Antineutrino Spectrum Predictions:

Nuclear Data Impact and Interplay

A. Mattera, R. Lorek, A.A. Sonzogni, E.A. McCutchan

National Nuclear Data Center

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

@BrookhavenLab

@NNDC_BNL

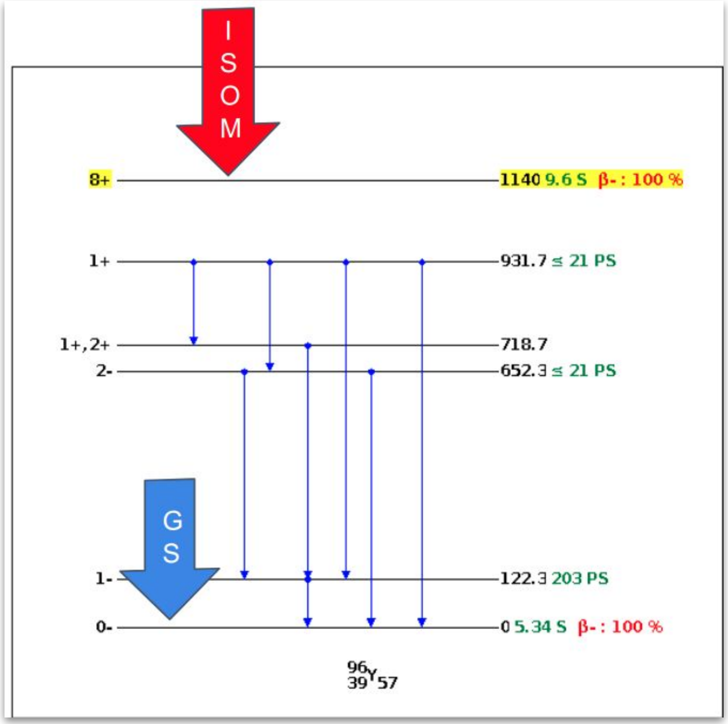
Outline

- The impact of isomeric yields on antineutrino calculations
- Madland & England model *vs* Experimental data: challenges and limitations
- Energy dependence of FYs and validation of fission models

Nuclear Data for Antineutrinos

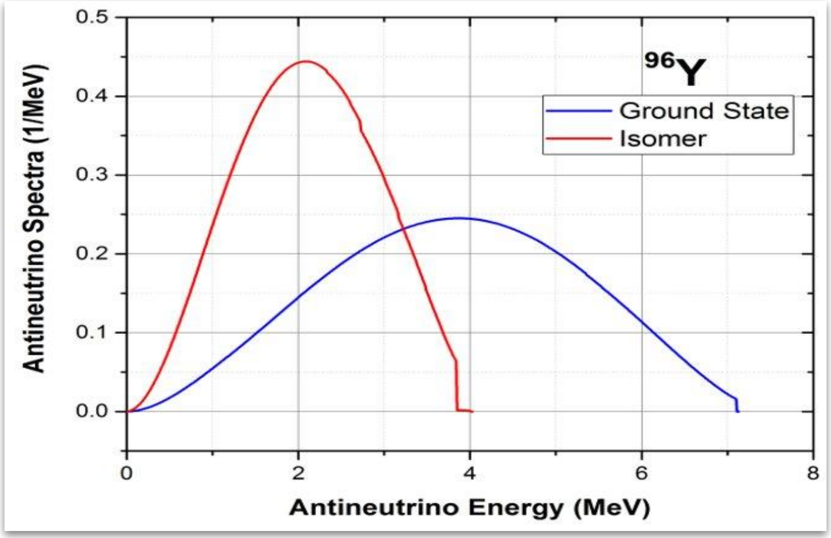
- Fission Yields are a key component of the Summation Method
- β-spectra and decay data
- Isomeric Yield Ratios represent another key component that is difficult to accurately predict, and must be based on experimental data.

$$IYR = \frac{Y_{isom}}{(Y_{isom} + Y_{gs})}$$



Isomeric Yields in ND libraries

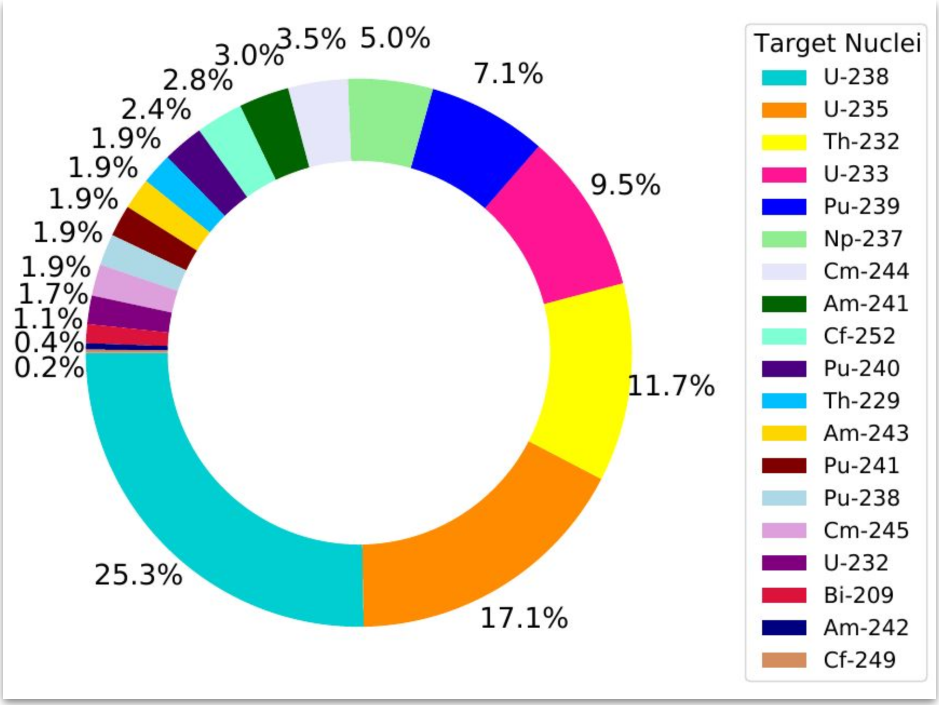
- β-decay of the IS or GS can result in dramatically different antineutrino spectra
- In most of the current libraries, IYRs are modelled using the Madland & England model
- 1-parameter model developed in the 1970s, that predicts the IYR for any nuclide with a known isomer



A new compilation of IYR experimental data

- Up-to-date compilation of all (500+) measured Isomeric Yields for any fissioning systems (62 unique fission products)
- Evaluation of the isomeric ratio for 42 products from low-energy neutron induced fission

