Juno Italia meeting

May 5 – 6, 2022

Antineutrinos from reactors

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Introduction

- Development of an analysis tool to generate and study the spectrum of antineutrinos from reactors

FEATURES

- Based on available nuclear data (**ab initio** calculation)
- Flexible and easy to use
- Can be coupled with reactor **burnup** simulations

Provides the **unoscillated** $\bar{\nu}_e$ spectrum with **infinite energy resolution**

↔

Known limitations

Uncertainties from nuclear data

To be used for **benchmark** analysis with experimental data (**TAO**, JUNO, …)

Input data

- We want transparent and easy to be updated/modified input data

LIVE CHART OF NUCLIDES

- Developed and maintained by the IAEA Nuclear Data Section (link)
- The **LiveChart API** (Application Programming Interface) allows the direct download of data
- The Livechart API works very effectively with **Python** data analysis libraries

↓

We load the **nuclear data** we need for the ab initio calculation (fission yields, half-lives, beta decay Q-values, …)

BETASHAPE

- The BetaShape program has been developed by the LNHB (Laboratoire National Henri Becquerel)
- Can be downloaded for free and run on most OS
- Its output was recently added to the Live Chart of Nuclides

↓

We produce a data library with all the **spectra of antineutrinos** emitted in beta decays

First step: equilibrium spectrum

- Generate the $\bar{\nu}_e$ spectra from the main fissile (^{235}U, ^{239}Pu, ^{241}Pu) and fissionable (^{238}U) isotopes at the **equilibrium** condition
- Most fission products have relatively short half-lives and reach equilibrium (**production rate = decay rate**) in a negligible timescale

SUMMATION SPECTRUM AT EQUILIBRIUM

$$S_\nu(E) = \sum_i f_i \, S_{\nu,i}(E) = \sum_i f_i \sum_j y_{i,j} \, S_{\nu,j}(E)$$

Fission fraction

Fission yields

$\bar{\nu}_e$ spectrum of j-th isotope

$i = {}^{235}$U, ^{238}U, ^{239}Pu, ^{241}Pu

Multiplication by IBD cross section

- Since TAO/JUNO will detect $\bar{\nu}_e$ through the IBD reaction, we multiply all $S_{\nu,j}(E)$ spectra by the IBD cross section:

$$S_{\nu,j}^{IBD}(E) = \sigma_{IBD}(E)\, S_{\nu,j}(E)$$

- We take $\sigma_{IBD}(E)$ from Eq. 25 in "A. Strumia, F. Vissani, arXiv:astro-ph/0302055"
- We produced a collection of $S_{\nu,j}^{IBD}(E)$ spectra for all β^- decaying fission products

In this way:

- we reduce the number of $\bar{\nu}_e$ spectra to be summed (1.8 MeV threshold)
- we can analyze the relative contribution of each fission product to the *"IBD detectable"* spectrum

Building the ^{235}U equilibrium spectrum

STEP 1: Load all **β^- decaying** isotopes through the LiveChart API

- The half-lives and Q-values of 2764 β^- decays are loaded in a Python dataframe (pandas)

STEP 2: Load the **fission yields** of ^{235}U from LiveChart

- 972 cumulative thermal fission yields of ^{235}U are loaded in another dataframe

STEP 3: **Merge** the two **dataframes** to allow for data selection based on β^- decays half-lives and Q-values

- 821 fission yields entries are left after cutting stable fission products
- 666 isotopes left after removing β^- decays with $Q < 1.8$ MeV

