Constraints for production of new experimental data (beta decay related)

A. Algora
IFIC (CSIC-Univ. of Valencia)

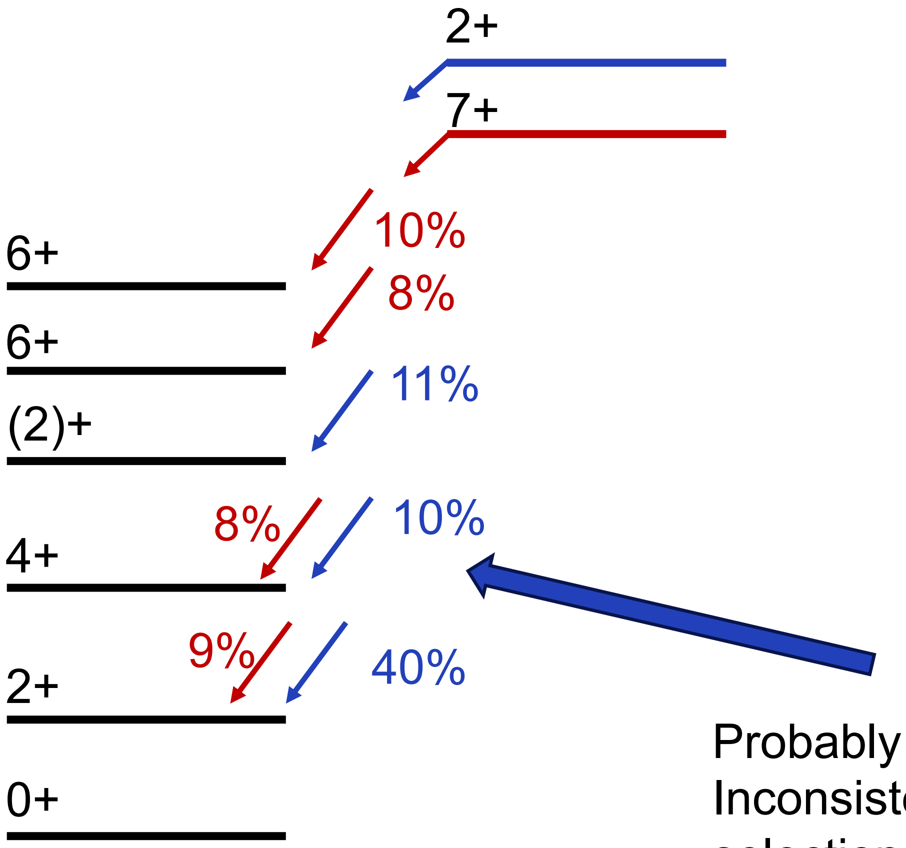
On behalf of the Beta Decay WP

A few days ago, I got a question ...

Data taken from a known nuclear database

Two isomers beta decay level scheme

Can I explain this?



Probably wrong.
Inconsistent with selection rules

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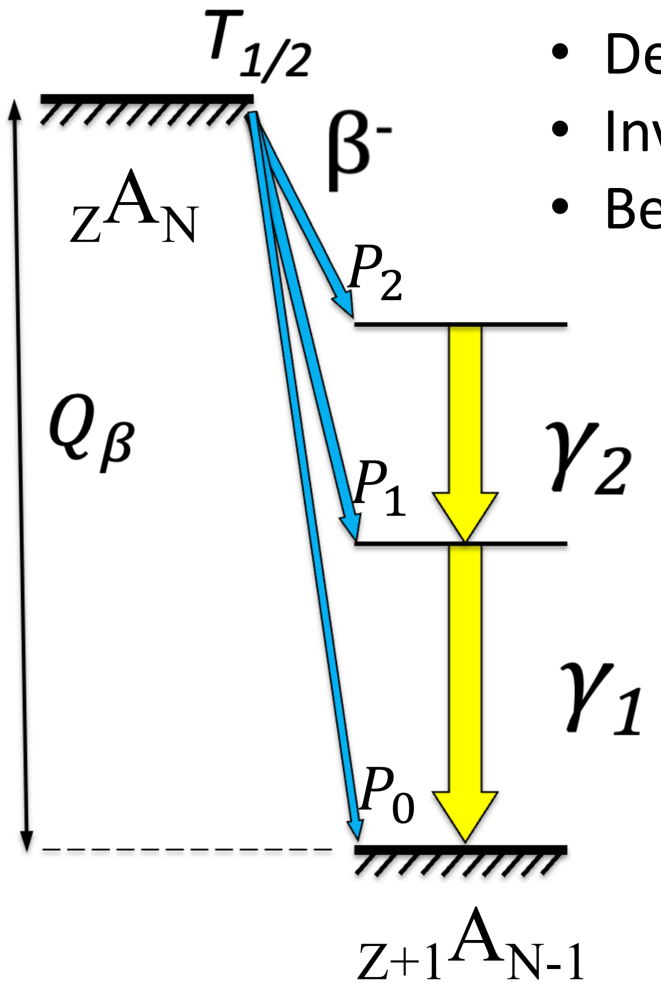
Question: Data needed for describing properly a beta decay



Primary experimental information needed

- Decay half-life
- Involved masses (Q values)
- Beta decay probabilities (feedings)

$$T_{1/2}, Q, f_i \equiv P_i * 100$$

$$t_i = \frac{T_{1/2}}{P_i} \quad \text{(partial half-life)}$$

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

$$f t_i \ (or\ Log\ f t_i)$$

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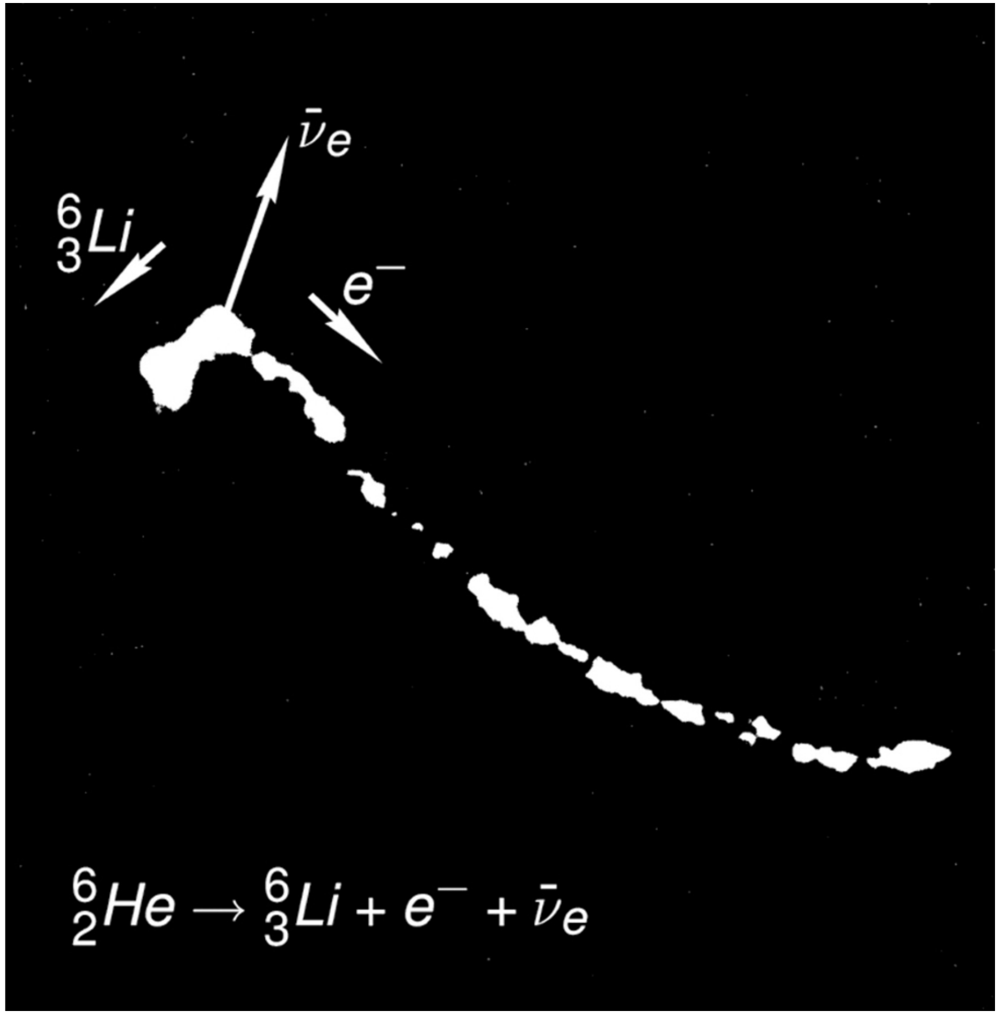

J. Csikai, Il Nuovo Cimento, 5 (1957) 1011–1012

Beta decay studies are not simple

Why is it so difficult?

Remember

Dear Radioactive Ladies and Gentlemen …

A letter written by Pauli from Tübingen 1930, made public in 1933 in the Solvay Conference

Intrinsic beaty: the possibility to study an elusive particle for the first time

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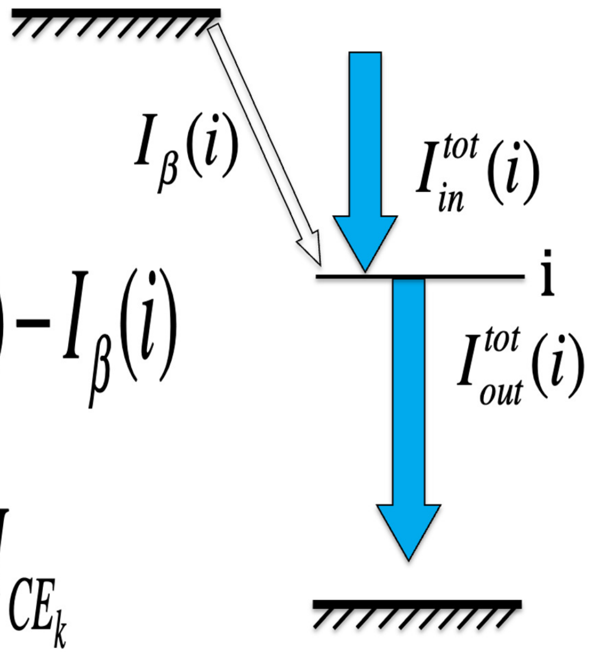
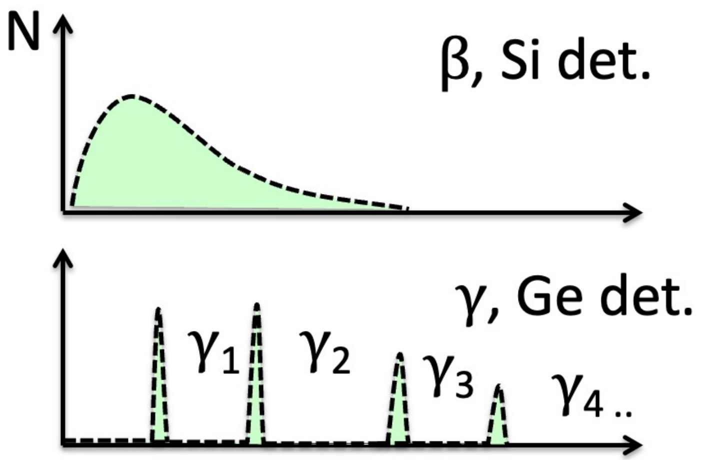
How the problem is typically addressed?



$$0 = I_{out}^{tot}(i) - I_{in}^{tot}(i) - I_\beta(i)$$

$$I^{tot}(i) = \sum_k I_{\gamma_k} + I_{CE_k}$$



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

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

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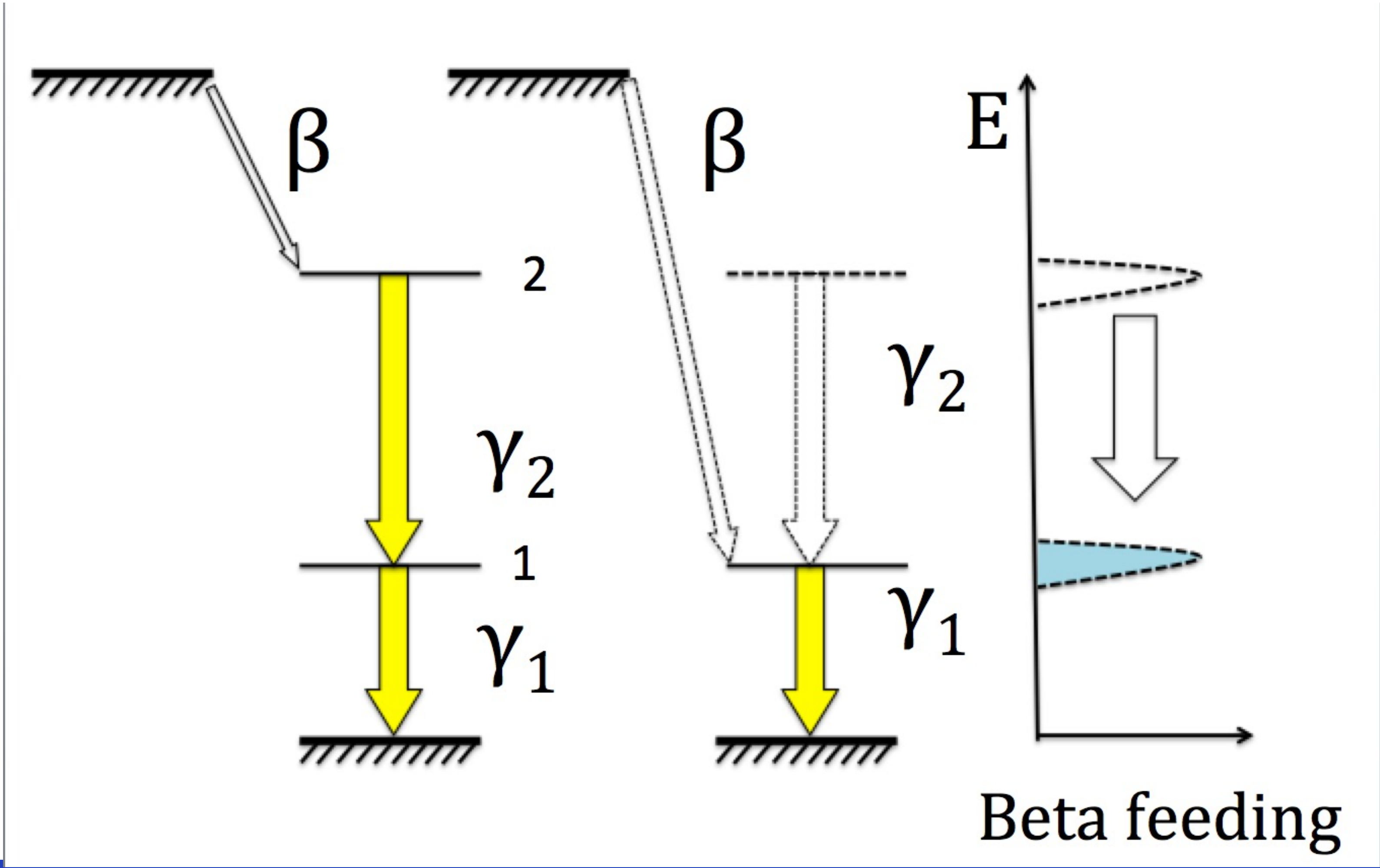
What can go wrong? Pandemonium effect



