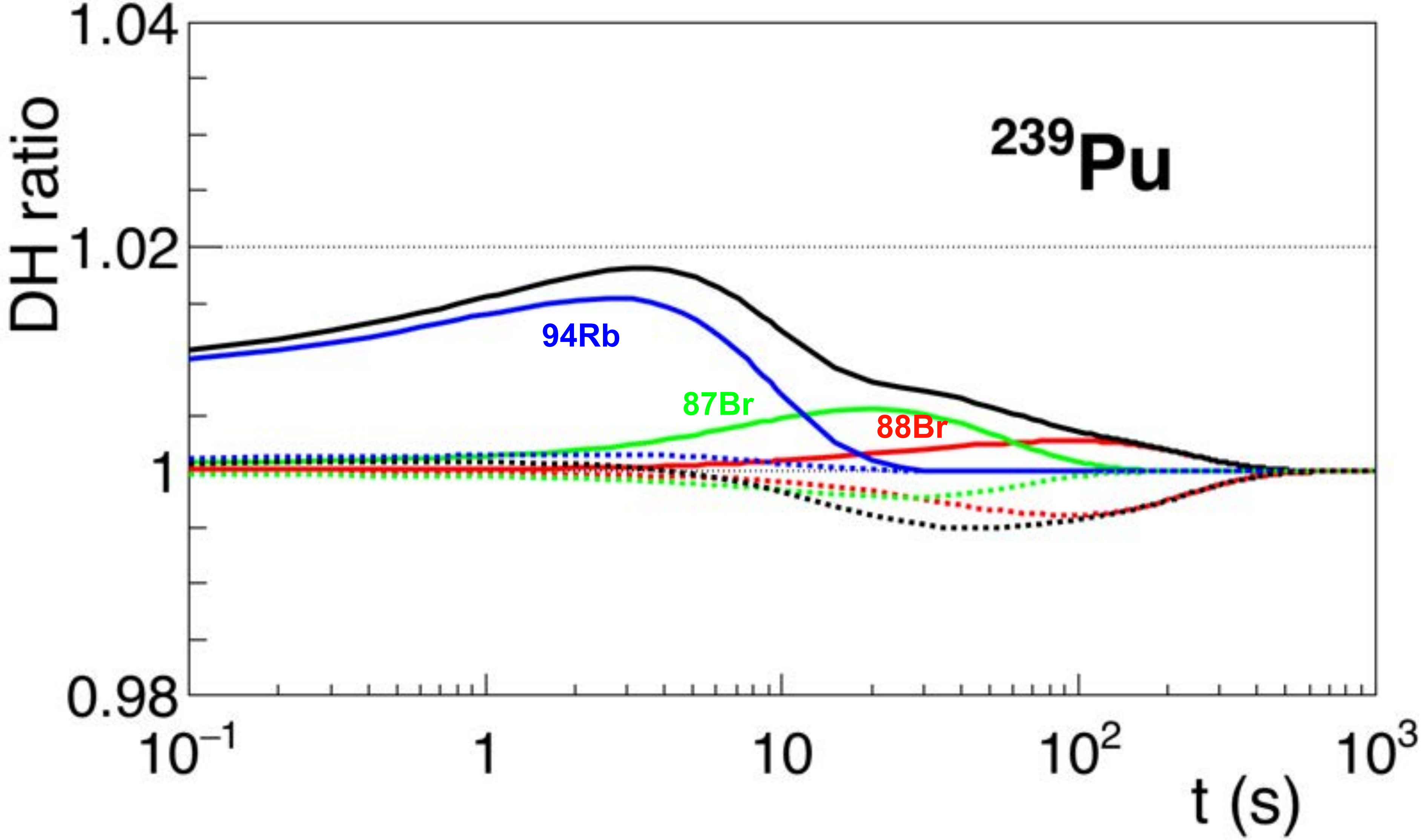


Decay heat impact of bdn emitters (replacing high resolution data by TAGS)



