Nuclear Reactor Antineutrinos, Hard to Detect, but with a Traceable Lineage

A.A. Sonzogni, E.A. McCutchan, T.D. Johnson

National Nuclear Data Center

Outline

- About the National Nuclear Data Center.
- Summation method.
- Relation to Decay Heat
- Fission yields effect
- A closer look into the Conversion method

About the NNDC

1952: Data activities started, Neutron Cross Section Compilation Group.

1961: Sigma center

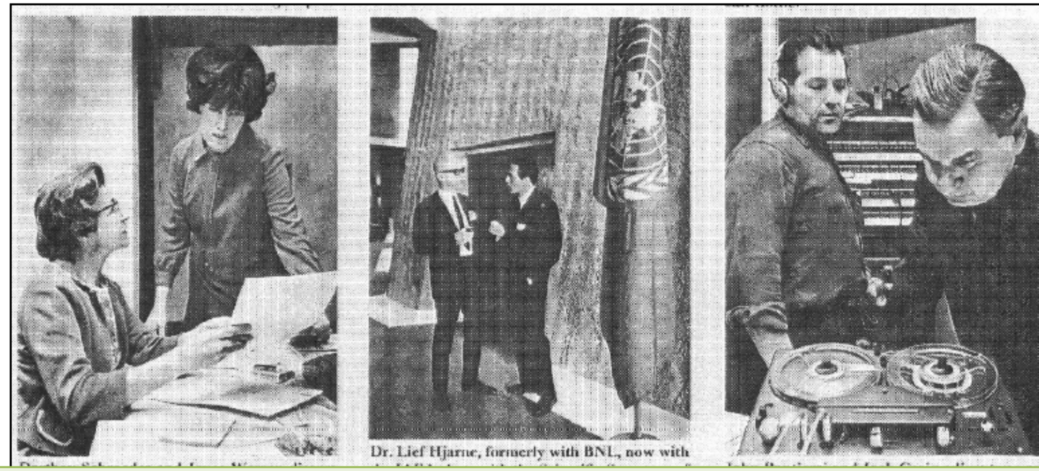
1967: National Neutron Cross Section Center

1977: National Nuclear Data Center

Located in Building 817 – part of NE department

www.nndc.bnl.gov

Some of our history in the Bulletin


Dr. Lief Hjarne, formerly with BNL, now with


Reactor Physics Chief Addresses Group

Dr. Ira F. Zartman, Chief of the Reactor Physics Branch of the AEC Division of Reactor Development and Technology (center) addresses members of the Cross Section Evaluation Working Group at their fifth semi-annual meeting. Dr. Zartman was one of the principal proponents of the formation of this group.

Honored guests at a meeting of the Cross Section Evaluation Working Group held recently at BNL were: (left to right) Dr. George Vineyard, Deputy Director of BNL; Dr. Ira F. Zartman, and Dr. Maurice Goldhaber, Director of BNL.

Photos by Humphrey

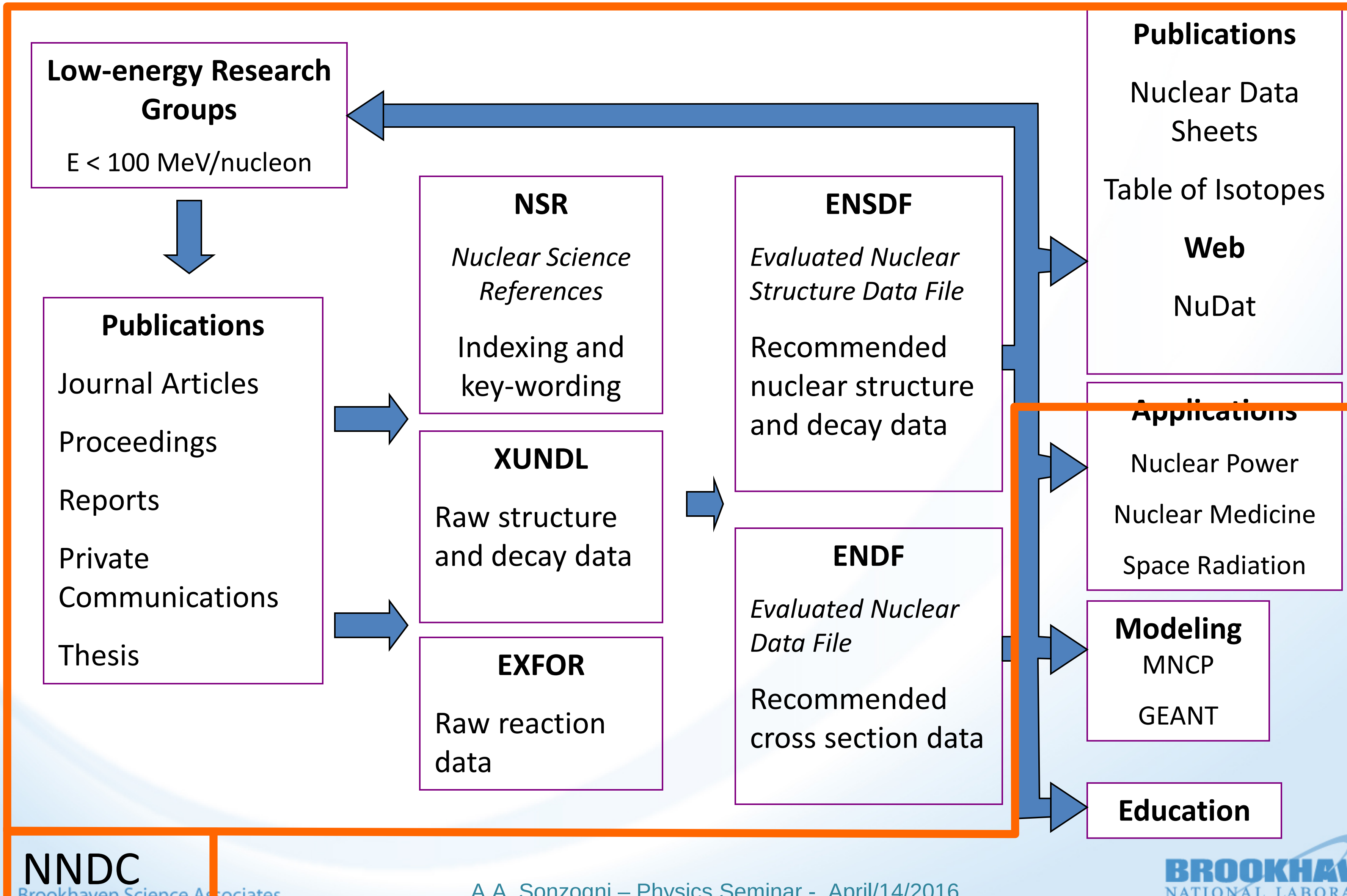
BNL Bulletin, September 26 1968.

These meetings still take place
Nuclear Data Week every November
The library is still around

Published and unpublished literature containing neutron data are stored in the NNCSC library. Georgia Irving retrieves data for use by the scientists working at the National Neutron Cross Section Center at Brookhaven National Laboratory.
—Rosen


Sol Perlstein and Vicky McLane during a 1973 EXFOR meeting in Moscow (BNL Bulletin).

Nuclear Data



Data Libraries

Managed by the NNDC

ENSDF, www.nndc.bnl.gov/ensdf
Contains nuclear structure and decay data.

ENDF/B, www.nndc.bnl.gov/endf
American. Main effort is for neutron-induced cross sections and spectra. It also contains fission and decay data in a numerical format.

JEFF, www.oecd-nea.org/dbdata/jeff/
European. Similar to ENDF/B.

JENDL, wwwndc.jaea.go.jp/jendl/jendl.html
Japanese. Similar to ENDF/B.

Additionally the NNDC is responsible for the decay data in ENDF/B that is needed for the calculations.

How to calculate antineutrino spectra

(1) Conversion Method: Use the precisely measured electron spectra following the thermal neutron fission of $^{235,238}U$ and $^{239,241}Pu$.

Fit the electron spectrum with a set of hypothetical decay branches.

Uses nuclear data to obtain effective Z as function of end point energy.

P. Huber, Phys. Rev. C 84, 024617 (2011).

(2) Summation Method: Combine fission yields with decay data.

P. Vogel et al. Phys. Rev. C 24, 1543 (1981).

Summation Method

The antineutrino spectrum for an equilibrated system is calculated as:

$$S(E_{\bar{\nu}}) = \sum CFY_i S_i(E_{\bar{\nu}})$$

where CFY_i is the cumulative fission yield defined recursively as:

$$CFY_i = IFY_i + \sum b_{ki} CFY_k$$

with b_{ki} the decay probability from level k to level i. In matrix notation:

$$\mathbf{CFY} = \mathbf{A} \times \mathbf{IFY}$$

where **IFY** are the independent fission yields, and the matrix **A** has the decay probability data.

$S_i(E_{\bar{\nu}})$ is the spectrum generated by the decay of a single level**:**

$$S_i(E_{\bar{\nu}}) = \sum I\beta_{lki} S_{lki}(Q\beta_i - E_{lki}, X, E_{\bar{\nu}})$$

$S_{lki}(Q\beta_i - E_{lki}, X, E_{\bar{\nu}})$ is the antineutrino spectrum generated in the decay to the level E_{lk} with intensity $I\beta_{lki}$ in the daughter, normalized to **1**.

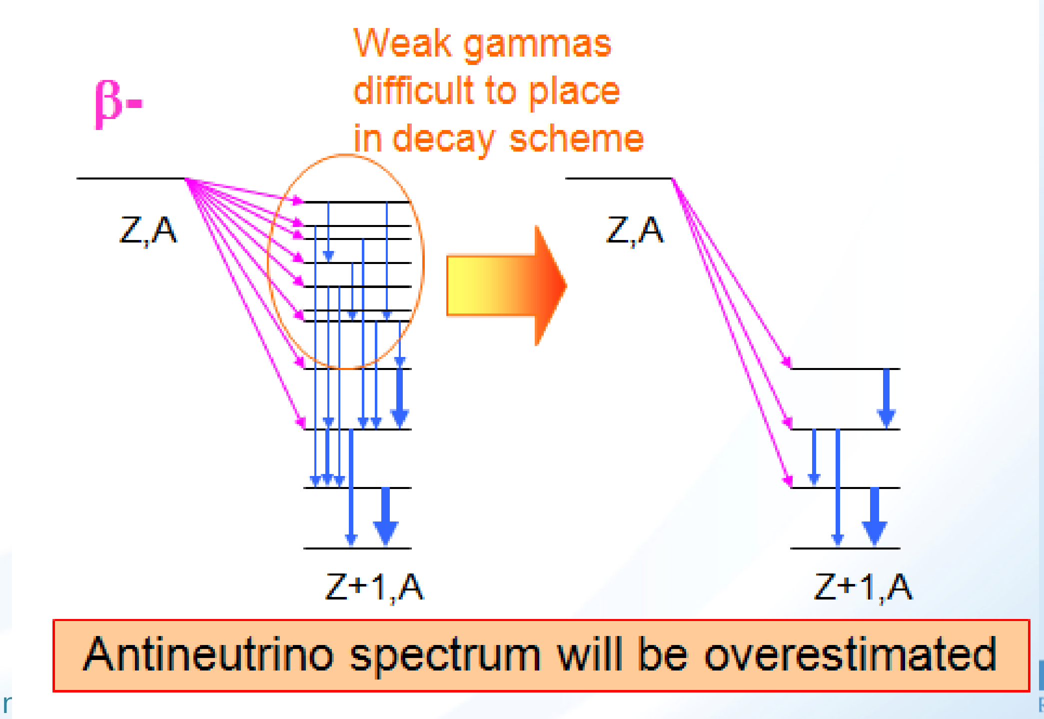
Summation Method

Some issues in this method:

- Cumulative Fission Yields have embedded decay probabilities, which should be compatible with the decay probabilities used in the spectra calculation.

- Decay data is only complete and of high quality for nuclides close to the valley of stability.

- For nuclides with a large Q-values, decay schemes obtained using Germanium detectors lead to large beta intensities for low-lying levels. One should use data from Total Absorption Gamma Spectroscopy (TAGS) experiments.



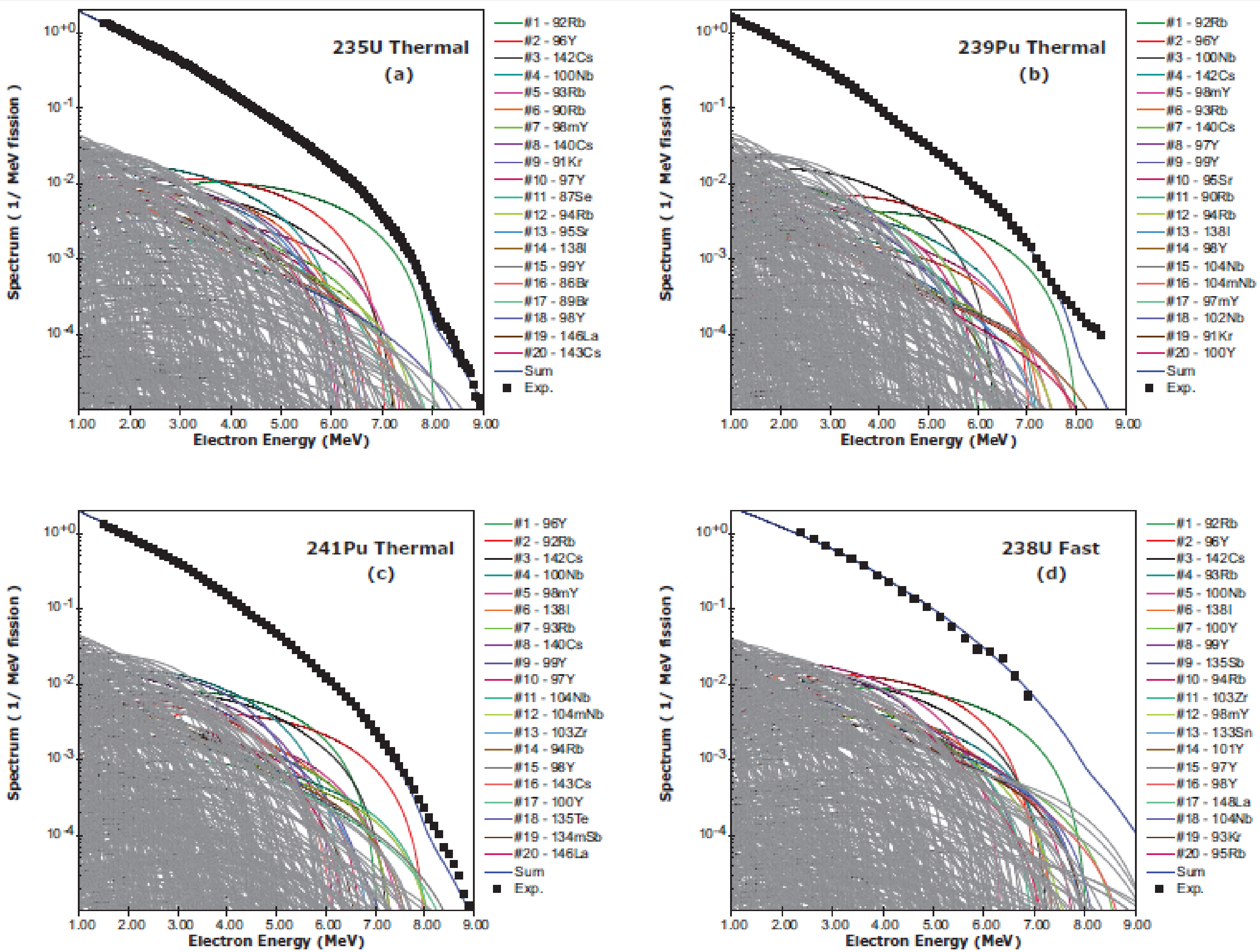
Summation Method

Update ENDF/B decay data with Iβ from TAGS and Rudstam data.

Surprisingly, fewer contributors at high energy.

