Beta decay studies for applications, nuclear structure and astrophysics

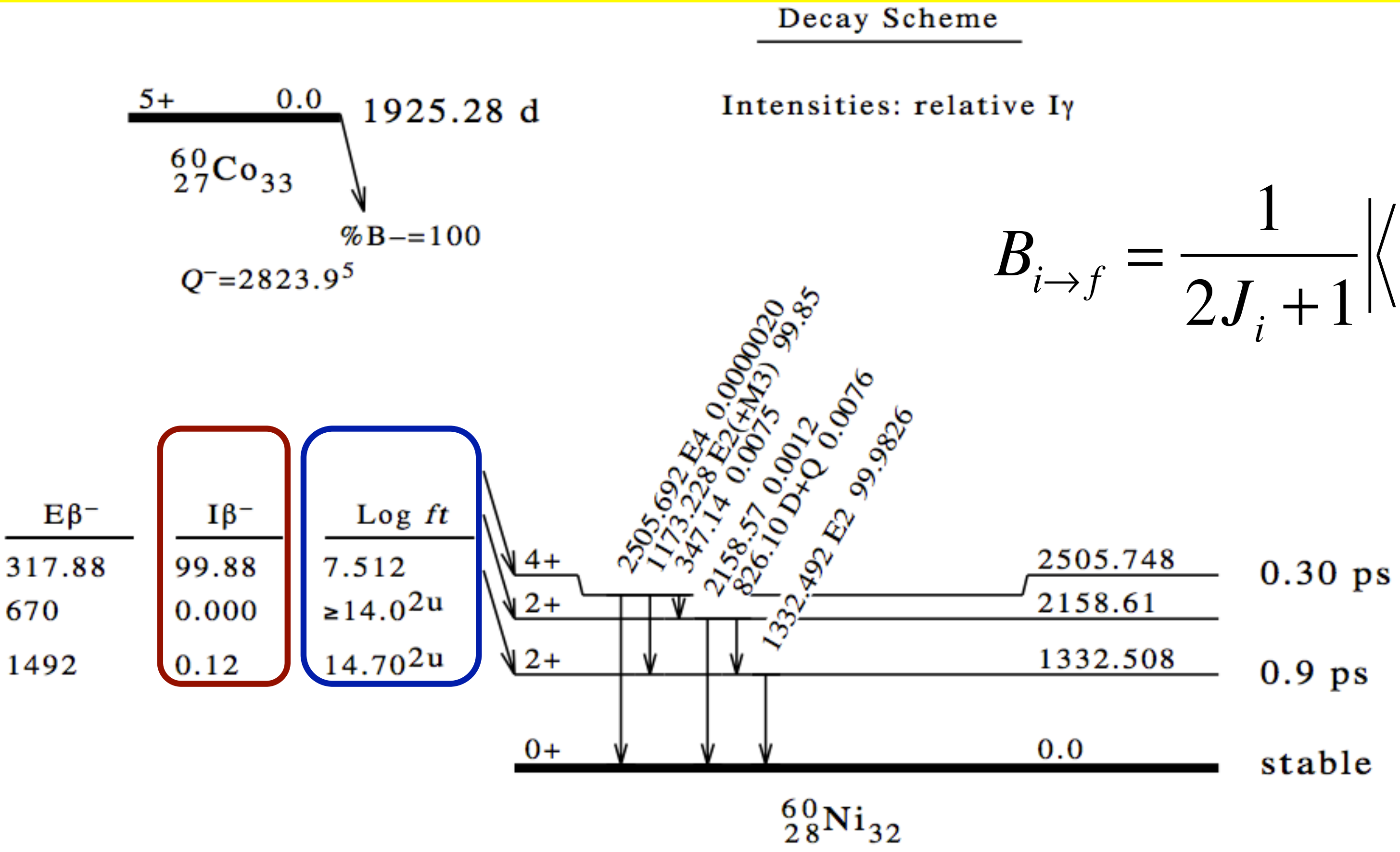
Alejandro Algora

IFIC, CSIC-University of Valencia, Spain

MTA ATOMKI, Debrecen, Hungary

SPES workshop, Milan, April 2015

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



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

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

Comparative half-life: ft

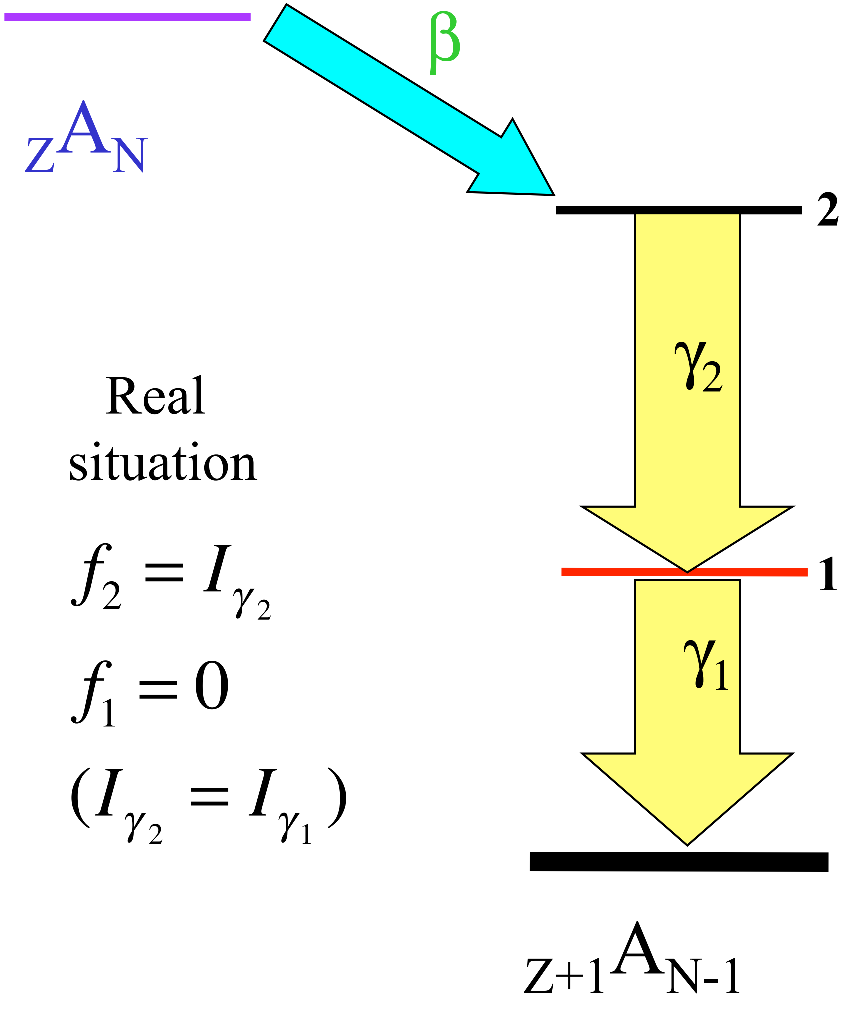
$$f(Z',Q) = const\cdot\int_0^{p_{\max}} F(Z',p)\,p^2(Q-E_e)^2\,dp$$

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

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

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

The problem of measuring the β-feeding

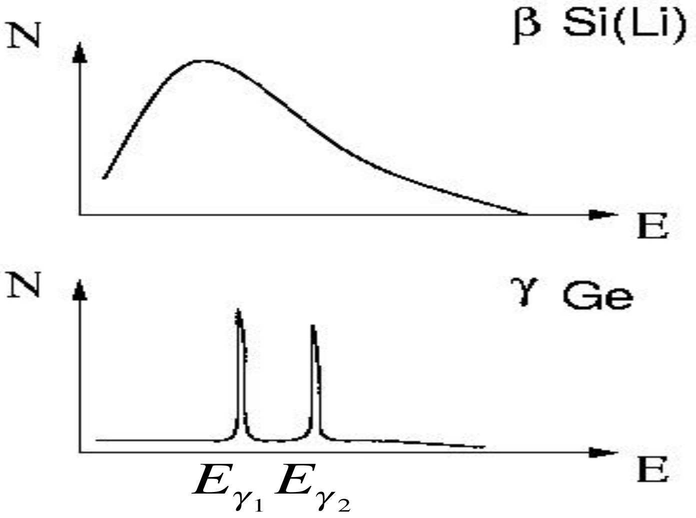


Real situation

$$f_2 = I_{\gamma_2}$$

$$f_1 = 0$$

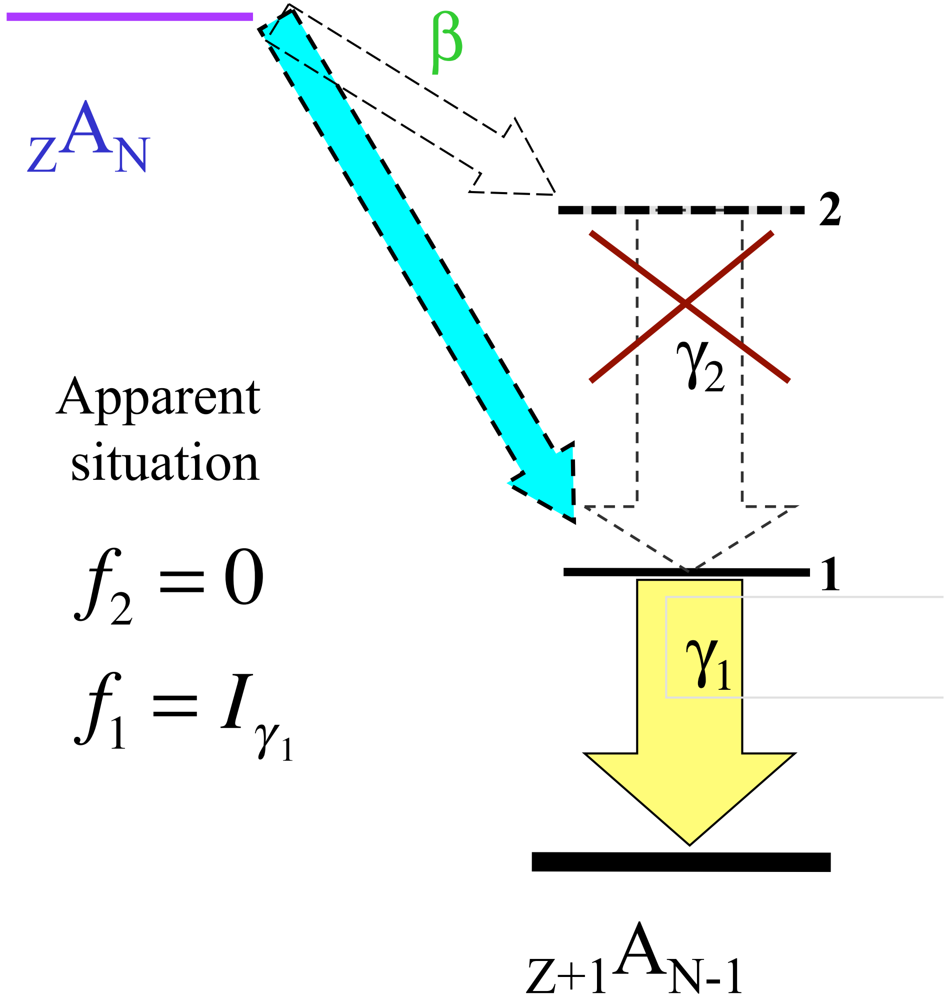
$$(I_{\gamma_2} = I_{\gamma_1})$$



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

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

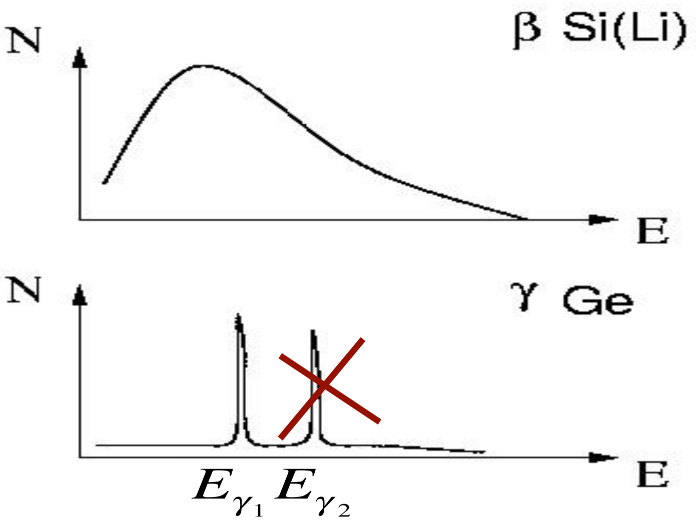
Experimental perspective:
the problem of measuring the β- feeding



Apparent situation

$$f_2 = 0$$

$$f_1 = I_{\gamma_1}$$



- What happens if we miss some intensity

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

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

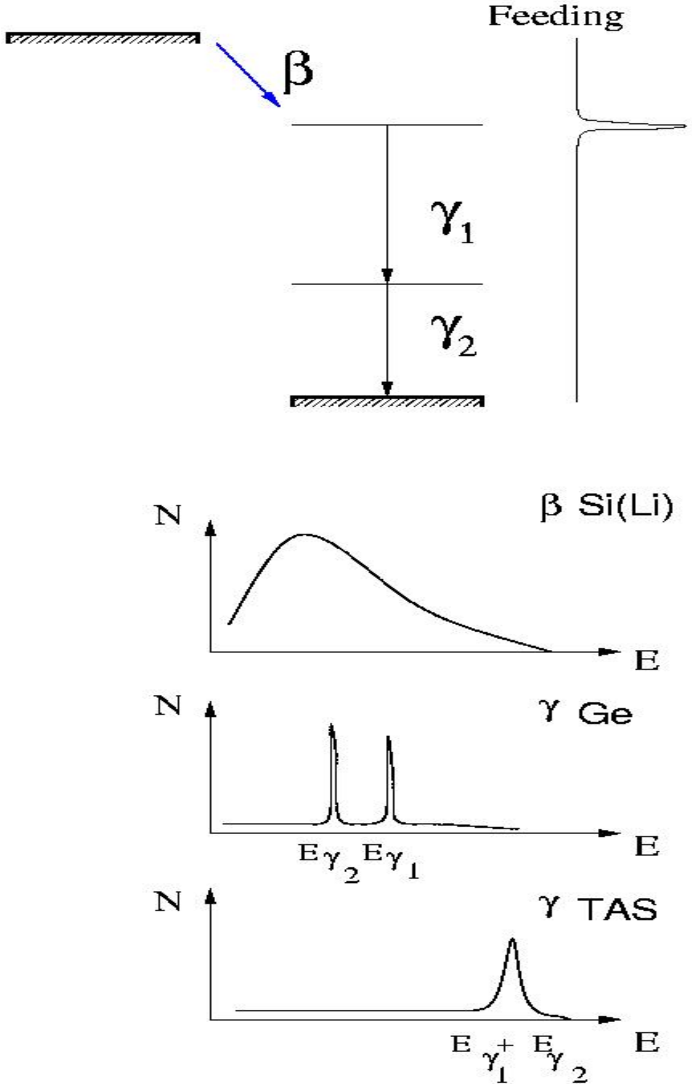
Pandemonium (The Capital of Hell)

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

John Martin (~ 1825)

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

TAGS measurements



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

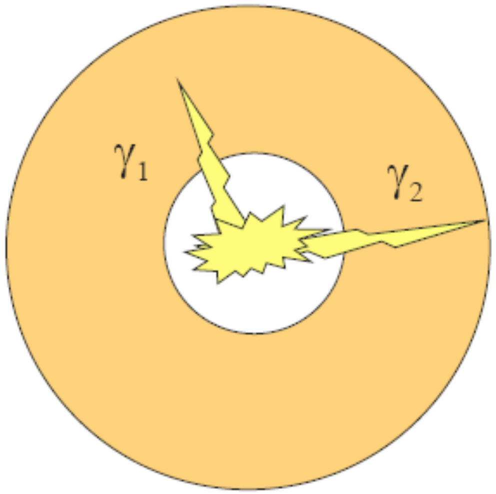
A TOTAL ABSORTION SPECTROMETER

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

A TAS is like a calorimeter!