Calculations by A. Sonzogni

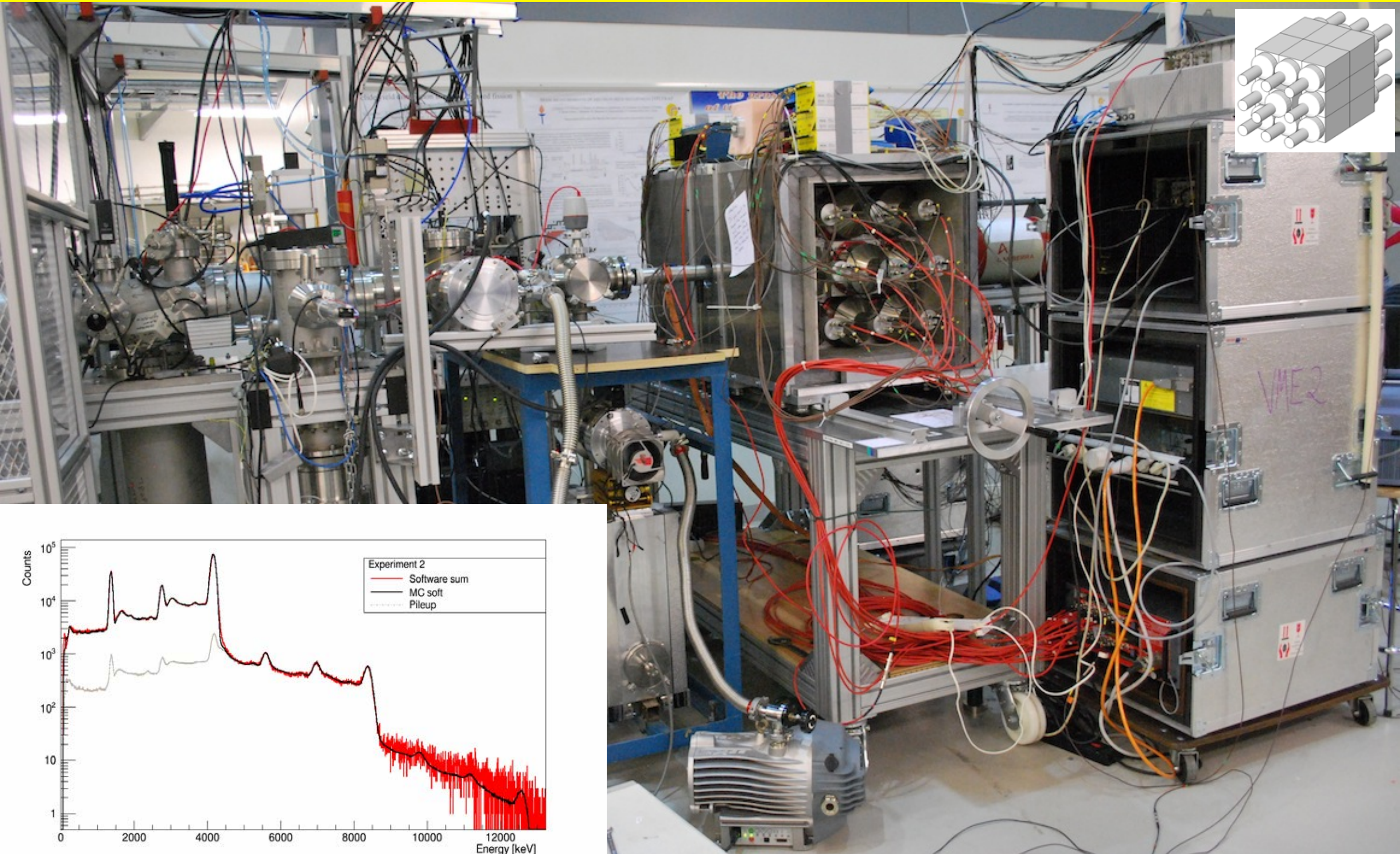
Decay heat impact of bdn emitters (replacing high resolution data by TAGS)



