Aggregate Decay Behavior of Fission Products in Nuclear Reactors

– Decay Heat, Reactor Antineutrino and the Pandemonium Problem –

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Quantities of Practical Importance Reflecting the Aggregate Behavior of Fission Products

(1) FP Decay Heat and the Energy Spectrum of Its Gamma-ray Component
(2) Delayed Neutrons and Its Energy Spectrum
(3) Reactor Antineutrino Flux and Spectrum

Summation Calculation Data Bases Coming From . .

(1) Single γ-ray Measurements
(2) γγ Coincidence Measurements
(3) **Total Absorption γ-ray Spectroscopy**
(4) Theories [**Gross theory**, QRPA, Hauser-Feshbach]

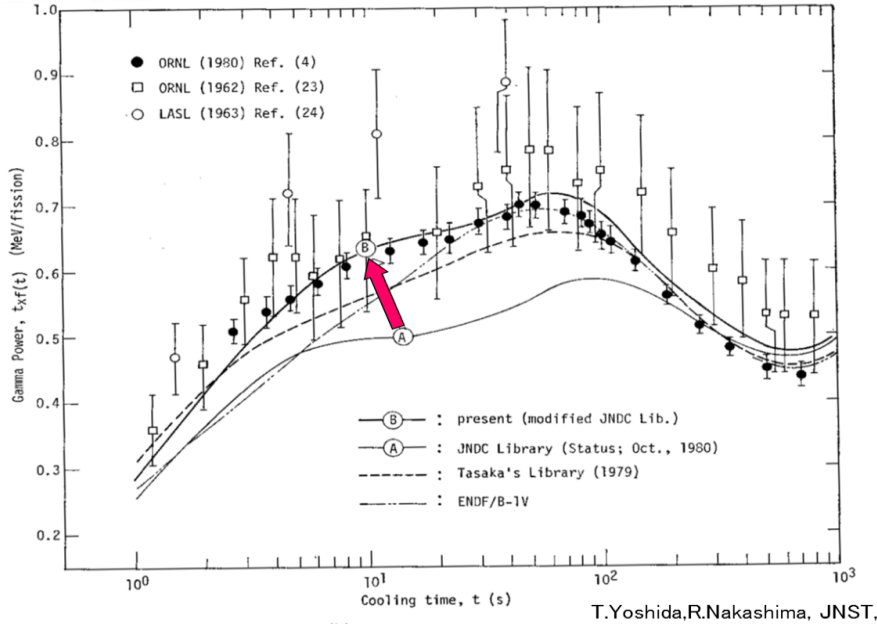
Brief History of Pandemonium Problem (1)

1977 Hardy's warning on β-decay schemes
Pandemonium Problem (*Phys. Lett.*, 71B)

1979 Preliminary Version of JNDC DP Decay Library + Gross Theory ⟷ Decay Heat

Serious discrepancy between calculation and experiments!

The same experiencec in UK (UKFPDD-2) and in the US (ENDF/B-V)

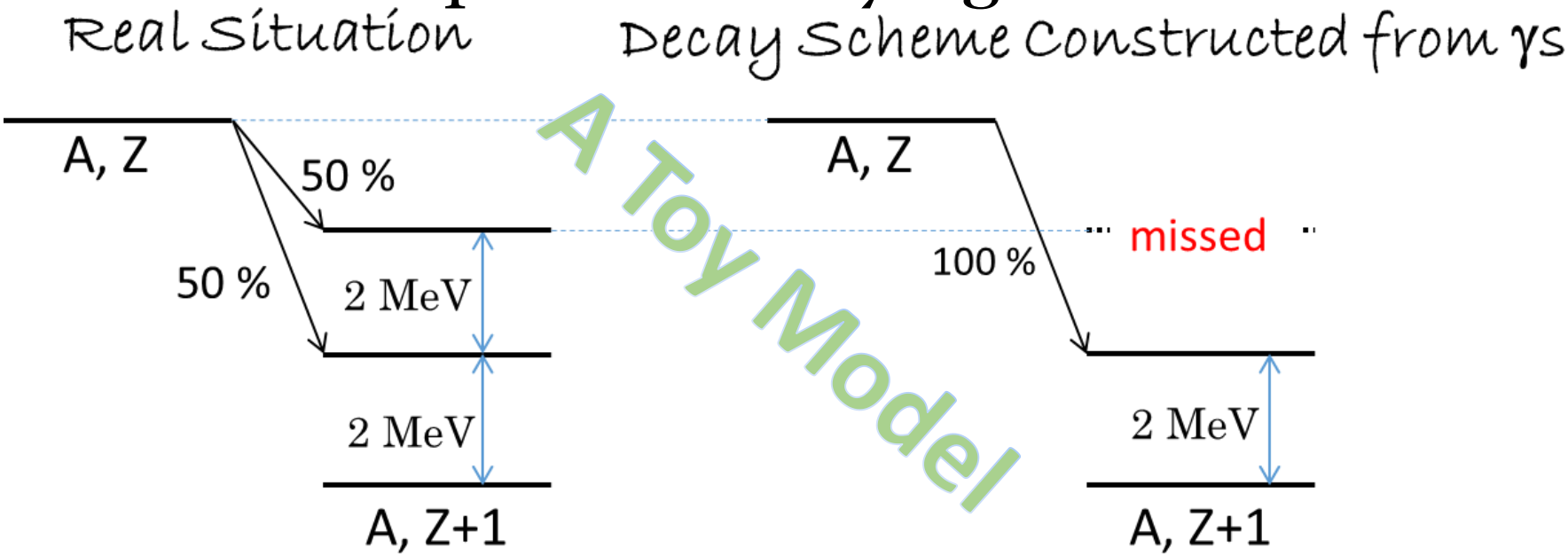


(b) γ-ray component

T.Yoshida,R.Nakashima, JNST, Vol.18 (1981) 393

1997 First Extensive TAGS Measurement (Idaho)

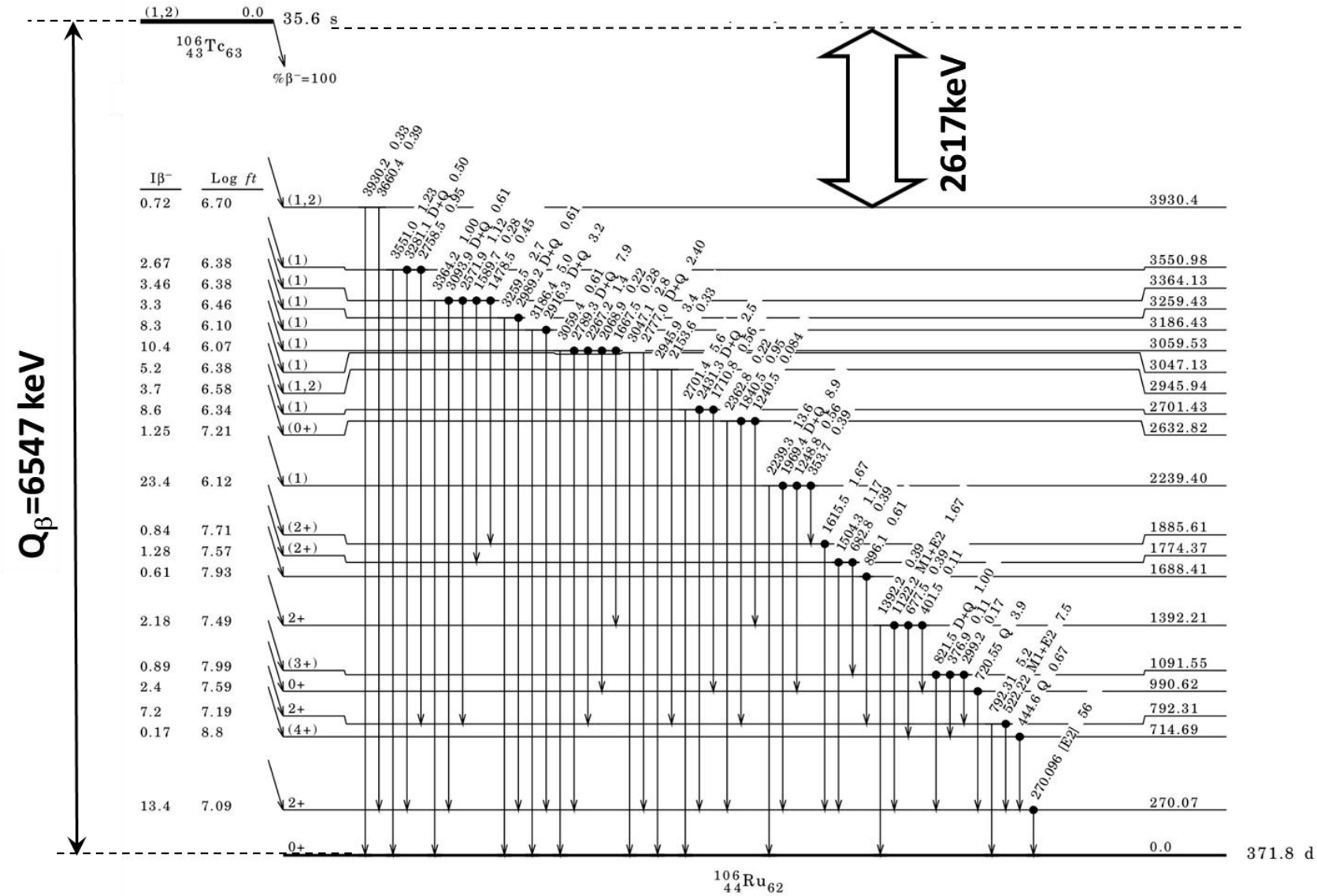
Pandemonium Problem Illustrated in a Simplified Decaying Nucleus