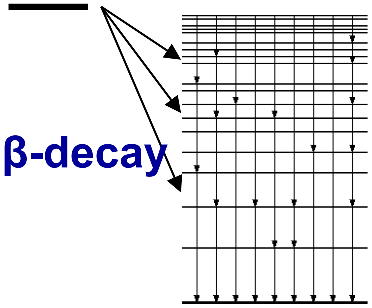
Big crystal, 4π

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



Analysis

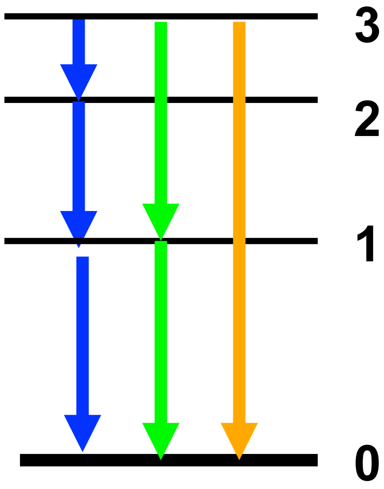
$$d_i = \sum_j R_{ij} f_j \quad or \quad \mathbf{d} = \mathbf{R} \cdot \mathbf{f}$$



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 **R** can be constructed by recursive convolution:

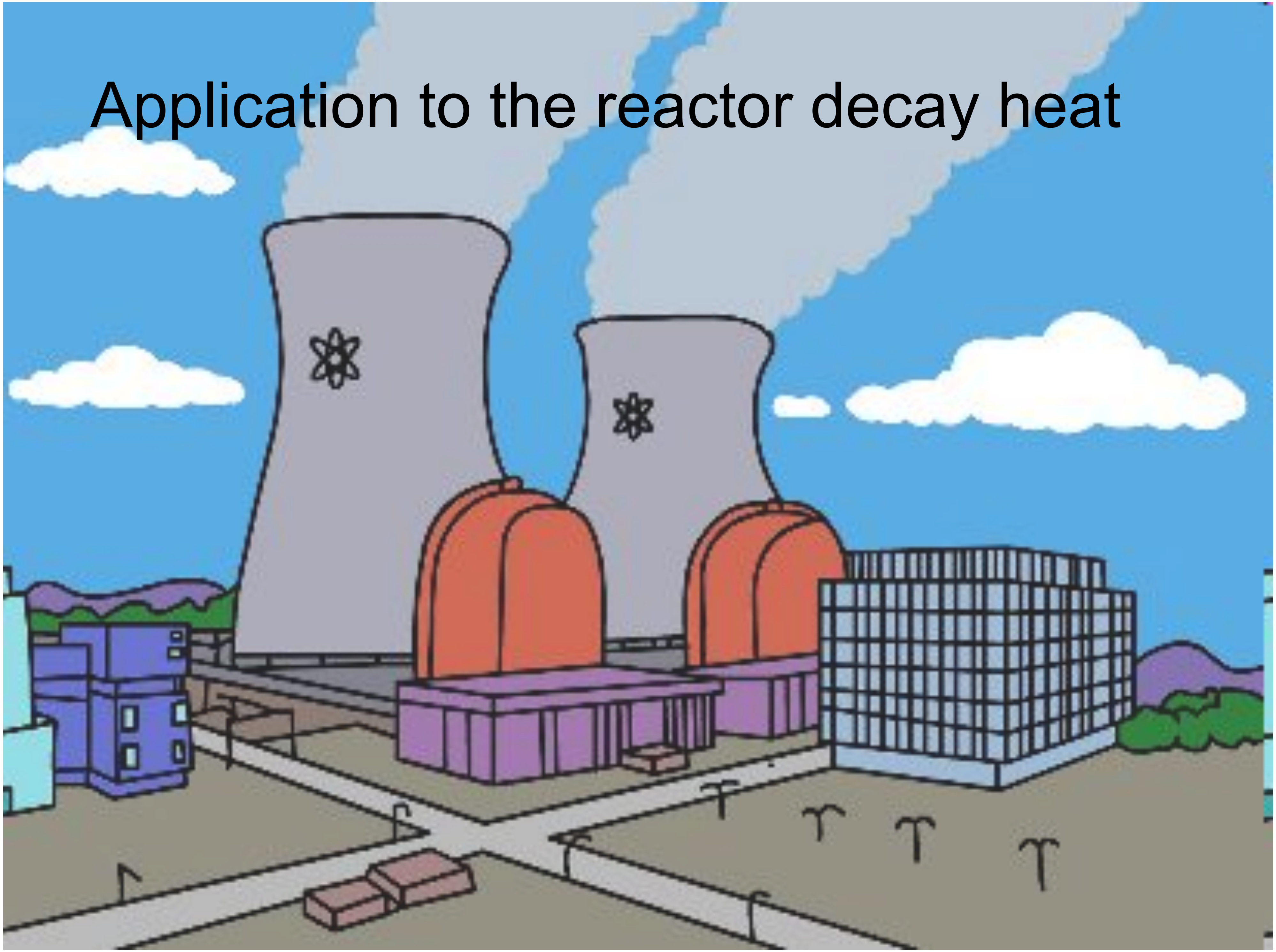
$$\mathbf{R_j} = \sum_{k=0}^{j-1} b_{jk} \mathbf{g_{jk}} \otimes \mathbf{R_k}$$



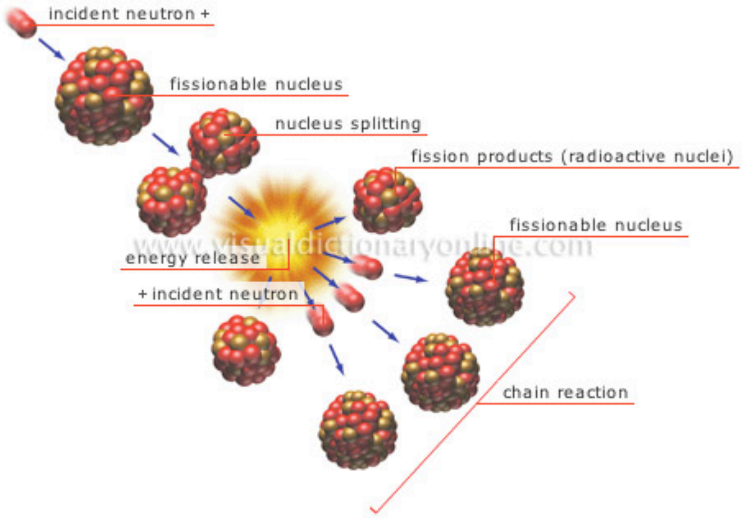
$\mathbf{g_{jk}}$: γ-response for *j* ➔ *k* transition
$\mathbf{R_k}$: response for level *k*
b_{jk}: branching ratio for *j* ➔ *k* transition

Mathematical formalization by Tain, Cano, et al.

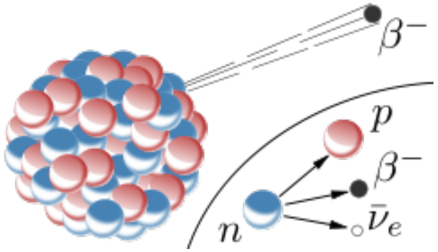
Application to the reactor decay heat



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)

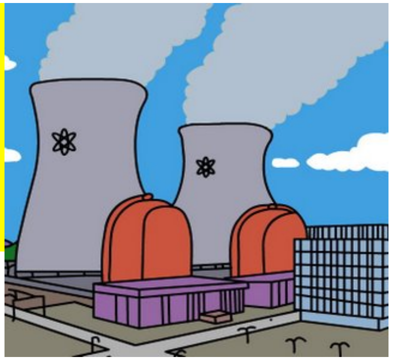


Energy released in the fission of ^{235}U

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

Decay heat: how to determine it ?



- Measure it (lacks flexibility and it is costly)
- Try to predict or calculate in the best way
  - Statistical method (the first solution)

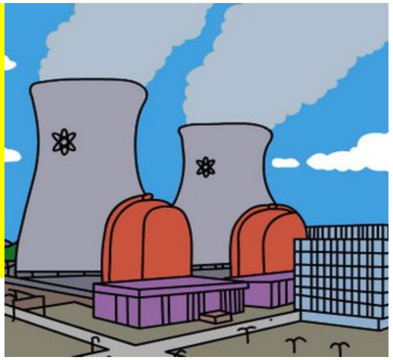
    Way and Wigner, Phys. Rev. 73 (1948) 1318

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

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

    later, Griffin, Phys. Rev. 134 (1964) B817
  - Summation calculations (next slide)

Decay heat: summation calculations



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

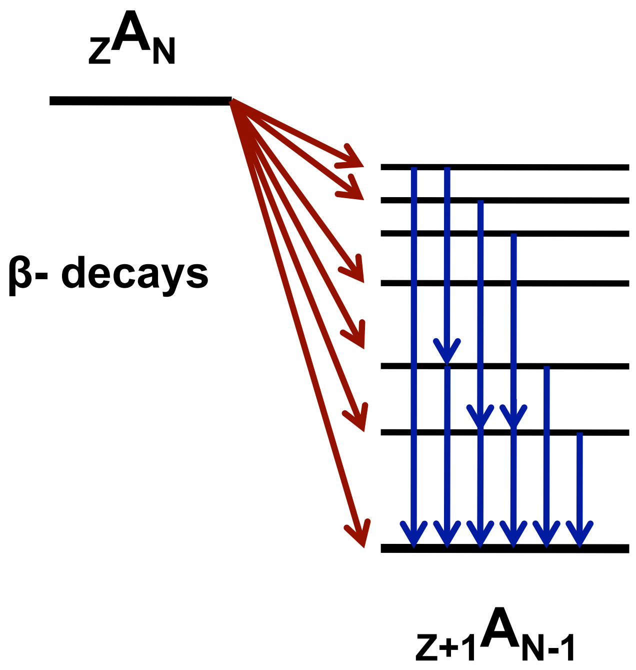
E_i	Decay energy of the nucleus i (gamma, beta or both)
λ_i	Decay constant of the nucleus i
N_i	Number of nuclei i at the cooling time t

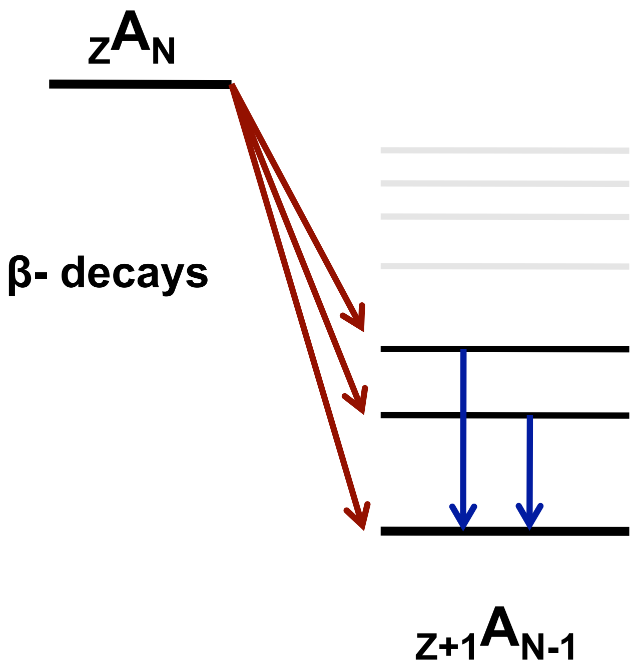
$$\lambda = \frac{\ln(2)}{T_{1/2}}$$

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)

Mean energies and Pandemonium

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





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

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

$\overline{E}_\beta$ overestimation

$\overline{E}_\gamma$ underestimation

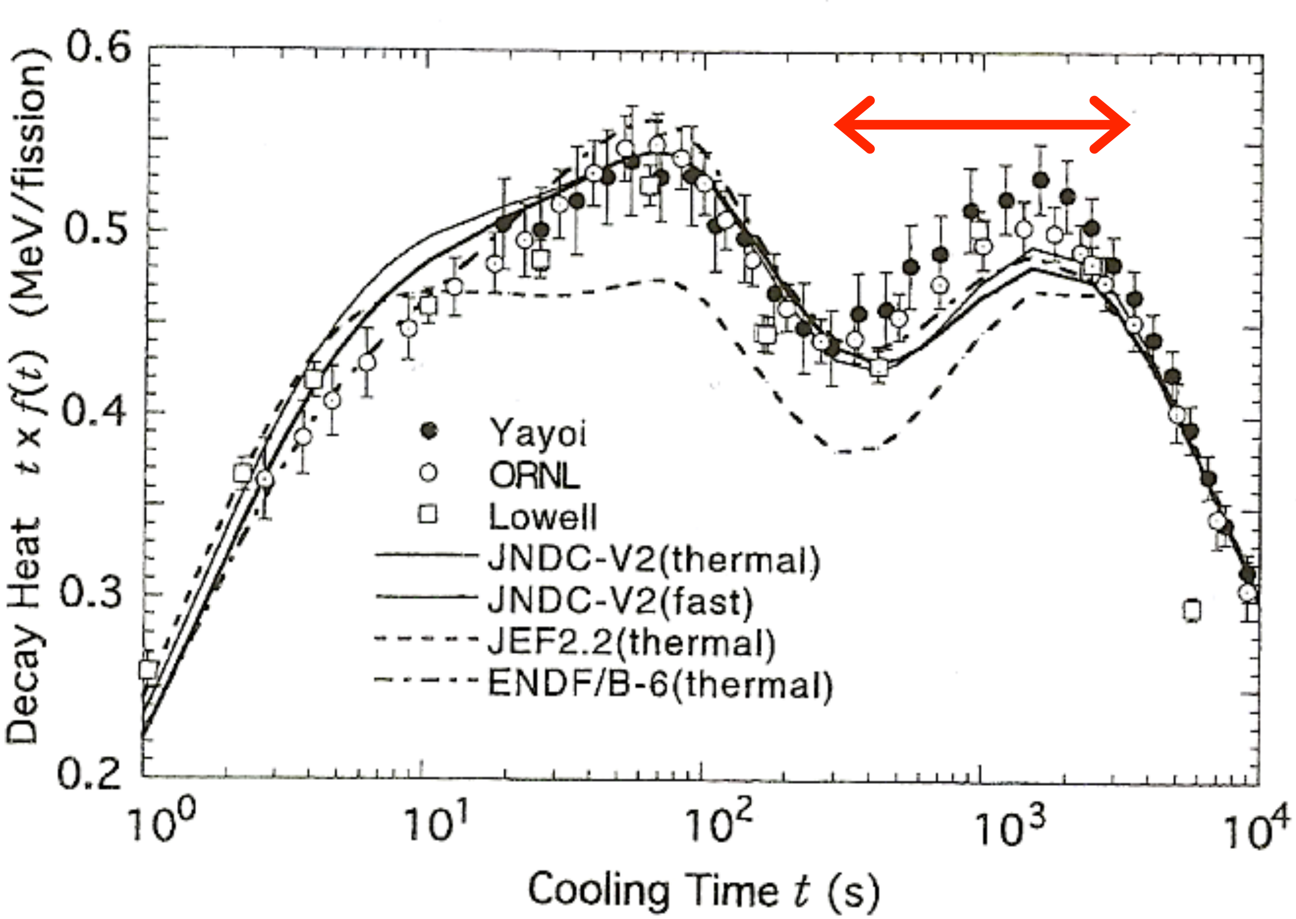
The beginning …

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

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

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

^{239}Pu example (γ component)