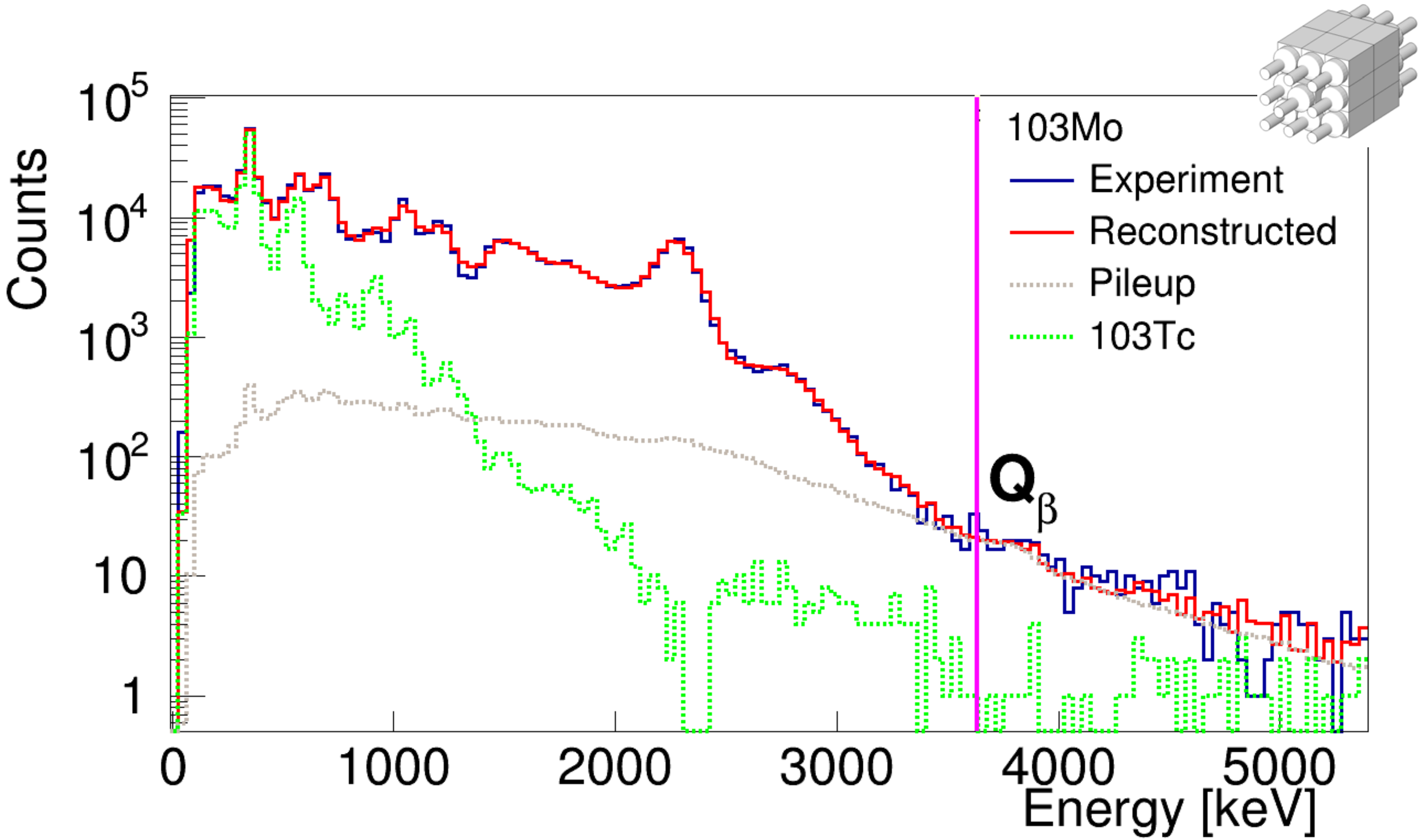
Calculations by A. Sonzogni

DTAS at Jyväskylä (Feb. 2014)