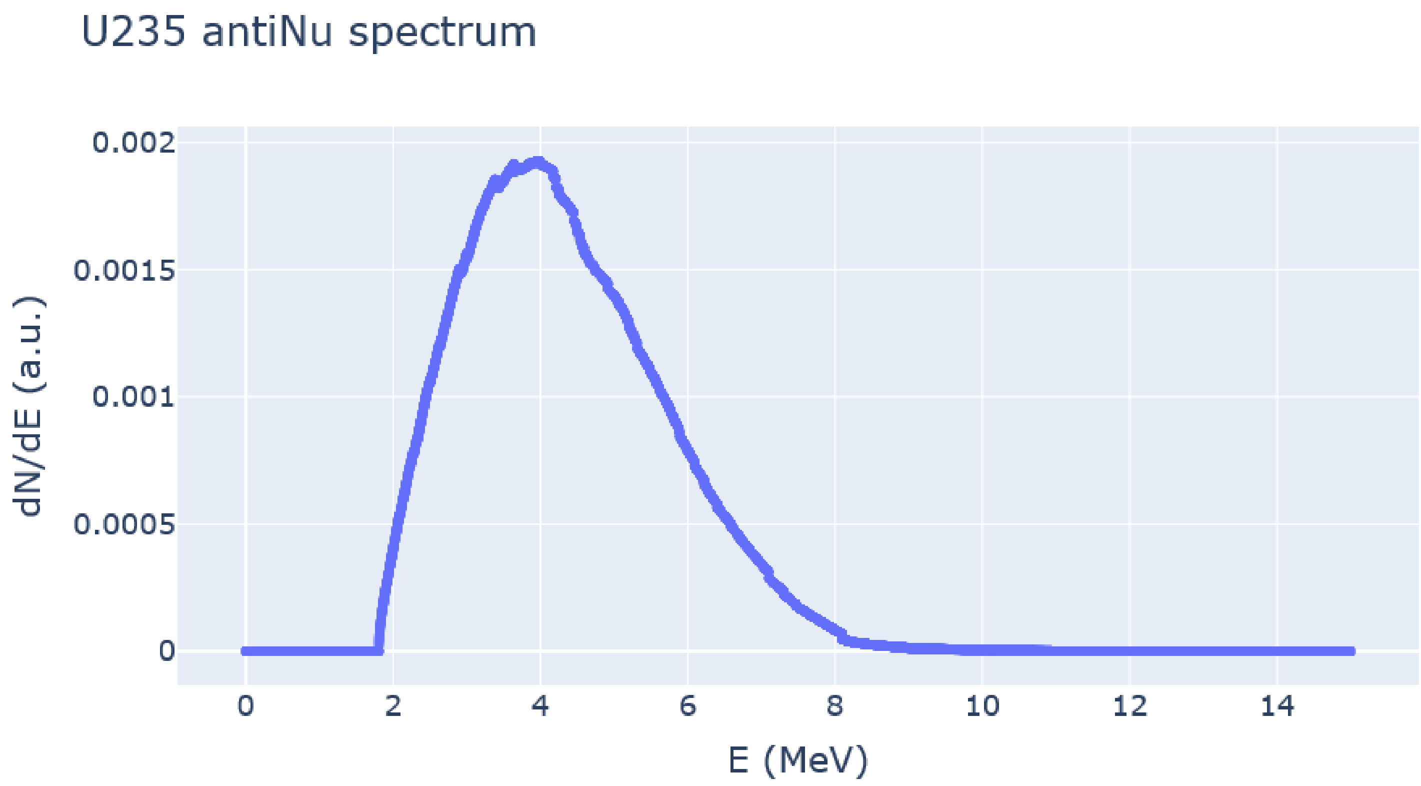
STEP 4: Load the **IBD-weighted $\overline{\nu}_e$ spectra** from the collection of $S_{\nu,j}^{IBD}(E)$ spectra

- 206 spectra out of 666 are missing from the BetaShape database…
- Currently, we still do not include the contribution from 124 metastables fission products that would need for a dedicated treatment

Building the ^{235}U equilibrium spectrum

STEP 5: Stack the $S_{\nu,j}^{IBD}(E)$ spectra multiplied by the fission yields y_j to get:

$$S_{\nu,i}(E) = \sum_j y_{i,j}\, S_{\nu,j}(E) \qquad i = {}^{235}\text{U}$$



Impact of missing/excluded data

How to quantify the impact of missing data?

- In the absence of spectral data, we cannot calculate their contribution (integral fraction) to the total spectrum…
- However, we can compute the fraction of missing data in terms of fission yields:

All selected ^{235}U fission yields (666)

$$\sum_j y_{i,j} = 4.602$$

(100%)

Metastables (124 decays)

$$\sum_j y_{i,j} = 0.327$$

(7.1%)

Missing data (209 decays)

$$\sum_j y_{i,j} = 0.119$$

(2.6%)