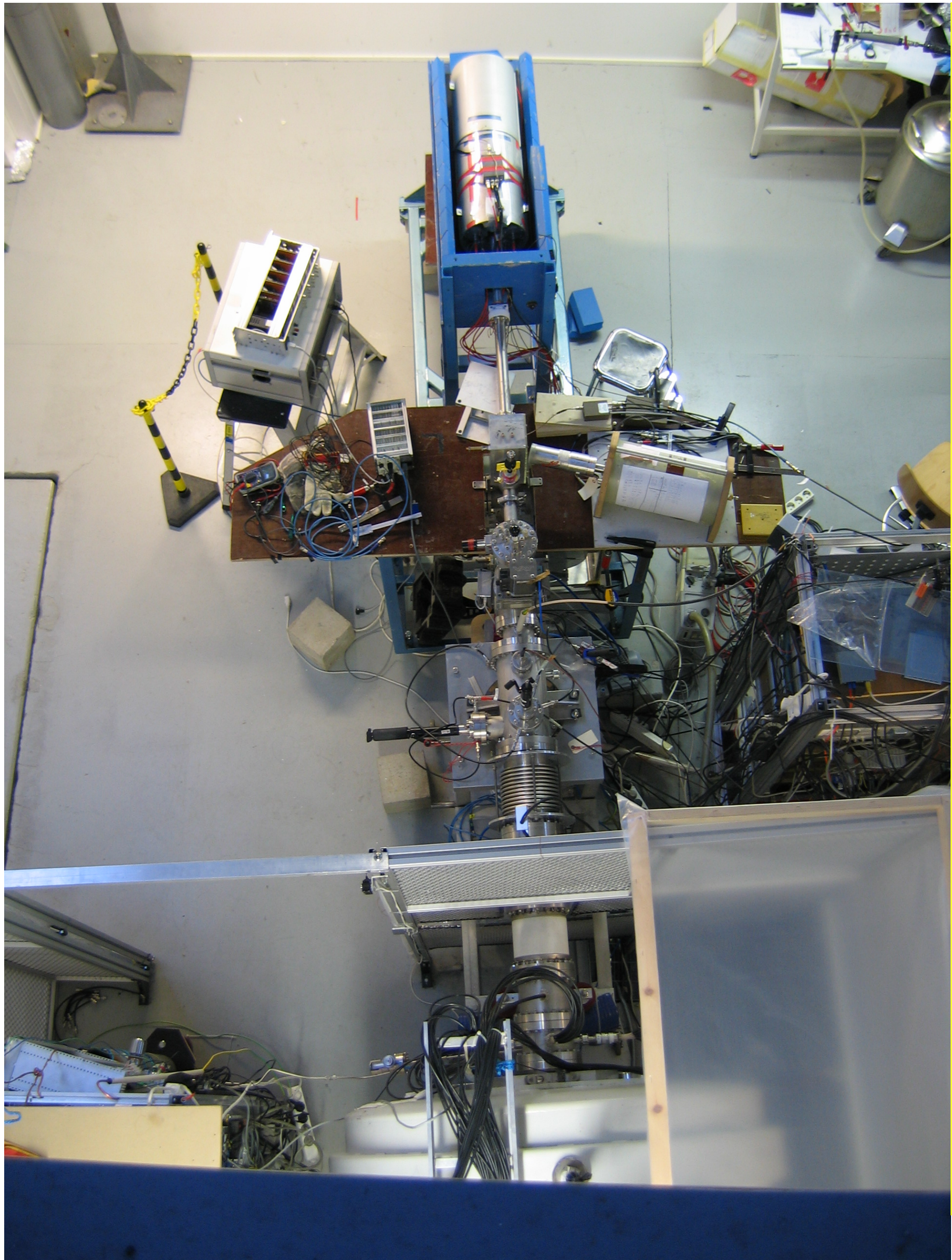


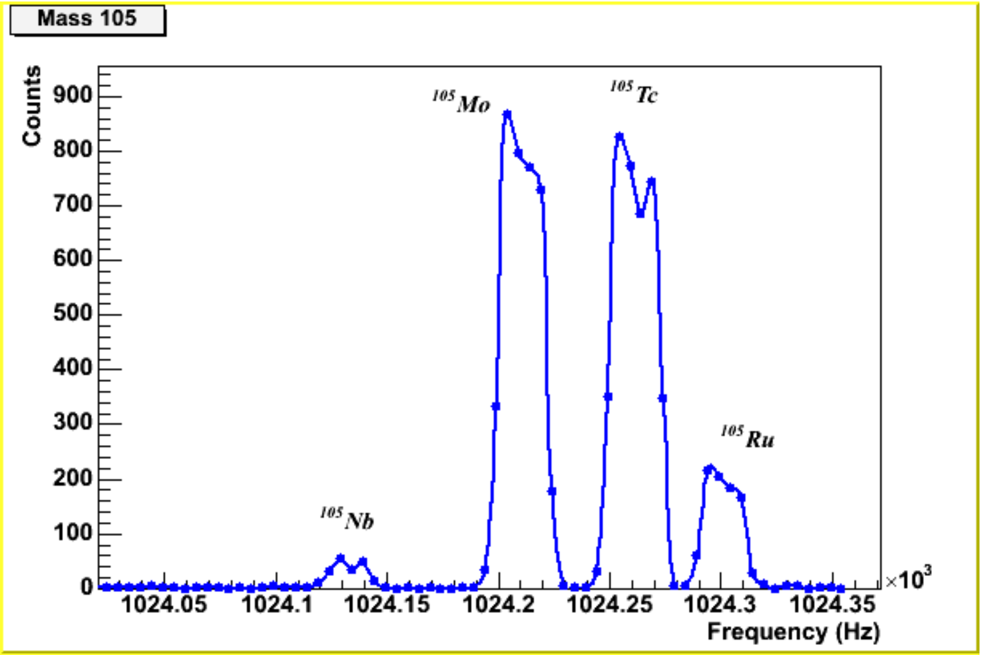
The “famous” list
WPEC-25 (IAEA working group)

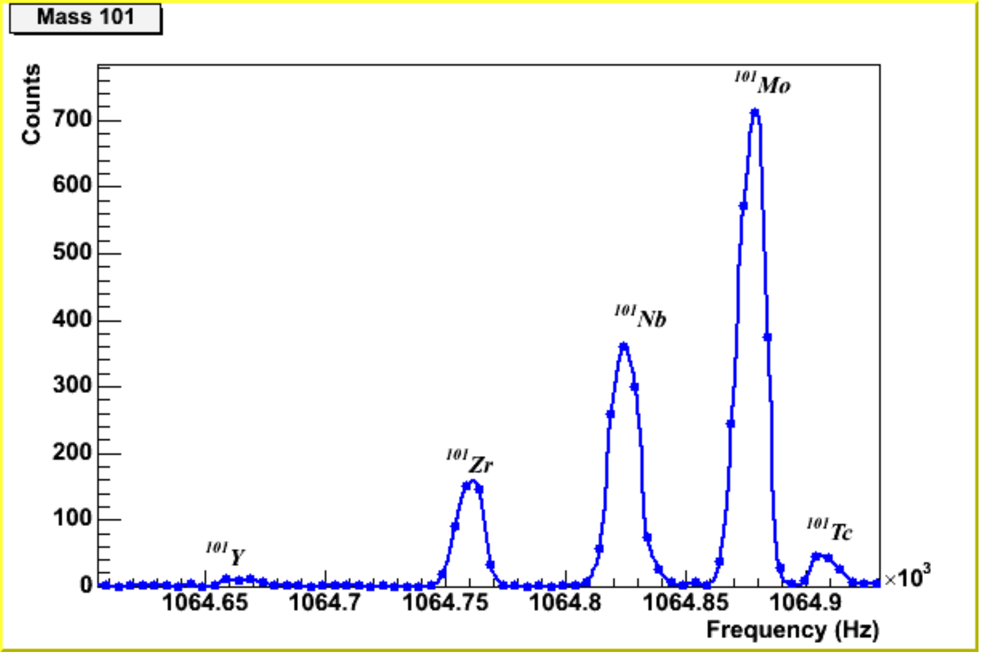
Radionuclide	Priority	Radionuclide	Priority	Radionuclide	Priority
35-Br-86	1	41-Nb-99	1	52-Te-135	2
35-Br-87	1	41-Nb-100	1	53-I-136	1
35-Br-88	1	41-Nb-101	1	53-I-136m	1
36-Kr-89	1	41-Nb-102	2	53-I-137	1
36-Kr-90	1	42-Mo-103	1	54-Xe-137	1
37-Rb-90m	2	42-Mo-105	1	54-Xe-139	1
37-Rb-92	2	43-Tc-102	1	54-Xe-140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

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

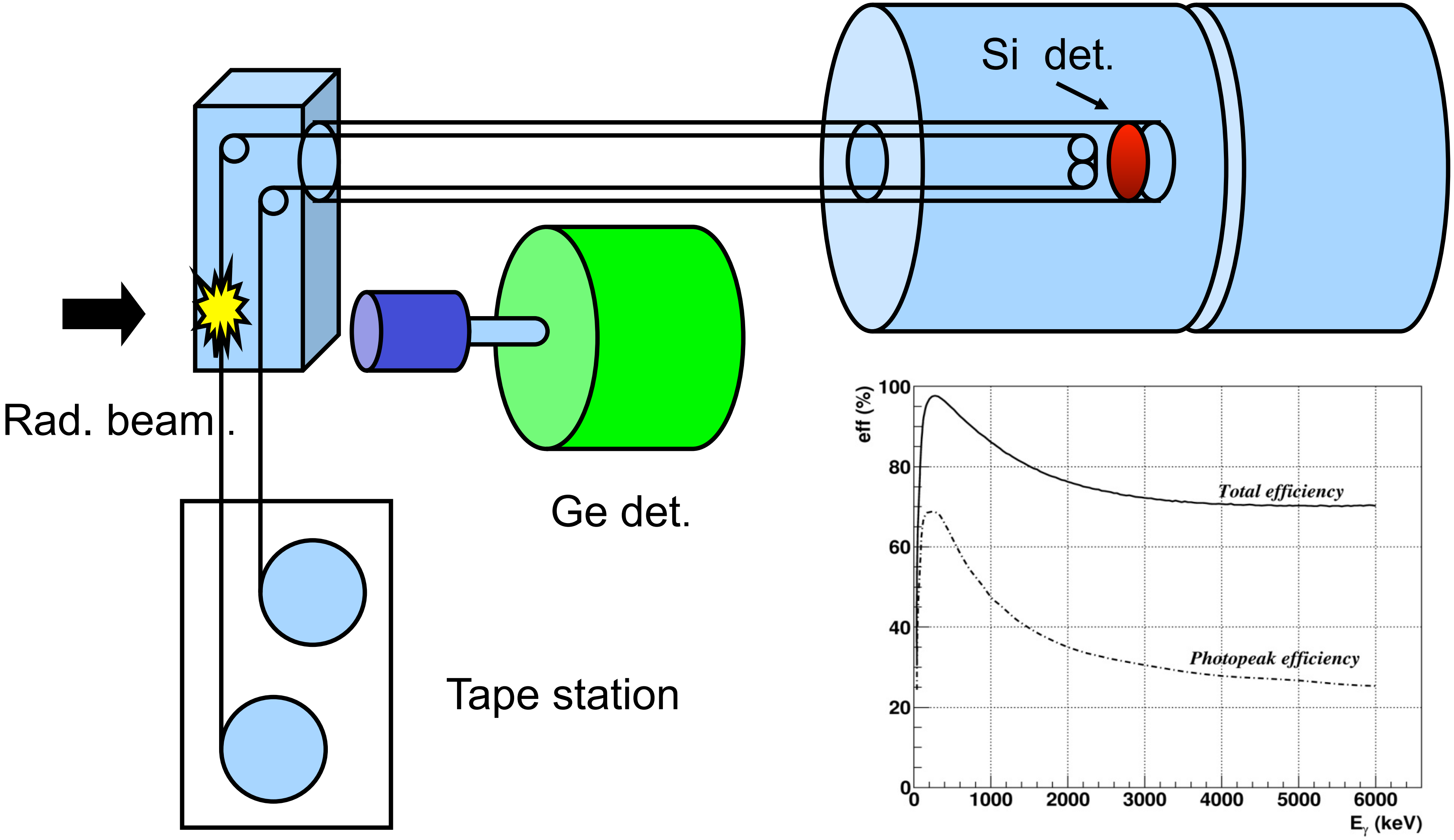
New feature: IGISOL + trap-assisted spectroscopy







TAS experimental setup at Jyväskylä (first and second experiment)