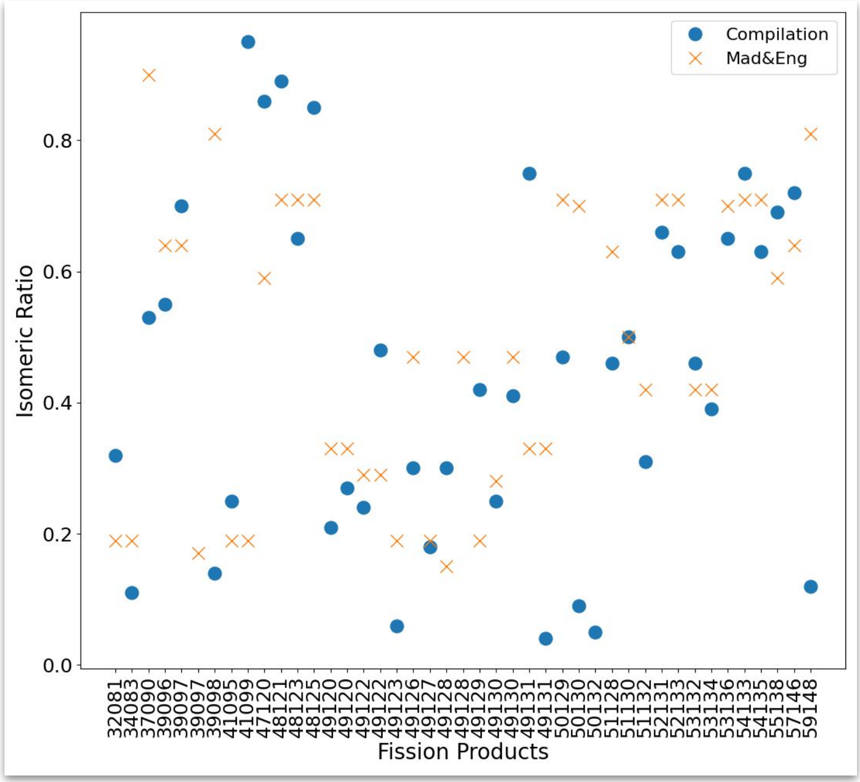
Work sponsored by the U.S. Department of Energy, National Nuclear Security Administration, Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D)



Sears, C.J. *et al.* **Compilation and Evaluation of Isomeric Fission Yield Ratios**. Nucl. Data Sheets 173 (2021): 118-143.

Experimental Data vs Madland & England

- of the 200+ isomeric yields that are included in the ND libraries, only 42 have experimental data at low energy.
- In about half the cases where data is available, the Madland & England model predicts a value that doesn't agree with the measurements



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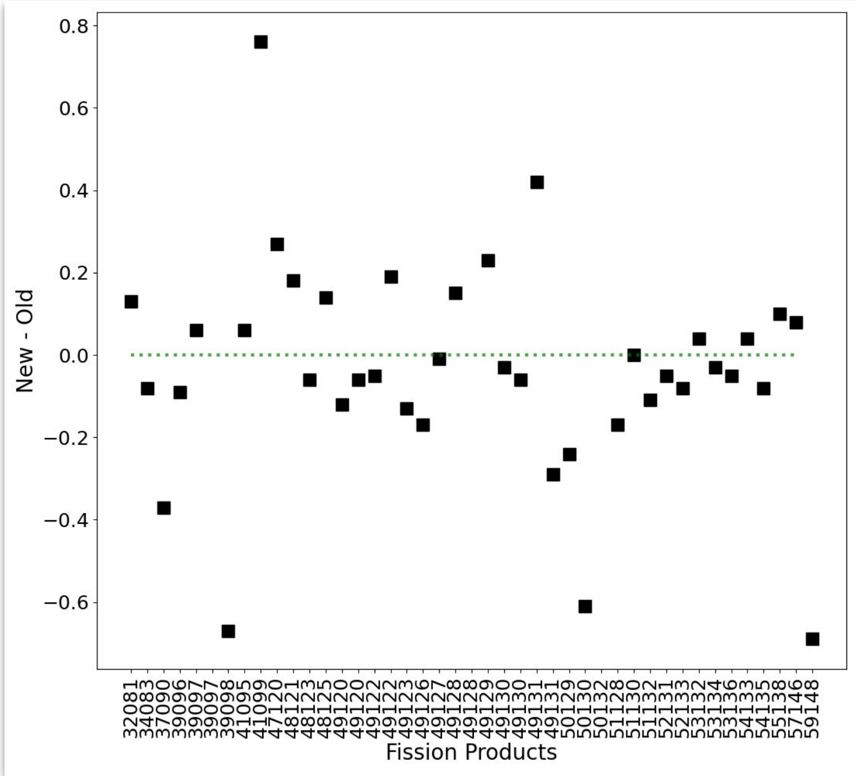
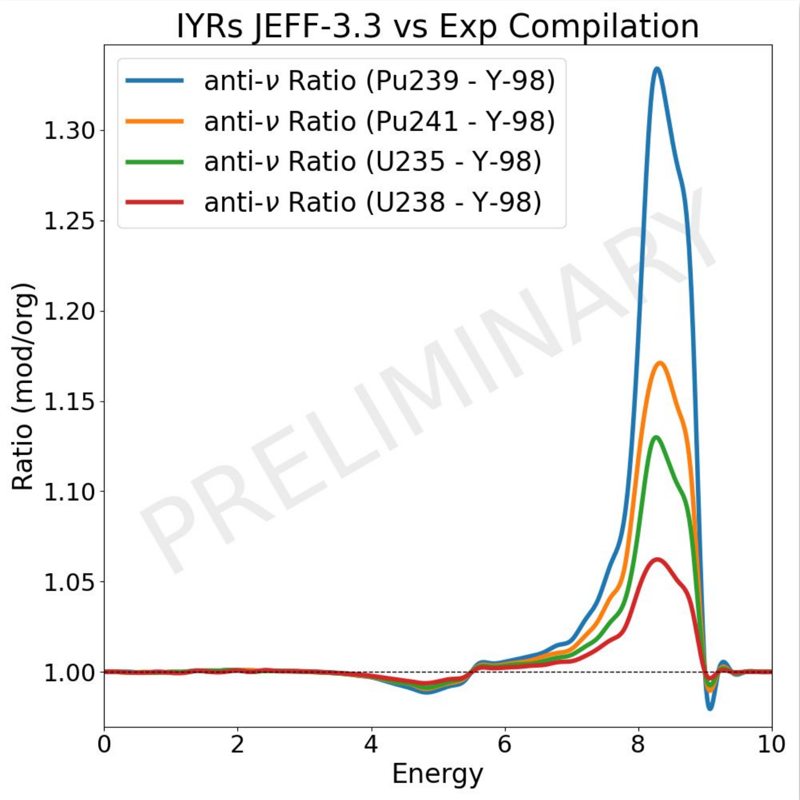


