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U.S. DEPARTMENT OF ENERGY

Some of the work performed at BNL in the last 3.75 years

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Nuclear Science & Technology Department

National Nuclear Data Center

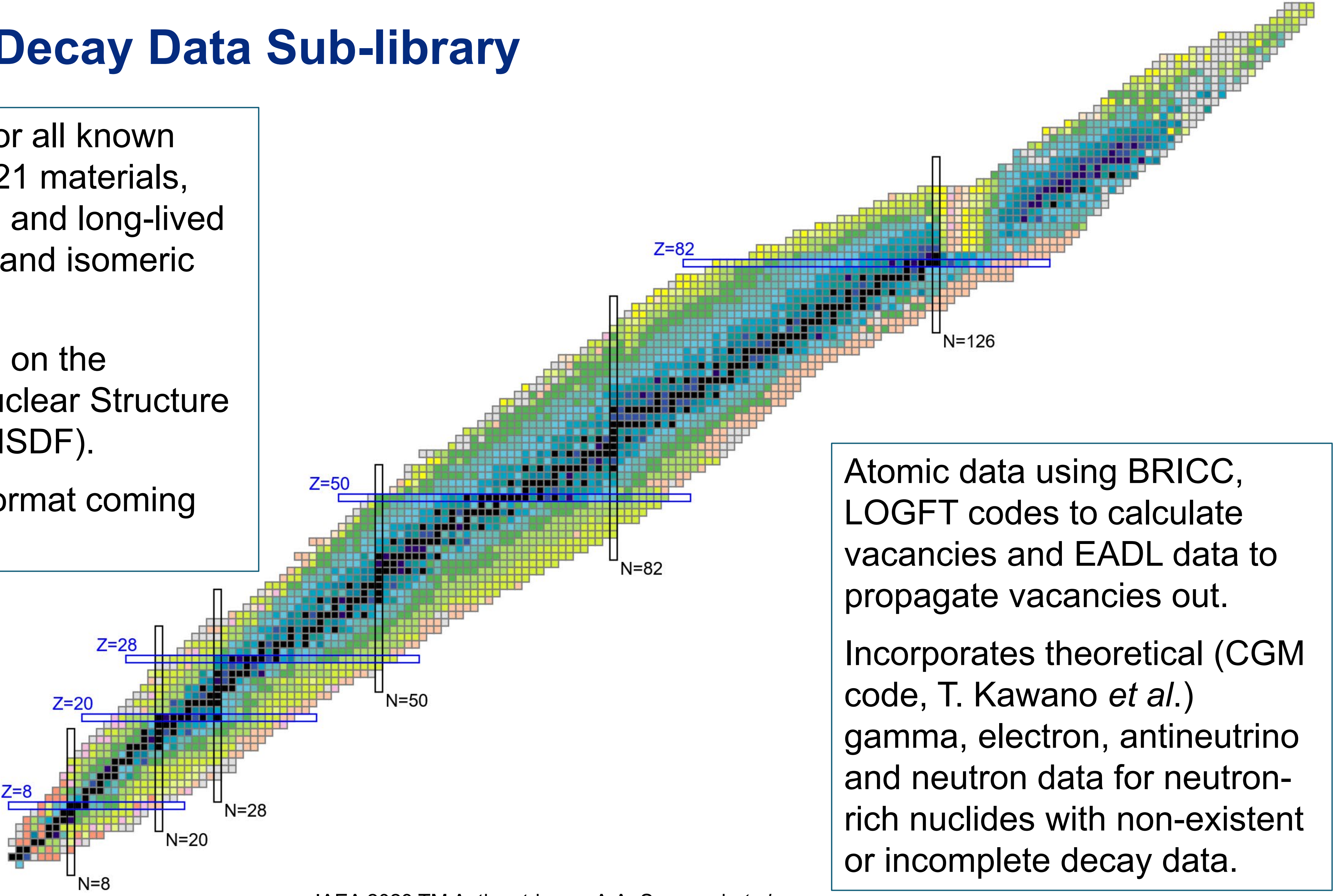
*: now at NASA, +: SULI/SURP interns

ENDF/B Decay Data Sub-library

Decay data for all known nuclides, 3,821 materials, that is, stable and long-lived ground state and isomeric levels.

Mostly based on the Evaluated Nuclear Structure Data File (ENSDF).

New JSON format coming soon!



Atomic data using BRICC, LOGFT codes to calculate vacancies and EADL data to propagate vacancies out.

Incorporates theoretical (CGM code, T. Kawano *et al.*) gamma, electron, antineutrino and neutron data for neutron-rich nuclides with non-existent or incomplete decay data.

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ENDF/B Contains TAGS data for 55 materials:

^{86}Br (ORNL), ^{87,88}Br (Valencia),
^{90,90m,91,93}Rb (INL), ^{94}Rb (Valencia),
^{93}Sr (Greenwood), ^{95}Y (INL),
^{101}Nb (Valencia), ^{103,104}Nbm (MSU),
^{105}Mo (Valencia), ^{102,104,105,106,107}Tc (Valencia),
^{140,141}Cs (INL),^{142}Cs (ORNL),
^{141,142,143,144,145}Ba (INL),
^{142,143,144,145}La (INL),
^{145,146,147,148}Ce (INL),
^{146,147,148,148m,149,151}Pr (INL),
^{149,151,153,154,155}Nd (INL),
^{152,153,154,155,156,157}Pm (INL),
^{157,158}Sm (INL), ^{158}Eu I(INL).

IB adjusted to match the electron spectra measured by Tengblad *et al.* for:

^{82}As, ^{89}Br, ^{90}Br, ^{95,96}Rb, ^{98,99}Y, ^{134}Sb, ^{138}I

ENDF/B available from the NNDC's GitLab server

Consistency Issues

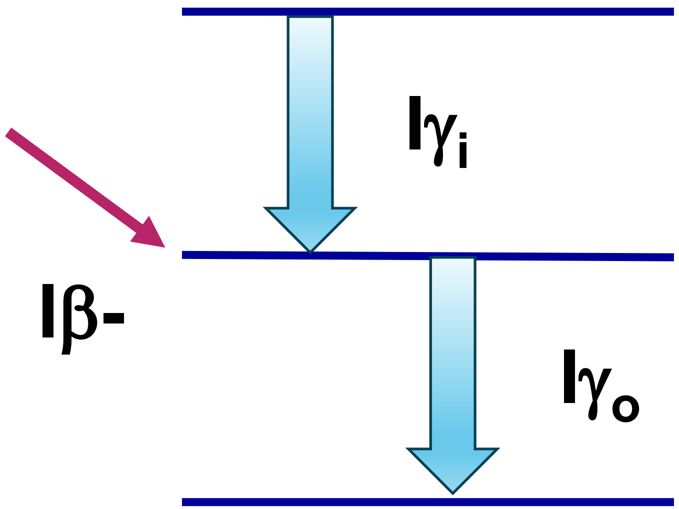
In ENSDF, absolute gamma + CE, **Iγ**, and beta intensities, **Iβ-**, are related by the intensity balance at each level.

In ENDF/B we use TAGS data for beta intensities and ELP, <Ee->, and EEM, <Eγ>.

The use of TAGS data in ENSDF and ENDF/B breaks the intensity balance, creating inconsistencies, that must be documented to alert the user. ENSDF evaluators often give the TAGS Iβ- **as comments**

If the ENSDF data agrees *within 10%* with the TAGS data, then we use ENSDF to avoid inconsistencies.

There are also inconsistencies if we use ELP, EEM and Iβs from TAGS and theoretical gamma, & neutron if present, spectra from CGM.



Intensity balance

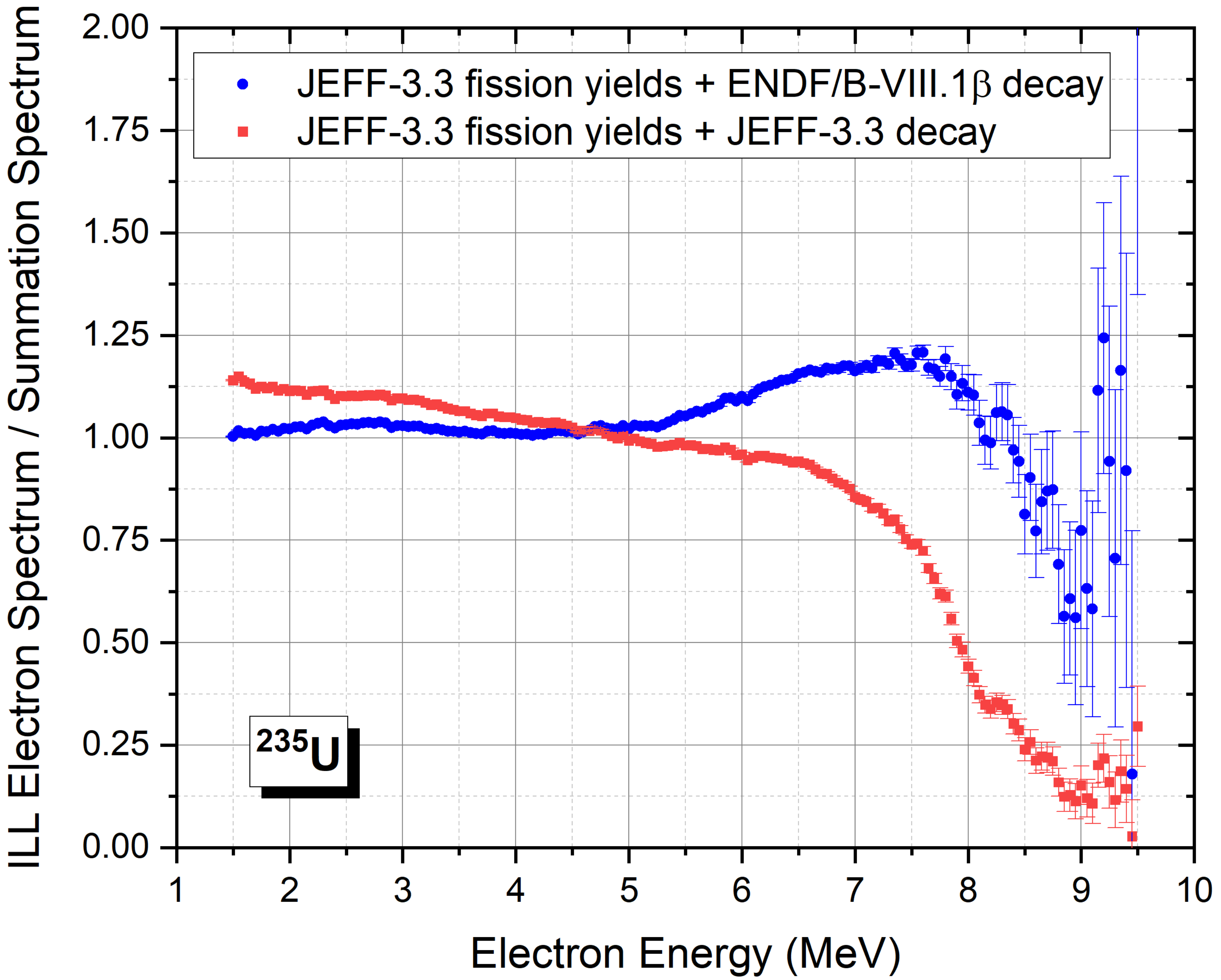
$$I\beta- = I\gamma_o - I\gamma_i$$

TAGS data effect on ^{235}U electron spectrum

Ratio of ^{235}U electron spectra measured at ILL by Schreckenbach *et al.* to two different summation calculations

Below 5 MeV, the use of JEFF-3.3 decay data overpredicts the spectrum because it doesn't include beta intensities from TAGS.

For higher energies, the underprediction is mainly from the lack of theoretical spectra in JEFF-3.3.