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

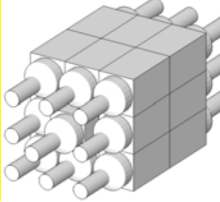


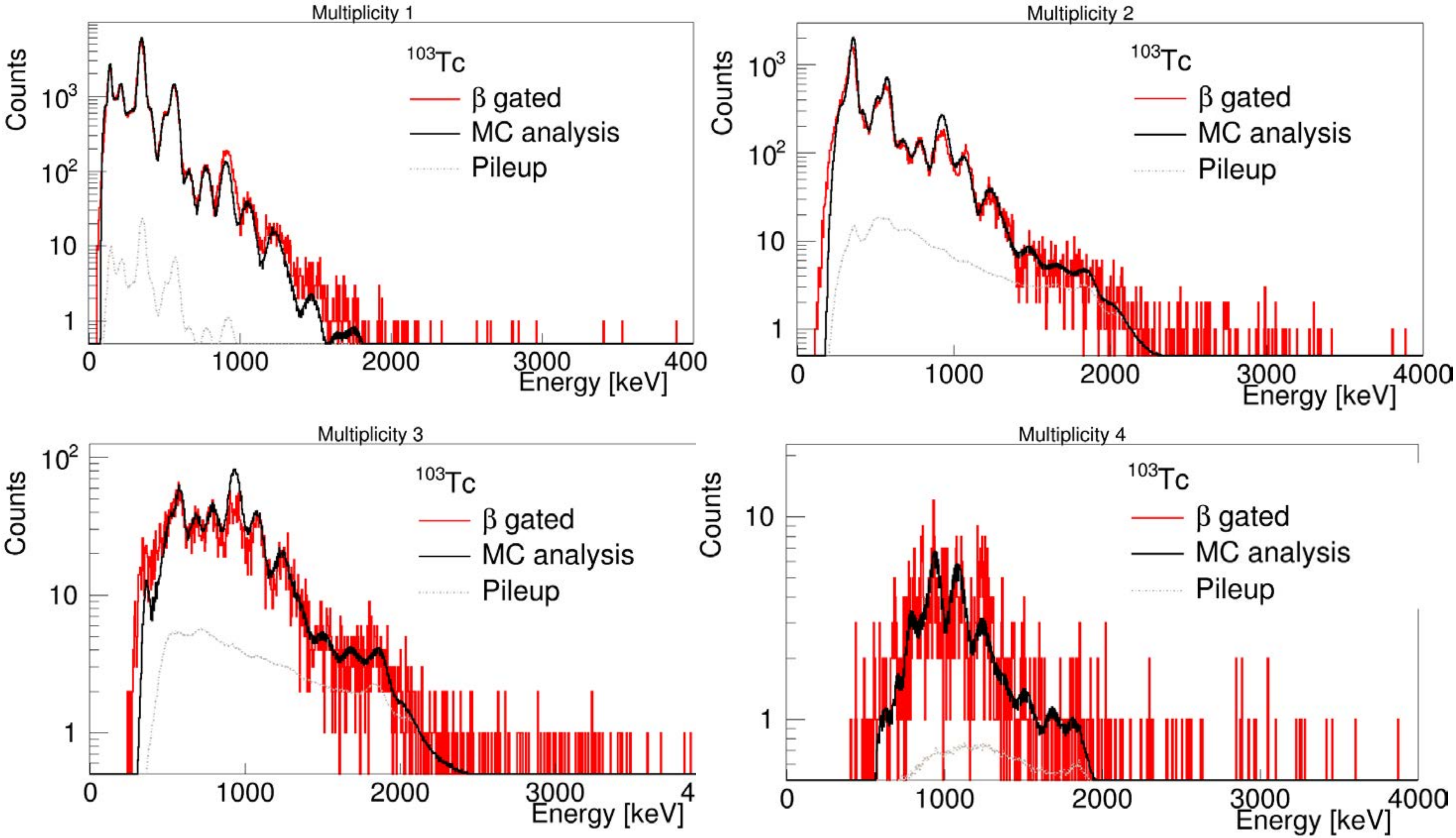
Analysis of 103Mo decay (preliminary)



Analysis by V. Guadilla, V. Guadilla PhD Thesis

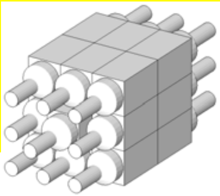
Analysis of 103Mo decay
(preliminary)