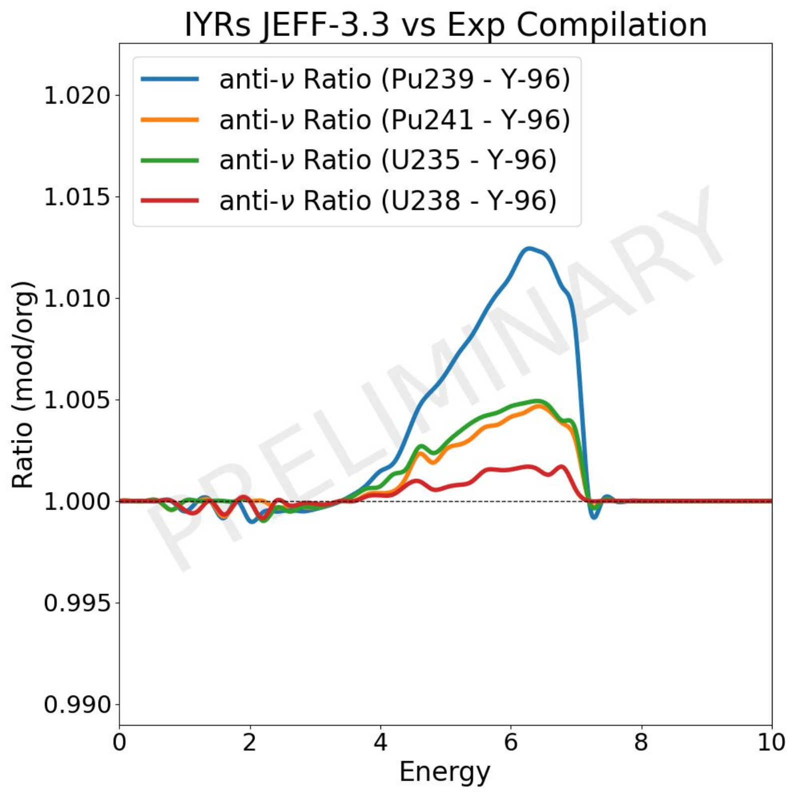
Isomeric Yield Ratios impact on anti-ν

- A sensitivity study identified a few key isomers (*e.g.*, ^{98}Y and ^{96}Y) whose IYR is key to a correct antineutrino spectrum calculation
- We are studying the effect of these nuclides and how different IYRs impact the anti-ν spectrum



Isomeric Yield Ratios impact on anti-ν

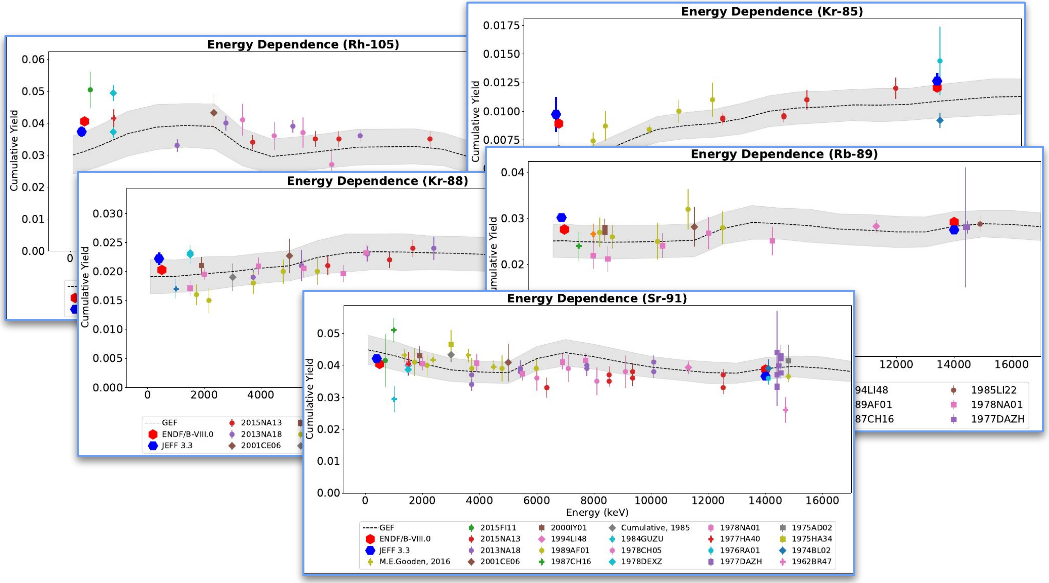
- ^{96}Y was also shown to be a major contributor in the *bump* region, with no data for low energy n-induced fission available for the compilation/evaluation
- The change, even if not as dramatic as ^{98}Y, impacts mostly in the *bump* region
- No low-energy n-induced data available at the time of the evaluation

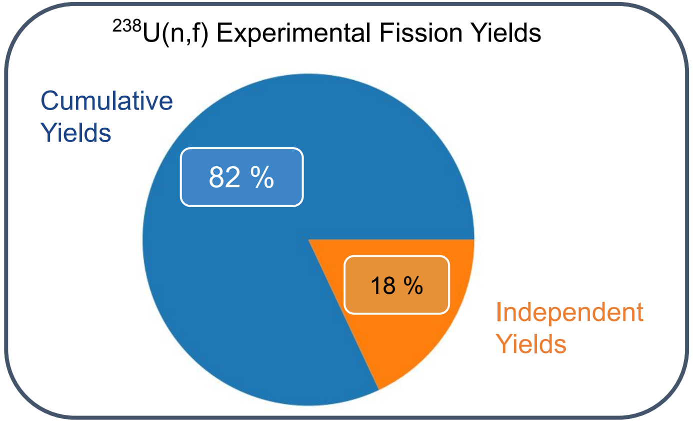


IYRs: take-home message

- Isomeric yield ratios are hard to model accurately: new measurements are needed for good evaluations
- The current model included in the FY evaluations is too simplistic to capture the complexity of isomeric yield ratios
- New models need to be developed, and can benefit from a complete and up-to-date compilation of experimental data for benchmarking

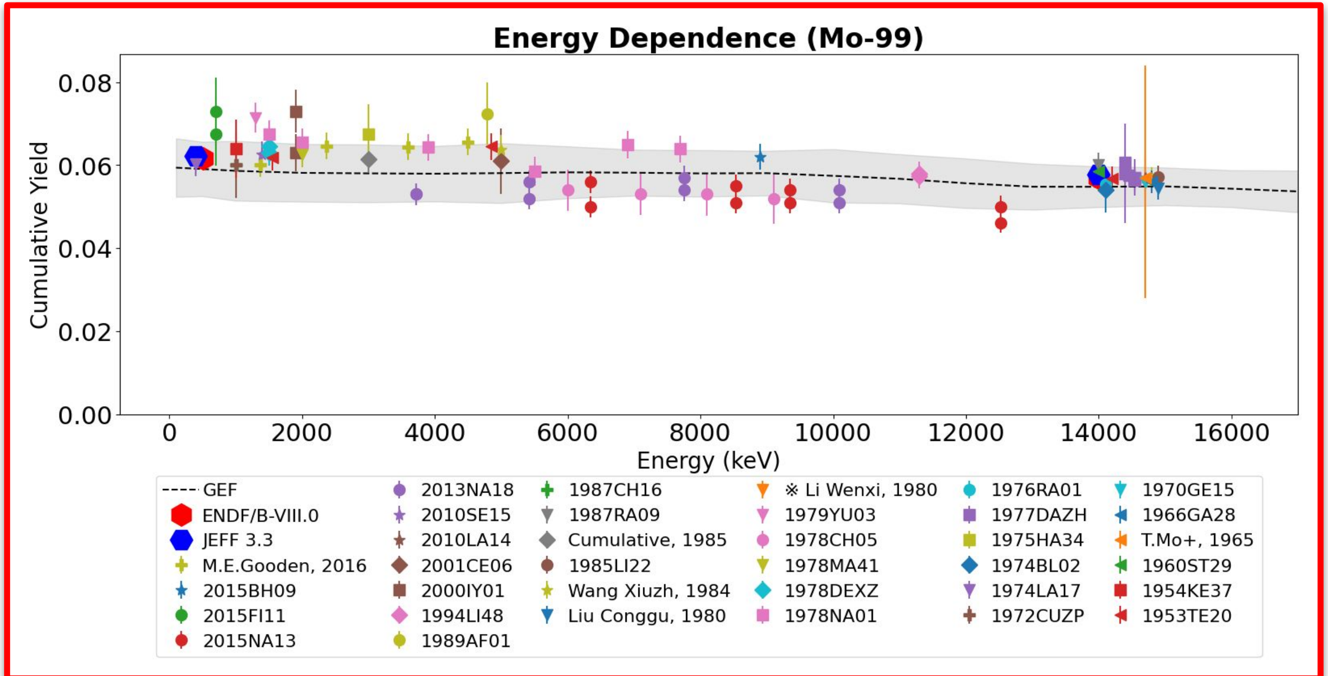
Towards a new evaluation: studies of energy dependence for model validation