E_β = 1.5 MeV → 2.0 MeV (0.5 MeV Increase)

E_γ = 3.0 MeV → 2.0 MeV (1.0 MeV Decrease)

E_{tot} = 3.5 MeV → 4.0 MeV (0.5 MeV Decrease)



Essentially all the high Q_β–valued current decay schemes suffer from the pandemonium problem viz. missing of β-transitions to high-lying states.

Persistence of the Pandemonium Problem in the Reactor Decay-Heat Calculation

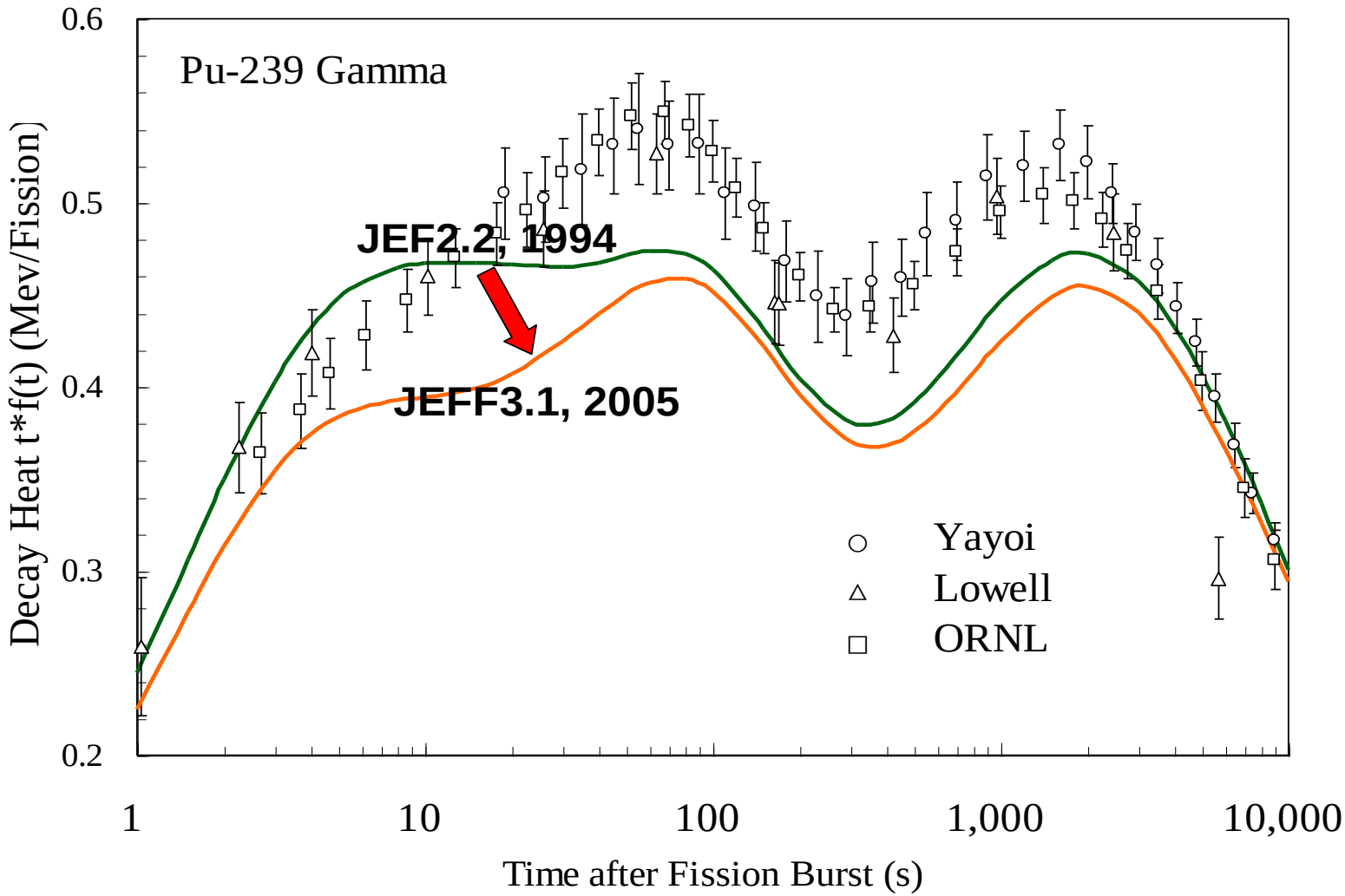


Fig. Gamma-ray Component of Decay Heat after Burst Fission in U-235

Brief History of Pandemonium Problem (2)

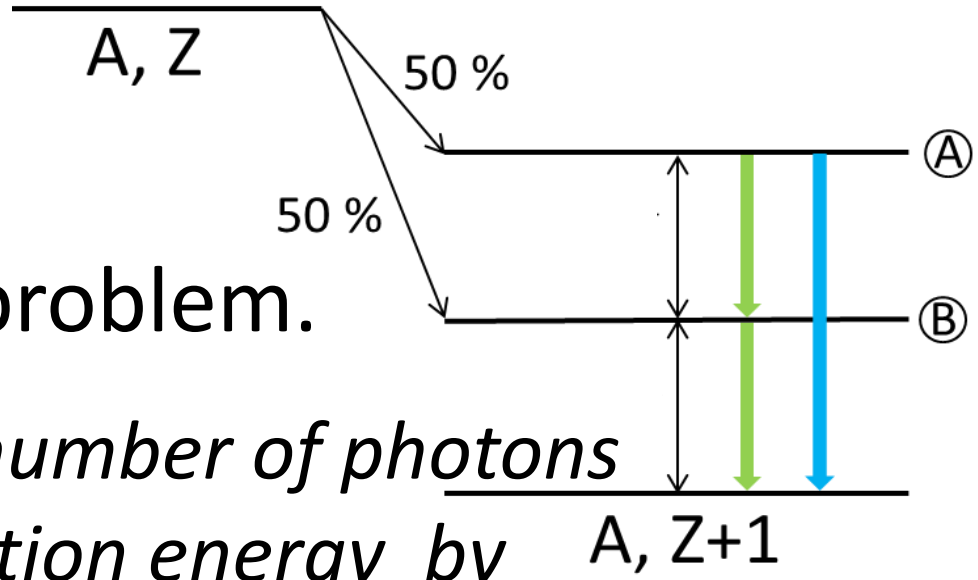
2005 OECD/NEA International Eval. Cooperation
"Assessment of FPDE for DH Calculations"

