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U.S. DEPARTMENT OF ENERGY

Studying the impact of isomeric yield ratios on reactor antineutrino spectra

A. Mattera, A.A. Sonzogni, E.A. McCutchan, R.J. Lorek, C. Sears, C. Billings

National Nuclear Data Center, Brookhaven National Laboratory

16th Varenna Conference on Nuclear Reaction Mechanisms

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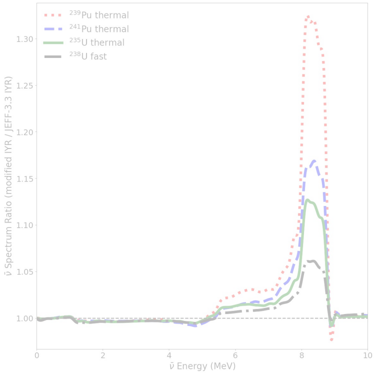
Outline

- The “bump” in antineutrino spectra
- Fission yields and isomers in antineutrino summation calculations
- Recommended experimental isomeric yield ratios
- Impact of recommended experimental isomeric yields
- Outlook



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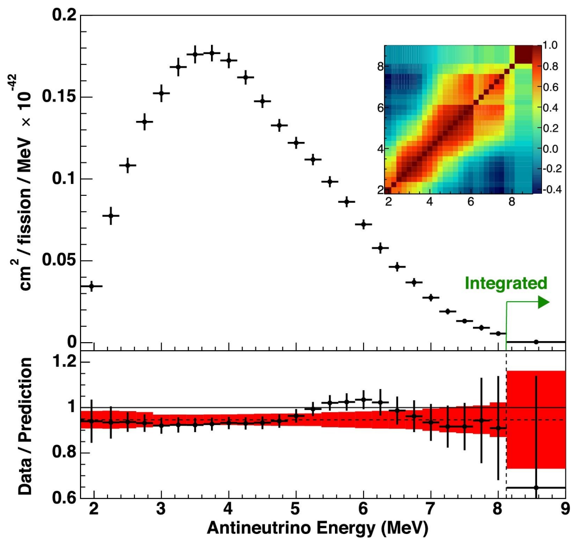
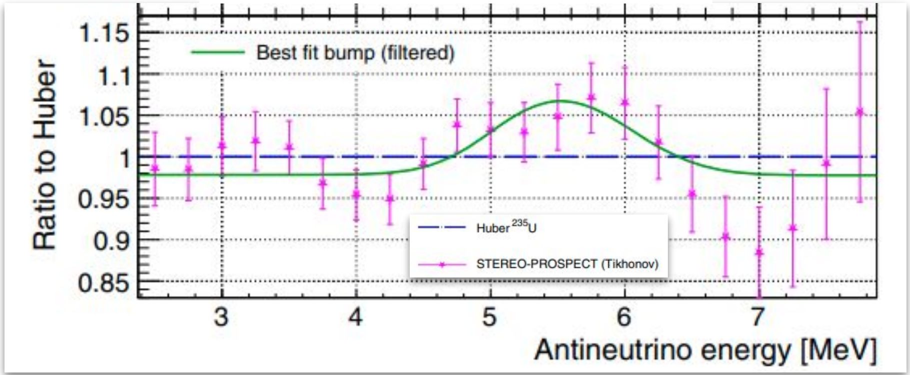
Reactor antineutrino spectra and "the bump"

- km-baseline experiments measured the antineutrinos from β⁻-decay of fission products
- 5% deficit of the total number of antineutrinos (RAA)
- Excess of antineutrinos between 5-7 MeV → "The Bump"



Cao, Jun, and Kam-Biu Luk. "An overview of the Daya Bay reactor neutrino experiment." *Nuclear Physics B* 908 (2016): 62-73.

PHYSICAL REVIEW LETTERS 128, 081802 (2022)



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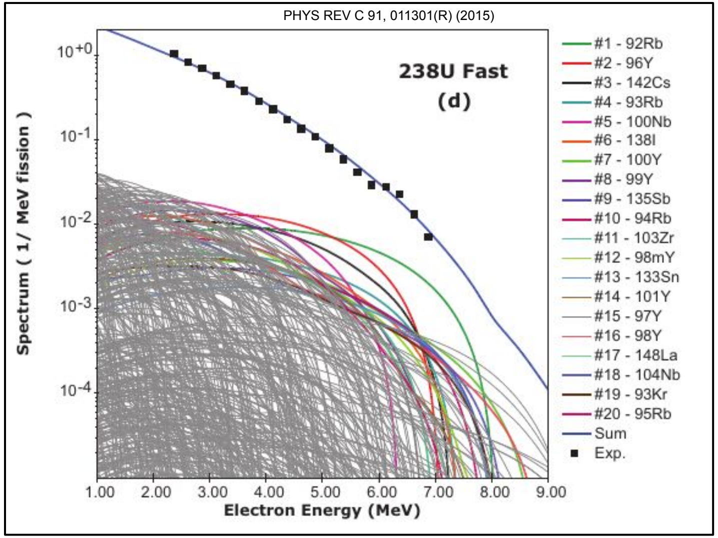
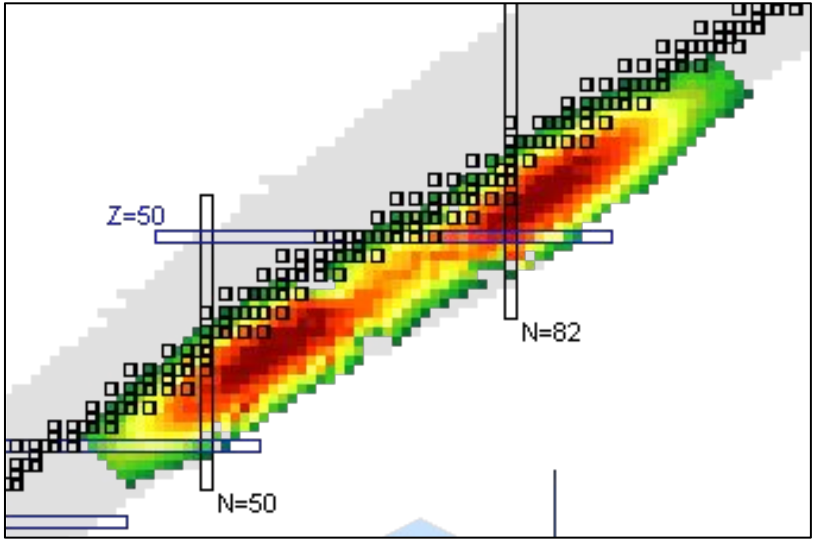
Fission Yields in anti-ν spectra summation calculations