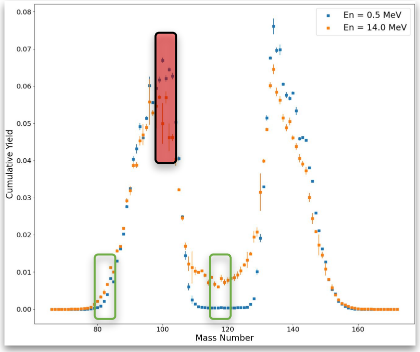




Compilation of experimental data for 250+ fission products (^{238}U(n,f)) as a function of neutron energy

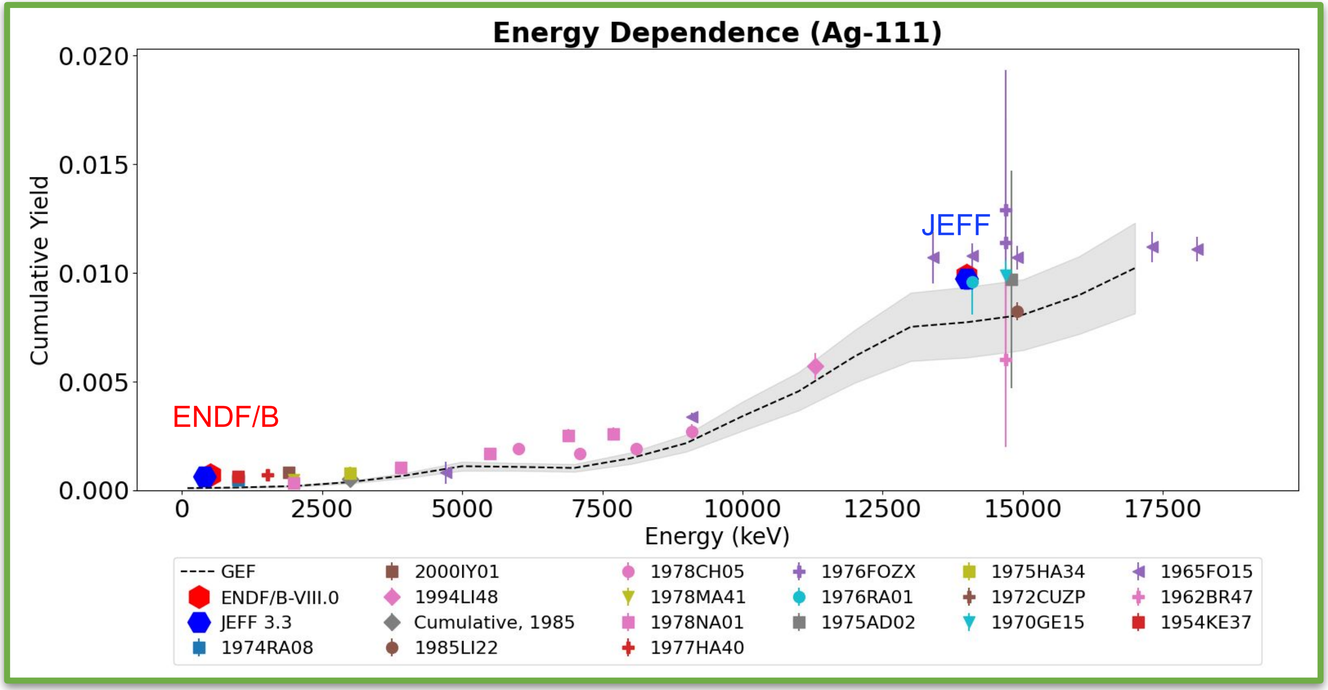
Selected results

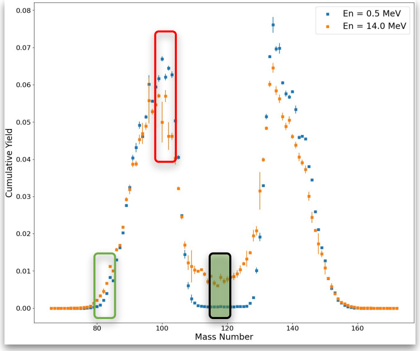




On the peaks of the distribution, there is an abundance of energy-dependent data that can be used to validate theoretical models

Selected results





While for very asymmetric and symmetric fission the number of points decreases with the lower yield, energy dependence studies of the end-of-chain nuclides is still possible

Summary

- Besides FY and decay data, Isomeric Ratios play a major role on reactor antineutrino calculations: new experimental as well as theoretical efforts are required to improve these values in future evaluations

- Experimental compilation of energy dependence of FYs can be used as a way to validate new models for predictions of the energy-dependence of FY