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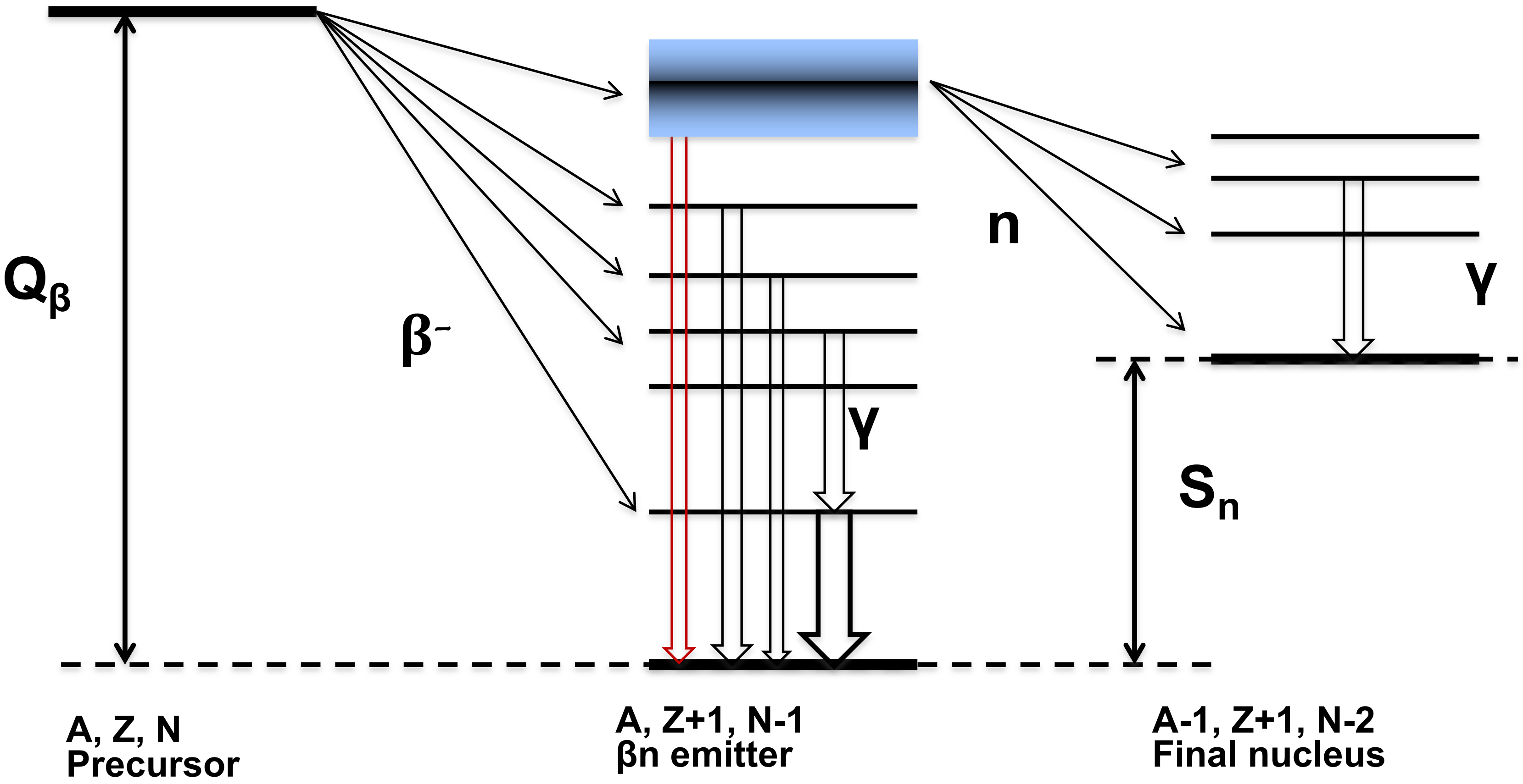
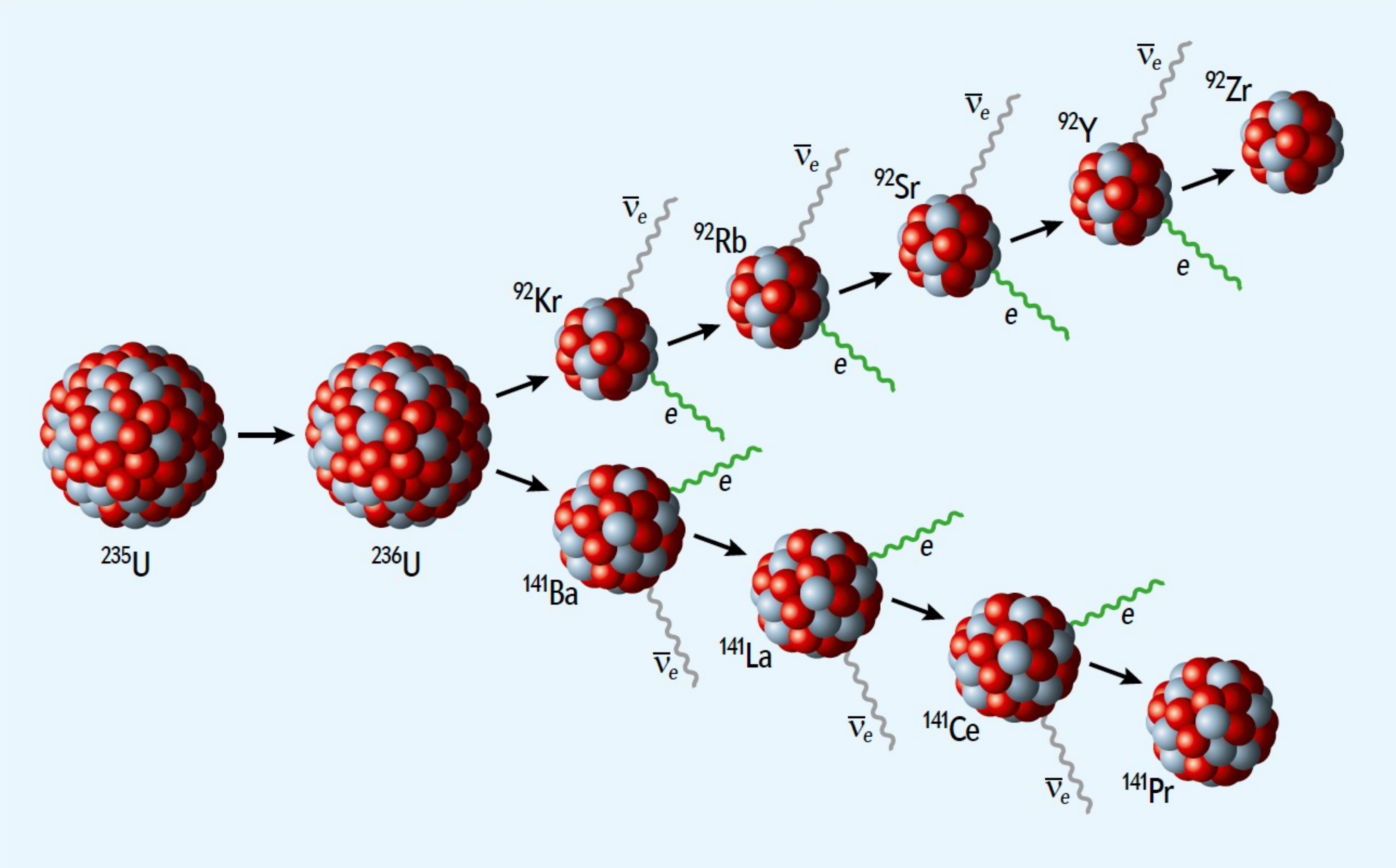
What can go wrong? Other challenges



Fission process and beta decay

Every fission is approximately followed by 6 beta decays (sizable amount of energy)
Reactors are the largest (manmade) pacific sources of neutrinos.
Produces $2x10^{20}$ ν/s



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Integral quantities for benchmarking fission yields

- 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

- Summation calculations of the antineutrino spectrum in reactors

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

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What was meant by “high quality decay data” for benchmarking

- Use of beta decay data that does not suffer from the Pandemonium effect
- Proper determination of the ground state to ground state feeding (it affects the global feeding normalization, and can be helpful in the determination of absolute gamma branches per decay of relevance for many applications.)
- In the case of beta decays that present beta delayed neutron emission, determination of the gamma/neutron competition above the neutron separation energy

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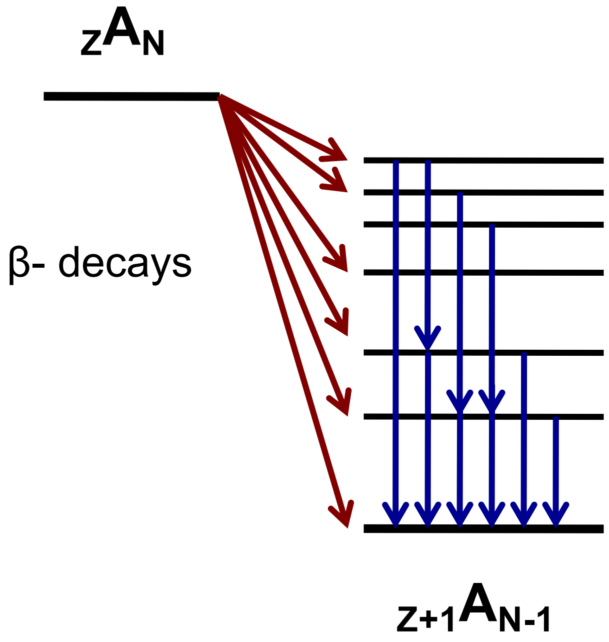
How the mean energies are determined ?
Measured or deduced (from beta decay studies)

DATA bases:
feeding or beta
decay prob.
distributions

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



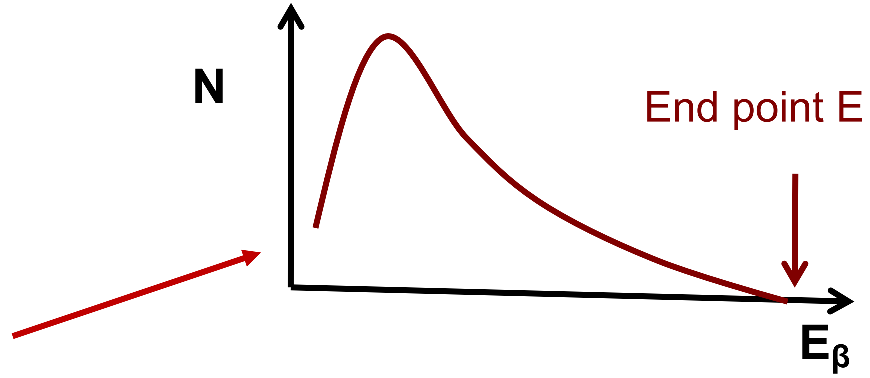
Key ingredient:
beta feedings

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

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

(Simplified way of calculation)

Beta spectrum for a
beta transition
(to a defined level)



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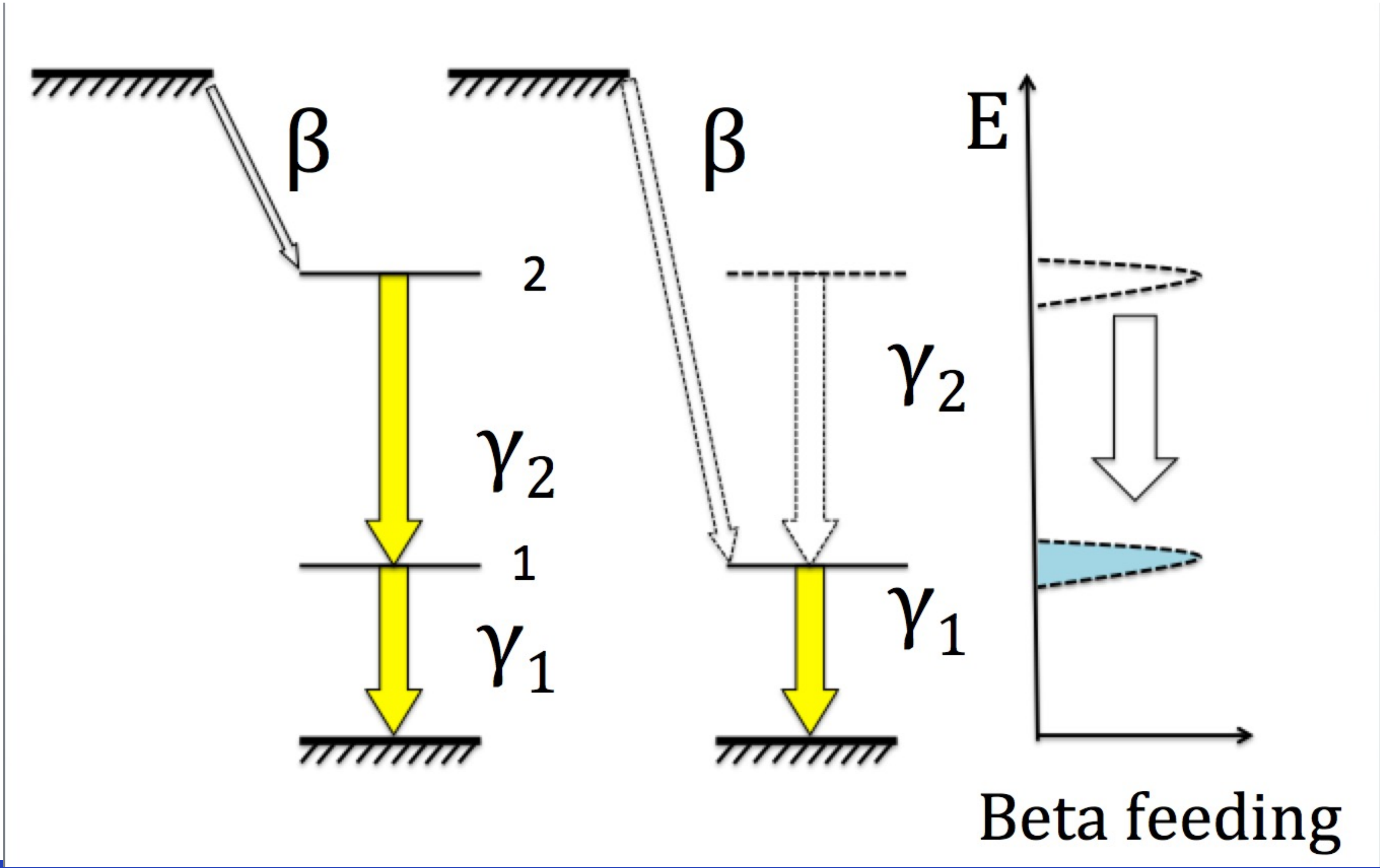

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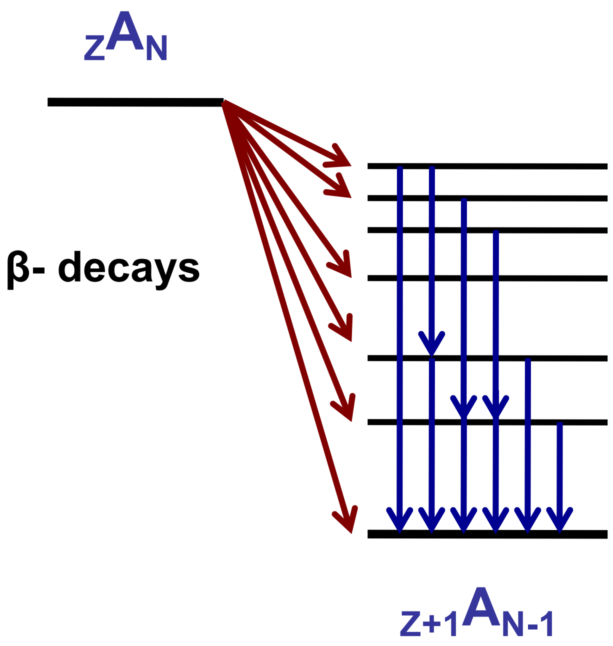
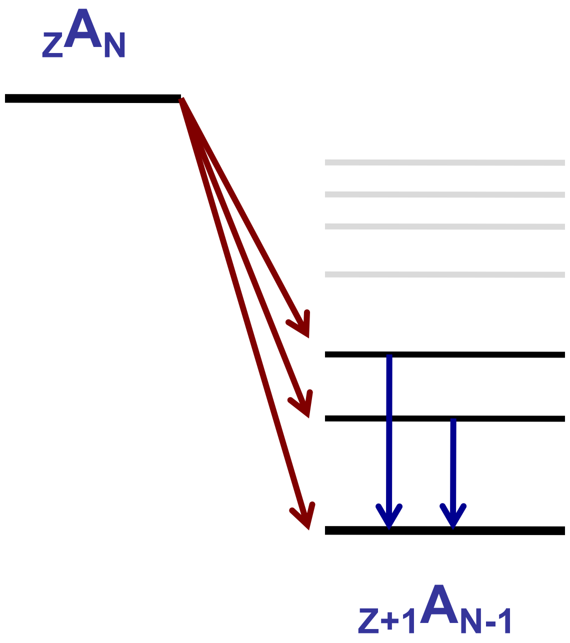
Effect of Pandemonium on summation calculations (decay heat example)

Real situation



Pandemonium situation



As a result of the Pandemonium, betas are estimated with higher energies from databases. Their spectra is harder. Incomplete level schemes can affect the antineutrino calculations as well. The gamma mean energies are reduced since you detect less gammas.
This is why you should avoid using data suspicious of suffering from Pandemonium

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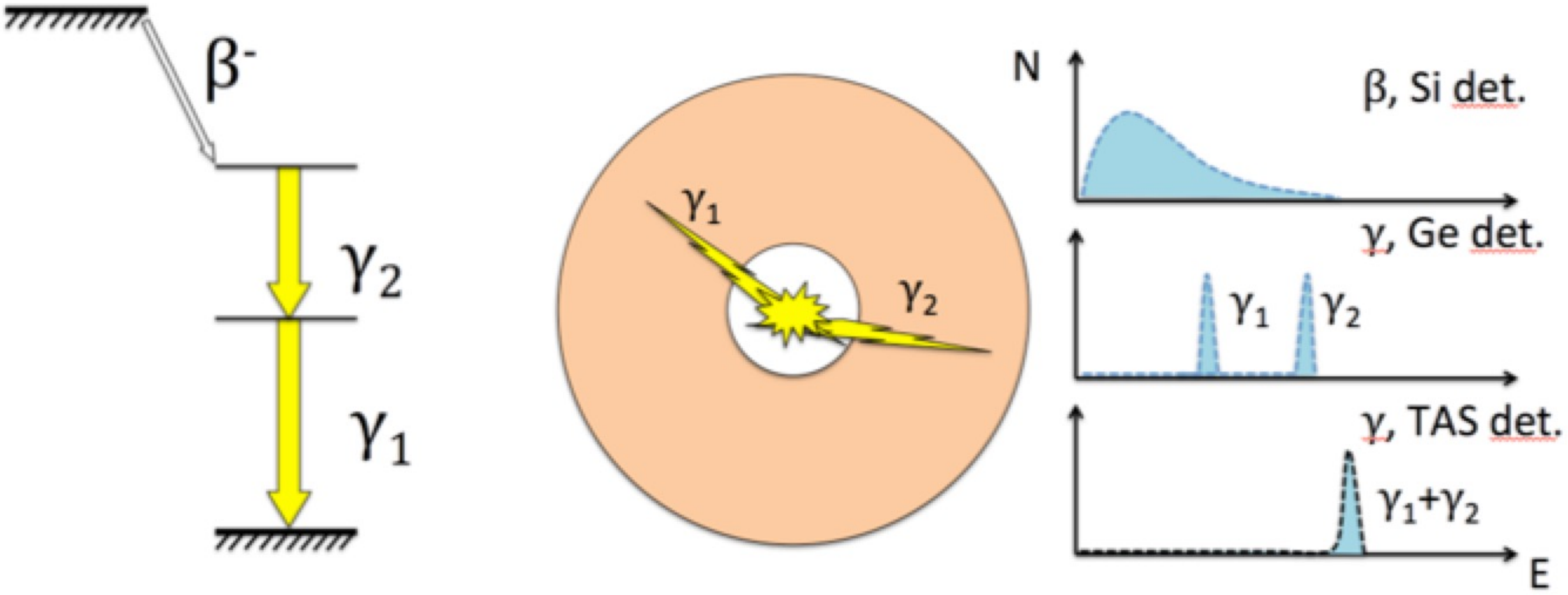
Total absorption spectroscopy applied to beta decay studies



$$d = R(B) \cdot f \qquad (note\ that\ f \equiv I_\beta)$$

Requirements: clean spectrum or a proper treatment of the contaminants, some knowledge of decay level scheme of the daughter, etc.