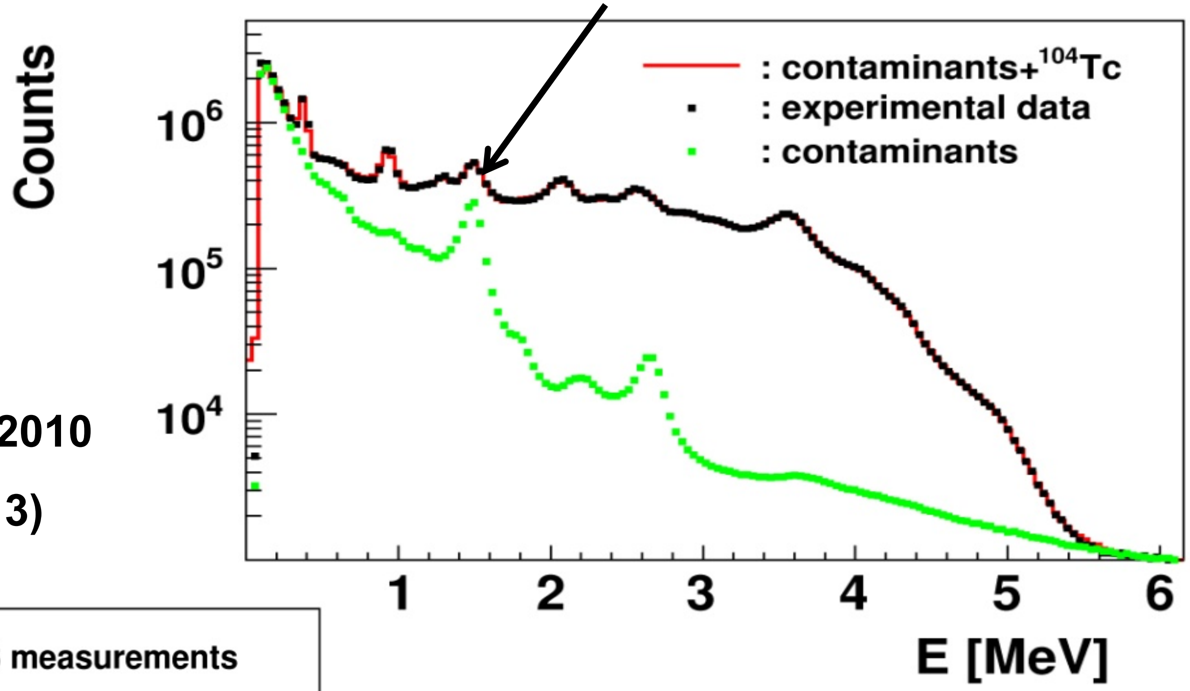


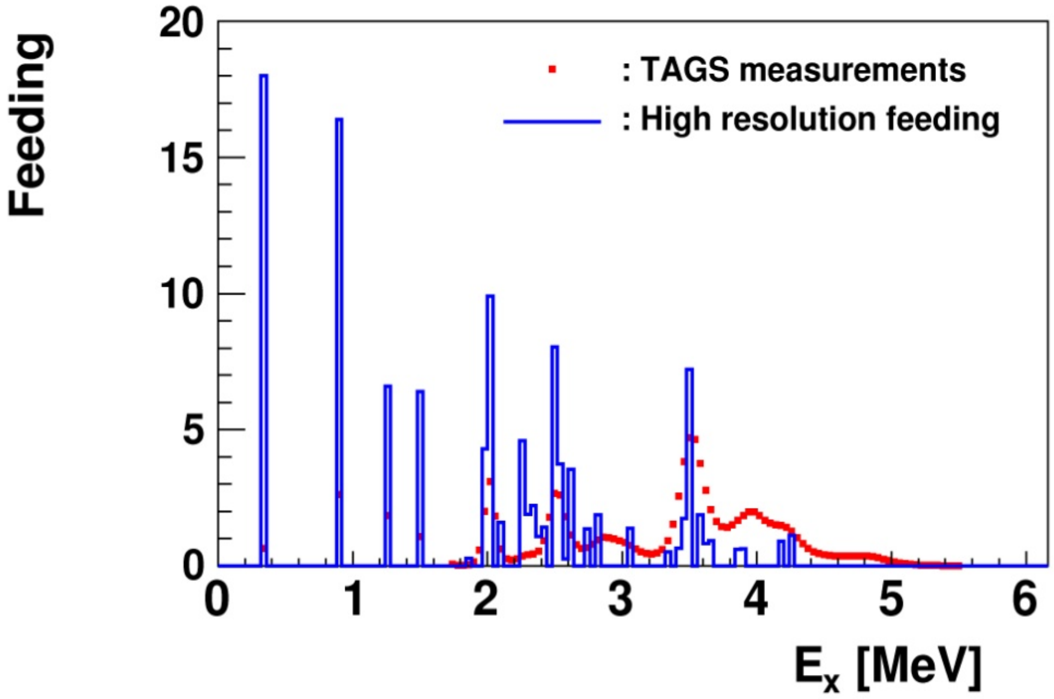
Results of the analysis for ^{104}Tc

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

D. Jordan, PhD Thesis, Valencia, 2010

D. Jordan, PRC 87, 044318 (2013)


d and R(b)*f^{final}



$T_{1/2}$ = 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

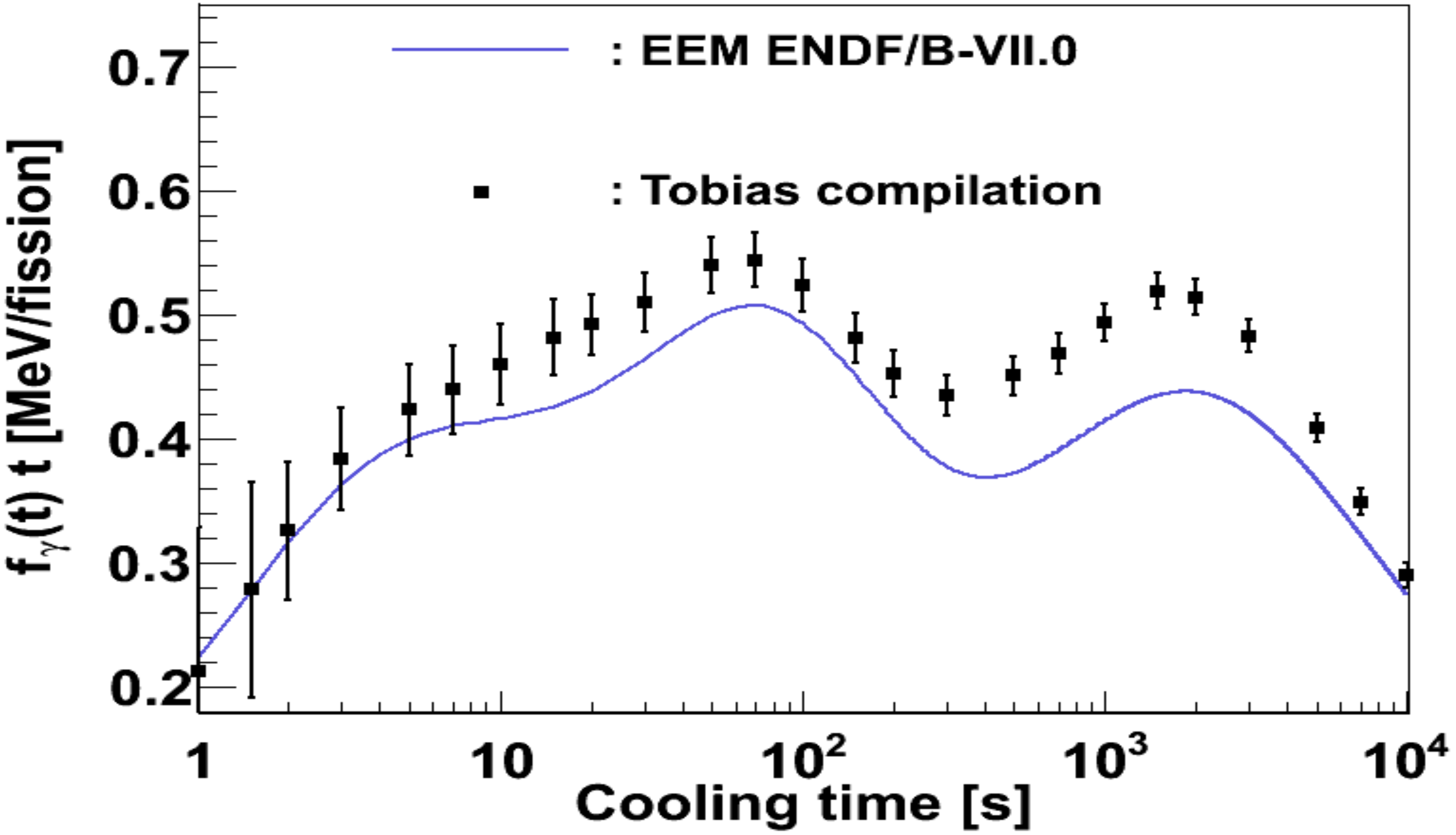
All results published up to now

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

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

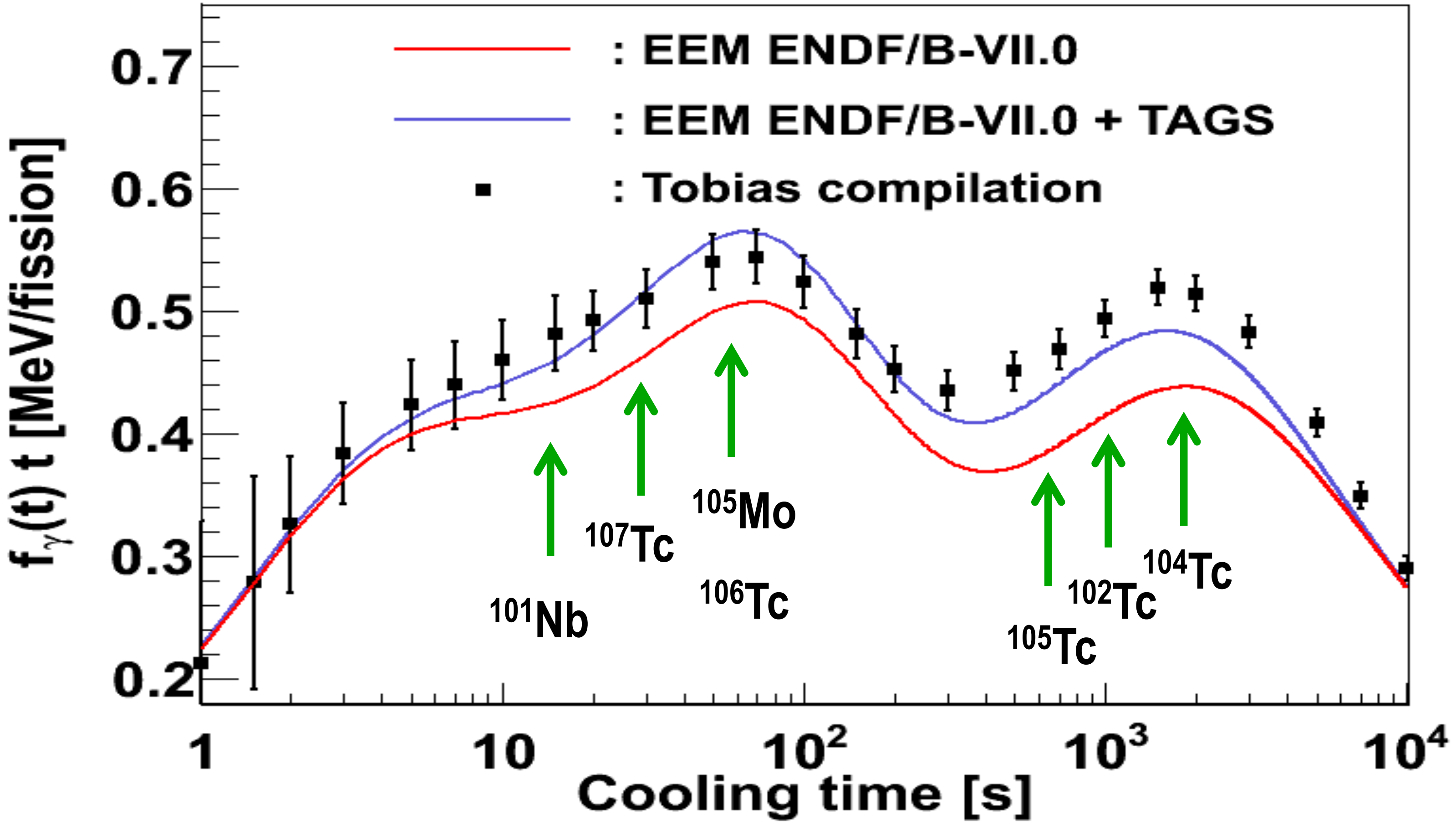
Impact of the results for ^{239}Pu: electromagnetic component

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



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



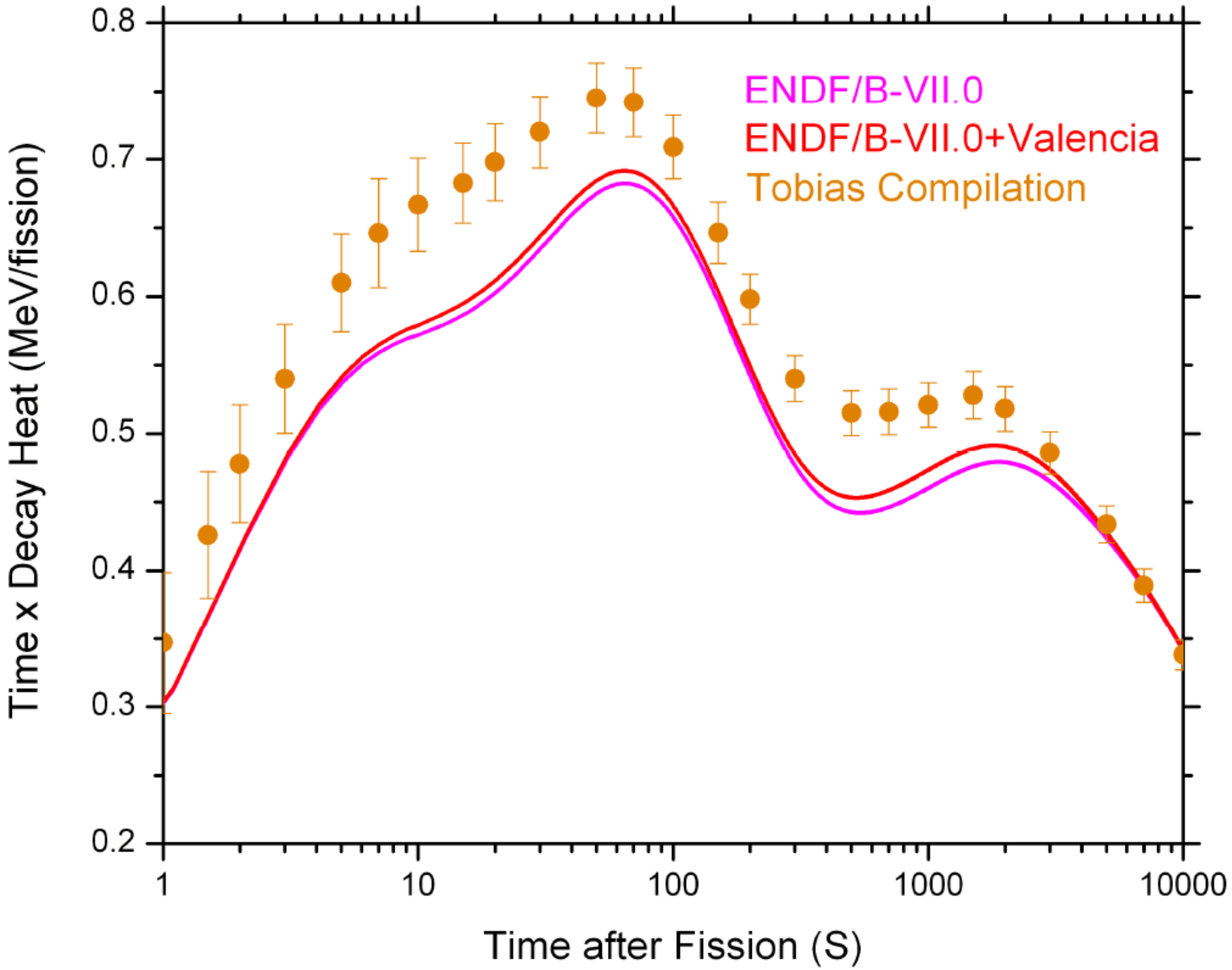
DH Courtesy A. Sonzogni

Algora, Phys. Rev. Letts. 105, 202505, PhD Thesis D. Jordan

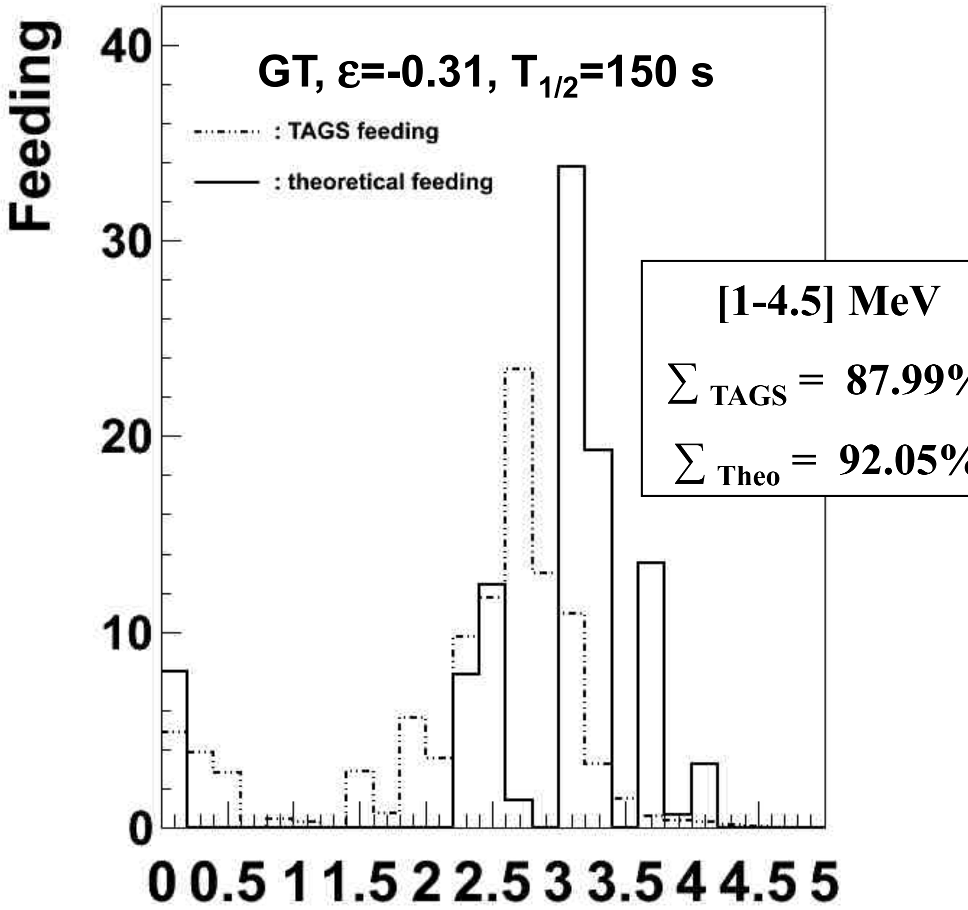
K. P. Rykaczewsky, Physics 3, 94 (2011)

