Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Progress towards understanding the source of the Reactor Antineutrino Anomaly

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Review of the ILL electron spectra normalization

Neutron flux at the ILL reactor (IAEA January 2023 workshop homework)

Thin ^{235}U, ^{239,241}Pu were placed inside the ILL reactor. Absolute spectra were obtained from:

$$N_\beta\,(\text{per fission}, \Delta E) = \frac{N_e^f}{N_e^{st}} \frac{\alpha\,\sigma_{st}(n_{th},\gamma)}{\sigma(n_{th},f)} \frac{n_{st}}{n_f}\,. \qquad (1)$$

N: number of electrons, f from fission, st from the calibration foil.

α: internal conversion coefficient.

σ: cross sections

n: Number of ions in the foils.

We reviewed all the data documented in the ILL articles and found **one problem case**.

ILL references:
F. von Feilitzsch, A. A. Hahn, and K. Schreckenbach, Phys. Lett. B **118**, 162 (1982).
K. Schreckenbach *et al*., Phys. Lett. B 160, 325 (1985).
A. A. Hahn *et al*., Phys. Lett. B **218**, 365 (1989).

^{207}Pb neutron capture cross section

Value used by ILL: **712 ± 10 mb**, best value available in 1981, 1985.
source: 1981 S.F. Mughabghab evaluation, based on an indirect measurement published in a 1963 conference proceeding.

Value from 2018 S.F. Mughabghab evaluation: **647 ± 9 mb**.
Additional sources:
610 ± 30 mb, Blackmon *et al*., PRC 65, 045801 (2002).
649 ± 14 mb, Schillebeeckx *et al*., EPJA 49, 143 (2013).

Ratio of cross sections: **647 / 712 = 0.908**.

Larger cross section --> Lower neutron flux --> Larger electron spectrum.

For more details, see Phys. Rev. C **108**, 024617 (2023).

A new ^{207}Pb neutron cross section evaluation should be available in ENDF/B-VIII.1, which would be needed for full simulation of the ILL setup.

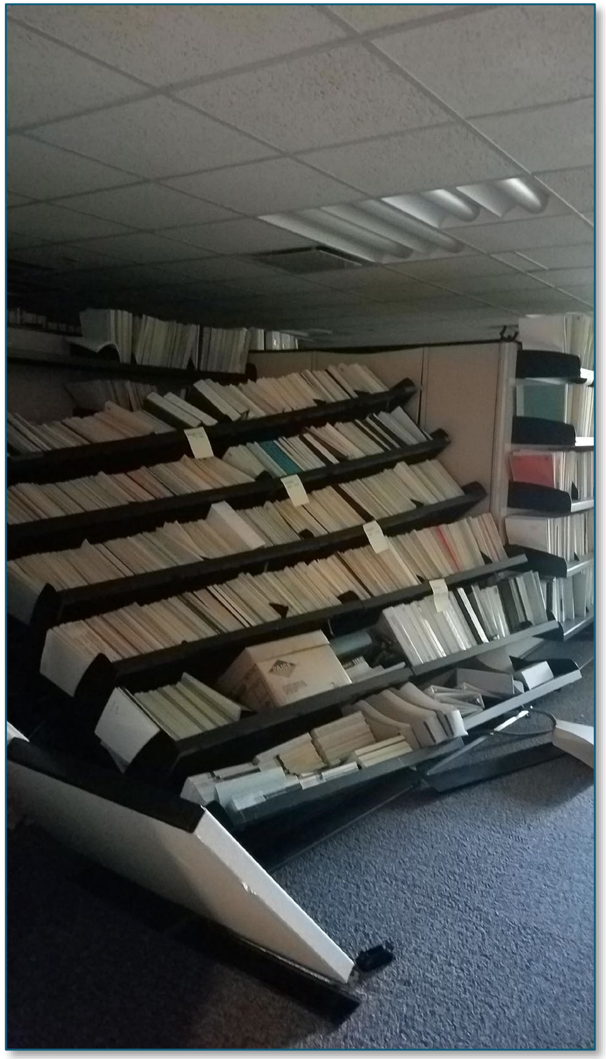
Could we re-analyze the ILL data with the updated cross section value? If so, a measurement of the **E1 K conversion coefficient** would be needed.

ORNL Dickens *et al.* data

NNDC library bookshelves collapse in May 2020

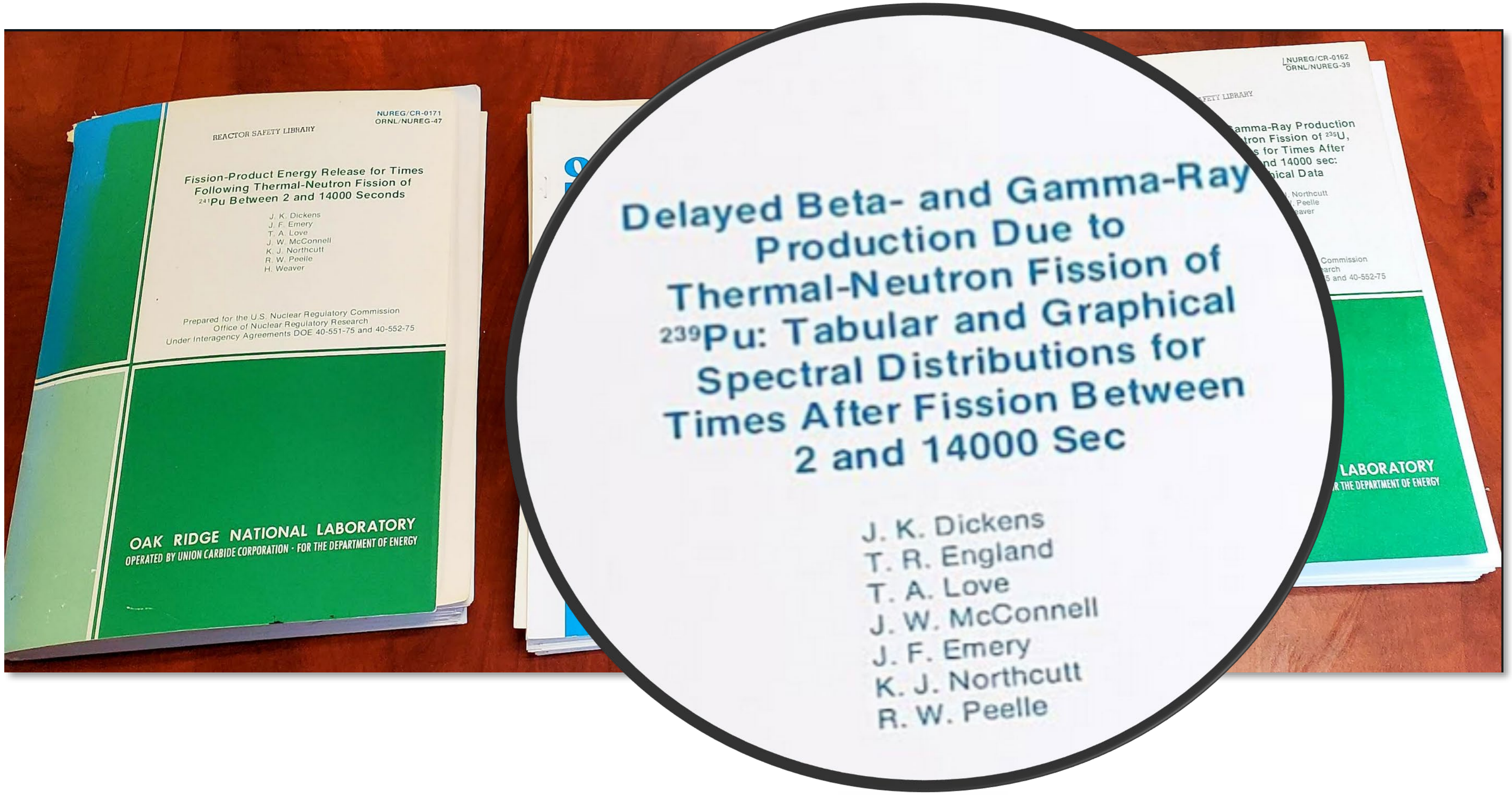
Pre-COVID

During COVID



ORNL delayed gamma and electron data

During the clean-up and cataloguing of the material, we found three very valuable reports with delayed electron and gamma spectrum following the thermal fission of ^{235}U and ^{239,241}Pu.



