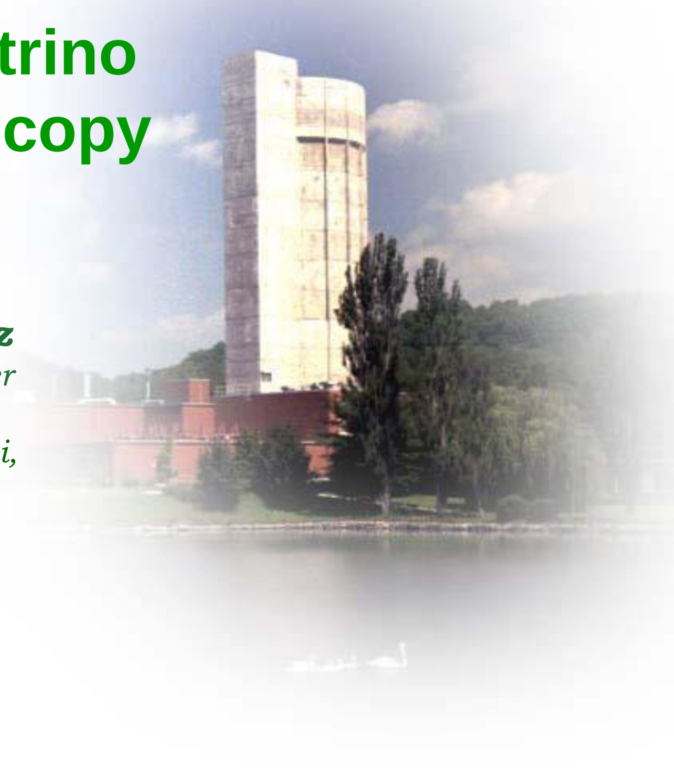
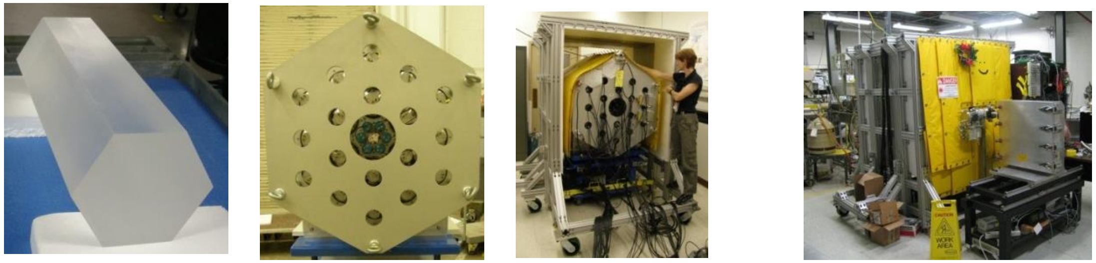
Beta-strength, decay heat and anti-neutrino spectra from Total Absorption Spectroscopy

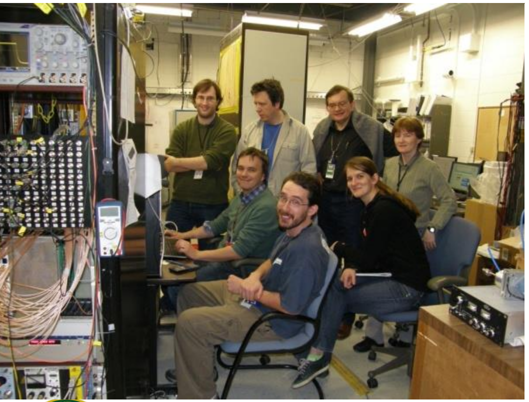


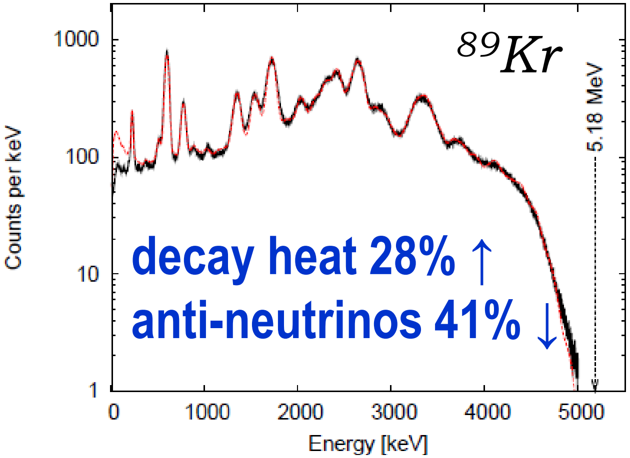
Krzysztof P. Rykaczewski
Physics Division, Oak Ridge National Laboratory

A.Fijałkowska, M.Wolińska-Cichocka, B.C. Rasco, K. C. Goetz
M. Karny, R.K. Grzywacz, C.J. Gross, E. Zganjar, J.W. Johnson, N. Brewer
J. Matta, K. Miernik, D. Miller, M. Madurga, S. Paulauskas, S. Padgett,
D. Stracener, C. Jost, R. Goans, E. Spejewski, J. C. Batchelder, L. Cartegni,
M. Al-Shudifat, J. H. Hamilton and A.V. Ramayya



An example of nuclear structure studies truly interesting for nuclear energy and fundamental neutrino physics





decay heat 28% ↑
anti-neutrinos 41% ↓

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Outline

1. Physics of beta decay of neutron-rich nuclei (fission fragment)

2. Results on β-strength in fission fragments, and their impact

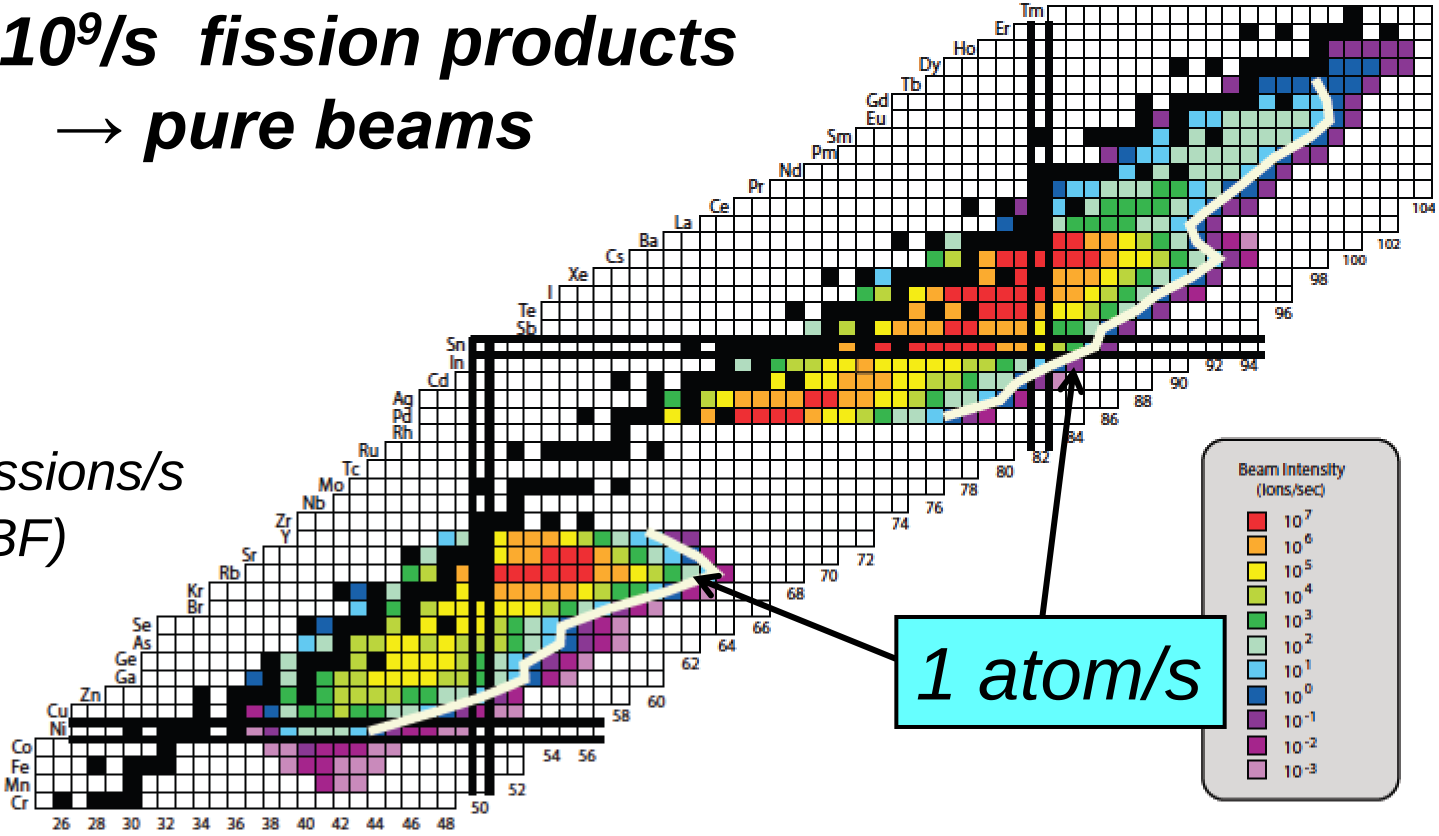
   - decay heat and reactor anti-neutrino anomaly
   - spectrum of high-energy reactor anti-neutrinos

Proton-induced fission of ^{238}U creates many neutron-rich nuclei, with a similar yield pattern as in a nuclear reactor

~10^9/s fission products

→ pure beams

(we had ***10^{11}*** *fissions/s at the HRIBF)*

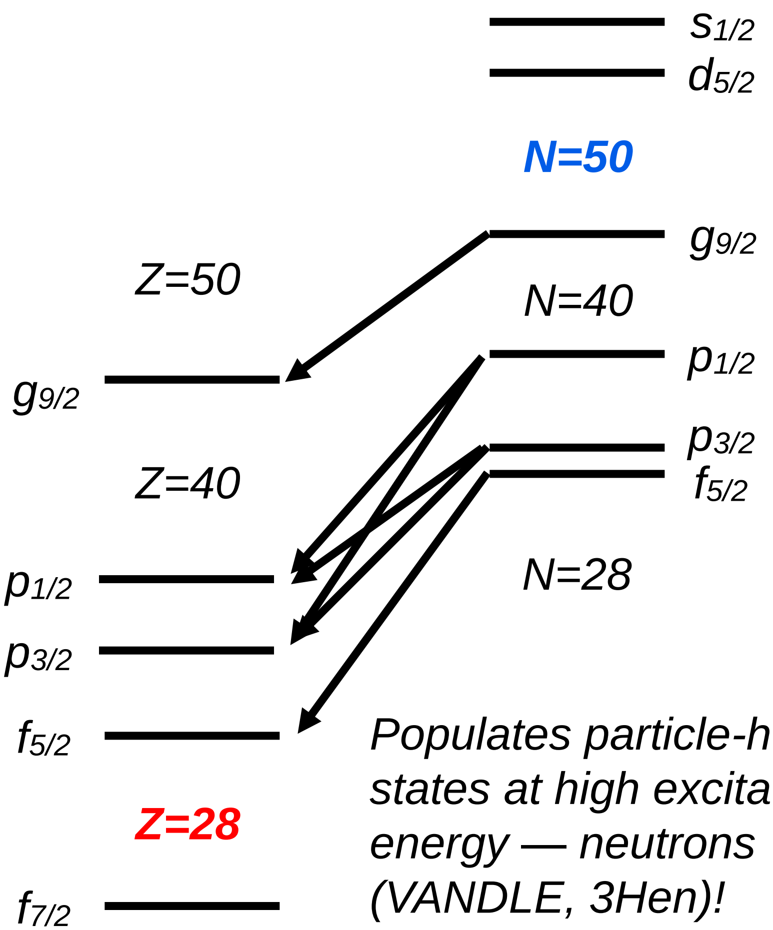


The chart of nuclides indicates by color the expected intensity of fission fragments delivered to the measuring end-station with 100 nA of 46 MeV protons on a thick UC$_x$ target.