DECAY DATA + **FISSION YIELDS**



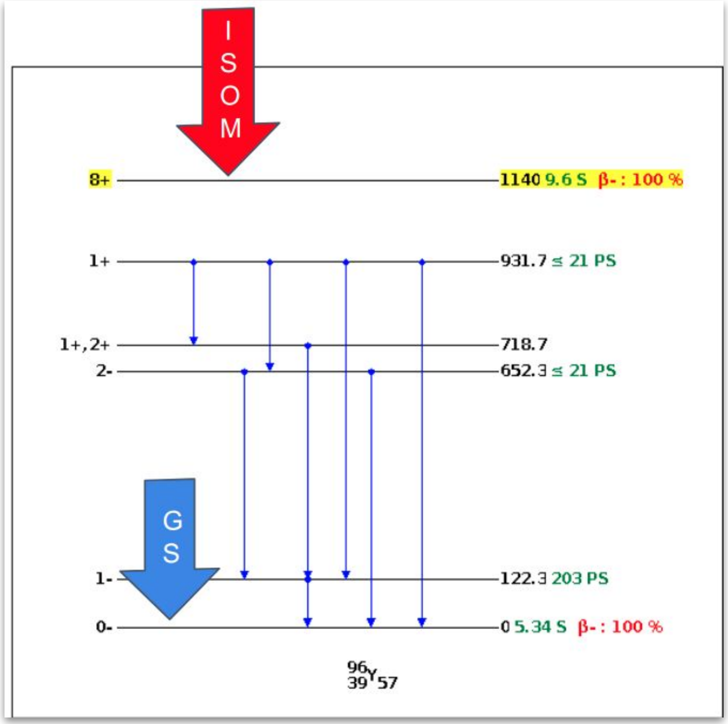


The contribution from the β-decay of each fission product is weighed with its fission yield

Isomeric Yield Ratios

- Fission Yields are a key component of the Summation Method
- ~200 fission products have a known long-lived excited state (isomer)
- **Isomeric Yield Ratios** represent another key component that is difficult to accurately predict, and must be based on experimental data.

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



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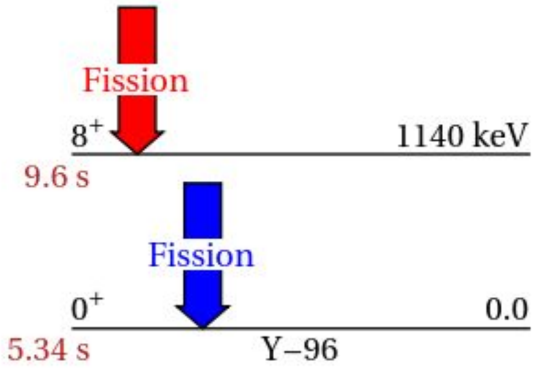
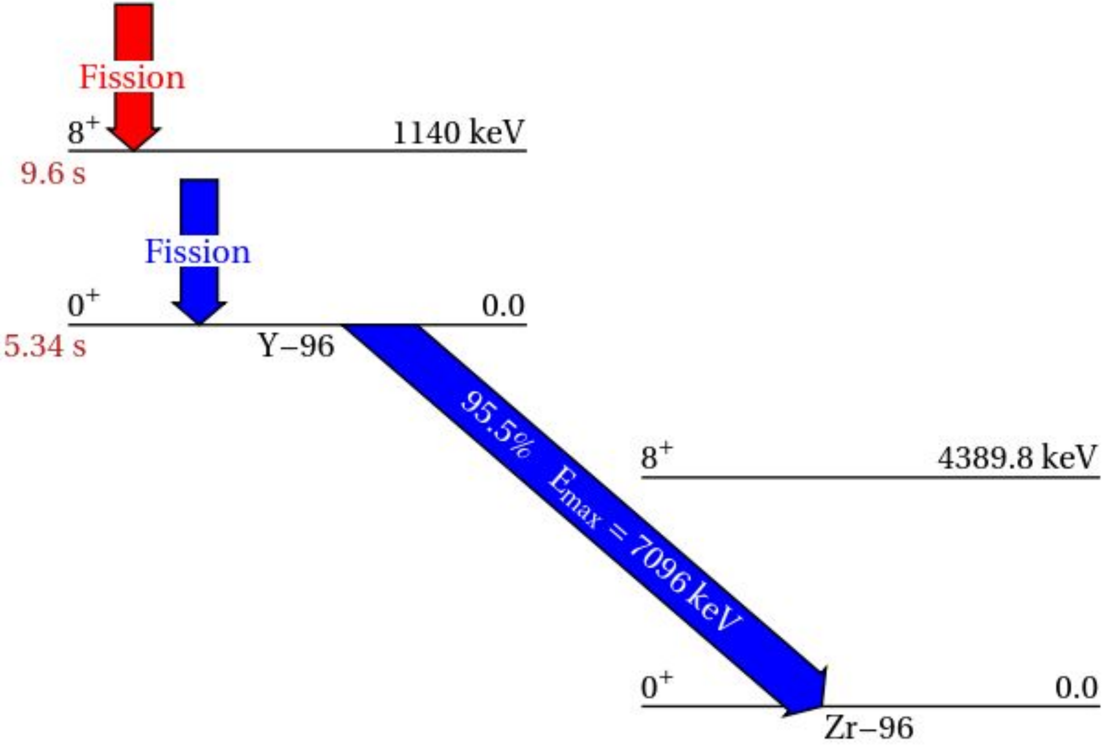
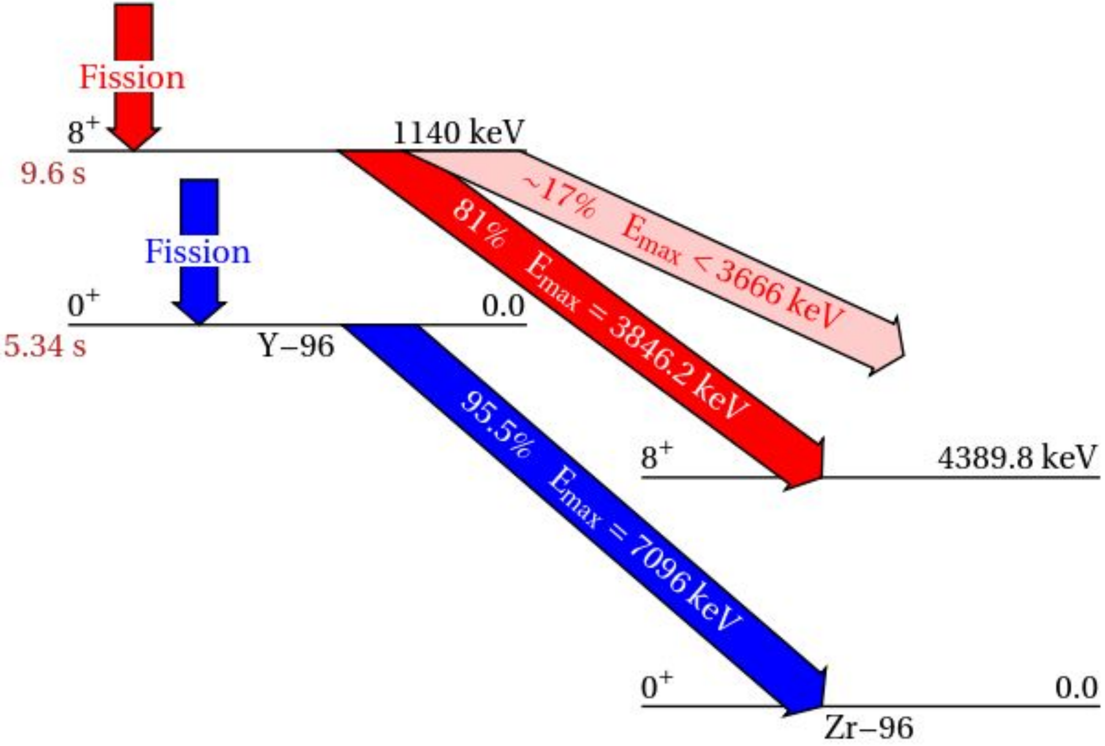
Isomers and antineutrino spectra