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How these challenging experiments are analyzed?

Measured spectrum without contaminants

$$d=R(B).f$$

Response matrix

Beta feeding distribution (goal)

Needs/challenges:

Well controled Monte Carlo simulations

Excellent calibration (energy and witdh)

Knowledge of the (B), branching ratio matrix (level sheme)

Methods for solving the inverse problem

Control of contaminants

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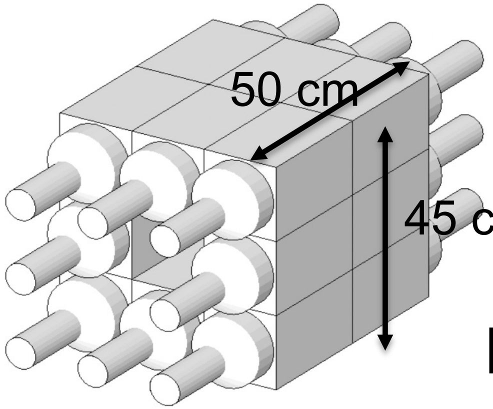
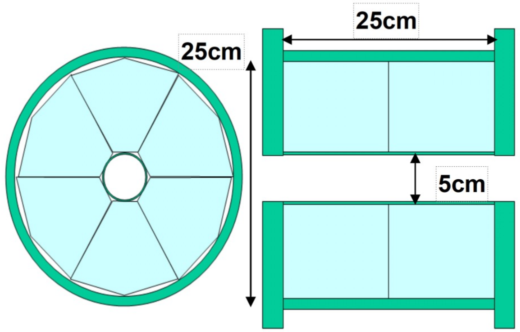
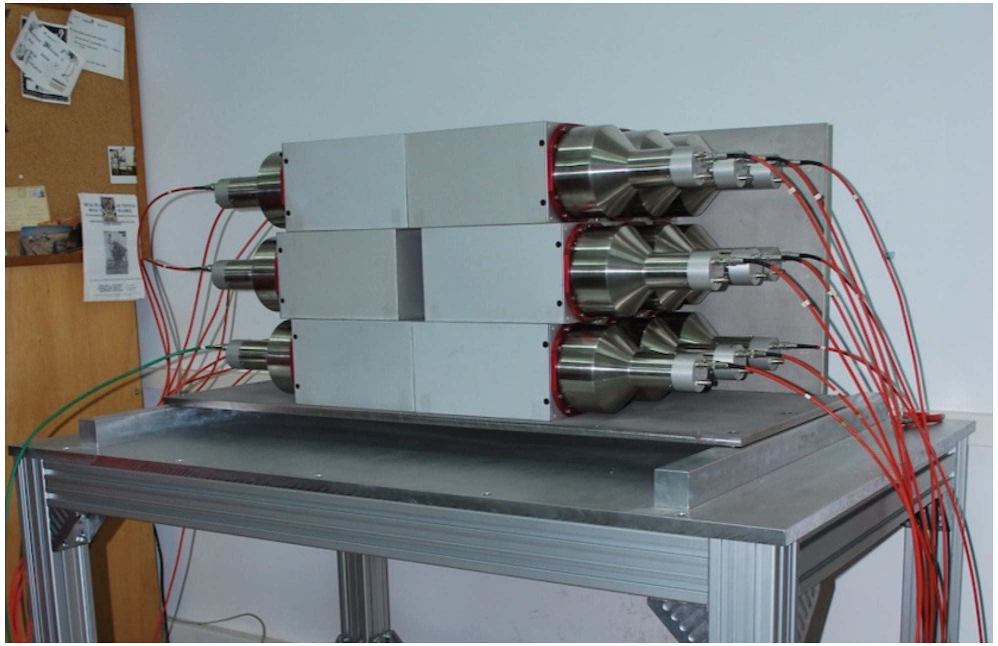
Examples of spectrometers we use

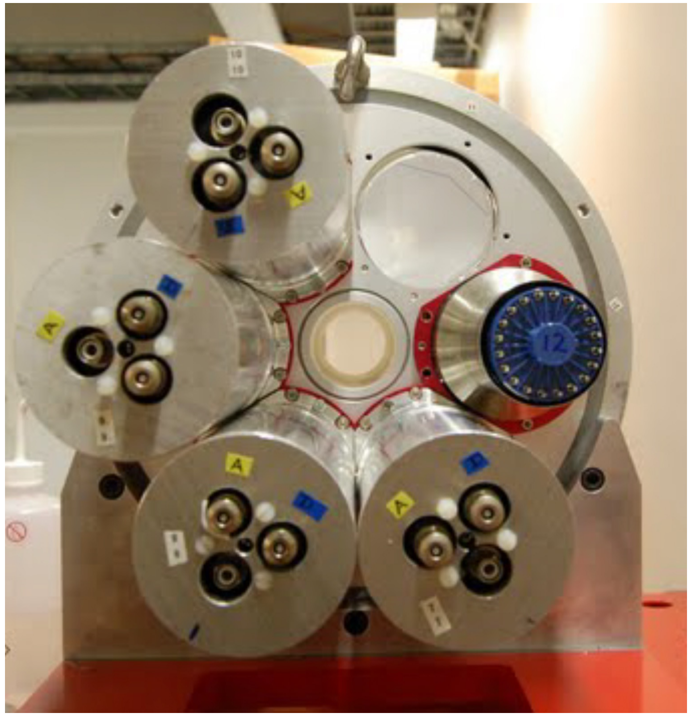


NaI



BaF_2





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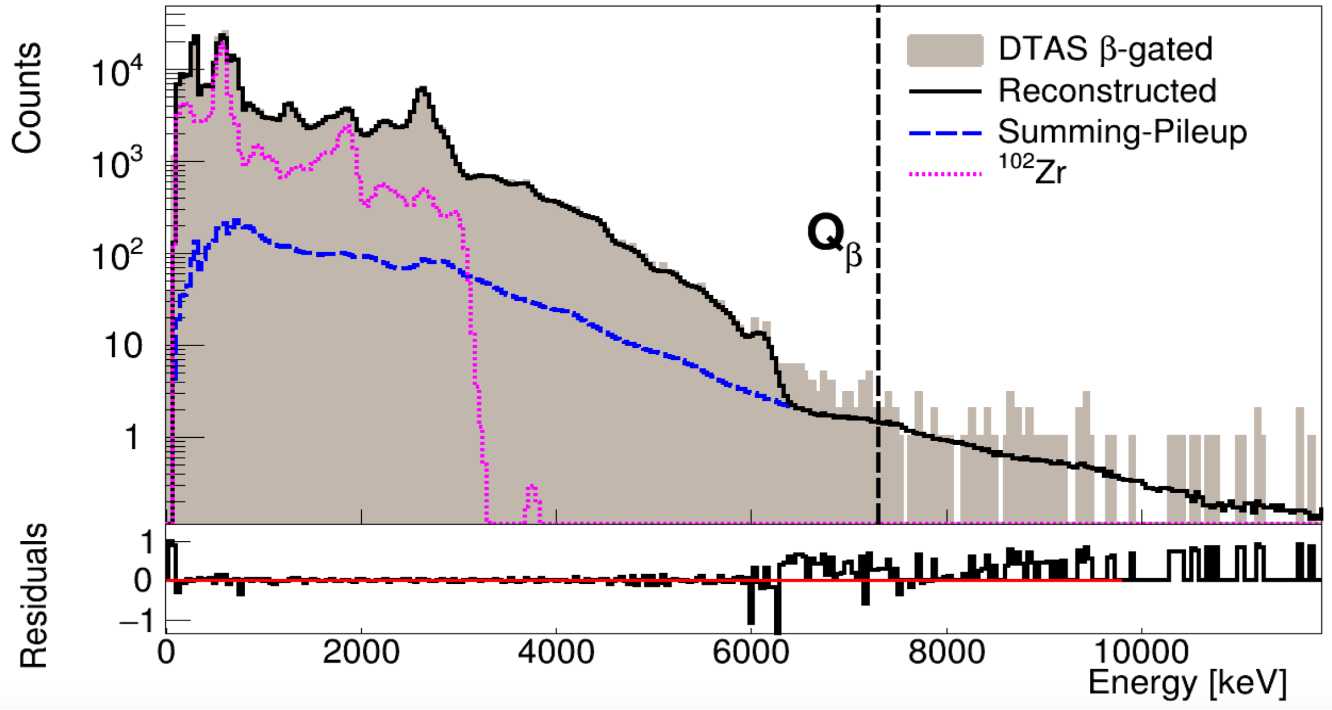
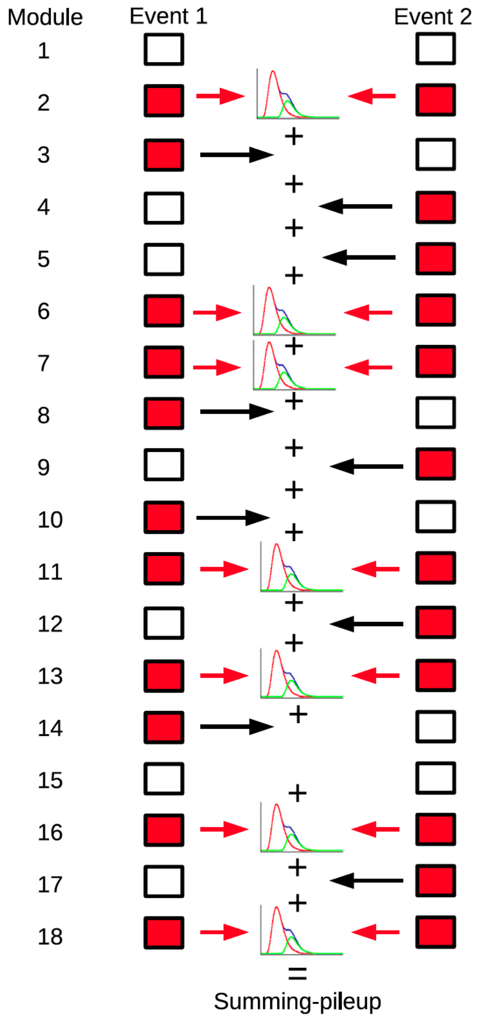
How these challenging experiments are analyzed?

Needs/challenges d=R(B).f

Control of contaminants. separate measurements, pile-up





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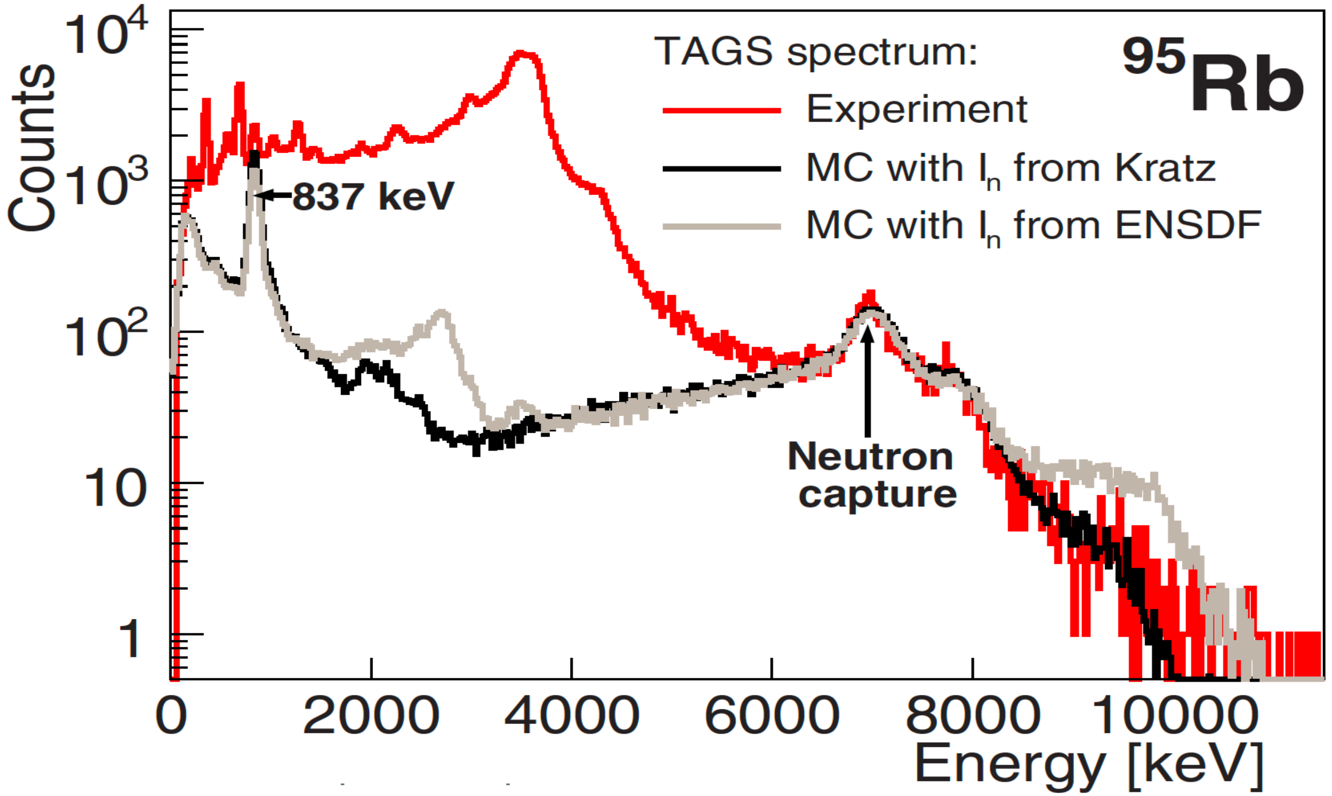
How these challenging experiments are analyzed?

Needs/challenges d=R(B).f

Another distortion: beta delayed neutrons, requires additional MC



V. Guadilla et al., PRC 100, 044305 (2019)

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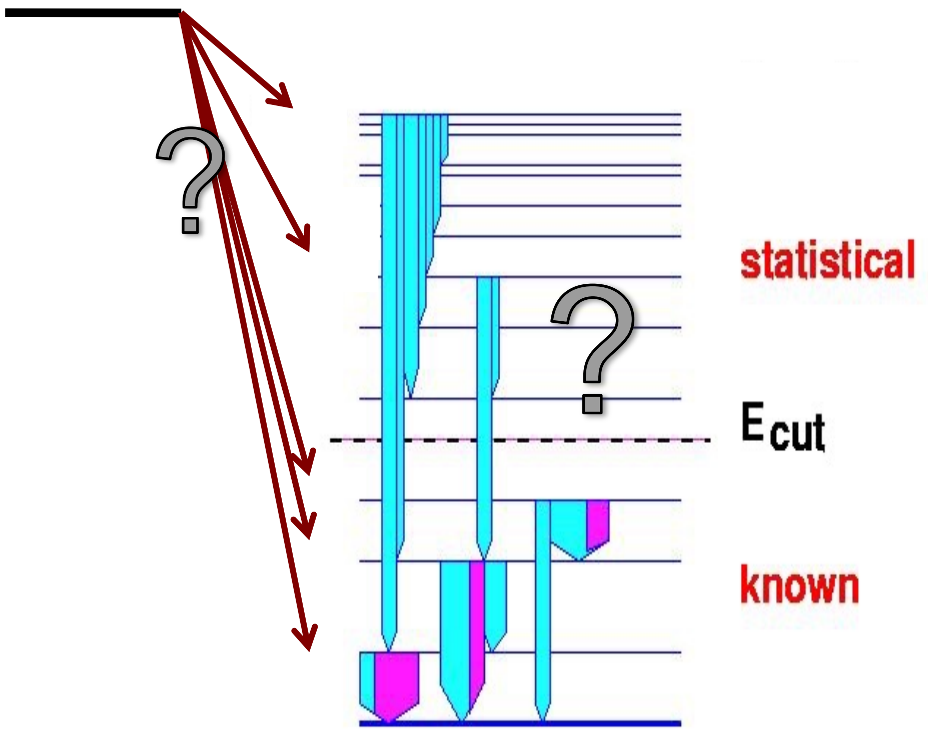
How these challenging experiments are analyzed?

Needs/challenges: response, inverse problem, algorithms

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

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

Mathematical formalization by Tain, Cano, et al.

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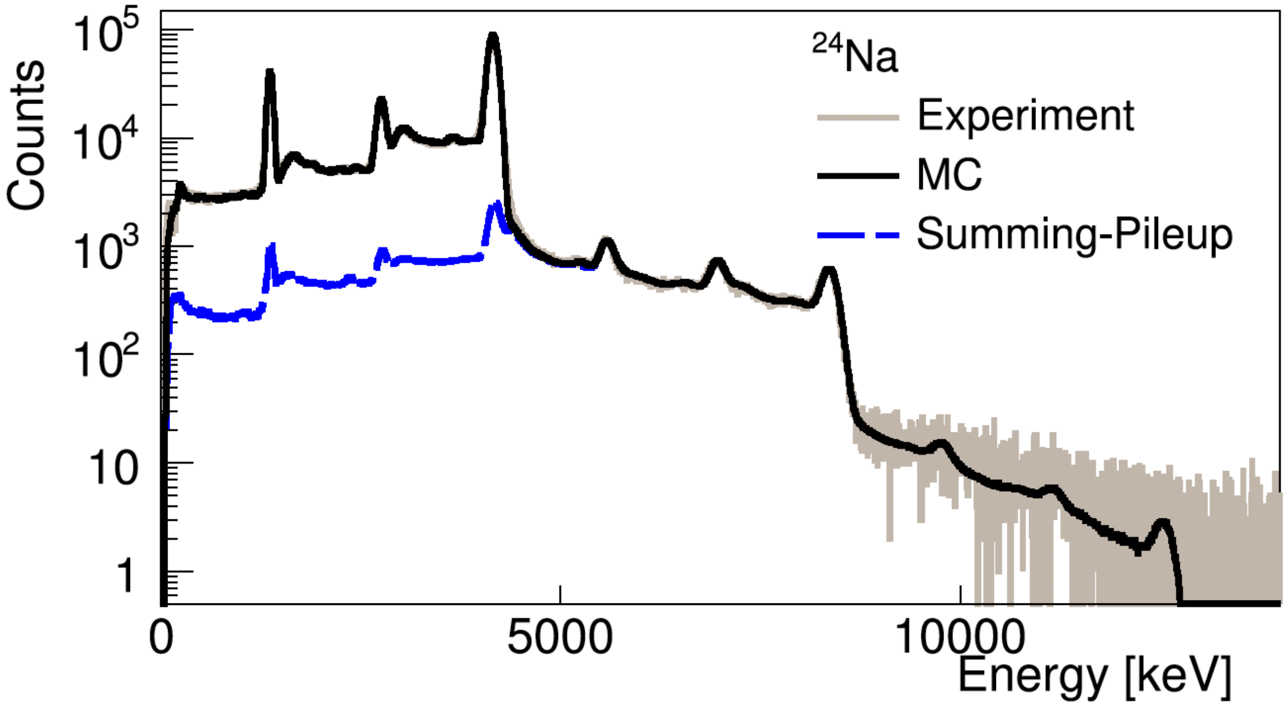
How these challenging experiments are analyzed?