REACTOR SAFETY LIBRARY

NUREG/CR-0171
ORNL/NUREG-47

Fission-Product Energy Release for Times Following Thermal-Neutron Fission of ^{241}Pu Between 2 and 14000 Seconds

J. K. Dickens
J. F. Emery
T. A. Love
J. W. McConnell
K. J. Northcutt
R. W. Peelle
H. Weaver

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Interagency Agreements DOE 40-551-75 and 40-552-75

OAK RIDGE NATIONAL LABORATORY
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Delayed Beta- and Gamma-Ray Production Due to Thermal-Neutron Fission of ^{239}Pu: Tabular and Graphical Spectral Distributions for Times After Fission Between 2 and 14000 Sec

J. K. Dickens
T. R. England
T. A. Love
J. W. McConnell
J. F. Emery
K. J. Northcutt
R. W. Peelle

NUREG/CR-0162
ORNL/NUREG-39

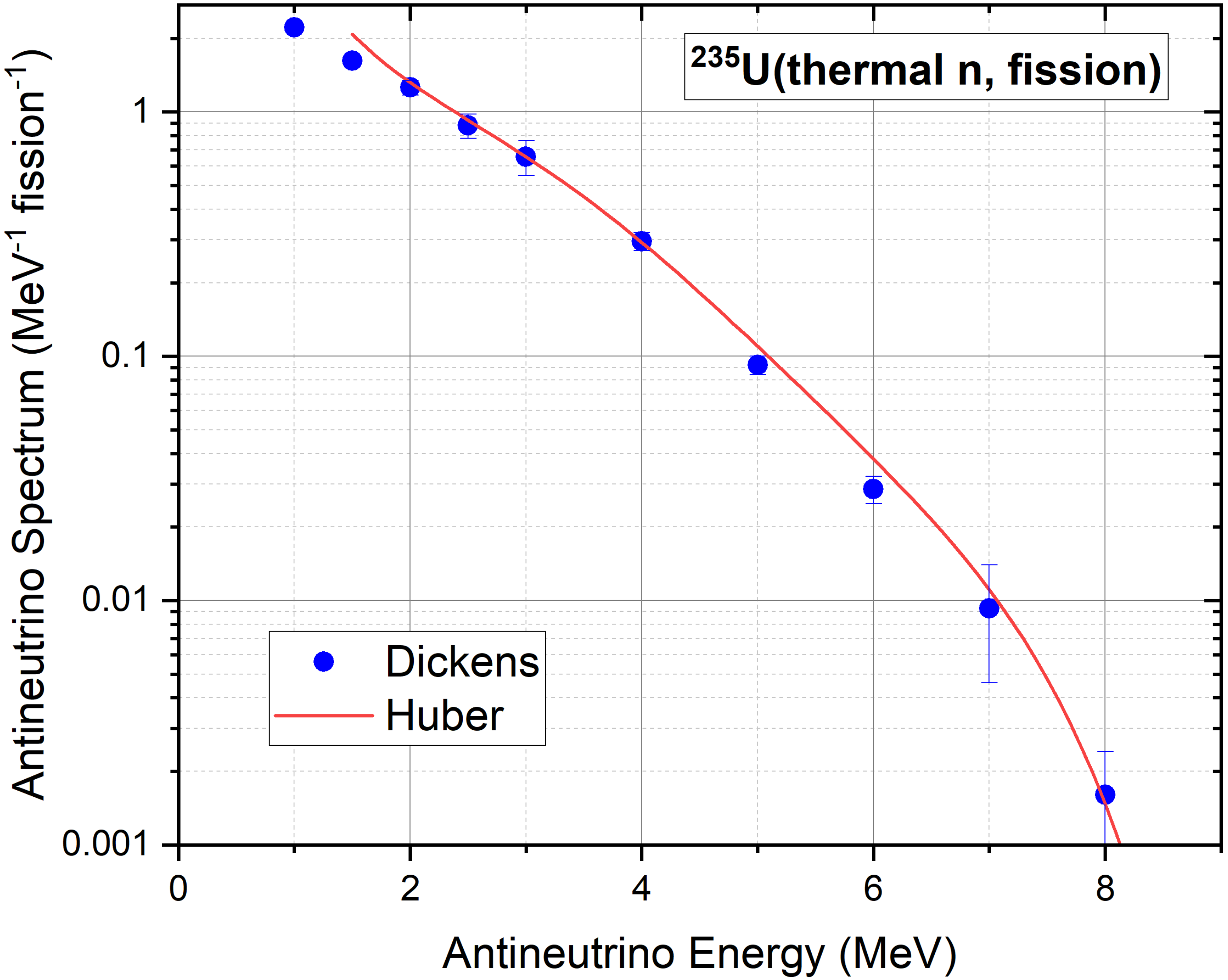
Only one report available online, which can’t be searched by content.

ORNL delayed gamma and electron data

The ^{235}U electron data, assisted with nuclear databases, was used in 1981 to obtain the corresponding antineutrino spectrum under equilibrium conditions.

J. K. Dickens, Phys. Rev. Lett. **46**, 1061 (1981).

Quite a good agreement with the corresponding Huber spectrum.



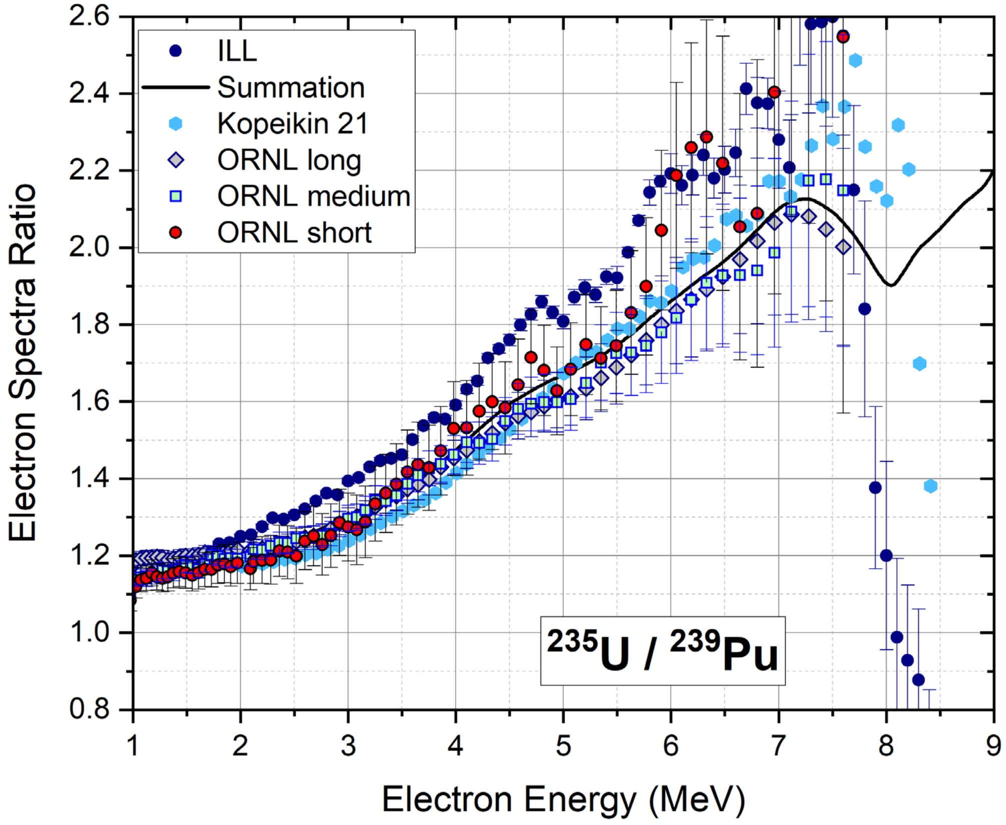
Electron Spectra Ratios

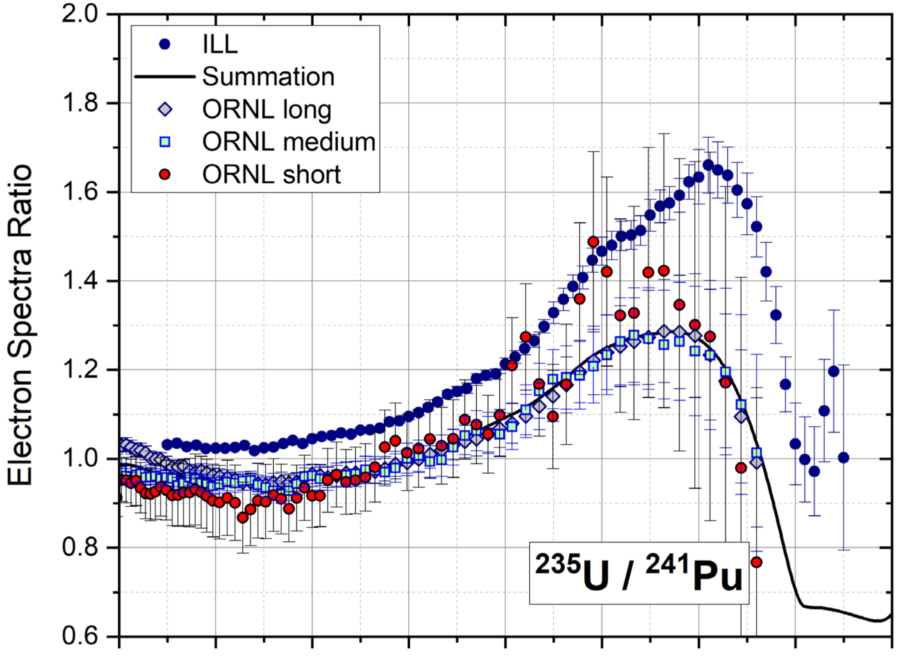
With the assistance of ENDF/B-VIII.1β decay data and JEFF-3.3 fission yields we are able to obtain ratios of electron spectra in equilibrium.