Nuclear structure, r-process nucleosynthesis, reactor applications and reactor anti-neutrino physics

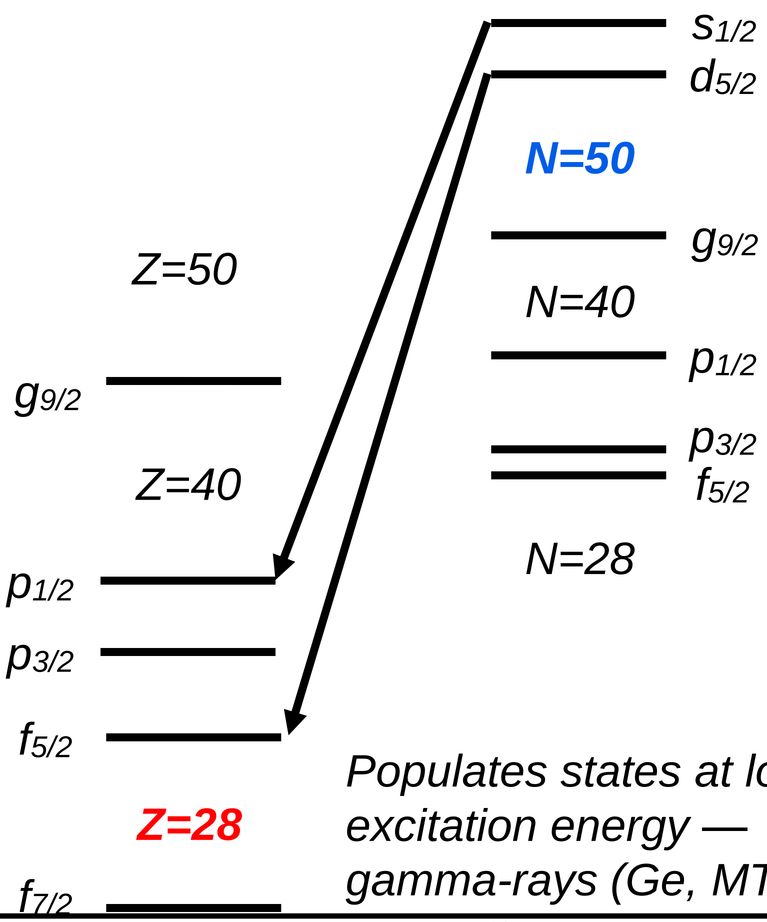
Exotic n-rich nuclei with large Q_β → competition between allowed and forbidden β-decays

Gamow-Teller transitions
large strength, small beta energy
no parity change
no angular momentum change
spin change 0,1



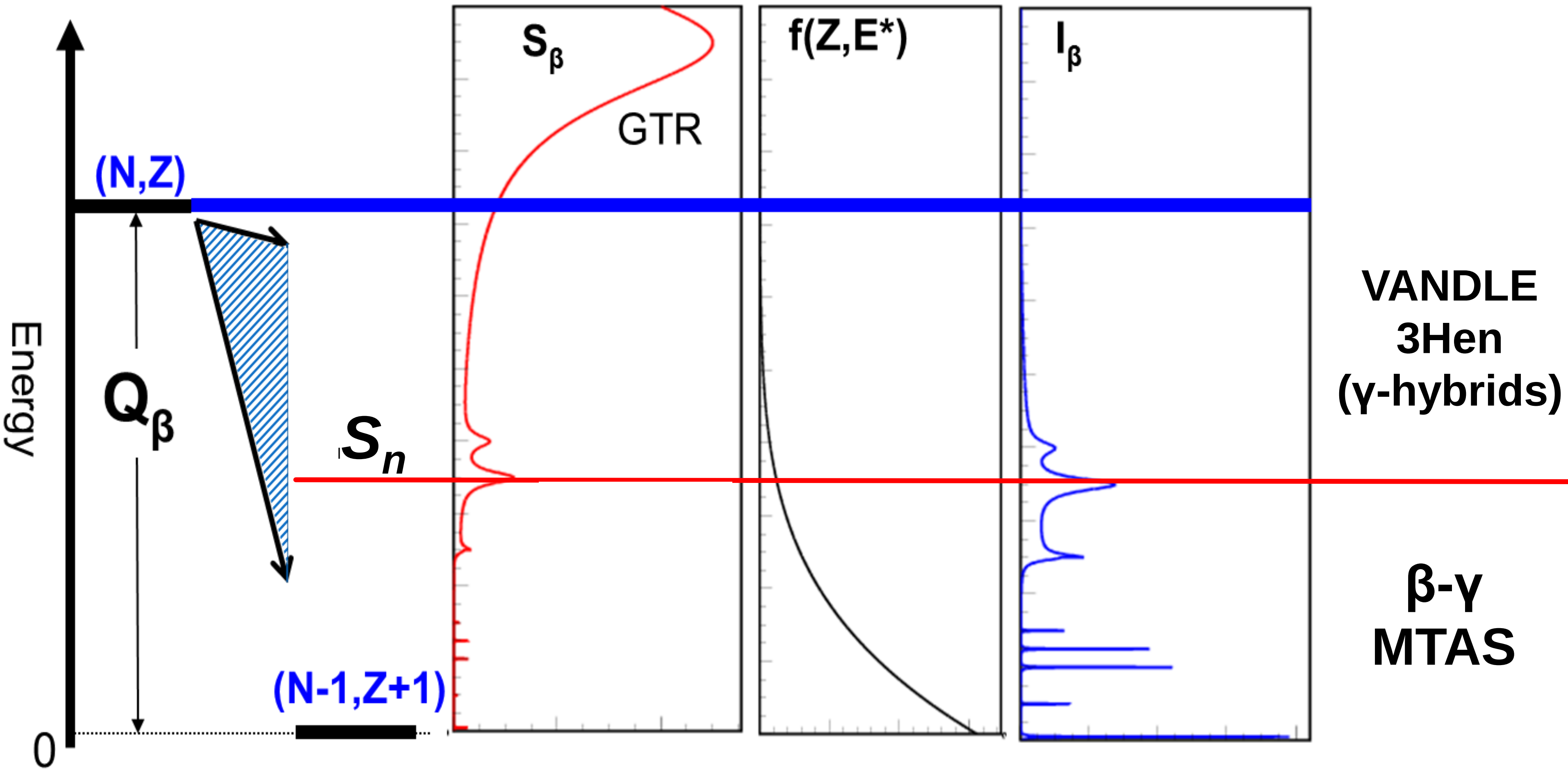
Populates particle-hole states at high excitation energy — neutrons (VANDLE, 3Hen)!

Forbidden transitions
small strength, large beta energy
parity change
angular momentum change
spin change 0,1,2



Populates states at low excitation energy — gamma-rays (Ge, MTAS)!

Complex β-decay of a very neutron-rich nucleus (like ^{91}Br)



VANDLE
3Hen
(γ-hybrids)

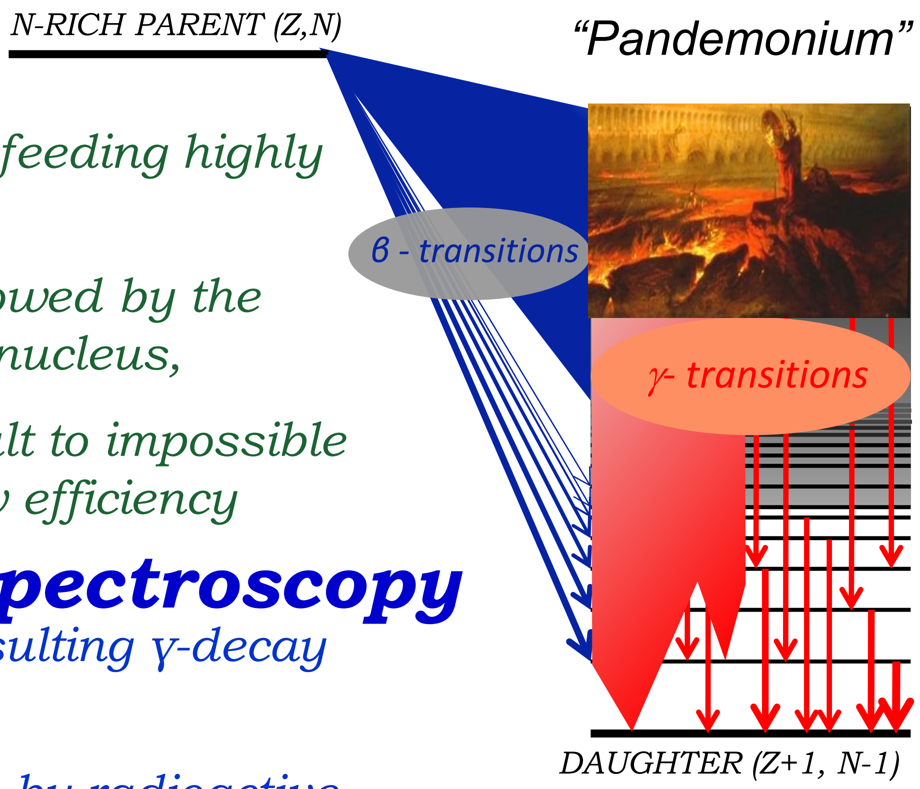
β-γ
MTAS

Complex β-decays

- *β-transitions (mostly Gamow-Teller) are feeding highly excited states,*
- *these many, weak β-transitions are followed by the cascades of γ-transitions in the daughter nucleus,*
- *these weak γ-transitions are very difficult to impossible to detect with radiation detectors with low efficiency*

Total absorption γ-spectroscopy

- *to determine* ***true β-feeding*** *and resulting γ-decay patterns (nuclear structure),*
- *to determine* ***"decay heat"*** *released by radioactive nuclei produced during a nuclear fuel cycle*
- *to determine* ***anti-neutrino spectrum*** *associated with β-decay of fission products,* $Y \rightarrow X^* + e^- + \overline{\nu}$



The true picture of the neutron-rich parent nucleus (Z,N), with many weak β-transitions and following low intensity γ-transitions.