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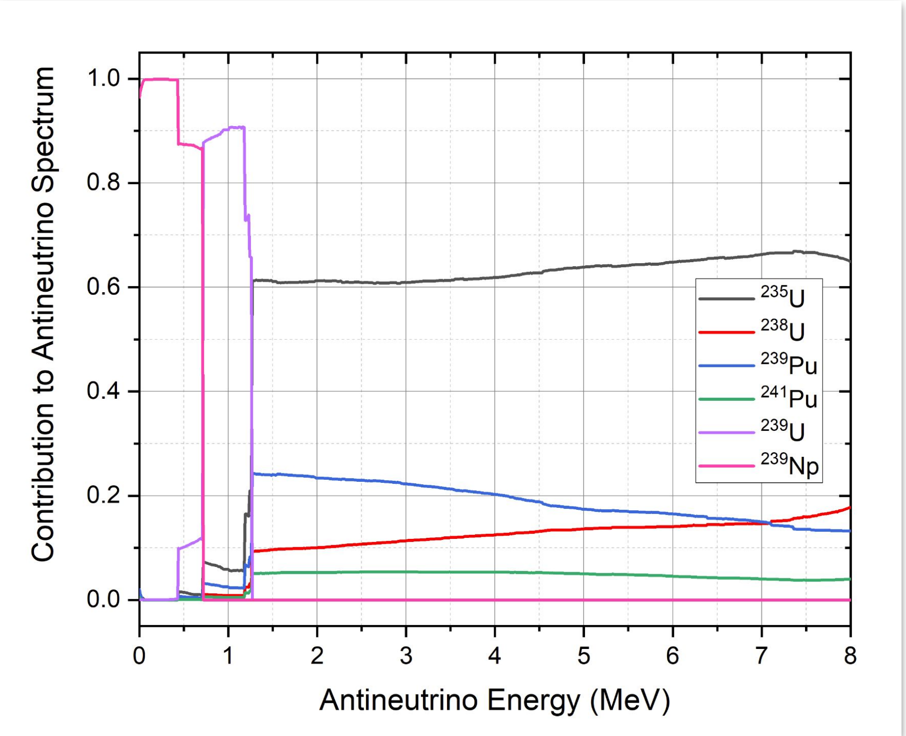
Backup Slides

Contribution below the IBD threshold

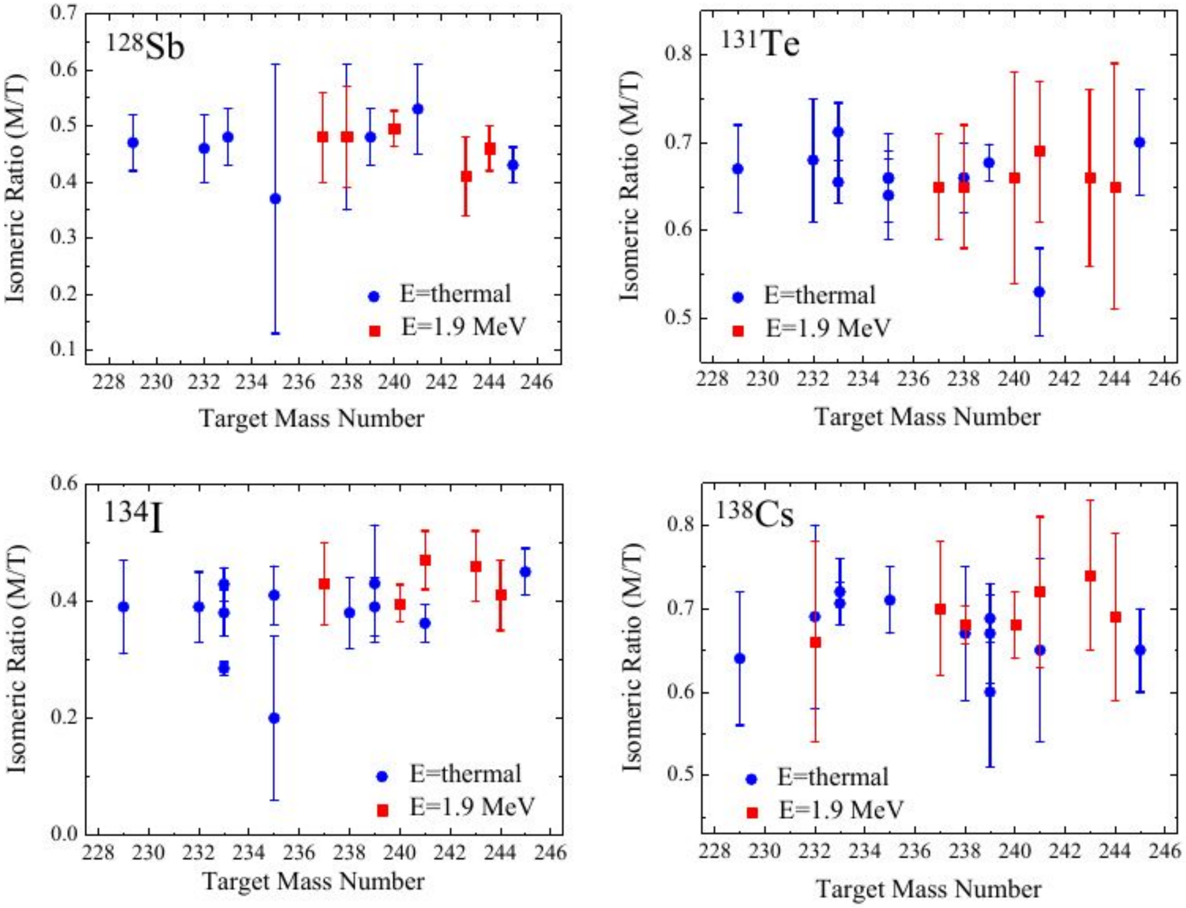
relative contribution of various actinides to the antineutrino spectrum



R. Lorek *et al.*, "Towards a more comprehensive understanding of electron antineutrino production in a nuclear reactor", TBP

Energy / CN dependence of IYRs

from Sears, C.J. *et al.* Compilation and Evaluation of Isomeric Fission Yield Ratios. Nucl. Data Sheets 173 (2021): 118-143.



Estimation of realistic CFY uncertainties with GEF, JEFF and ENDF/B

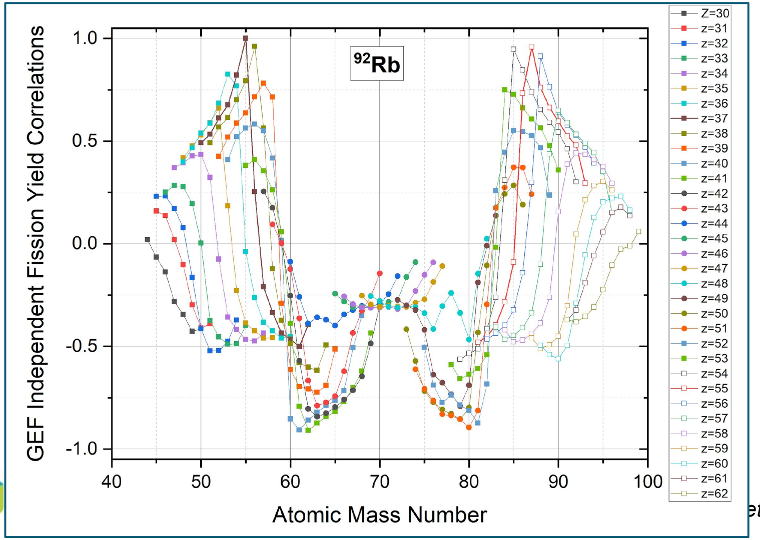
GEF independent fission yield covariances (MC code, run for a long time)