2006, 2009, 2014, 2018
IAEA/NDC Consultants' Meeting on TAGS

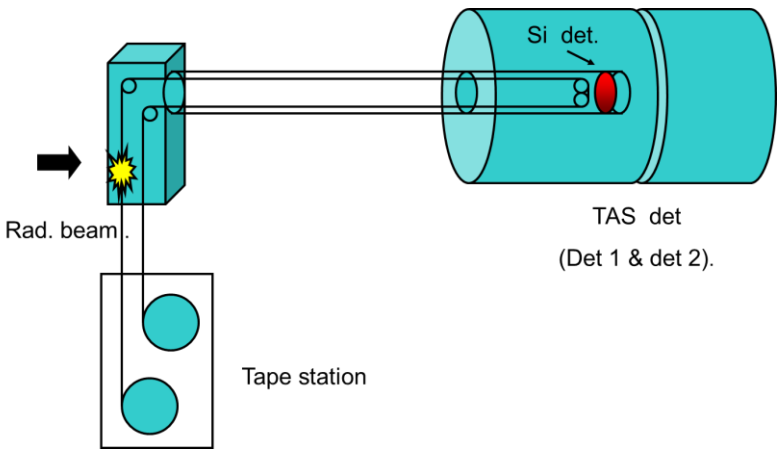
2010 The First TAGS Data from Valencia, PRL
followed by many

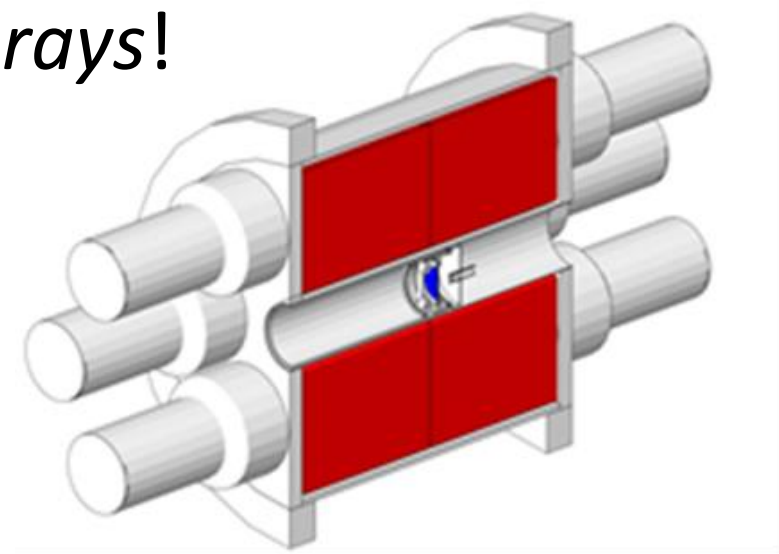
2016 The First TAGS Data from ORNL, PRL
followed by many

TAGS is expected to be free from the pandemonium problem.

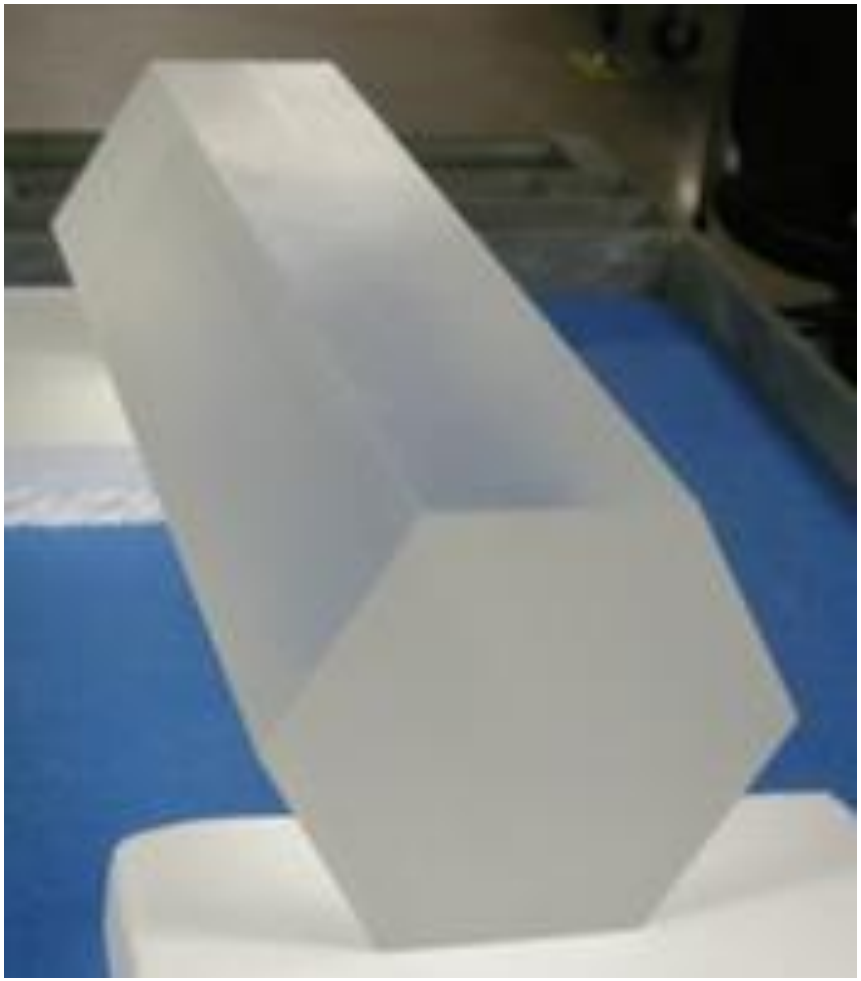


It does not count the number of photons but the total de-excitation energy by absorbing all the cascade γ-rays!