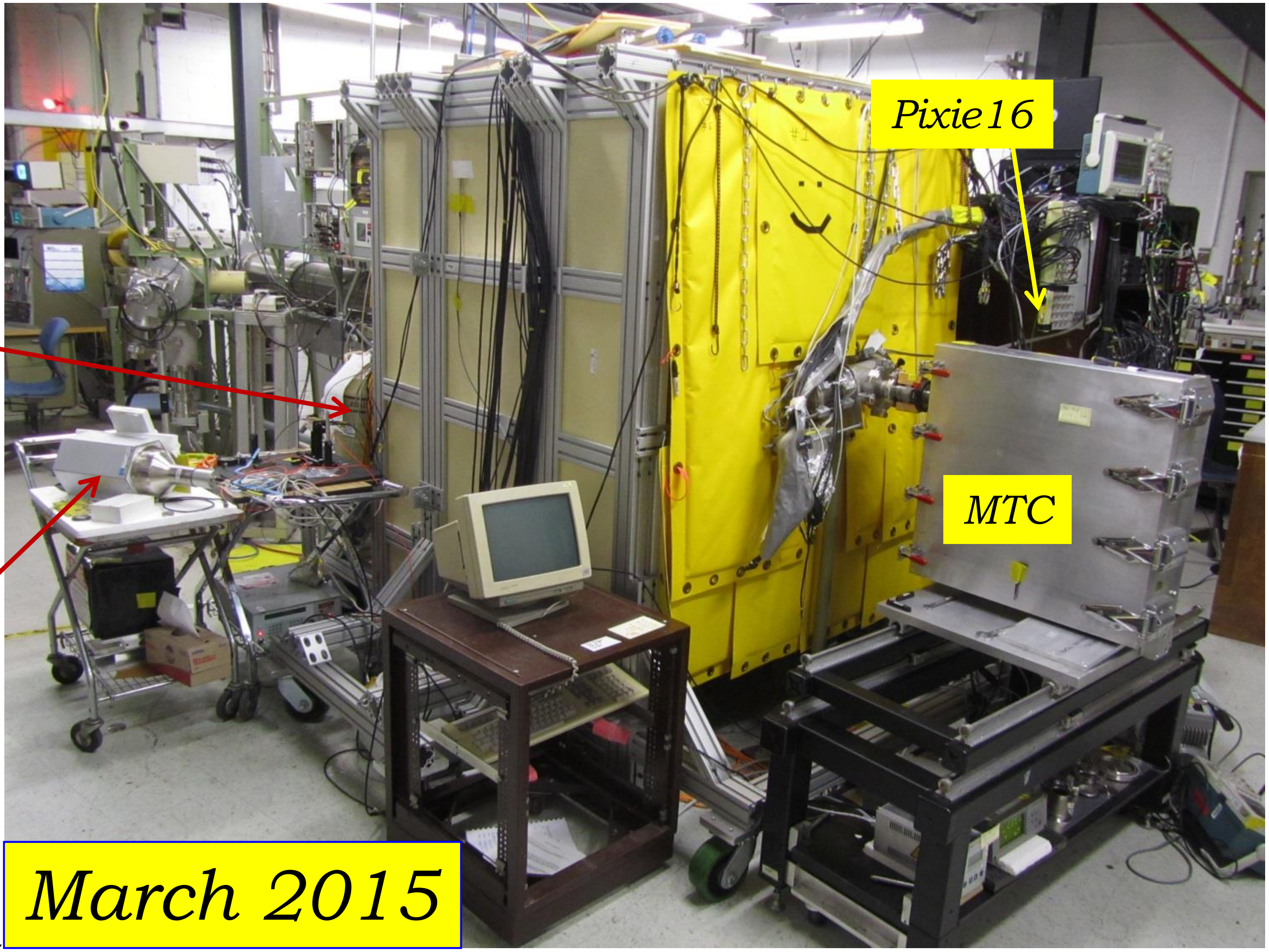
J. Hardy et al., Physics Letters 71 B, 307, 1977

A. Algora et al., PRL 105, 202501, 2010

K. P. Rykaczewski, Viewpoint in Physics 3, 94, 2010

K. P. Rykaczewski, 2013 McGraw-Hill Yearbook of Science and Technology, p.9

Unique “state-of-art” MTAS on-line to the mass separator OLTF



Data ACQ
digital pulse processing
(R. Grzywacz et al.)

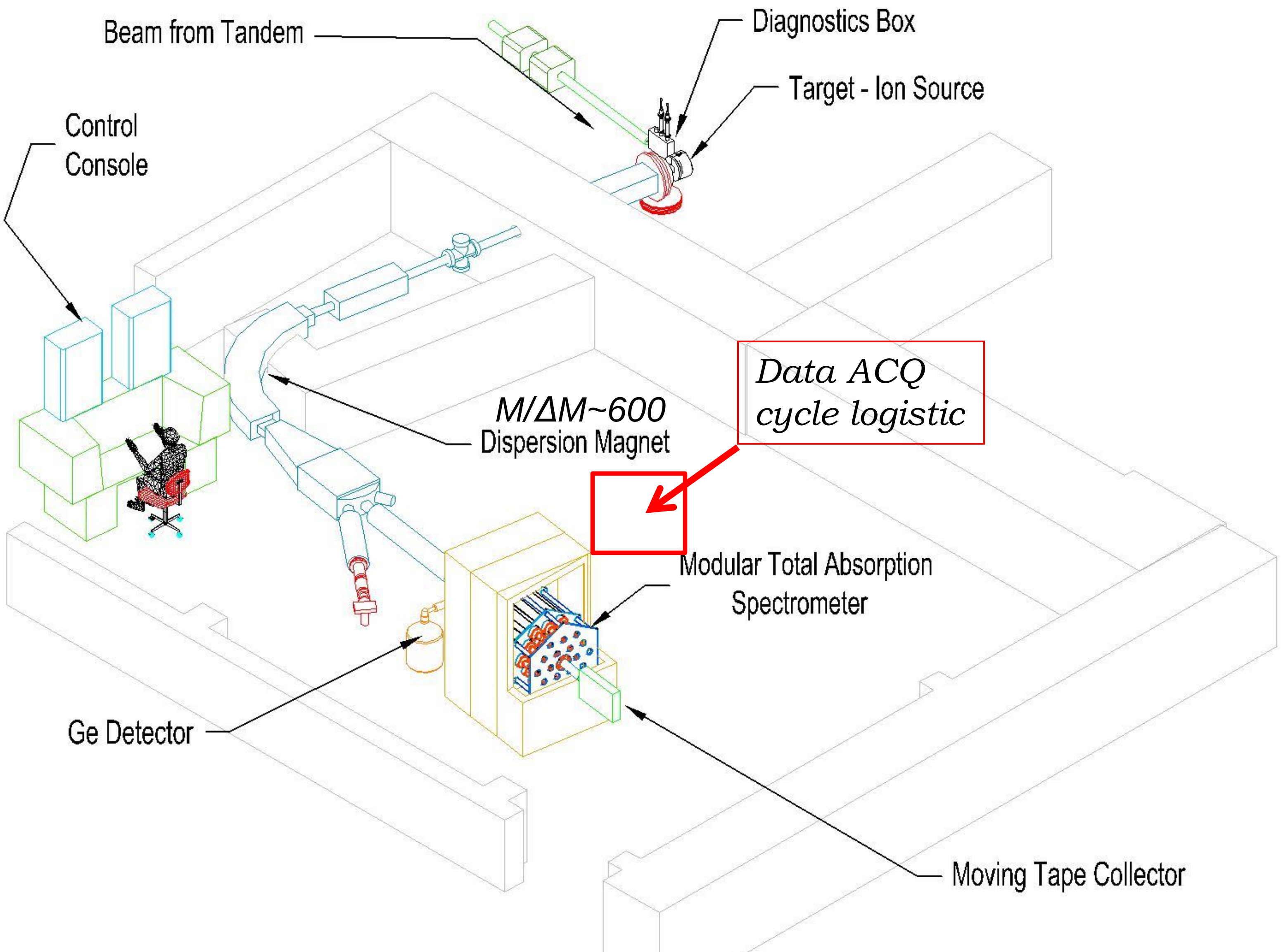
Ge detector
for monitoring
collection point

Reference NaI(Tl) crystal with pulsed blue laser light for monitoring amplification changes. Laser light was split between reference and central/inner ring detectors.
K.C. Goetz, R. Grzywacz (UTK)

Multi-point temperature monitor, MTC and OLTF cycle control (C.J. Gross)

Many months of calibrations and perfecting the response function
e.g., Rasco et al., NIM 788, 139, 2015; Wolinska et al, NDS 120, 22, 2014

~ 50nA protons

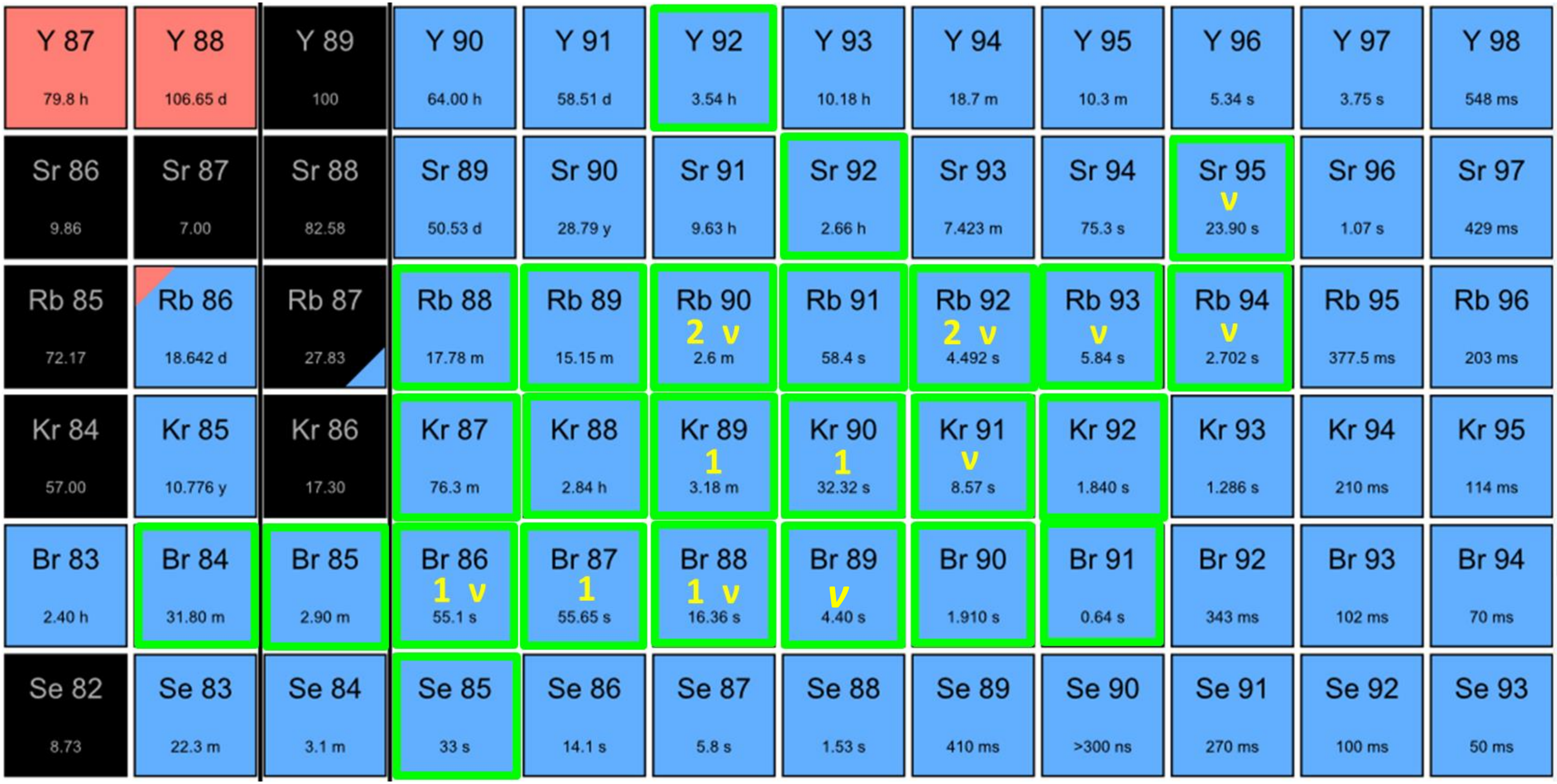


M/ΔM~600

Data ACQ cycle logistic

On-Line Test Facility OLTF = mass separator on-line to ORNL’s Tandem (last on-line mass separator in the US)