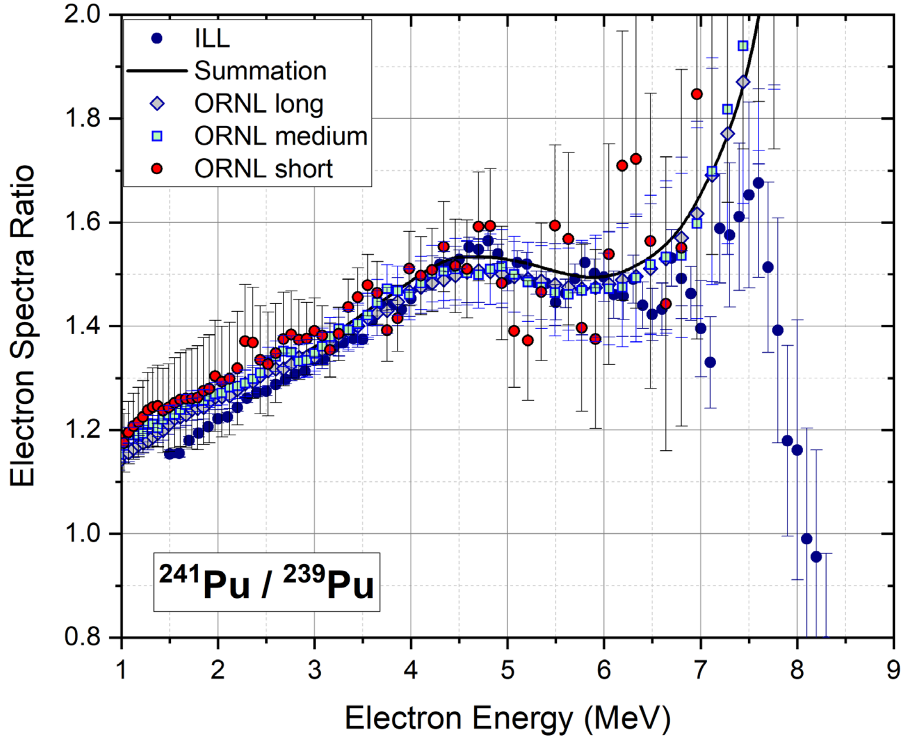
R_{59} agrees better with Kopeikin *et al.*

R_{51} also illustrates issues with ^{235}U normalization.

Behavior of ILL R_{59} and R_{19} at high energies disagree with summation, possibly indicating contamination in the ^{239}Pu target.







Phys. Rev. C **108**, 024617 (2023).

Can we obtain antineutrino spectra?

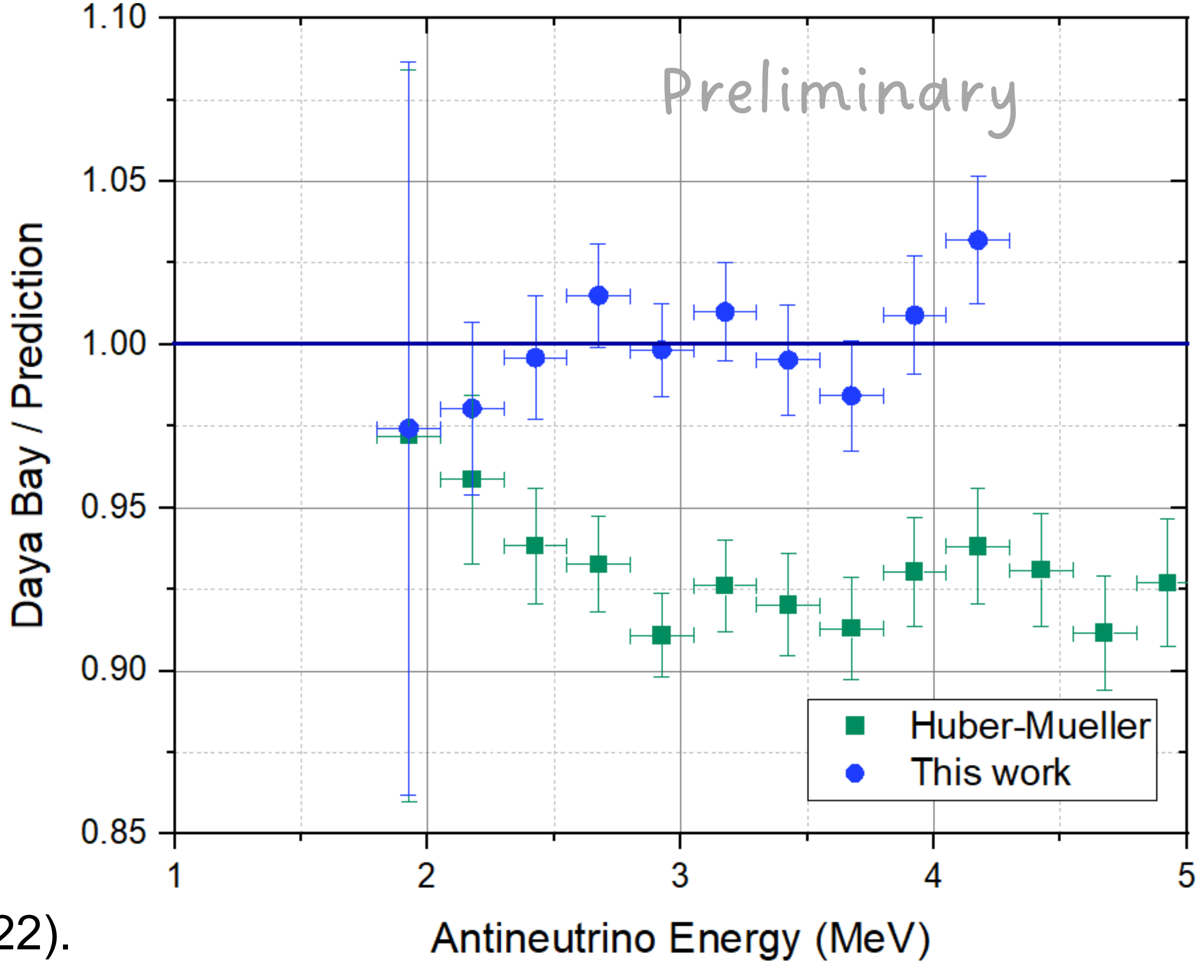
We have derived electron spectra in equilibrium using:

$$S^a_{eq,i} = S^a_{m,i} + \sum \left(CFY^a_j - Y^a_{j,i}\right) S_j,$$

We derived corresponding antineutrinos by:
- renormalize ILL data,
- perform a conversion fit.