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

Impact of the results for ^{235}U



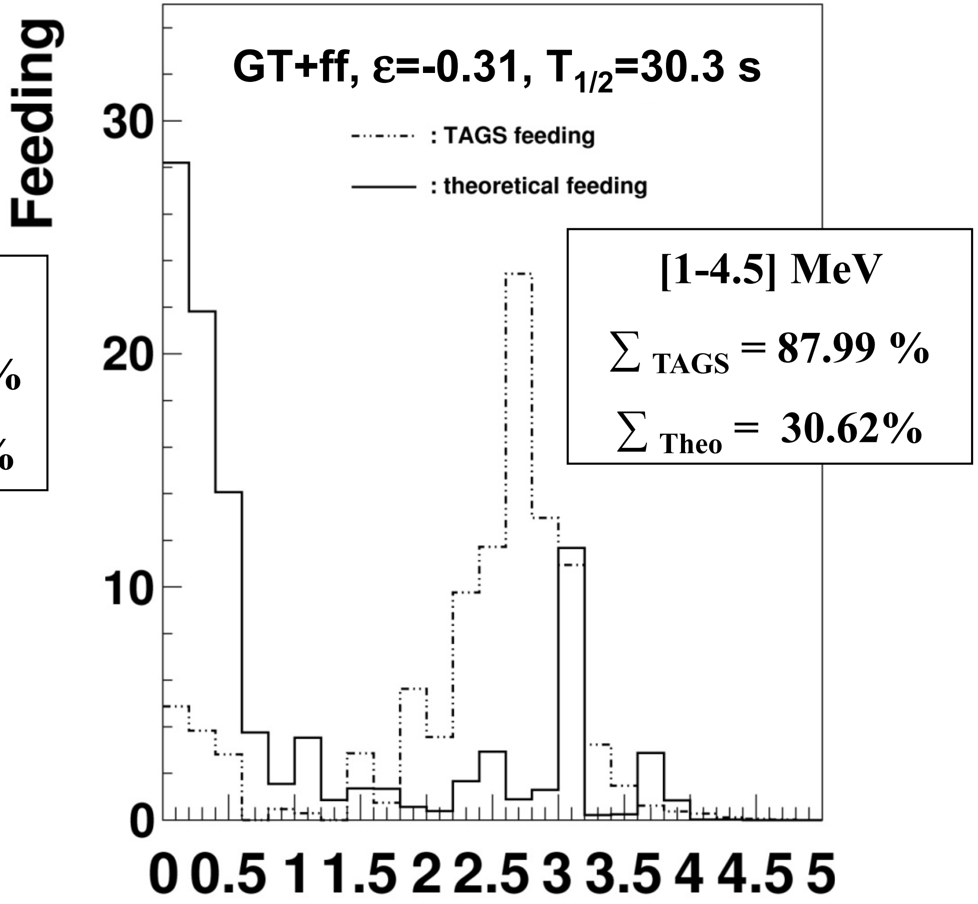
Results of QRPA calculations
^{105}Mo, $T_{1/2}$(exp) = 35.6 s



[1-4.5] MeV

$\sum_{\text{TAGS}}$ = 87.99%

$\sum_{\text{Theo}}$ = 92.05%



[1-4.5] MeV

$\sum_{\text{TAGS}}$ = 87.99 %

$\sum_{\text{Theo}}$ = 30.62%

[0-0.5] MeV

$\sum_{\text{TAGS}}$ = 11.51%

$\sum_{\text{Theo}}$ = 7.94%

E_x [MeV]

[0-0.5] MeV S

$\sum_{\text{TAGS}}$ = 11.51%

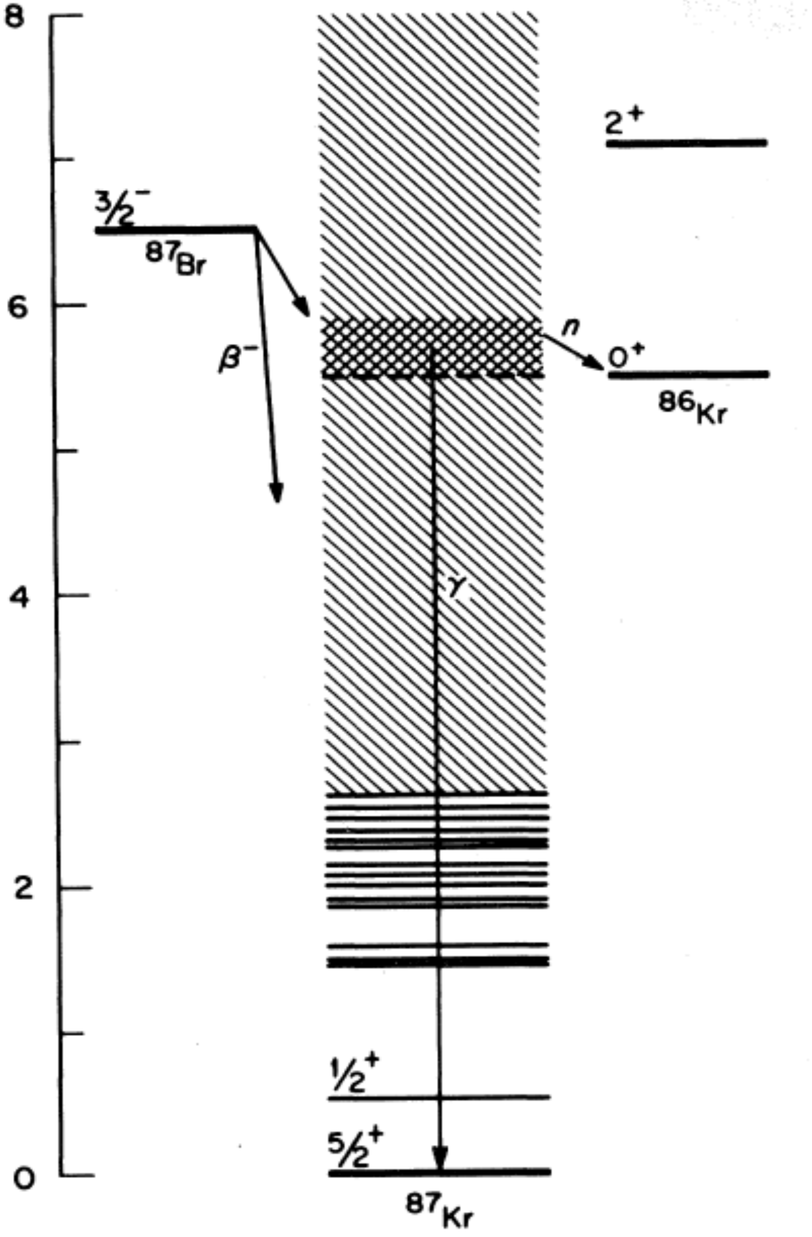
$\sum_{\text{Theo}}$ = 67.84 %

E_x [MeV]

Kratz *et al.*

P. Möller FRDM QRPA

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



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

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

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

Analysis of ^{87}Br

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

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

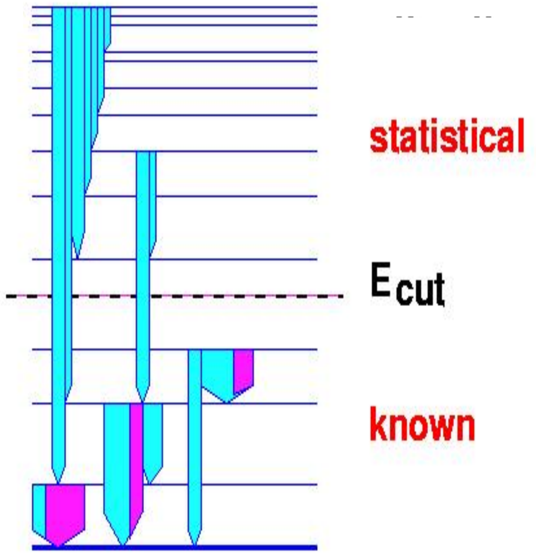
$$P\left(f_j | d_i\right) = \frac{P\left(d_i | f_j\right) P\left(f_j\right)}{\sum_j P\left(d_i | f_j\right) P\left(f_j\right)}$$

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

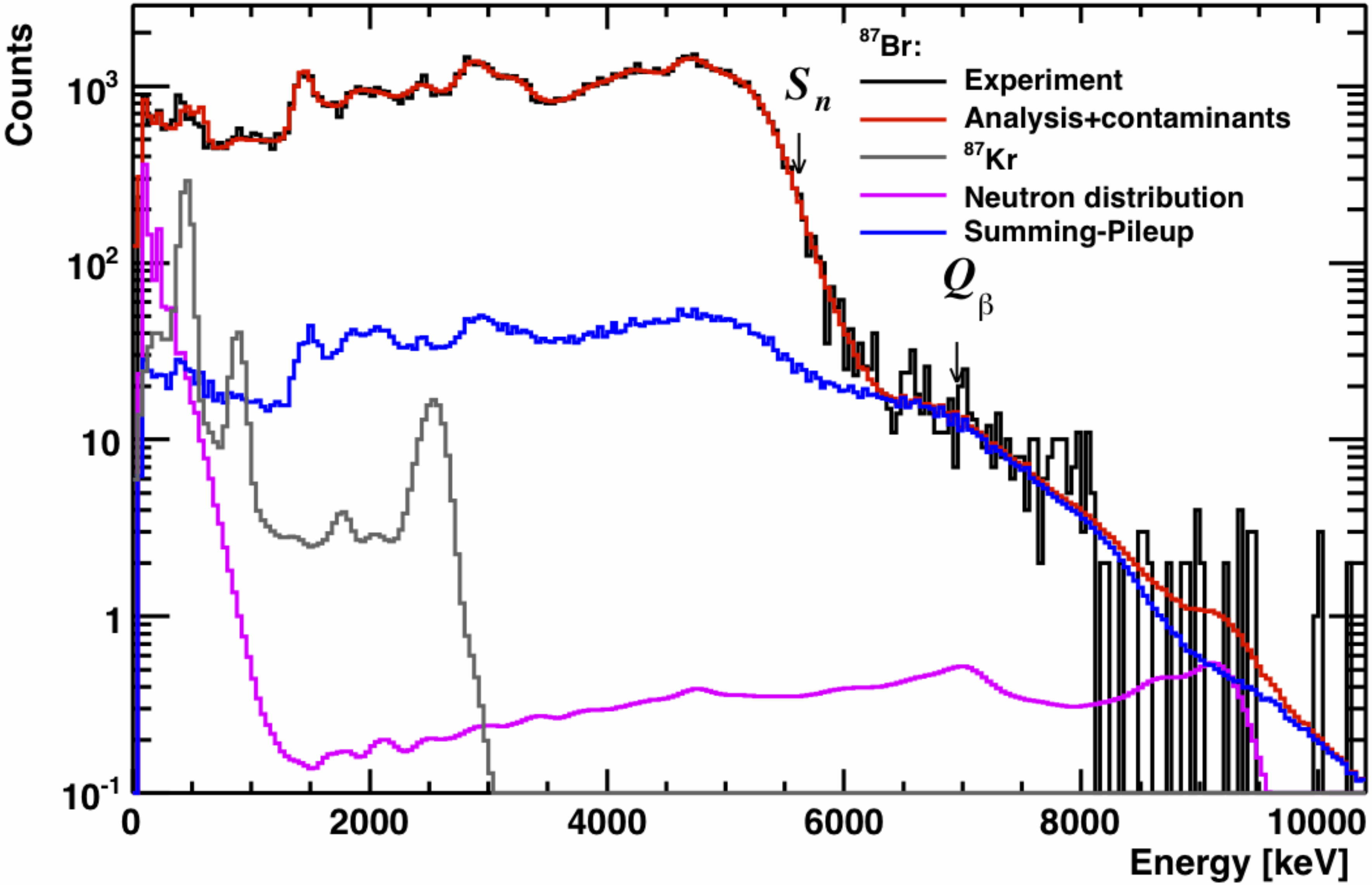
Tain et al. NIM A571 (2007) 719,728

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

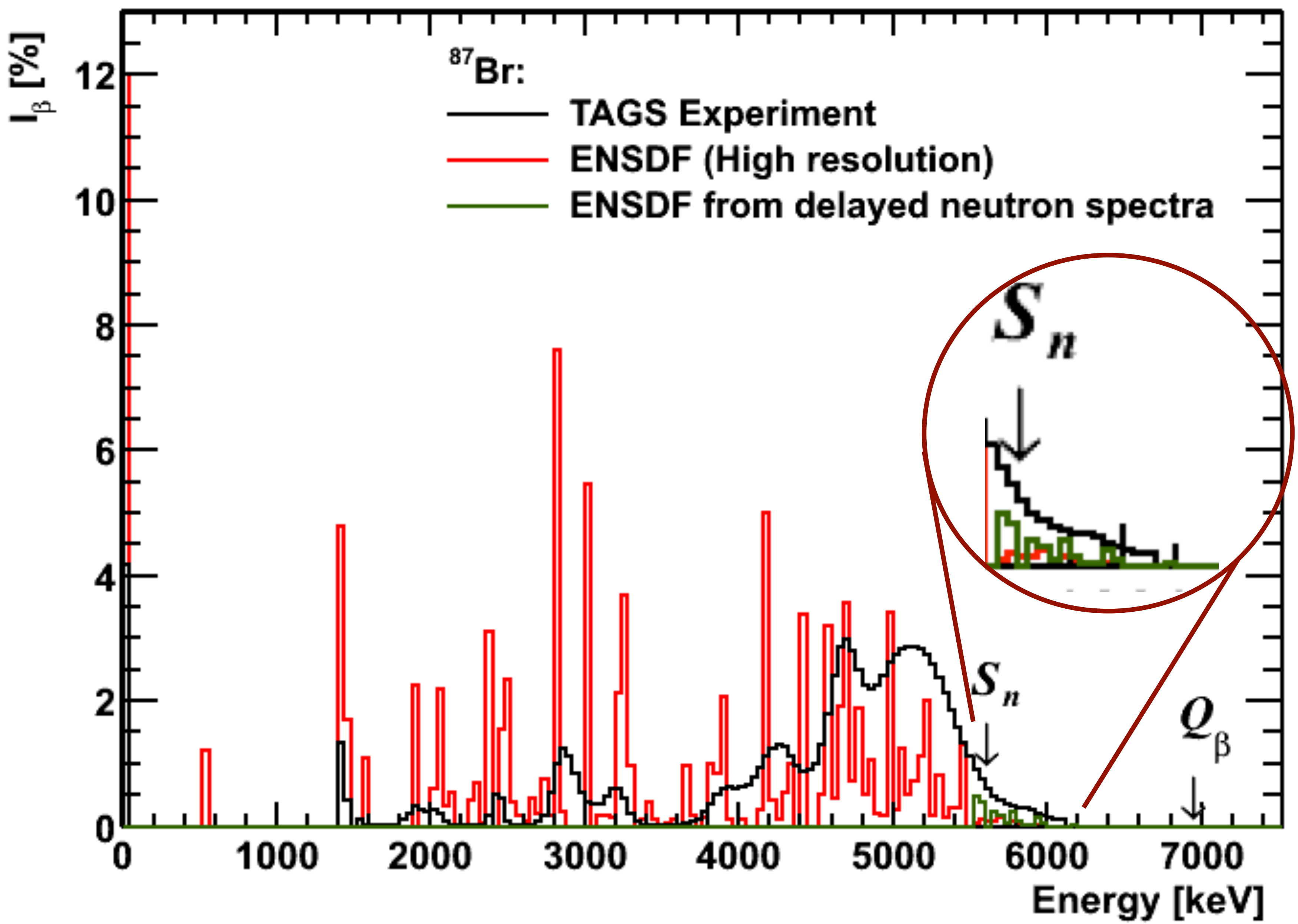
From 1520 keV excitation up to the Q_β =6852(18) value we use an statistical nuclear model to create the branching ratio matrix (Back Shifted Fermi formula for the level density & γ-ray strength functions)