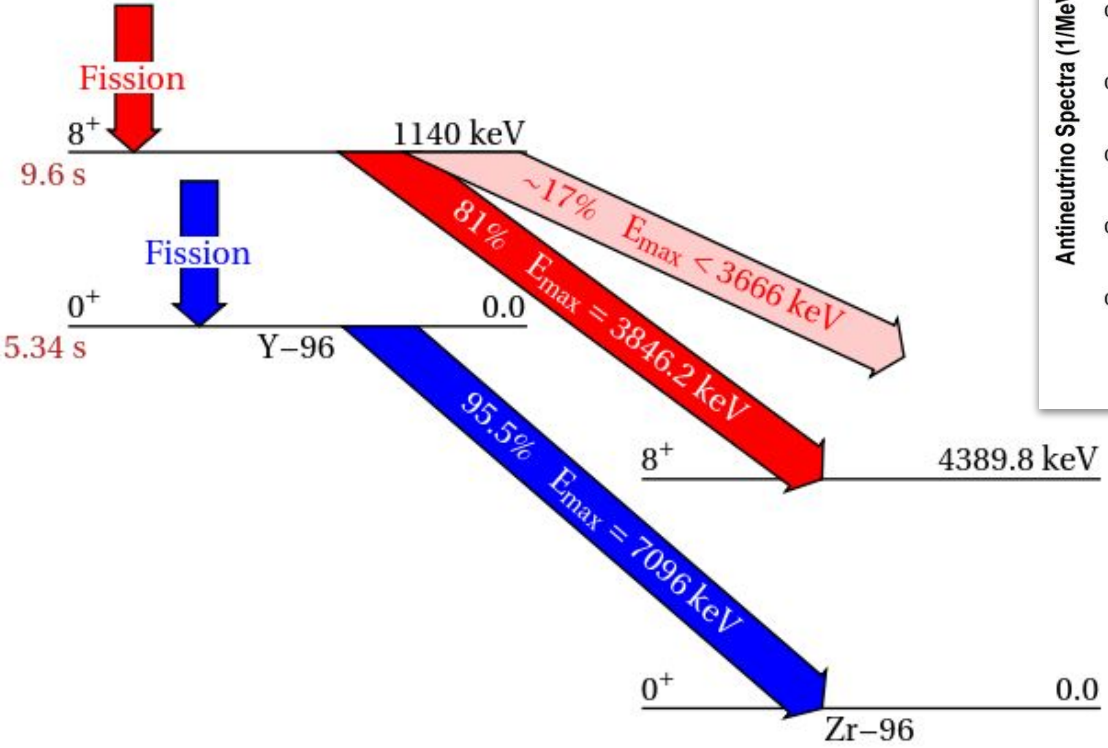
Isomers and antineutrino spectra

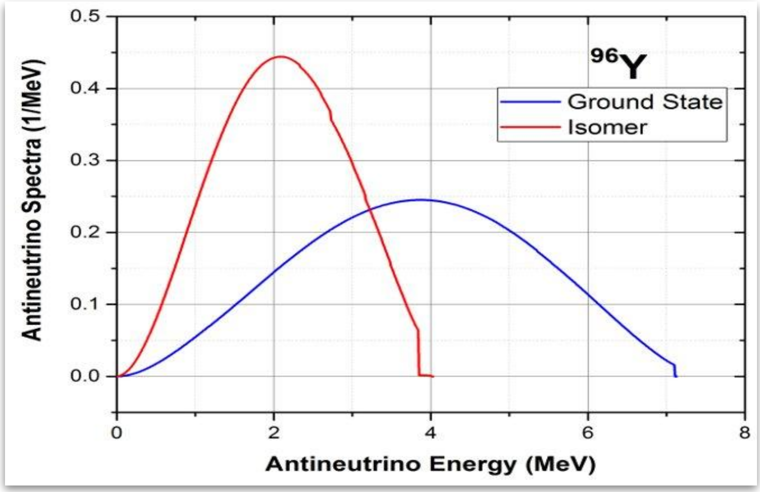


Isomers and antineutrino spectra



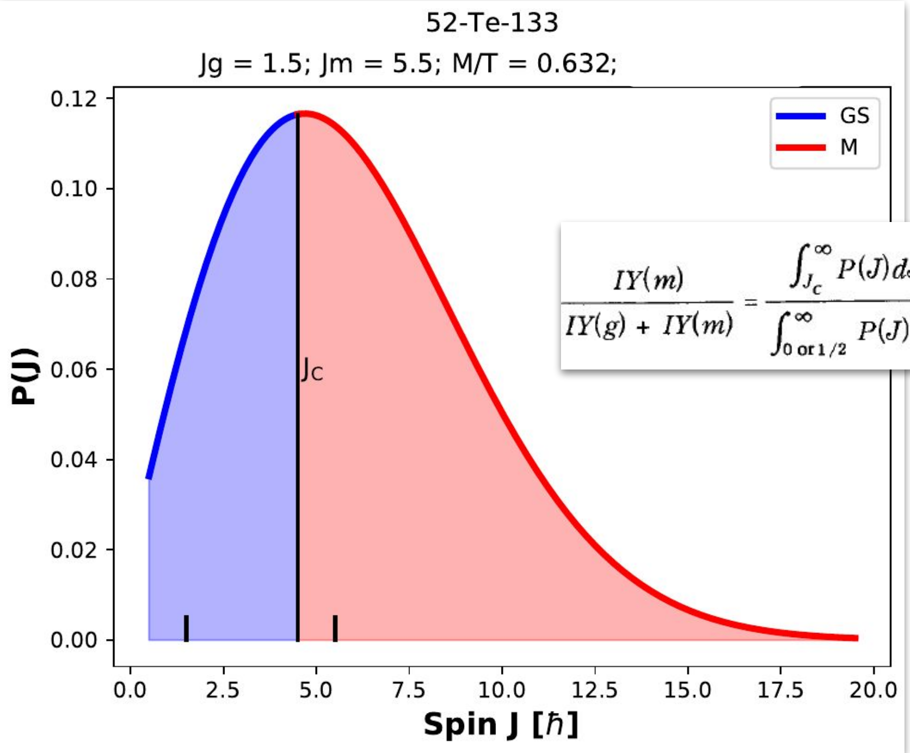
Isomers and antineutrino spectra





The importance of each curve is weighted by the yield that populates the G.S. or the isomer

IYRs in current FY evaluation



$$\frac{IY(m)}{IY(g) + IY(m)} = \frac{\int_{J_c}^{\infty} P(J)dJ}{\int_{0 \text{ or } 1/2}^{\infty} P(J)dJ}$$

NUCLEAR SCIENCE AND ENGINEERING: **64**, 859-865 (1977)

The Influence of Isomeric States on Independent Fission Product Yields

David G. Madland and Talmadge R. England

University of California, Los Alamos Scientific Laboratory, Theoretical Division
P. O. Box 1663, Los Alamos, New Mexico 87545