TAGS Detector used by Valencia group
（Courtesy of A. Algora）

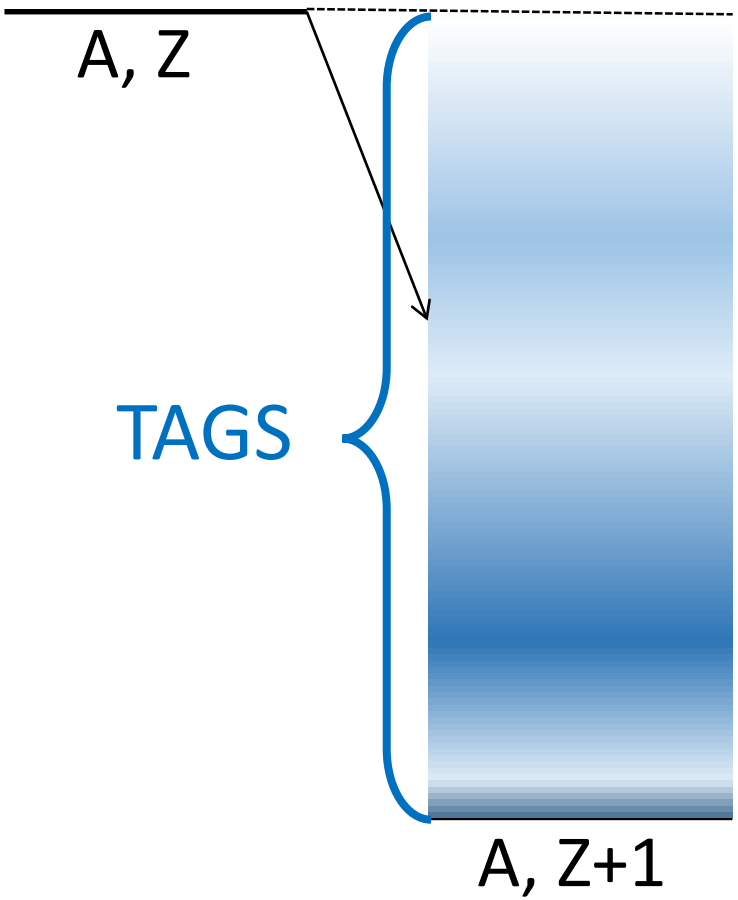


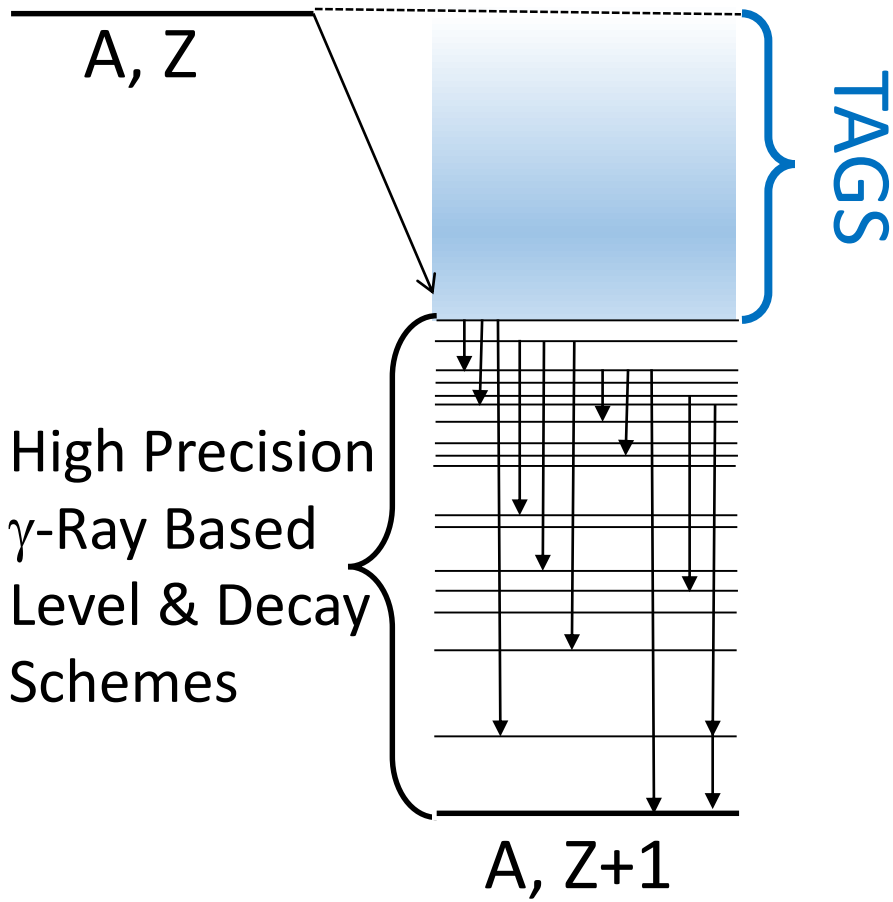
MTAS Detector of the ORNL TAGS Project (2012~2017)
NaI Scintilater Module and Modular Detector set up
（Courtesy of K. Rykazcewski）

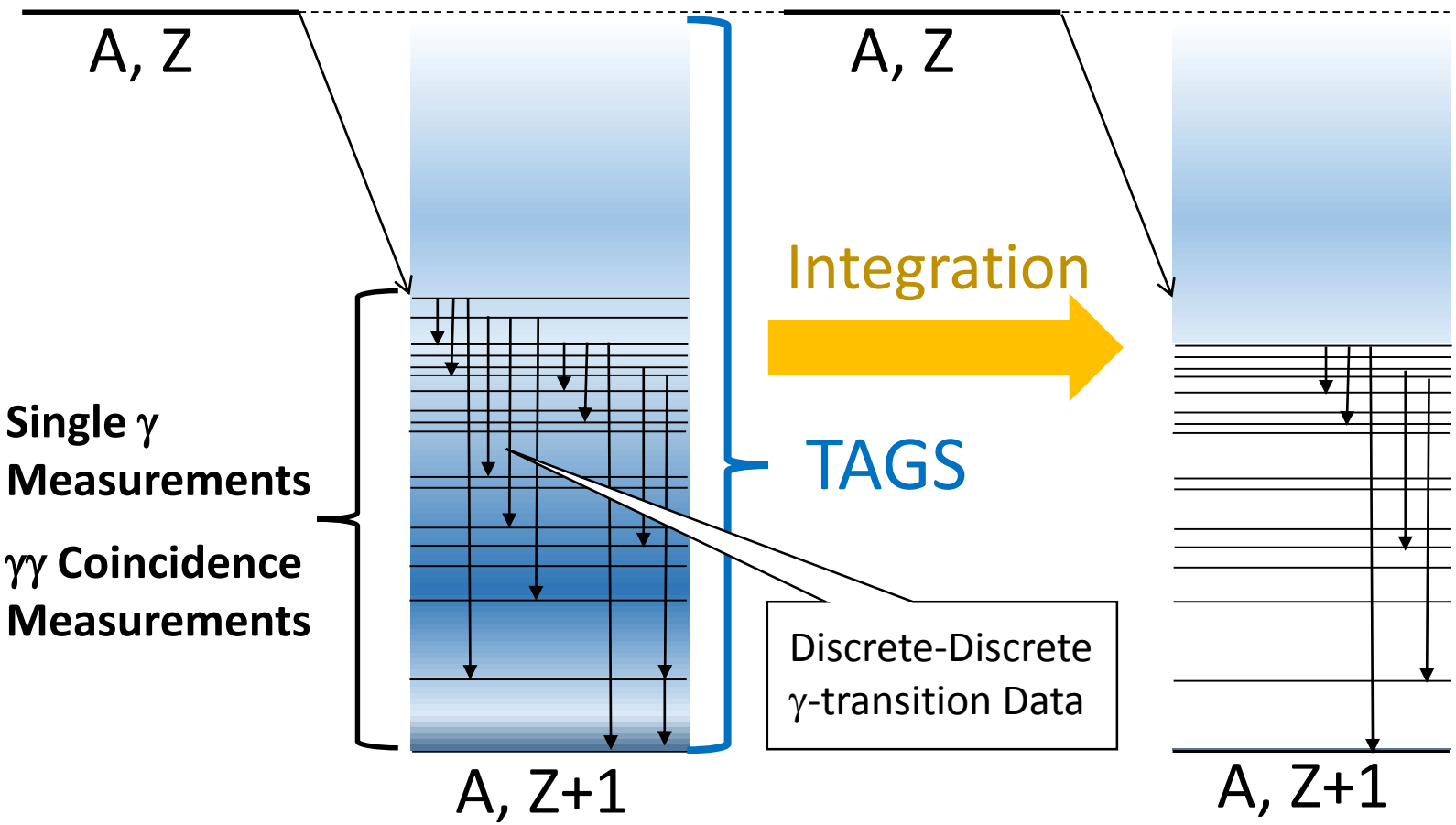
Two Possible Ways of Exploit the Merit of the TAGS Data

(1) Full Use of the TAGS Data Forgetting about the Current Schemes base on High Precision γ-Ray Data ➡ Enough for Decay Heat Calculations

(2) Combine Both Sets to Exploit the Merits Both of the High Precision and the Pandemonium-Free TAGS Data ➡ Much Wider Range of Applications