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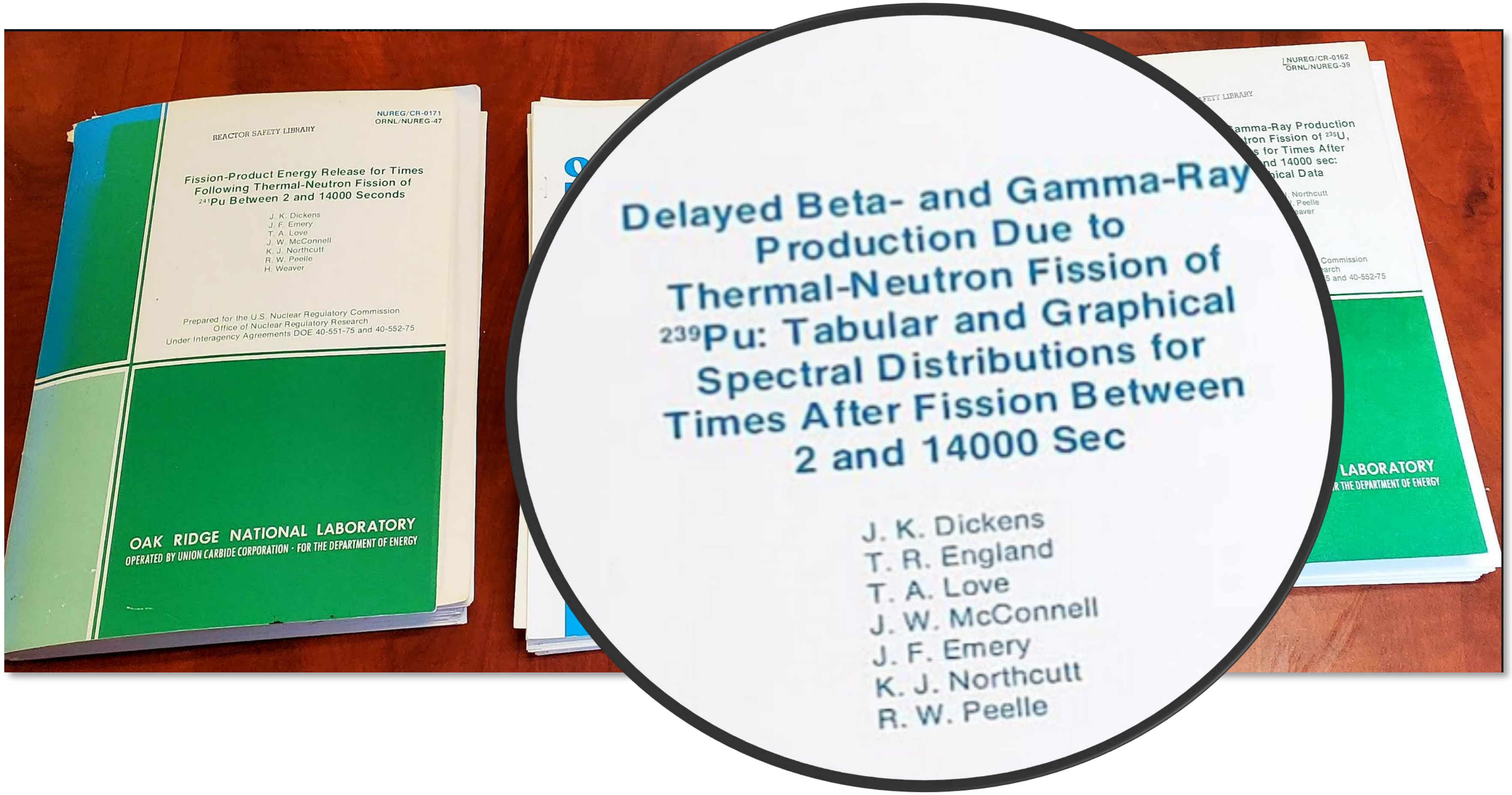
New Stuff!

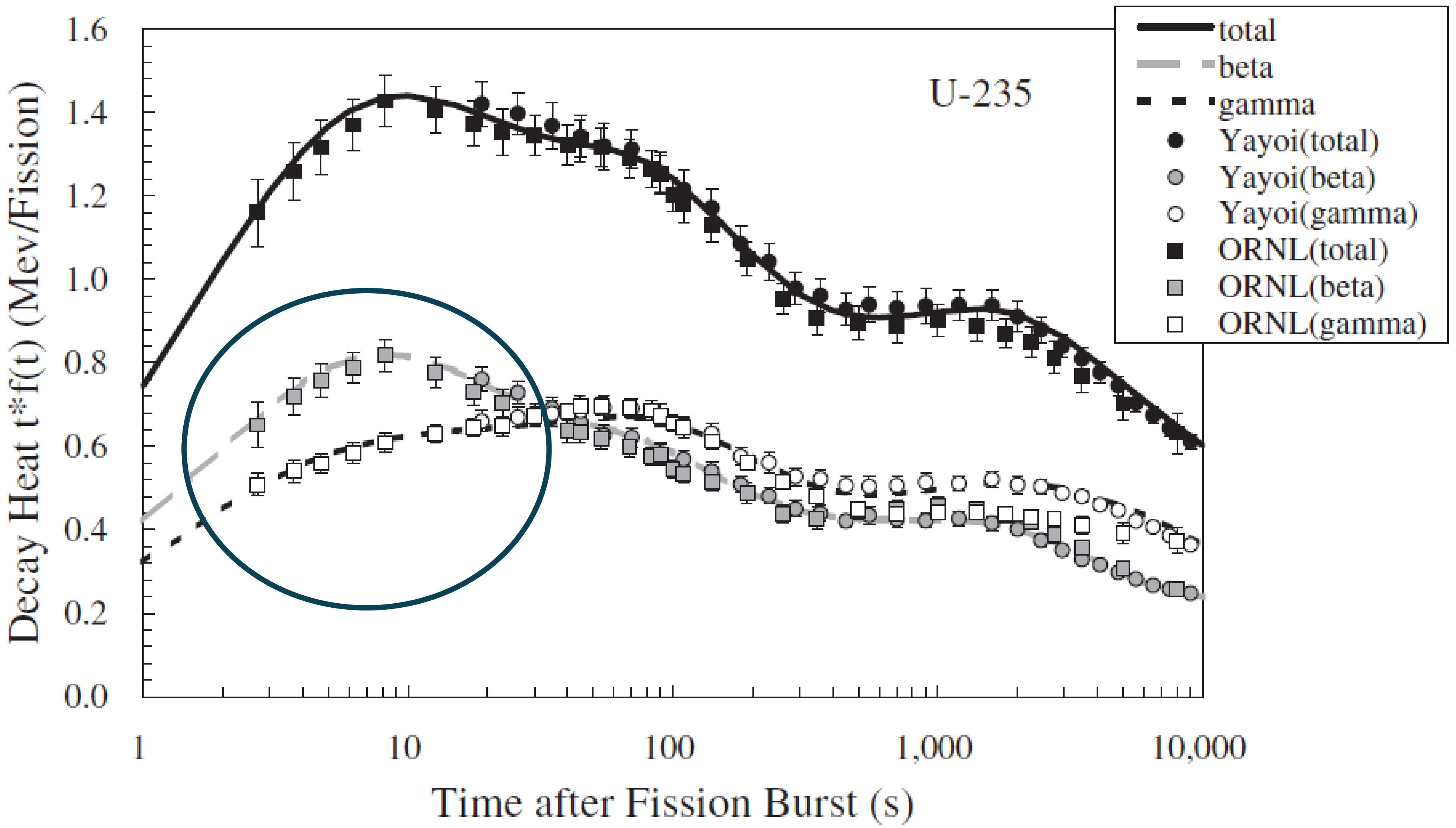
ORNL delayed gamma and electron data

- A couple of NNDC library bookshelves collapsed in May 2020.
- Among them we found three very valuable reports with delayed electron and gamma spectrum following the thermal fission of ^{235}U and ^{239,241}Pu.

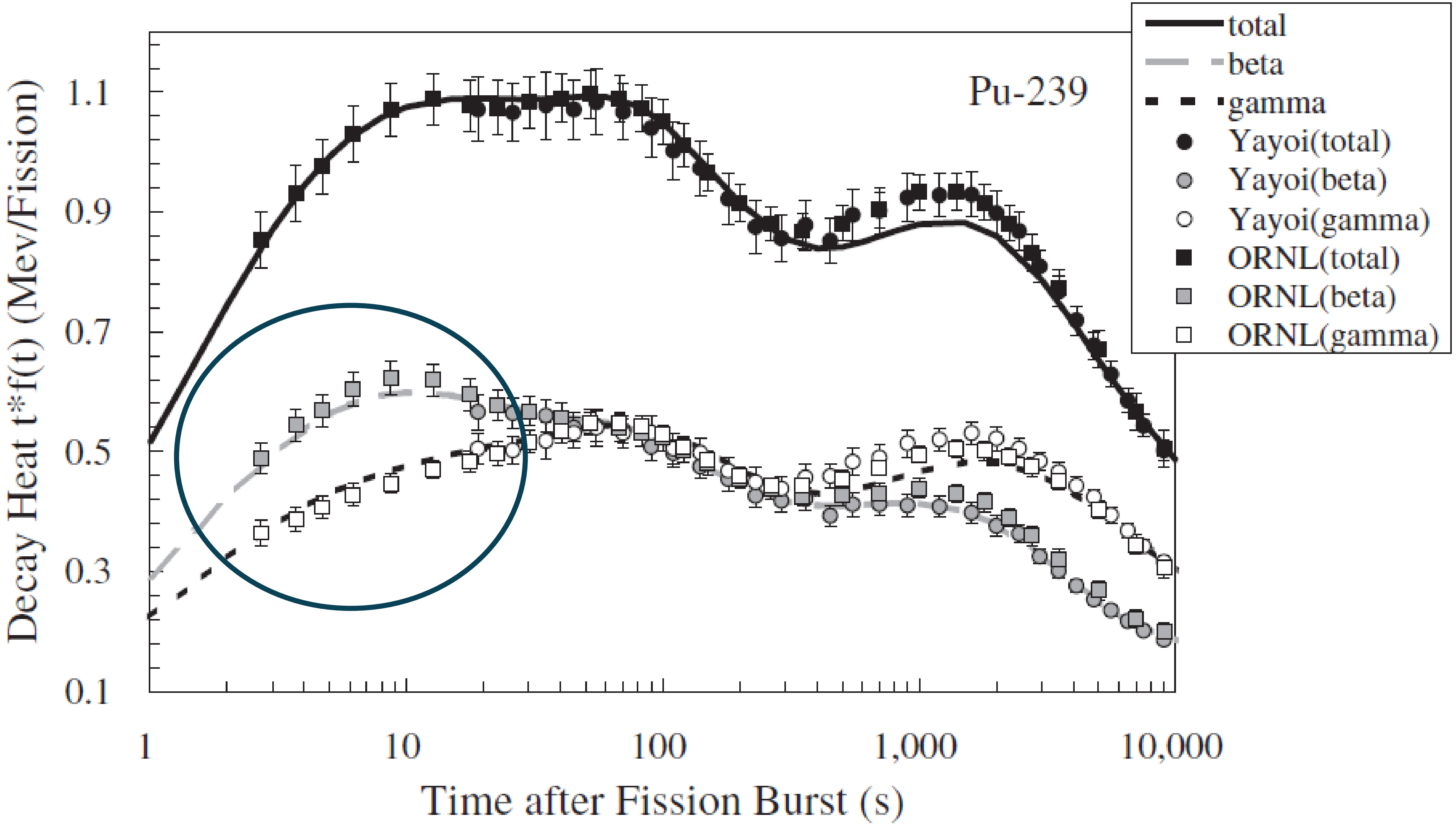


Only one report available online, which can't be searched by content.

We knew of this data because it is the **only decay heat measurement at times shorter than 20** seconds, and that for larger times **agree quite well with the Yayoi measurements**.