18 decays out of 209 have fission yields summing up to 2.5%

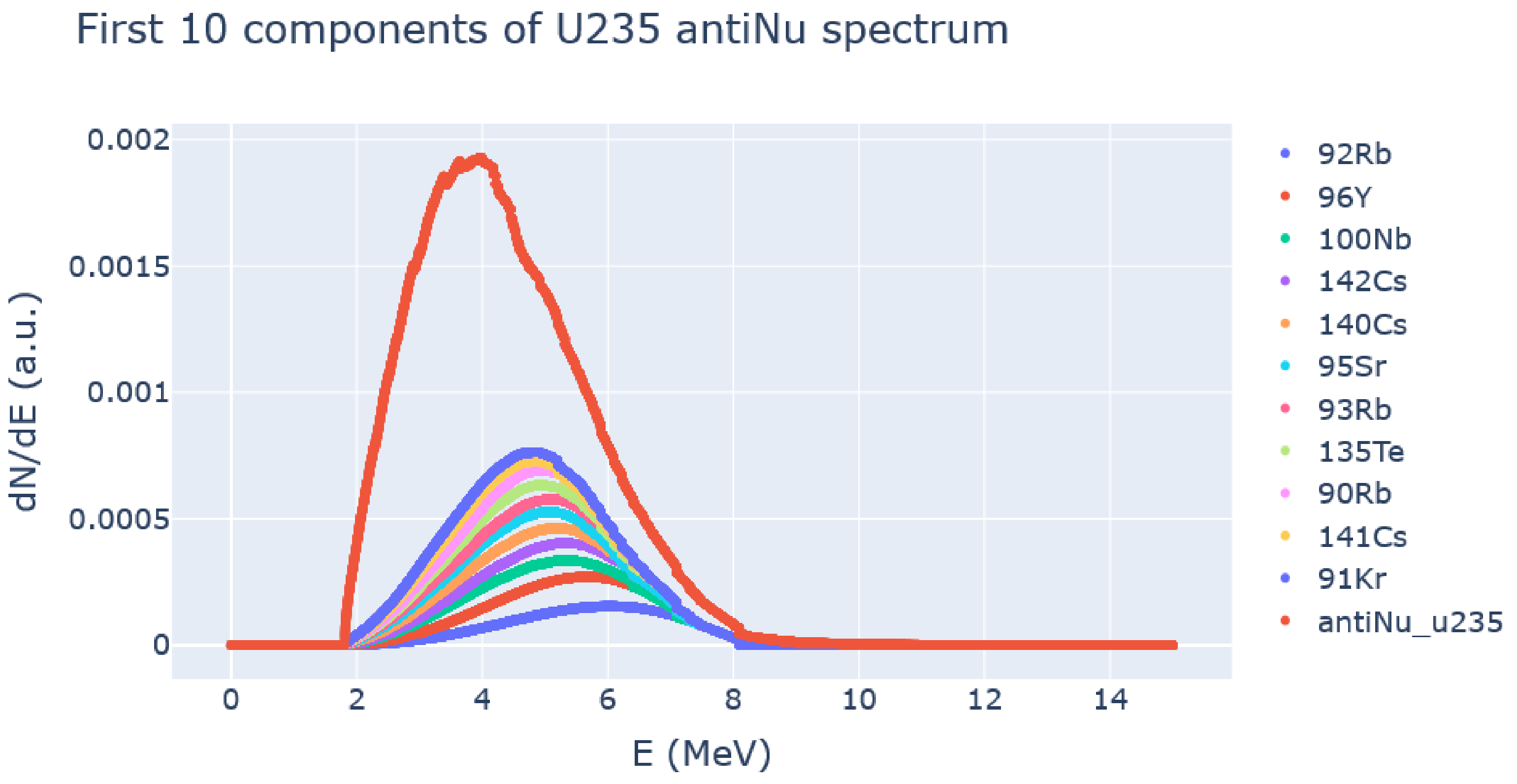
Included data (333 decays)

$$\sum_j y_{i,j} = 4.156$$

(90.3%)