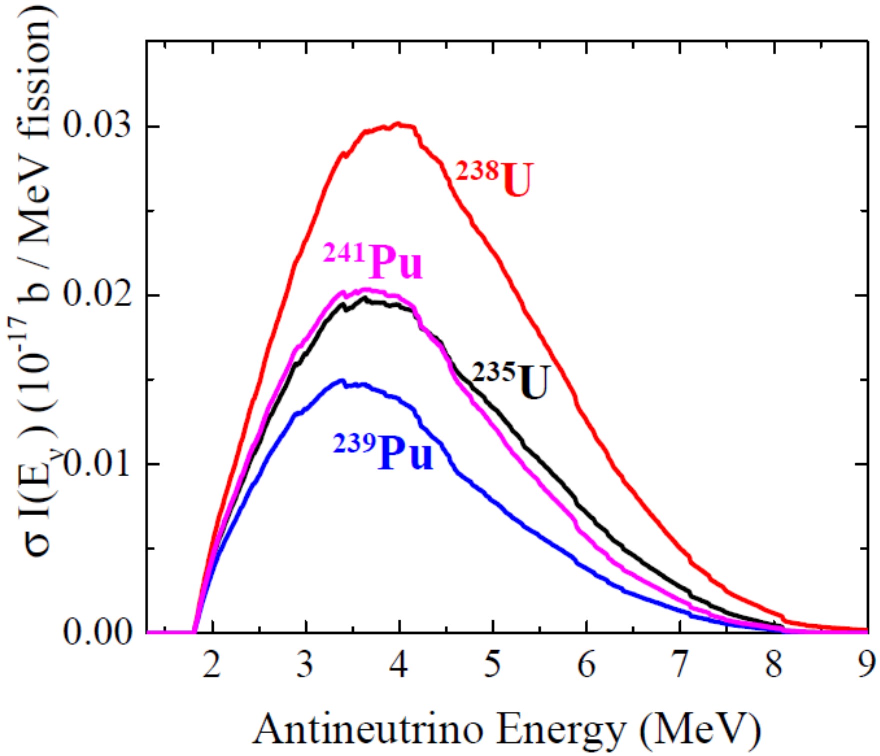
Calculations using JEFF yields (compatibility).

It includes calculated spectra for very neutron rich nuclides (Moller-Kawano)



A.A. Sonzogni, T.D. Johnson, E.A. McCutchan, PRC91, 011301(R) (2015)

Systematics of all fissioning systems

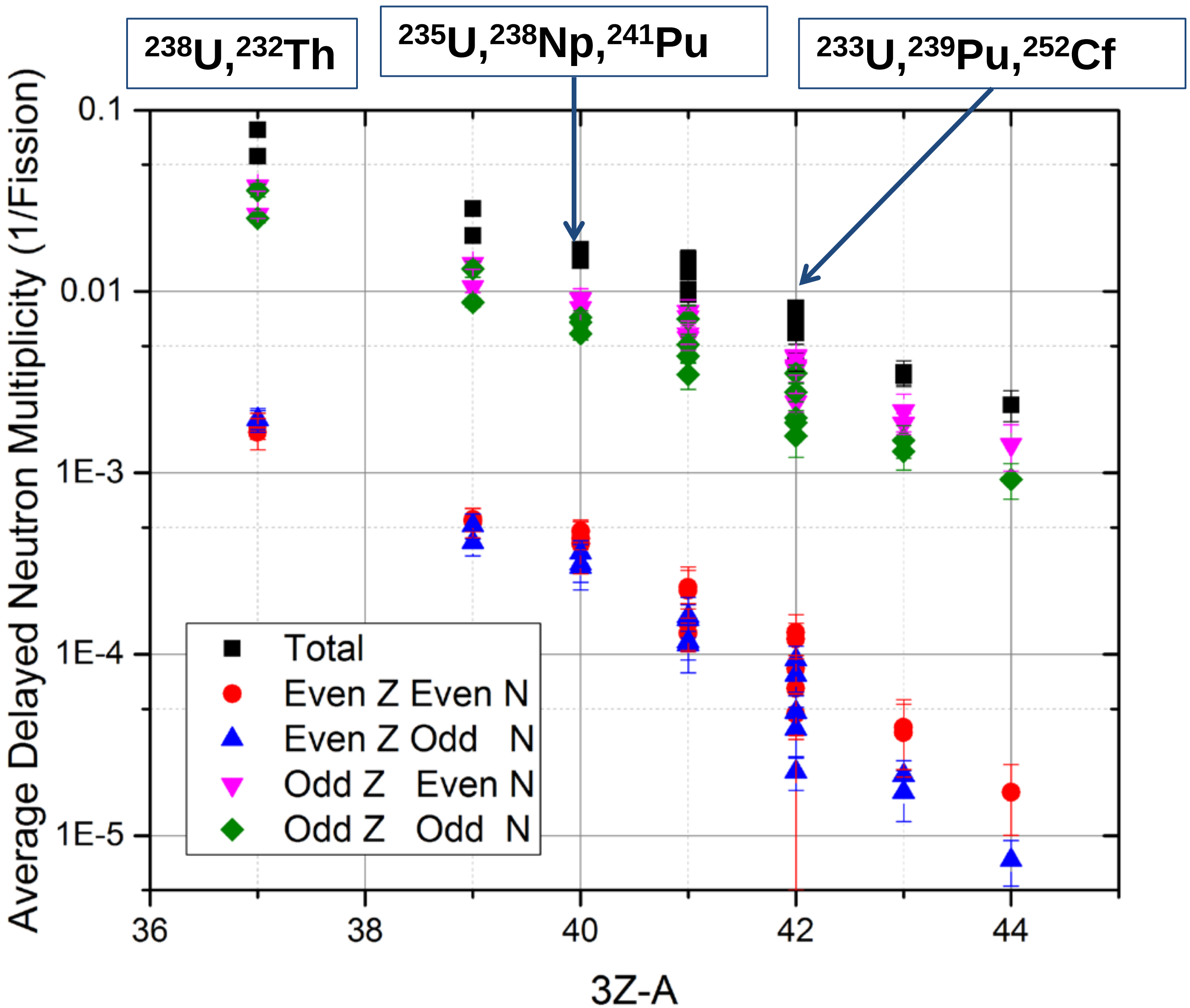


Nucleus	Delayed neutron multiplicity
238U	4.78E-2
235U	1.59E-2
241Pu	1.62E-2
239Pu	0.65E-2

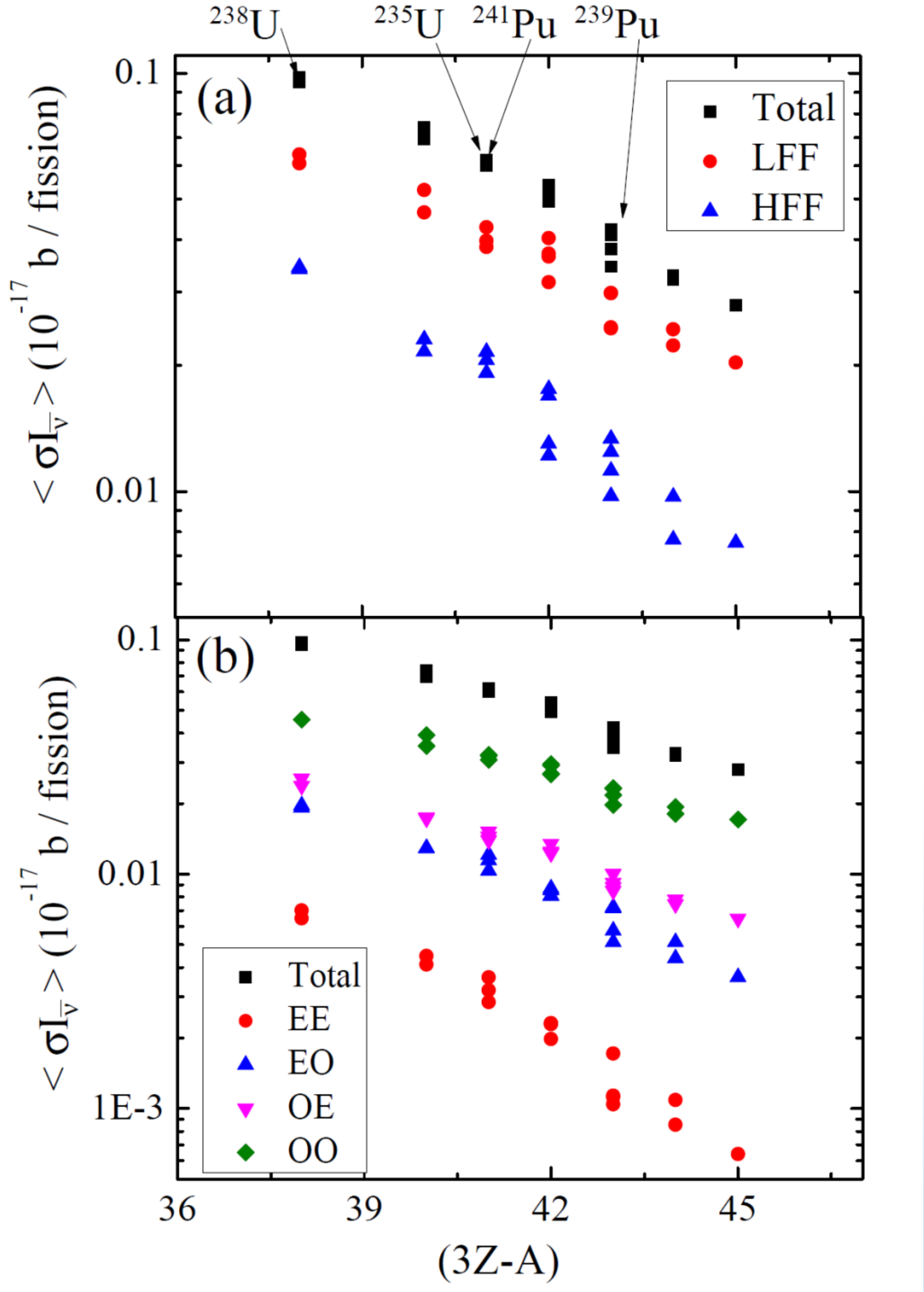
Link to delayed neutron yield commonly parameterized by