Reconsideration of the Theoretical Supplementation of Decay Data in Fission Product Decay Heat Summation Calculations
N. Hagura, T. Yoshida, T. Tachibana, Journal of Nuclear Science and Technology, 43:5, 497 (2012)



Reconsideration of the Theoretical Supplementation of Decay Data in Fission Product Decay Heat Summation Calculations
N. Hagura, T. Yoshida, T. Tachibana, Journal of Nuclear Science and Technology, 43:5, 497 (2012)

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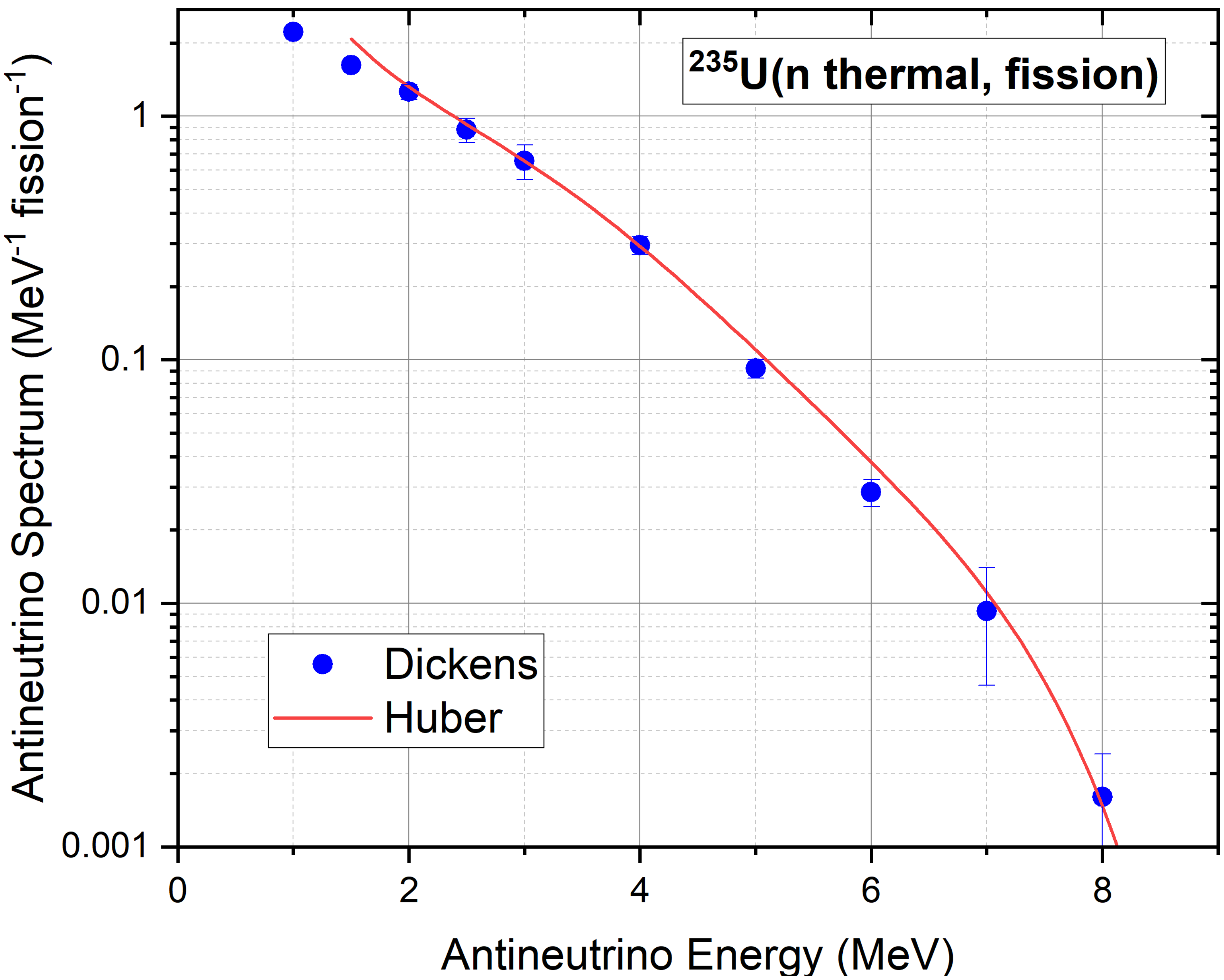
Pioneer ^{235}U antineutrino spectrum

We later learned that the antineutrino spectrum derived by Dickens from this data, published in 1981, agrees quite well with that from Huber published in 2011.

Cited by P. Vogel 1981 seminal summation work,
but not cited by anyone else.



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

ORNL irradiations

Nucleus	Irradiation time	Delay time	Counting time	Number of measurements
^{235}U	1 s	1.7 s	110 s	14
^{239}Pu	1 s	1.7 s	130 s	15
^{241}Pu	1 s	1.7 s	130 s	15
^{235}U	10 s	10.7 s	795 s	14
^{239}Pu	5 s	17.7 s	1,198 s	15
^{241}Pu	5 s	17.7 s	1,198 s	15
^{235}U	100 s	69.7	13,500 s	15
^{239}Pu	100 s	250 s	13,950 s	13
^{241}Pu	50 s	195 s	13,975 s	14

ORNL delayed gamma and electron data

We scanned and digitized 260 tables in them.

The three reports were also converted to PDF with a high-quality scanner.

SPECTRUM OF BETA RAYS FOLLOWING A
1-SEC THERMAL-NEUTRON IRRADIATION OF 235-U

START COUNT 1.7 SEC AFTER END OF IRRADIATION
COUNT FOR 1 SEC

E(BETA) MEV	I(BETA) BETAS/MEV/FISSION	DELTA(I)	E(BETA) MEV	I(BETA) BETAS/MEV/FISSION	DELTA(I)
0.170	6.165E-02	1.725E-02	2.360	2.876E-02	2.376E-03
0.190	6.137E-02	1.621E-02	2.440	2.979E-02	2.225E-03
0.210	6.526E-02	1.503E-02	2.520	2.762E-02	2.236E-03
0.230	6.306E-02	1.416E-02	2.600	2.541E-02	1.992E-03
0.250	5.038E-02	1.428E-02	2.680	2.455E-02	2.028E-03
0.275	3.483E-02	1.351E-02	2.760	2.152E-02	1.790E-03
0.305	4.465E-02	1.261E-02	2.840	2.110E-02	1.829E-03
0.335	5.053E-02	1.200E-02	2.920	2.286E-02	1.798E-03
0.365	3.868E-02	1.181E-02	3.000	2.161E-02	1.723E-03
0.395	4.900E-02	1.040E-02	3.080	1.979E-02	1.605E-03
0.425	5.634E-02	8.080E-03	3.160	1.912E-02	1.641E-03
0.455	4.487E-02	6.473E-03	3.250	1.731E-02	1.453E-03
0.485	4.124E-02	6.370E-03	3.350	1.511E-02	1.459E-03
0.520	4.157E-02	6.210E-03	3.450	1.423E-02	1.427E-03
0.560	3.806E-02	6.007E-03	3.550	1.341E-02	1.325E-03
0.600	4.655E-02	5.720E-03	3.650	1.194E-02	1.211E-03
0.640	4.650E-02	5.494E-03	3.750	1.124E-02	1.192E-03
0.680	4.170E-02	5.041E-03	3.860	1.096E-02	1.118E-03
0.720	4.542E-02	5.219E-03	3.980	8.477E-03	9.773E-04
0.760	4.723E-02	5.027E-03	4.100	7.076E-03	8.971E-04
0.800	4.563E-02	4.847E-03	4.220	8.038E-03	9.409E-04
0.840	4.492E-02	4.314E-03	4.340	7.549E-03	8.592E-04
0.880	4.421E-02	4.224E-03	4.460	6.097E-03	7.555E-04
0.925	4.146E-02	4.096E-03	4.580	5.240E-03	7.304E-04
0.975	3.910E-02	4.052E-03	4.700	4.450E-03	6.177E-04
1.025	3.927E-02	3.813E-03	4.820	3.616E-03	6.158E-04
1.075	3.916E-02	3.792E-03	4.940	3.298E-03	5.290E-04
1.125	4.191E-02	3.772E-03	5.070	3.512E-03	5.573E-04
1.175	4.227E-02	3.596E-03	5.210	3.117E-03	5.103E-04
1.225	3.825E-02	3.450E-03	5.350	2.046E-03	3.941E-04
1.275	4.006E-02	3.443E-03	5.490	1.186E-03	3.331E-04
1.325	4.434E-02	3.359E-03	5.630	8.613E-04	2.784E-04
1.375	4.259E-02	3.204E-03	5.770	1.206E-03	3.043E-04
1.430	3.922E-02	3.117E-03	5.910	1.661E-03	3.705E-04
1.490	4.012E-02	3.096E-03	6.050	1.563E-03	3.282E-04
1.550	4.006E-02	3.078E-03	6.190	1.179E-03	2.962E-04
1.610	3.899E-02	2.929E-03	6.330	8.528E-04	2.444E-04
1.670	4.172E-02	2.833E-03	6.480	5.584E-04	1.968E-04
1.730	4.210E-02	3.054E-03	6.640	3.596E-04	1.556E-04
1.790	3.591E-02	2.930E-03	6.800	3.175E-04	1.506E-04
1.850	3.206E-02	2.776E-03	6.960	3.000E-04	1.360E-04
1.910	3.434E-02	2.729E-03	7.120	2.205E-04	1.096E-04
1.970	3.638E-02	2.796E-03	7.280	1.163E-04	8.782E-05
2.040	3.519E-02	2.687E-03	7.440	4.344E-05	7.642E-05
2.120	3.387E-02	2.592E-03	7.600	1.287E-05	7.216E-05
2.200	3.238E-02	2.461E-03	7.760	6.546E-06	7.580E-05
2.280	2.949E-02	2.442E-03			