Needs/challenges d=R(B).f

Validation of Monte Carlo simulations with well-know sources

Excellent calibration (energy and witdh), for both exp. and MC



V. Guadilla et al., PhD thesis

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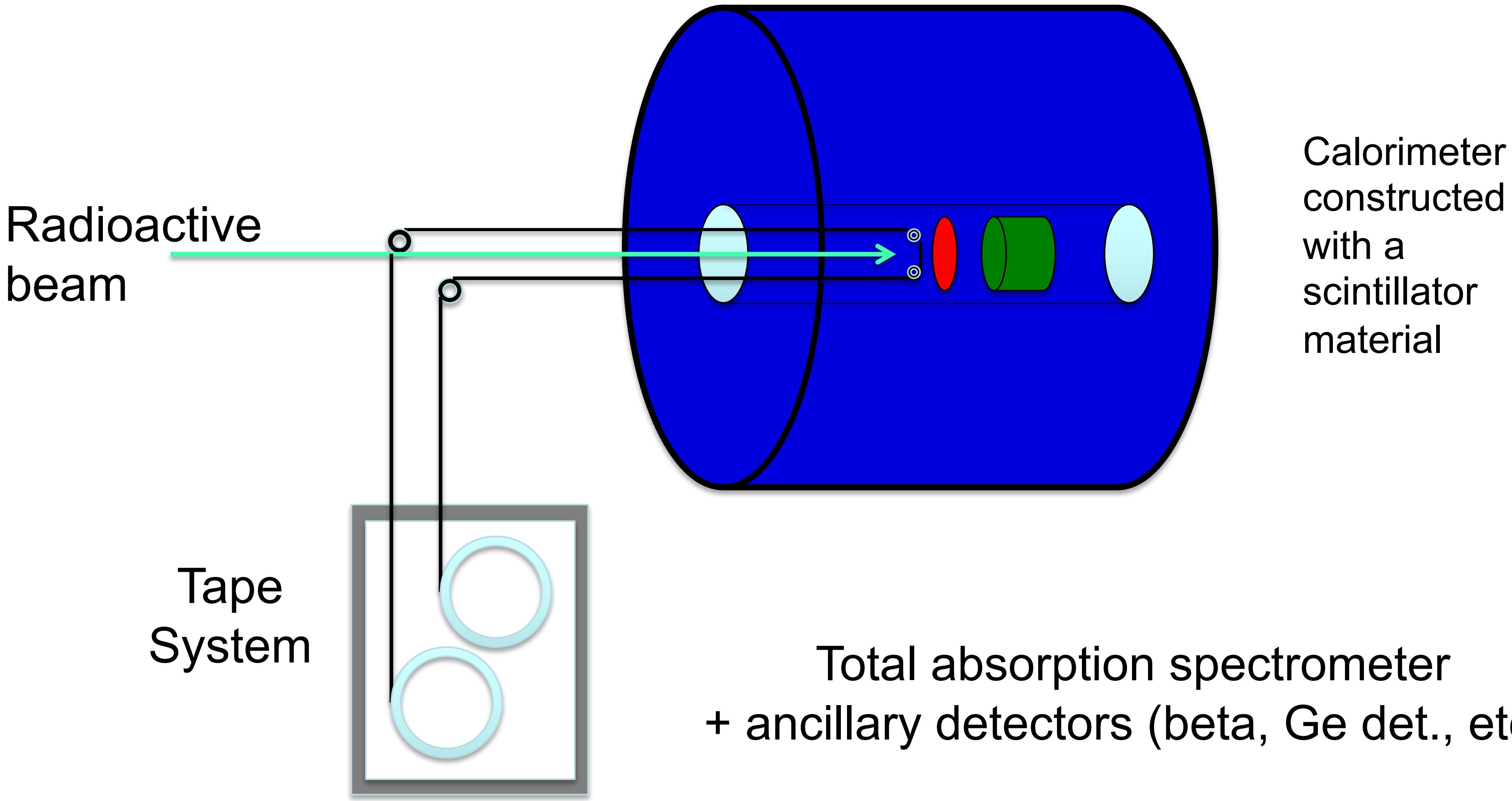
Typical total absorption experiments



Total absorption spectrometer
+ ancillary detectors (beta, Ge det., etc.)

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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)

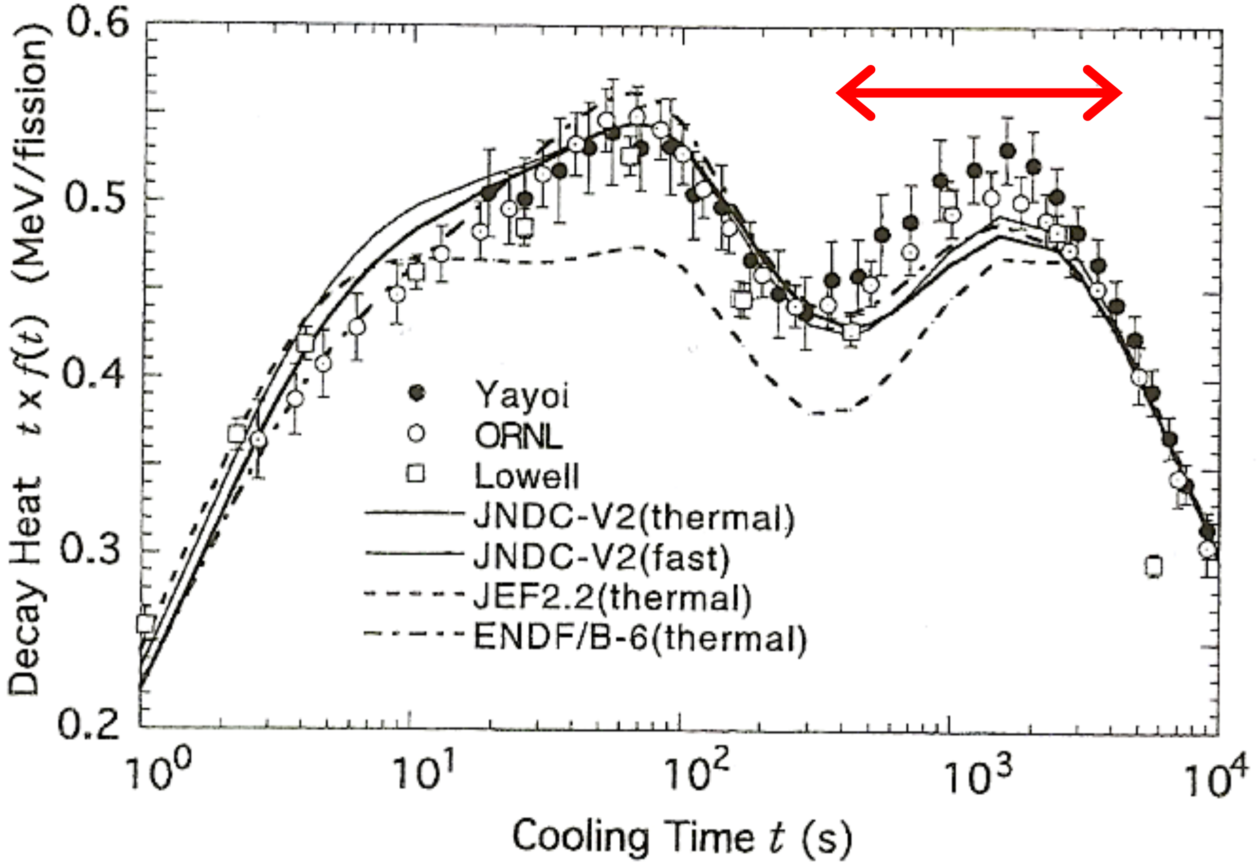
^{239}Pu example (similar situation for ^{235,238}U)

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

Suggestion TAGS measurements !!!

^{239}Pu example

(fission pulse decay heat γ component)



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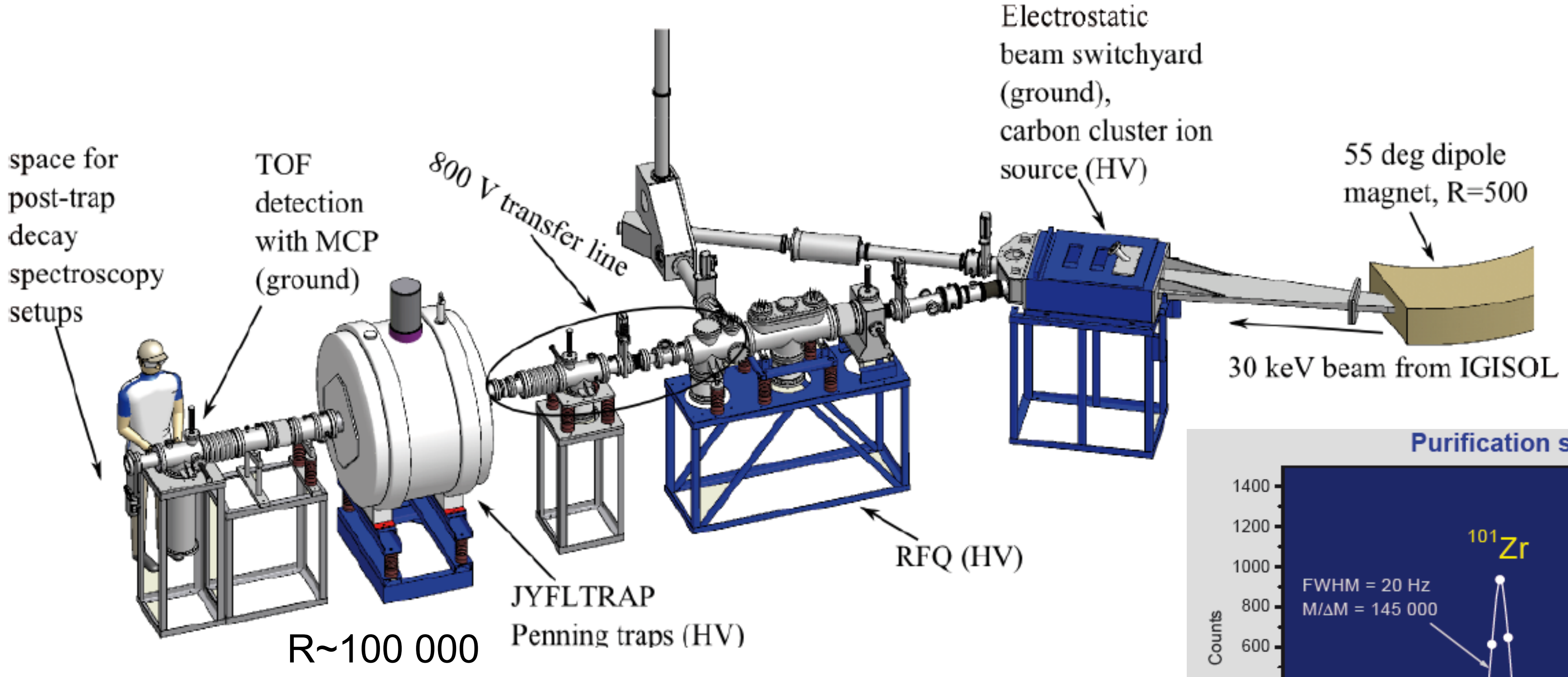
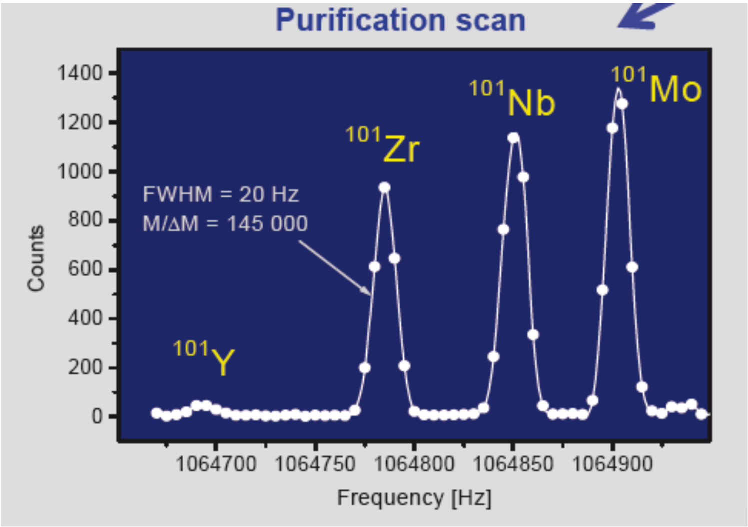
Why JYFL(IGISOL)?: ion guide technique + a bonus





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!

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

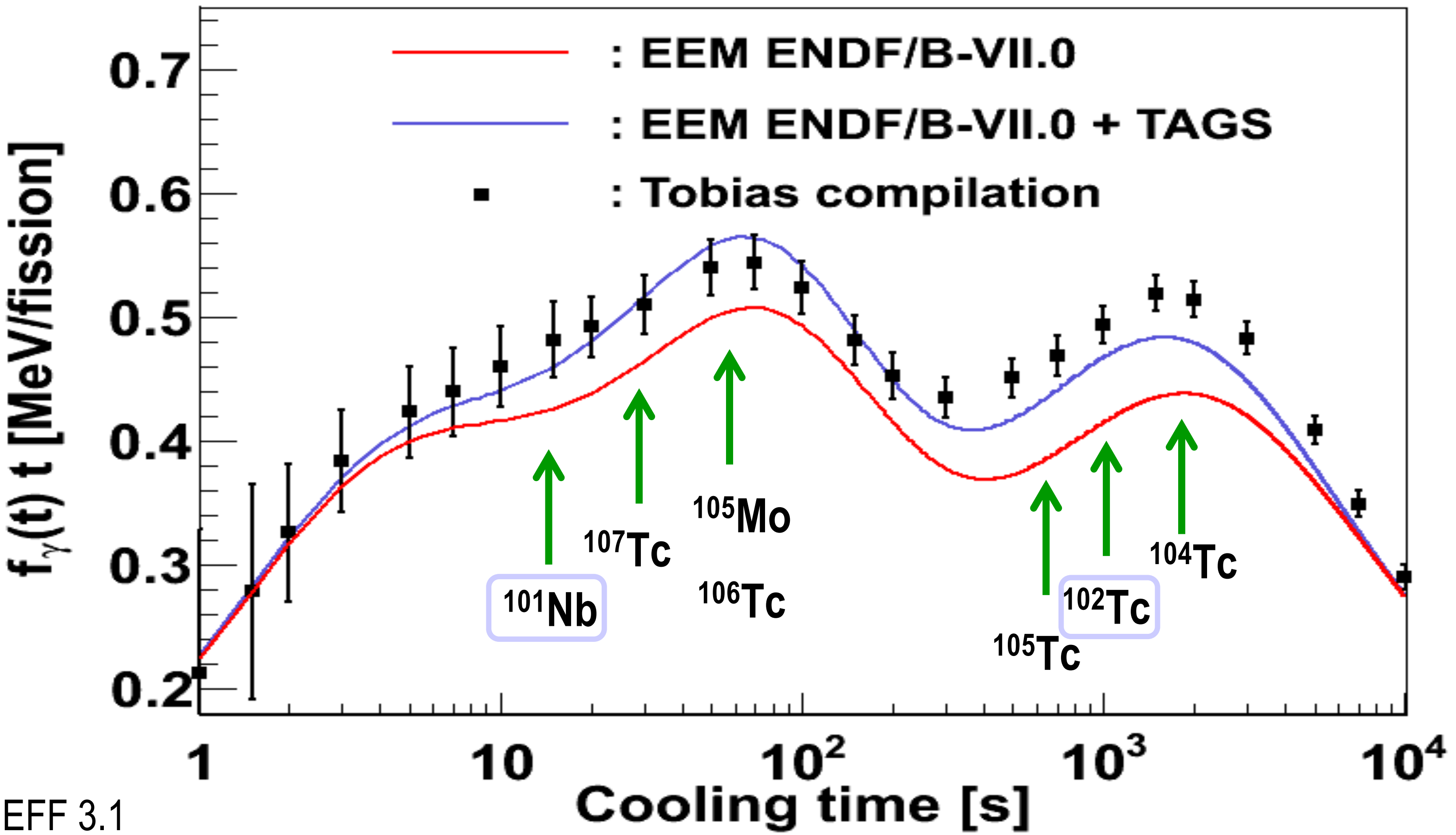
Motivated by Yoshida *et al.* (Journ. of Nucl. Sc. and Tech. 36 (1999) 135) and WPEC-25

Algora, Phys. Rev. Letts. 105, 202505,

PhD Thesis D. Jordan,

K. P. Rykaczewsky

Physics 3, 94 (2011)



DH Courtesy A. Sonzogni

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

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Tables extracted from « Beta-decay studies for applied and basic nuclear physics », Algora et al. Eur. Phys. J. A 57 (2021) 85, 2020

Some published and on-going cases for Decay Heat and Antineutrino Spectrum calculations

Table 2. List of parent nuclides identified by the WPEC-25 (Nuclear Energy Agency working group) that should be measured using the total absorption technique to improve the predictions of the decay heat in reactors [48,49]. These nuclides are of relevance for conventional reactors based on ^{235}U and ^{239}Pu fission. The list contains 37 nuclides. Rel. (relevance) stands for the priority of the measurement. Isotopes marked with asterisks show the measurements performed by our collaboration. Nuclides marked with † are also relevant for the ^{233}U/^{232}Th fuel, see additional cases in Table 3. The isotopes are identified according to the Z-Symbol-A notation; m stands for metastable or isomeric state.