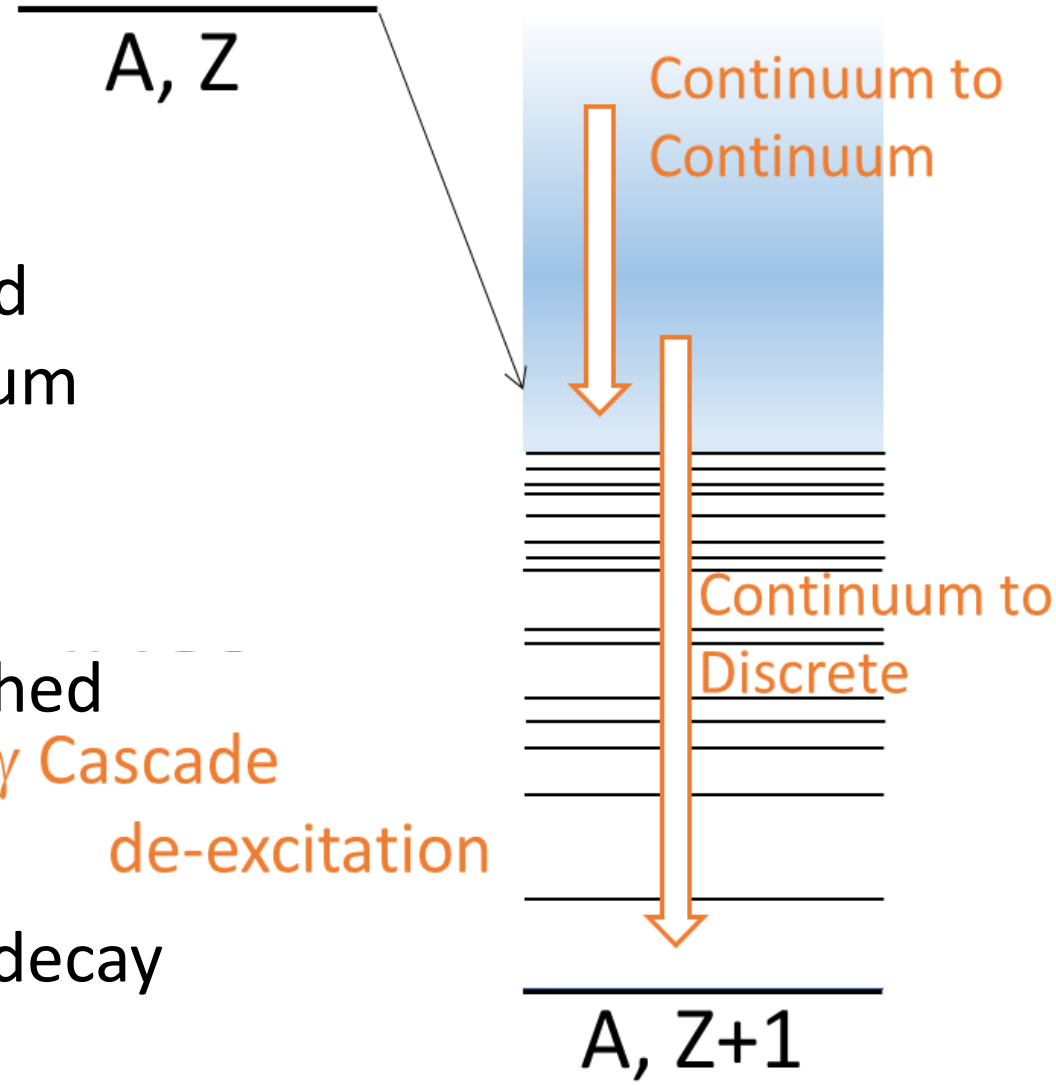
At the present, TAGS is the only source of experimental information on β-feeding free from the pandemonium problem. But its energy resolution is very low, and it gives us no information on the γ-ray de-excitation process.

Integration of the Current and TAGS Data Requires Further Efforts

(1) To find appropriate junction energy

(2) To calculate and to add
Continuum – Continuum
Continuum – Discrete
γ-ray transitions.

This can be accomplished by Hauser-Feshbach theory with help of the gross theory of β-decay and/or QRPA



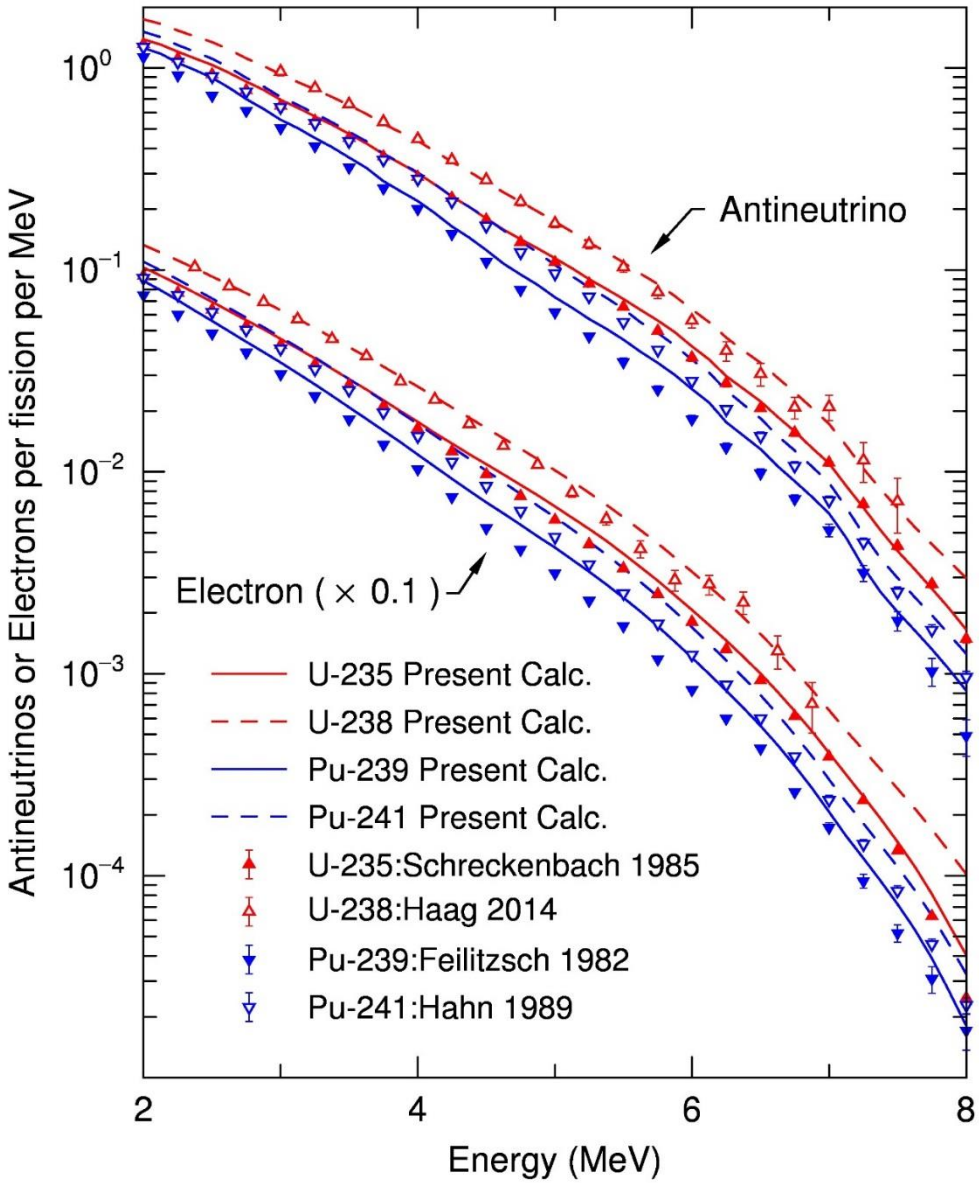


Fig. Reactor Antineutrino Energy Spectra; Comparison Between the Current Prediction Basis (ILL) and Gross Theory Calculation