SPECTRUM OF GAMMA RAYS FOLLOWING A
1-SEC THERMAL-NEUTRON IRRADIATION OF 235-U

START COUNT 1.7 SEC AFTER END OF IRRADIATION
COUNT FOR 1 SEC

E(GAMMA) MEV	Y(GAMMA) GAMMAS/MEV/FISSION	DELTA(Y)	E(GAMMA) MEV	Y(GAMMA) GAMMAS/MEV/FISSION	DELTA(Y)
0.055	6.644E-02	2.294E-02	1.940	2.461E-02	4.447E-03
0.065	5.819E-02	2.371E-02	1.980	2.375E-02	4.390E-03
0.075	8.902E-02	2.578E-02	2.020	2.073E-02	4.175E-03
0.085	8.564E-02	2.711E-02	2.060	2.106E-02	4.161E-03
0.095	1.875E-01	3.228E-02	2.100	1.958E-02	3.934E-03
0.105	1.999E-01	3.293E-02	2.140	1.634E-02	3.731E-03
0.115	3.303E-01	3.885E-02	2.180	1.581E-02	3.641E-03
0.125	3.502E-01	3.948E-02	2.220	1.593E-02	3.732E-03
0.135	2.101E-01	3.194E-02	2.260	1.631E-02	3.630E-03
0.145	2.212E-01	3.185E-02	2.300	1.790E-02	3.800E-03
0.155	2.146E-01	3.190E-02	2.340	1.842E-02	3.630E-03
0.165	1.861E-01	3.147E-02	2.380	1.666E-02	3.756E-03
0.177	1.744E-01	2.782E-02	2.425	1.370E-02	3.392E-03
0.192	1.504E-01	2.558E-02	2.475	1.428E-02	3.518E-03
0.207	1.440E-01	2.430E-02	2.525	1.614E-02	3.686E-03
0.222	9.575E-02	2.157E-02	2.575	1.424E-02	3.410E-03
0.237	9.042E-02	2.080E-02	2.625	8.989E-03	3.084E-03
0.252	1.302E-01	2.219E-02	2.675	1.019E-02	3.018E-03
0.267	1.356E-01	2.269E-02	2.725	1.370E-02	3.493E-03
0.282	1.453E-01	2.285E-02	2.775	7.259E-03	2.479E-03
0.297	1.770E-01	2.422E-02	2.825	7.410E-03	2.840E-03
0.313	1.115E-01	1.994E-02	2.875	1.264E-02	3.156E-03
0.327	7.916E-02	1.719E-02	2.925	9.374E-03	2.818E-03
0.342	9.228E-02	1.793E-02	2.975	8.217E-03	2.711E-03
0.357	1.009E-01	1.825E-02	3.030	1.123E-02	2.863E-03
0.372	1.077E-01	1.859E-02	3.090	8.185E-03	2.542E-03
0.387	1.337E-01	1.917E-02	3.150	7.076E-03	2.416E-03
0.402	1.540E-01	1.980E-02	3.210	1.178E-02	2.638E-03
0.417	1.289E-01	1.808E-02	3.270	1.259E-02	2.842E-03
0.432	1.351E-01	1.670E-02	3.330	1.125E-02	2.567E-03
0.447	1.281E-01	1.227E-02	3.390	1.208E-02	2.736E-03
0.462	1.732E-01	1.340E-02	3.450	8.719E-03	2.279E-03
0.477	1.782E-01	1.390E-02	3.510	4.352E-03	1.928E-03
0.492	1.552E-01	1.267E-02	3.570	4.901E-03	1.870E-03
0.507	1.565E-01	1.297E-02	3.630	4.056E-03	1.885E-03
0.522	1.895E-01	1.415E-02	3.690	1.984E-03	1.590E-03
0.540	2.417E-01	1.563E-02	3.750	3.353E-03	1.704E-03
0.560	2.199E-01	1.489E-02	3.810	4.129E-03	1.875E-03
0.580	1.569E-01	1.277E-02	3.870	2.687E-03	1.739E-03
0.600	1.616E-01	1.262E-02	3.935	2.998E-03	1.785E-03
0.620	1.224E-01	1.104E-02	4.005	2.645E-03	1.671E-03
0.640	8.861E-02	9.464E-03	4.075	2.564E-03	1.435E-03
0.660	7.754E-02	9.320E-03	4.145	4.661E-03	1.777E-03
0.680	6.201E-02	8.234E-03	4.215	4.367E-03	1.584E-03
0.700	5.975E-02	8.494E-03	4.285	4.120E-03	1.618E-03
0.720	5.620E-02	8.008E-03	4.355	5.539E-03	1.696E-03
0.740	5.855E-02	7.930E-03	4.425	6.104E-03	1.529E-03
0.760	6.558E-02	8.553E-03	4.495	3.299E-03	1.310E-03
0.780	7.649E-02	8.764E-03	4.565	8.540E-04	8.732E-04
0.800	1.165E-01	1.005E-02	4.635	8.829E-04	1.002E-03
0.820	1.382E-01	1.045E-02	4.705	1.284E-03	8.776E-04
0.840	1.028E-01	9.131E-03	4.775	1.291E-03	8.662E-04
0.860	6.998E-02	7.751E-03	4.845	6.989E-04	7.474E-04
0.880	6.356E-02	7.960E-03	4.915	1.546E-04	5.911E-04
0.900	5.671E-02	7.393E-03	4.985	4.240E-04	6.745E-04
0.920	5.635E-02	7.550E-03	5.060	1.217E-03	7.666E-04
0.940	7.137E-02	8.014E-03	5.140	1.589E-03	8.047E-04
0.962	8.254E-02	8.424E-03	5.220	1.111E-03	7.333E-04
0.987	7.295E-02	8.022E-03	5.300	4.972E-04	6.524E-04
1.013	6.109E-02	7.368E-03	5.380	3.978E-04	5.835E-04
1.037	5.538E-02	7.415E-03	5.460	6.213E-04	5.494E-04
1.062	5.841E-02	7.283E-03	5.540	6.726E-04	5.351E-04
1.088	7.811E-02	8.085E-03	5.620	3.490E-04	4.451E-04
1.112	8.971E-02	8.352E-03	5.700	2.413E-04	5.292E-04
1.138	7.471E-02	7.654E-03	5.780	3.819E-04	6.121E-04
1.162	5.264E-02	6.828E-03	5.860	3.316E-04	5.247E-04
1.187	4.898E-02	6.692E-03	5.945	7.530E-05	4.391E-04
1.215	6.253E-02	7.215E-03	6.035	-1.195E-04	3.274E-04
1.245	6.322E-02	7.249E-03	6.125	5.305E-05	3.217E-04
1.275	5.428E-02	6.606E-03	6.215	5.742E-04	4.353E-04
1.305	5.040E-02	6.833E-03	6.305	8.111E-04	4.756E-04
1.335	3.724E-02	5.786E-03	6.395	5.998E-04	3.840E-04
1.365	3.157E-02	5.917E-03	6.485	4.228E-04	3.273E-04
1.395	4.118E-02	5.958E-03	6.575	2.436E-04	2.627E-04
1.425	4.050E-02	6.068E-03	6.665	9.068E-05	2.144E-04
1.455	2.662E-02	5.010E-03	6.755	3.998E-05	2.079E-04
1.485	2.633E-02	5.123E-03	6.850	5.603E-05	1.814E-04
1.515	3.125E-02	5.061E-03	6.950	6.806E-05	1.753E-04
1.545	2.979E-02	4.909E-03	7.050	7.264E-05	1.697E-04
1.580	3.310E-02	5.226E-03	7.150	5.288E-05	1.613E-04
1.620	3.200E-02	5.109E-03	7.250	3.127E-05	1.587E-04
1.660	2.571E-02	4.712E-03	7.350	1.769E-05	1.470E-04
1.700	2.474E-02	4.637E-03	7.450	2.533E-05	1.380E-04
1.740	2.997E-02	4.841E-03	7.550	1.456E-05	1.395E-04
1.780	3.316E-02	5.184E-03	7.650	9.129E-06	1.398E-04
1.820	2.704E-02	4.631E-03	7.750	1.529E-05	1.338E-04
1.860	2.673E-02	4.667E-03	7.850	1.906E-05	1.278E-04
1.900	2.549E-02	4.481E-03			

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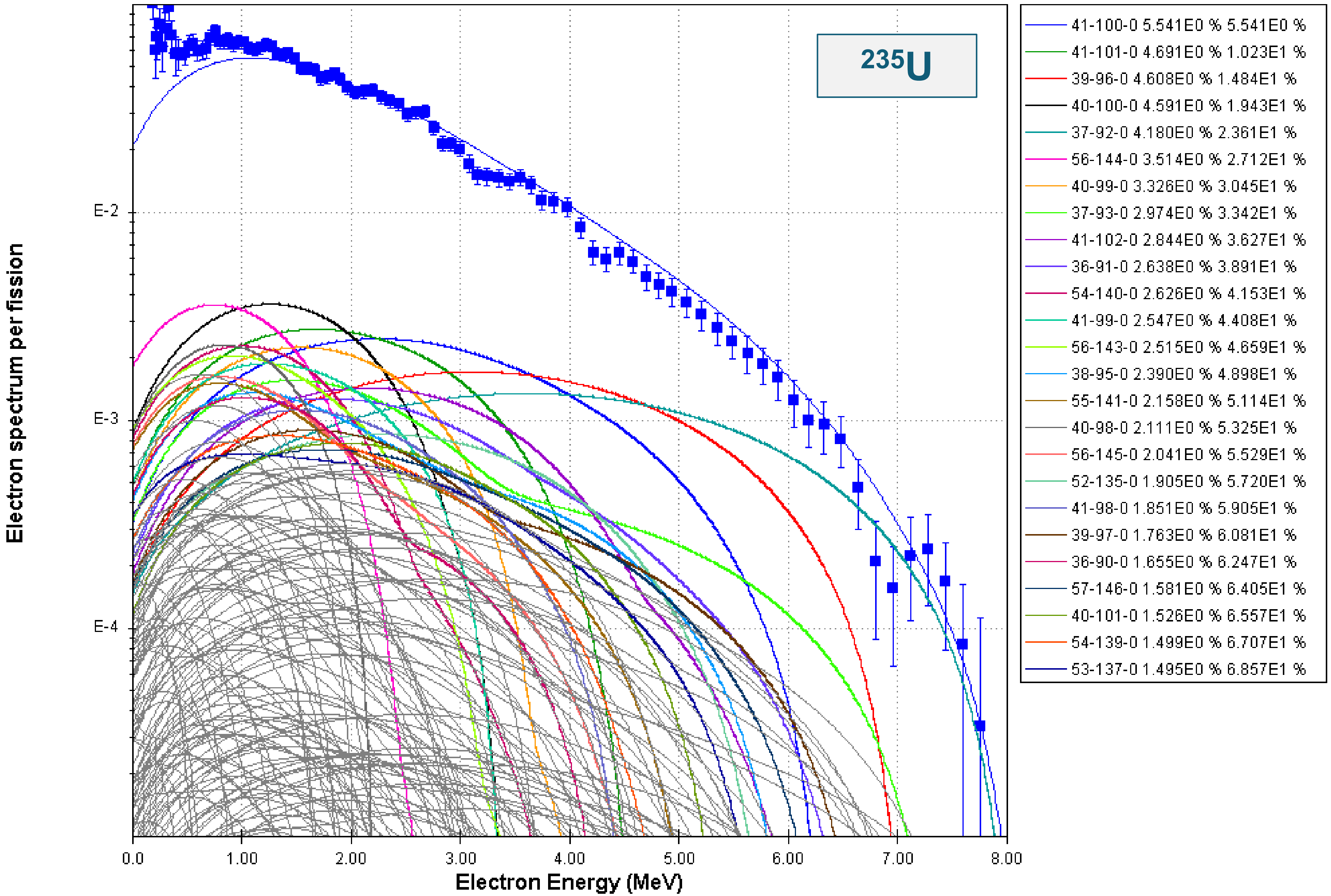
We are grateful to SULI interns Zharia Harris, Becket Hill, Bryan Palaguachi and Matthew Seeley, who help digitizing and understanding the data.

Beta-delayed electrons

- Measurements are compared with summation calculations, ENDF/B-VIII.1β decay and JEFF-3.3 yields, which highlights the 25 most important contributors.

- Good agreement is seen for ^{235}U, in this case 1-second irradiation, 6.7-second waiting period, and 3-second counting interval.



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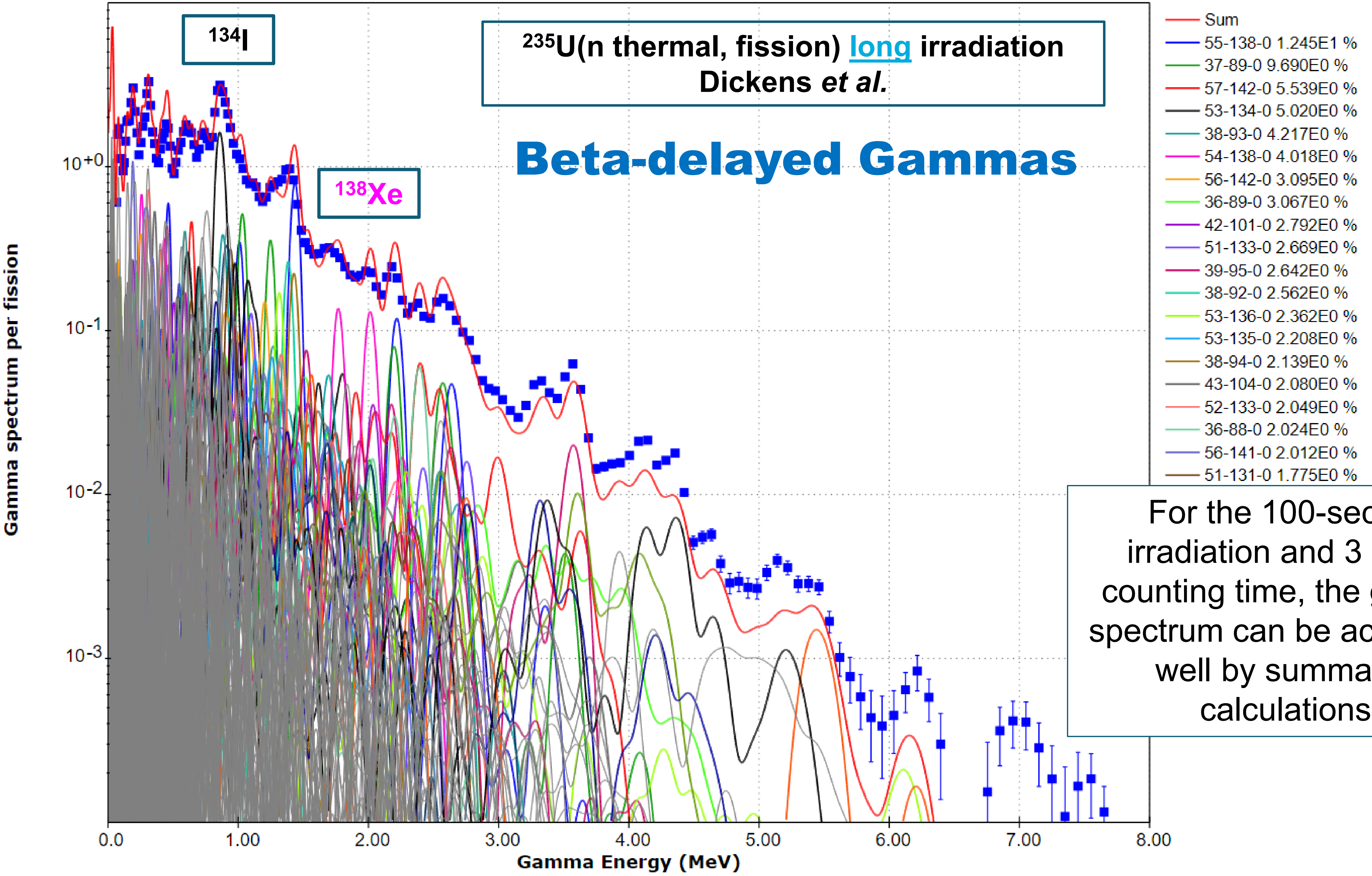
Beta-delayed Gammas