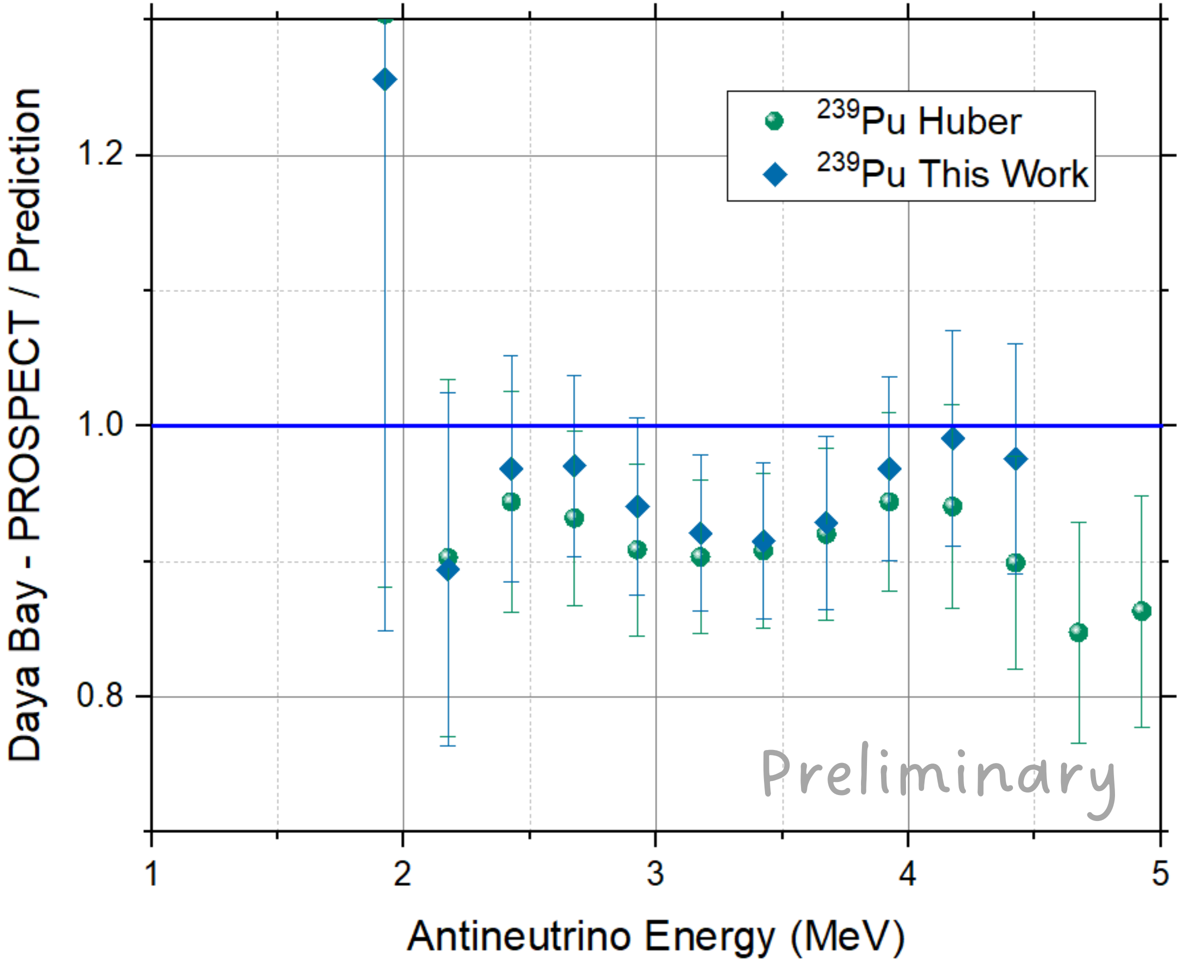
Note that:
- Plot only contains **DB uncertainties**.
- $\Delta S^a_{m,i}$ are not known, so we can only obtain approximate antineutrino spectrum uncertainties.
- ORNL electron spectra data is only reliable up to 4.5 MeV.

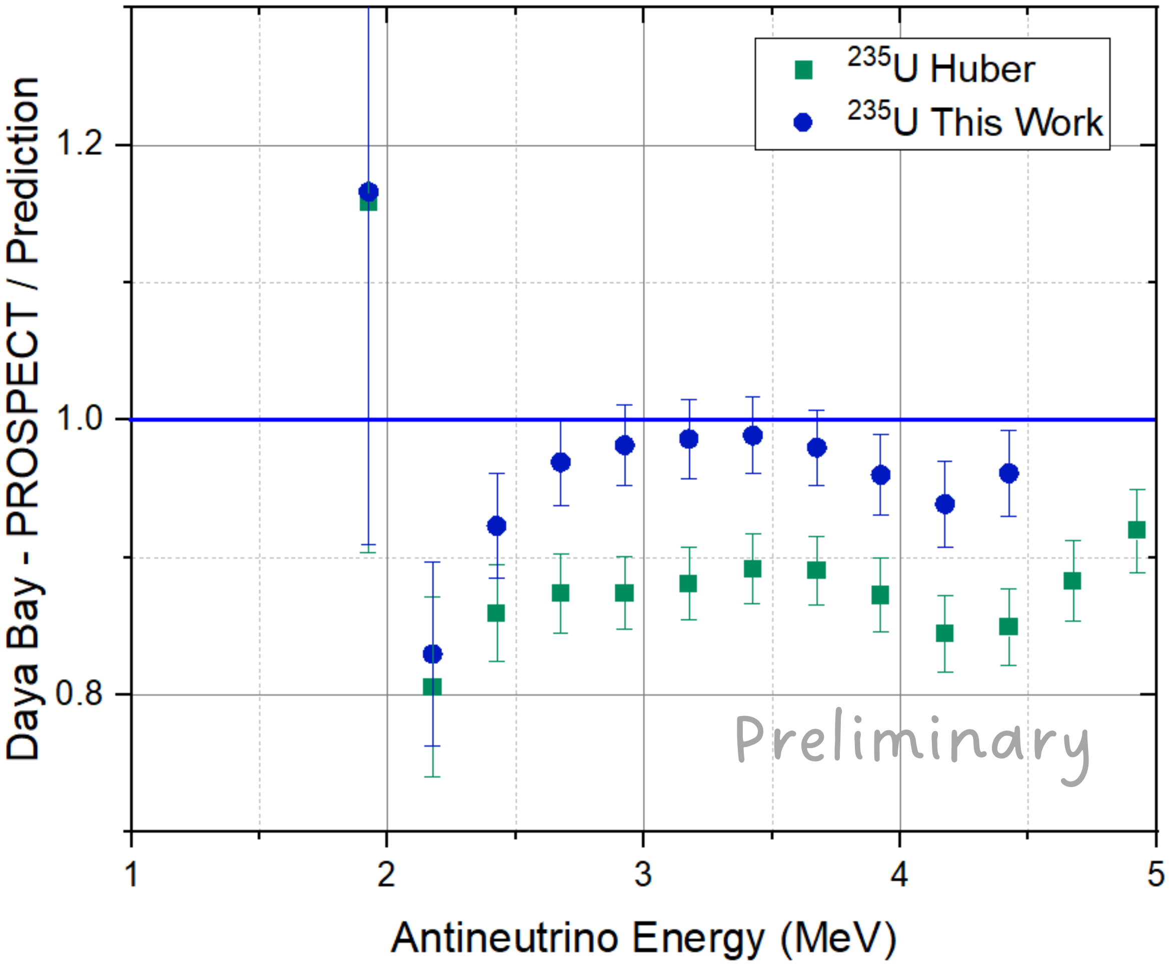
DB ref.: F.P. An *et al*., Phys. Rev. Lett. **129**, 041801 (2022).



- The underprediction at the top of the IBD spectrum – the source of the anomaly, goes away.
- Unfortunately, we can't access the energy area relative to the bump.
- Only way forward is a new measurement with high resolution, high signal to noise ratio, and a robust normalization procedure.

Can we obtain antineutrino spectra?





Daya Bay – PROSPECT ref.: F.P. An *et al.*, Phys. Rev. Lett. **128**, 081801 (2022)

Analysis of NEOS data

2022 NEOS Spectrum (IAEA January 2023 workshop homework)

Z. Atif et al., Phys. Rev. D **105**, L111101 (2022)

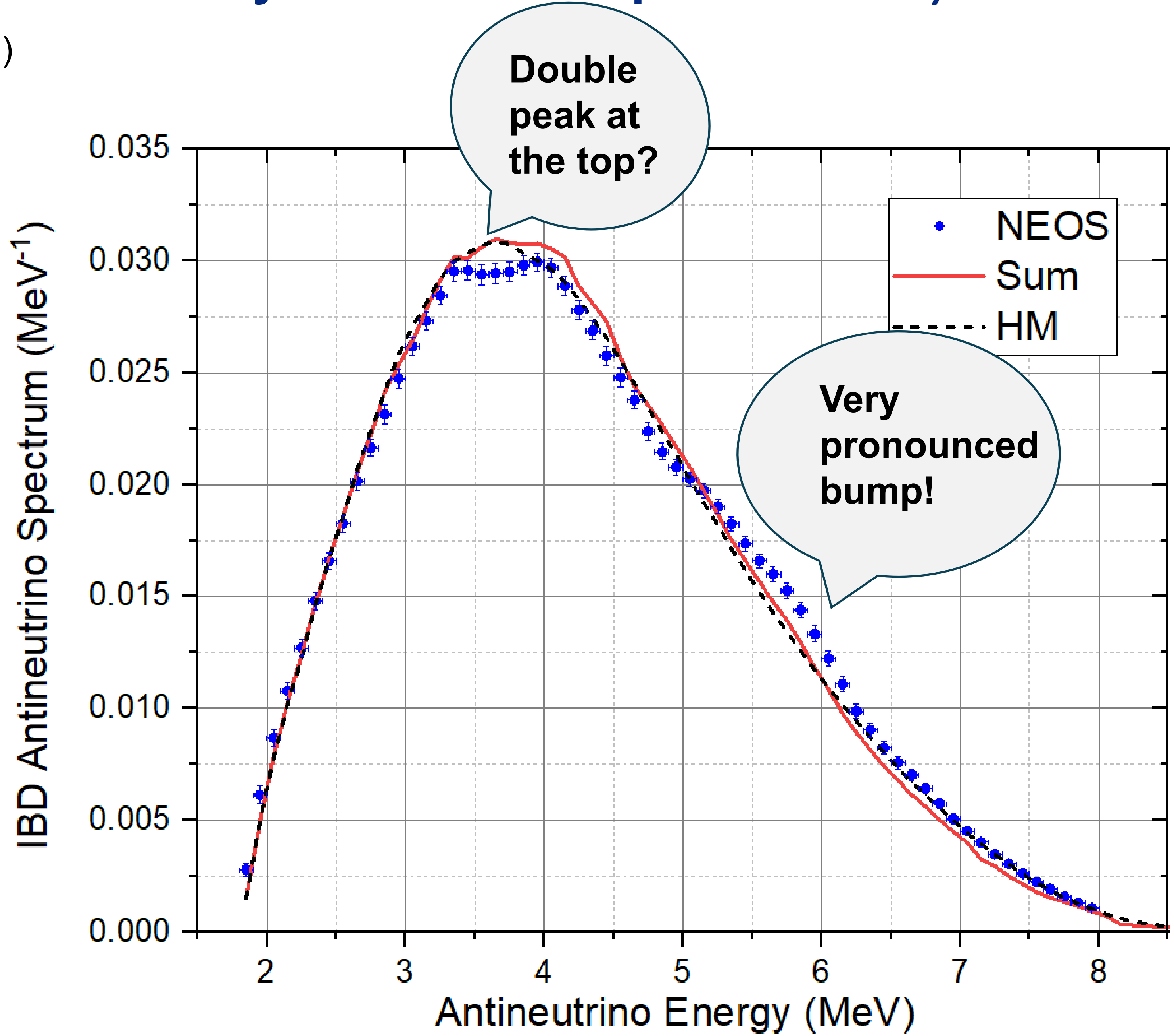
- 180 days of NEOS data,
- 24 m,
- Hanbit Nuclear Power Plant,
- 6 reactors, each with
- 2.8 GWth maximum power.