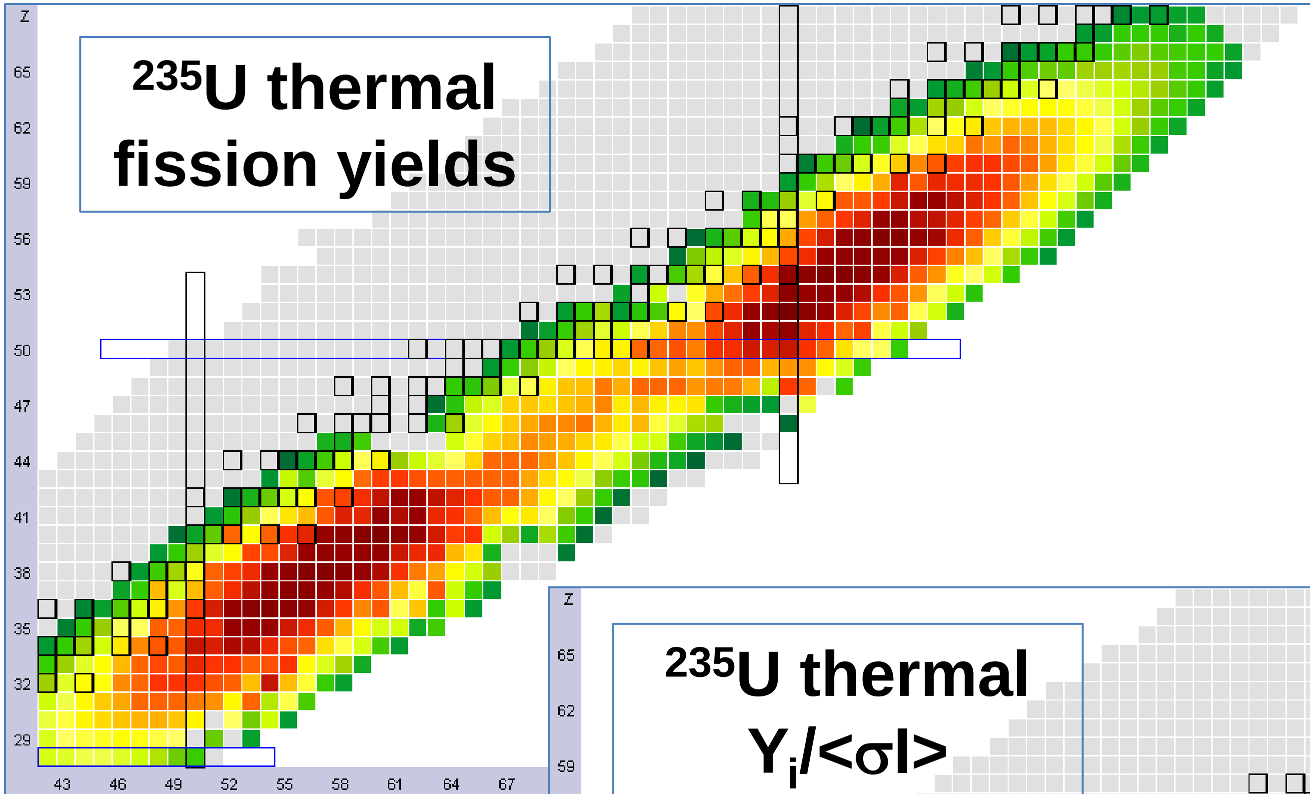
$$\boxed{3Z-A}$$

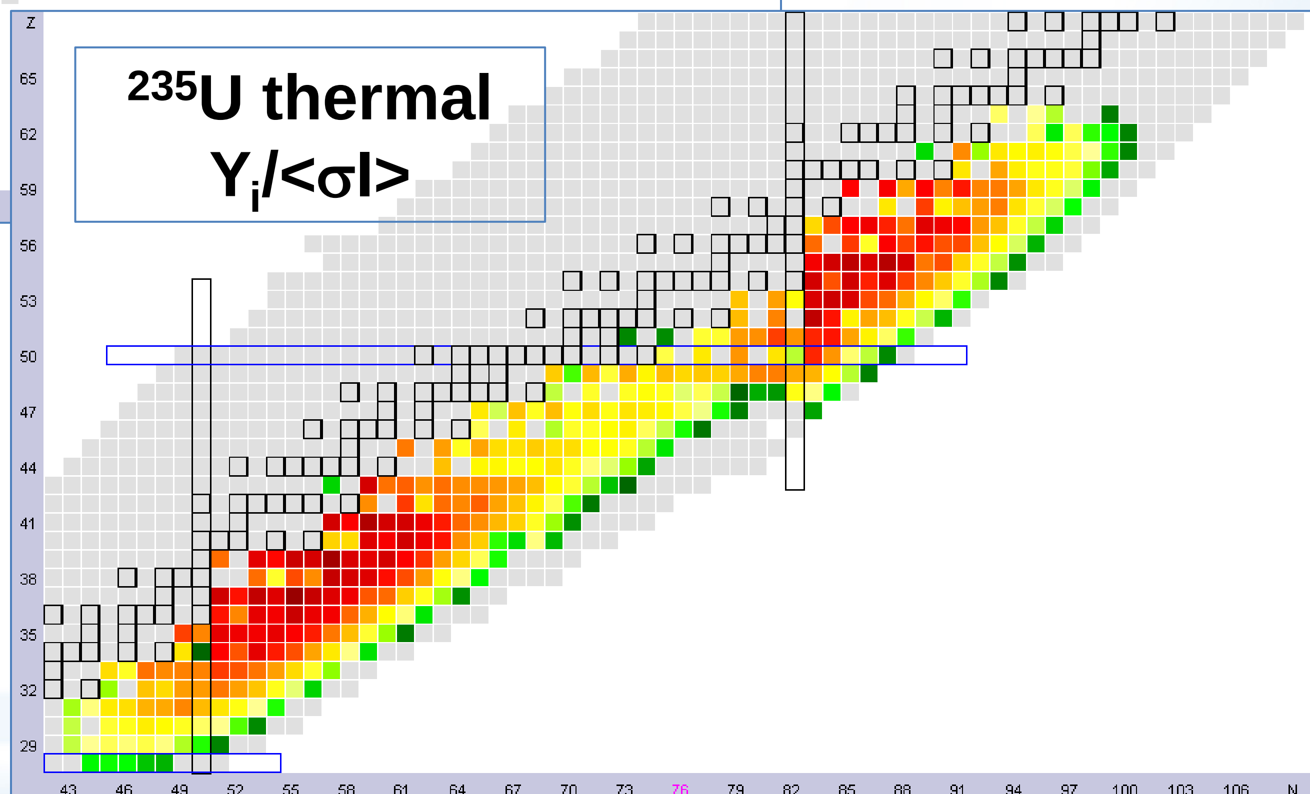
Systematics of Delayed nu-bars



Systematics of integrated IBD weighted spectra



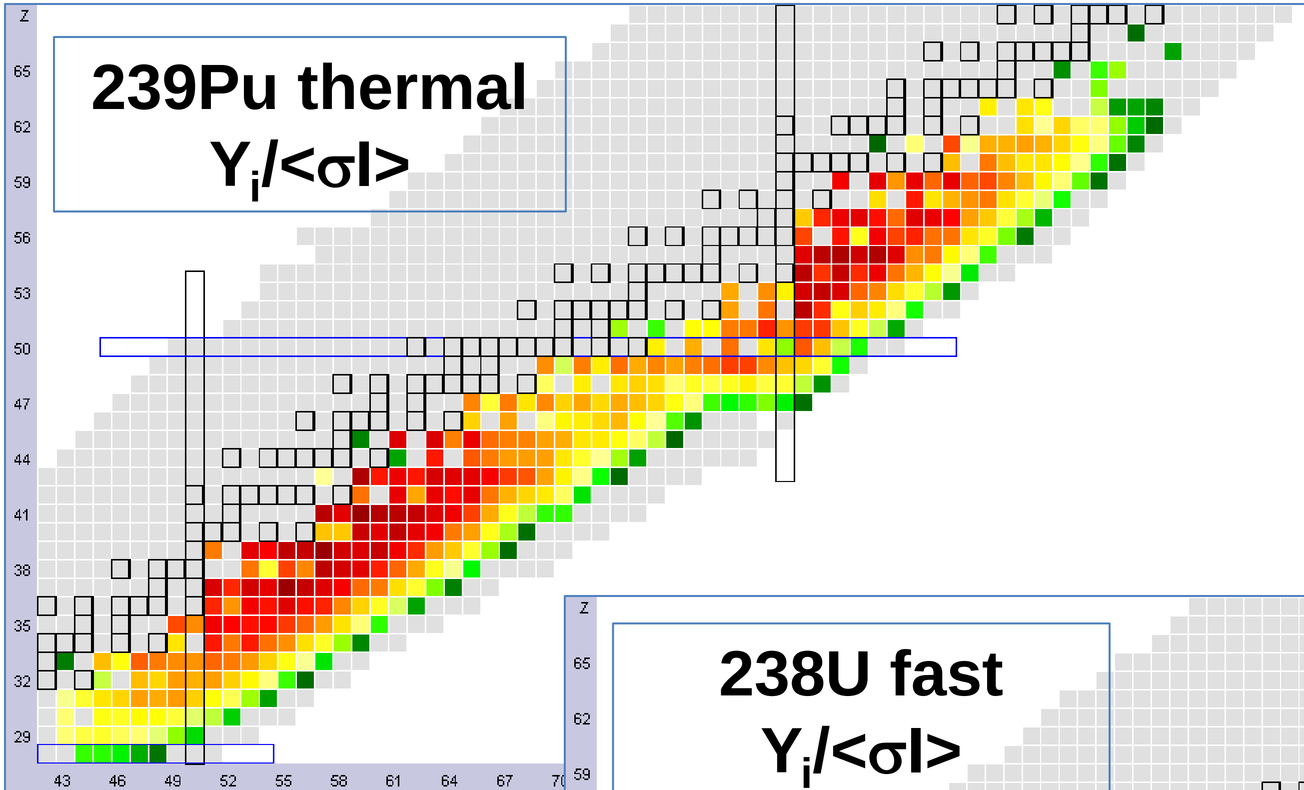


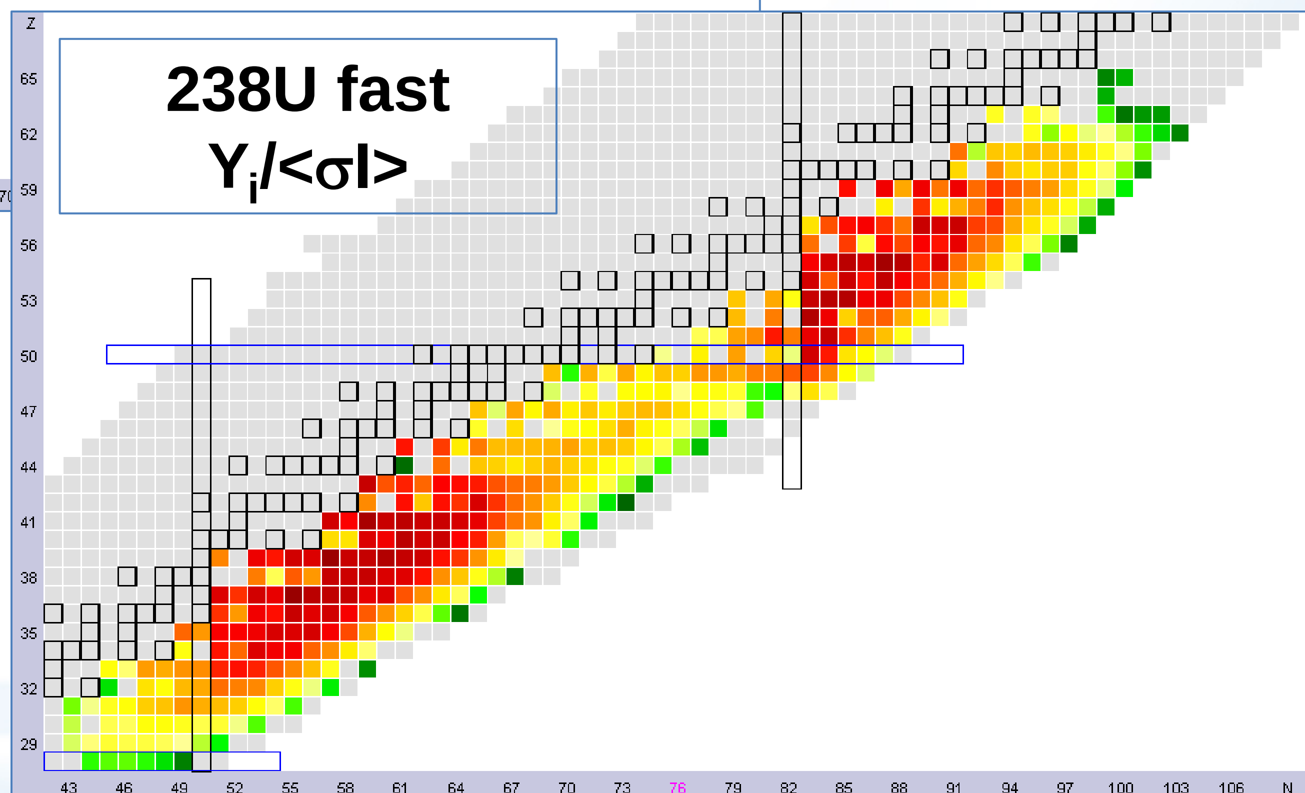


$Y_i/\langle\sigma I\rangle$: fractional contribution to antineutrino multiplicity above threshold

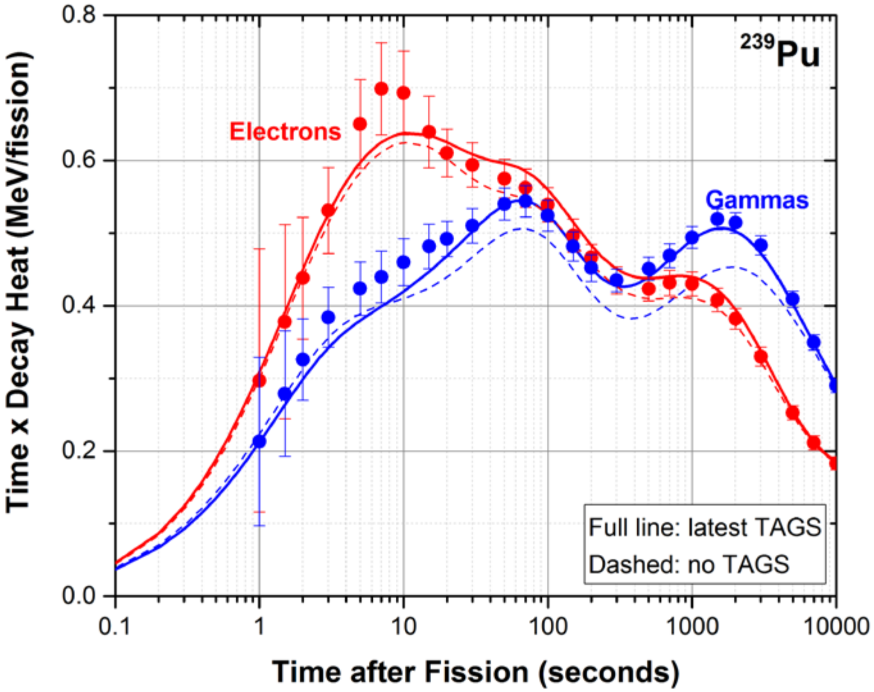
$Y_i = CFY_i \int \sigma(e) I \nu i(e)$

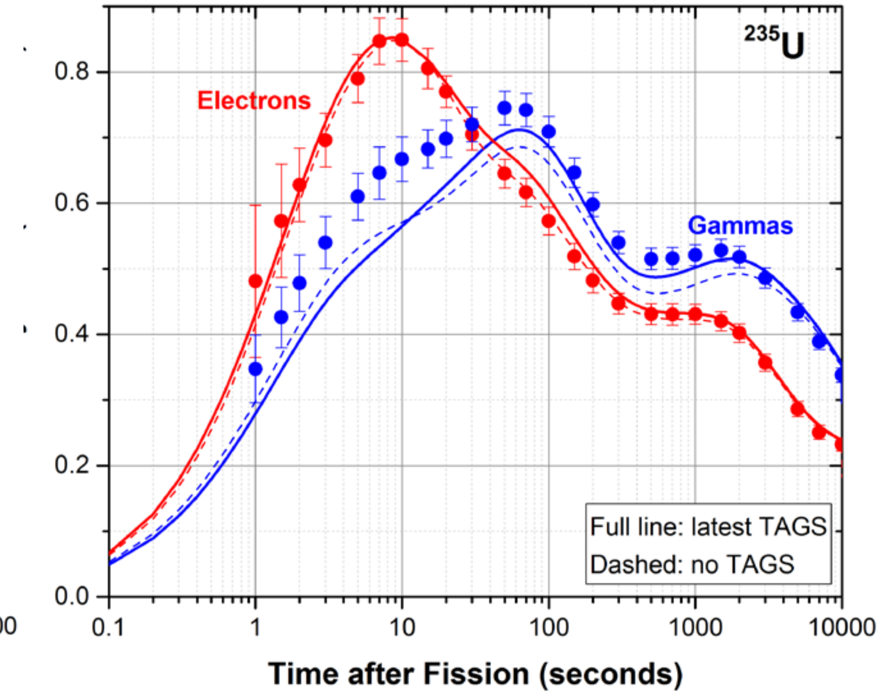
$\langle\sigma I\rangle = \Sigma Y_i$


239Pu thermal
$Y_i/\langle\sigma I\rangle$
Z
65
62
59
56
53
50
47
44
41
38
35
32
29
43
46
49
52
55
58
61
64
67
70

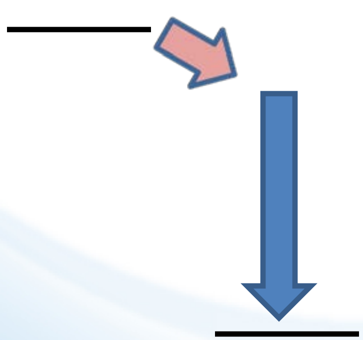

238U fast
$Y_i/\langle\sigma I\rangle$
Z
65
62
59
56
53
50
47
44
41
38
35
32
29
43
46
49
52
55
58
61
64
67
70
73
76
79
82
85
88
91
94
97
100
103
106
N

Relation to Decay Heat



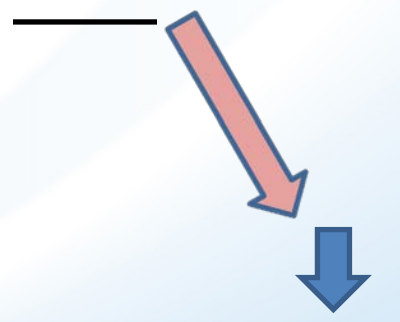


High excitation energy β- feeding



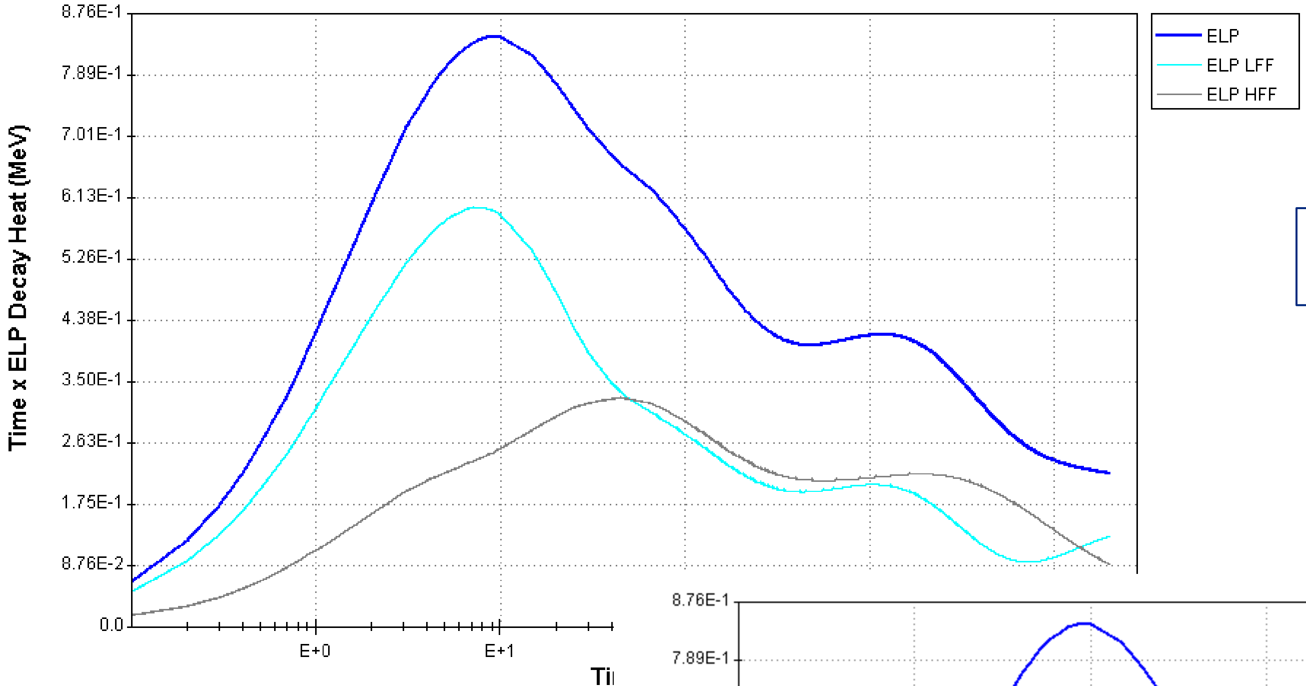
Large <Eγ>
Small <Eβ>
Small <Eν>
Neutrons
Longer $T_{1/2}$