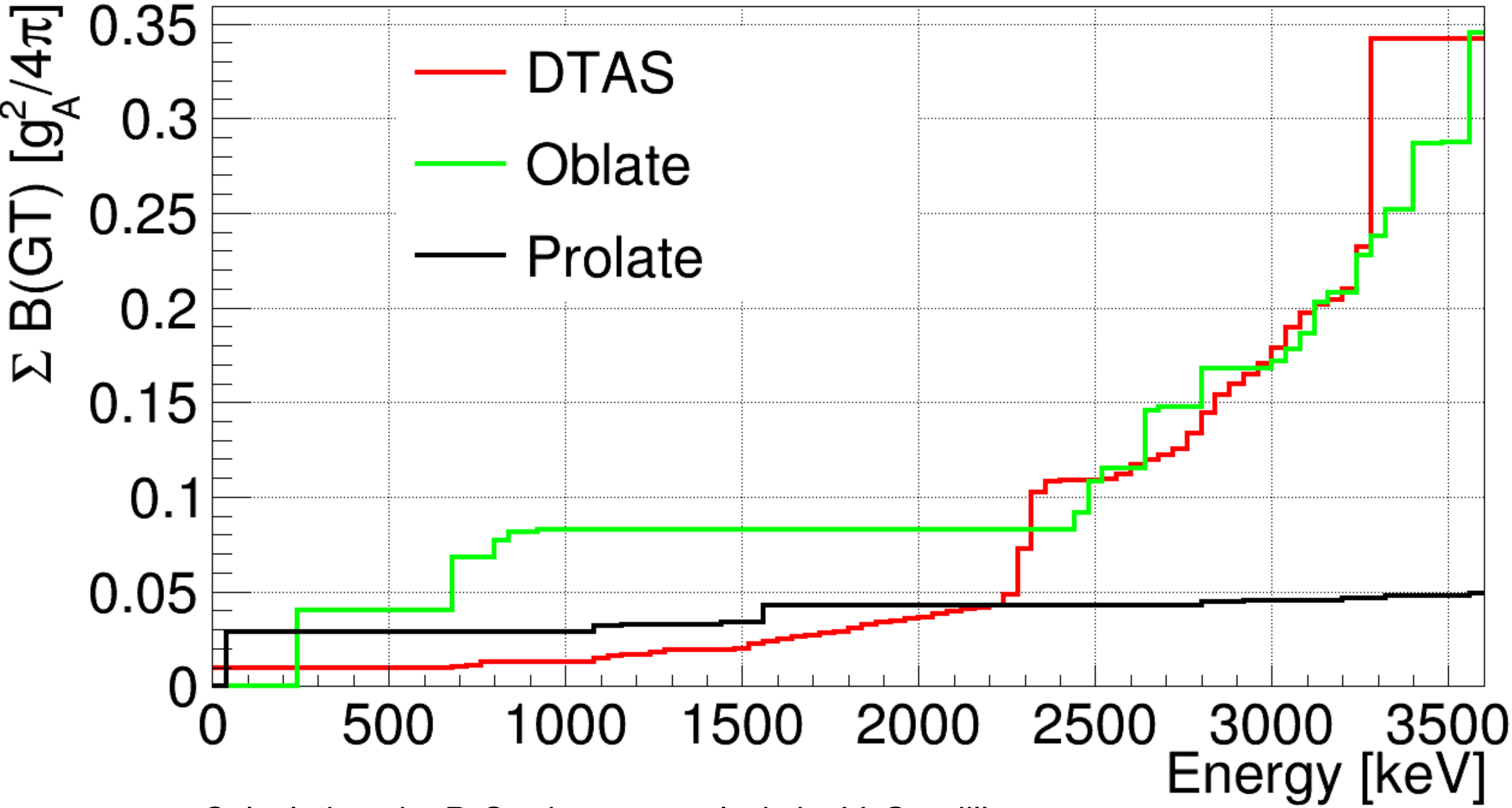




Analysis by V. Guadilla, V. Guadilla PhD Thesis

Comparison with theory (preliminary)

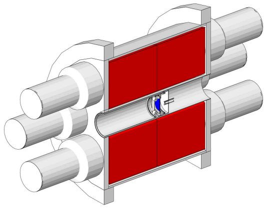




Calculations by P. Sarriguren, analysis by V. Guadilla

Other models: Moller ^{103}Mo prolate, ETSFI-Q ^{102}Mo oblate, ^{103}Mo prolate

Summary of the presented cases (mean Egamma)



Parent	ENDSF	TAS	Rudstam
86Br	3296	3822(54)	3420(500)
87Br	3009	3938(67)	3560(130)
88Br	2892	4609(78)	4290(180)
91Rb	2335	2669(29)	2335(33)
94Rb	1729	4063(66)	4120(250)
103Mo	-	1333*()	-

The INEL TAS value for 91Rb is 2707(76) keV

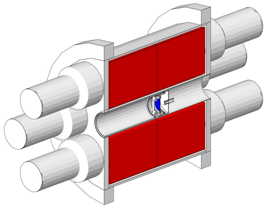
^{86}Br value by Oak Ridge group (4110 (411) keV)