It predicts IYR with minimal information on the fission products:

- Isomeric ratio is split based on the J_g / J_m assuming a statistical P(J):

$$P(J) = P_0(2J + 1) \exp[-(J + \tfrac{1}{2})^2 / \langle J^2 \rangle]$$

- 1-parameter (J_{rms}) that fixes the P(J) distribution for **all** FFs

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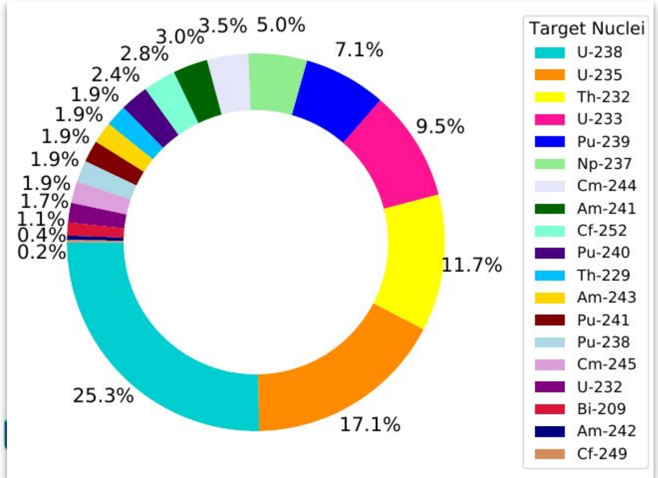
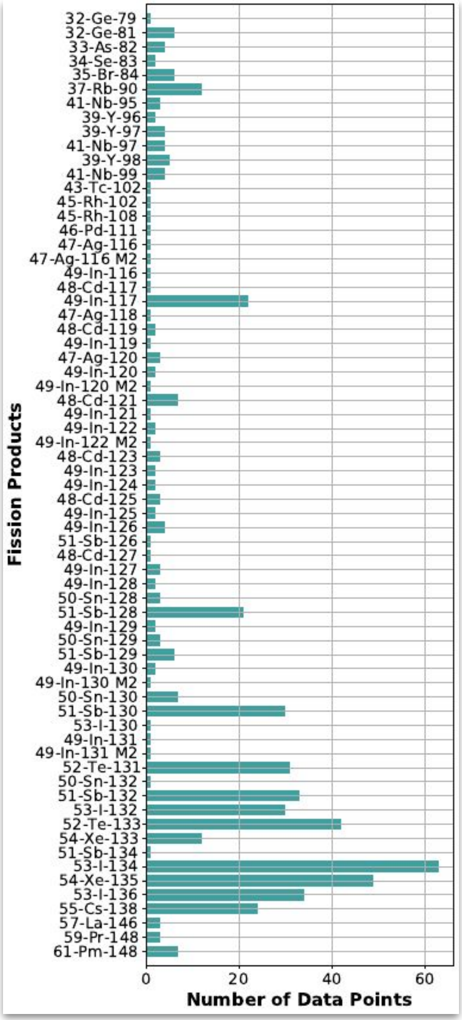
Recommended experimental IYRs

- compiled 538 independent isomeric yield ratios, from 39 compound nuclei, and 62 unique fission products

- 5x the amount of data available to Madland & England when they developed the model



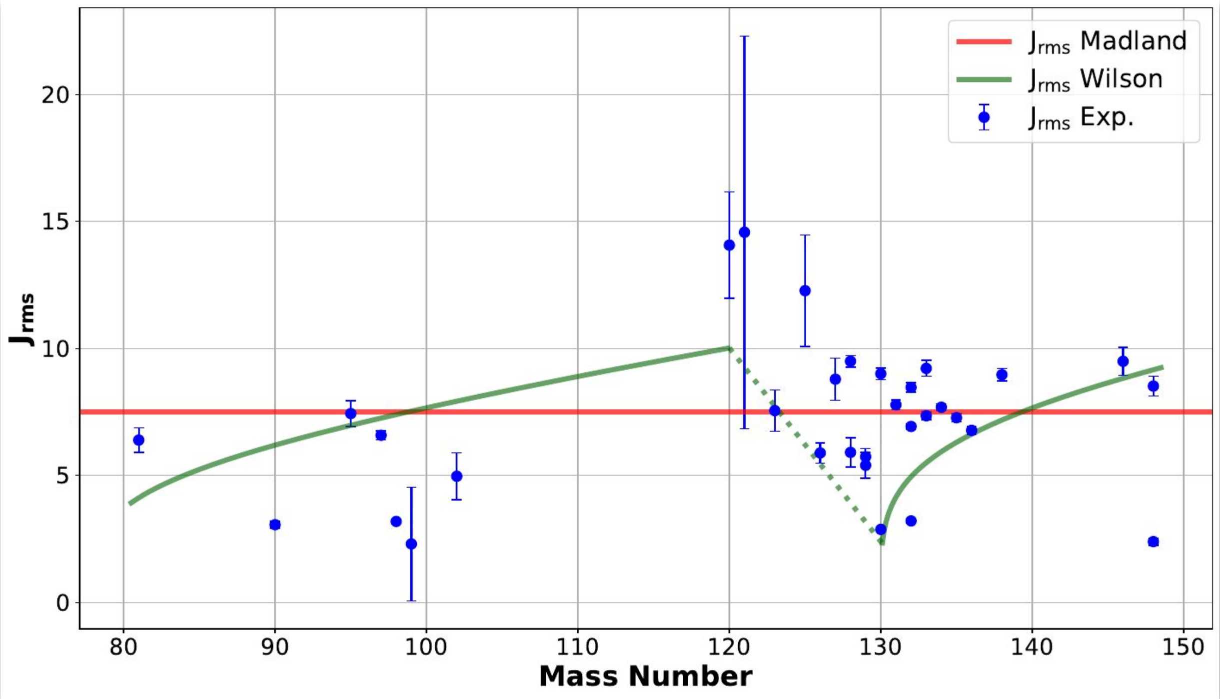
- Wealth of new data can be used to benchmark new models for the prediction of IYRs