Low excitation energy β- feeding

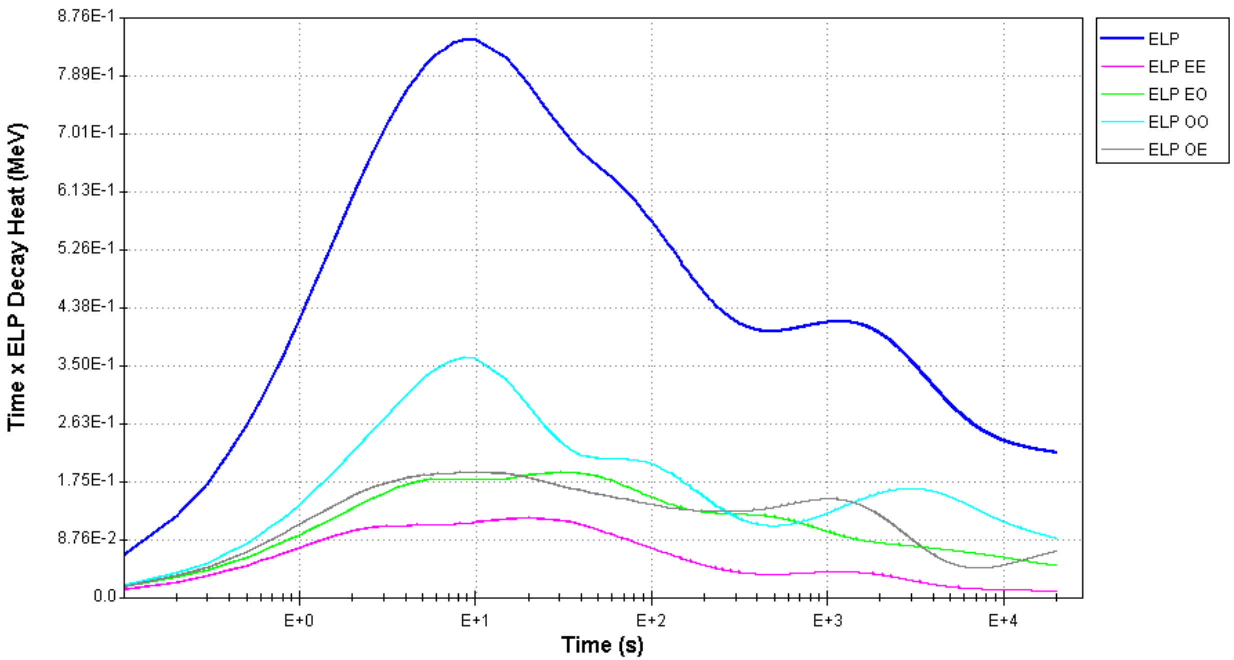


Small <Eγ>
Large <Eβ>
Large <Eν>
No neutrons
Shorter $T_{1/2}$

Relation to decay heat

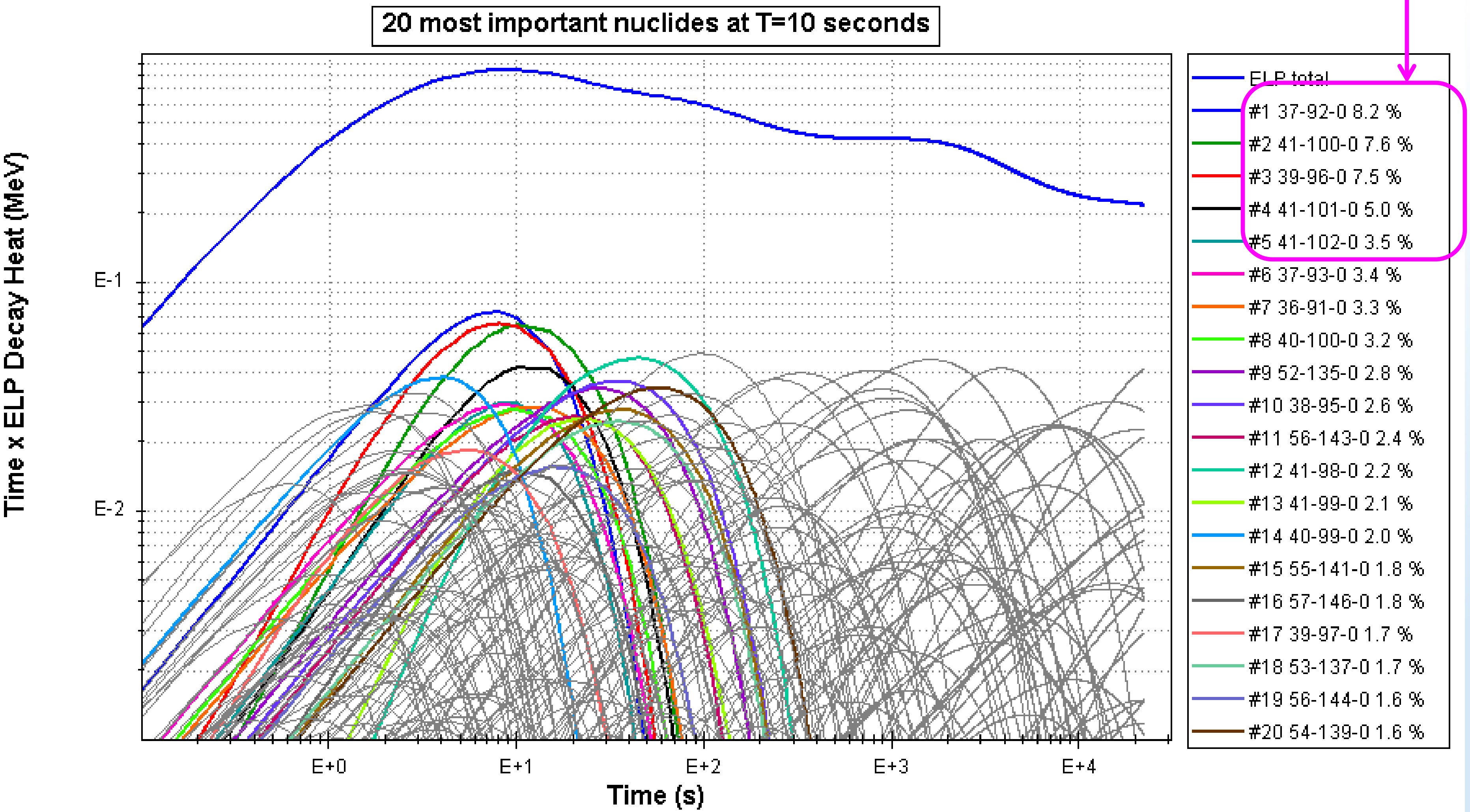


235U Thermal



235U Thermal

^{92}Rb, ^{100}Nb, ^{96}Y, ^{101}Nb, ^{102}Nb

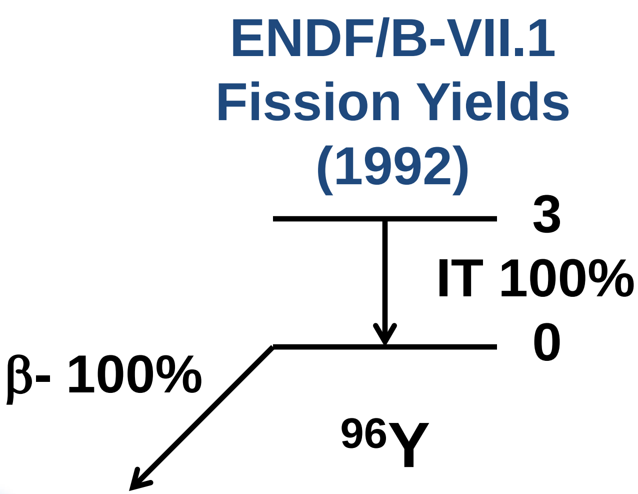


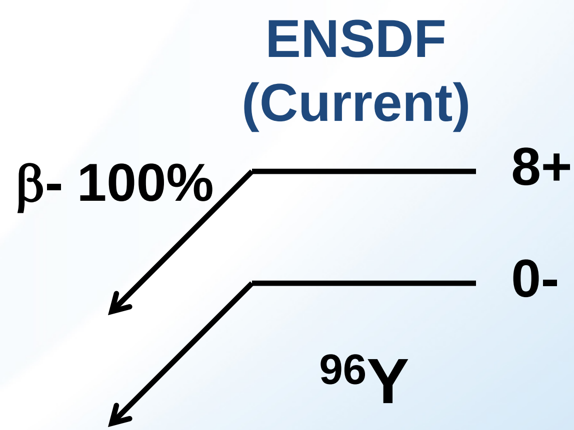
Fission Yield Effects

$$S(E_{\bar{\nu}}) = \sum CFY_i S_i(E_{\bar{\nu}})$$

ENDF/B fission yields were released in 1992. We studied the effect of corrections due to a) better decay data, b) improved isomeric ratios, c) anomalous yields.

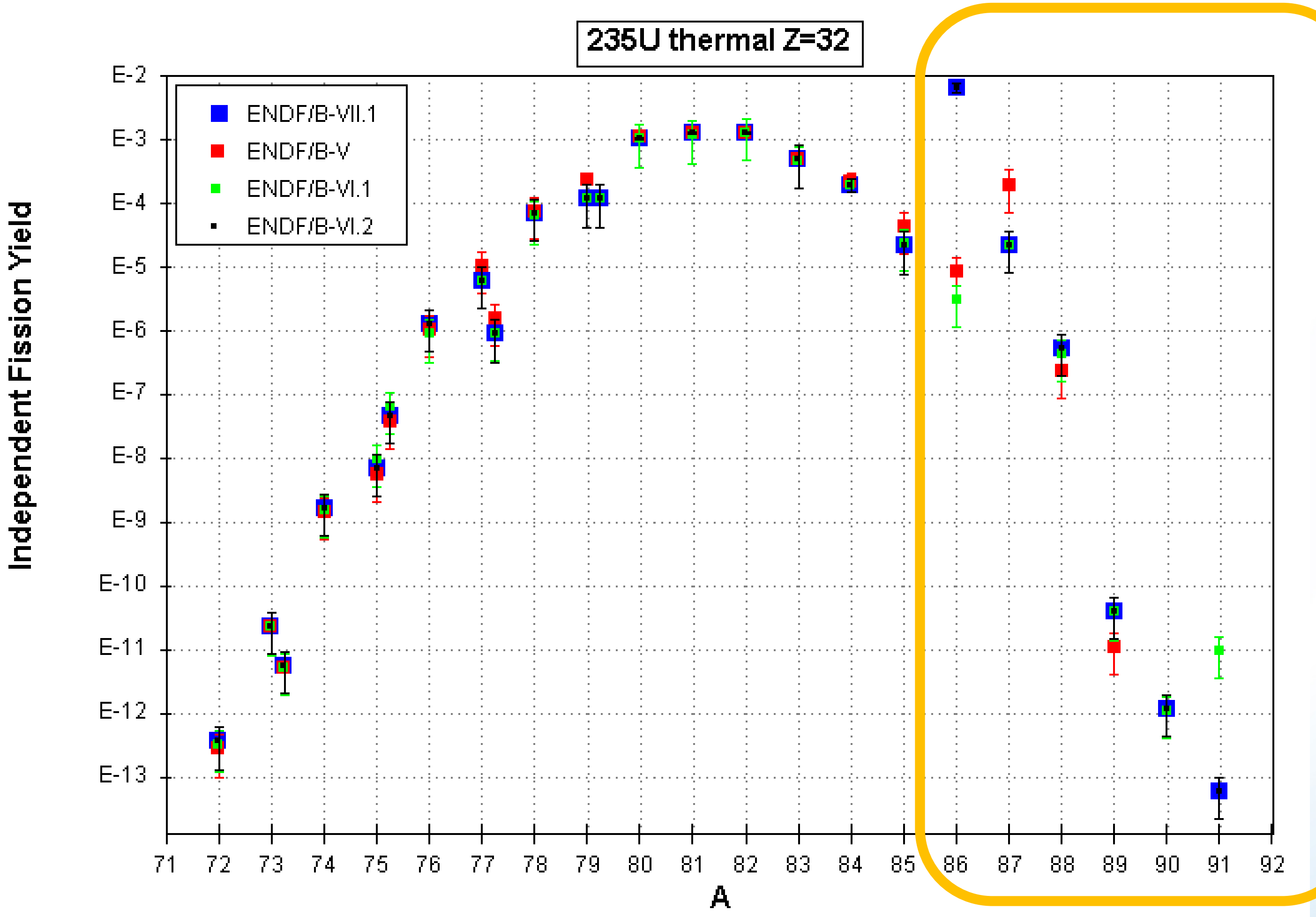
^{96}Y, example of compatibility issues with current decay data





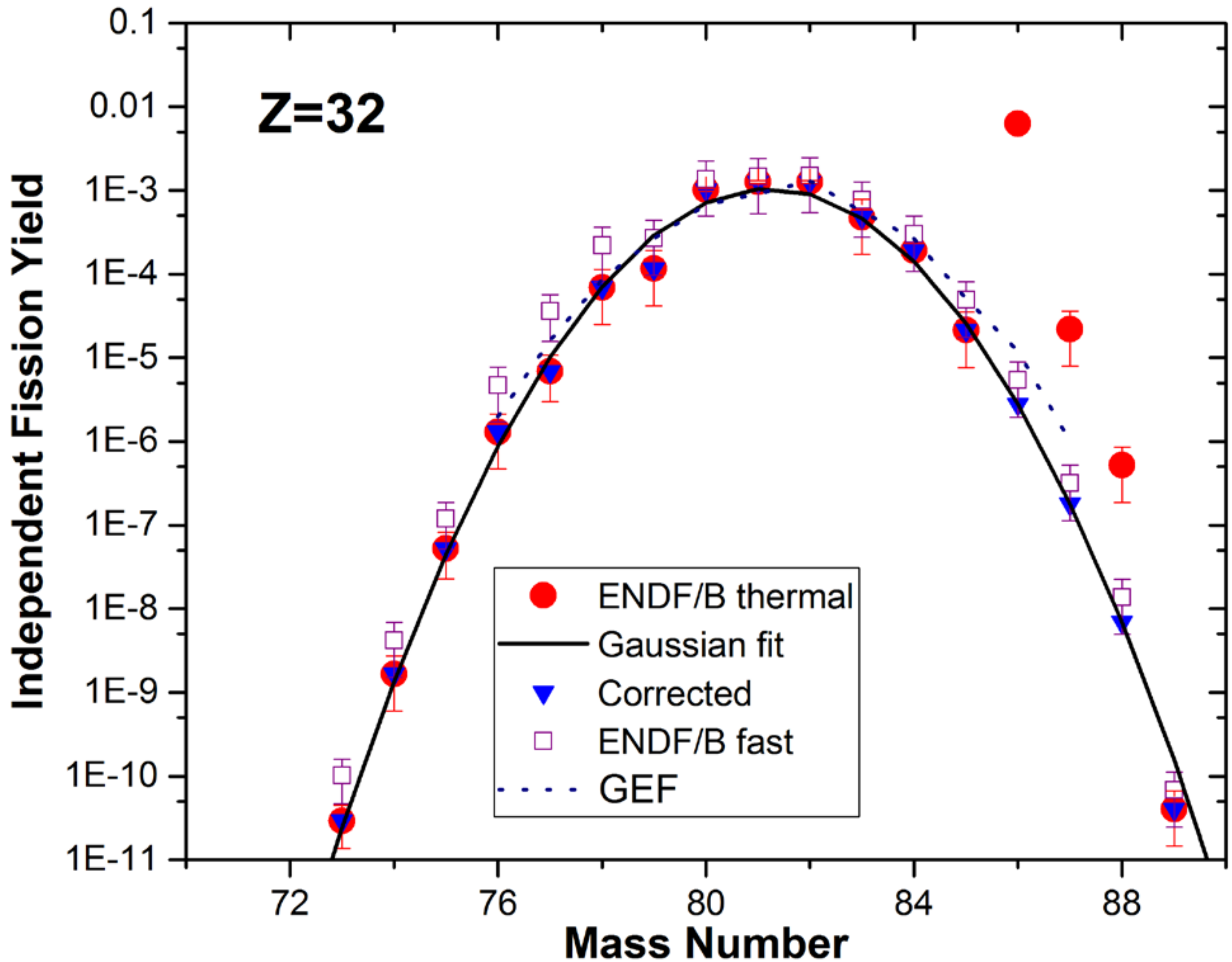
A.A. Sonzogni, E.A. McCutchan, T.D. Johnson, P. Dimitriou, PRL 116, 132502 (2016).