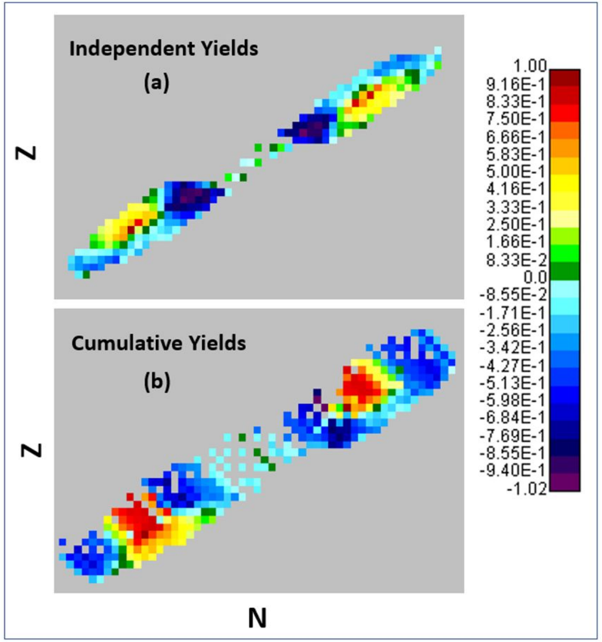
→ GEF independent fission yield Correlations

→ GEF independent fission yield correlations including isomers Cor(GS,Iso)=-1

→ Hybrid GEF/JEFF-3.3 covariances using ΔIFY from JEFF-3.3

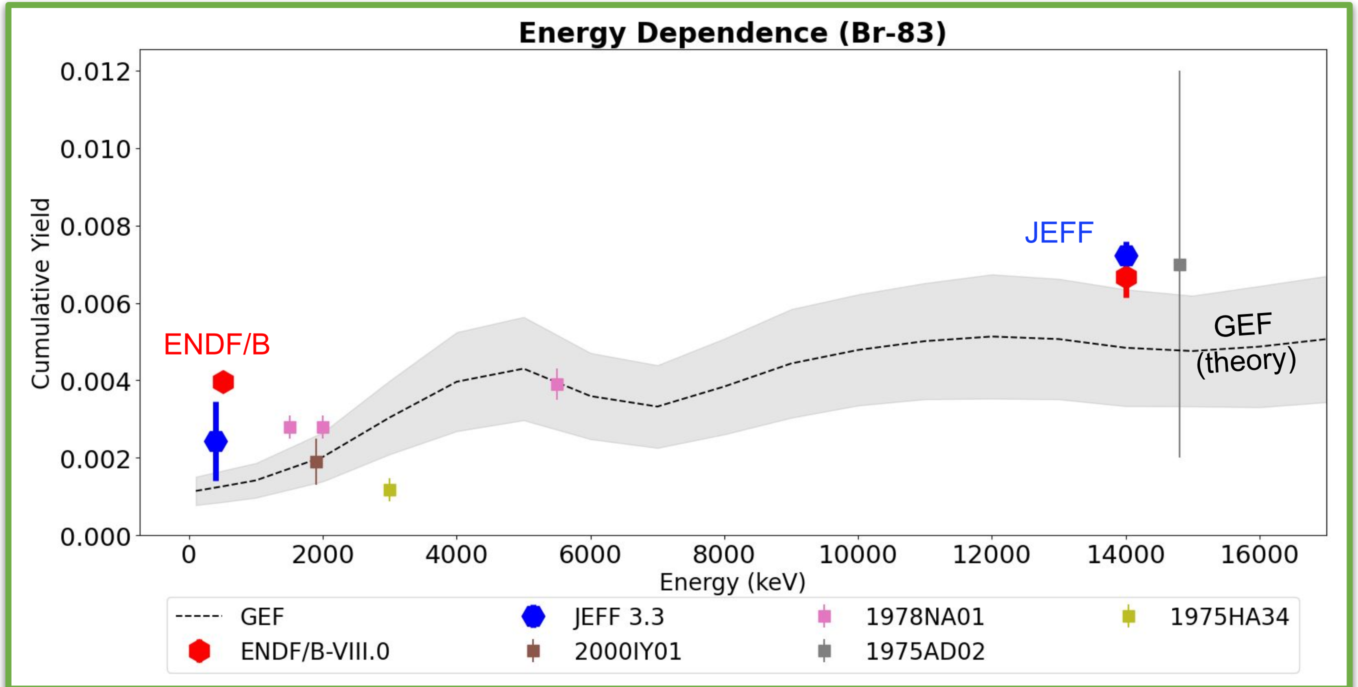
↓ Hybrid GEF, JEFF-3.3, ENDF/B-VIII.0 cumulative fission yield covariances using ENDF/B-VIII.0 decay data

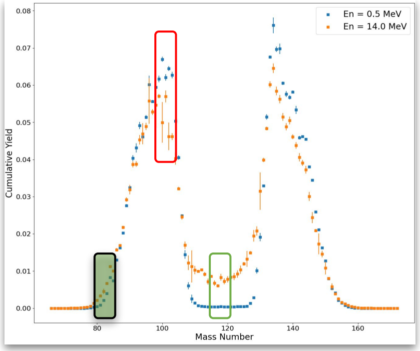




Independent and cumulative fission yield correlations for ^{92}Rb.

Selected results





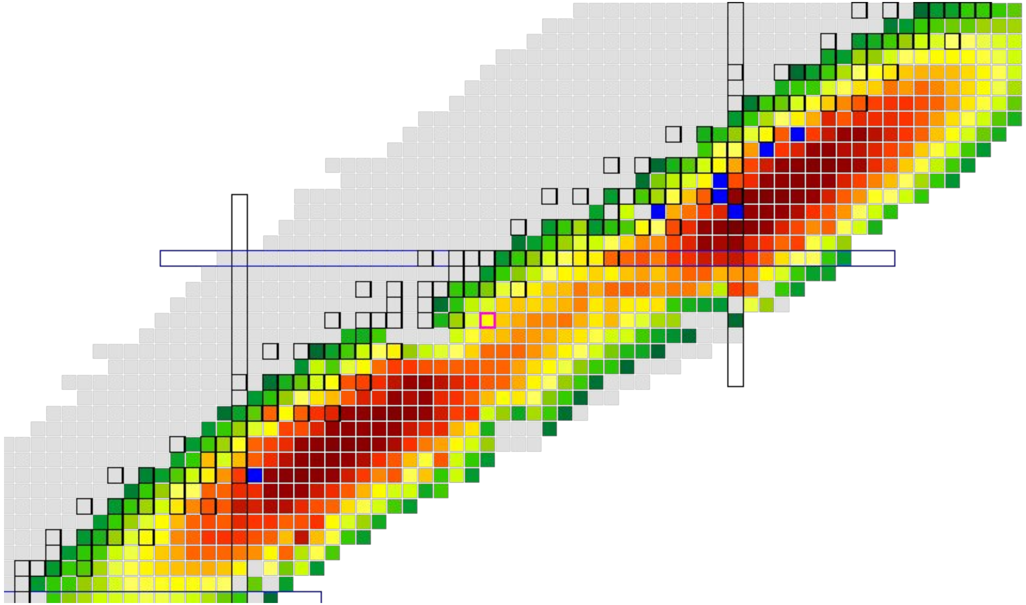
The current evaluated data libraries only have points at 0.5 and 14 MeV (fast / high-energy).

The experimental data are in most cases compatible with the GEF model.