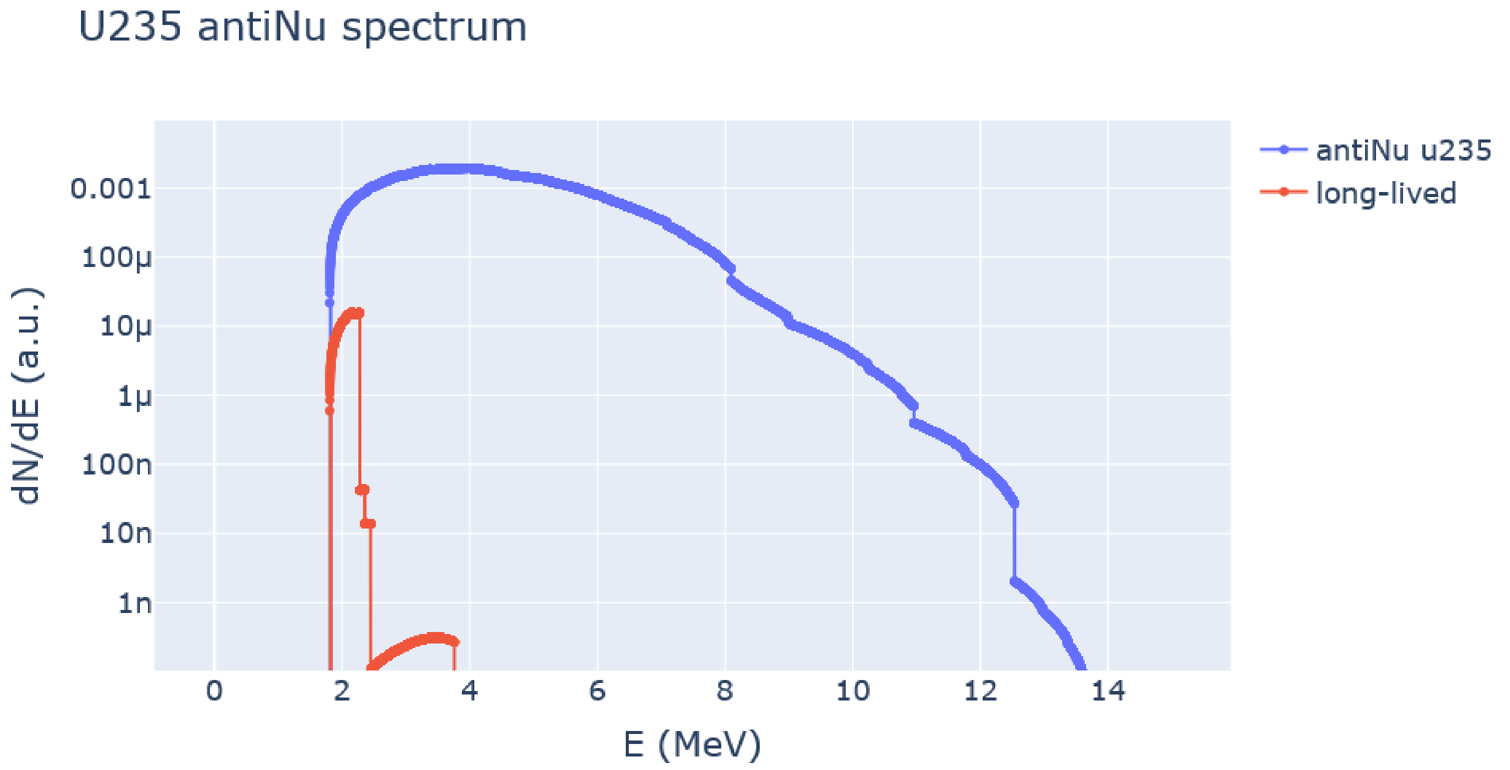
How many spectra to reach 99% ?

- 117 spectra out of the 333 included ones are needed to reach 99% integral of the ^{235}U $S_{\nu,j}^{IBD}(E)$ spectrum
- The first 10 spectra ordered by integral area are shown below