Decays measured with MTAS in January 2012 and March 2015

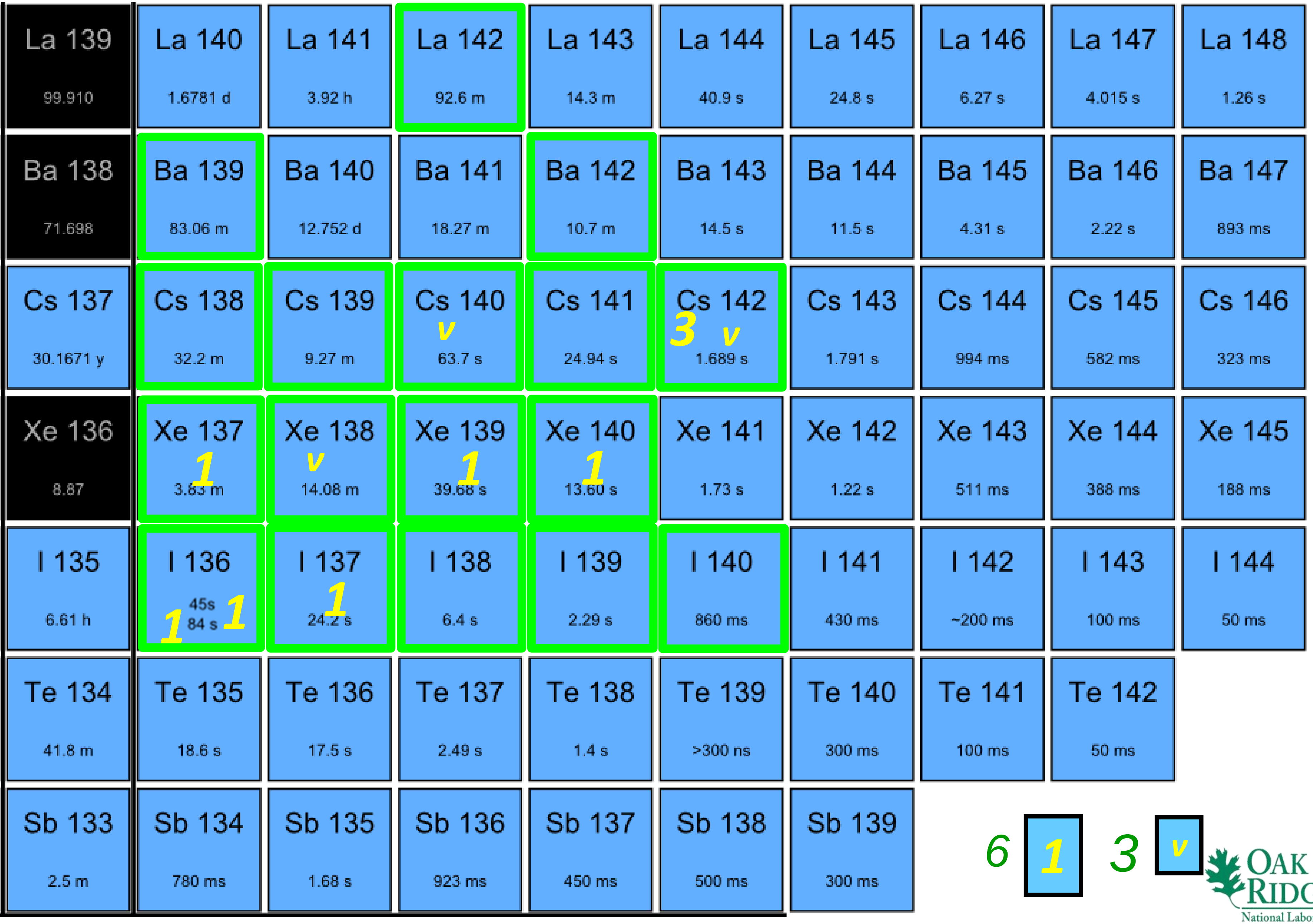


Y 87 79.8 h	Y 88 106.65 d	Y 89 100	Y 90 64.00 h	Y 91 58.51 d	Y 92 3.54 h	Y 93 10.18 h	Y 94 18.7 m	Y 95 10.3 m	Y 96 5.34 s	Y 97 3.75 s	Y 98 548 ms
Sr 86 9.86	Sr 87 7.00	Sr 88 82.58	Sr 89 50.53 d	Sr 90 28.79 y	Sr 91 9.63 h	Sr 92 2.66 h	Sr 93 7.423 m	Sr 94 75.3 s	Sr 95 v 23.90 s	Sr 96 1.07 s	Sr 97 429 ms
Rb 85 72.17	Rb 86 18.642 d	Rb 87 27.83	Rb 88 17.78 m	Rb 89 15.15 m	Rb 90 2 v 2.6 m	Rb 91 58.4 s	Rb 92 2 v 4.492 s	Rb 93 v 5.84 s	Rb 94 v 2.702 s	Rb 95 377.5 ms	Rb 96 203 ms
Kr 84 57.00	Kr 85 10.776 y	Kr 86 17.30	Kr 87 76.3 m	Kr 88 2.84 h	Kr 89 1 3.18 m	Kr 90 1 32.32 s	Kr 91 v 8.57 s	Kr 92 1.840 s	Kr 93 1.286 s	Kr 94 210 ms	Kr 95 114 ms
Br 83 2.40 h	Br 84 31.80 m	Br 85 2.90 m	Br 86 1 v 55.1 s	Br 87 1 55.65 s	Br 88 1 v 16.36 s	Br 89 v 4.40 s	Br 90 1.910 s	Br 91 0.64 s	Br 92 343 ms	Br 93 102 ms	Br 94 70 ms
Se 82 8.73	Se 83 22.3 m	Se 84 3.1 m	Se 85 33 s	Se 86 14.1 s	Se 87 5.8 s	Se 88 1.53 s	Se 89 410 ms	Se 90 >300 ns	Se 91 270 ms	Se 92 100 ms	Se 93 50 ms

1 Priority **1** for decay heat simulation according to NEA 2007 assessment (**5**)

v Decay among 20+ most important ones for high energy reactor anti-neutrino spectra, Sonzogni et al., PR C 2015 (**9**)

Decays measured with MTAS in January 2012 and March 2015



La 139 99.910	La 140 1.6781 d	La 141 3.92 h	La 142 92.6 m	La 143 14.3 m	La 144 40.9 s	La 145 24.8 s	La 146 6.27 s	La 147 4.015 s	La 148 1.26 s
Ba 138 71.698	Ba 139 83.06 m	Ba 140 12.752 d	Ba 141 18.27 m	Ba 142 10.7 m	Ba 143 14.5 s	Ba 144 11.5 s	Ba 145 4.31 s	Ba 146 2.22 s	Ba 147 893 ms
Cs 137 30.1671 y	Cs 138 32.2 m	Cs 139 9.27 m	Cs 140 v 63.7 s	Cs 141 24.94 s	Cs 142 3 v 1.689 s	Cs 143 1.791 s	Cs 144 994 ms	Cs 145 582 ms	Cs 146 323 ms
Xe 136 8.87	Xe 137 1 3.83 m	Xe 138 v 14.08 m	Xe 139 1 39.68 s	Xe 140 1 13.60 s	Xe 141 1.73 s	Xe 142 1.22 s	Xe 143 511 ms	Xe 144 388 ms	Xe 145 188 ms
I 135 6.61 h	I 136 45s 1 1 84 s	I 137 1 24.2 s	I 138 6.4 s	I 139 2.29 s	I 140 860 ms	I 141 430 ms	I 142 ~200 ms	I 143 100 ms	I 144 50 ms
Te 134 41.8 m	Te 135 18.6 s	Te 136 17.5 s	Te 137 2.49 s	Te 138 1.4 s	Te 139 >300 ns	Te 140 300 ms	Te 141 100 ms	Te 142 50 ms	
Sb 133 2.5 m	Sb 134 780 ms	Sb 135 1.68 s	Sb 136 923 ms	Sb 137 450 ms	Sb 138 500 ms	Sb 139 300 ms			

6 1 3 v

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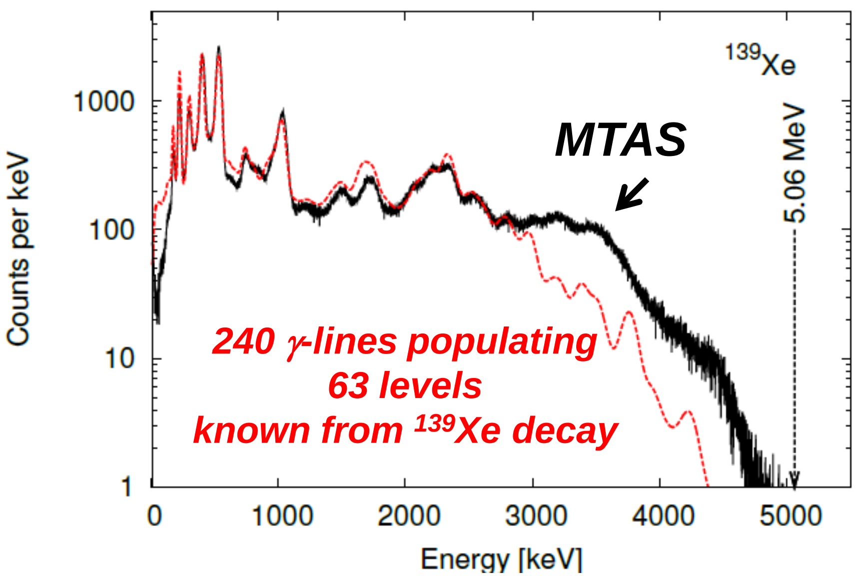
Priority "1" ^{139}Xe → ^{139}Cs decay ($T_{1/2}$= 39.7 s)

cumulative yield of ^{139}Xe in n_{th} + ^{235}U fission is about 5%

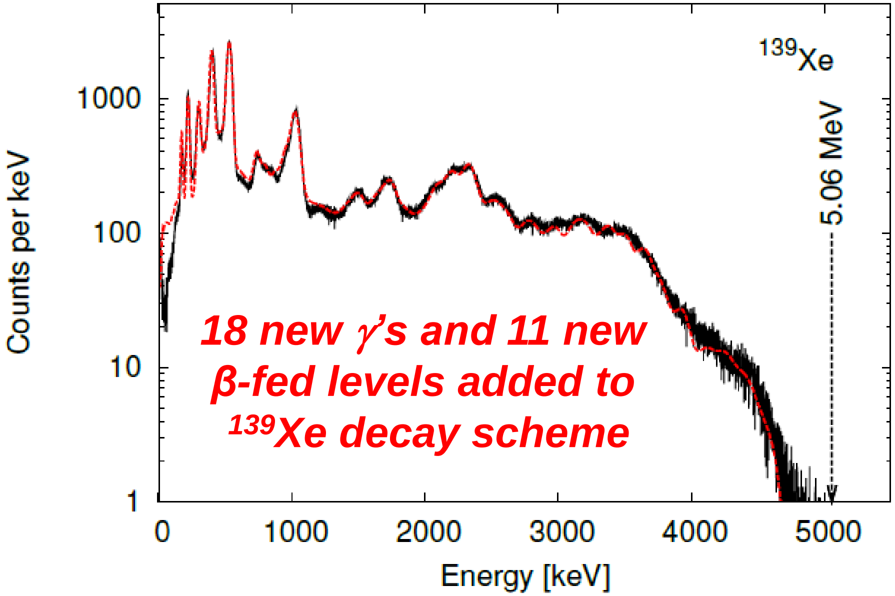
MTAS full spectrum ENSDF decay scheme



MTAS

240 γ-lines populating 63 levels known from ^{139}Xe decay

MTAS full spectrum - evaluated



18 new γ's and 11 new β-fed levels added to ^{139}Xe decay scheme

MTAS result:

average ***gamma*** *energy release per ^{139}Xe decay increased from 935 keV to 1370 keV*