Madland & England *vs* Wilson

A new parametrization of J_{rms} following Wilson's[1] prescription does not lead to better IYR predictions

it is not easy to predict IYRs where no data are available!



[1] Wilson, J. N., et al. "Angular momentum generation in nuclear fission." Nature 590.7847 (2021): 566-570.

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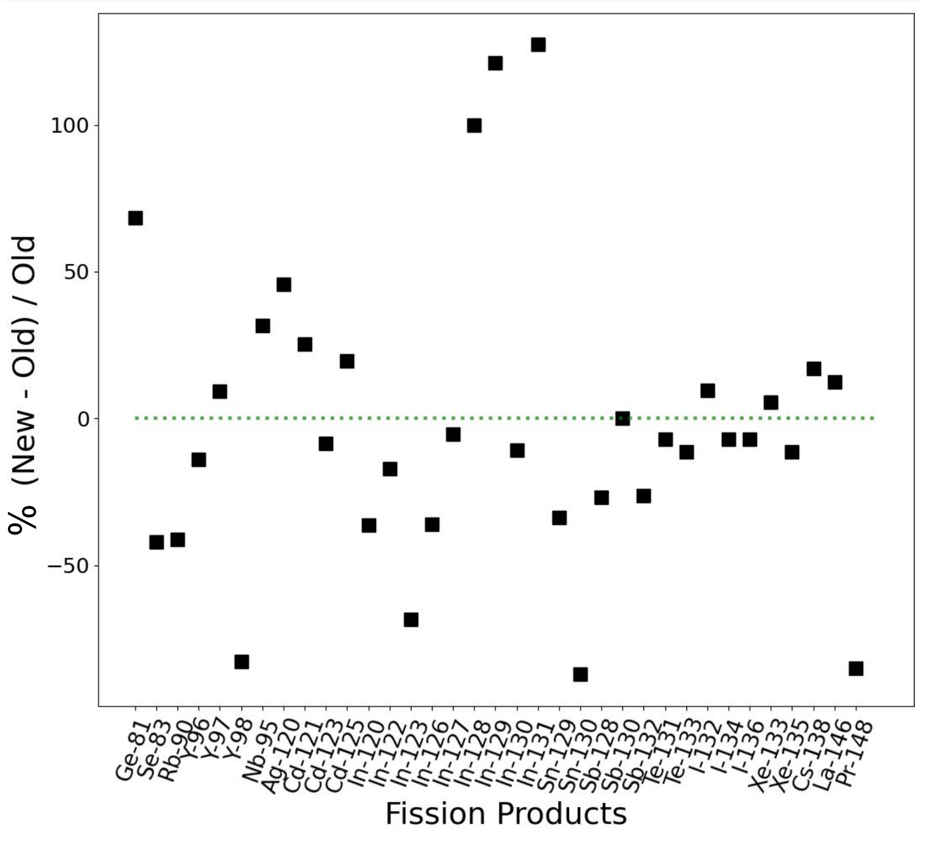
Experimental IYRs evaluation

- of the 200+ isomeric yields that are included in the ND libraries, 42 have exp. data at “low energy”.

- In about half the cases where data is available, the libraries contain a value that doesn’t agree with the measurements

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



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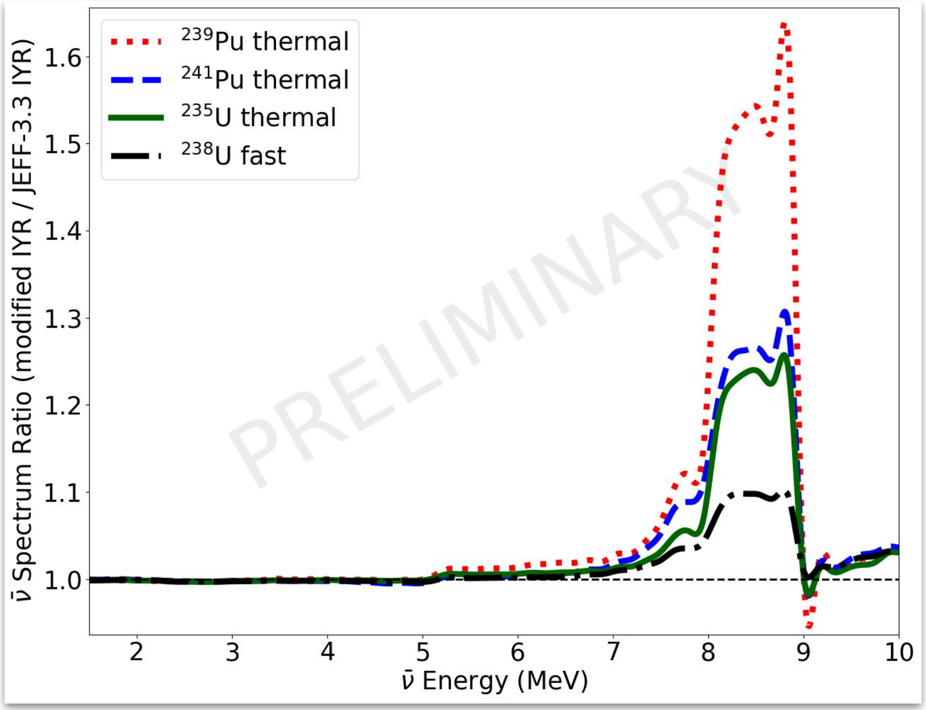
Impact of experimental values on anti-ν spectra