$f_{235}=0.655$, $f_{238}=0.072$,
$f_{239}=0.235$, $f_{241}=0.038$.

Possibly the highest resolution and statistics of all short baseline experiments.

Also, with the highest f_{235} of all power reactor experiments.

Data only includes an unnormalized spectrum with a 100 keV binning.



Fine Structure

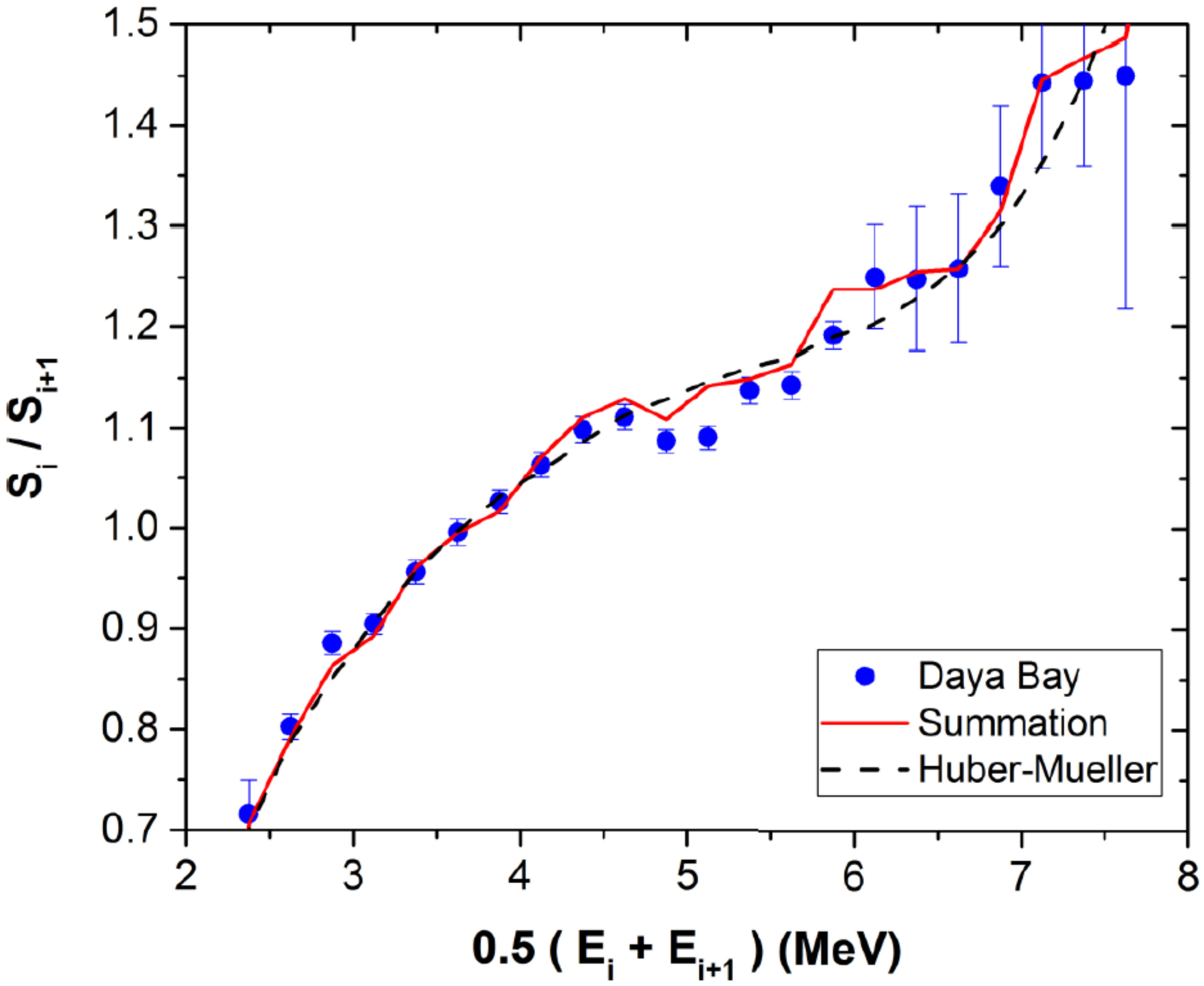
The presence of individual fission products can be revealed using the ratio of adjacent spectrum values:

$$R_i = S_i / S_{i+1},$$

with uncertainty given by:

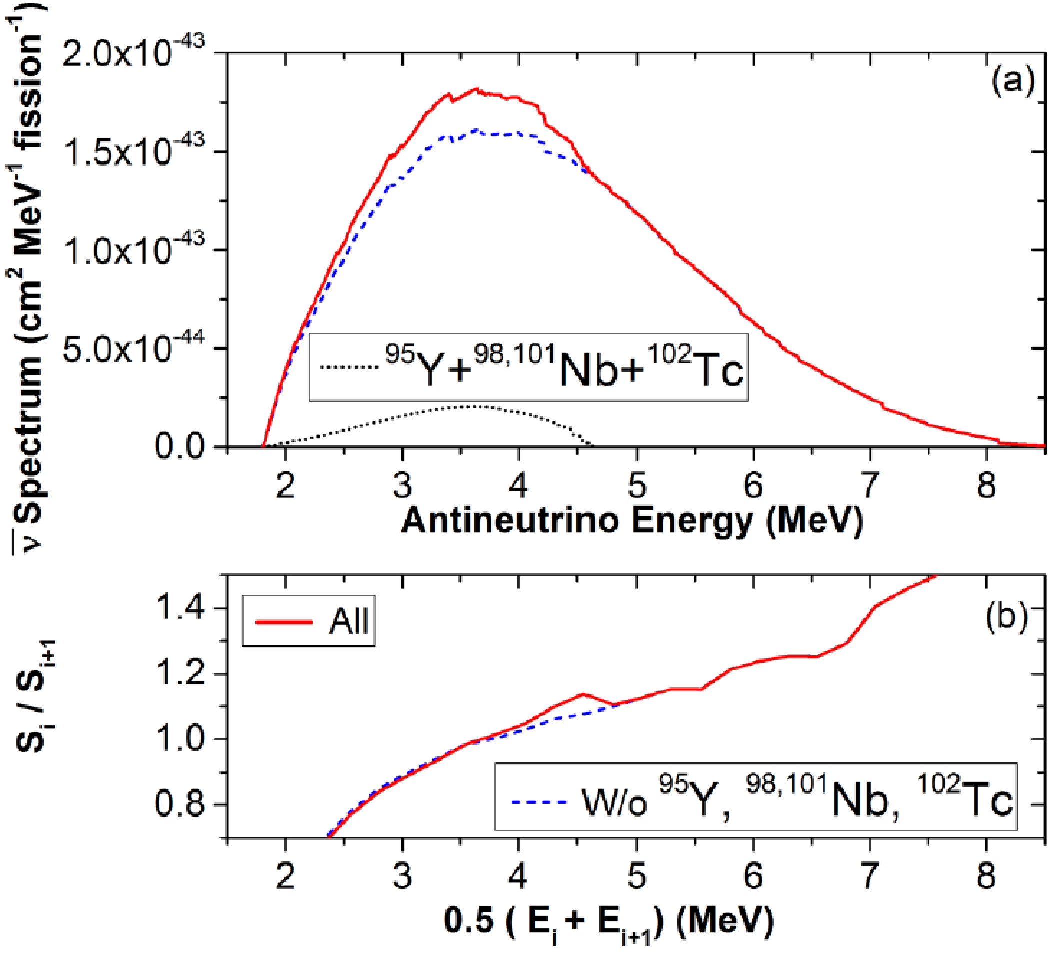
$$\Delta^2 R_i = S_{i+1}^{-2}\sigma_{i,i} + S_i^2 S_{i+1}^{-4}\sigma_{i+1,i+1} - 2S_i S_{i+1}^{-3}\sigma_{i,i+1},$$