47 % increase

average ***beta*** *energy release per ^{139}Xe decay decreased from1774 keV to 1573 keV*

13 % decrease

Aleksandra Fijałkowska et al., Nuclear Data Sheets 120, 26 (2014)

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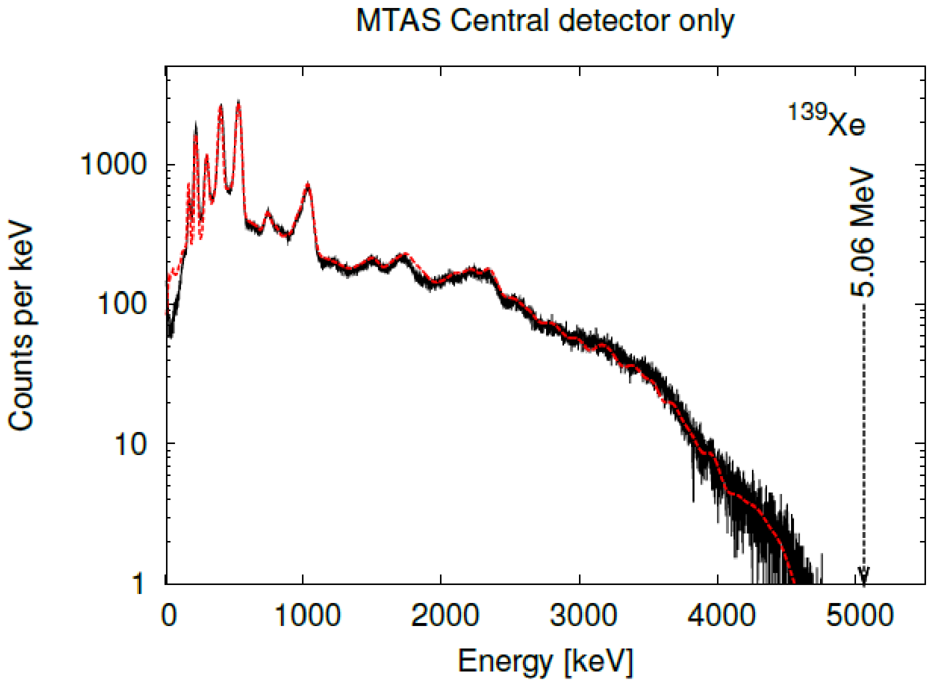
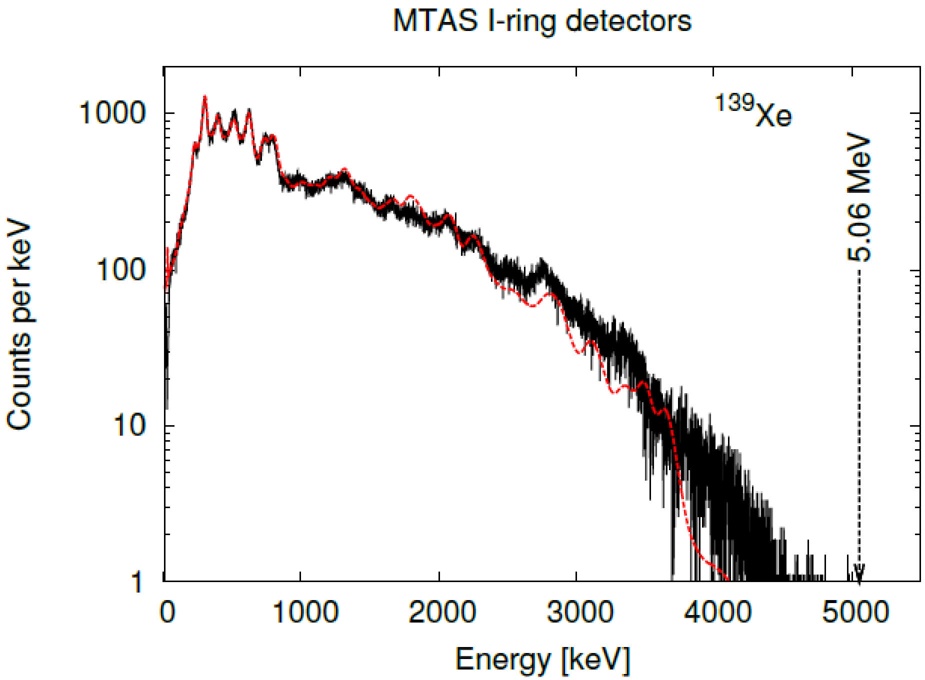
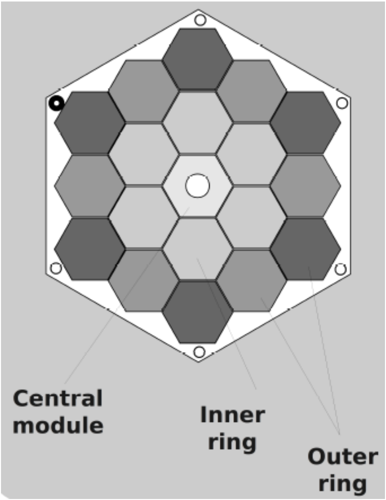
Measured *and* ***modified*** *^{139}Xe decay in central and inner rings of MTAS*



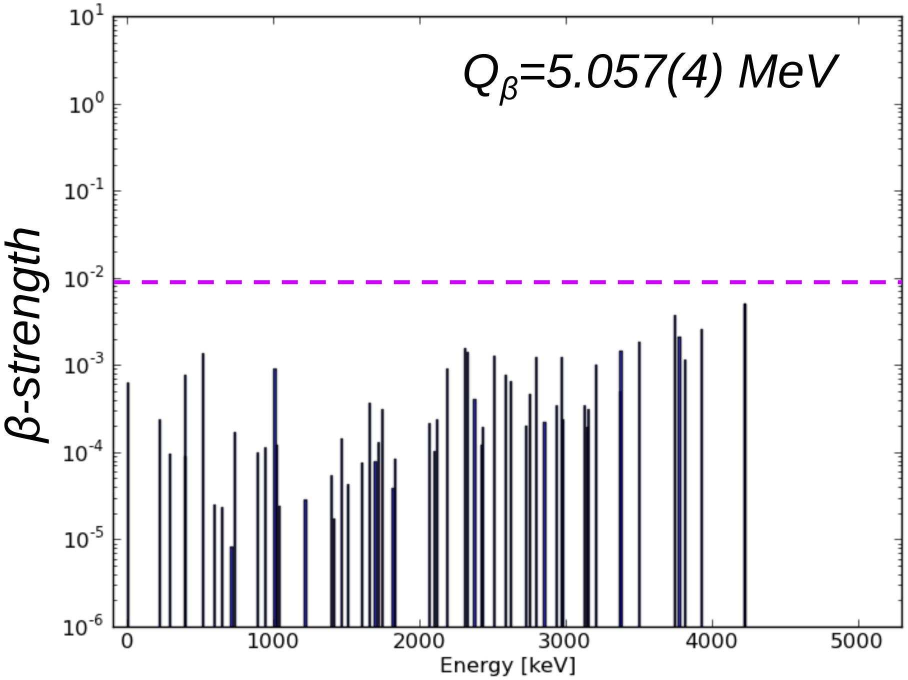




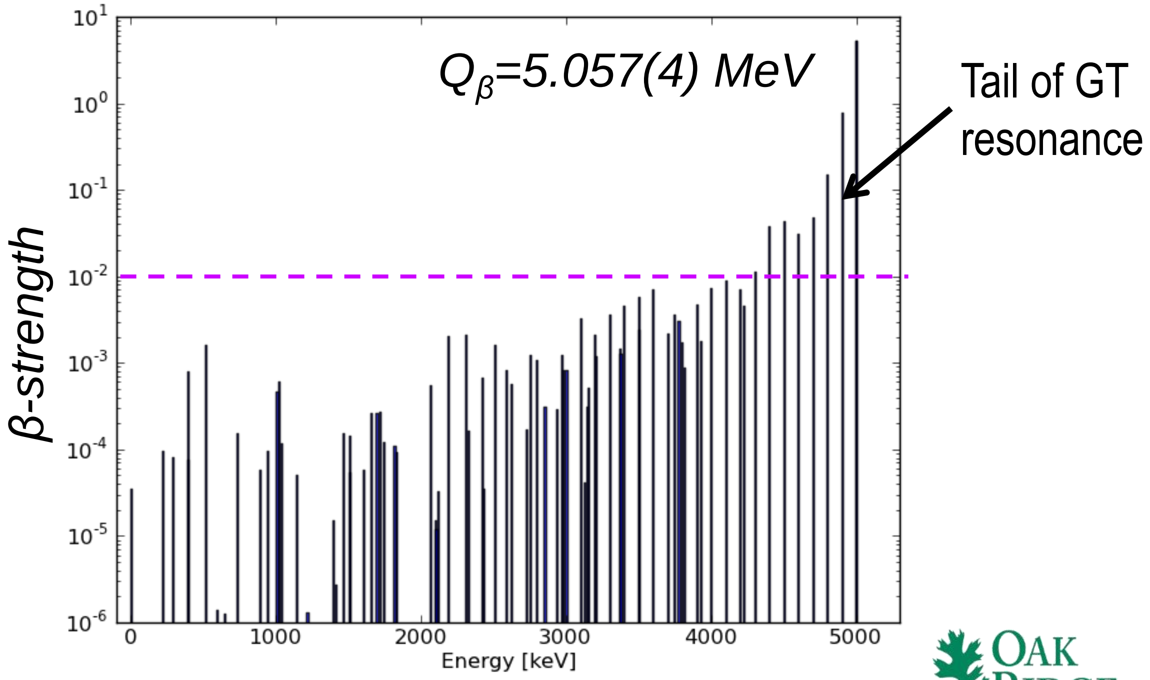
Modular construction of MTAS helps to validate results !