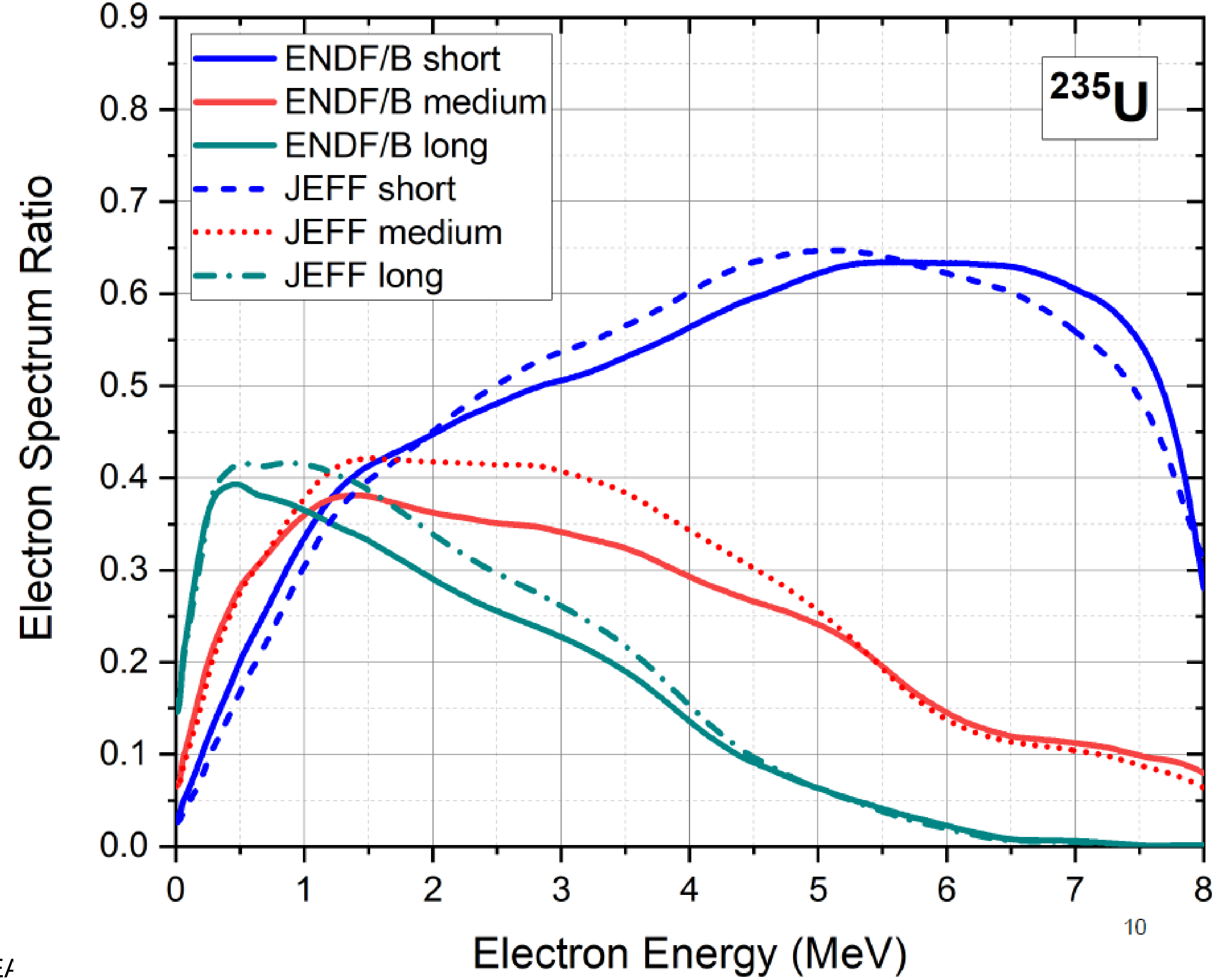
^{235}U(n thermal, fission) long irradiation
Dickens *et al.*



For the 100-second irradiation and 3 hours counting time, the gamma spectrum can be accounted well by summation calculations.

What percentage of the equilibrium spectrum do these irradiations capture?

- ❑ The 1-second irradiation captures about 30-65% of the equilibrium spectrum in the 1 to 8 MeV region.
- ❑ The medium and long irradiations capture considerably less, therefore correction is larger, that is, more reliance on the summation method.
- ❑ Differences between JEFF-3.3 and ENDF/B-VIII.0 decay data are due to the implementation of TAGS data in the ENDF/B.



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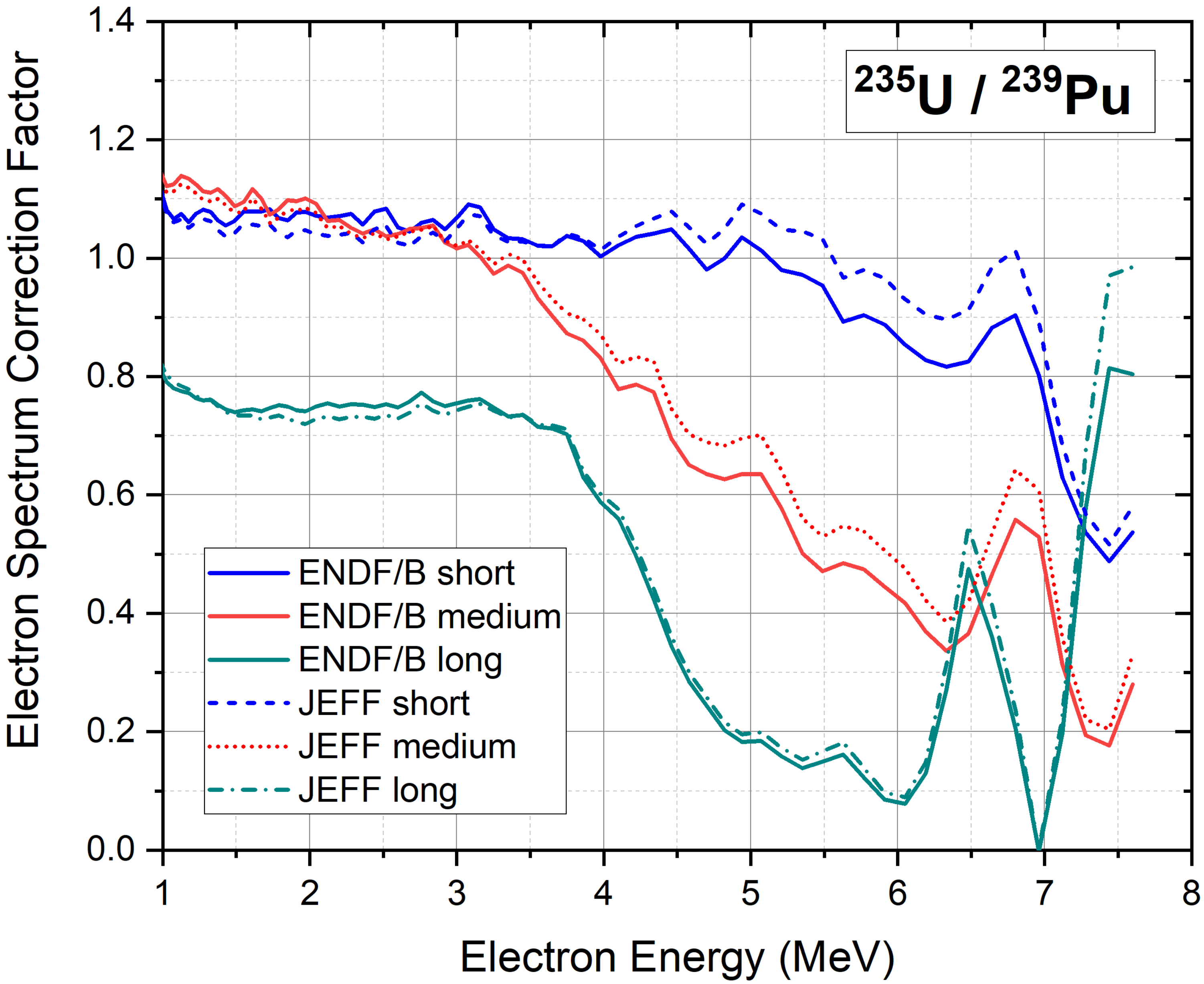
Issues

- We don't have the full data set, despite that we searched for it, with the help of David Glasgow from ORNL.
- We can calculate ratio of electron spectra similar to Kopeikin et al, but corrections are needed.
- The uncertainty of the sum spectra are not available, need to fix that.



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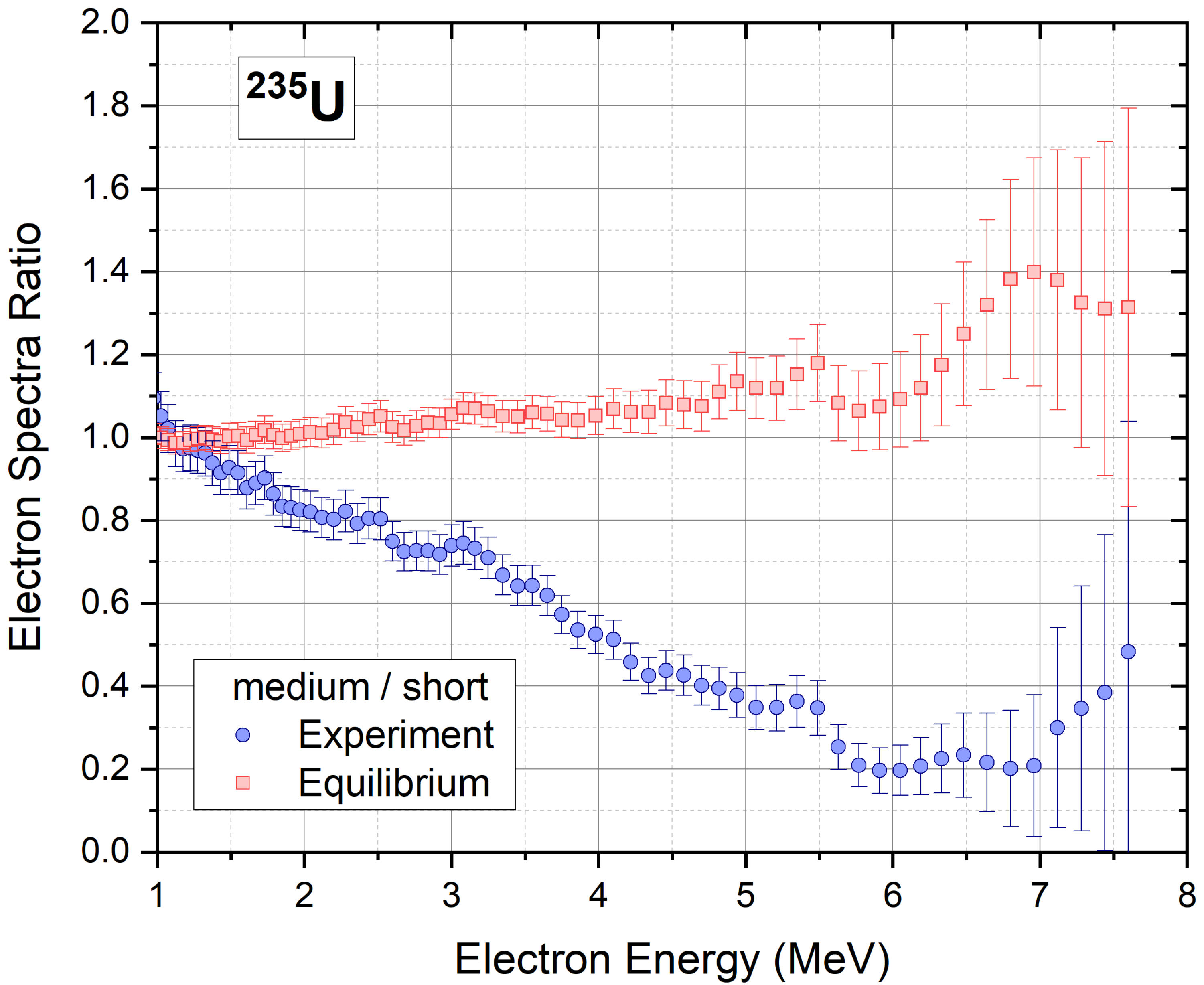
Issues