- Spectrum shown as a ratio to the benchmark (JEFF-3.3)
- Virtually no difference below 5 MeV
- Overall increase elsewhere:

  up to + 5% at 6 MeV

  up to +60% at 8 MeV



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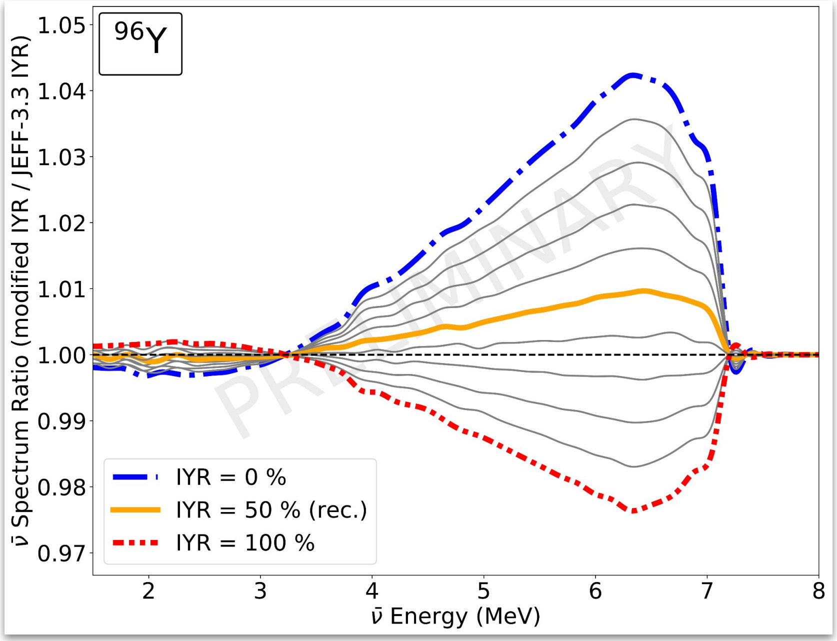
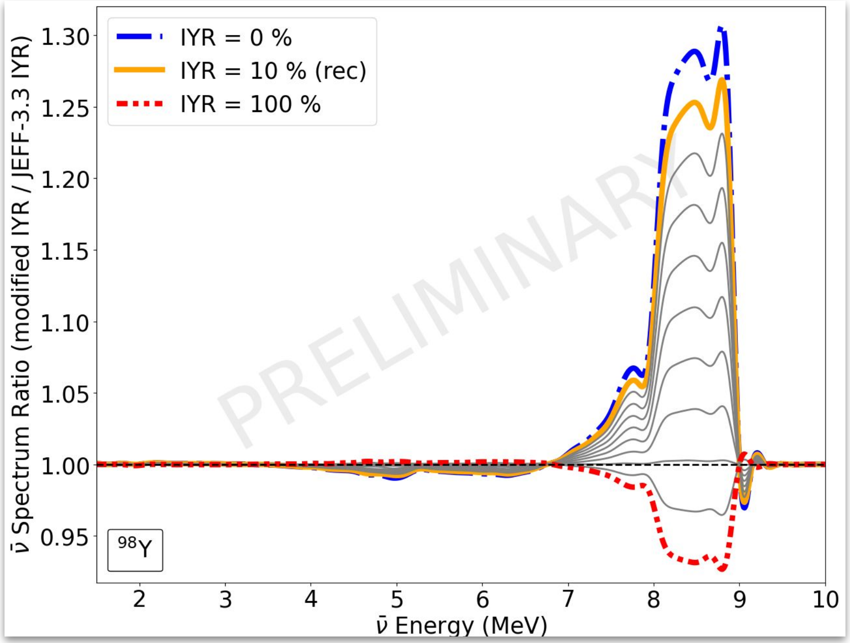
Wildly uneven contribution of different FPs





IYR_{th} = 65% → IYR_{exp} = 50 %
CFY ≈ 5 %

IYR_{th} = 81% → IYR_{exp} = 14 %
CFY ≈ 3 %

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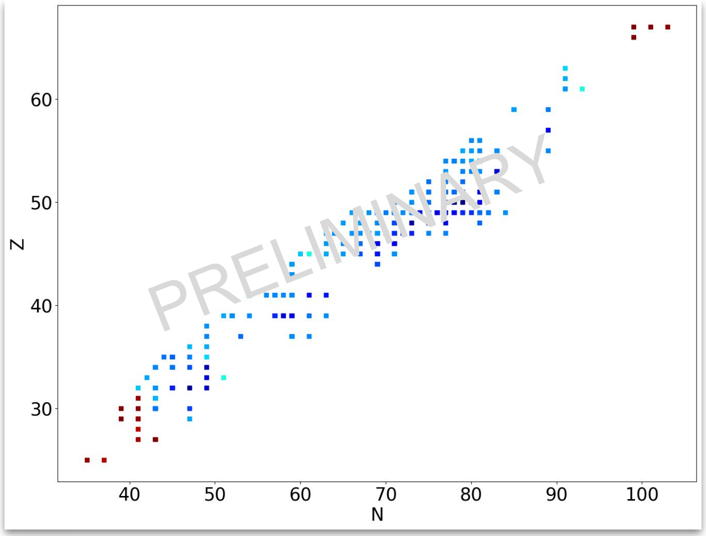
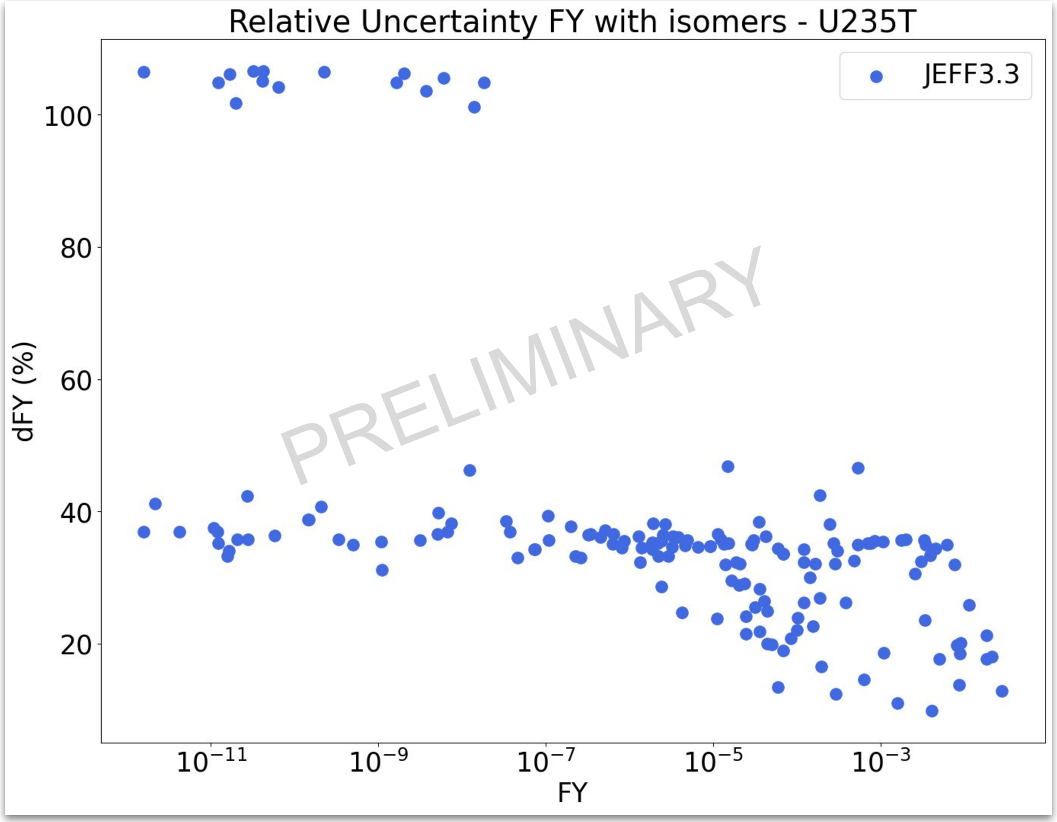
A broader sensitivity study: uncertainties