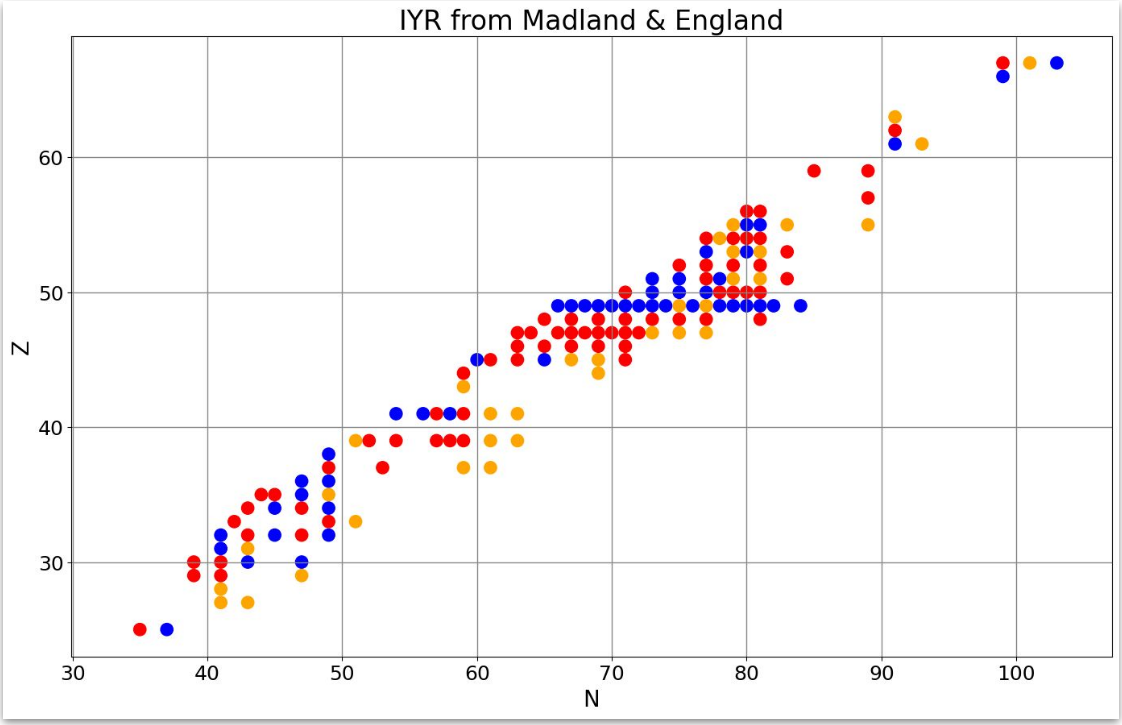
ND identify the correct trend and are mostly compatible with experimental data.

Experimental efforts

- NA22-sponsored program to measure Fission Yields decay data (γ-energies and intensities)
- Important for applications (*e.g.,* forensics, non-proliferation), but also for Fission Yields determination



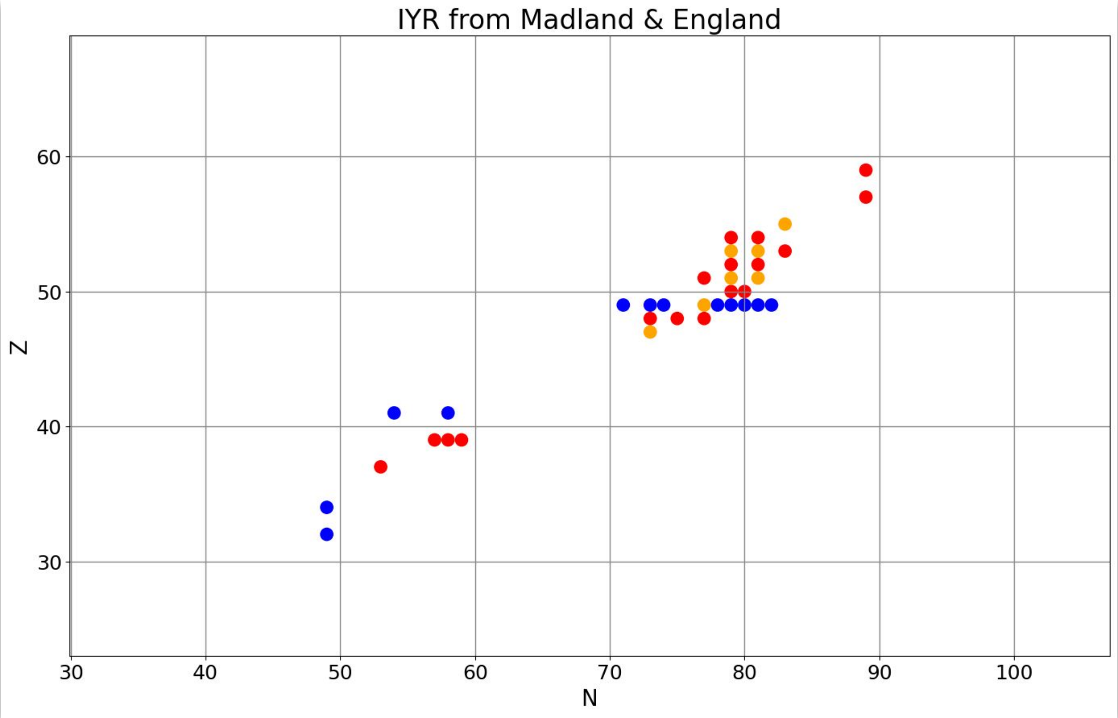
Experimental Data vs Madland & England



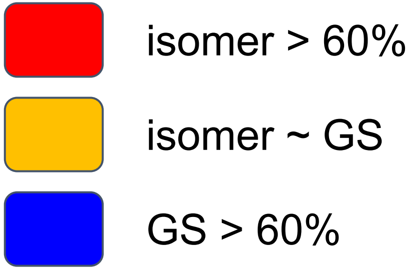
Simple model, but prediction of the IYR is available for every nuclide with a known isomer (150+ for $^{235}U(n_{th},f)$)