Isotope	Rel.	Isotope	Rel.	Isotope	Rel.
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		

Table 6. List of nuclides identified by the IAEA TAGS Consultants that should be measured using the total absorption technique to improve the predictions of the reactor antineutrino spectra. These nuclides are of relevance for conventional reactors based on ^{235}U and ^{239}Pu nuclear fuels. The list contains 34 nuclides [103]. Relevance (Rel.) stands for the priority of the measurement. Isotopes marked with asterisks show the measurements performed by our collaboration, m stands for metastable or isomeric state.

Isotope	Rel.	Isotope	Rel.	Isotope	Rel.
36-Kr-91	2	39-Y-97m	1	53-I-138*	2
37-Rb-88	1	39-Y-98m	1	54-Xe-139	1
37-Rb-90	1	39-Y-99*	1	54-Xe-141	2
37-Rb-92*	1	40-Zr-101	1	55-Cs-139	1
37-Rb-93*	1	41-Nb-98*	1	55-Cs-140*	1
37-Rb-94*	2	41-Nb-100*	1	55-Cs-141	2
38-Sr-95*	1	41-Nb-101*	1	55-Cs-142*	1
38-Sr-96	1	41-Nb-102*	1	57-La-146	2
38-Sr-97	2	41-Nb-104m	2		
39-Y-94	1	52-Te-135	1		
39-Y-95*	1	53-I-136	2		
39-Y-96*	1	53-I-136m	1		
39-Y-97	2	53-I-137*	1		

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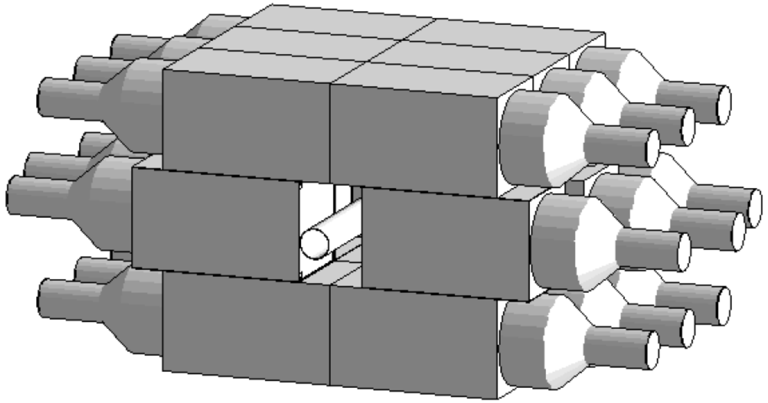
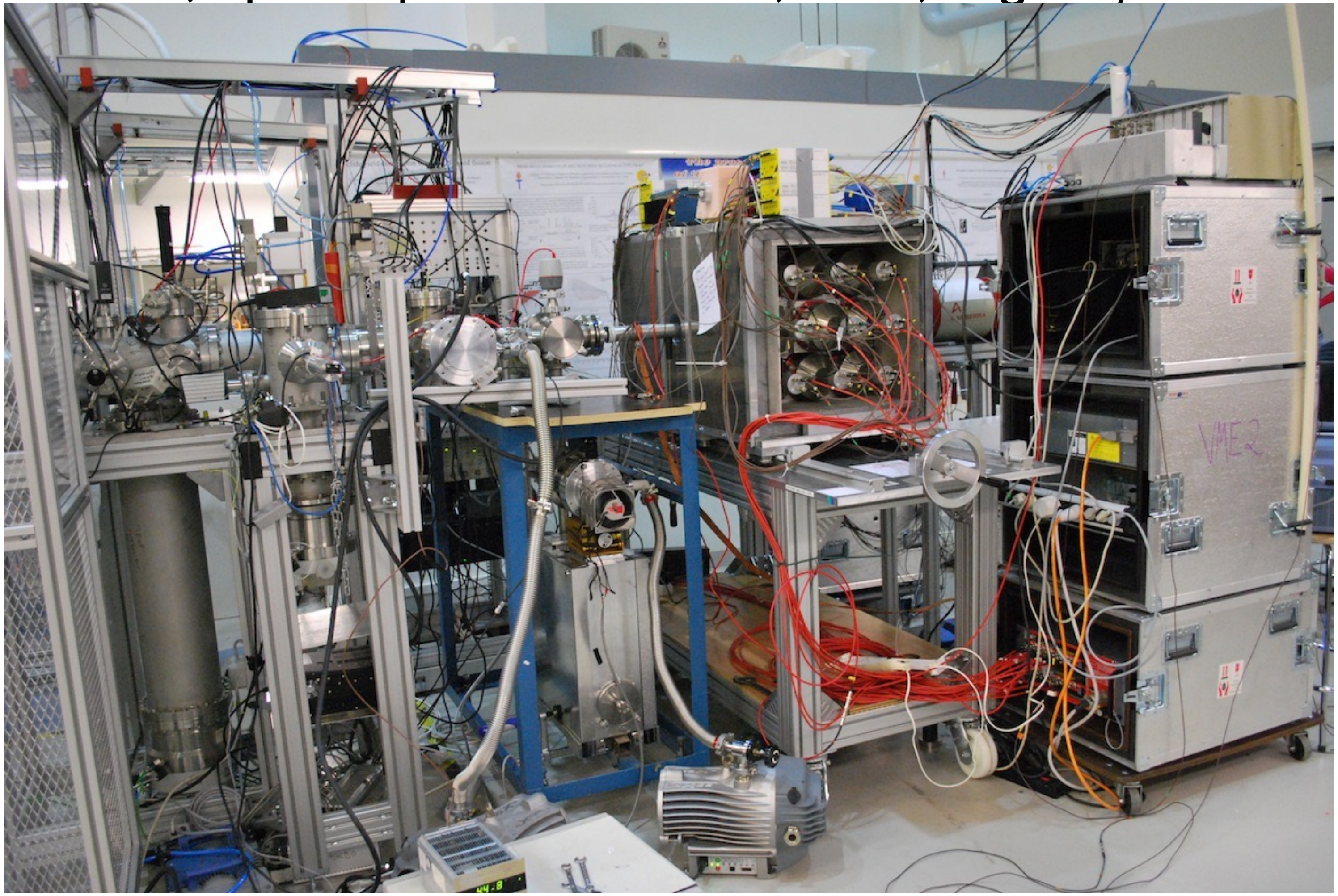
DTAS at Jyväskylä (Feb. 2014)

(Subatech-Valencia Collab., spokespersons: Fallot, Tain, Algora)





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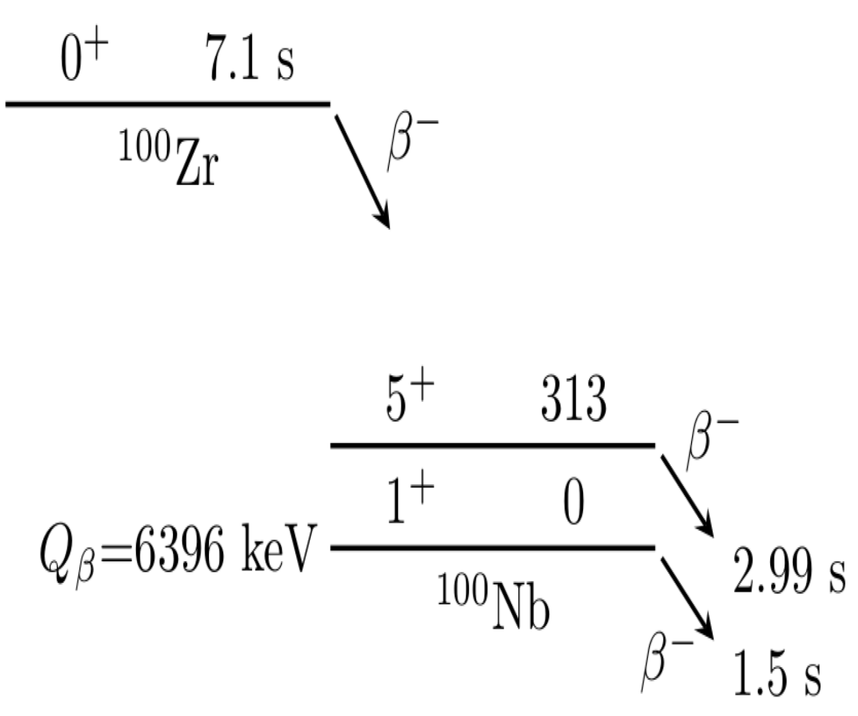
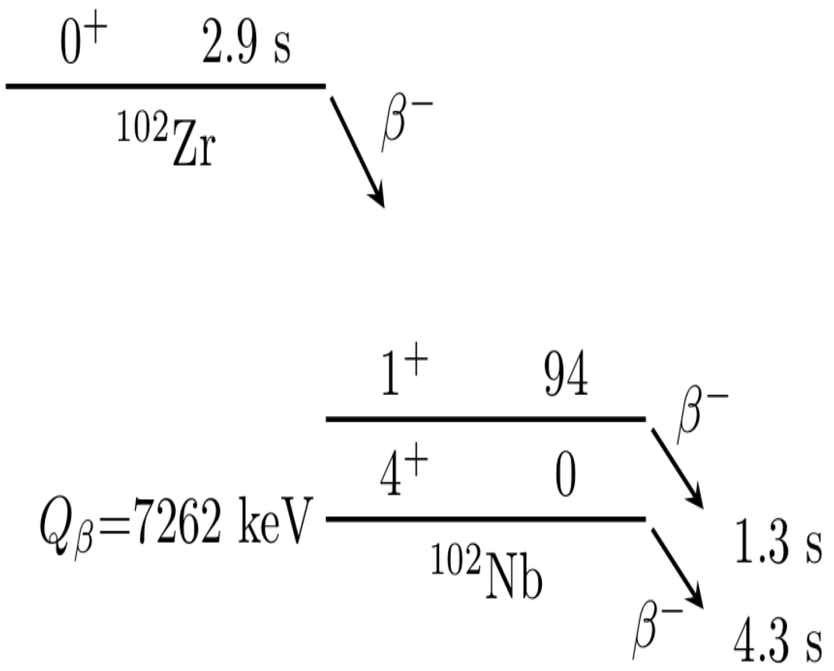
Example: the challenging ^{100,102}Nb cases (from 18(+5) relevant decays measured)





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

Challenge: small separation energy, similar half-lives

Tricks: Production through the parent, purification cycles in the Penning Trap (Ramsey cleaning), separation using different sorting times

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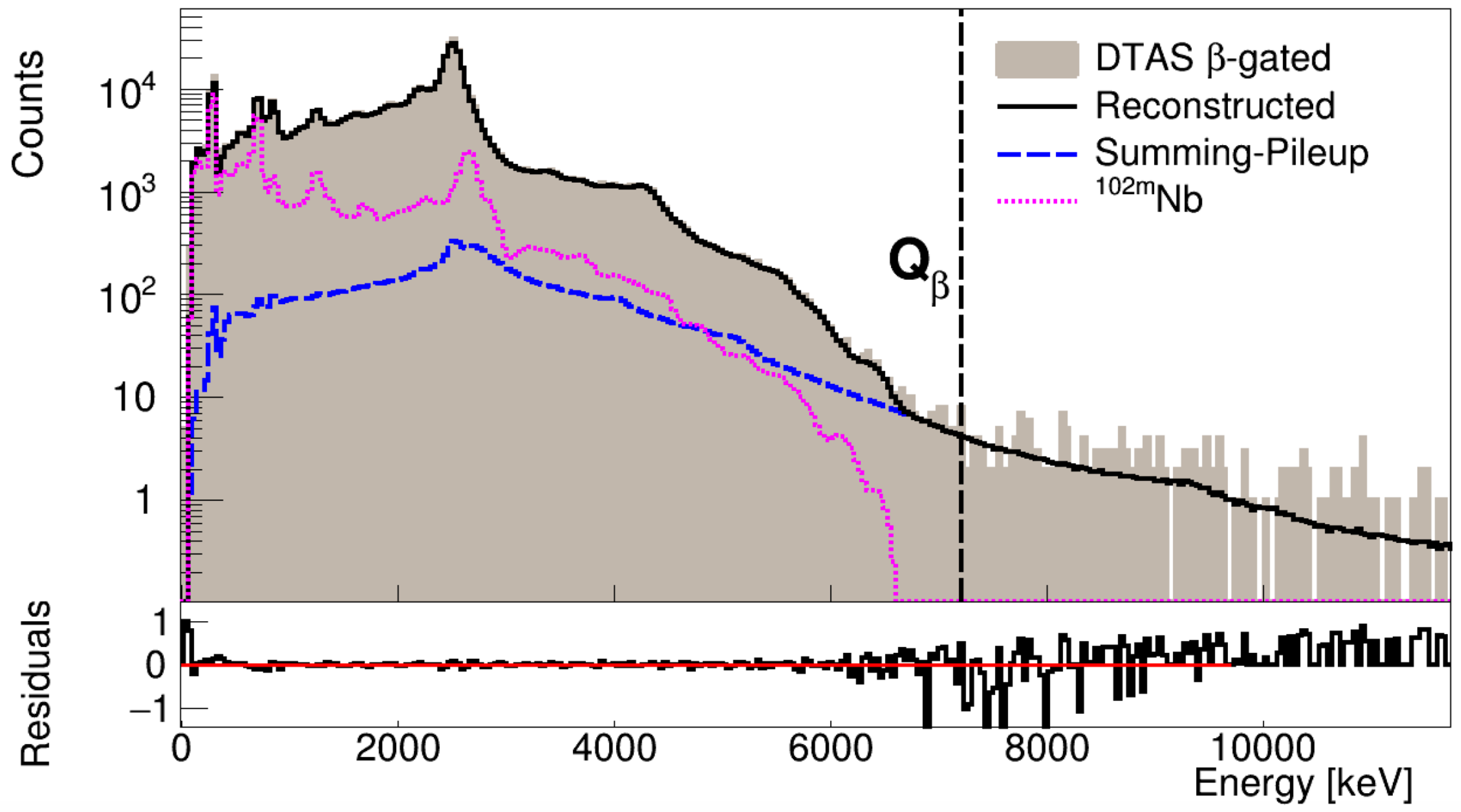
^{102gs}Nb decay (4+ state)



V. Guadilla et al., PhD thesis and V. Guadilla et al., PRL 112.042502

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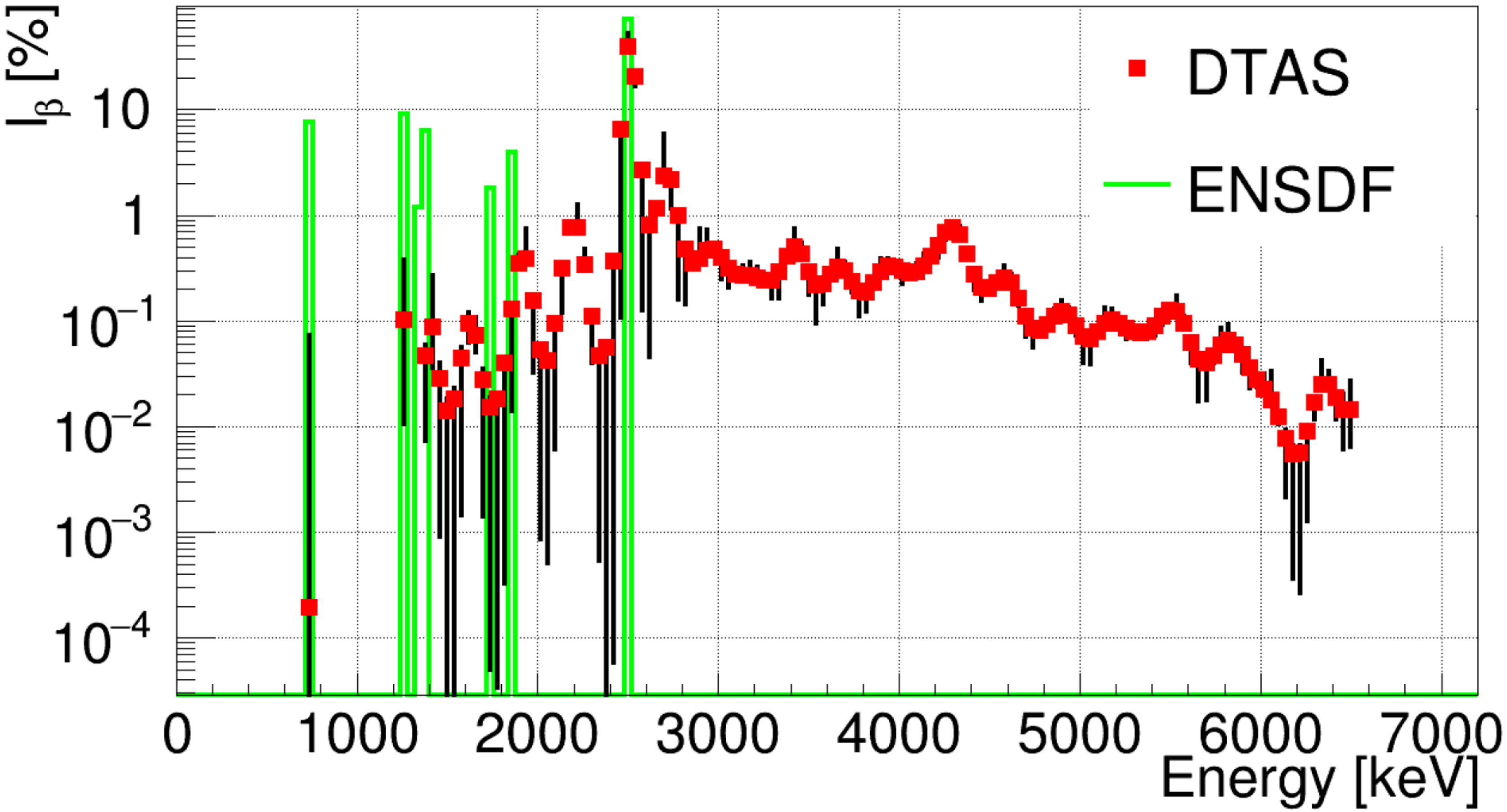
^{102gs}Nb decay (4+ state)