Are uncertainties in the libraries capturing the uncertainty on IYR?





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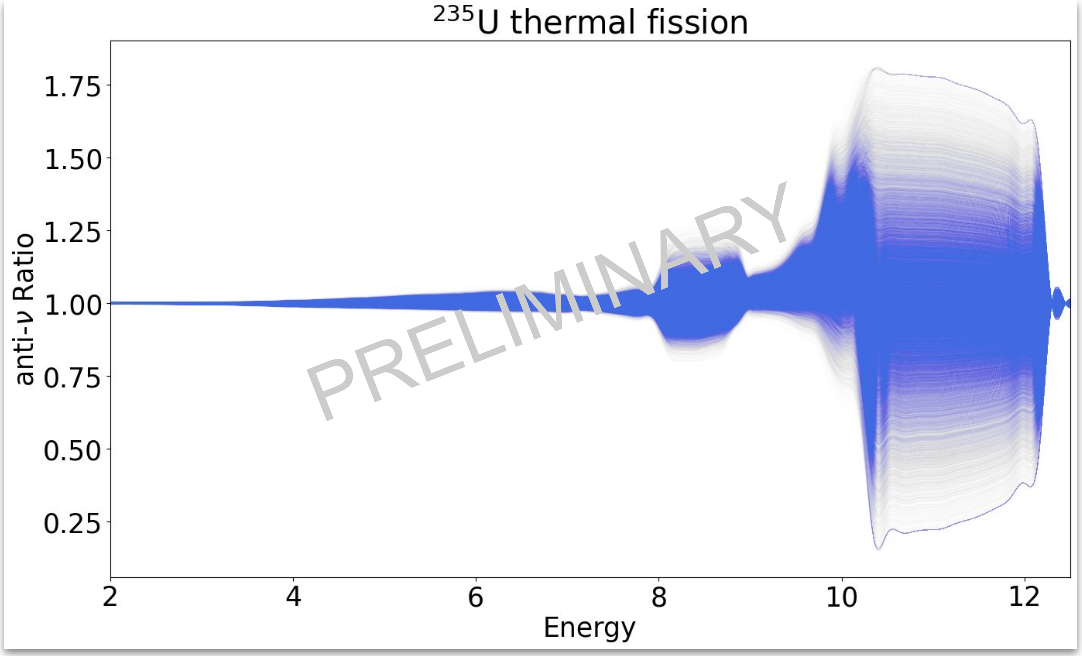
A broader sensitivity study: uncertainties

Brute-force sensitivity study: how do uncertainties (likely underestimated) of IYRs as a whole affecting the spectrum?

Uncertainties explode at high energies, where only a few isotopes make up a large fraction of the anti-ν spectrum



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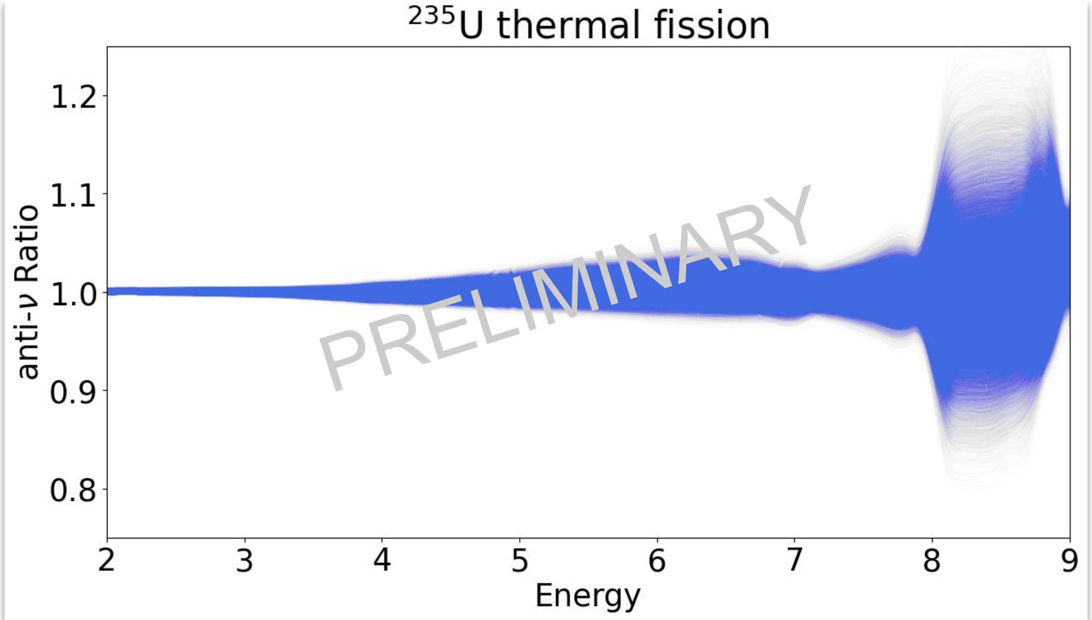
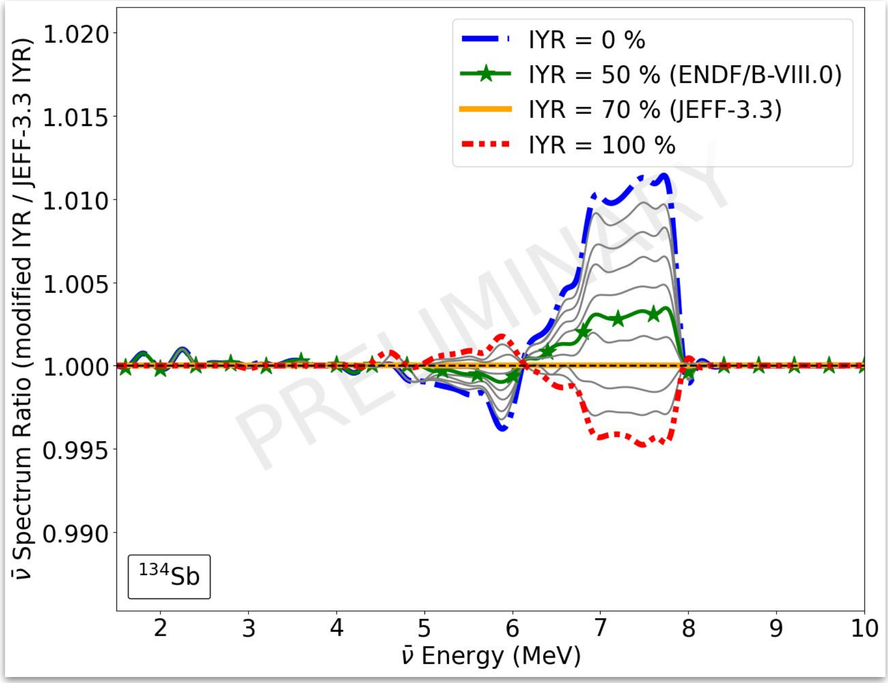