- To check and possibly reassure ourselves, we can calculate the ratio of the medium/short irradiation and apply corrections.
- The corrected ratio should be closed to one.
- Uncertainties include summation model uncertainties using a Monte Carlo method.



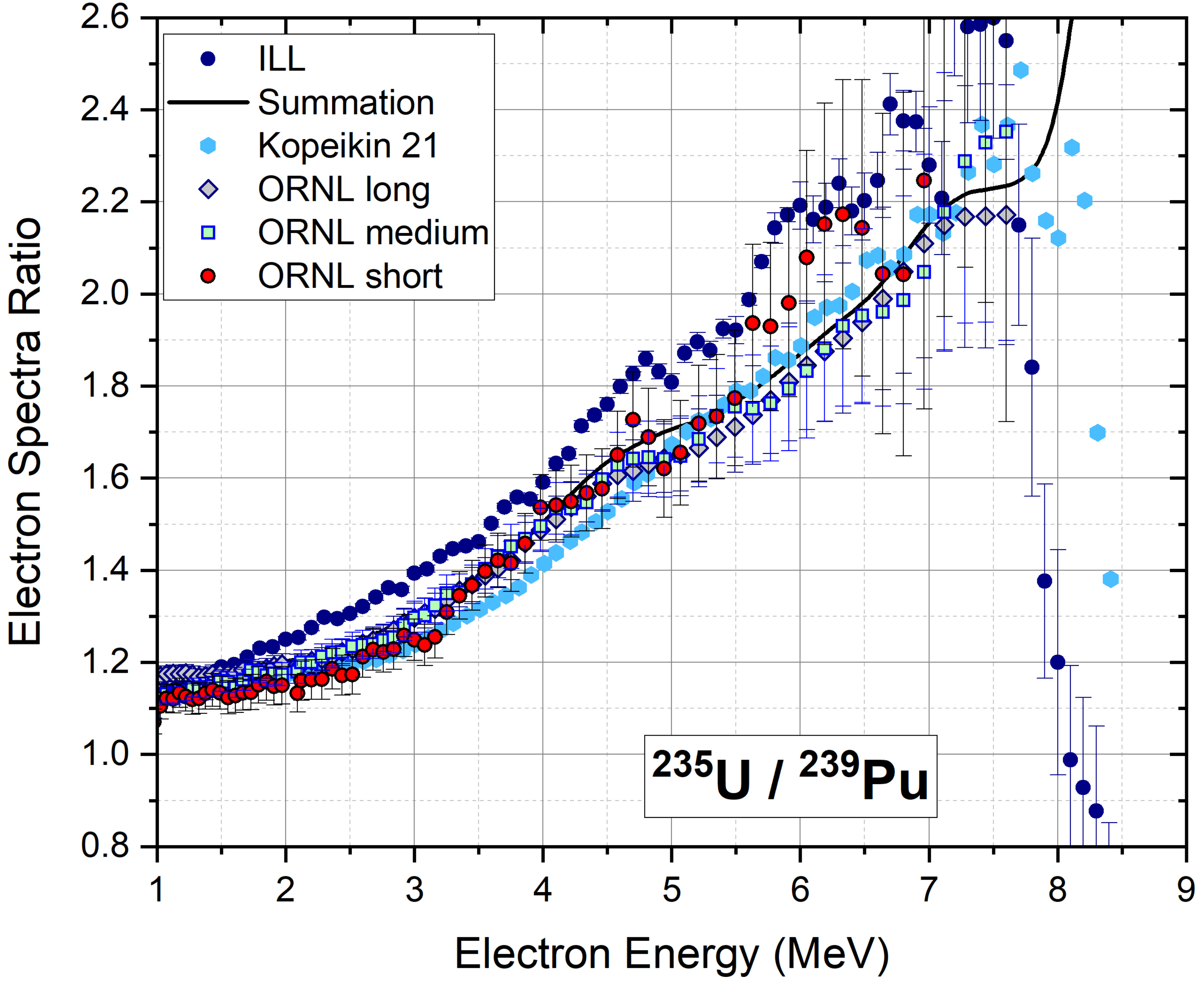
Results!

- Both summation and derived ORNL values are lower than ILL ones.

- For energies lower than 3.5 MeV the ORNL values are very close to Kopeikin's.

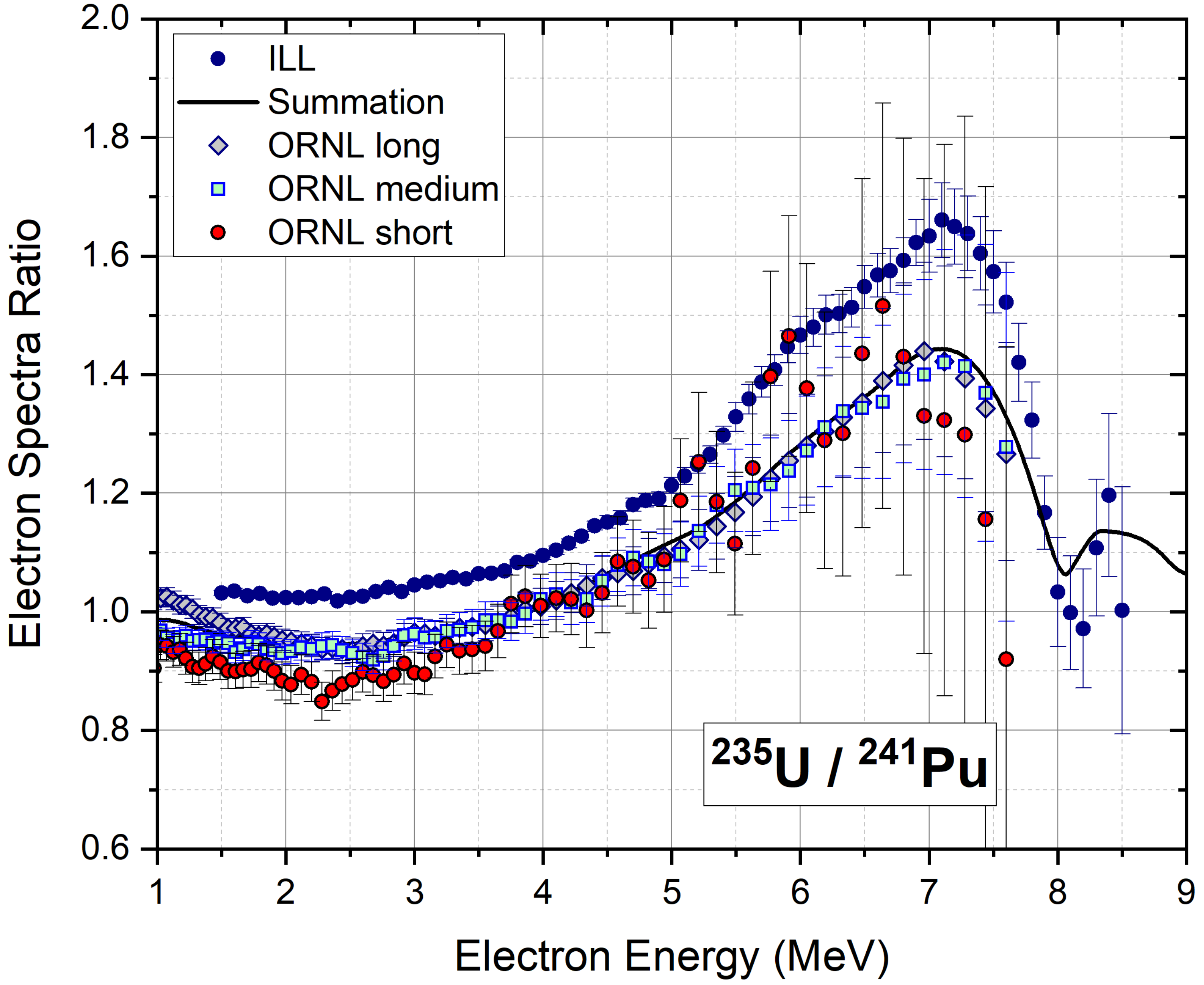
- At 4 MeV, the ORNL values are about half-way between ILL and Kopeikin's.

- Note that for energies higher than 7.5 MeV, ILL and Kopeikin's values unexpectedly drop, which is not supported by summation calculations, a ^{235}U or ^{241}Pu contamination in the ^{239}Pu target could be the reason.



Results!

- Both summation and ORNL values are lower than ILL ones.
- Seems to indicate that the ^{235}U ILL electron spectrum is too high.
- ILL ratio shape agrees with summation for high energies.



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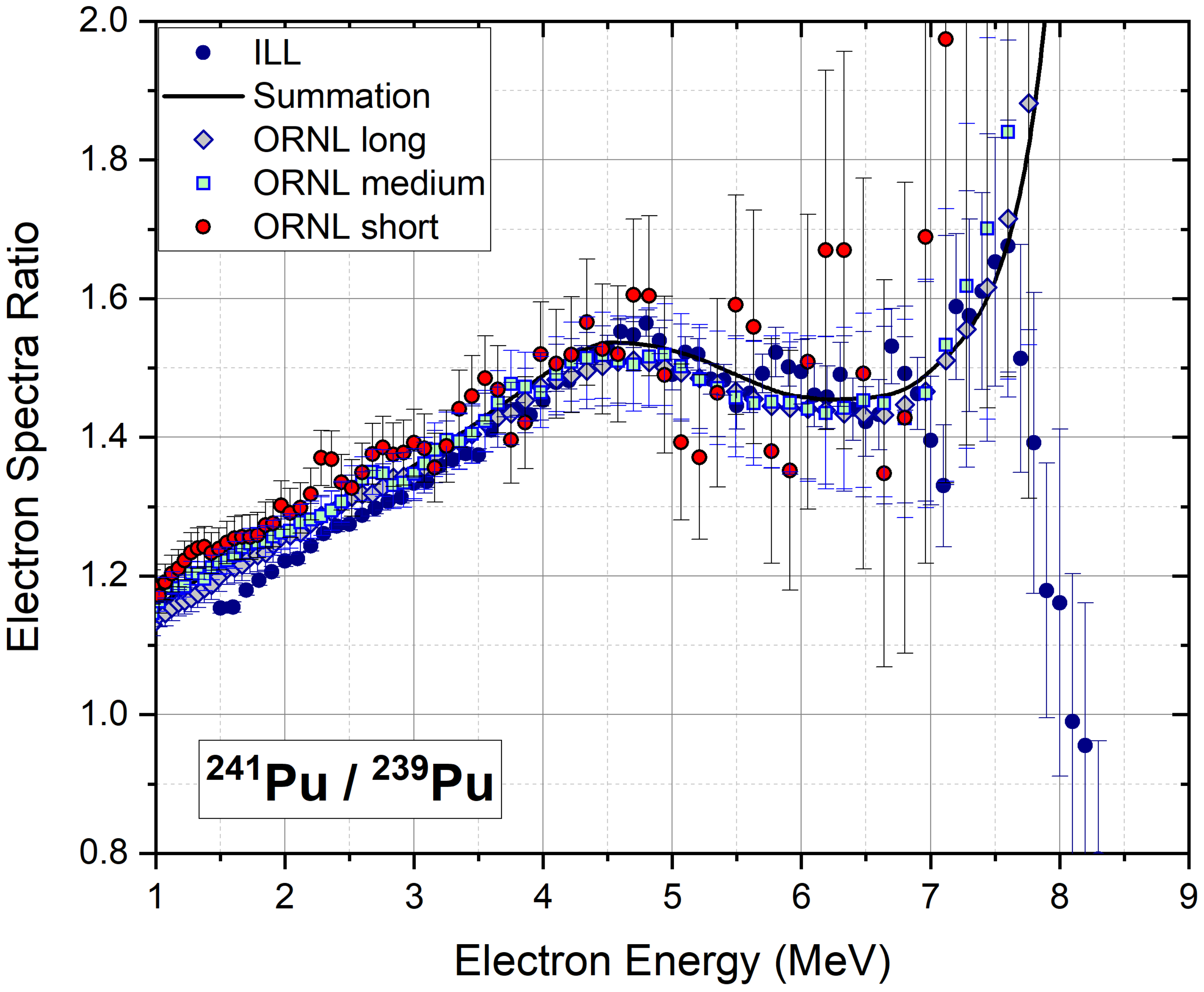
Results!