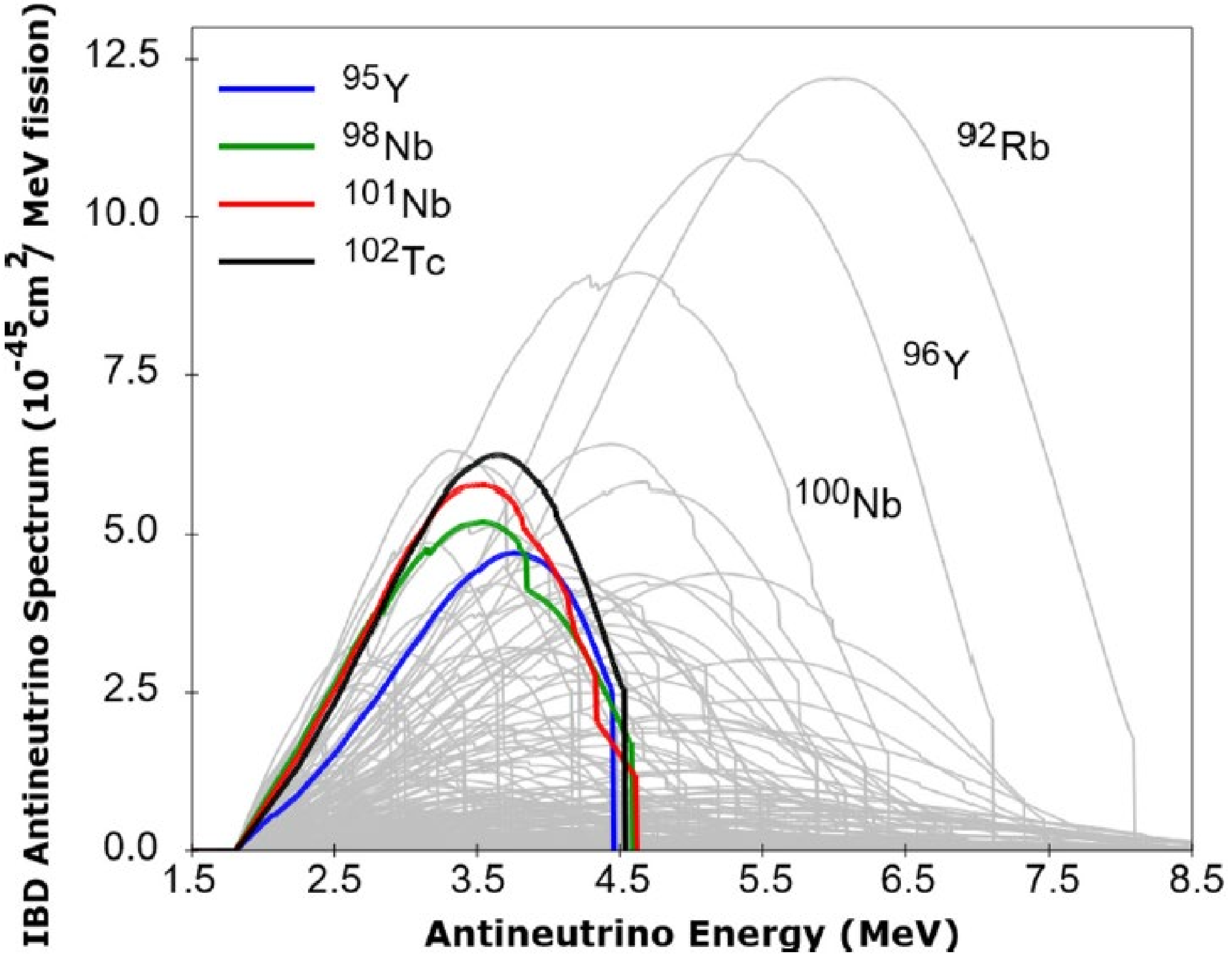
With **σ** the covariance matrix.



Phys. Rev. C **98**, 014323 (2018)

Our 2018 analysis





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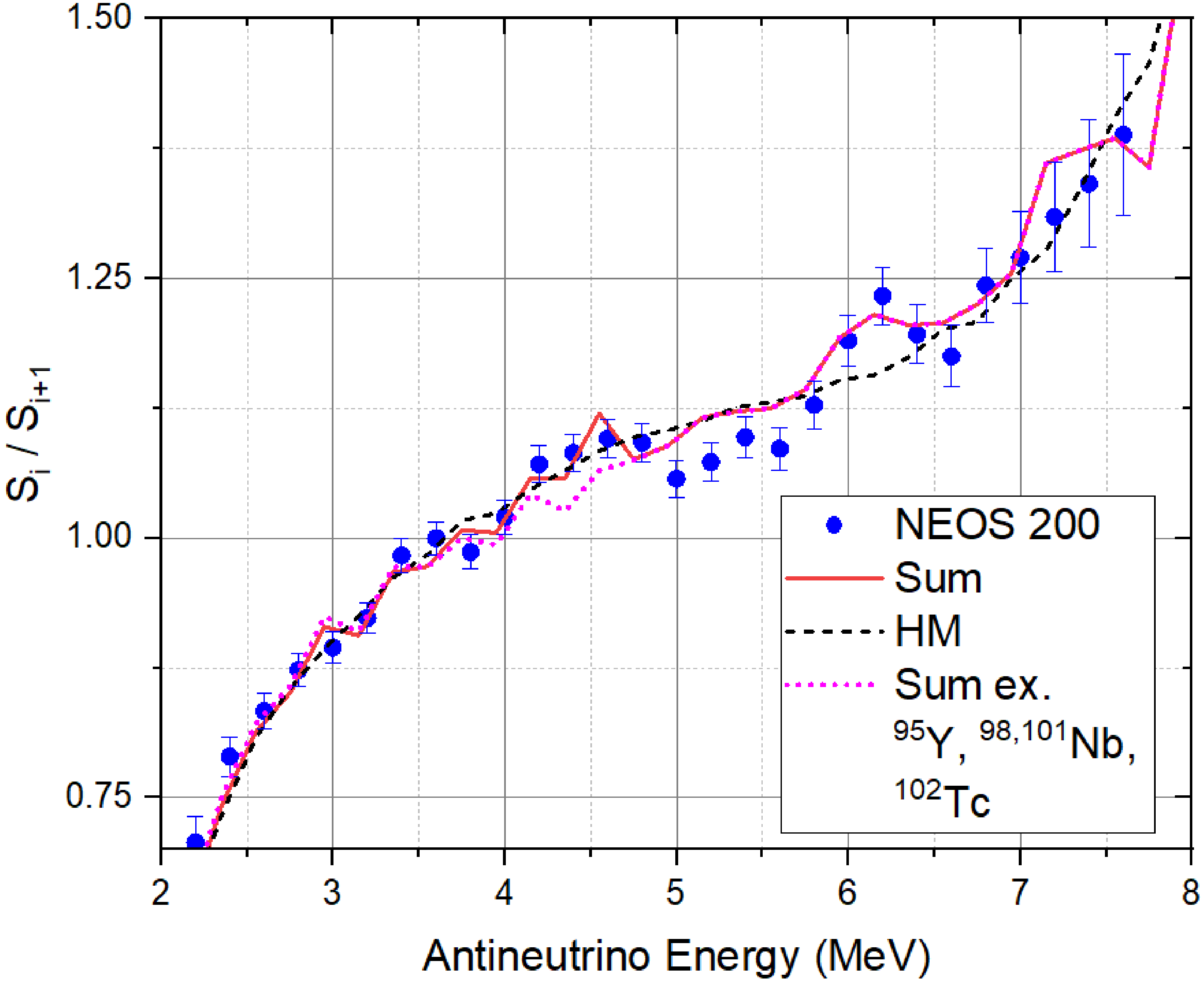
2022 NEOS Spectrum Fine Structure

Observation of ^{95}Y, ^{98,101}Nb and ^{102}Tc, note the 200 keV binning.