A broader sensitivity study

- Analysis of all fission products with a known isomer included in ENDF
- Varied the value within physical boundaries
- Identified a list of fission products, whose yield could affect the antineutrino spectra (e.g., Sb-134, Nb-100, La-146, Rb-90)



Summary and Outlook

- New evaluated isomeric ratios result in an **increased antineutrino flux** compared to the current FY libraries **up to 60%** for specific energies and fissile targets.
- Experimental data on IYRs exist only for a fraction of the fission products, and uncertainty on the FYs does not always capture the uncertainty on the IYR
- A sensitivity study shows that **a number of other isomers could** considerably **affect the antineutrino spectrum**, especially at high energies
- Provide a **high-priority list of IYRs** to be measured for reactor antineutrino calculations

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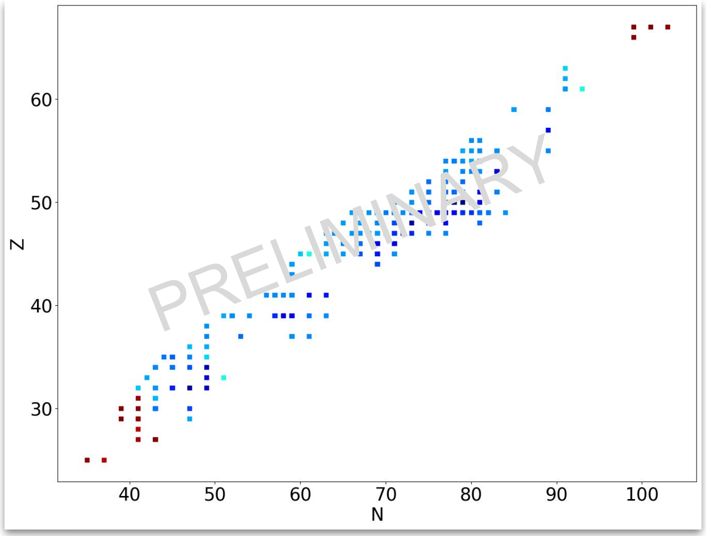

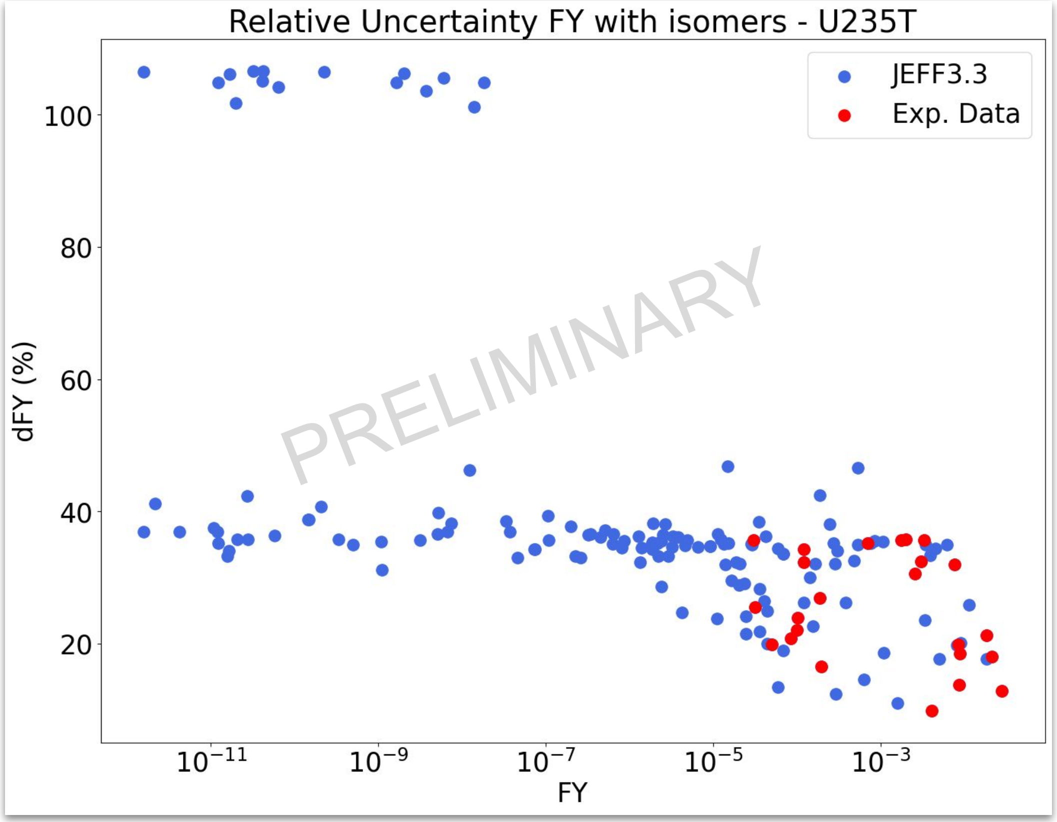

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