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



Deduced feedings from 87Br decay



^{87}Br feedings and mean energies

	ENSDF	TAGS
$\langle E_\beta \rangle$[keV]	1656(75)	1017(16)
$\langle E_\gamma \rangle$ [keV]	3345(35)	4242(30)
% above Sn	0.58	3.5 %

Q_β=6817(5) keV

Sn= 5515.4(8)

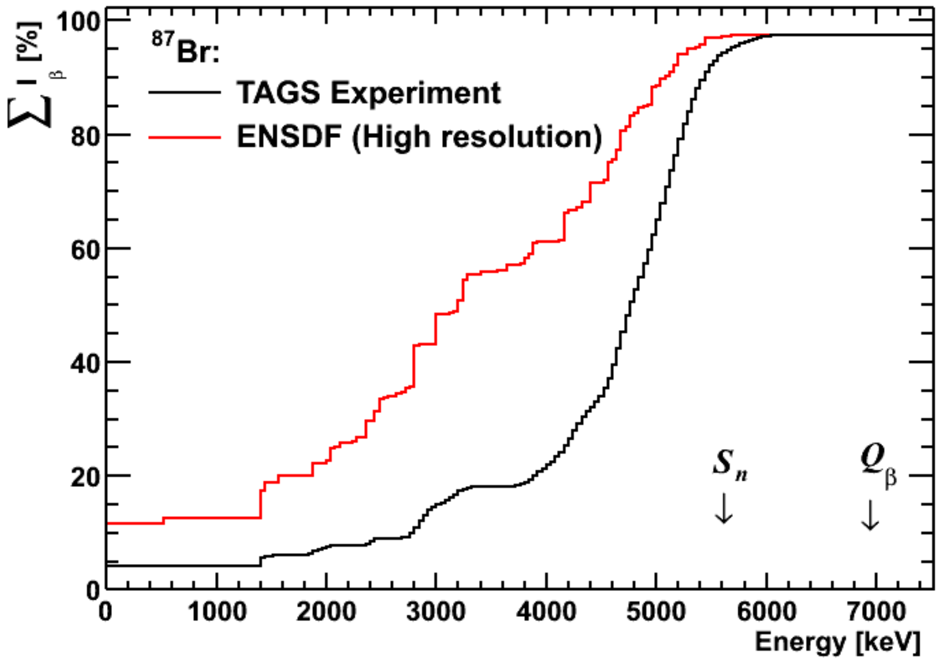
$T_{1/2}$=55.65(13) s

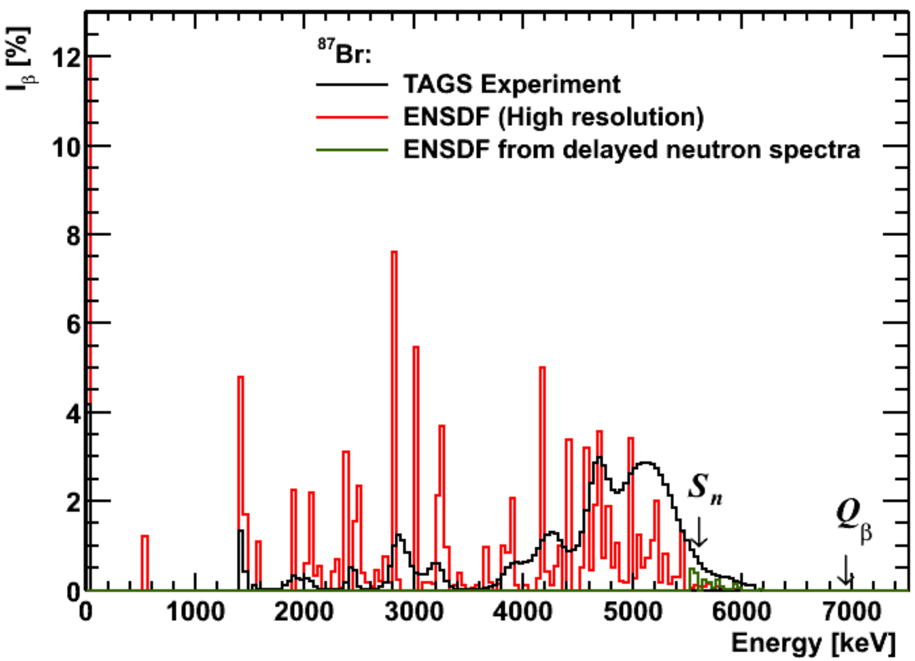
Pn (^{87}Br) = 2.52(7)%

Cum fiss. (^{235}U) =0.02

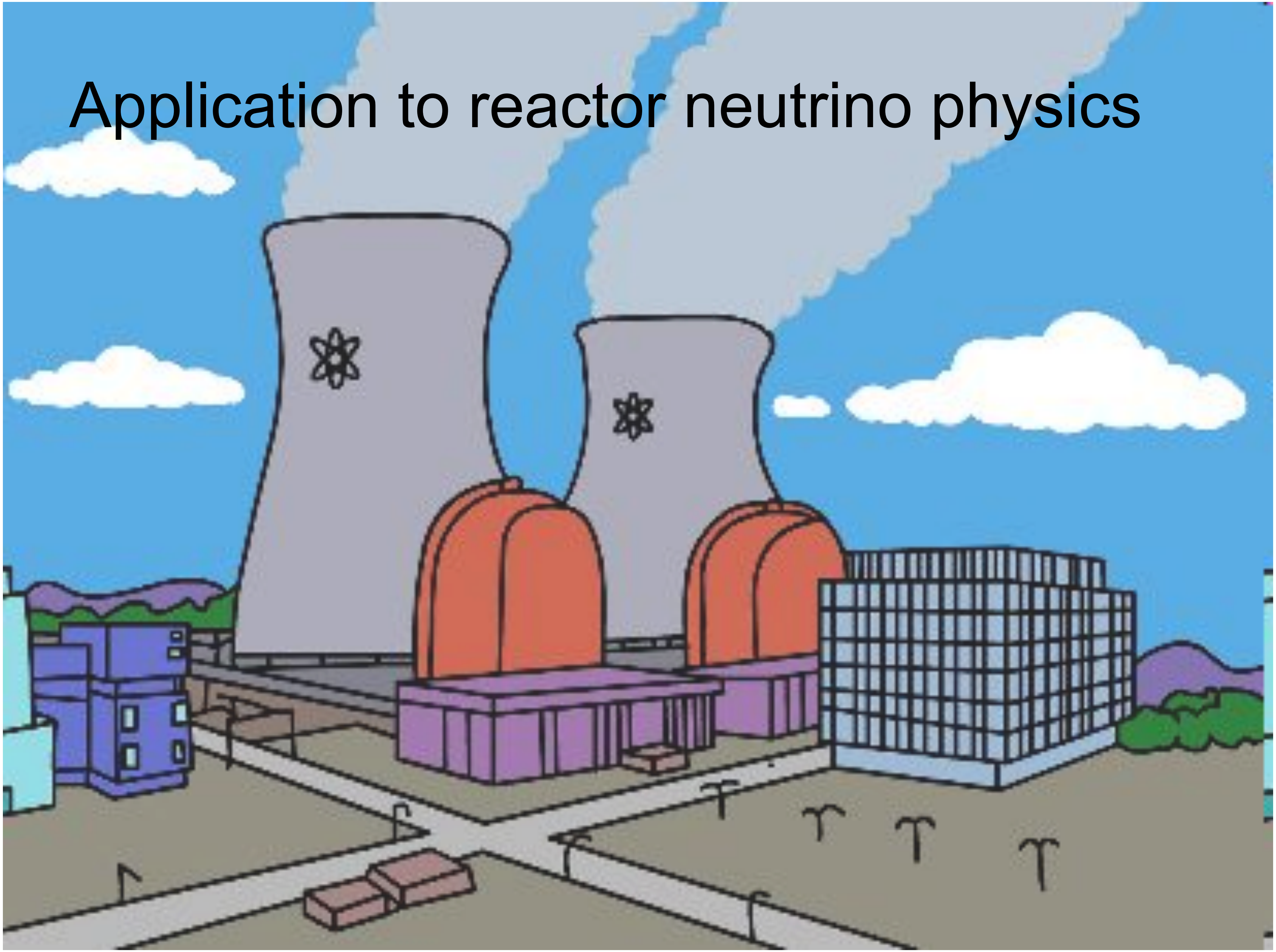
Cum fiss.(^{239}Pu) =0.005

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



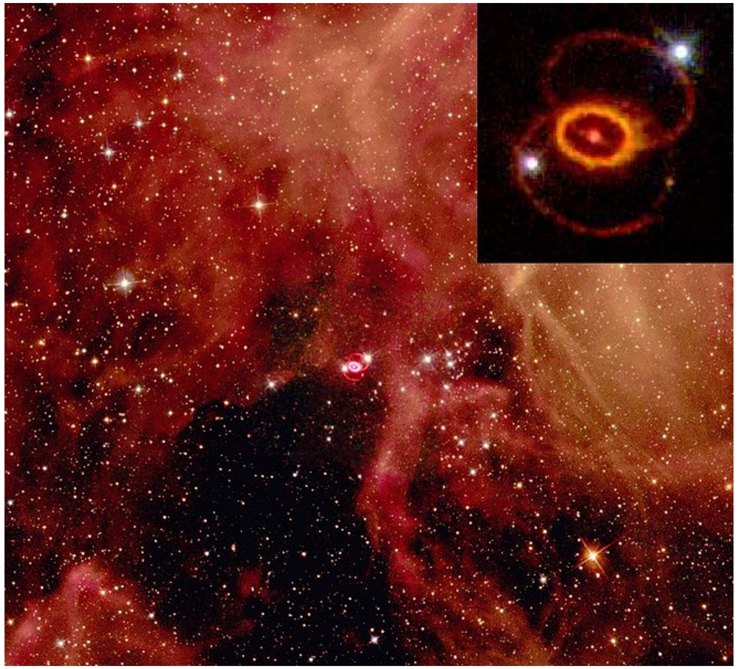


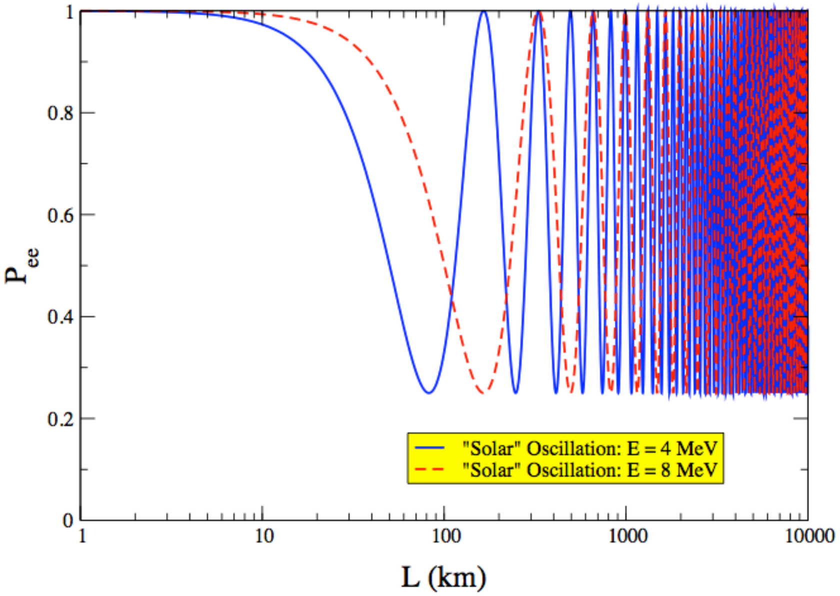
Application to reactor neutrino physics



Why worth studying: neutrinos as messengers

- We hear about many types of neutrinos: solar neutrinos, geo-neutrinos, atmospheric neutrinos, supernova neutrinos, Big Bang neutrinos, reactor neutrinos, etc., etc.
- They can provide information about the processes that happen inside those objects, (inaccessible and harsh environments), because they can travel very long distances without interaction.
- Quantum effects at macroscopic scales





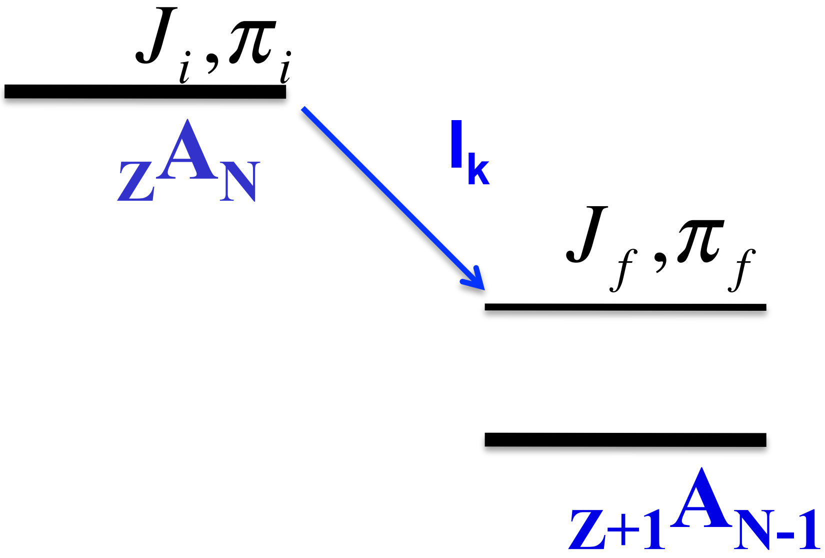
Osscilations !!!

(solar neutrino deficit, atm. neutrino deficit, ^{238}U,^{232}Th, ^{40}K content, etc.)