^{86,87,88}Ge yields in the historical releases of ENDF/B yields

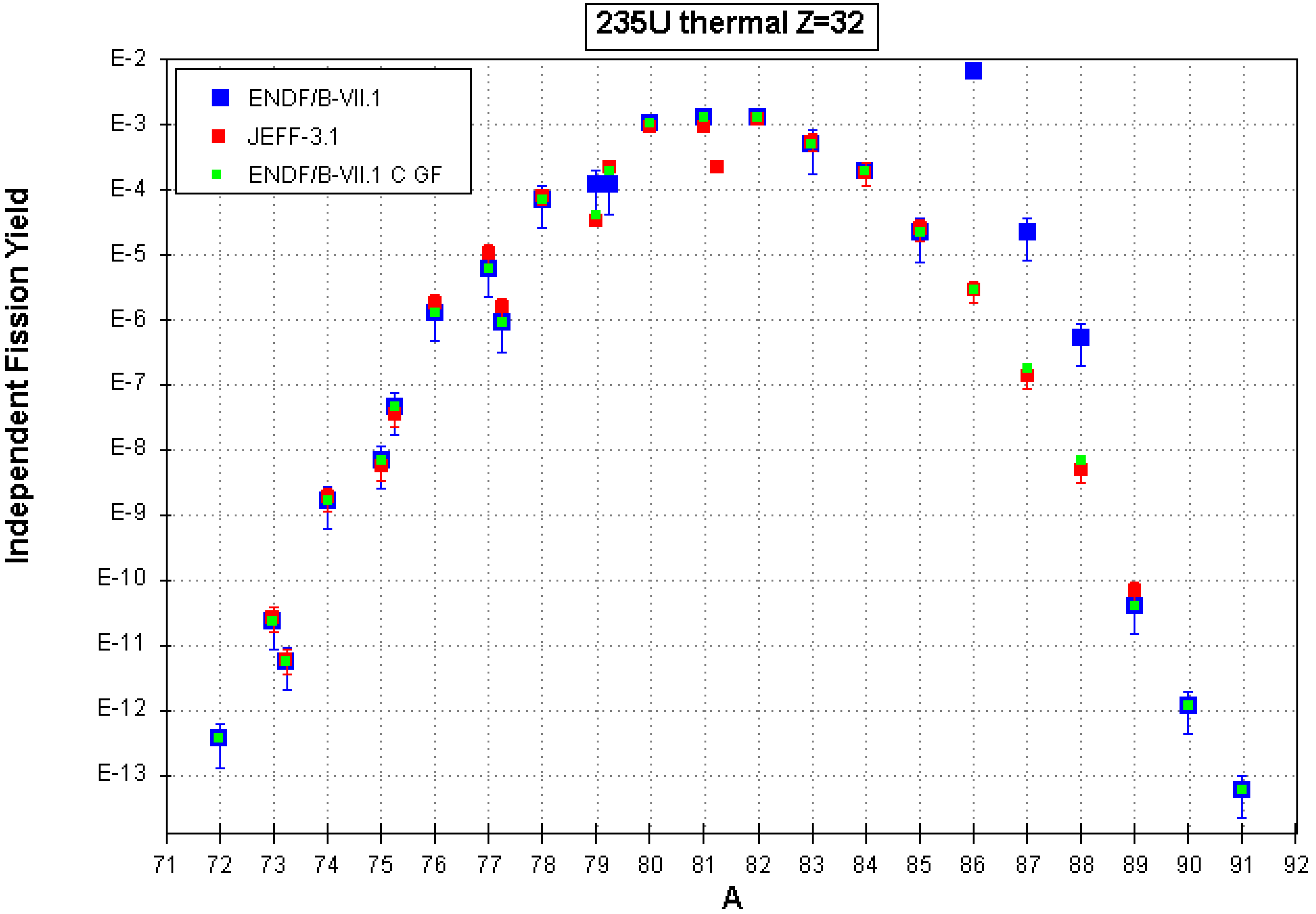


Discovery reported after 1992

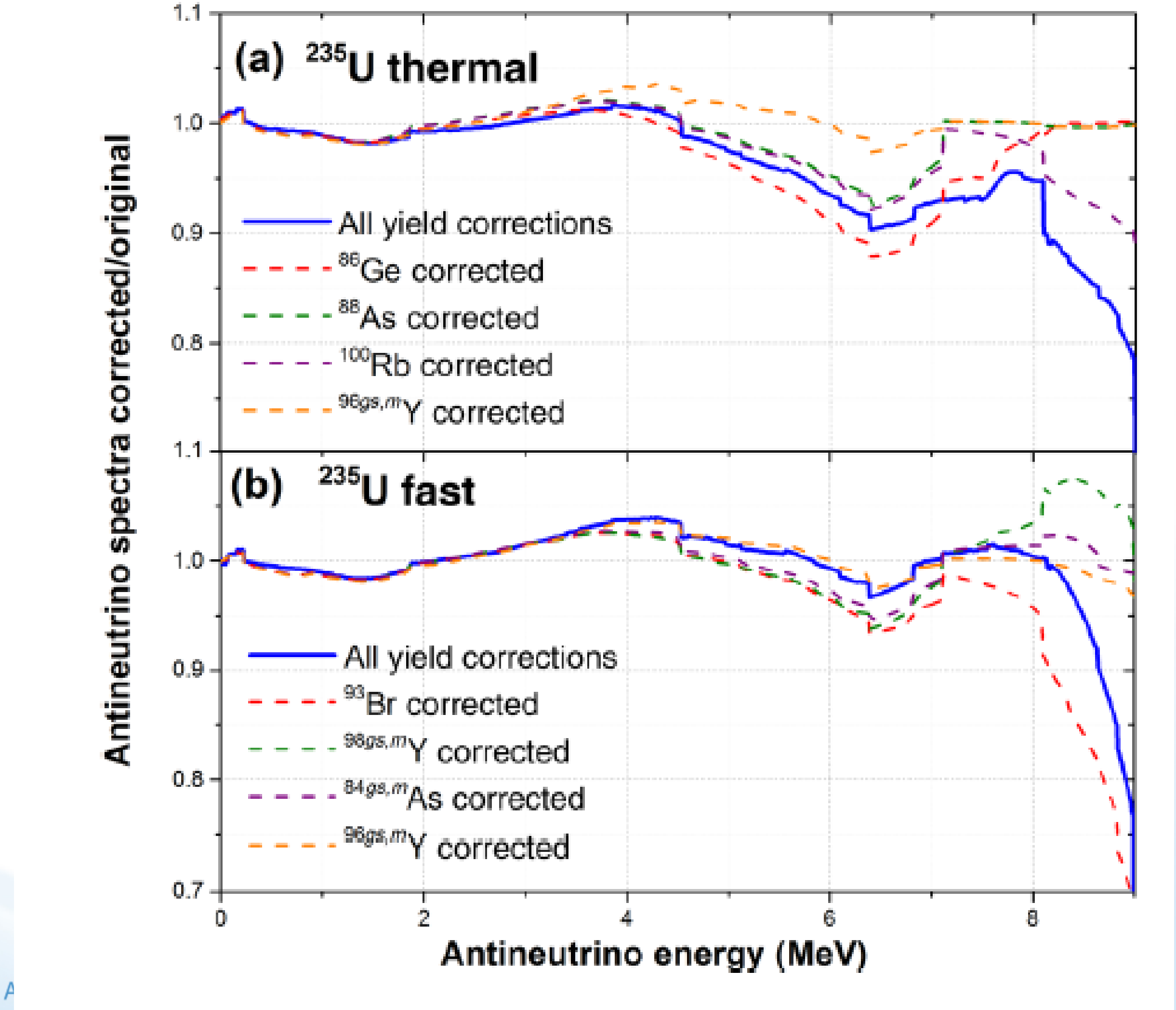
We concluded that the ^{86,87,88}Ge yields should be corrected, did so using a weighted Gaussian fit.



Ge independent yields after the corrections



Effects on the antineutrino spectrum when all corrections are applied, as well when only one nucleus is corrected.



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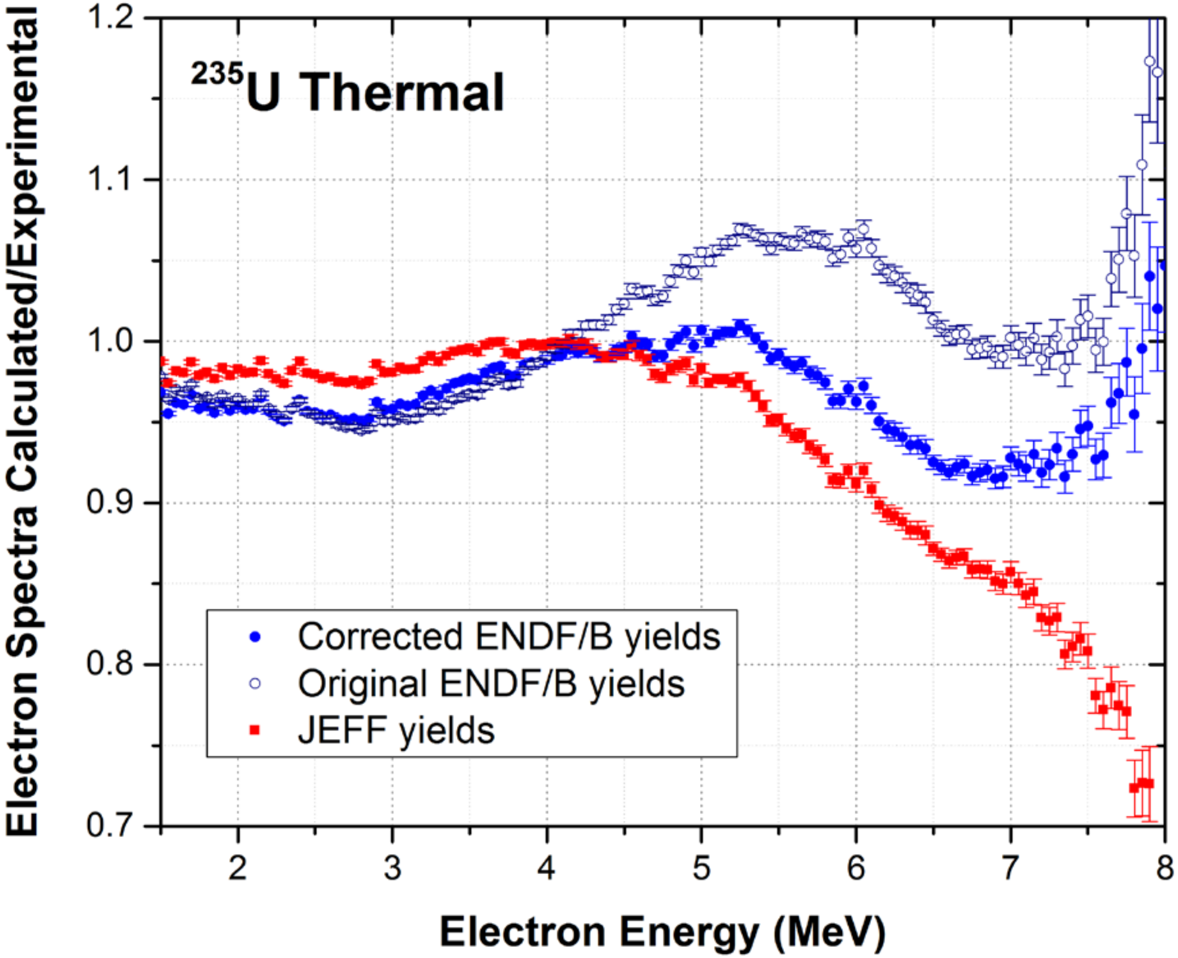
Thermal ^{235}U spectrum

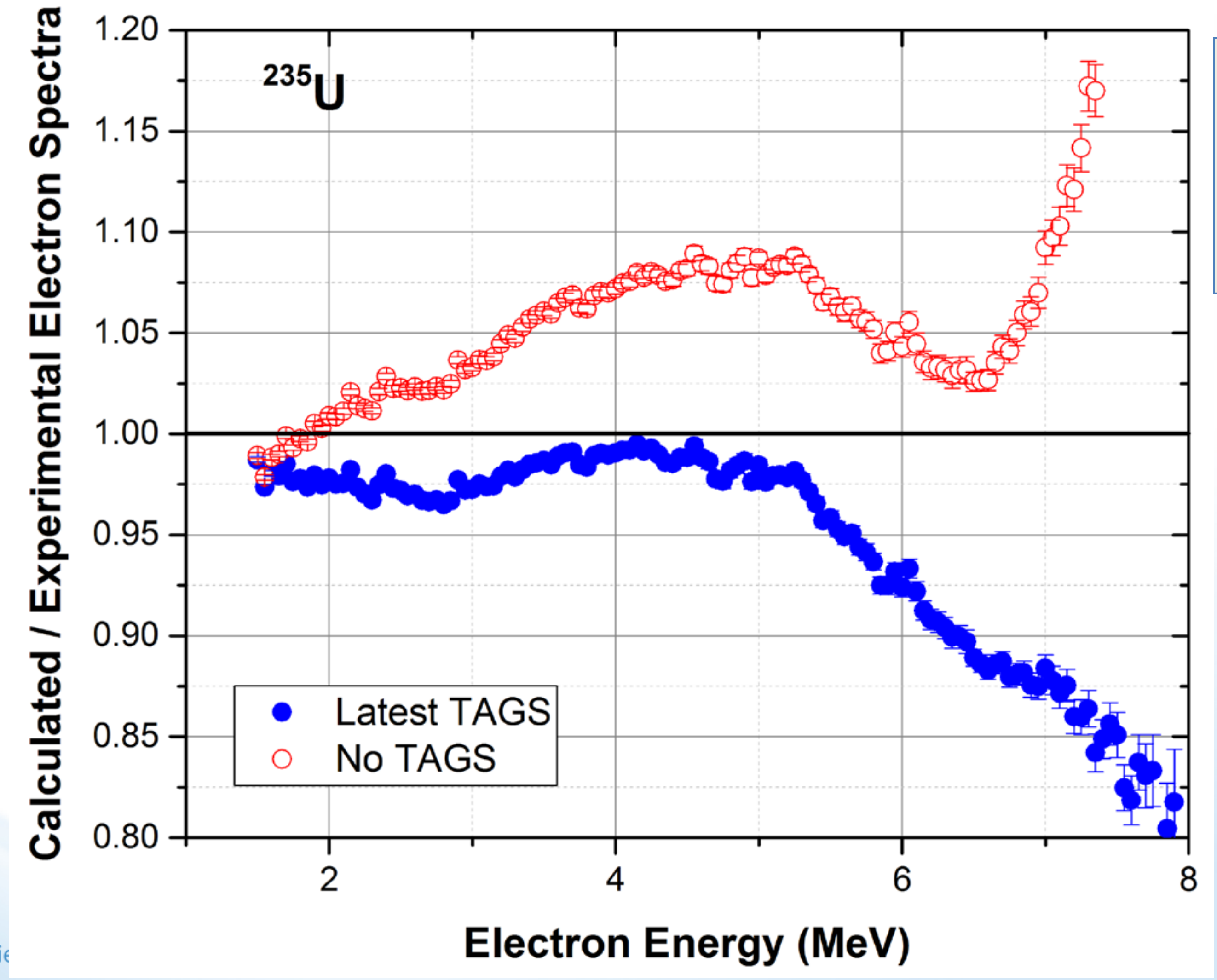


Corrected yields:

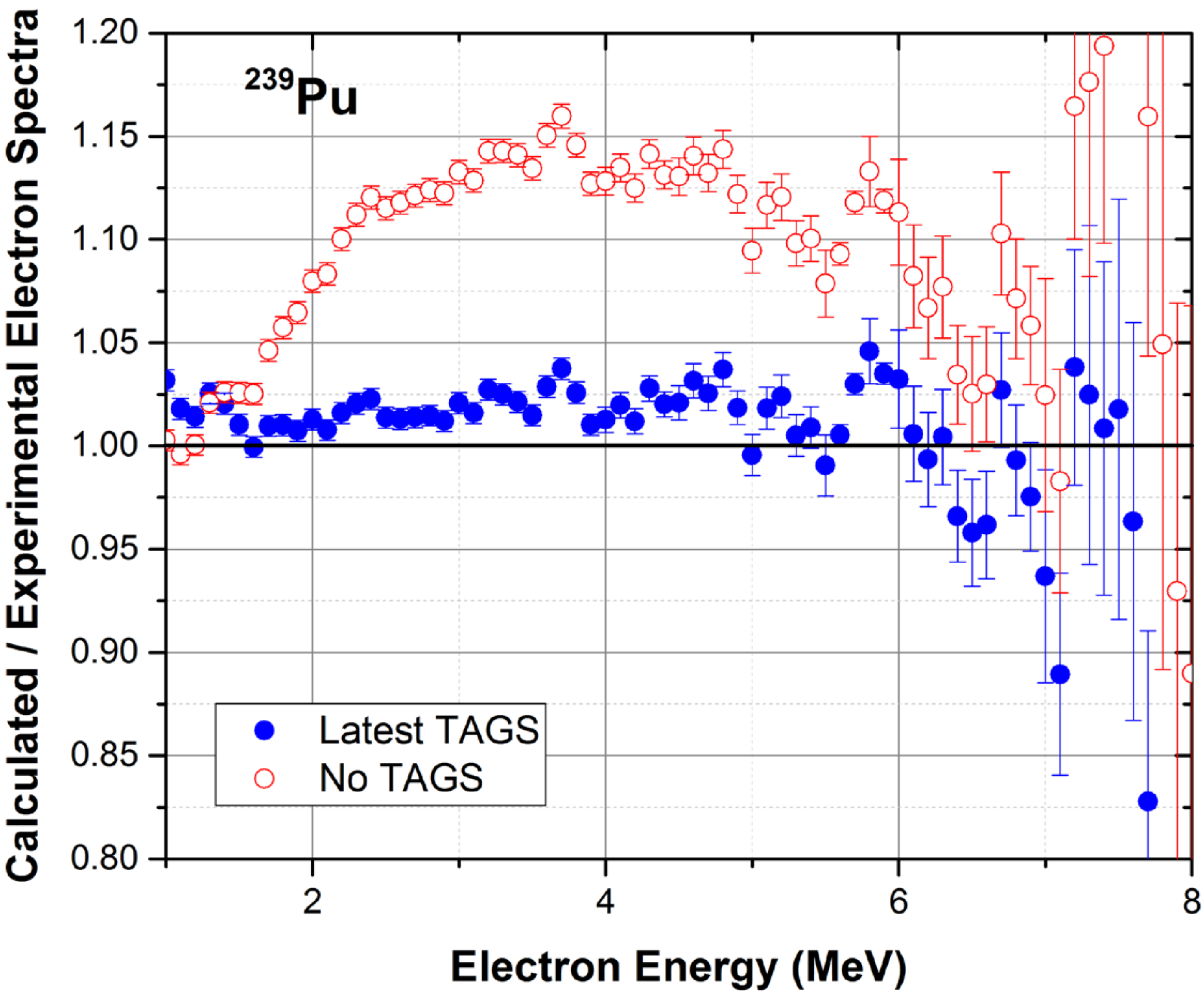
- No electron excess.
- Better agreement with JEFF.