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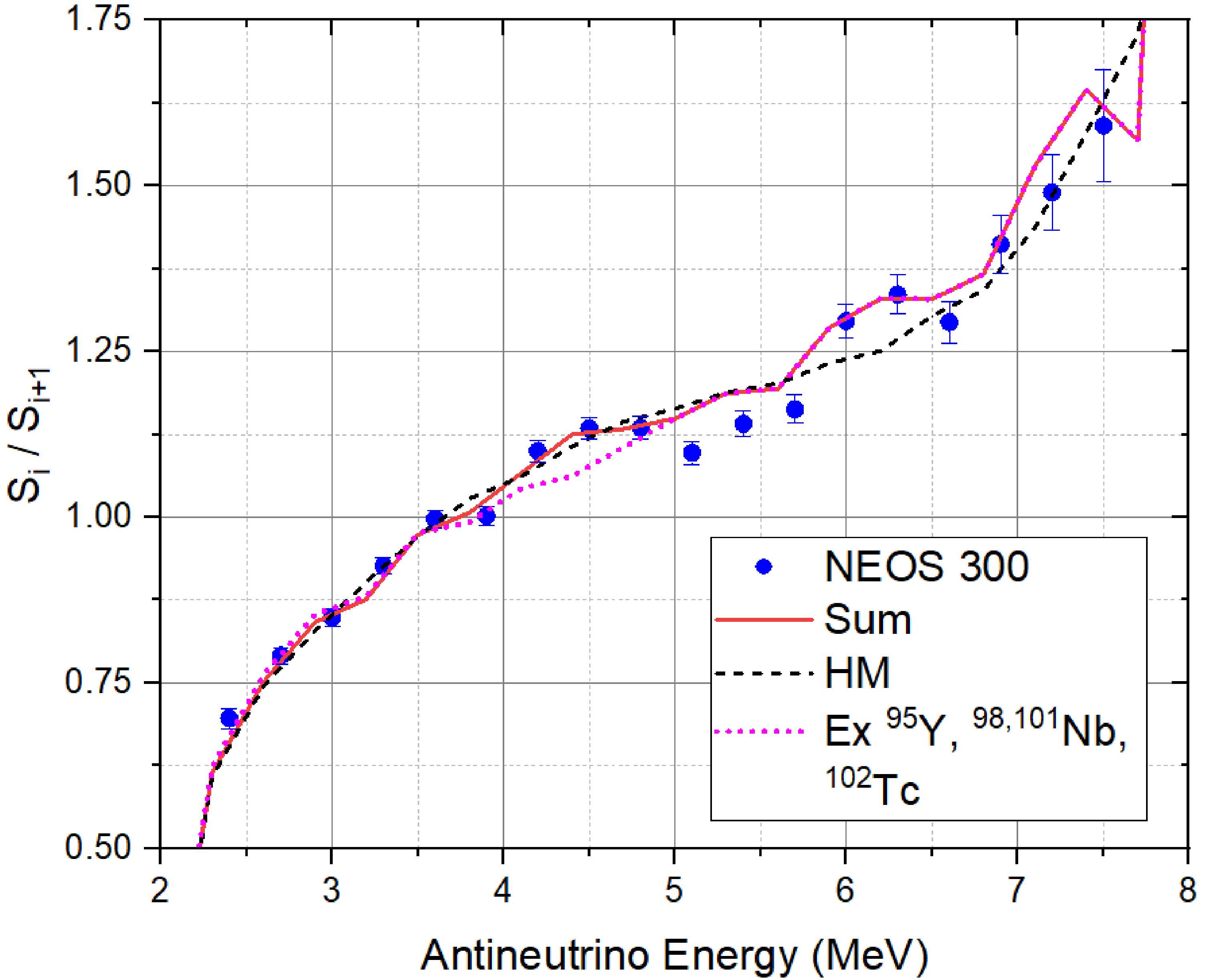
2022 NEOS Spectrum Fine Structure

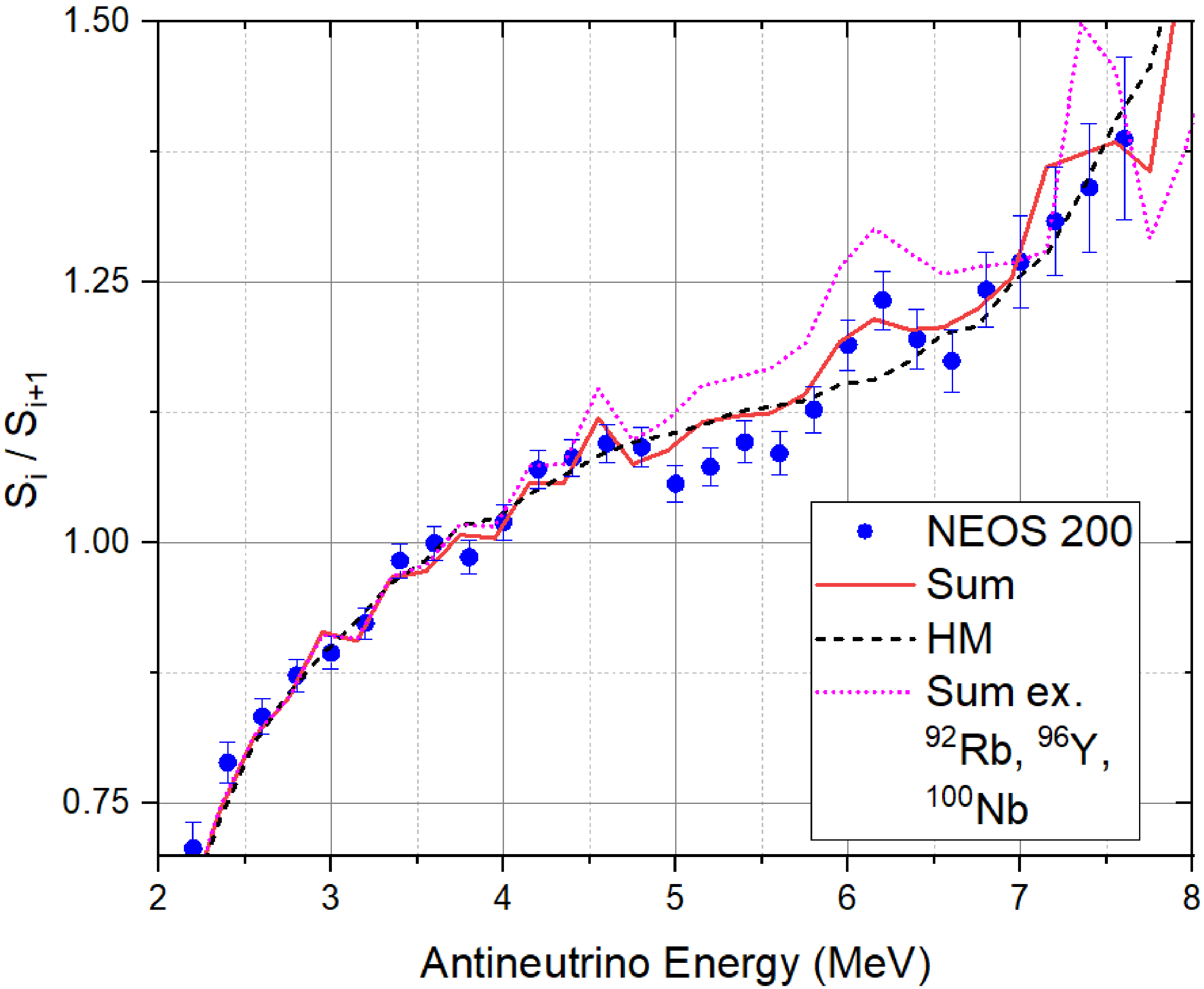
Observation of ^{95}Y, ^{98,101}Nb and ^{102}Tc, note the 300 keV binning.



2022 NEOS Spectrum Fine Structure

With the more precise NEOS data we are able to see the effect of ^{92}Rb, ^{96}Y and ^{100}Nb.

Note that the decay schemes for these nuclides are well known experimentally.