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

Neutrino 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)

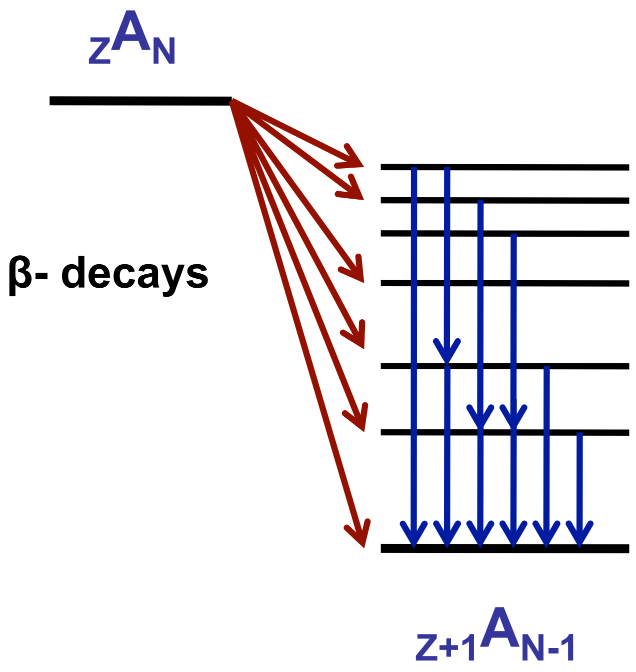
$$S(E)=\sum_n \lambda_n N_n S_n(E)/r=\sum_n CFY_n S_n(E)$$

Decay heat summation calculation

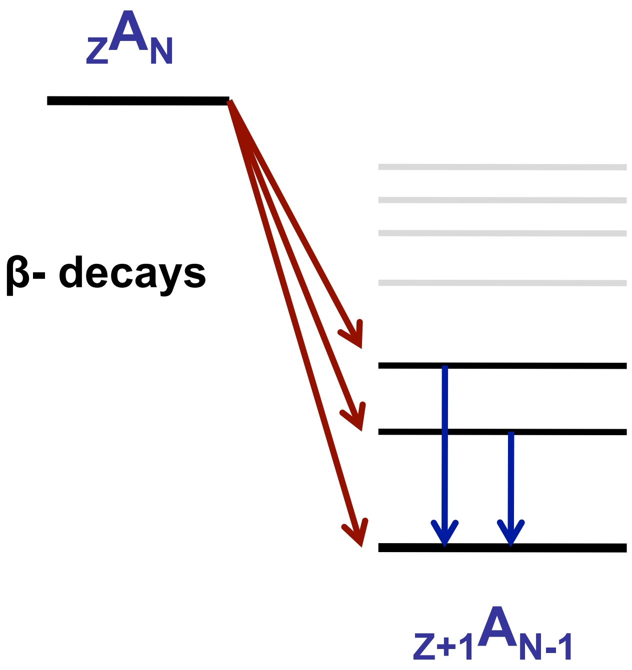
$$f(t)=\sum_i E_i\lambda_i N_i(t)$$

Pandemonium and summation calculations

Real situation



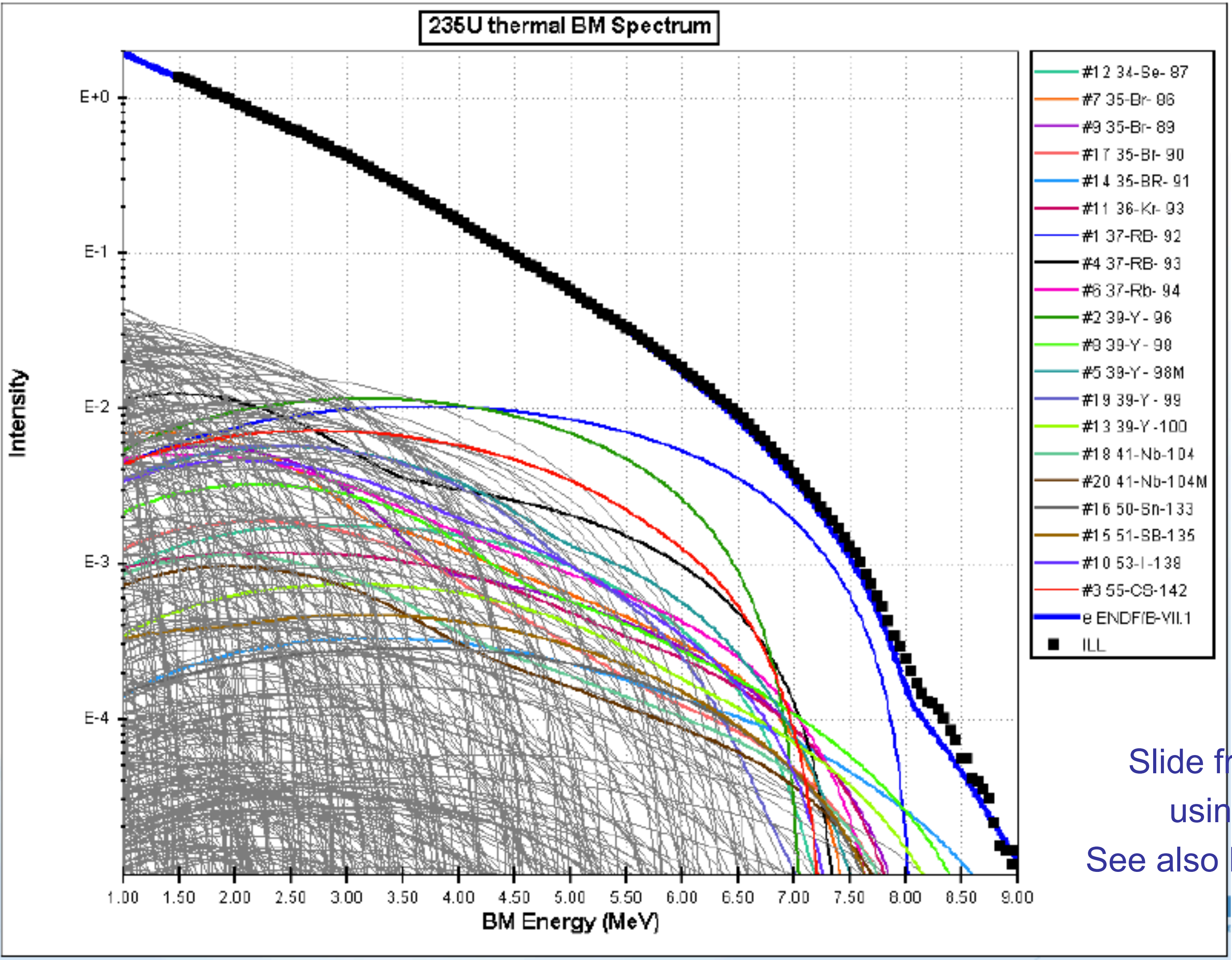
Pandemonium situation



As a result of the Pandemonium, betas and neutrinos are estimated with higher energies from databases. Their spectra is harder.

This is why TAS measurements are very important

Role of individual decays

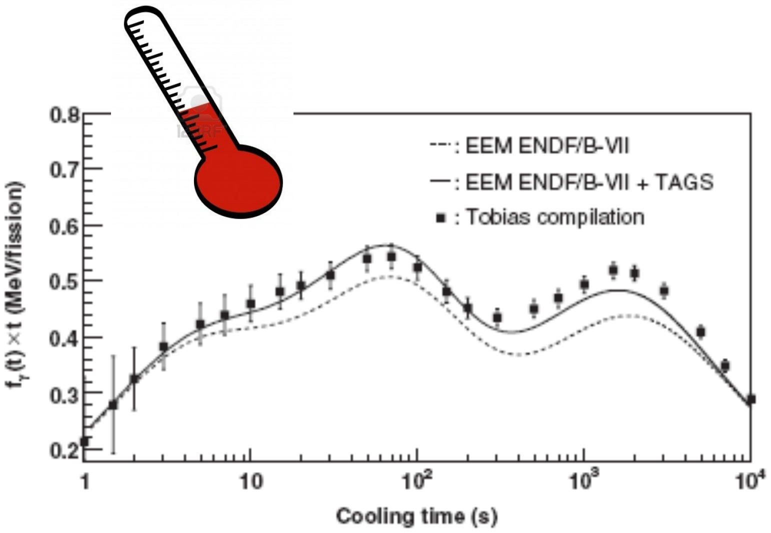


How to identify
the main players

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

Slide from A. Sonzogni
using ENDF VII.1
See also PRC 81,011301(R)

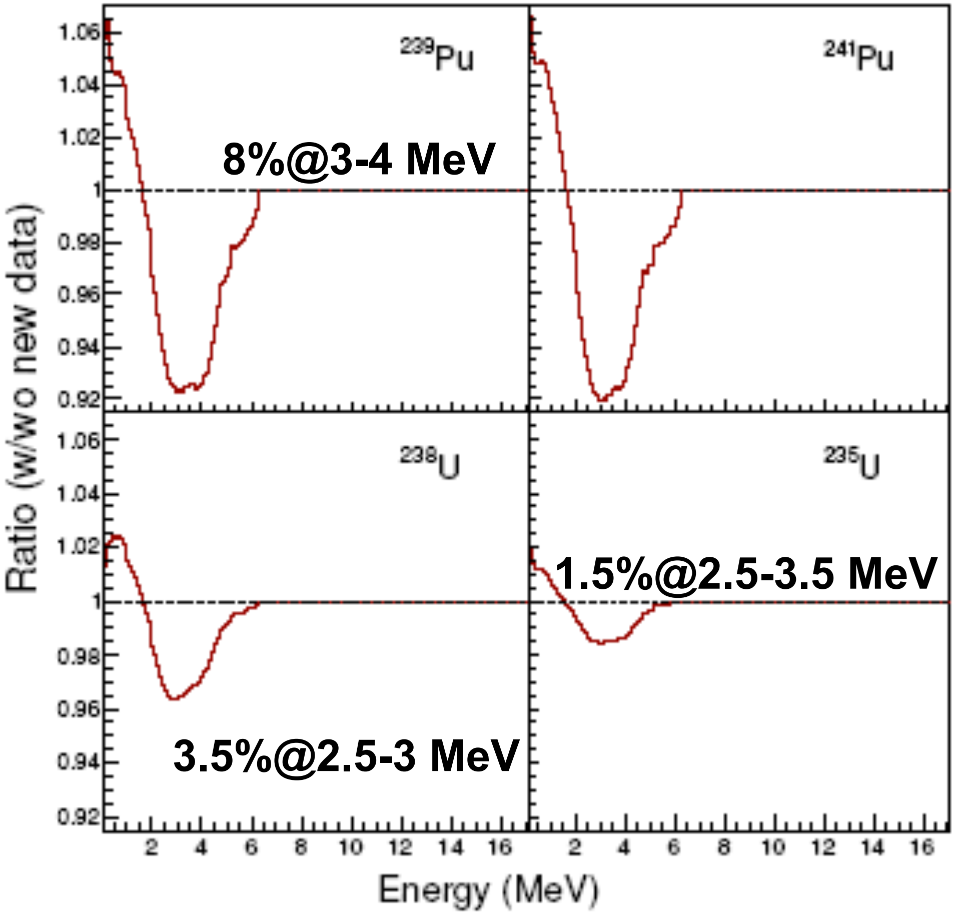
Impact of our published data (up to now)



Dolores Jordan, PhD thesis

Algora et al., PRL 105, 202501, 2010

M. Fallot et al., PRL 109.202504



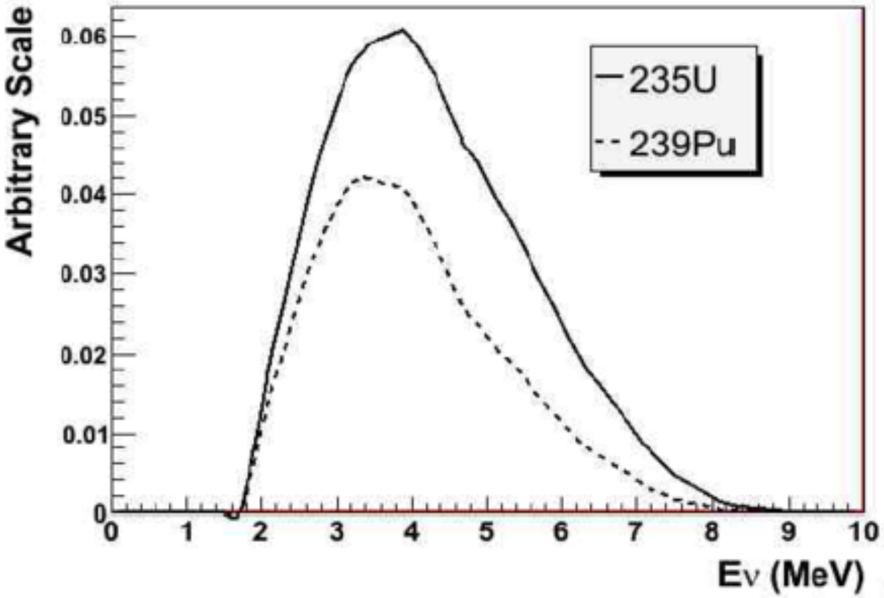
Ratio between 2 antineutrino spectra built with and without the ^{102,104,105,106,107}Tc, ^{105}Mo, ^{101}Nb TAS data

Non-proliferation application: monitoring reactor power and illegal manipulations with the fuel

	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	3.2×10^{-43}cm^2	2.8×10^{-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.**
- **We have recently performed an experiment to measure some Rb, Sr, Y, Nb, I and Cs with this goal in mind (IGISOL, trap assisted DTAS) (Fallot, Tain, Algora), proposal from 2010 before it was fashionable**



New questions: reactor anomaly ?

(Mention et al. Phys. Rev. D83, 073006 (2011))

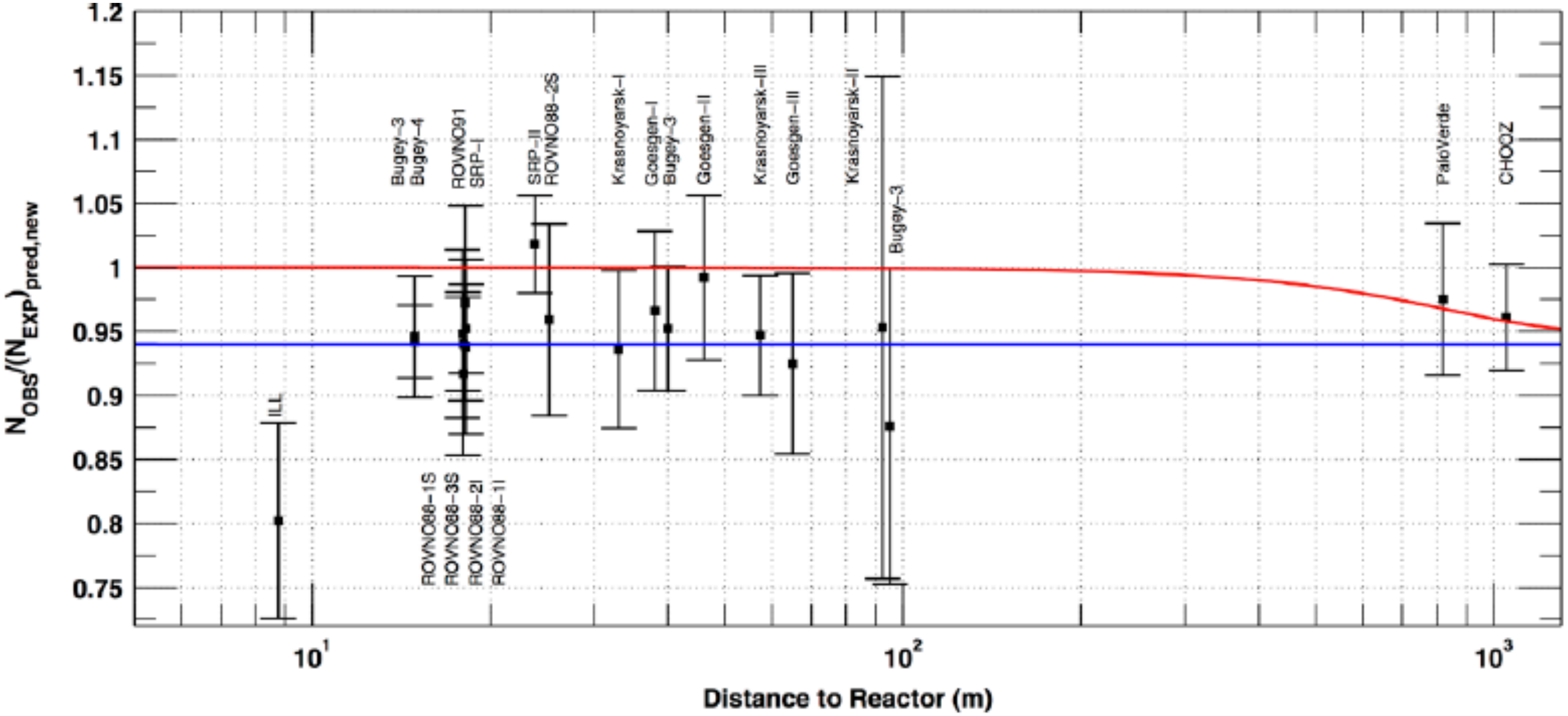


Illustration of the reactor anomaly. Rates in various experiments are compared with the expectations based on the Mueller et al. (2011) spectrum. The mean is 0.943+-0.023.