Latest TAGS data

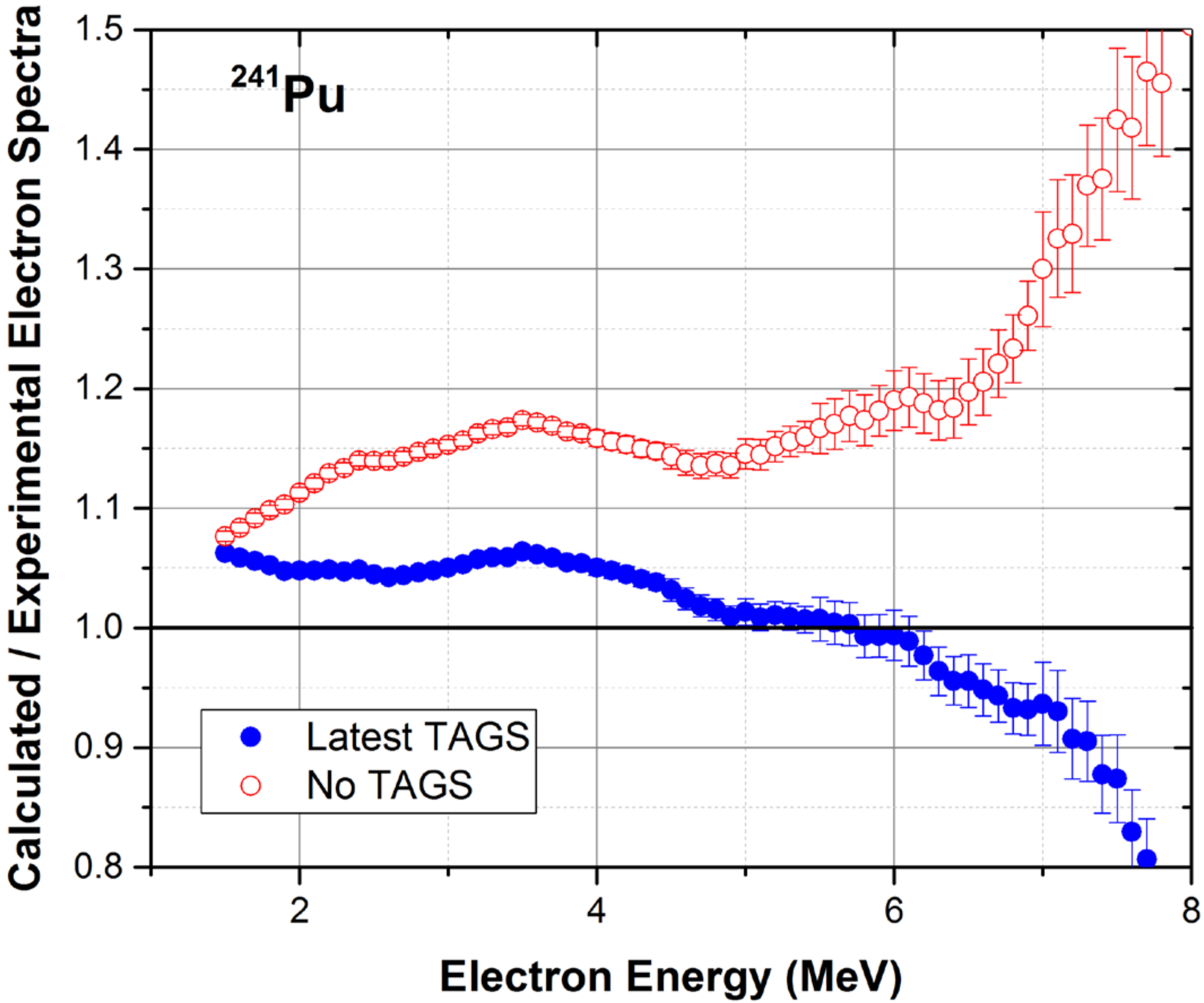
ENDF/B-VIII.0 will be released next year.   We have included more TAGS data and compare results without TAGS



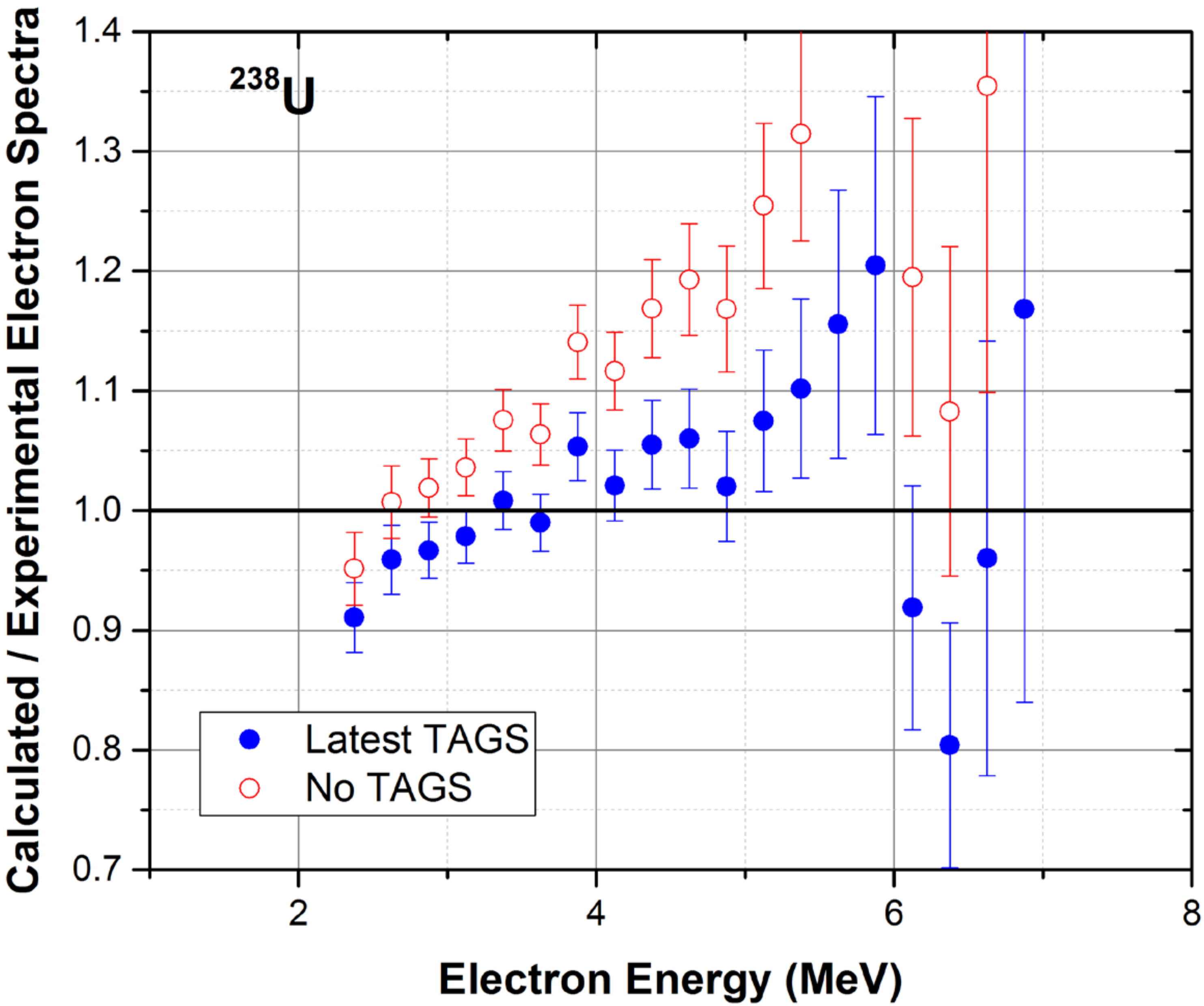
All calculations with JEFF yields



239Pu
Calculated / Experimental Electron Spectra
Electron Energy (MeV)
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
2
4
6
8
Latest TAGS
No TAGS

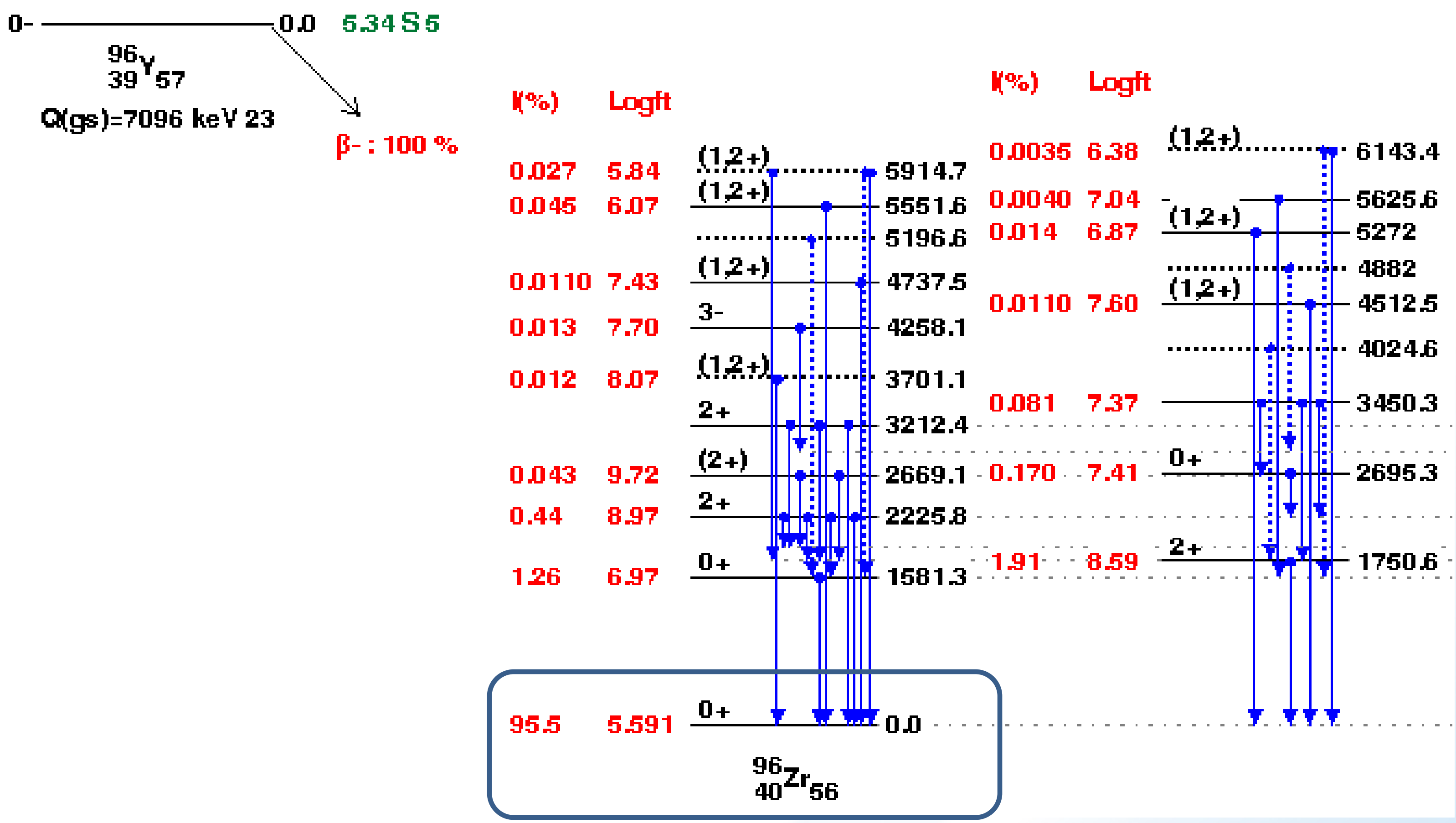


^{241}Pu
Calculated / Experimental Electron Spectra
Electron Energy (MeV)
Latest TAGS
No TAGS
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
2
4
6
8



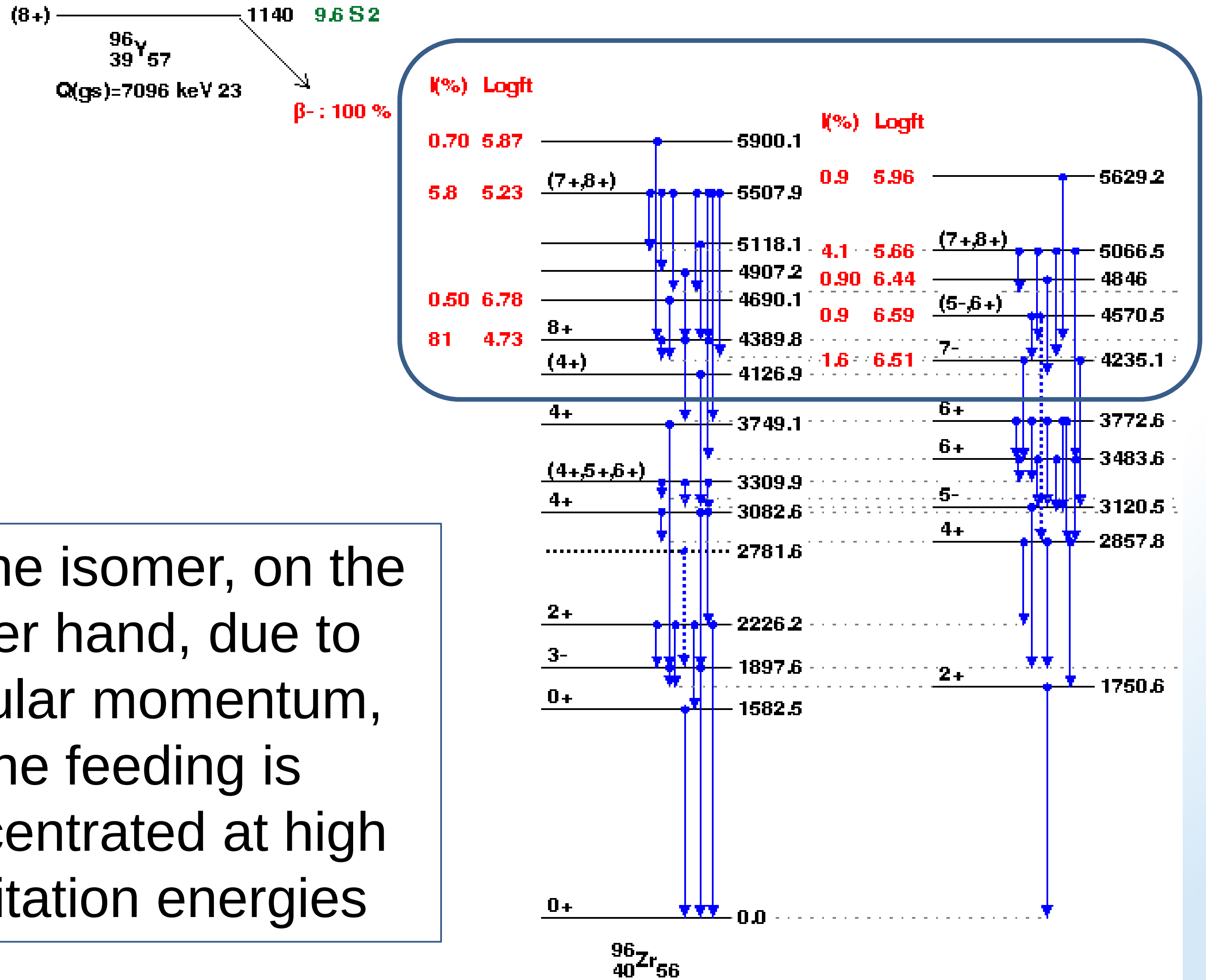
Calculated / Experimental Electron Spectra
Electron Energy (MeV)
238U
Latest TAGS
No TAGS
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
2
4
6
8