- isomer > 60%
- isomer ~ GS
- GS > 60%

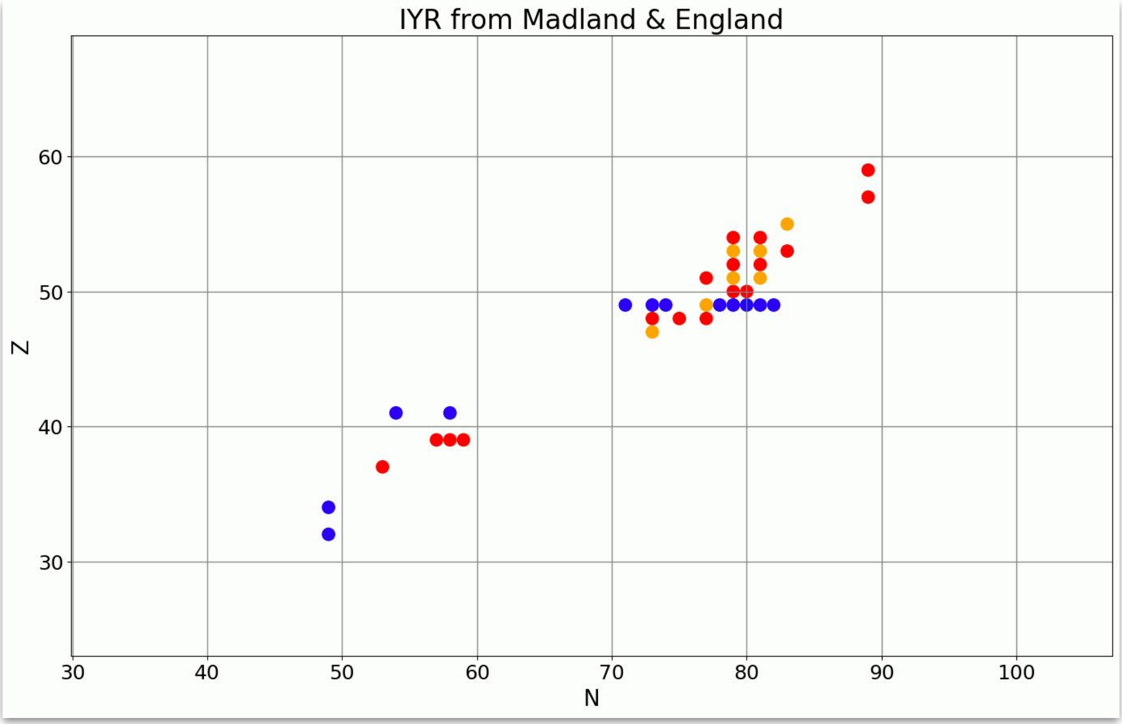
Experimental Data vs Madland & England



Low-energy data is only available for 42 fission products



Experimental Data vs Madland & England



The M&E model often predicts a different ratio from the measured one

- isomer > 60%
- isomer ~ GS
- GS > 60%

Experimental Data vs Madland&England vs Wilson

TABLE II: Recommended IYR values for all low-energy (thermal to 2 MeV) n-induced fission reactions on any fissionable target. The recommended yield ratios are expressed in the M/T form. The number of data points in brackets represents the number of values excluded from the average because considered statistical outliers.

Fission Product	Recomm. IYR (M/T)	Nr. of data points
32-Ge-81	0.32(4)	3
34-Se-83	0.11(7)	1
37-Rb-90	0.526(30)	3 *(1)*
41-Nb-95	0.248(29)	1
39-Y-97	0.695(14)†	1
39-Y-98	0.139(6)	2
41-Nb-99	0.83(17)	1 *(1)*
45-Rh-102	0.44(14)	1
47-Ag-120	0.86(4)	2 *(1)*
49-In-120	0.21(20)	1
49-In-120 M2	0.27(25)	1
48-Cd-121	0.89(11)	1
49-In-122	0.24(10)	1
49-In-122 M2	0.48(20)	1
48-Cd-123	0.65(6)	2
49-In-123	0.07(7)	
48-Cd-125	0.85(5)	
49-In-126	0.30(5)	
49-In-127	0.185(31)	
49-In-128	0.30(7)	
51-Sb-128	0.463(16)†	
49-In-129	0.42(6)	
50-Sn-129	0.47(4)	
49-In-130	0.25(5)	
49-In-130 M2	0.41(7)	
50-Sn-130	0.089(7)	
51-Sb-130	0.499(17)†	

†: uncertainty recalculated fr... value to reflect possible syste... (see text for details).

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Nuclear Data Sheets 173 (2021) 118–143
Nuclear Data Sheets
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Compilation and Evaluation of Isomeric Fission Yield Ratios

C.J. Sears,[1,2] A. Mattera,[1,*] E.A. McCutchan,[1] A.A. Sonzogni,[1] D.A. Brown,[1] and D. Potemkin[1,3,4]
[1] *National Nuclear Data Center, Brookhaven National Laboratory, Bldg. 817, P.O. Box 5000, Upton, NY 11973-5000*
[2] *Smith College, 10 Elm Street, Northampton, MA 01063*
[3] *Stony Brook University, 100 Nicolls Road, Stony Brook, NY 11794*
[4] *William Floyd High School, 240 Mastic Beach Road, Mastic Beach, NY 11951*

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...rensics, and astrophysics. In some cases, the ... state and a long-lived excited state, and the ...e isomeric ratio. In this work, we present a ...sion yield ratios for all target and projectile ...d to provide recommended isomeric fission

42 recommended experimental yield **ratios** for **low-energy neutron-induced fission**

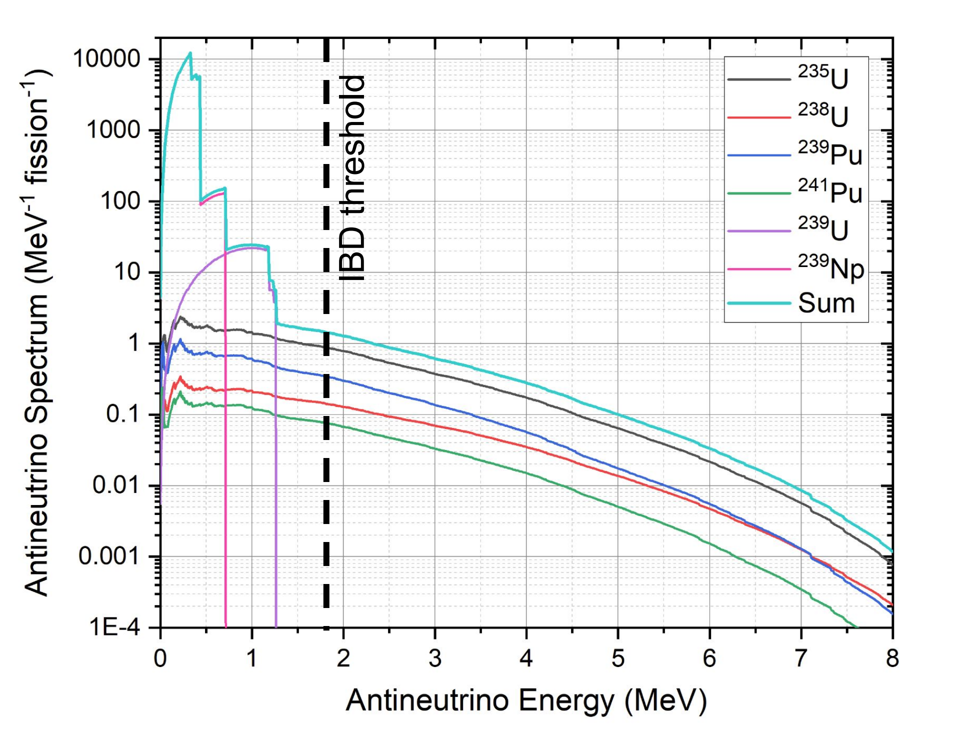
+

Remaining IYRs from M&E

Contribution below the IBD threshold

- Below the IBD threshold, the antineutrino spectrum is dominated by the β-decay of minor actinides created in neutron capture on ^{238}U

- the quality of ^{239}U and ^{239}Np decay data can be improved with new experiments



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