V. Guadilla et al., PhD thesis and V. Guadilla et al., PRL 112.042502

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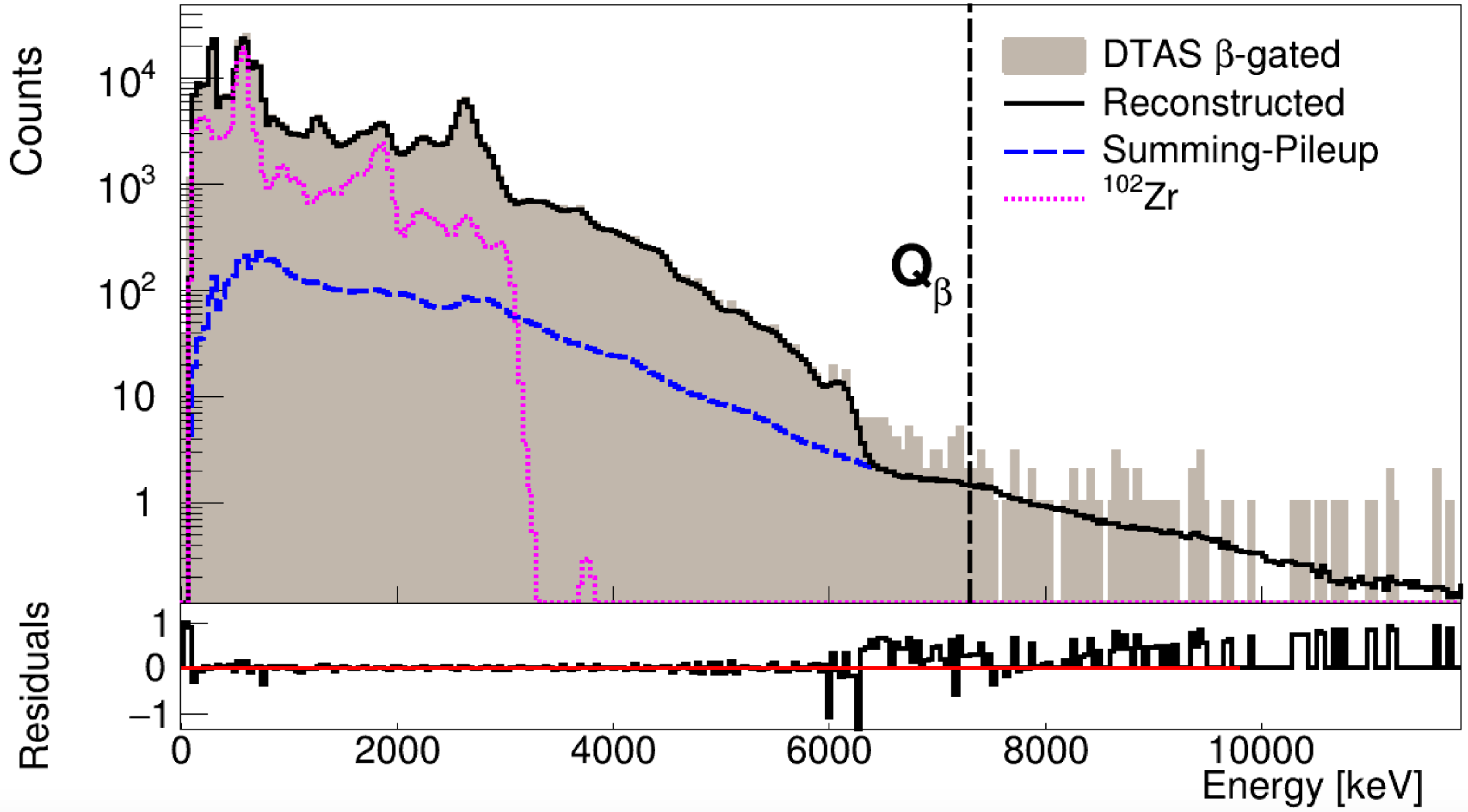
^{102m}Nb decay (1+ state, 94 keV)



V. Guadilla et al., PhD thesis and V. Guadilla et al., PRL 112.042502

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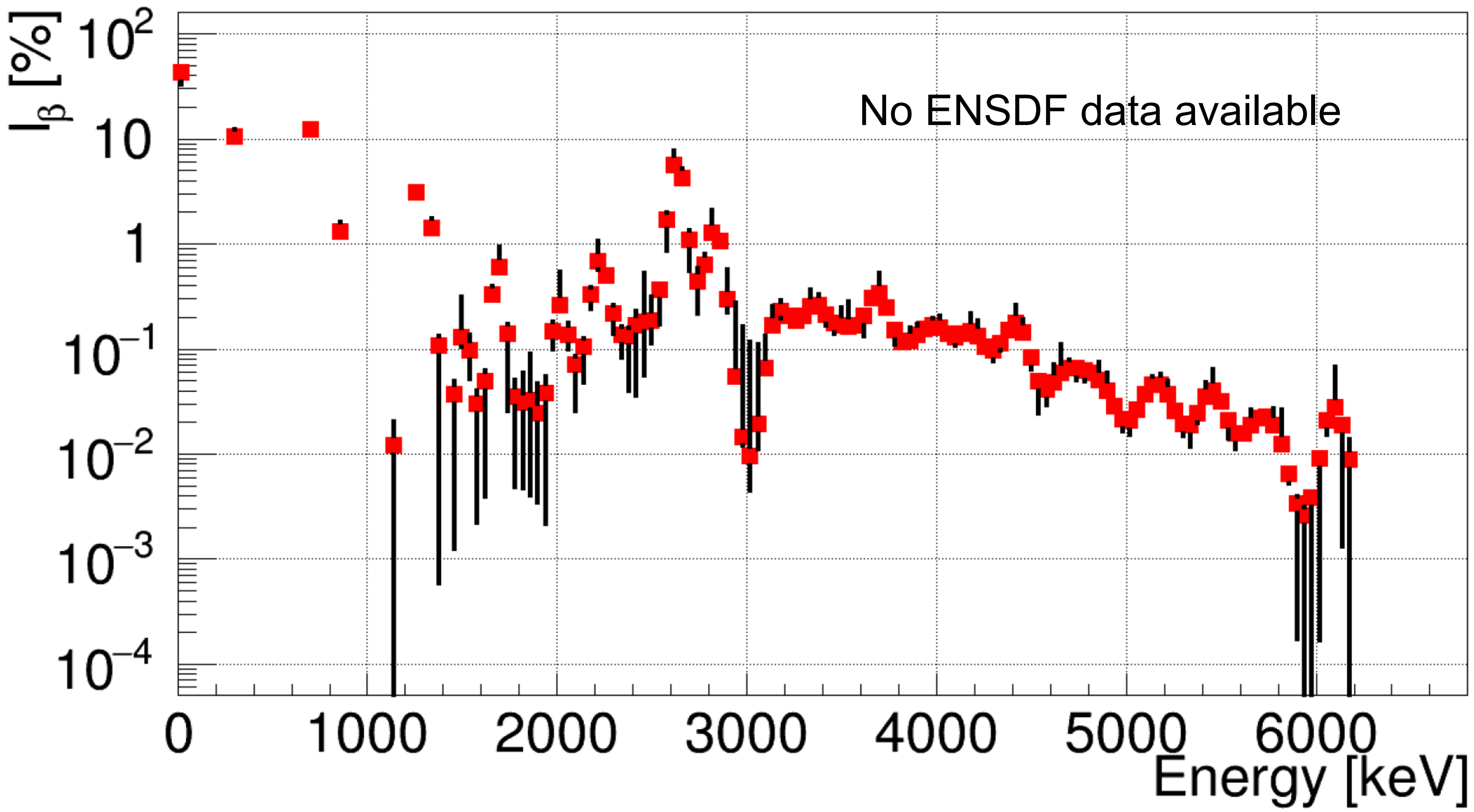
^{102m}Nb decay (1+ state, 94 keV)



V. Guadilla et al., PhD thesis and V. Guadilla et al., PRL 112.042502

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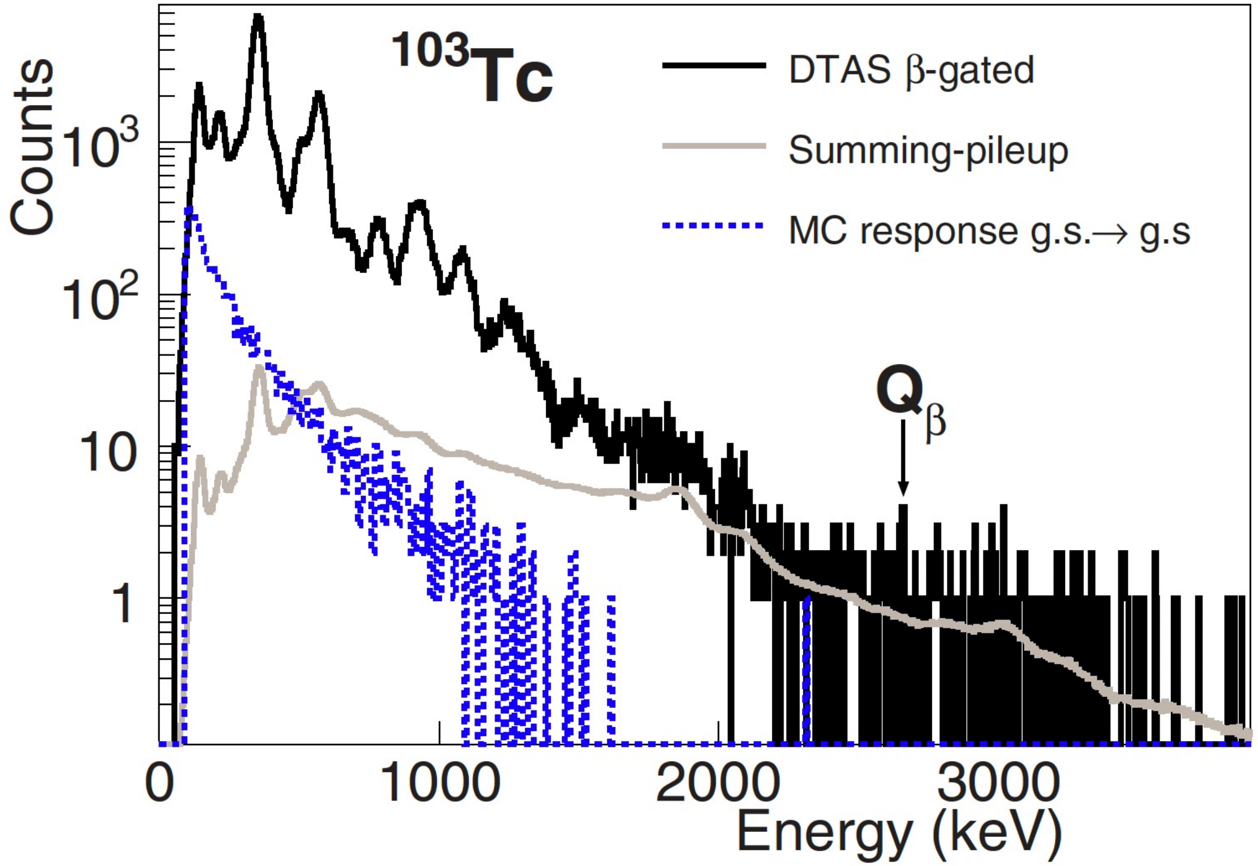
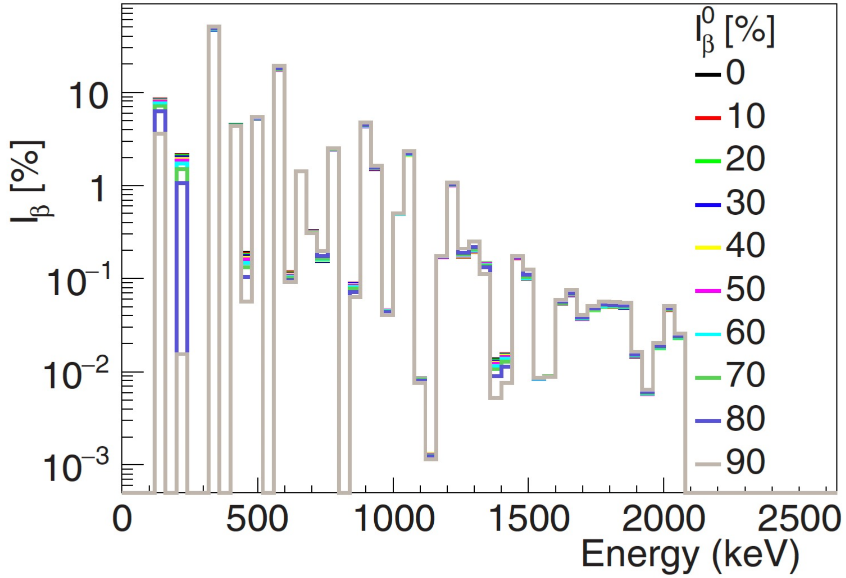
^{103}Tc decay (an odd TAGS case) Bad luck or serendipity?



Guadilla et al. PRC 102, 064304 (2020)

TAGS analysis insensitive to the assumed ground state feeding



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A new method for determining the gs to gs feeding from TAGS exp.

Based on a comparison of the number of counts detected in the beta detector (N_β) with the number of counts detected in the TAS in coincidence with the betas ($N_{\beta\gamma}$)

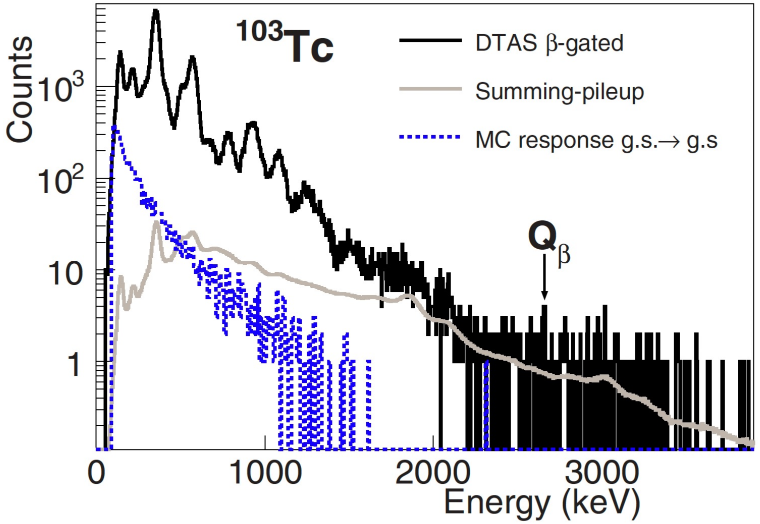
$$I_\beta^0 = \frac{1 - \frac{N_{\beta\gamma}}{N_\beta}\frac{\bar{\varepsilon}_\beta^*}{\bar{\varepsilon}_{\beta\gamma}^*}}{1 + \frac{N_{\beta\gamma}}{N_\beta}\frac{\varepsilon_\beta^0 - \bar{\varepsilon}_\beta^*}{\bar{\varepsilon}_{\beta\gamma}^*} - \frac{\varepsilon_{\beta\gamma}^0}{\bar{\varepsilon}_{\beta\gamma}^*}}.$$

ε_β^*, $\varepsilon_{\beta\gamma}^*$ are average efficiencies to excited states

ε_β^0, $\varepsilon_{\beta\gamma}^0$ average efficiencies to gs

Corrected form in comparison with the earlier work of Greenwood et al. NIM A317 (1992) 175

The method was tested with synthetic data.



$I_\beta^0(^{103}Tc) = 45.6(+1.5\text{-}0.9)$

ENSDF value 34(8)

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Ground state feedings obtained with the new method

	I_β^0 (%)		
Isotope	ENSDF	TAGS	$4\pi\gamma-\beta$
^{95}Rb	$\leqslant 0.1$	$0.03^{+0.11}_{-0.02}$	$-0.2(42)$
^{100gs}Nb	50(7)	46^{+16}_{-15}	40(6)
^{102m}Nb	—	$42.5^{+9.3}_{-10.0}$	44.3(28)
^{100}Tc	93.3(1)	93.9(5)	92.8(5)
^{103}Tc[a]	34(8)	—	$45.6^{+1.5}_{-0.9}$
^{137}I	45.2(5)	$50.8^{+2.7}_{-4.3}$	45.8(13)
^{140}Cs	35.9(17)	$39.0^{+2.4}_{-6.3}$	36.0(15)

[a]For this decay the I_β^0 numbers include the intensity to the first excited state in ^{103}Ru at 2.81(5) keV.