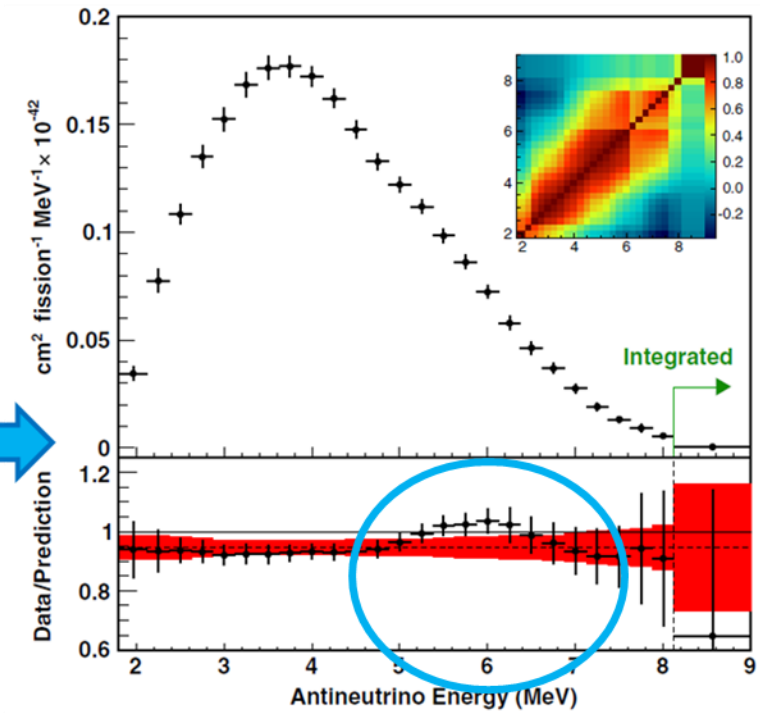
Reactor-Antineutrino Spectral Anomaly

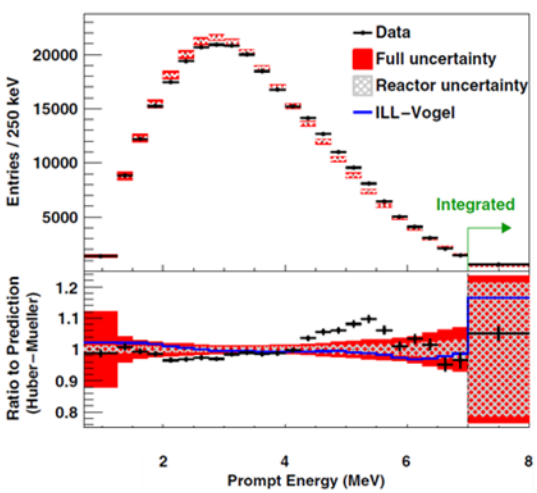
– Daya Bay, Double Chooz and RENO Experiments

Direct Measurement of the Antineutrino Energy Spectra through the IBD reaction:

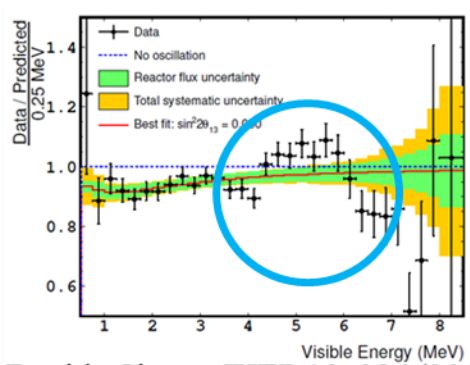
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$E_\nu = E_{promp} + 0.78\text{MeV}$$

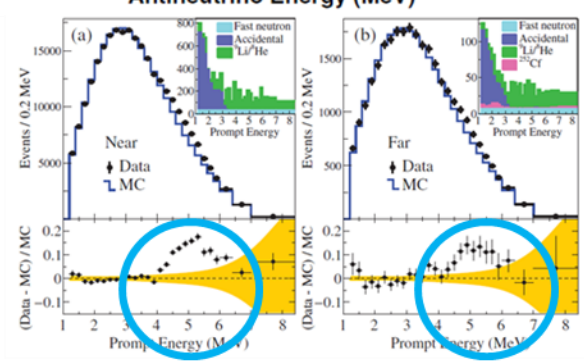




Daya Bay, PRL 116, 061801 (2016)



Double Chooz, JHEP 10, 086 (2014)



RENO, PRL 116, 211801 (2016)

Concluding Remarks

- Hardy *et al*.'s warning, the pandemonium problem, demonstrated its decisive impact in nuclear safety (DH).
- The pandemonium problem in decay heat calculations has long been circumvented by introducing the gross theory of beta-decay in Japan and in the US.
- Final solution against the pandemonium problem can be provided by the TAGS experimental data.
- TAGS has, however, its own weak points: Very low energy resolution, no information about the gamma-ray de-excitation, no gamma-ray branching data, …
- In addition to use TAGS data as it is, it also can be combined with the high-resolution γ-based decay schemes for wider range of applications.

Thank You for Your Attention

以下おまけ

Total Gamma-Ray Spectroscopy Saves the Calculation from the Pandemonium

β-ray Component

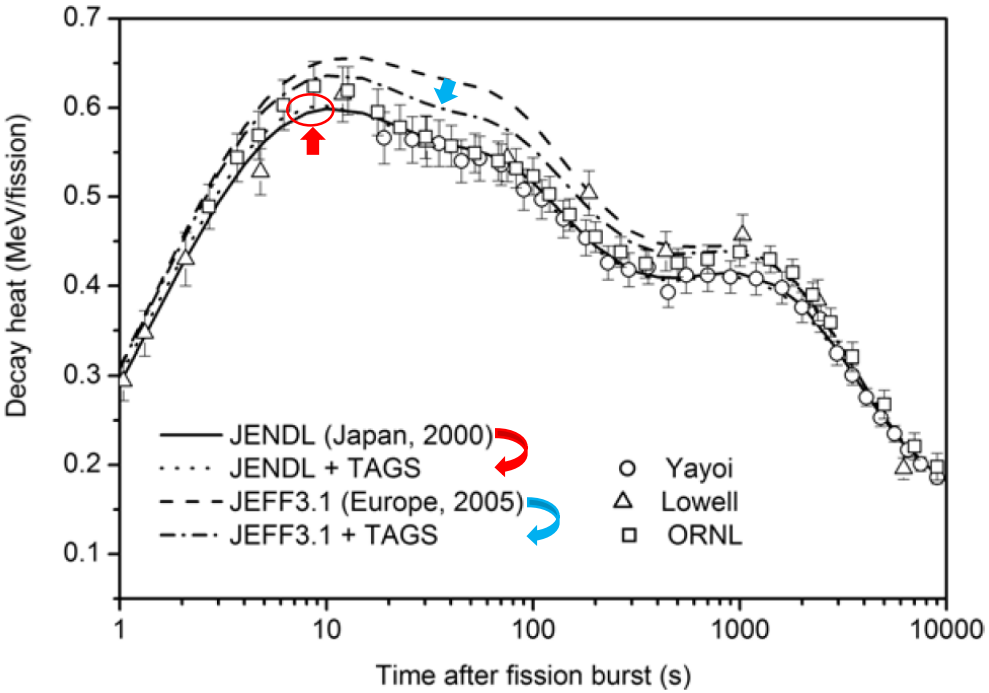


Figure 2. Light-particle decay heat following thermal fission burst of ^{239}Pu (as in Figure 1), with and without TAGS data being adopted in JENDL and JEFF-3.1

γ-ray Component

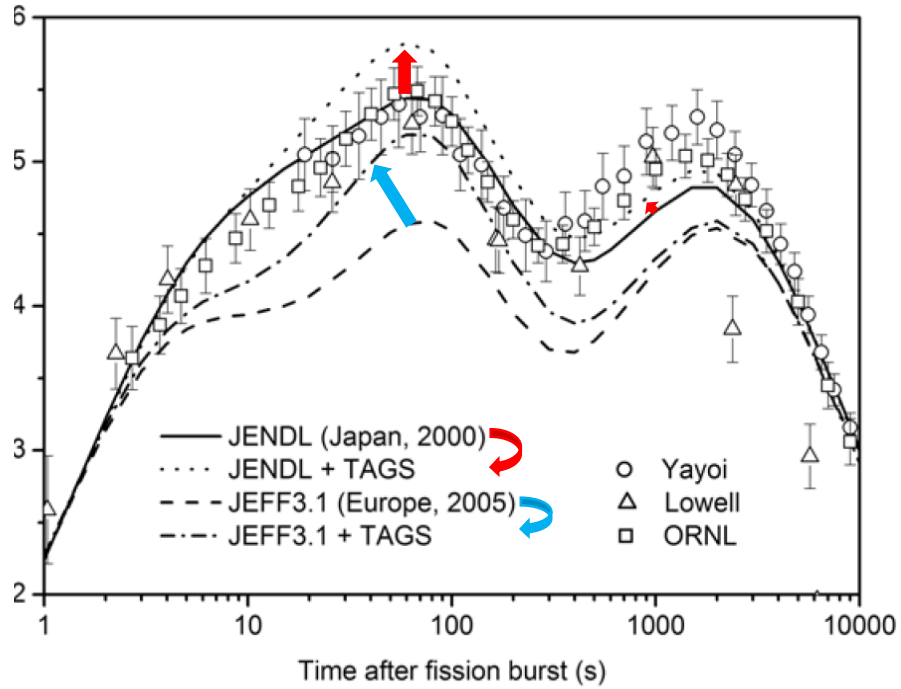


Figure 4. Electromagnetic decay heat following thermal fission burst of ^{239}Pu (as in Figure 3), with and without TAGS data being adopted in JENDL and JEFF-3.1