see also B.C. Rasco et al., ARIS 2014 proceedings

β-strength in ^{139}Xe decay
ENSDF



β-strength in ^{139}Xe decay
MTAS



A. Fijałkowska
PhD thesis 2015

OAK RIDGE
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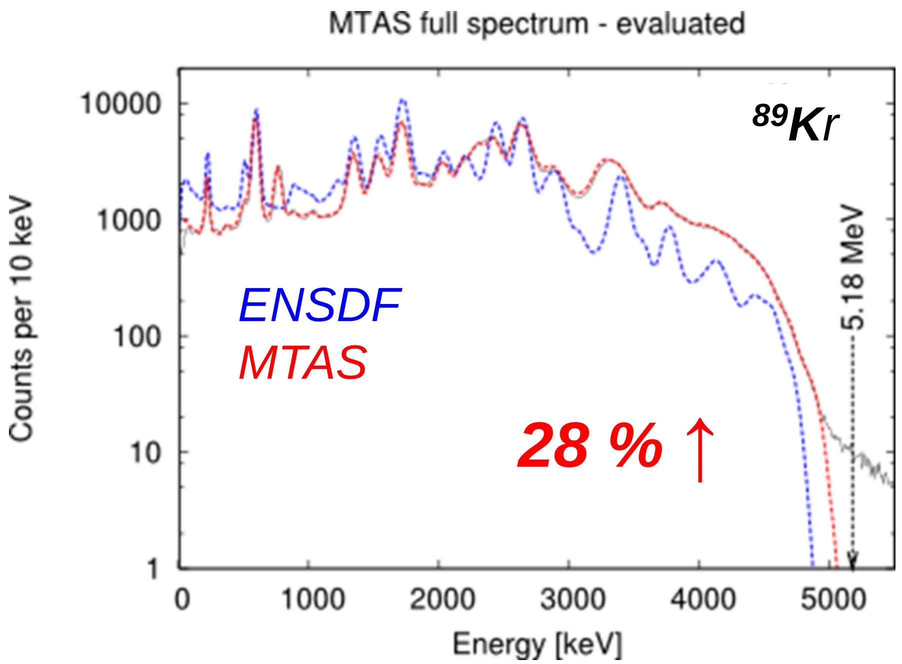
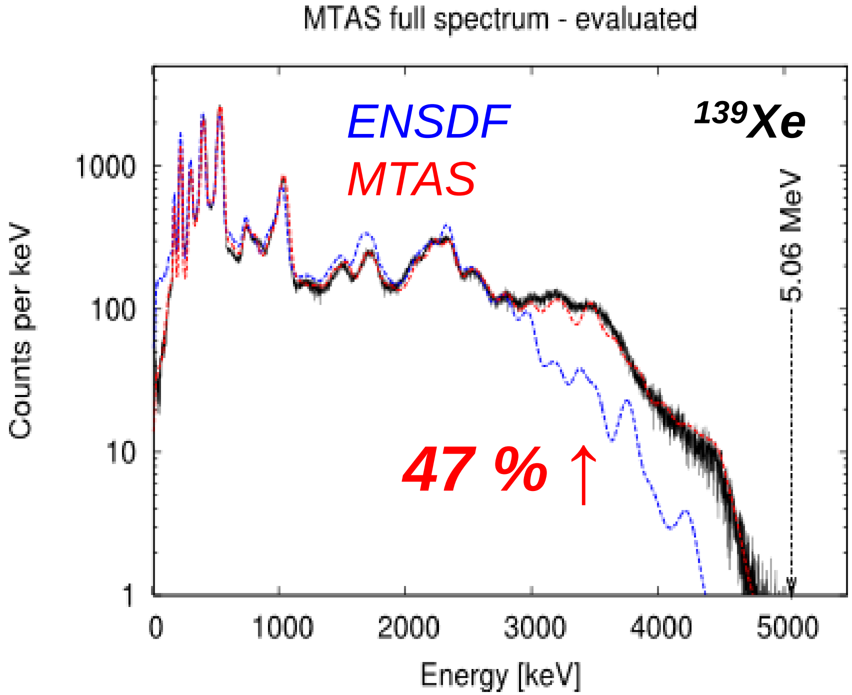
Decay heat *<E_γ> in ^{89}Kr and ^{139}Xe studied with MTAS*

production in n_{th}+ ^{235}U: ^{89}Kr ~ 4.5% and ^{139}Xe ~ 5 %


MTAS full spectrum - evaluated


MTAS full spectrum - evaluated

MTAS** results for ^{89}Kr and ^{139}Xe decays point to **much larger <E_γ> values

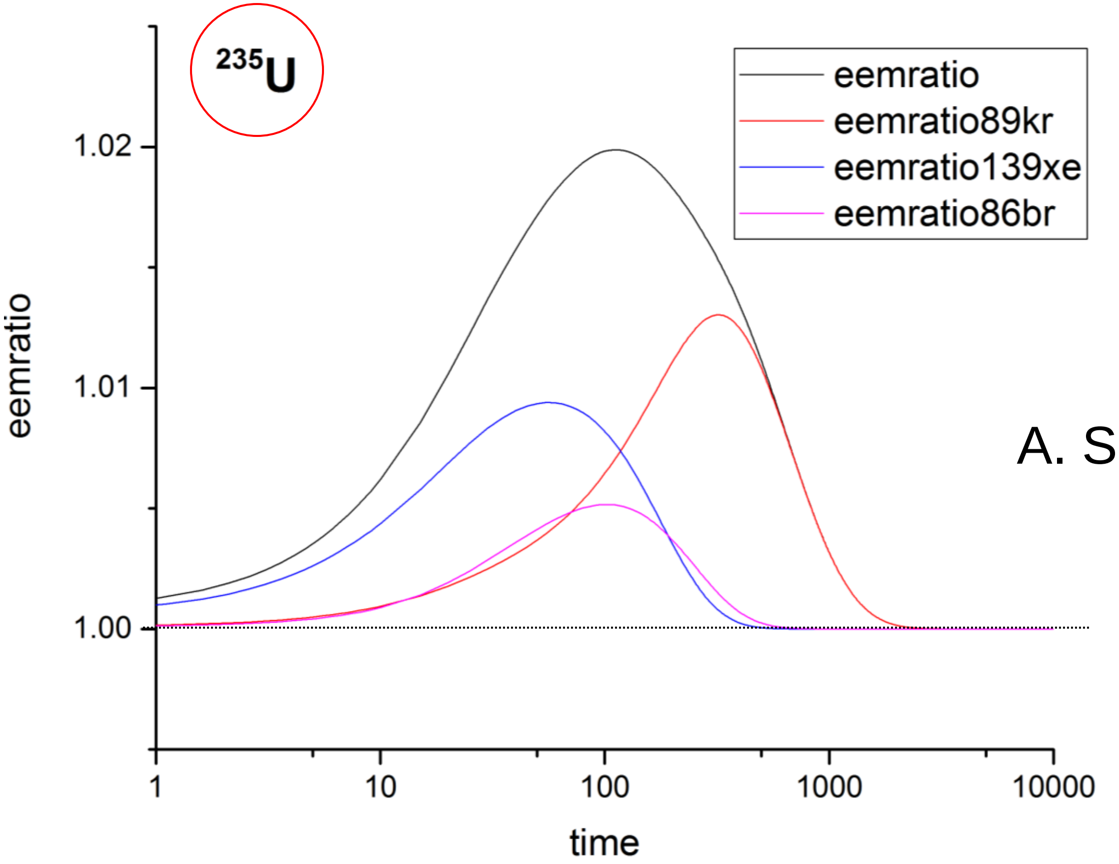
^{89}Kr: 1801 keV (ENSDF) to 2304 keV (MTAS), ^{139}Xe: from 935 keV to 1370 keV.

*Respectively, **average beta and anti-neutrino energy go down***

^{89}Kr: <E_β>=1462 keV (ENSDF) to <E_β>=1222 keV (MTAS),
^{139}Xe:1774 keV to 1573 keV

Impact of ^{86}Br,^{89}Kr and ^{139}Xe on total decay heat pattern

Gamma decay heat ratio: (MTAS and ENSDF)/ENSDF



eem = gamma

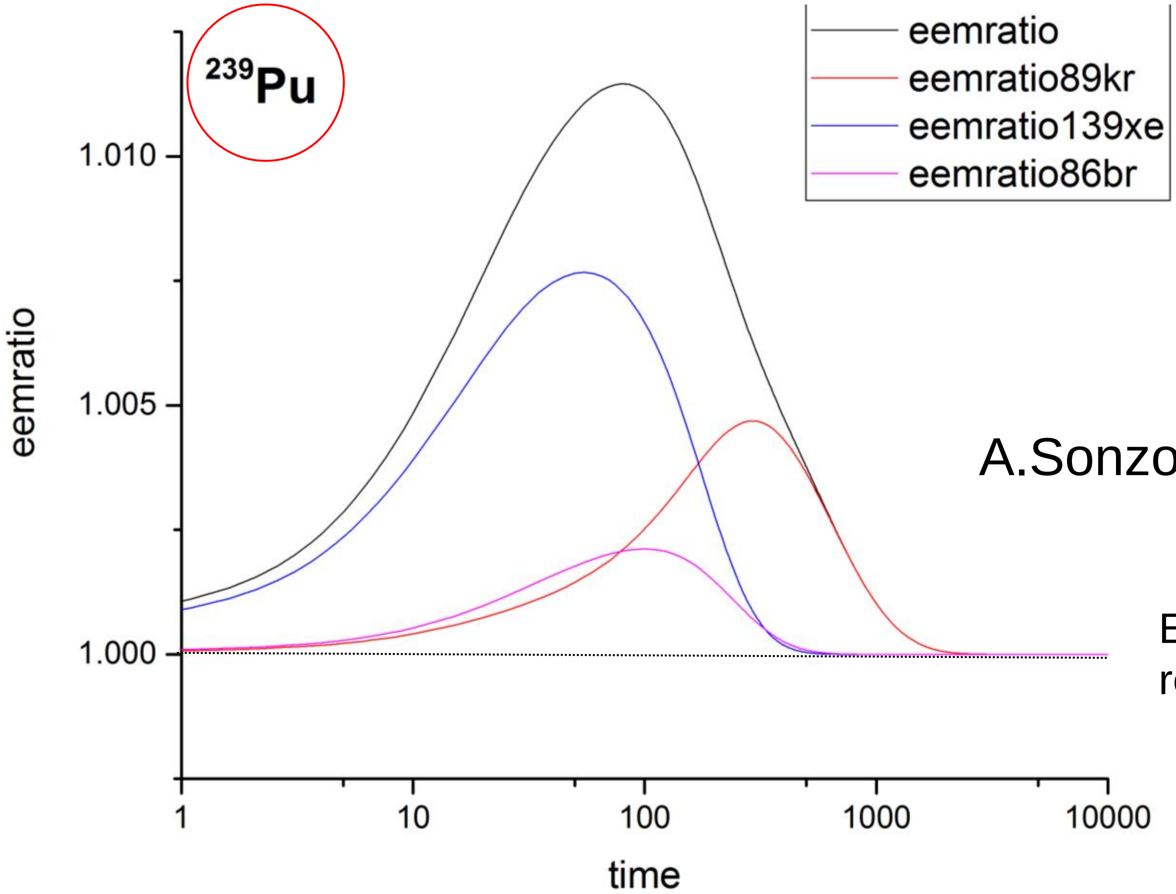
A. Sonzogni June 2015

ENSDF
reference

For ^{235}U component of nuclear fuel, three out of 11 priority “1” decays measured with MTAS result in up to 2 % change per time unit in total decay heat between 5 s and 1000 s after fission