Guadilla et al. PRC 102, 064304

Reduced uncertainties and consistency with the TAGS results

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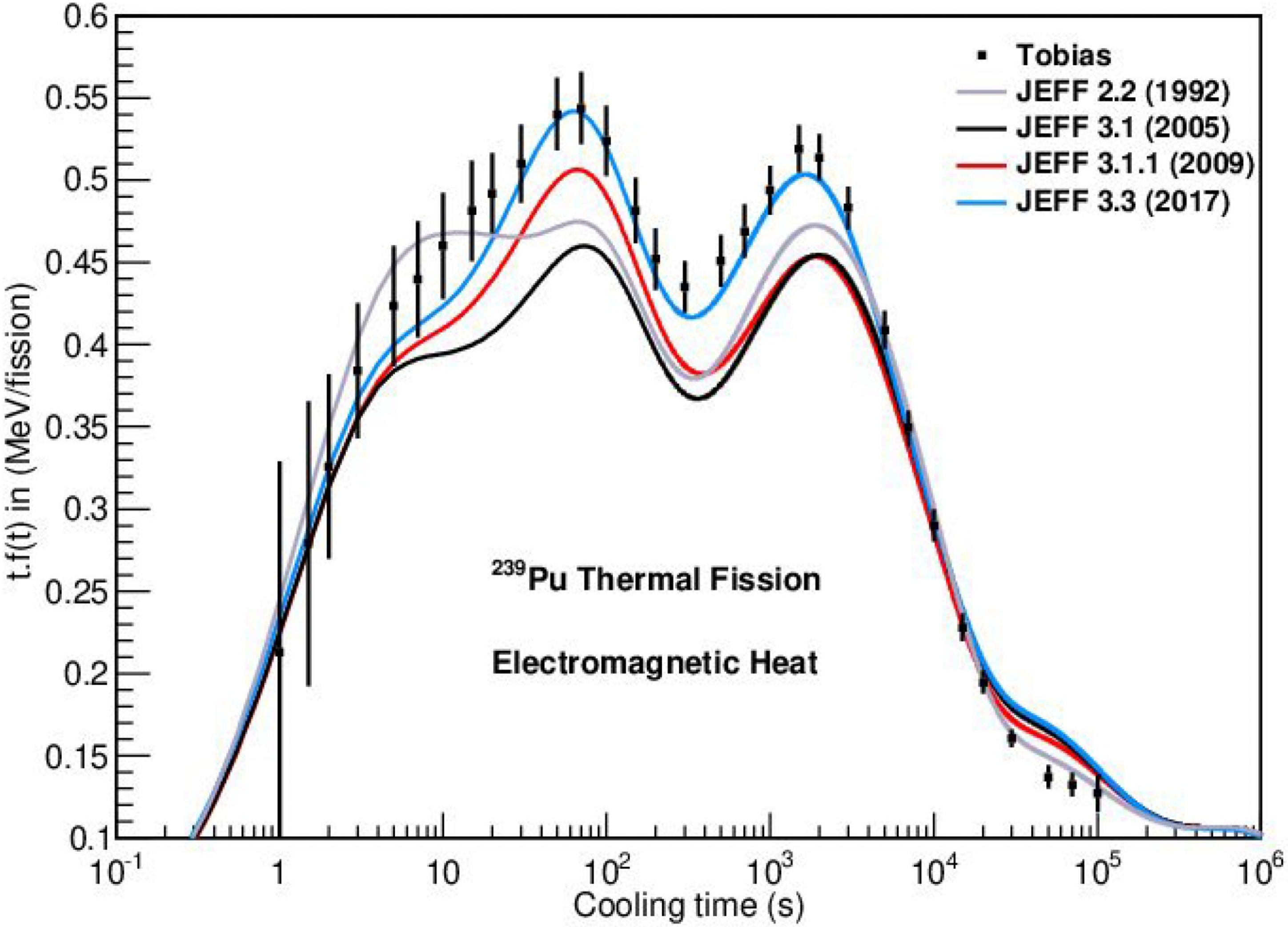
Impact of the measurements for ^{239}Pu



Nichols, Dimitriou, et al.,
Eur. Phys. J. A (2023) 59:78
https://arxiv.org/abs/2212.10335

Courtesy of L. Giot with SERPENT

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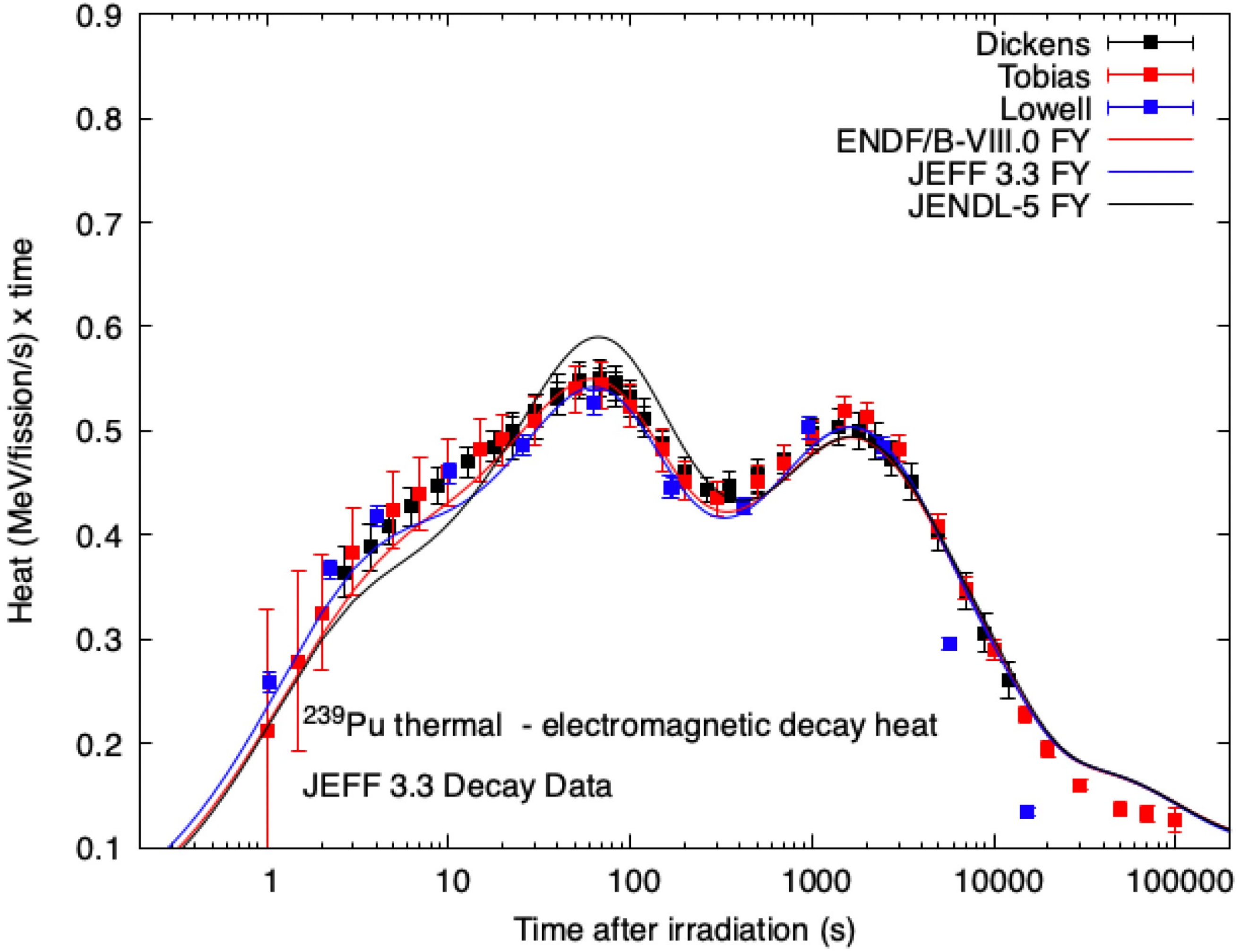
Impact of the fission yields for ^{239}Pu



Nichols, Dimitriou, et al.,
Eur. Phys. J. A (2023) 59:78
https://arxiv.org/abs/2212.10335

Courtesy of L. Giot with SERPENT

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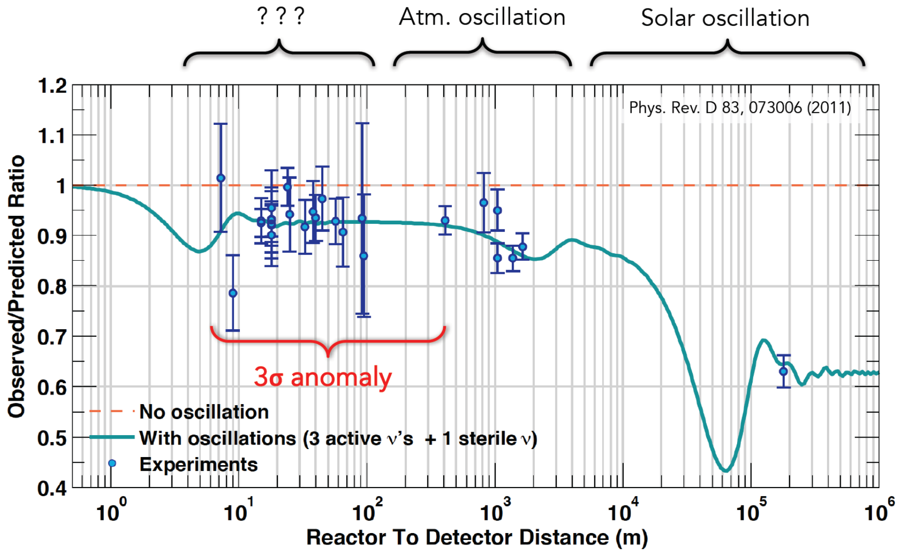
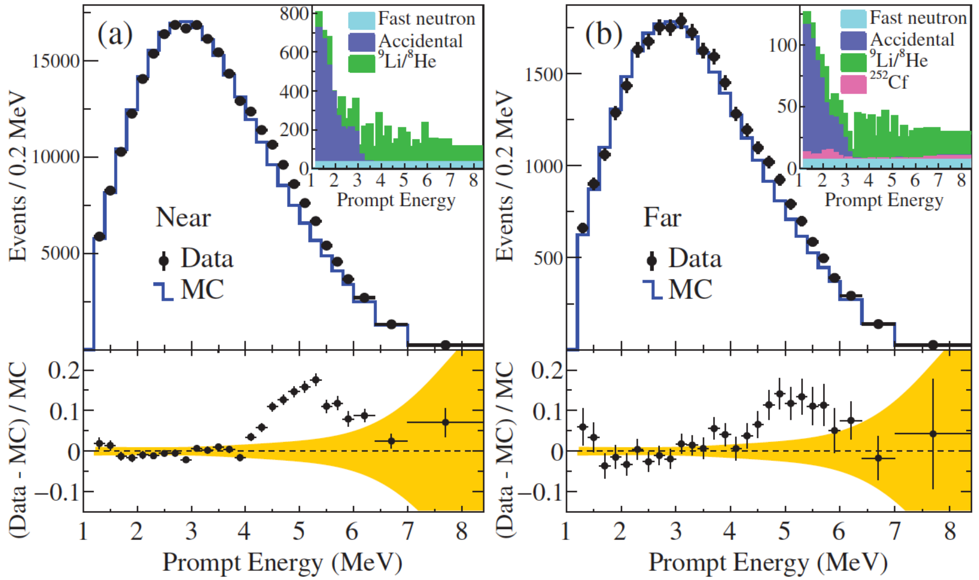
Two problems have attracted considerable attention



Reactor anomaly ?

Deficit in the number of antineutrinos detected in short base lines, compared with the predictions of the Huber-Muller model. It can be explained by the existence of a sterile neutrino.
Mention et al. PRD 83.073006

Spectrum distortion (~5 MeV)



RENO results, PRL 116, 211801 (2016)
Seen also in DAYA BAY
Many possible explanations have been discussed, from problems with the measurements to problems with the antineutrino models

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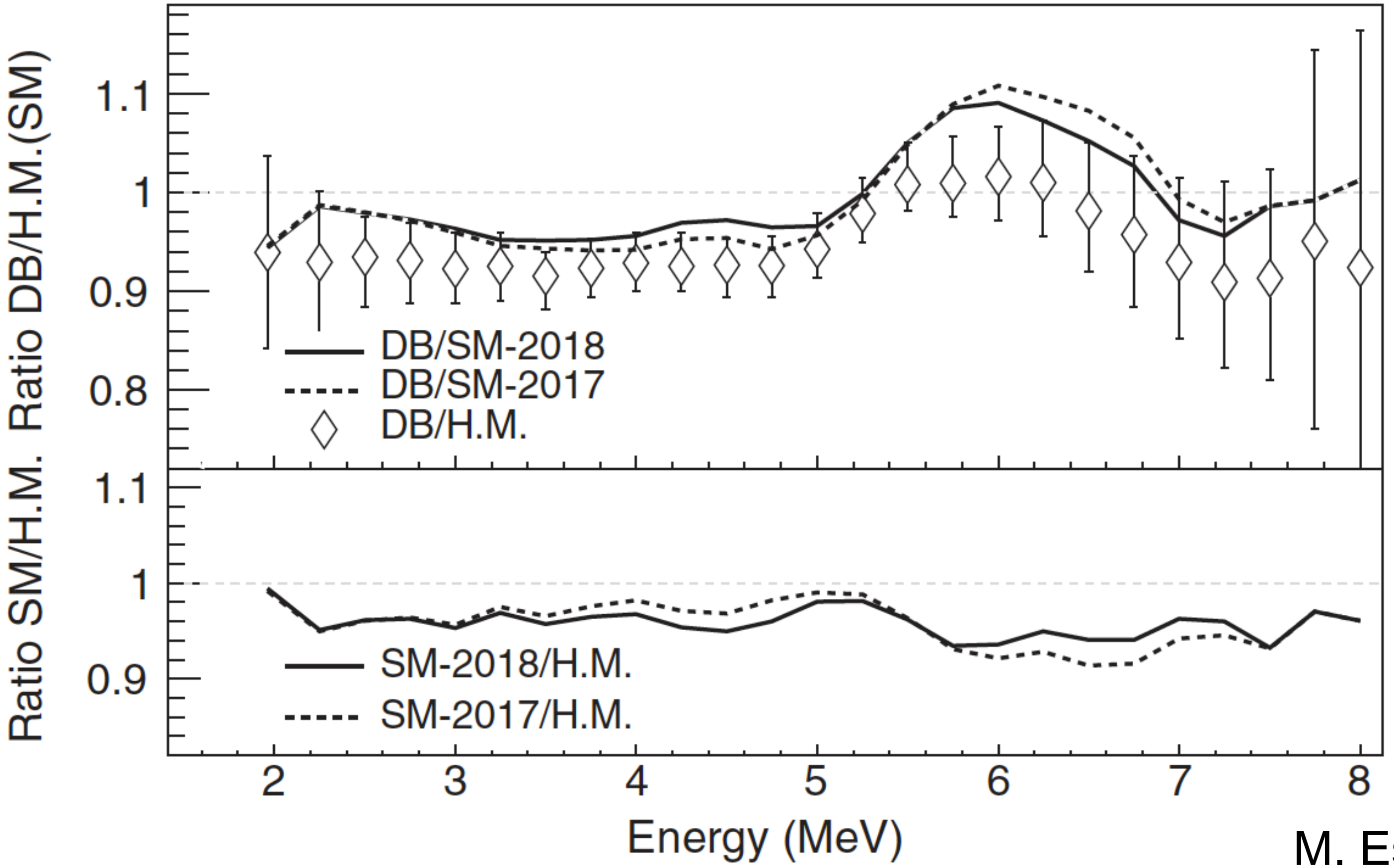
Reactor anomaly, the bump?

Results from the application of a new summation calculation including all our TAS measurements. The discrepancy with the antineutrino meas. within this model is of the order of 2 %



Subatech calculations
Estienne, Fallot, et al.

Summation is slightly better than the Hueber-Mueller conversion in the 2-5 MeV range

M. Estienne, M. Fallot, et al. PRL 123, 022502 (2019)

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We continue working …, this is a marathon

More than 35 decays measured.

In September 2022, a new experiment was performed in Jyvaskyla using trap assisted spectroscopy.

Data has been analyzed by Julien Pepin, co-supervised by Valencia-Nantes

85Se decay analyzed, more comming (cases promised for APRENDE, new man power in the horizon)

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Other challenges

How to translate these data into databases

The BR matrix should be incorporated and this is not trivial.

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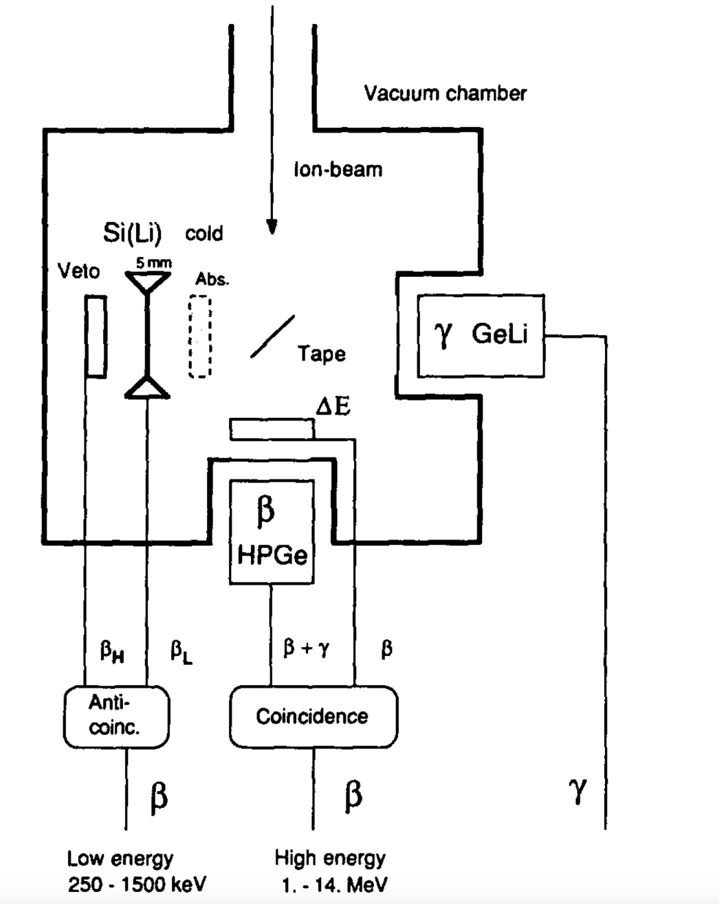
New frontier: beta shape measurements

Earlier attempts:
Tengblad, Rudstam, et al. Nucl. Phys. A503 (1989) 136; Atomic Data and Nuclear and Data Tables 45 (1990)239



The continuous spectra was considered important for testing beta decay data consistency and for determining mean beta (and gamma energies with other setup) released in beta decays for decay heat and for antineutrino summation calculations.