Fijalkowska *et al*. Acta Phys. Polonica B 45, 545

*** Preliminary**

E. Valencia, et al, PRC95, 024320 (2017); S. Rice et al. PRC 96, 014320 (2017); V. Guadilla et al., in preparation

Summary of the presented cases (mean Ebeta)



Parent	ENDSF	TAS	Rudstam
86Br	1944	1670(28)	1920(20)
87Br	1599	1159(32)	1410(10)
88Br	2491	1665(38)	1680(10)
91Rb	1560	1388(22)	1560(30)
94Rb	2019	2329(32)	2830(70)
103Mo	-	485*()	-

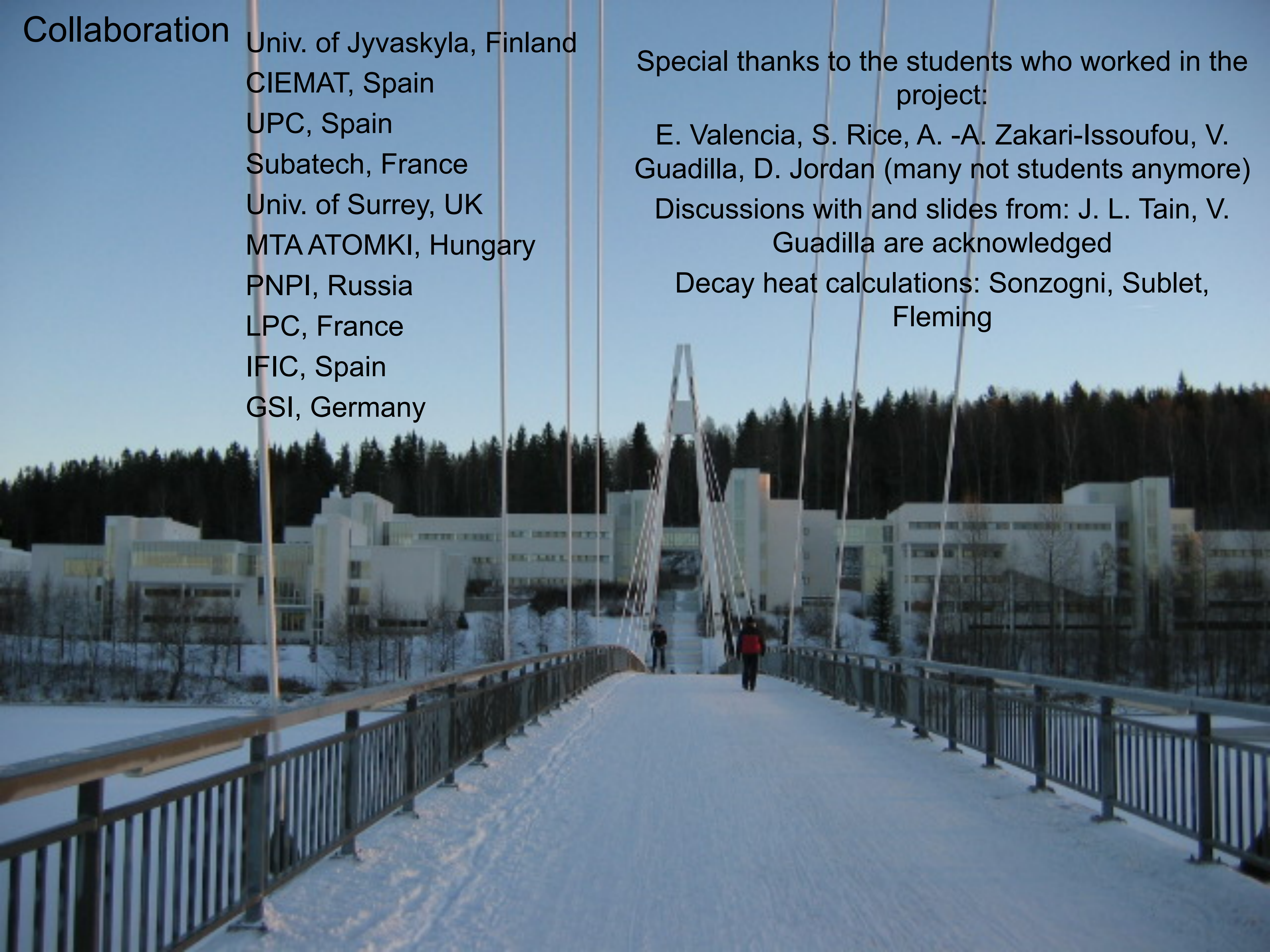
The INEL TAS value for 91Rb is 1367(44) keV