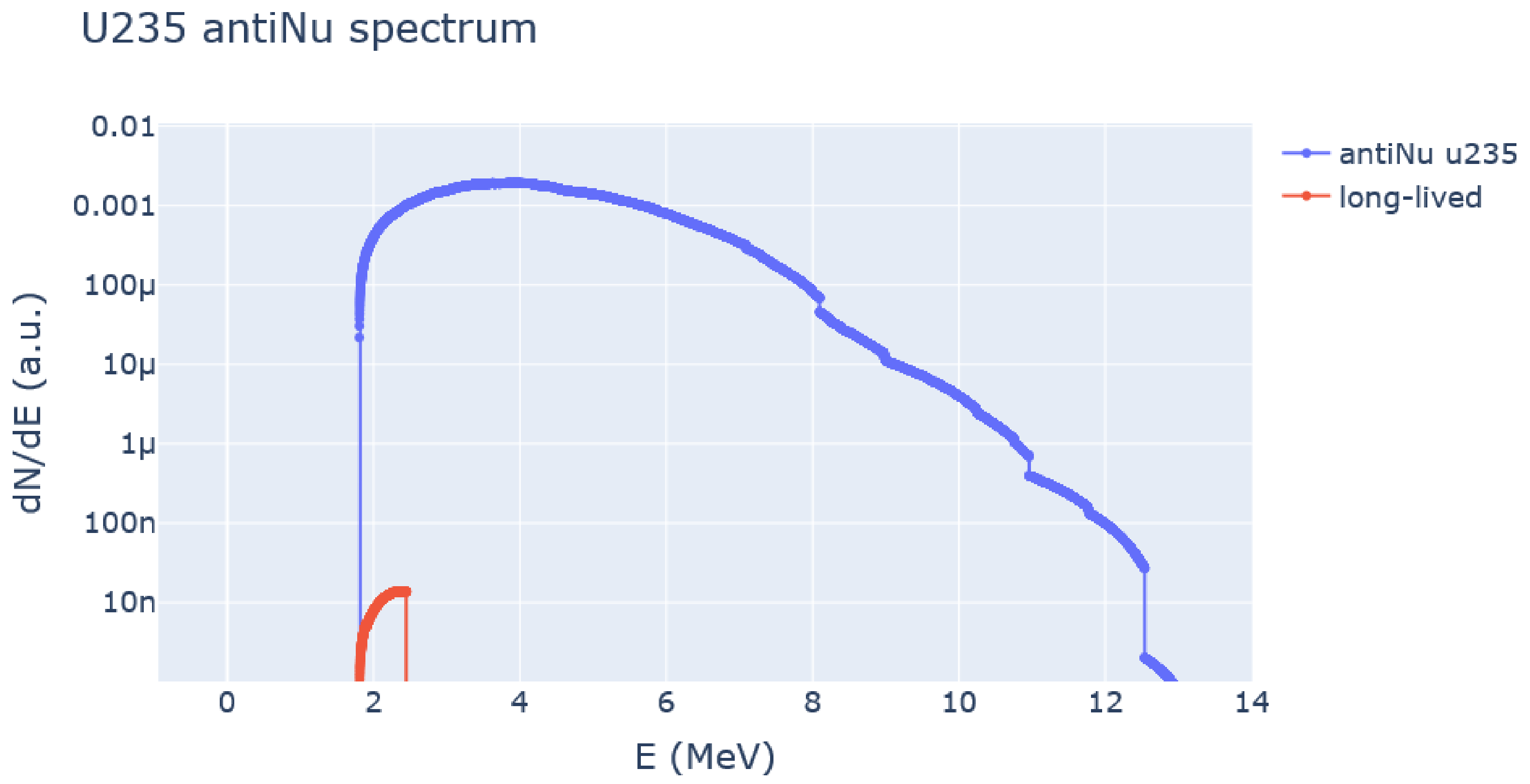
Impact of isotopes with $T_{1/2} > 24$ h

- We selected long-lived fission products with $T_{1/2} > 24$ h that do not *immediately* reach equilibrium (on a reactor cycle timescale, let's say 1 year)
- Their contribution to the ^{235}U $S_{\nu,j}^{IBD}(E)$ spectrum is 0.083% of integral area
- At the maximum around 2.3 MeV, they account for about 2% of total spectrum