Impact of ^{86}Br, ^{89}Kr and ^{139}Xe on total decay heat pattern

Gamma decay heat ratio: (MTAS and ENSDF)/ENSDF



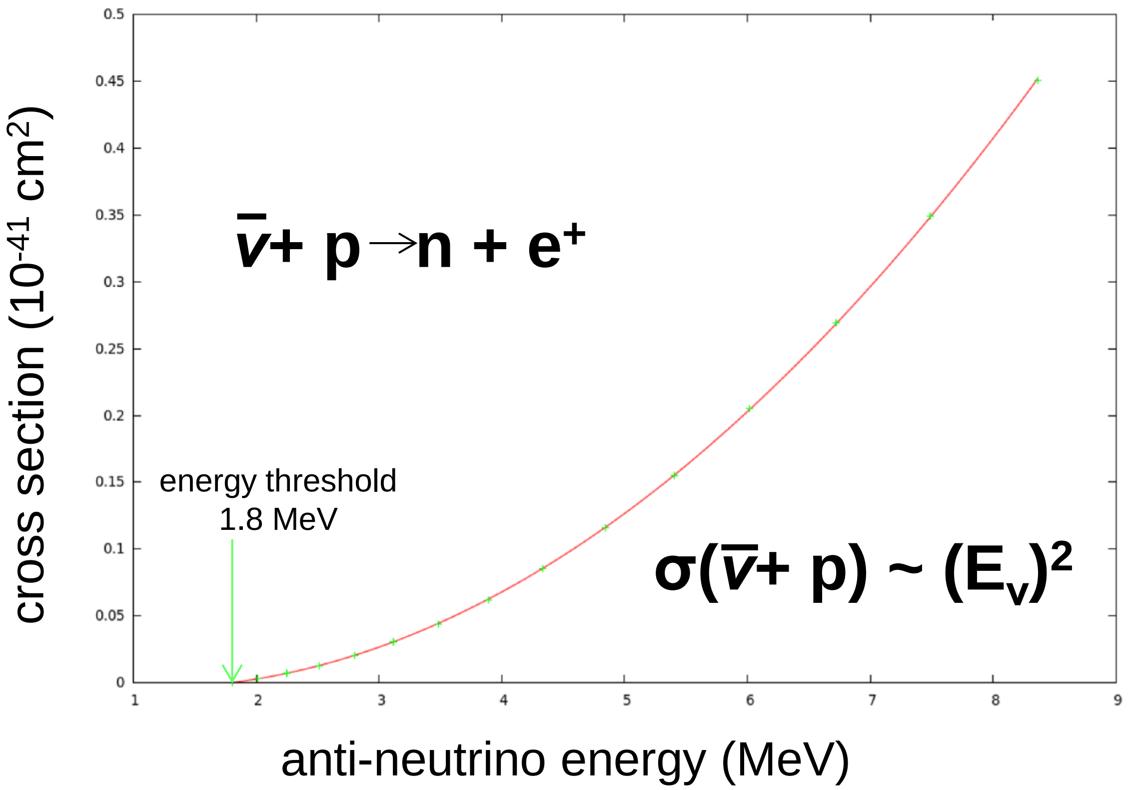
eem = gamma

A.Sonzogni June 2015

ENSDF
reference

For ^{239}Pu component of nuclear fuel, three out of 11 priority “1” decays measured with MTAS result in up to 1 % change per time unit in total decay heat between 5 s and 1000 s

Anti-neutrino interactions with protons



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

$\sigma(\bar{\nu} + p) \sim (E_\nu)^2$

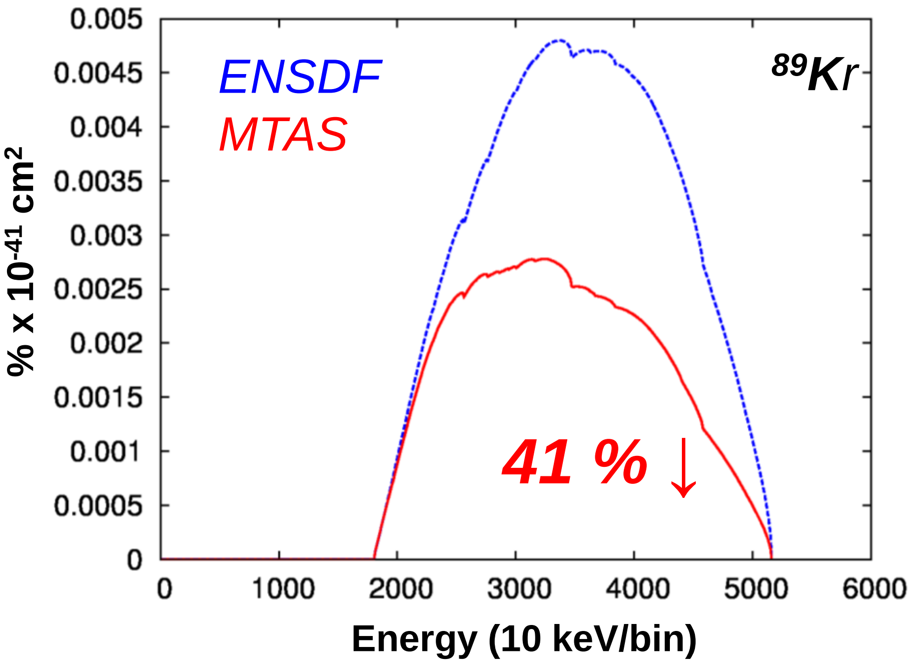
High energy anti-neutrinos have higher cross section for the interactions with protons, i.e.,
have higher probability to be removed from $\bar{\nu}$ beam.

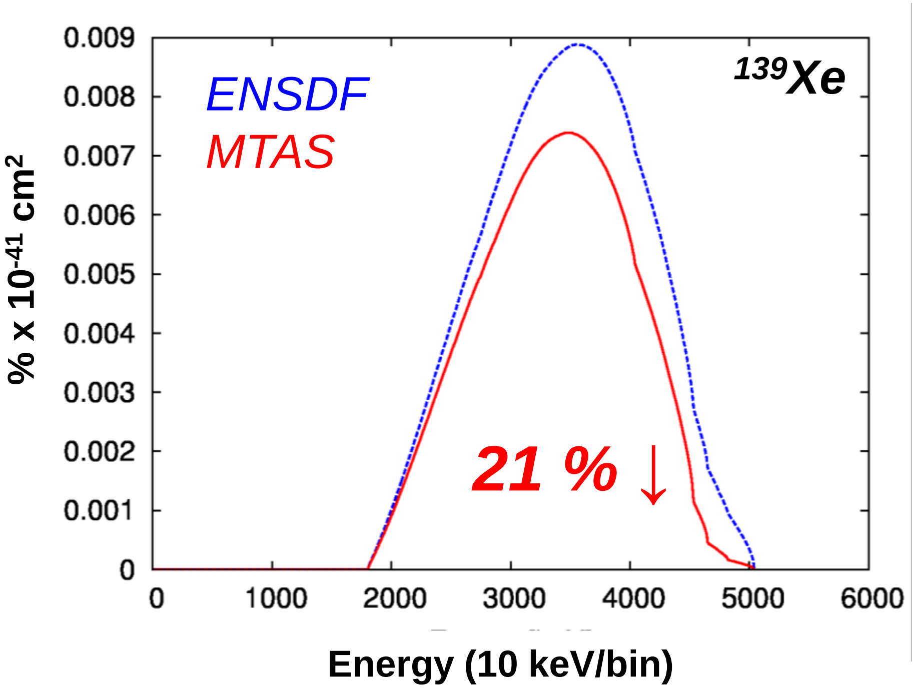
For anti-neutrinos with energies below 1.8 MeV energy threshold: no interactions on protons.

A. Strumia and F. Vissani, PL B 564, 42, 2003

Interacting anti-neutrinos emitted in ^{89}Kr and ^{139}Xe decay

Number of interactions of ^{89}Kr and ^{139}Xe anti-neutrinos per 10 keV energy bin (in % x 10^{-41} cm^2 units).





reactor antineutrino anomaly defined as observed/expected signals

94.3(23) % ⟶ ~ 6 % missing

Mention et al., PR D 83, 2011

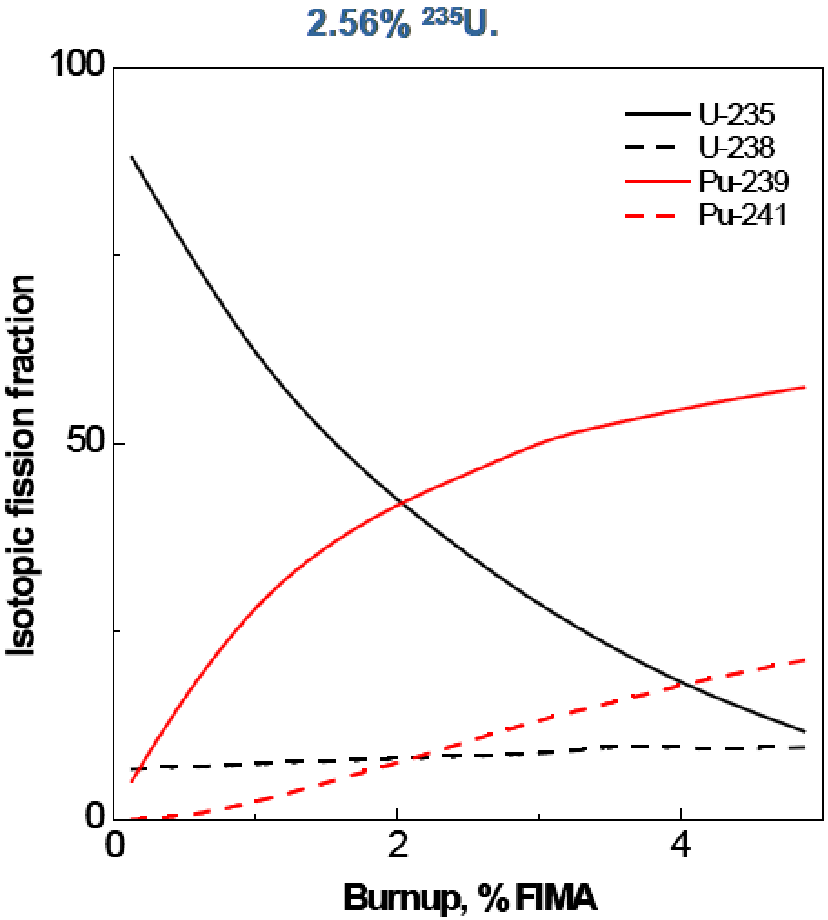
Impact - reactor anti-neutrino physics

MTAS results for ^{89}Kr and ^{139}Xe decays account for

3 to 2 of the "missing 6 %" difference

in the reactor anti-neutrino anomaly, depending on a burn-up phase.