Possible explanation:

1)Wrong reactor flux or its error

2)Bias in all experiments

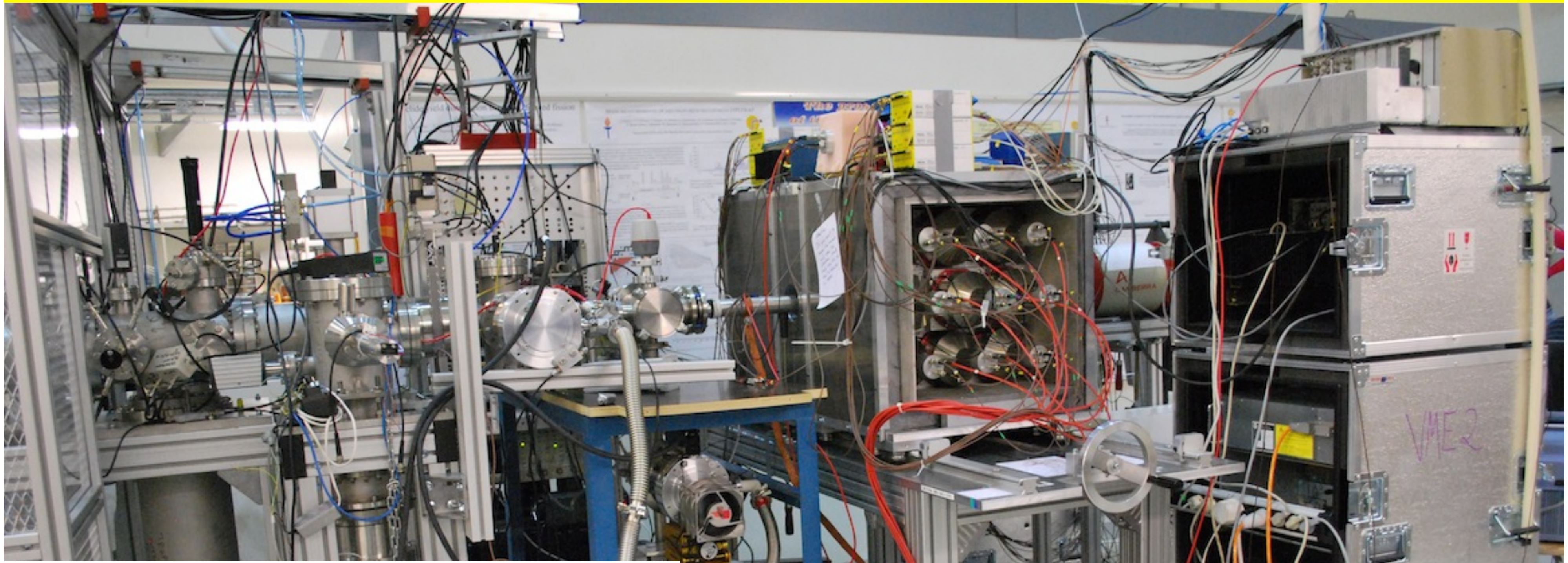
3)New physics at short baseline involving a sterile 4th neutrino ν_{new} with $\Delta m^2 \sim 1eV^2$ and mixing with ν_e with $\theta_{new} \sim 10^0$

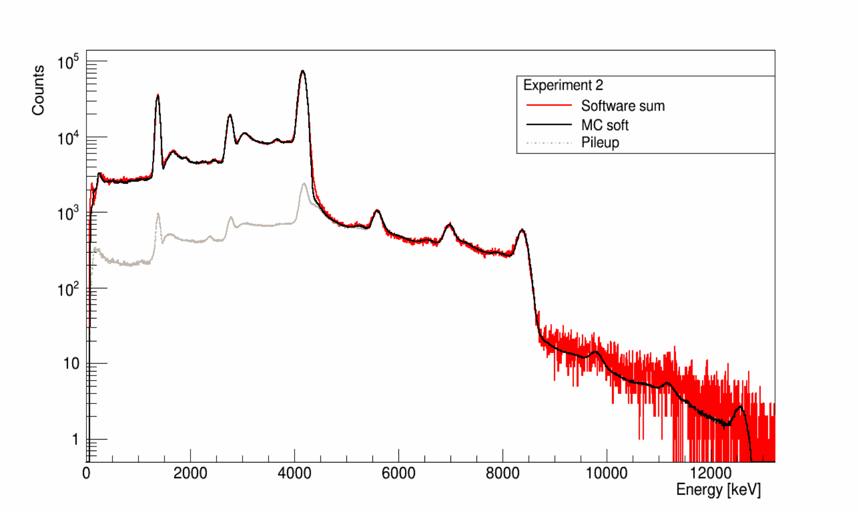
Slide from P. Vogel

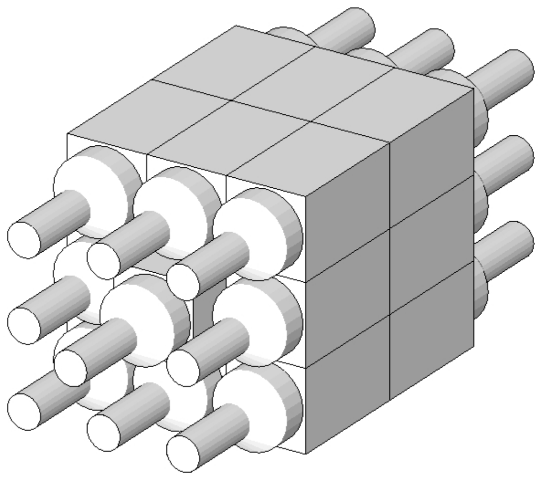
The explanation 3) could be supported by several other, so far unconfirmed anomalies. It would involve unexpected but significant "New Physics"

DTAS at Jyväskylä (Feb. 2014)

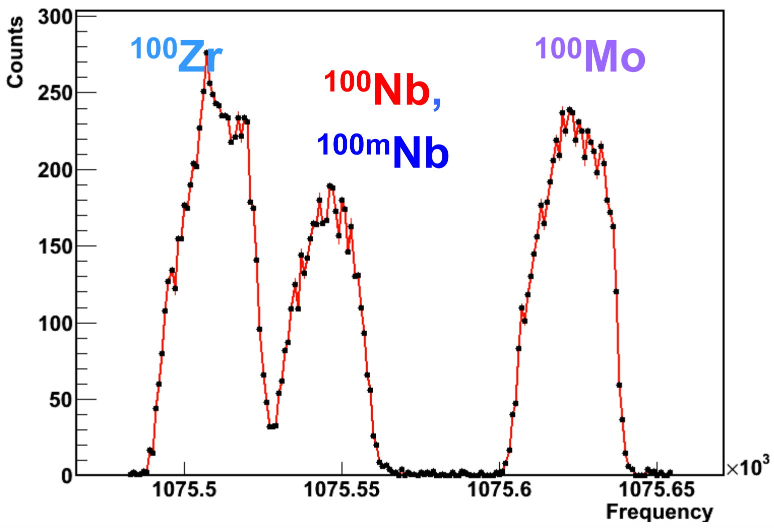
(experiment in collaboration with Subatech, France)

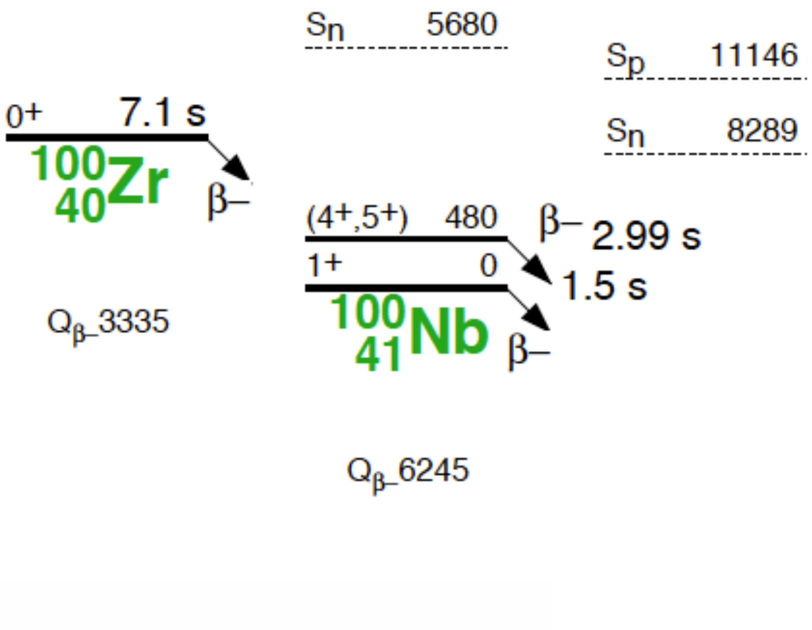


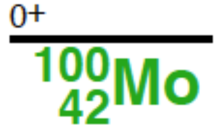


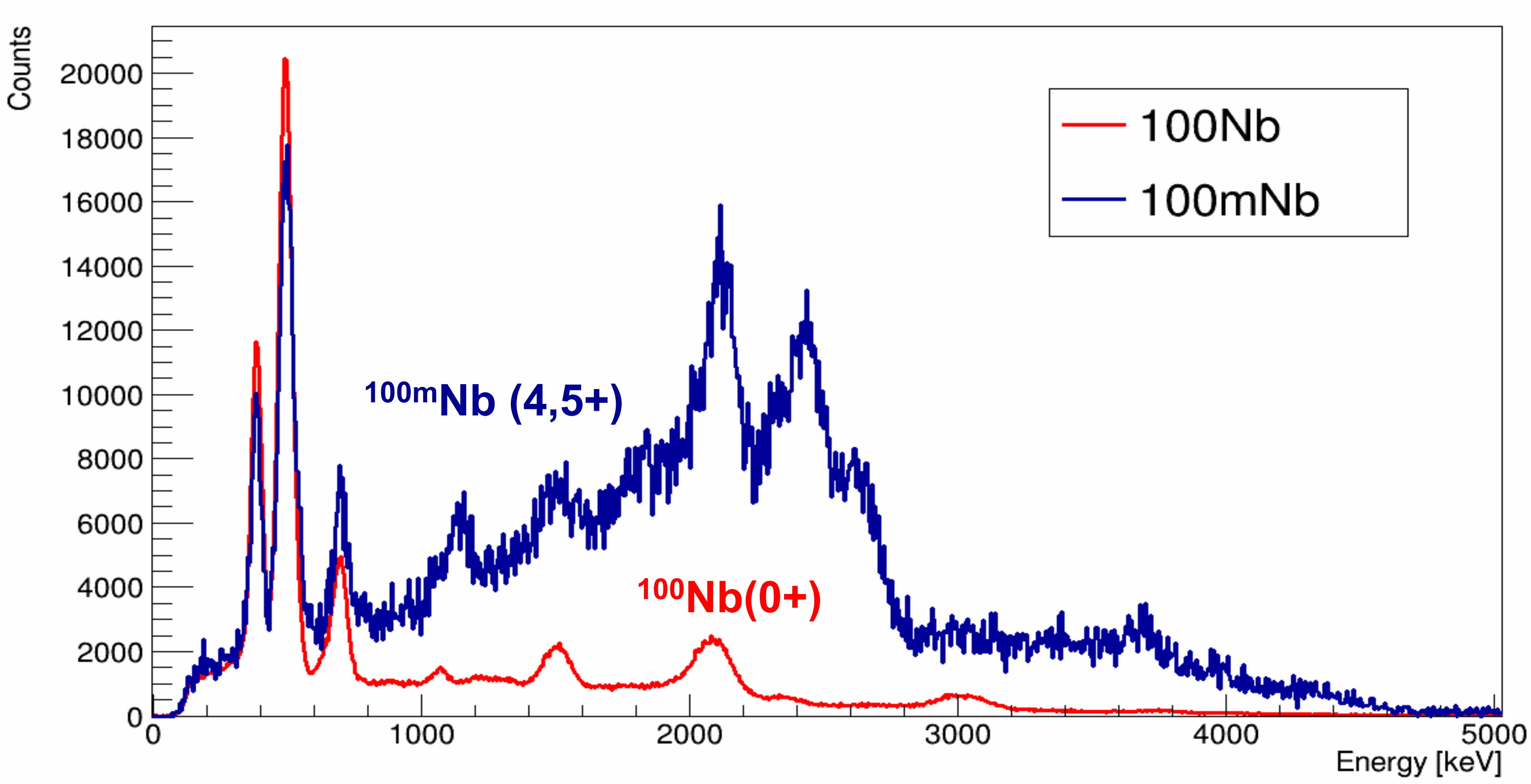


JYFLTRAP, A=100 Mass Scan

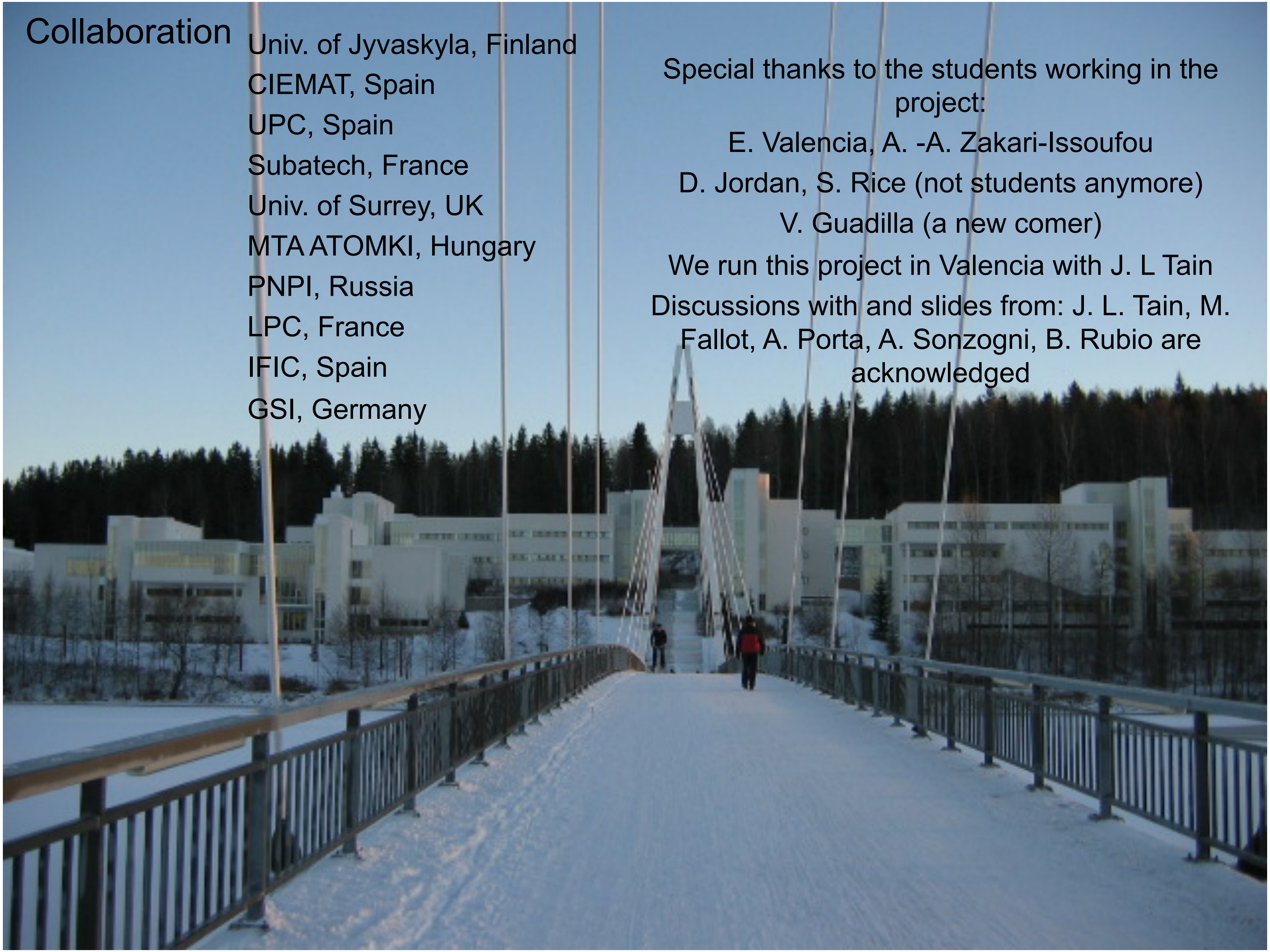








Beta gated TAS spectra of the two isomers



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 working in the project:

E. Valencia, A. -A. Zakari-Issoufou

D. Jordan, S. Rice (not students anymore)

V. Guadilla (a new comer)

We run this project in Valencia with J. L Tain

Discussions with and slides from: J. L. Tain, M. Fallot, A. Porta, A. Sonzogni, B. Rubio are acknowledged

THANK YOU