Antineutrino Spectrum Predictions:

Nuclear Data Impact and Interplay

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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.

\[ IYR = \frac{Y_{\text{isom}}}{(Y_{\text{isom}} + Y_{\text{gs}})} \]
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)

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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In about half the cases where data is available, the Madland & England model predicts a value that doesn’t agree with the measurements.
A sensitivity study identified a few key isomers (e.g., $^{98}\text{Y}$ and $^{96}\text{Y}$) 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-$\nu$ spectrum.
Isomeric Yield Ratios impact on anti-\(\nu\)

- \(^{96}\text{Y}\) 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 \(^{98}\text{Y}\), 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
On the peaks of the distribution, there is an abundance of energy-dependent data that can be used to validate theoretical models.
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

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.
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 ($\gamma$-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

- isomer > 60%
- isomer ~ GS
- GS > 60%
Experimental Data vs Madland & England

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

<table>
<thead>
<tr>
<th>Fission Product</th>
<th>Recomm. IYR (M/T)</th>
<th>Nr. of data points</th>
</tr>
</thead>
<tbody>
<tr>
<td>33-Ge-81</td>
<td>0.32(1)</td>
<td>3</td>
</tr>
<tr>
<td>34-Se-81</td>
<td>0.14(1)</td>
<td>1</td>
</tr>
<tr>
<td>37-Rb-90</td>
<td>0.32(30)</td>
<td>3 (1)</td>
</tr>
<tr>
<td>41-Nb-95</td>
<td>0.24(29)</td>
<td>1</td>
</tr>
<tr>
<td>54-V-97</td>
<td>0.695(14)</td>
<td>1</td>
</tr>
<tr>
<td>59-Y-98</td>
<td>0.139(6)</td>
<td>2</td>
</tr>
<tr>
<td>41-Nb-99</td>
<td>0.83(17)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>45-Rh-102</td>
<td>0.44(14)</td>
<td>1</td>
</tr>
<tr>
<td>47-Ag-123</td>
<td>0.86(1)</td>
<td>2 (1)</td>
</tr>
<tr>
<td>49-In-123</td>
<td>0.21(2)</td>
<td>1</td>
</tr>
<tr>
<td>49-In-123 M2</td>
<td>0.27(35)</td>
<td>1</td>
</tr>
<tr>
<td>48-Cd-121</td>
<td>0.88(11)</td>
<td>1</td>
</tr>
<tr>
<td>49-In-122</td>
<td>0.24(10)</td>
<td>1</td>
</tr>
<tr>
<td>49-In-123 M2</td>
<td>0.48(30)</td>
<td>1</td>
</tr>
<tr>
<td>49-Cd-123</td>
<td>0.60(5)</td>
<td>2</td>
</tr>
<tr>
<td>49-In-123</td>
<td>0.57(7)</td>
<td>1</td>
</tr>
<tr>
<td>49-Cd-125</td>
<td>0.80(5)</td>
<td>1</td>
</tr>
<tr>
<td>49-In-125</td>
<td>0.38(5)</td>
<td>1</td>
</tr>
<tr>
<td>49-In-127</td>
<td>0.34(1)</td>
<td>1</td>
</tr>
<tr>
<td>49-In-128</td>
<td>0.39(7)</td>
<td>1</td>
</tr>
<tr>
<td>51-Sb-128</td>
<td>0.435(16)</td>
<td>1</td>
</tr>
<tr>
<td>49-In-129</td>
<td>0.42(5)</td>
<td>1</td>
</tr>
<tr>
<td>50-Sb-129</td>
<td>0.47(1)</td>
<td>1</td>
</tr>
<tr>
<td>49-In-130</td>
<td>0.25(5)</td>
<td>1</td>
</tr>
<tr>
<td>49-In-130 M2</td>
<td>0.34(1)</td>
<td>1</td>
</tr>
<tr>
<td>50-Sb-130</td>
<td>0.099(7)</td>
<td>1</td>
</tr>
<tr>
<td>51-Sb-130</td>
<td>0.396(17)</td>
<td>1</td>
</tr>
</tbody>
</table>

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 $^{238}\text{U}$.
- The quality of $^{239}\text{U}$ and $^{239}\text{Np}$ decay data can be improved with new experiments.

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