*** Preliminary**

E. Valencia, et al, PRC95, 024320 (2017); S. Rice et al. PRC 96, 014320 (2017); V. Guadilla et al., in preparation

Conclusions

- I hope I have shown that total absorption measurements can provide useful data for applications related to nuclear reactors, in particular for decay heat calculations (and for neutrino physics applications)
- We are running a research program related to this topic, that can also have an impact in nuclear structure and astrophysics (not discussed in detail here)
- Our presently studied cases will allow us to draw some conclusions about other available data sets (Greenwood, Rudstam) that are used in reactor applications. In particular the study of 91Rb shows the need for a renormalization of the mean gamma energies of Rudstam et al.



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

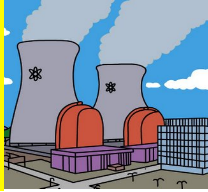
Special thanks to the students who worked in the project:

E. Valencia, S. Rice, A. -A. Zakari-Issoufou, V. Guadilla, D. Jordan (many not students anymore)

Discussions with and slides from: J. L. Tain, V. Guadilla are acknowledged

Decay heat calculations: Sonzogni, Sublet, Fleming

Examples of databases



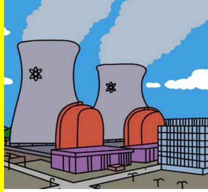
JEFF: Joint Evaluated Fission and Fussion File Nuclear Data Library
(Collaboration of the NEA Databank participating countries)
Current version JEFF 3.2
https://www.oecd-nea.org/dbdata/jeff/

ENDF: USA effort
Current version: ENDF/B-VII (ENDF/B-VIII.b5)
http://www.nndc.bnl.gov/exfor/endf00.jsp

JENDL: Japanese effort
Current version: JENDL-4.0
http://wwwndc.jaea.go.jp

See also CENDL, ROSFOND, etc.

The JENDL example (taken from an old slide)



JENDL FP Decay Data File 2011 and Fission Yields Data File 2011

(Ref. J. Katakura, JAEA-Data/Code 2011-025)

Table 2.1 Number of nuclides of various types

No. of Nuclides		Data Types
1284 (1229)		Total number of contained nuclides
142 (142)		Stable nuclides
1142 (1087)		Unstable nuclides or states
252 (197)		Isomeric states
	22 (8)	Second isomeric states
1102 (1053)		Gamma spectra
	683 (622)	Discrete gamma spectra
	509 (557)	Continuous gamma spectra
922 (899)		Beta spectra
	499 (467)	Discrete beta spectra
	486 (525)	Continuous beta spectra
156 (152)		Positron or EC spectra
5 (5)		Alpha spectra

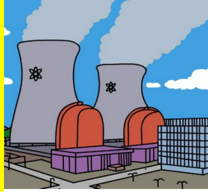
JENDL/FPD-2000 in parentheses

TAGS data is included

Potential Pandemonium nuclei supplemented by theory

Beta delayed neutron fraction suplemented by Kratz-Hermann formula when there is no data

Some selected publications



V. E. Schrock, Progress in Nuclear Energy, Vol 3, pp 125-156

A. Tobias, Progress in Nuclear Energy, Vol 5, pp. 1-93

K. Tasaka, J. Katakura, Nucl. Data for Science and Technolgoy (1988 MITO) pp. 819-826

M. Akiyama, et al. Progress in Nuclear Energy, Vol 32, pp. 53-60

Y. Ohkawachi, A. Shono, Journal of Nucl. Science and Technology, Supl. 2, p 493

A. Nichols, Lectures given at the Workshop on Nuclear Reaction Data and Nuclear Reactors: Physics, Design and Safety,Trieste, 25 February – 28 March 2002

A. Algora, J. L. Tain, Decay heat and nuclear data, Intech
https://www.intechopen.com/books/nuclear-reactors/decay-heat-and-nuclear-data

M. Fleming, J.-C. Sublet, CCFE-R(15)28/S1 Report

See also the IAEA reports indc-nds-0499, indc-nds-0577, indc-nds-0599, indc-nds-0676

T. Yoshida et al. extensive work on application of Gross-Theory to substitute nuclear data