NUCLEAR SCIENCE AND ENGINEERING: **93**, 193-203 (1986)

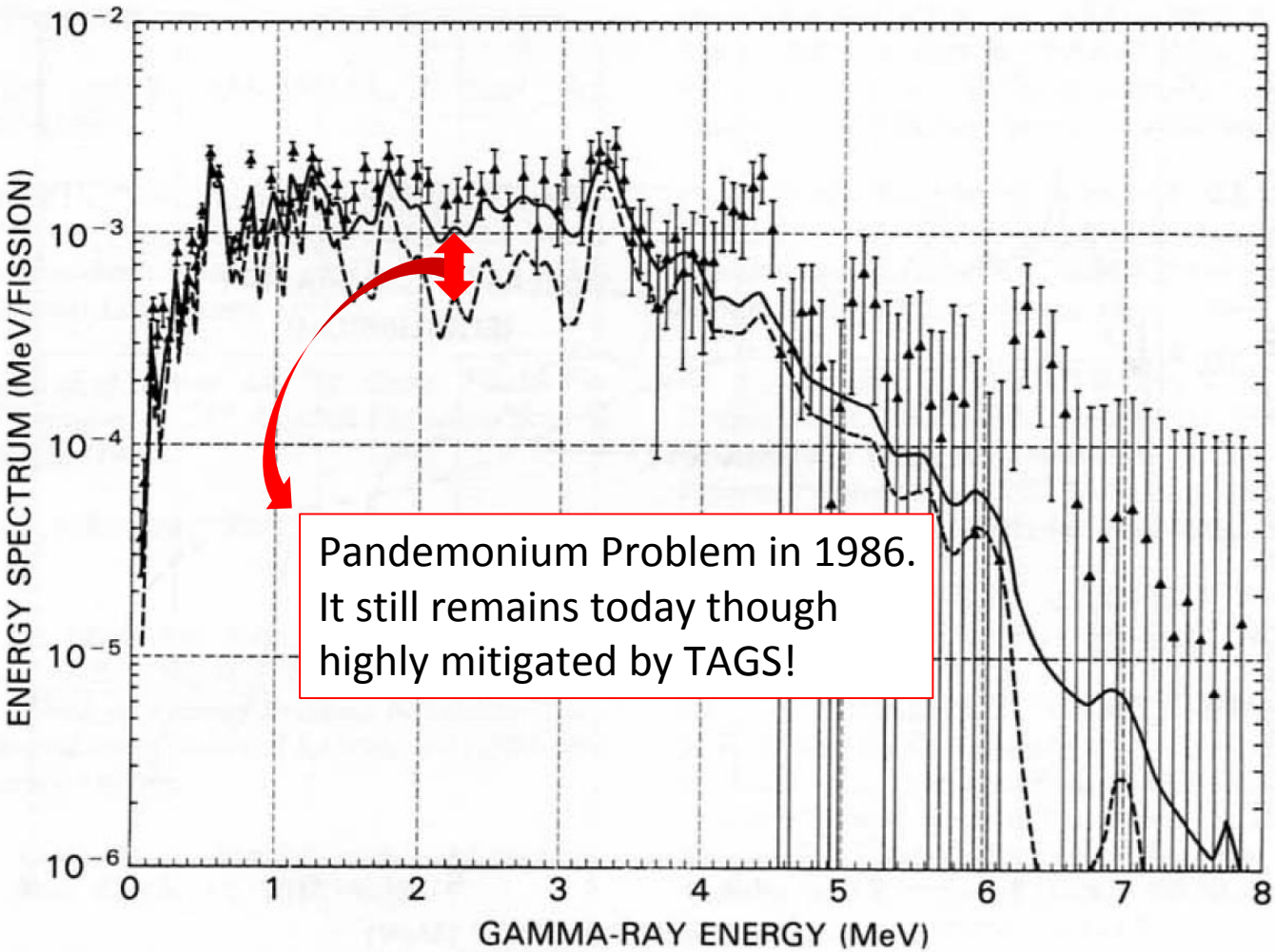
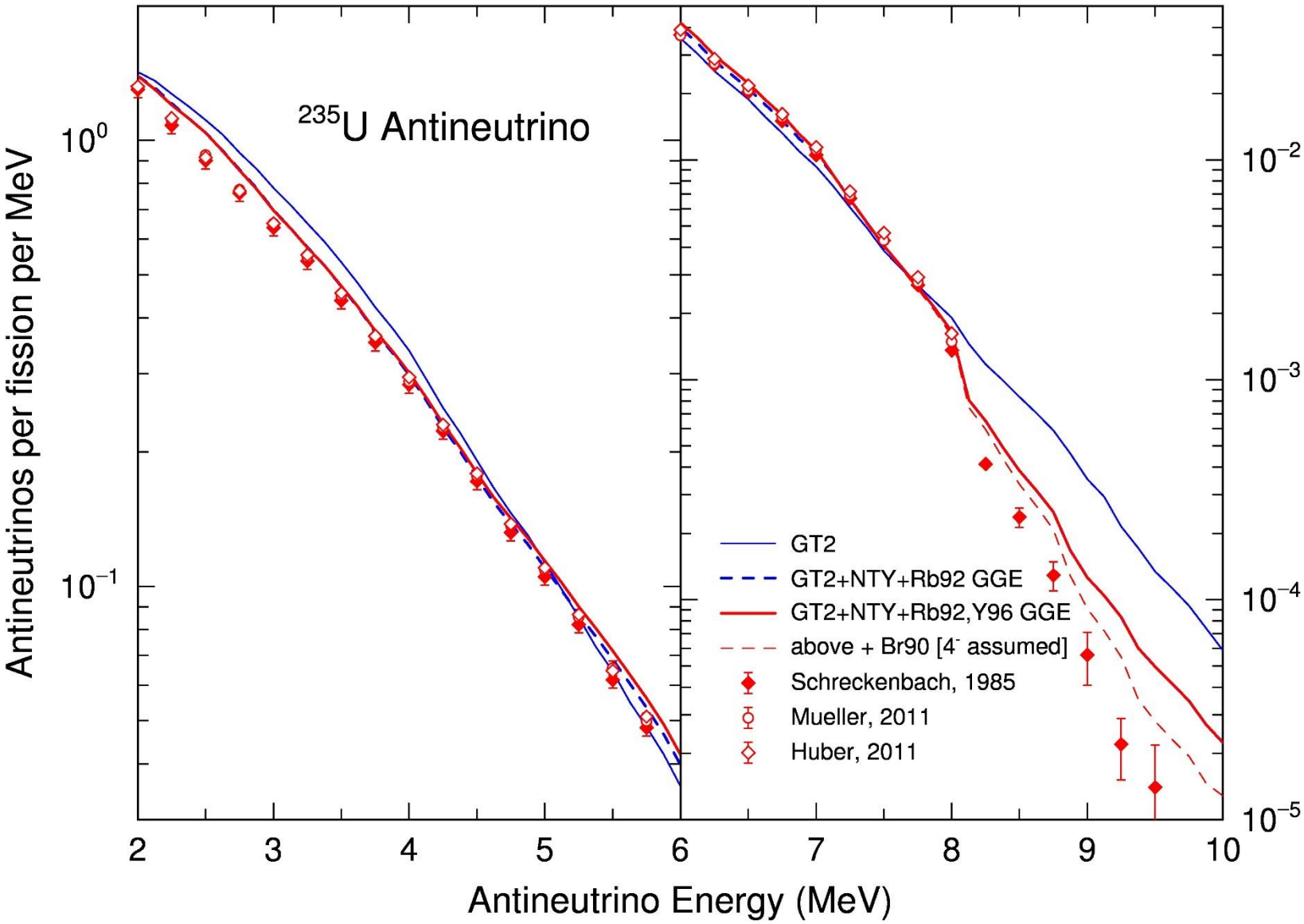


Fig. 10. Energy spectra from a ^{235}U sample after a burst irradiation and 2.7-s cooling. The dashed curve is the calculation where only measured spectra of individual nuclides are included in the summation of Eq. (6). The solid curve is the calculation where the unknown spectra are complemented by theoretical spectra given by the present model. The solid triangles are the Oak Ridge National Laboratory measurement of Ref. 20.