Here, a reference number of interacting reactor anti-neutrinos is calculated using ENSDF



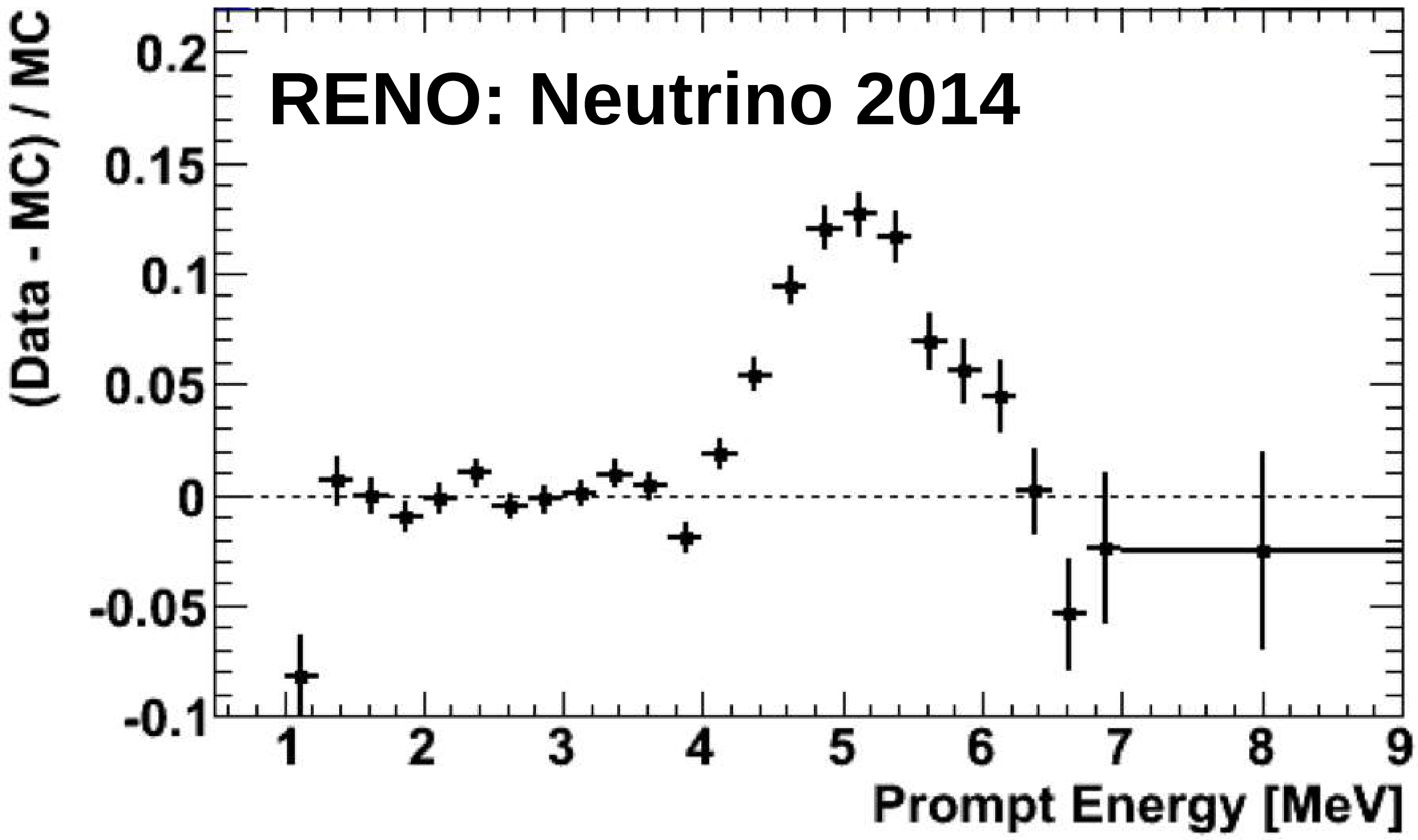
from Ian Gauld, 2014

ORNL Nuclear Reactor Science Group

(ORIGEN for SCALE)

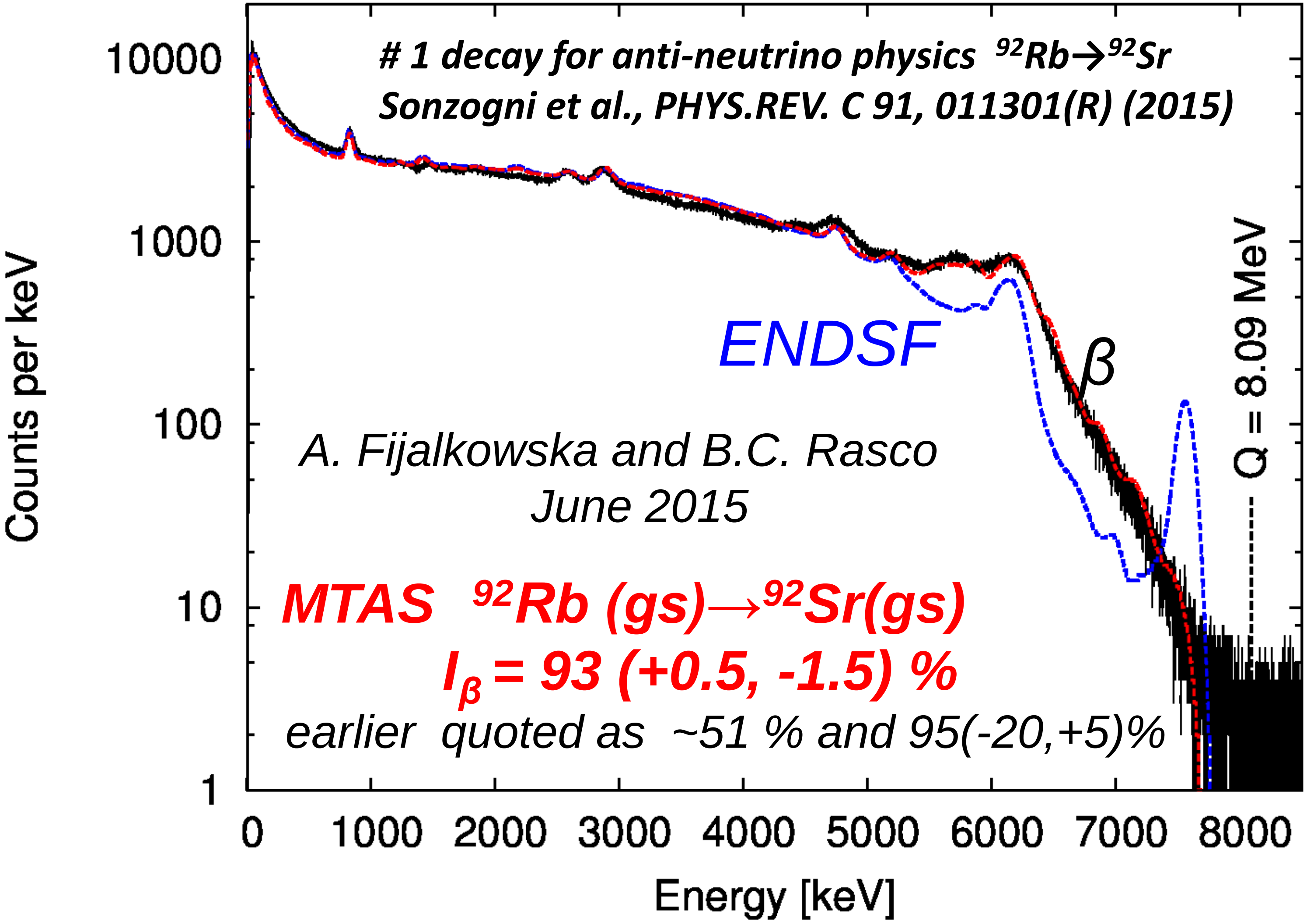
Recent $\overline{\nu}e$ energy measurements (RENO, Daya Bay, Double Chooz) also disagree with existing models

(e.g., Dan Dwyer, NDNCA meeting, May 2015)



Anti-neutrino energy = Prompt Energy + 0.8 MeV

^{92}Rb decay measured with Tandem-OLTF-MTAS (March 2015)



 # 1 decay for anti-neutrino physics ^{92}Rb→^{92}Sr

Sonzogni et al., PHYS.REV. C 91, 011301(R) (2015)

A. Fijalkowska and B.C. Rasco

June 2015

MTAS ^{92}Rb (gs)→^{92}Sr(gs)

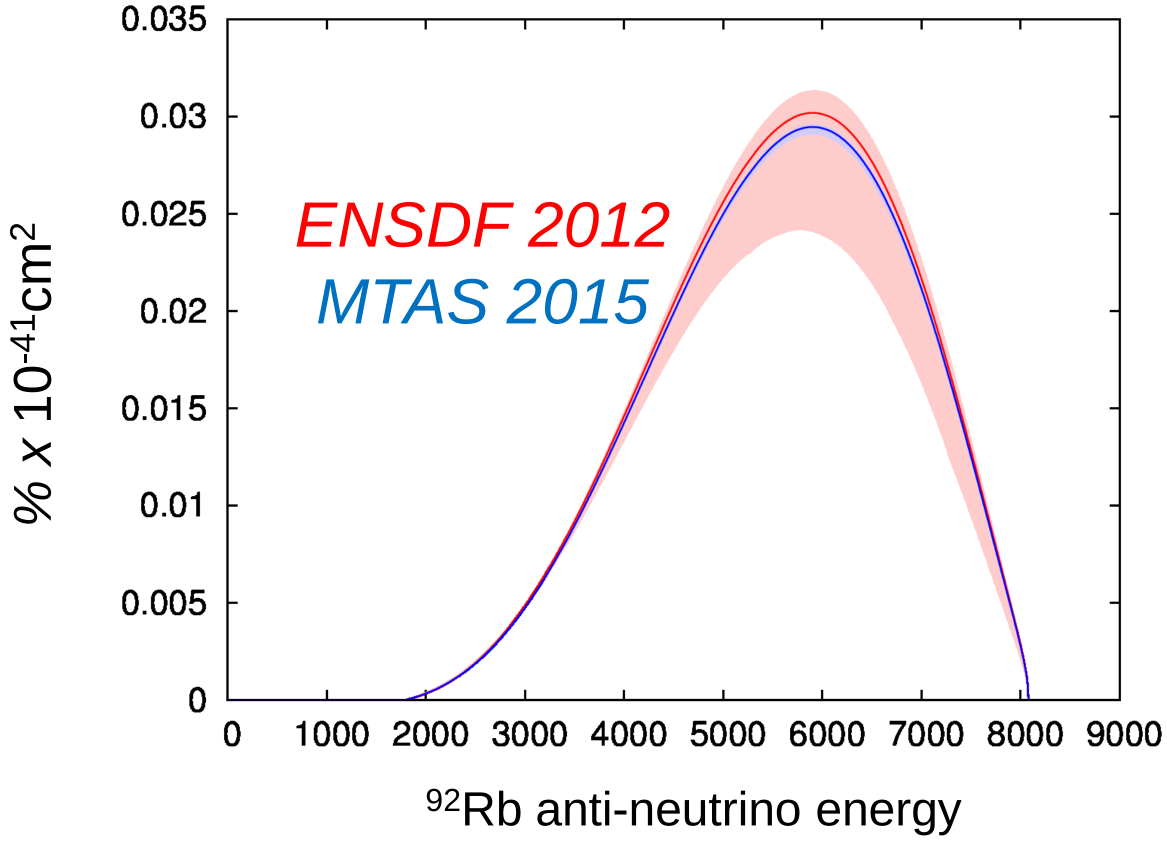
I_β = 93 (+0.5, -1.5) %

earlier quoted as ~51 % and 95(-20,+5)%

$12 \cdot 10^6$ counts in β-gated MTAS total gamma absorption spectrum (counts per keV)

Impact of MTAS measurement of ^{92}Rb gs-gs branching ratio on a number of anti-neutrinos interacting with matter

Aleksandra Fijałkowska and Charlie B. Rasco, July 2015



ENSDF 1992: 51(2)% → interacting antineutrinos 6.95(-0.14,+0.28) % x 10^{-41} cm^2

ENSDF 2012: 95.2(-20,+5)% → interacting antineutrinos 10.05(-1.77,+0.23) % x 10^{-41} cm^2

MTAS 2015: 93(-1.5,+0.5)% → interacting anti-neutrinos 9.81(-0.12,+0.04) % x 10^{-41} cm^2

Summary

We got important results on decay properties in fission products,
in particular on β-strength function and its consequences:

- decay heat (11 priority “1” cases out of initial list of 27 from NEA 2007)
- reactor anti-neutrino interactions with matter (“anomaly”, as above)
- reactor anti-neutrino energy spectra (“bump”, 12 out of 20+ apparent contributors)
- branching ratios and high energies in βn-emission
- new decay schemes and single-particle level properties (> 20)
- new nuclear structure model analyses (R.K. Grzywacz, I.N. Borzov)