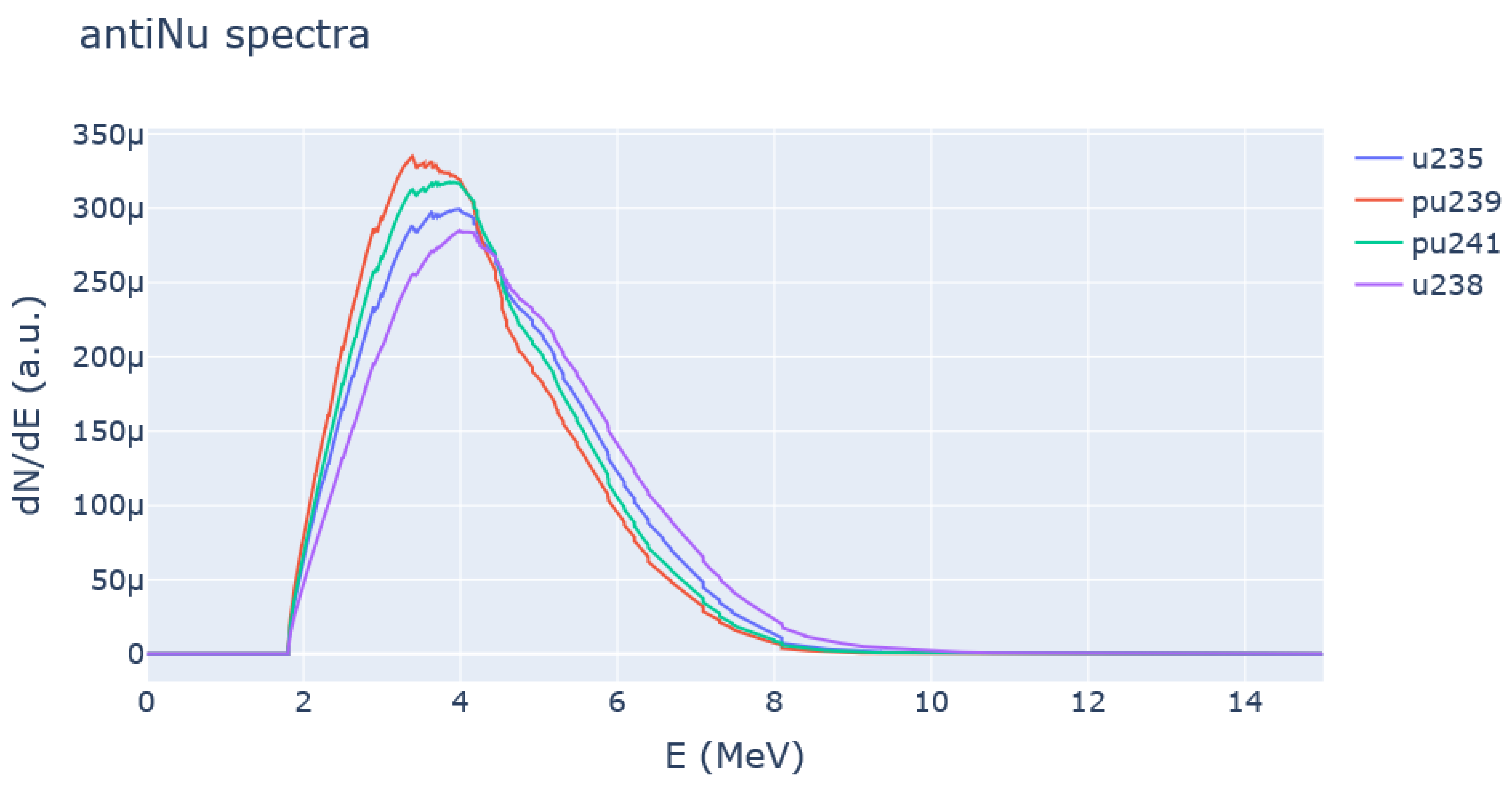


Impact of isotopes with $T_{1/2} > 10$ d

- There are only 3 fission products: ^{124}Sb (60.2 d), ^{126}Sb (12.5 d), and ^{156}Eu (15.2 d)
- Their contribution to the ^{235}U $S_{\nu,j}^{IBD}(E)$ spectrum is 0.0001% of integral area
- At the maximum around 2.4 MeV, they account for about 1.4×10^{-5} of total spectrum



Comparison of ^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U spectra



Comparison of ^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U spectra

	^{235}U	^{239}Pu	^{241}Pu	^{238}U
Fission Products (Q>1.8 MeV)	666	720	726	697
Fission Products included	333	357	358	342
% FY included	90.3%	87.2%	87.7%	87.4%
# of spectra to get 99% integral	117	134	141	127
Impact long-lived $T_{1/2} > 10$ d	1.0×10^{-6}	1.2×10^{-5}	1.5×10^{-5}	3.1×10^{-6}

Conclusions

- A flexible and easy to use tool for generating ***ab initio* antineutrino spectra** is under development
- A preliminary analysis of equilibrium spectra from ^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U fissions has been conducted.
  - We still have to include the contribution from metastable fission products
- The impact of off-equilibrium long-lived isotopes seems to be negligible…
  - …but we still have to check if they are parent isotopes of short-lived daughters that would be off-equilibrium as well
- The LiveChart API allows also to import **uncertainties** associated to FY data
  - We plan to study the impact of such uncertainties in the next future
  - Through this tool we can focus on the uncertainties of most relevant isotopes
- This tool will be **integrated with PWR reactor simulations** (see next talk) to analyze the antineutrino spectrum dependence as a function of burnup (fission fractions)
- This tool will allow to investigate the **fine structures** of the **unoscillated** $\bar{\nu}_e$ spectrum measured by TAO

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Thanks for your attention

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