96Y – one nuclide with a large effect



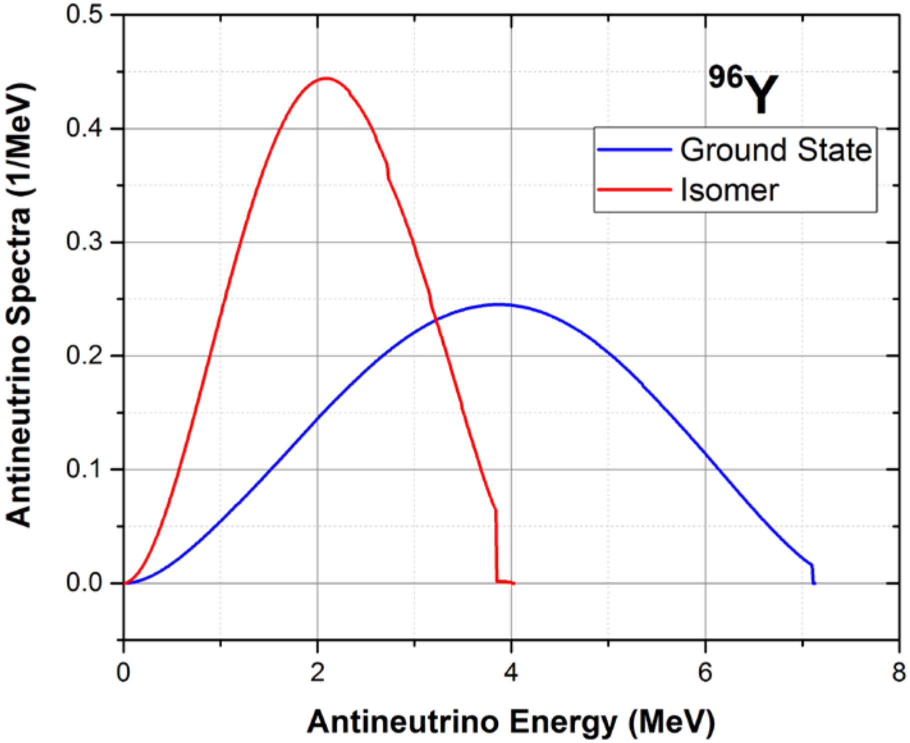
95.5 % of the decay is ground state to ground state

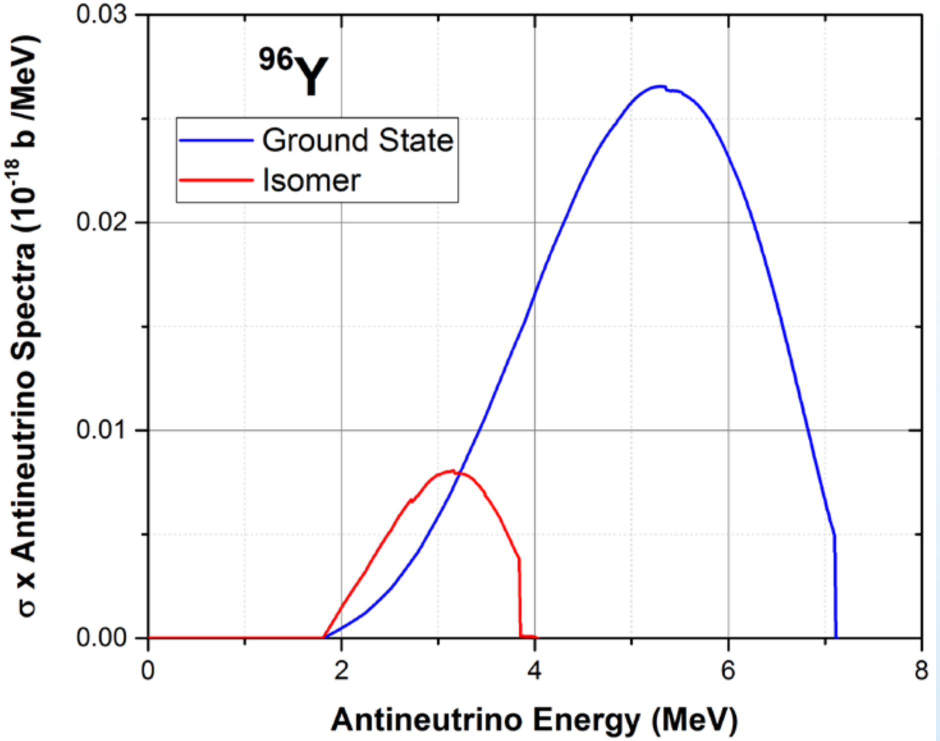
96Y – one nuclide with a large effect



For the isomer, on the other hand, due to angular momentum, the feeding is concentrated at high excitation energies

^{96}Y – Two Different Isomers





Both spectra are normalized to 1

The ground state produces about 7 times more antineutrinos above the threshold than the isomer

^{96}Y – Isomeric Ratio Effect

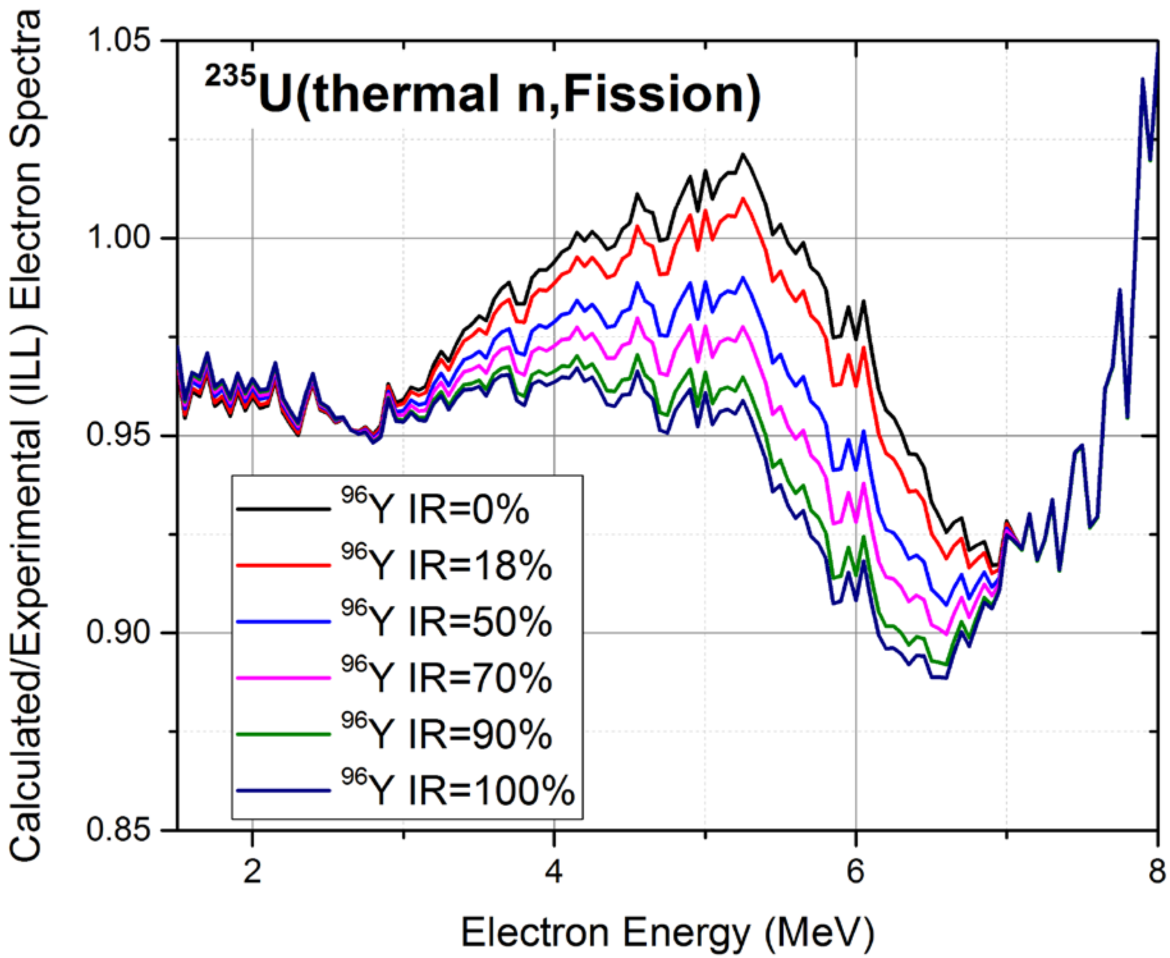
^{96}Y Isomeric Ratio:

$$IR = \frac{IFY(^{96m}Y)}{IFY(^{96m}Y) + IFY(^{96gs}Y)}$$

At about 5.2 MeV, changing IR from 0 to 100% changes the calculated to experimental ratio by 7%.

CFY ~ 0.05

There is no journal publication of IR.



Estimates of IR vary from 18% to 70%

Beta spectra shapes

Recent article by X. Mougeot
PRC **91**, 055504 (2015)

- Behrens-Buhring Fermi function BJ).
- Radiative, Screening, no Weak Magnetism
- Survey of all precisely measured beta transitions

TABLE I. Experimental shape factors of allowed transitions.

Parent	Mode	E_0	Experimental shape factor
^{110m}Ag	β^-	529.9	$1 - 0.01W$
^{115}Cd	β^-	584.5	$1 - 0.0007W$
^{115}Cd	β^-	620.1	$1 - 0.0009W$
^{114}In	β^-	1988.6	$1 - 0.0015W$
^{130}I	β^-	1005	$1 + 0.04W$
^{130}I	β^-	587	$1 + 0.04W$
^{131}I	β^-	606.3	$1 + 0.02W$
^{134}Cs	β^-	415.64	1
^{134}Cs	β^-	658.39	1

Parent	Mode	E_0	Experimental shape factor
First forbidden nonunique			
^{84}Rb	β^+	783	$1 - 0.073W$
^{86}Rb	β^-	699.2	$1 - 0.64W - 0.46/W + 0.14W^2$
^{91}Y	β^-	339.5	1
^{99}Mo	β^-	848.1	$1 + 0.049W - 0.0047/W + 0.034W^2$
^{99}Mo	β^-	1214.5	$1 - 0.01W$
^{111}Ag	β^-	694.7	$1 - 0.01W$
^{111}Ag	β^-	1036.8	$1 - 0.016W$
^{115m}Cd	β^-	339.1	$1 + 0.011W$
^{115m}Cd	β^-	1629.7	$1 - 0.78W - 17.2/W$
^{122}Sb	β^-	1419.6	$1 - 0.012W + 0.003W^2$
^{124}Sb	β^-	2301.6	$q^2 + \lambda_2 p^2 + 7.3$
^{124}I	β^+	1534.9	$1 - 0.046W$
^{139}Ba	β^-	2151	$1 - 0.219W + 0.147/W + 0.02W^2$
^{140}La	β^-	2165.7	$q^2 + \lambda_2 p^2 + 2.3$
^{141}Ce	β^-	435	$1 - 0.28W$
^{141}Ce	β^-	580.4	$1 - 0.28W$
^{144}Ce	β^-	318.6	$1 - 0.342W$
^{142}Pr	β^-	586.6	1
^{143}Pr	β^-	934.1	$1 - 0.018W$
^{144}Pr	β^-	2997.4	$1 + 0.0376W - 0.118/W - 0.0077W^2$
^{147}Nd	β^-	364.7	$1 - 0.2W$
^{147}Nd	β^-	804.6	$1 - 0.17W$
^{146}Pm	β^-	795	$1 - 0.394W - 0.275/W + 0.044W^2$

Mostly low Q
Most need an experimental shape factor

First forbidden non-unique dominate the high energy part of the spectra

Conclusions

Summation method

Updated the ENDF/B decay data to incorporate new TAGS and other decay data that are relevant to antineutrinos or decay heat. File is available to anyone (with caveats).

Decomposed total spectrum into individual contributions, derived systematics of the energy integrated cross section weighted antineutrino spectrum.

Studied the effect of correcting thermal ^{235}U ENDF/B fission yields. Without these corrections results will not be reliable, leading to a fast spectrum softer than the thermal. Correction leads to better agreement with JEFF. File is available to anyone (with caveats).

Identified pieces of data, such as the ^{96}Y Isomeric Ratio, that have big impact and could merit a precise measurement. A proposal to ILL was submitted.

Conclusions II

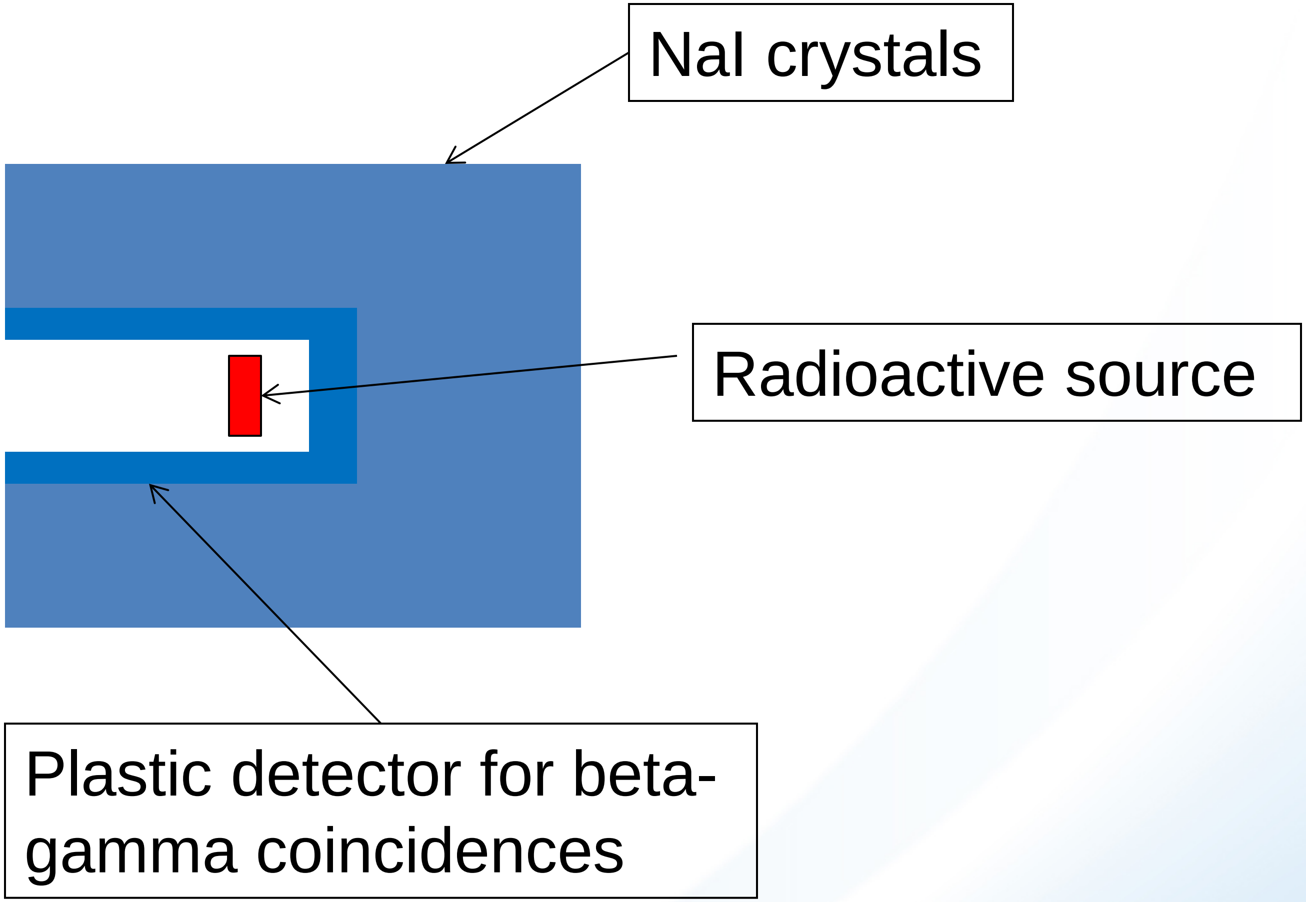
Conversion method

We wonder if a validation work was performed for high Q-values (3 MeV and higher) for nuclides with Z=30-60.