- Both summation and ORNL values are higher than ILL ones.
- Normalization issues in the ^{239}Pu and ^{241}Pu ILL electron spectra are possibly present.
- ILL ratio values at high energies disagree with summation values. ^{241}Pu fission products are more neutron rich than ^{239}Pu ones, therefore they produce more energetic electrons. A contamination in the ^{239}Pu target could be the reason.



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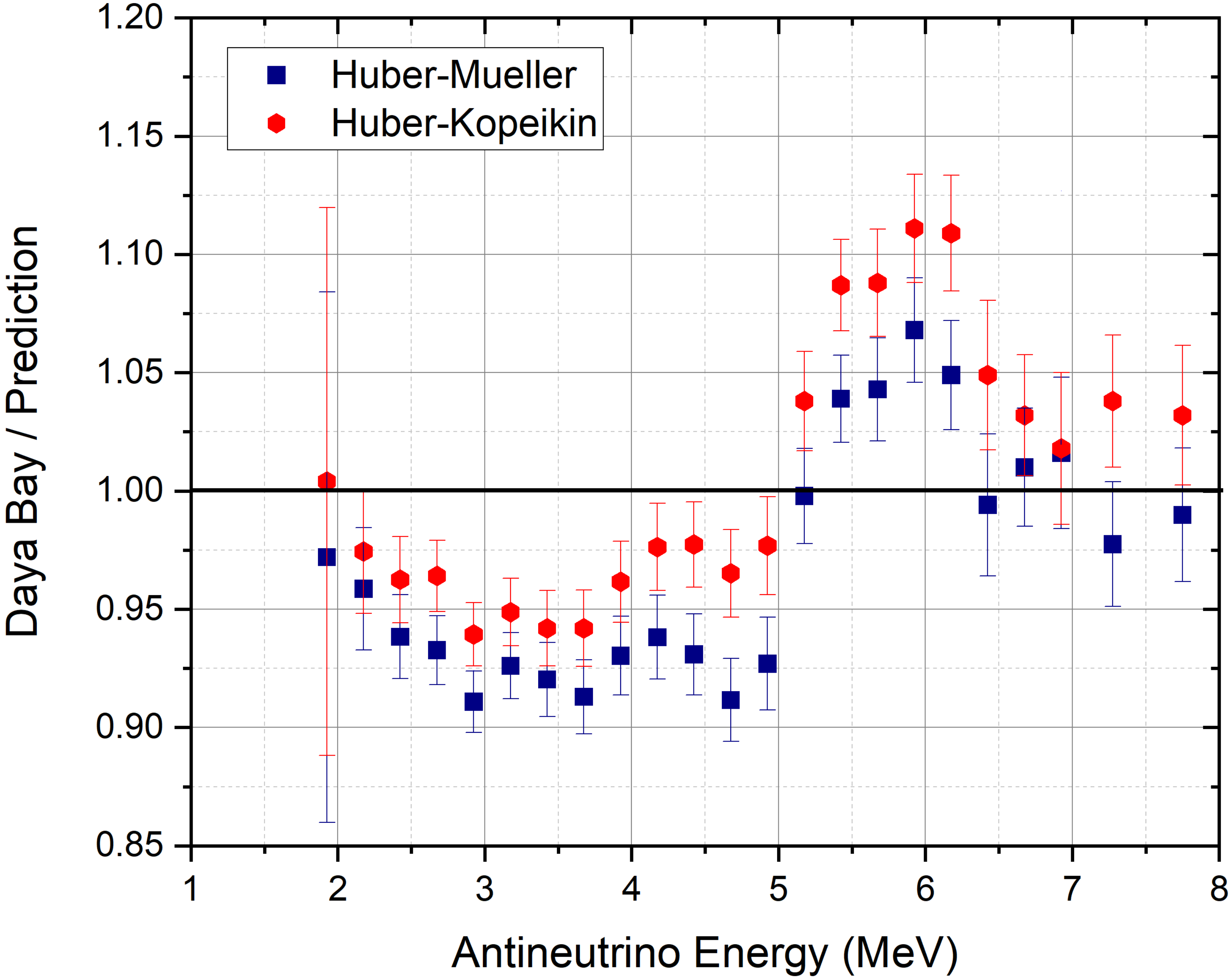
Additionally,

- The modified Kopeikin ^{235}U and ^{238}U antineutrino spectra combined with Huber's ^{239}Pu and ^{241}Pu do not agree that well with the Daya Bay spectra
- The overprediction (dip) at 2-5 MeV and underprediction (bump) at 5-7 MeV persist.
- We definitely need newly measured electron spectra to properly account for the antineutrino spectra produced by nuclear reactors.



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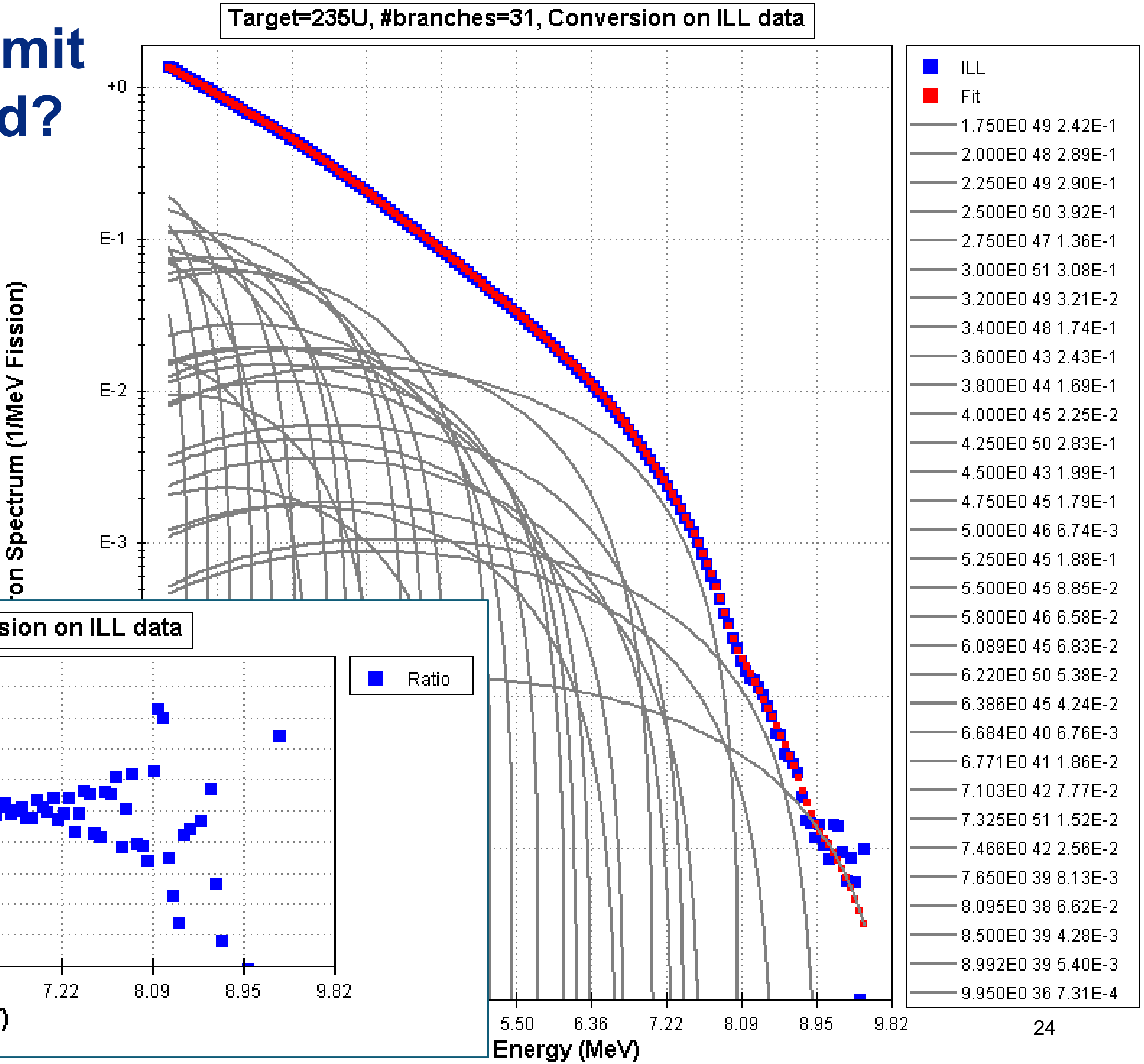
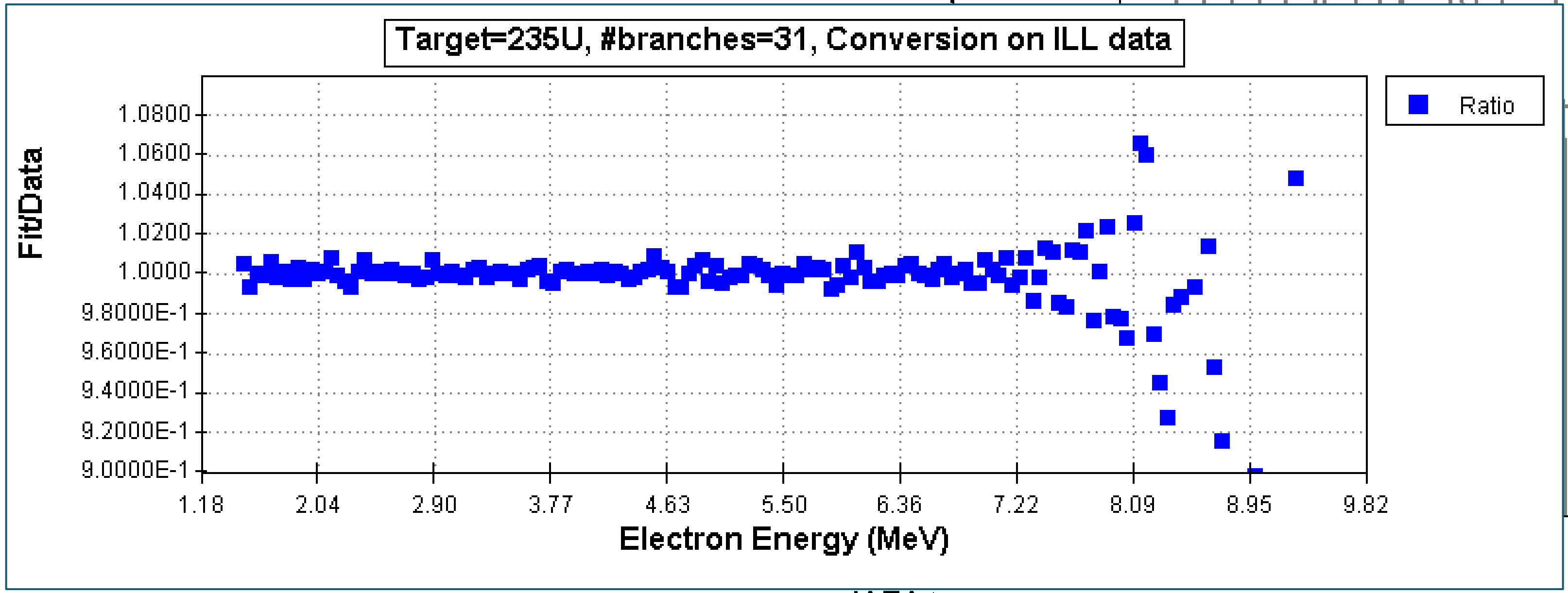
Daya Bay High Energy Neutrinos