Measurements performed at Osiris (Studsvik) and CERN-ISOLDE

In principle these measurements are free from the problems that can have deduced spectra from other type of measurements (assumptions about the shape)

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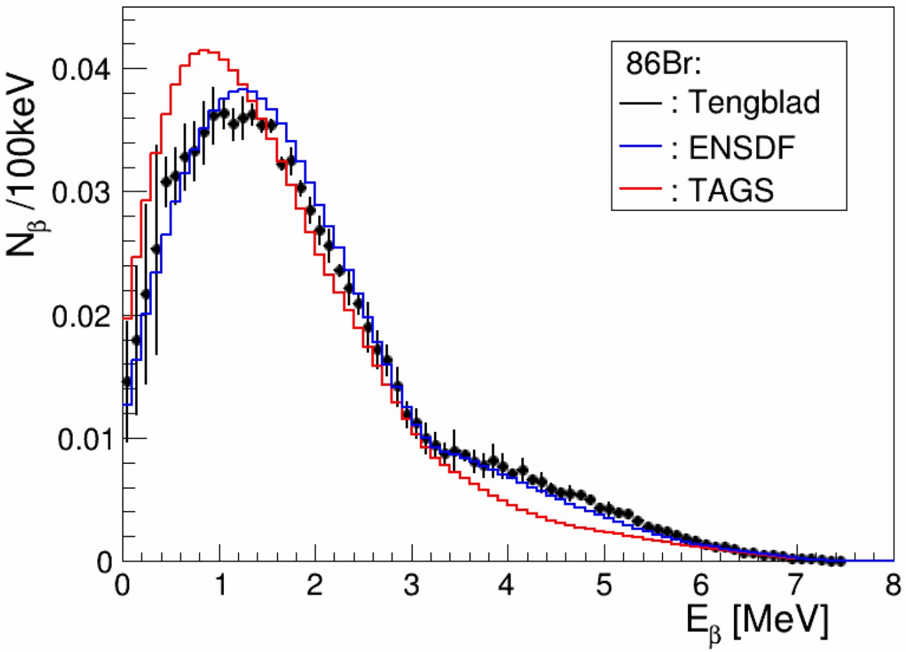
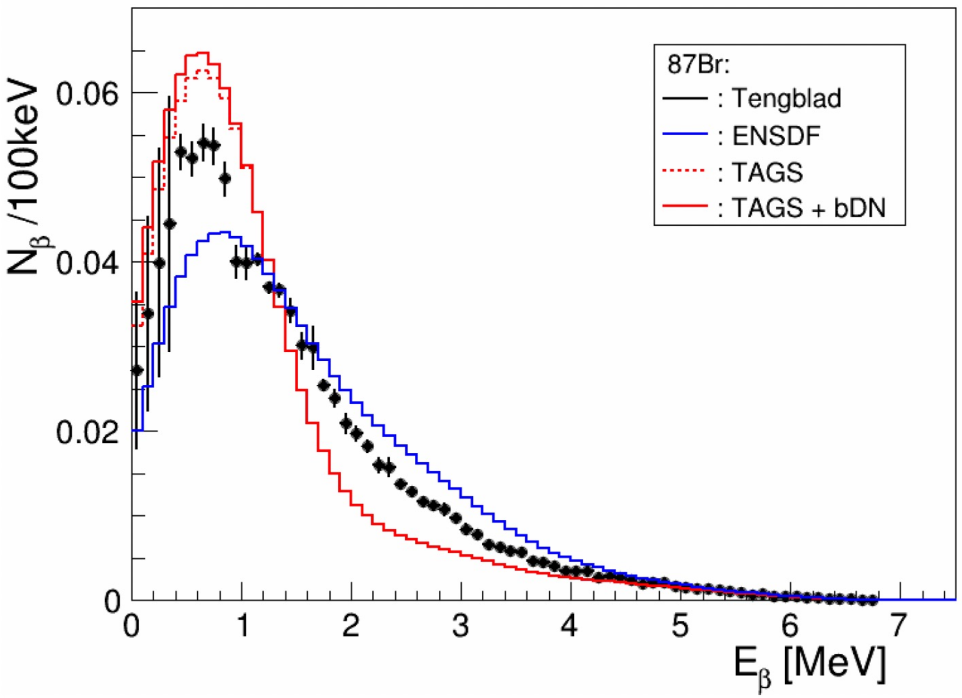
Extra possible control of consistency

Comparison with shapes from TGAS results





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Measurements of the shape of the beta spectrum

I206, I233, I233Add IGISOL proposals, Univ. of Jyväskylä

Spokespersons: A. Algora, M. Fallot, W. Gelletly, local contact: Tommi Eronen

Objetive: measure the shape of the beta spectrum of the most relevant fission Products using isotopically pure beams (trap assisted spectroscopy)

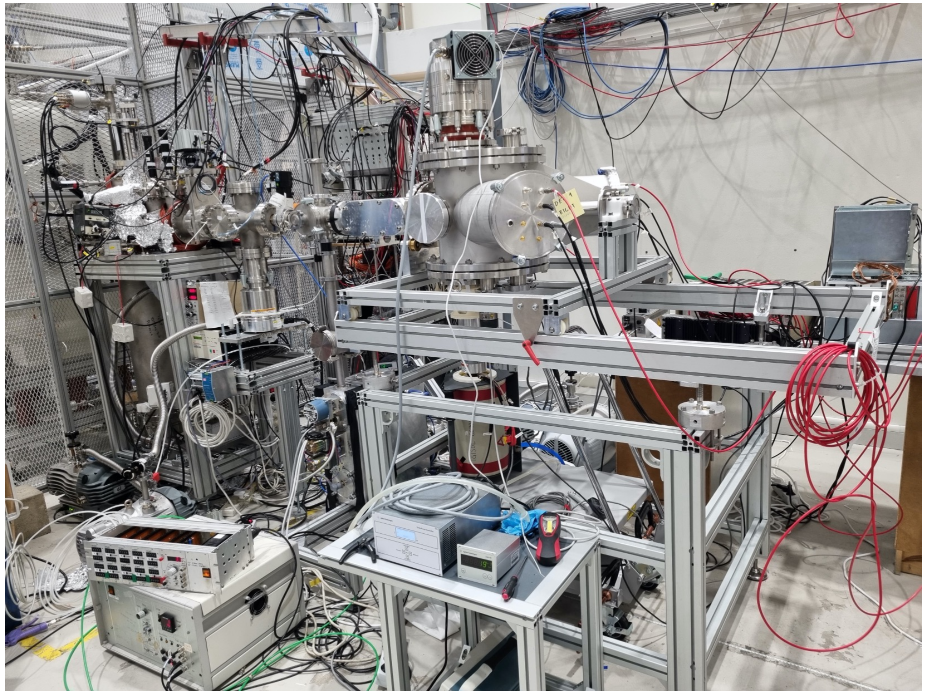
Several works and publications emphasize the need of such measurements:

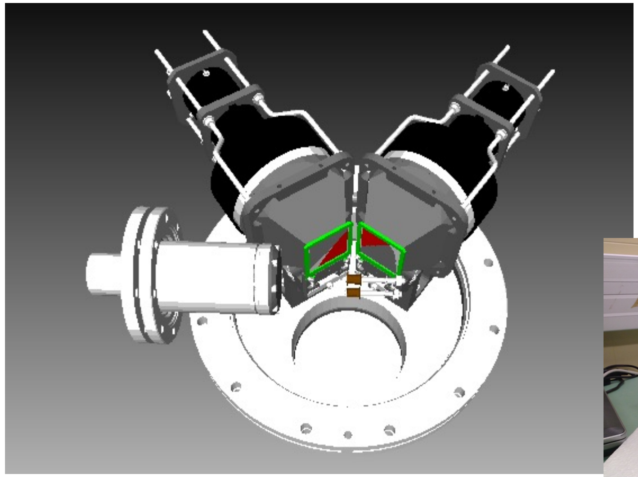
Hayes et al. PRL 112.202501 (2014)

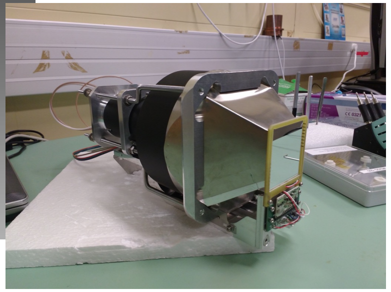
Sonzogni et al. , PRL 119.112501 (2017)

Hayen et al. PRC 99.031311 (2019)

Technical Meeting (IAEA, 2019), Report INDC-NDS-0786







Valencia-Nantes-Surrey-Jyväskylä Collaboration

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How these challenging experiments are analyzed?

Needs:

Excellent calibration (energy and withd)

Well controled Monte Carlo simulations

Methods for solving the inverz problem

$$d=R.o$$

Measured spectrum without contaminants

Response matrix

Original spectrum (goal)

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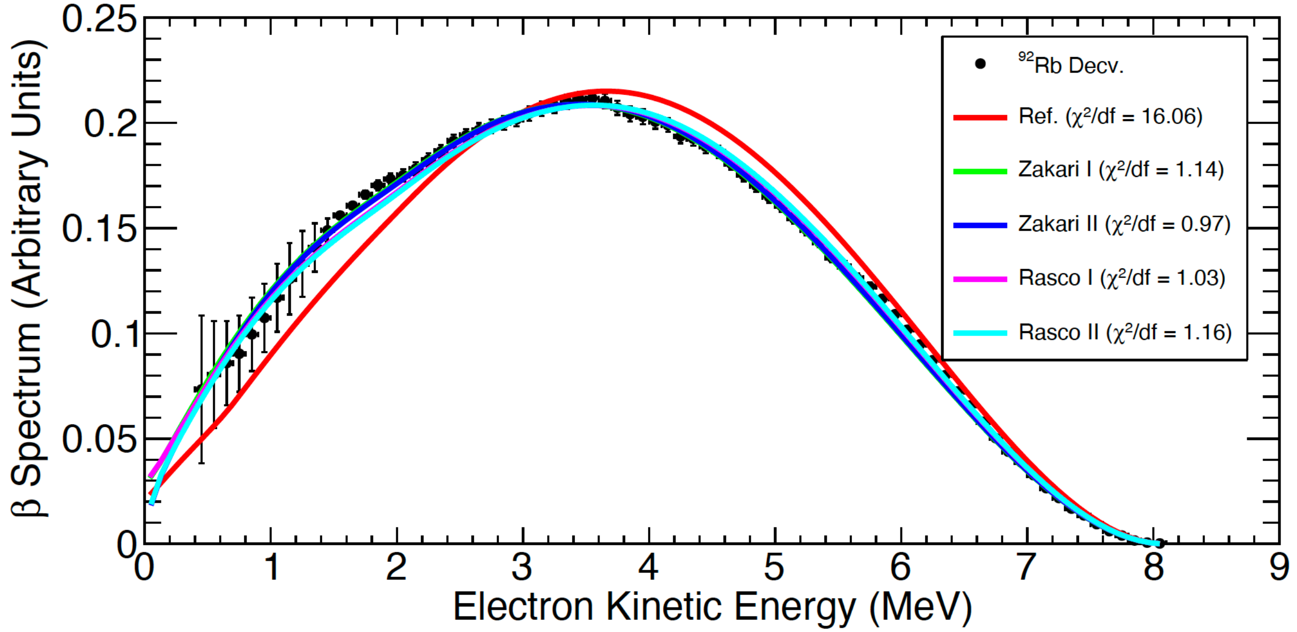
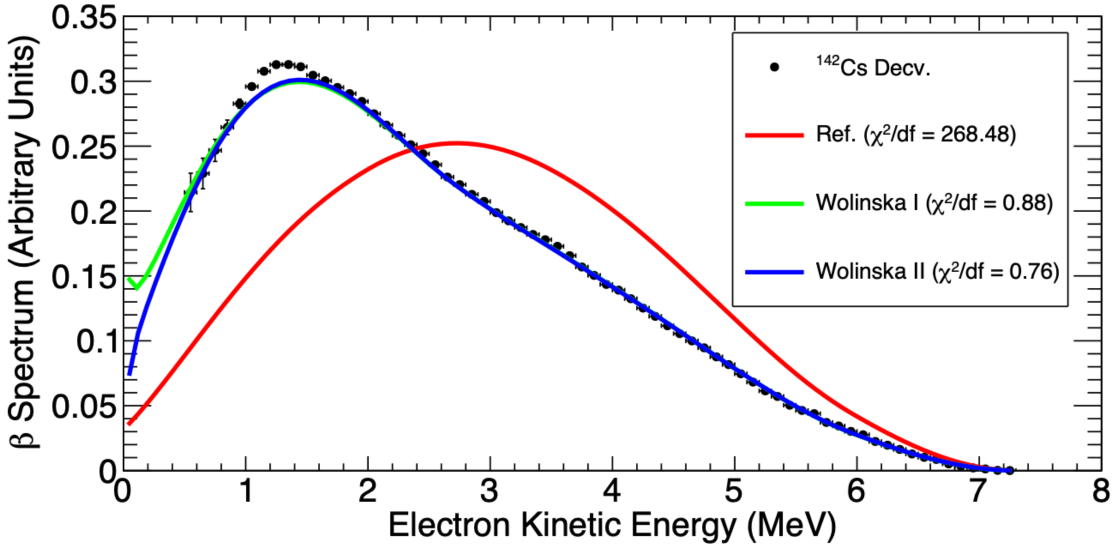
Independent test of TAGS measurements, confirmation of shape corrections



G. Alcalá et al., Phys. Rev. Letts. 135, 142502 (2025)

Test of the shape corrections applied for this important cases for neutrino physics



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Summary

- We hope we have shown that total absorption measurements can provide useful data for applications related to nuclear reactors, in particular for decay heat calculations and for anti-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 here)
- This data can be used to constrain fission yields -decay data in those applications
- The experimental methods introduced can be employed to measure additional beta decays needed to fix fission yields issues.

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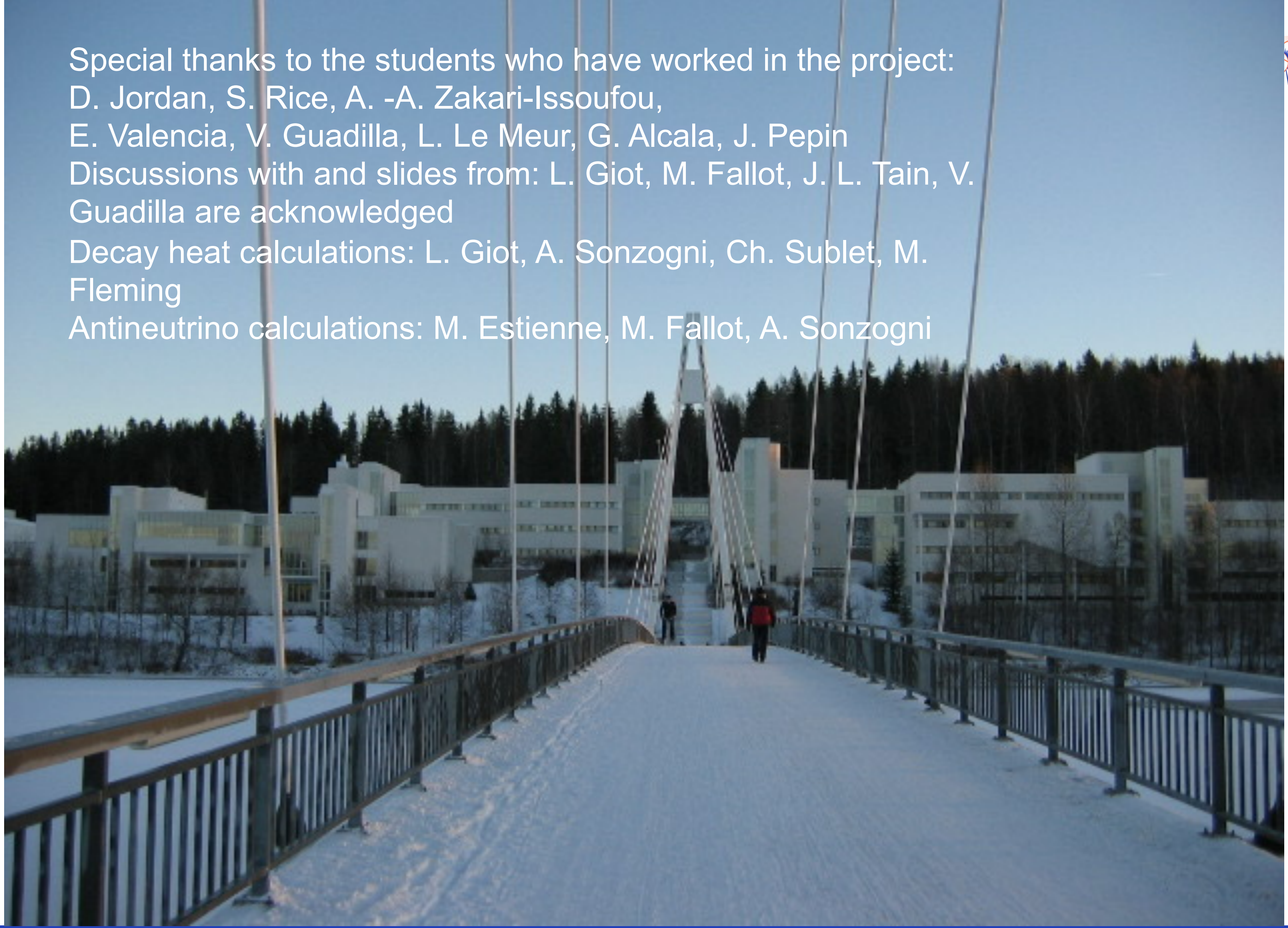
Collaboration

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

Special thanks to the students who have worked in the project:
D. Jordan, S. Rice, A. -A. Zakari-Issoufou,
E. Valencia, V. Guadilla, L. Le Meur, G. Alcala, J. Pepin
Discussions with and slides from: L. Giot, M. Fallot, J. L. Tain, V. Guadilla are acknowledged
Decay heat calculations: L. Giot, A. Sonzogni, Ch. Sublet, M. Fleming
Antineutrino calculations: M. Estienne, M. Fallot, A. Sonzogni



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Get in touch for more information:

https://aprende-project.eu/

contact@aprende-project.eu

Thank you!

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