A closer look into this method is needed.

Supplemental Material

TAGS (Total Absorption Gamma Spectroscopy) experiments



TAGS measure the gamma spectrum after beta decay with low resolution but high efficiency.

Decay Heat:

The gamma decay heat is defined as:

$DH\gamma\ (t)=\Sigma\ \lambda_k <E\gamma>_k N_k$
$DH\beta\ (t)=\Sigma\ \lambda_k <E\beta>_k N_k$

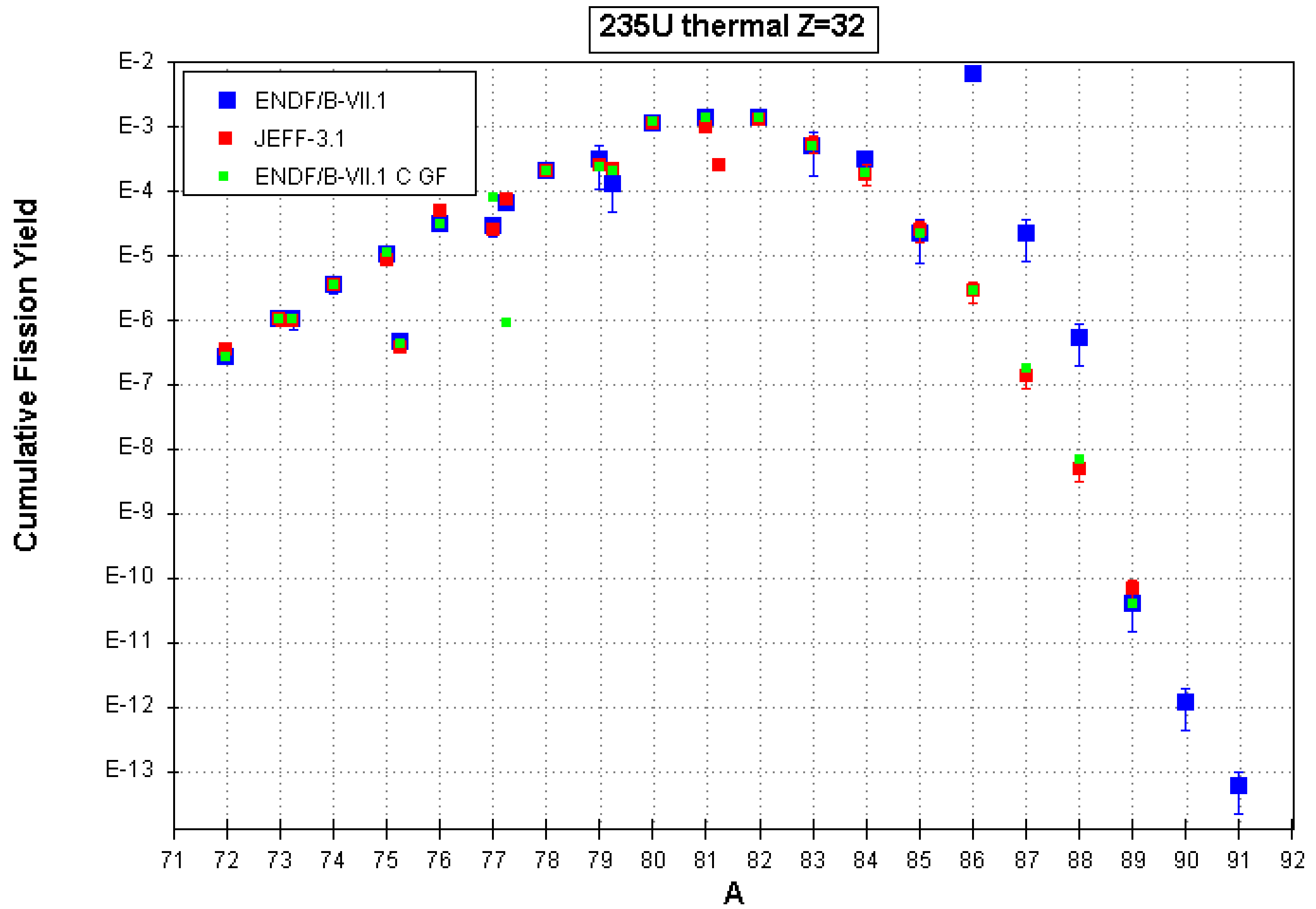
Where $<E\gamma>_k$ and $<E\beta>_k$ are the mean gamma and beta energy released in the decay of the k-material

The N_k follow the following set of linearly coupled eqs:

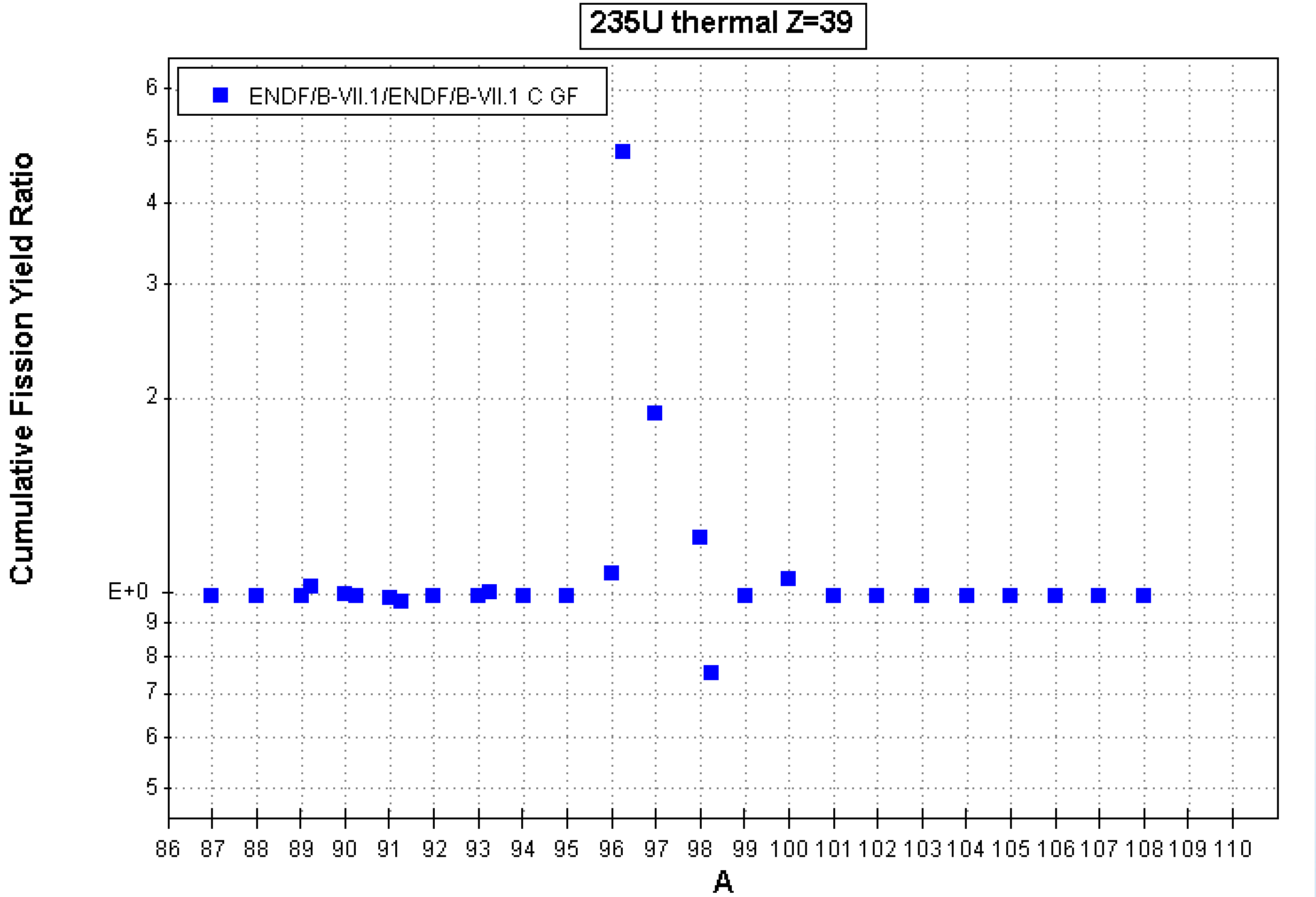
$dN_k/dt = -\lambda_k N_k + \Sigma\ b_{ik} \lambda_i N_i$

Which are solved numerically with the boundary condition: $N_k(0) = IFY_k$

Ge cumulative yields after the corrections

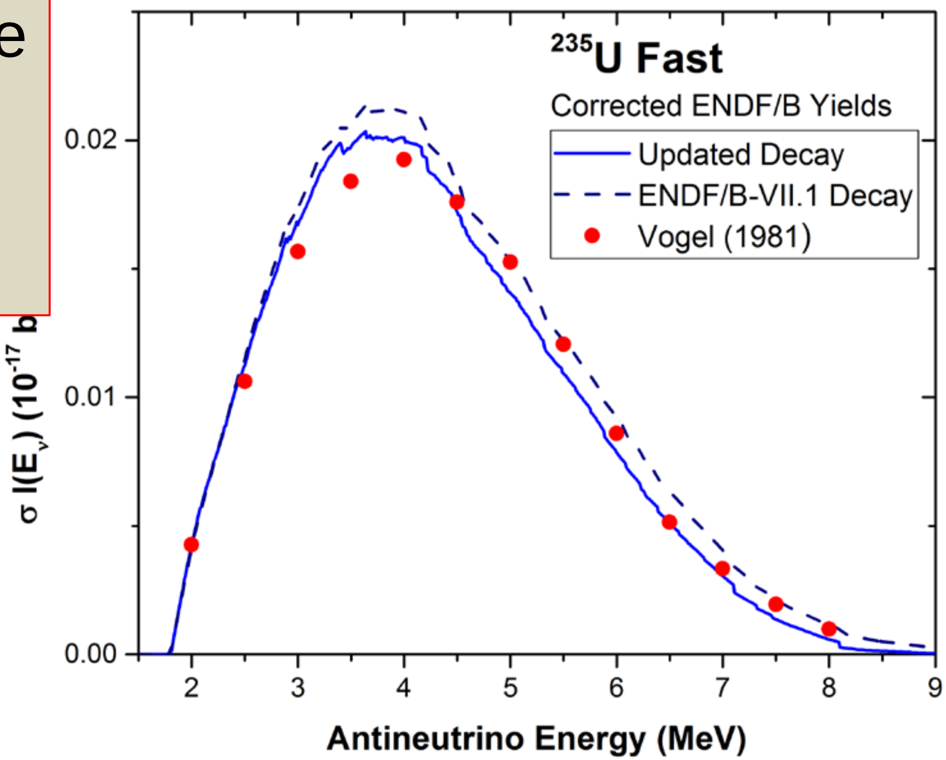


Yttrium original / corrected cumulative yields, reflecting changes in the isomeric ratio and the decay data



Spectrum for fast neutrons

- Significant differences in the shape with 1981 values.
- TAGS data make a big difference.



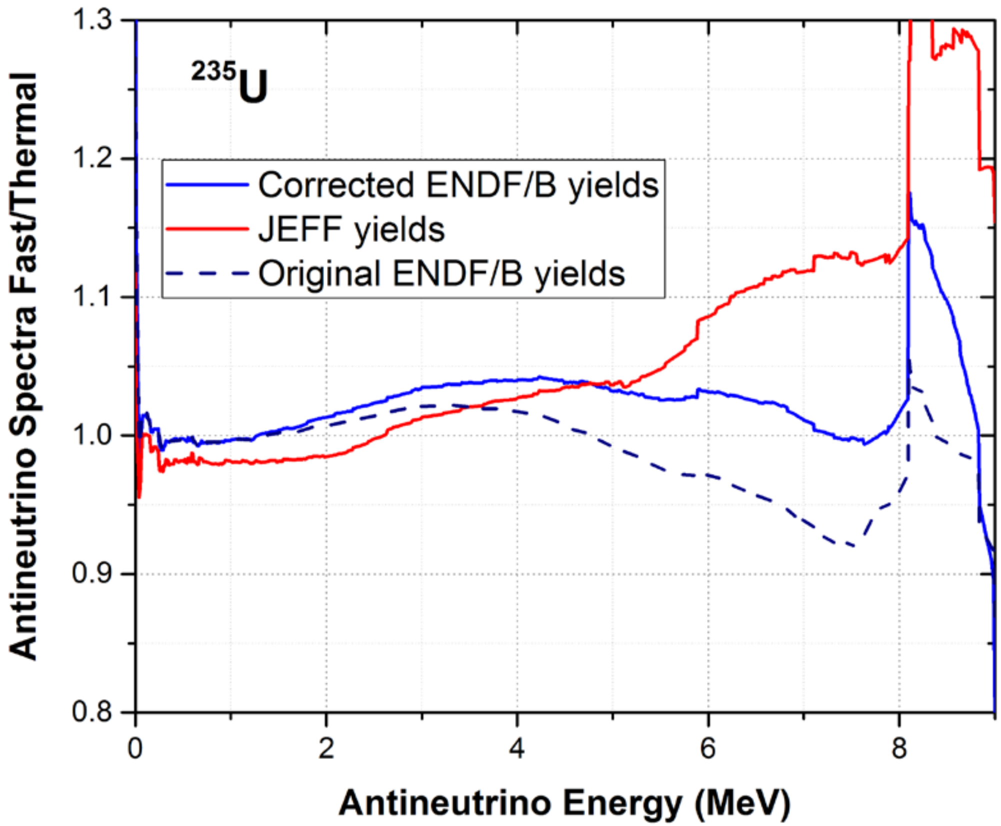
Spectrum for fast neutrons

- For fast neutrons, the increase in excitation energy makes the fission yield distribution broader.

- The delayed nu-bar per 100 fissions increases from 1.585 to 1.67.

- When using corrected fission yields, the antineutrino spectrum for fast neutrons is harder than the spectrum for thermal neutrons.

- In agreement with JEFF yields and as expected.



We used isomeric ratios measured by Bail et al for ^{239}Pu PRC **84**, 034605 (2011)

TABLE V. Sum of the ground-state and the first isomeric-state yields ($S = Y^{GS} + Y^m$) and ratio between the isomeric yield and the sum [$R = Y^m/(Y^{GS} + Y^m)$]. Results obtained in this work (Loh.) are compared with those from JEFF-3.1.1 [5].

Mass	Nuclide	$S_{\mathrm{Loh.}}$ (%)	$S_{\mathrm{JEFF\text{-}3.1.1}}$ (%)	$R_{\mathrm{Loh.}}$ (%)	$R_{\mathrm{JEFF\text{-}3.1.1}}$ (%)
98	$_{39}$Y	2.433 ± 0.280	2.310 ± 0.512	19.6 ± 3.3	80.8 ± 25.3
99	$_{41}$Nb	0.710 ± 0.108	0.850 ± 0.280	20.0 ± 4.2	18.8 ± 8.7
133	$_{52}$Te	4.779 ± 0.468	4.646 ± 0.534	60.6 ± 8.4	70.7 ± 11.5
134	$_{53}$I	2.612 ± 0.614	2.248 ± 0.545	42.7 ± 11.3	42.4 ± 14.6
136	$_{53}$I	3.290 ± 0.375	3.358 ± 0.591	75.5 ± 11.7	70.1 ± 17.4
138	$_{55}$Cs	1.420 ± 0.383	1.033 ± 0.348	60.3 ± 17.7	58.7 ± 28.0
146	$_{57}$La	1.035 ± 0.101	1.258 ± 0.213	71.7 ± 9.9	64.3 ± 15.4

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