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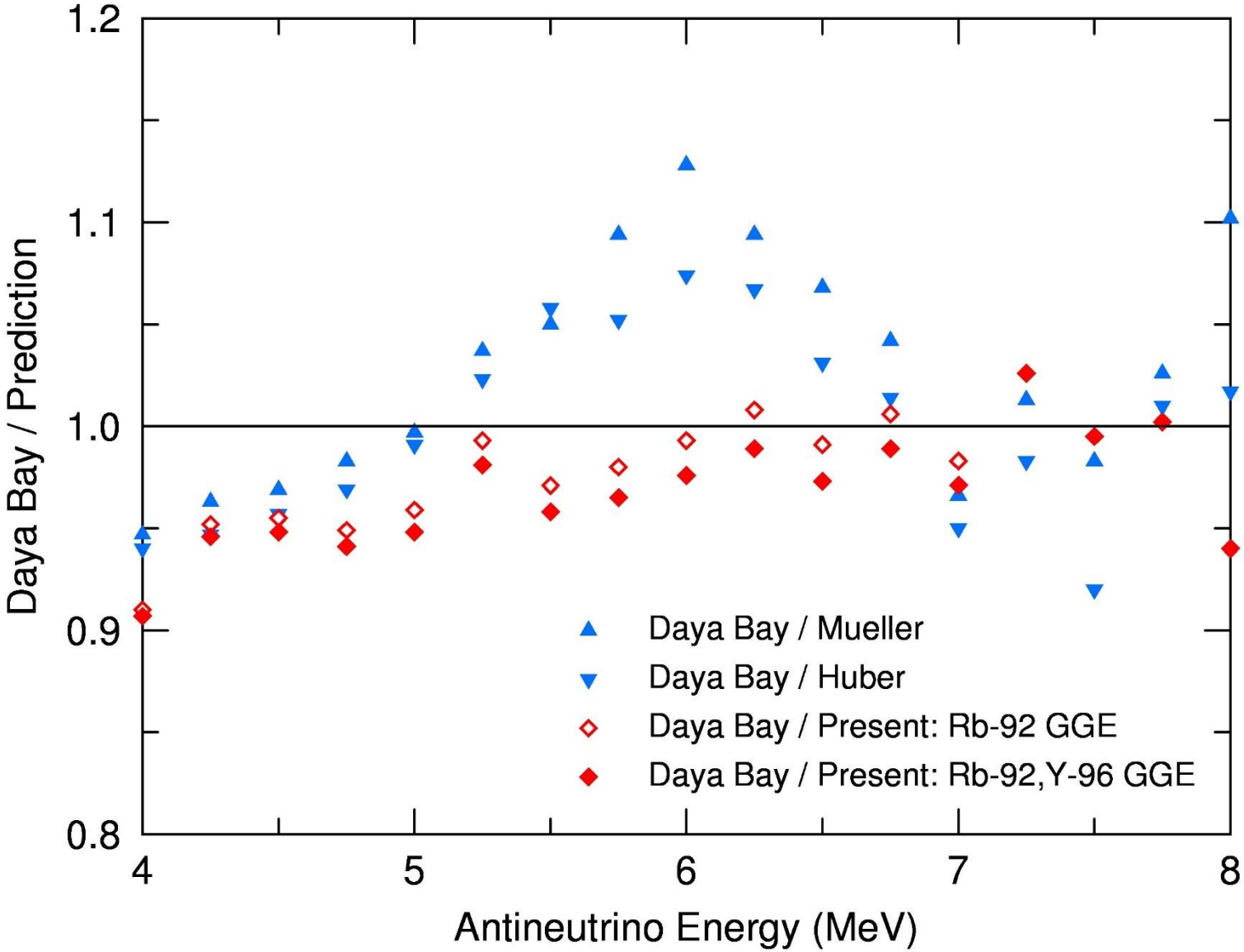
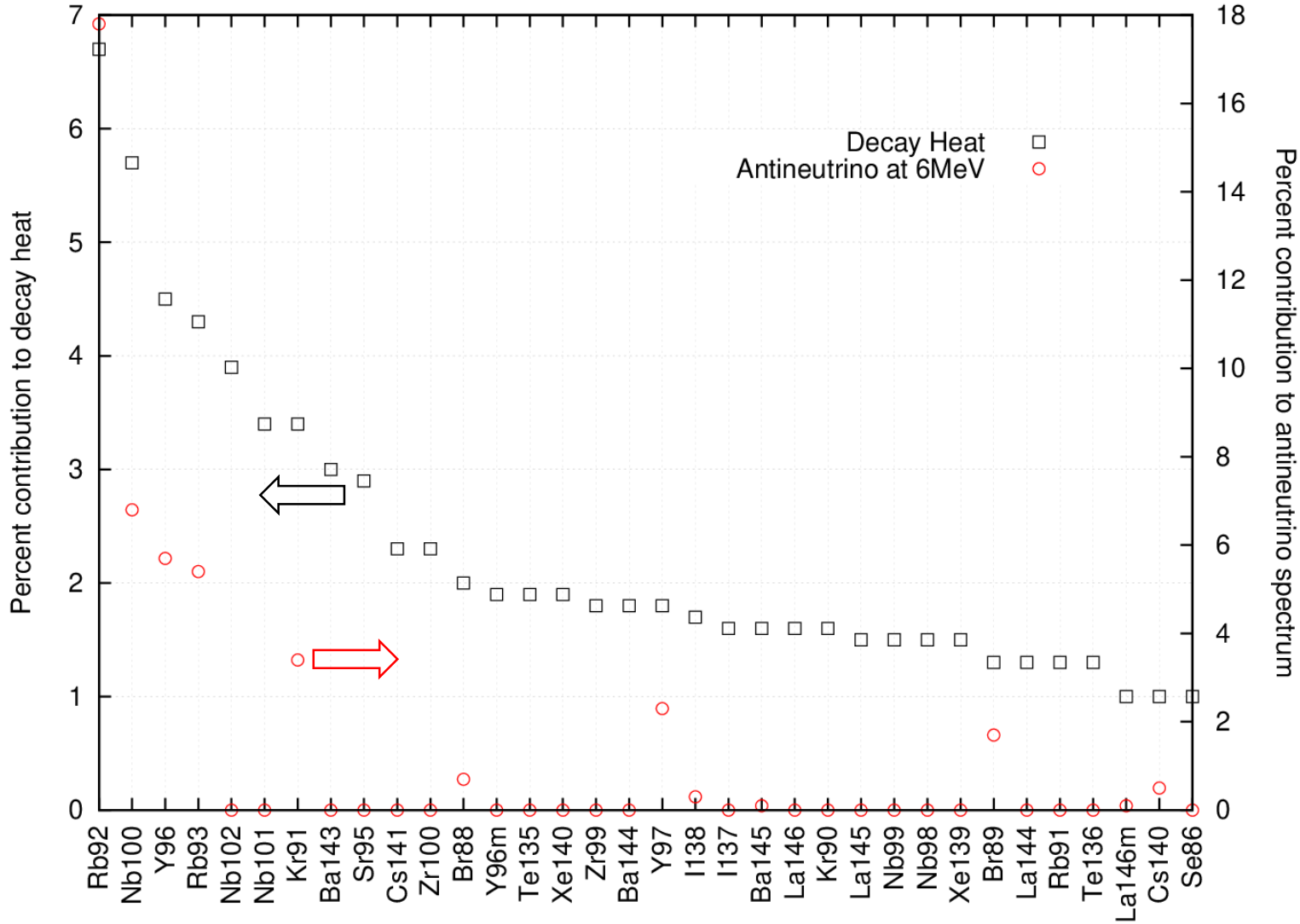

1.2
1.1
1.0
0.9
0.8
Daya Bay / Prediction
4
5
6
7
8
Antineutrino Energy (MeV)
Daya Bay / Mueller
Daya Bay / Huber
Daya Bay / Present: Rb-92 GGE
Daya Bay / Present: Rb-92,Y-96 GGE



Contributing FPs vary depending on the quantity, the irradiation and the cooling times and the energy