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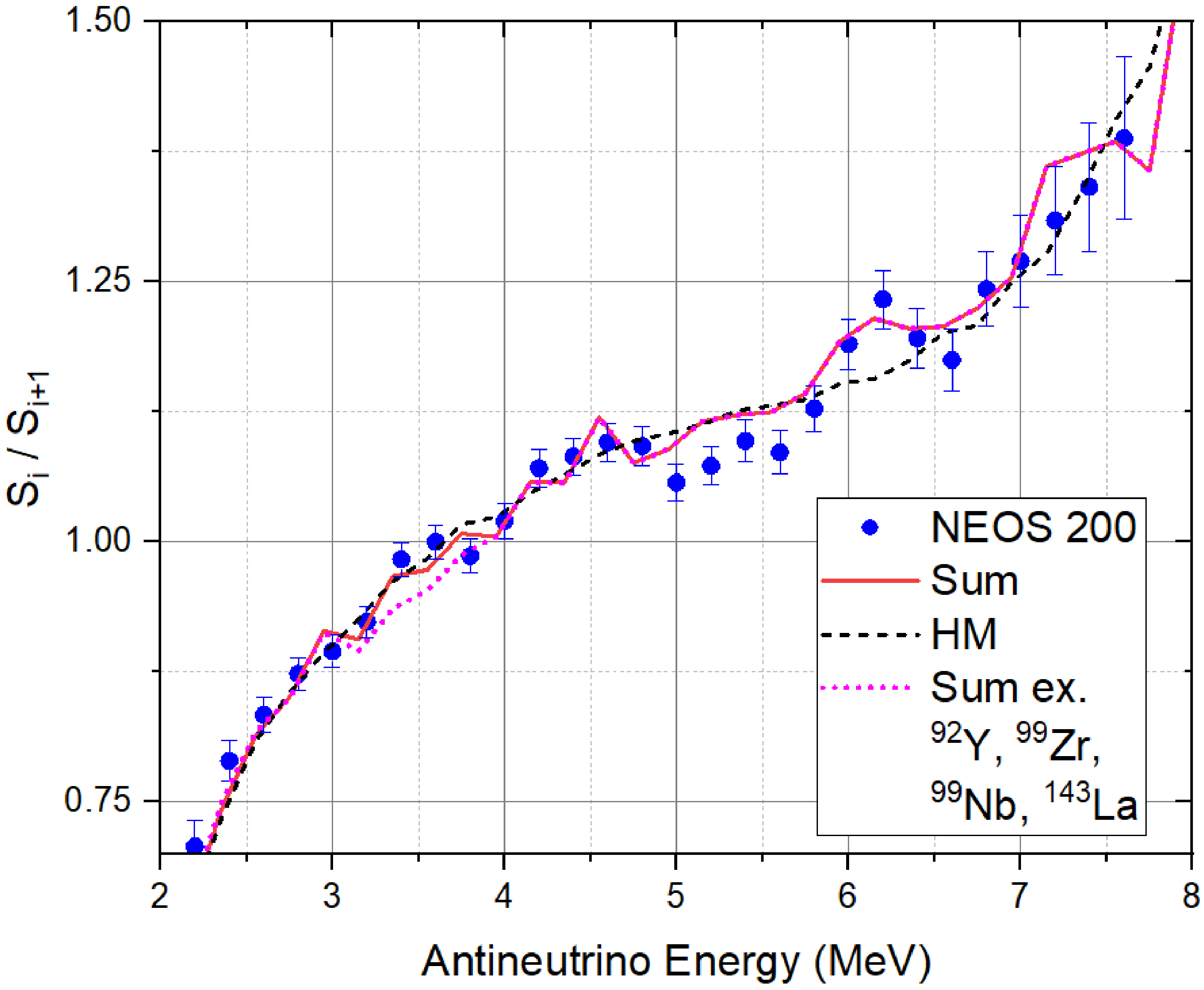
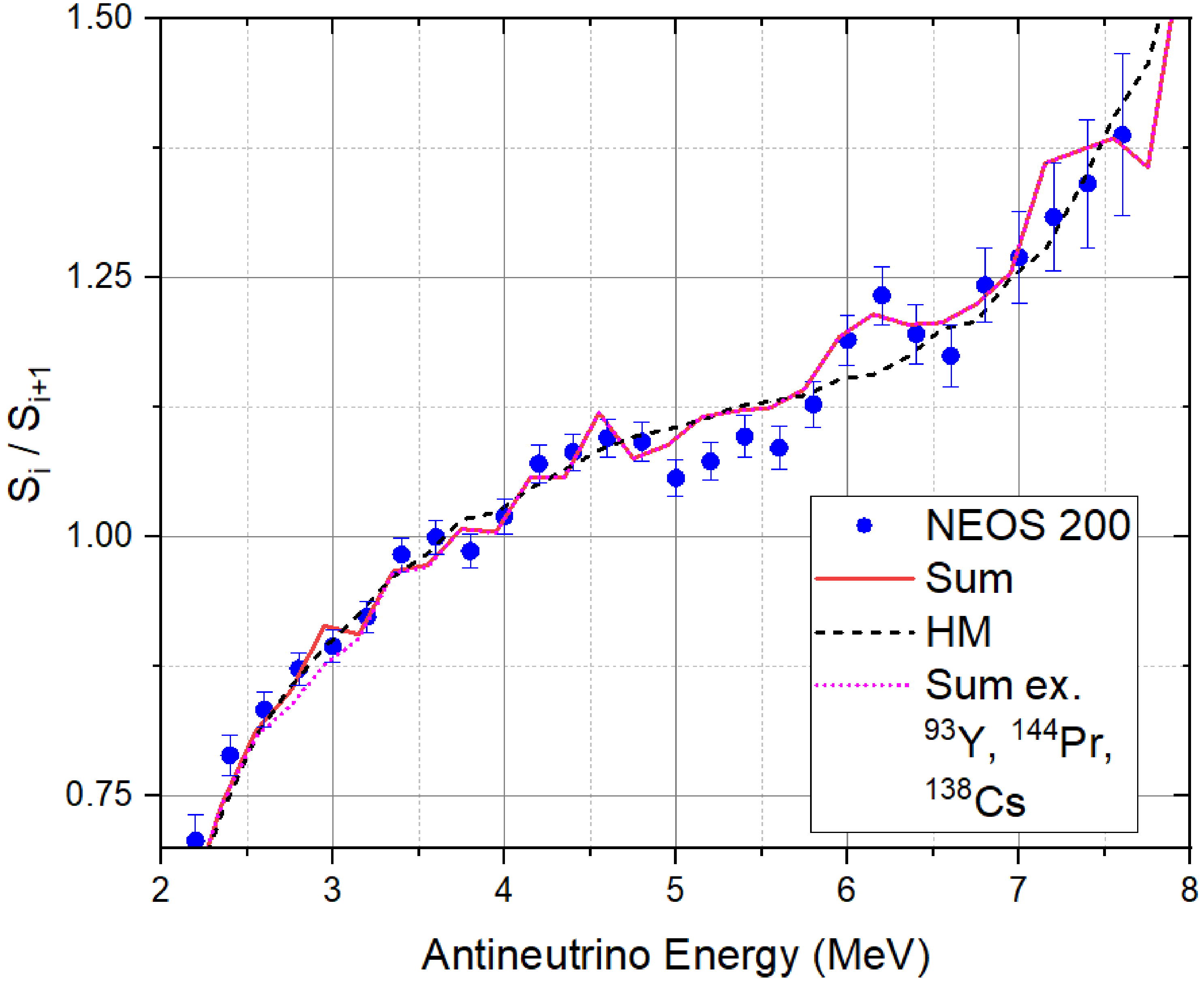
2022 NEOS Spectrum Fine Structure

As well as ^{92}Y, ^{99}Zr, ^{99}Nb, and ^{143}La.



2022 NEOS Spectrum Fine Structure

And ^{93}Y, ^{144}Pr, and ^{138}Cs.



Conclusions

- We think that the source of the RAA is the use of a higher **$^{207}\text{Pb}(n,\gamma)$** cross section.

- Could we re-analyze the ILL ^{235}U and ^{241}Pu data with a **647+- 9 mb** value?

- If so, we could also measure the K alpha conversion coefficient instead of relying in a theoretical BRICC calculation.

- The behavior of $\boldsymbol{R_{59}}$ and $\boldsymbol{R_{19}}$ at electron energies higher than 7.5 MeV is disquieting. Possible contamination in the ^{239}Pu target?

- Renormalization of the ILL spectra data with the ORNL ones lead to a considerable better agreement with Daya Bay IBD spectrum, **eliminating the RAA**.

- We really need to re-measure the ^{235,238}U and ^{239,241}Pu electron spectra with (i) high resolution, (ii) high signal to noise ratio, and (iii) very robust normalization procedure.

- Latest NEOS IBD spectrum can’t be accounted for by summation calculations at the top of the spectrum – where, coincidentally, summation is the most reliable…

- The effect of some more nuclides was identified in the NEOS adjacent points ratio plot.

Acknowledgements

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Backup material

BRICC

The l=0 neutron capture on ^{207}Pb(s=1/2-) leads to a 1- state in ^{208}Pb.

This state decays with an E1 gamma with an energy of 7367.7 keV.

The electron from the conversion to the K shell was used by ILL.

The current BRICC tables have an upper limit of 6 MeV.

The extrapolated value from a polynomial fit gives α_K=9.2E-5, ILL used α_K=9.25E-5.