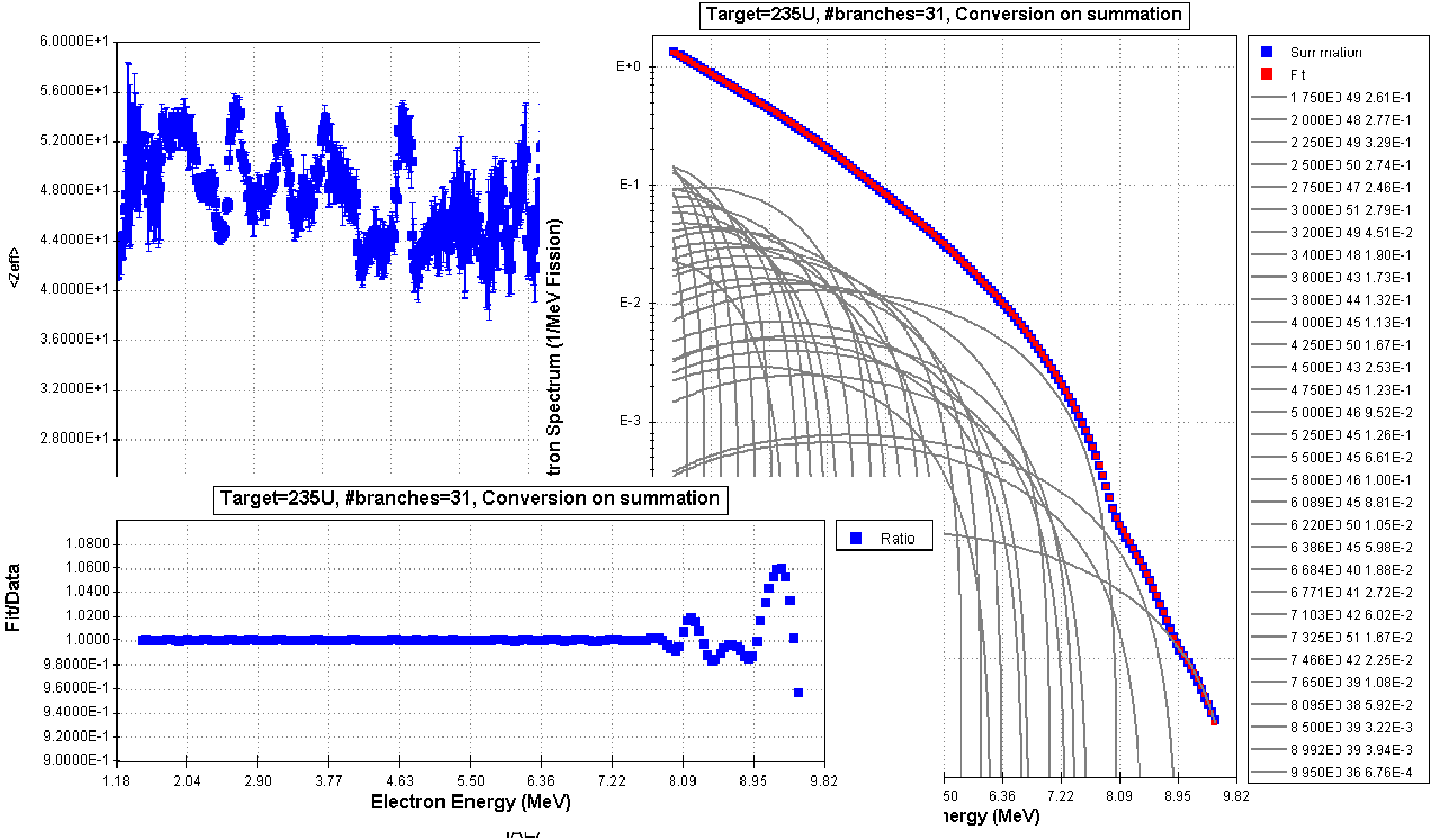
What's the upper energy limit for the conversion method?

We fitted 31 branches, and for
E > 7 MeV reliably decreases quickly.

Note that that some branches correspond to physical cases, ex ^{96}Y for 7.103 Q, a=7.77E-2, larger than CFY=4.65E-2. ^{92}Rb for Q=8.095 a=6.62E-2, larger than CFY=4.37E-2.

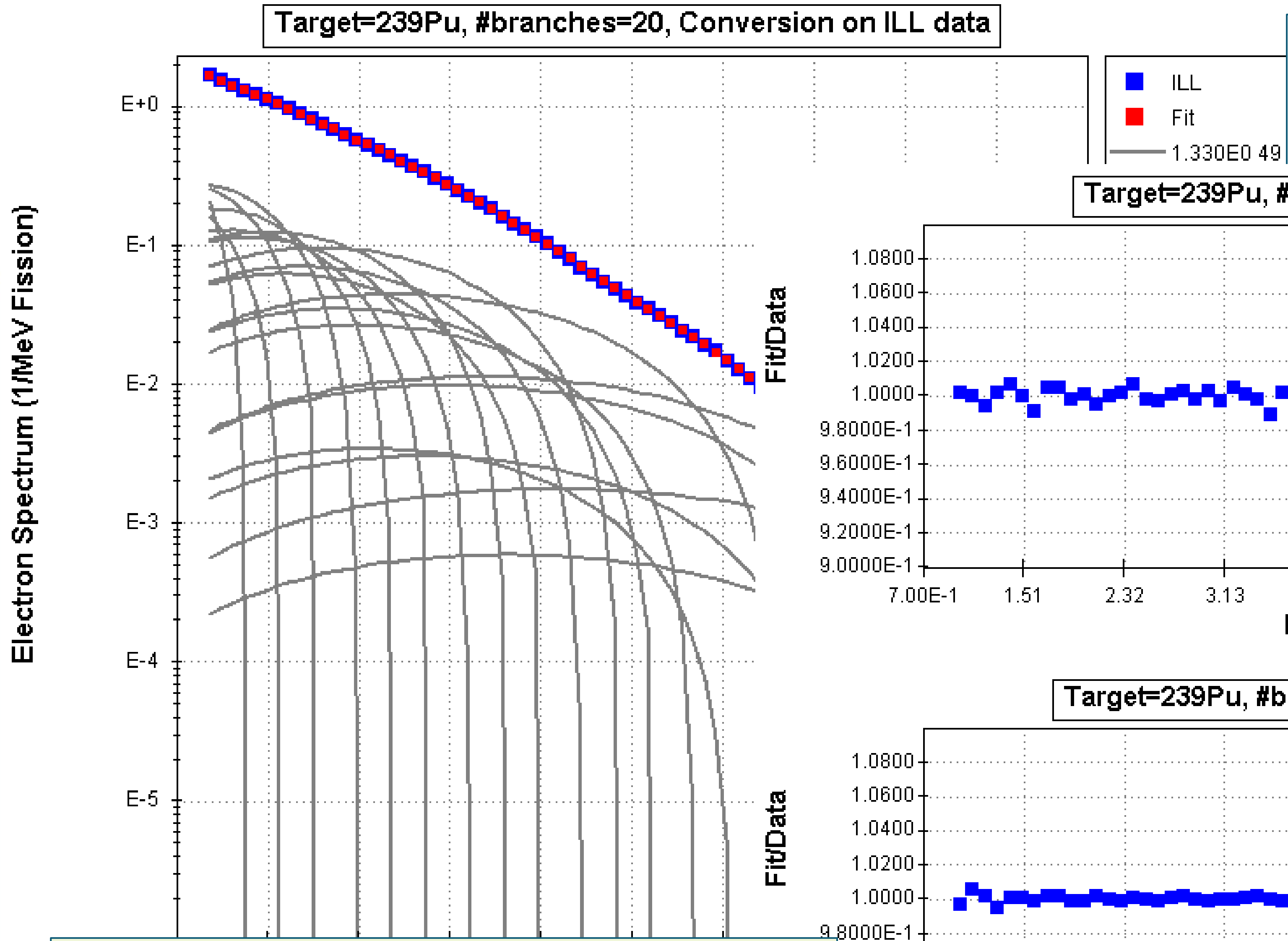


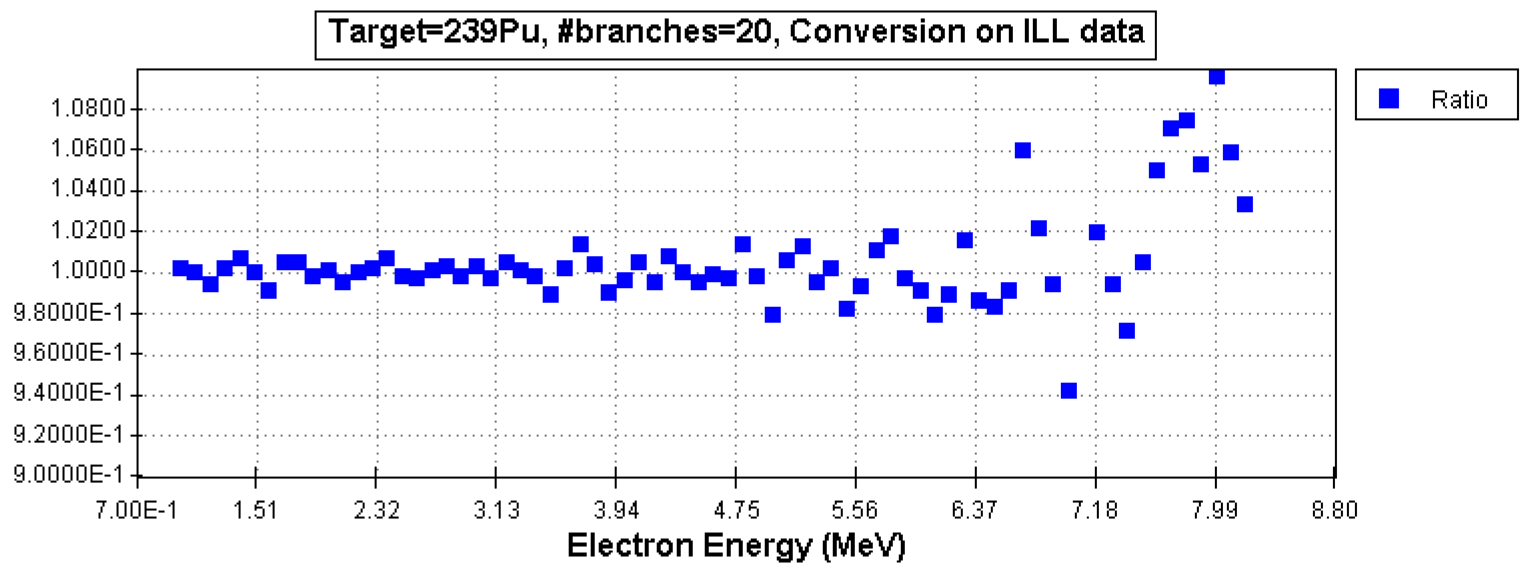


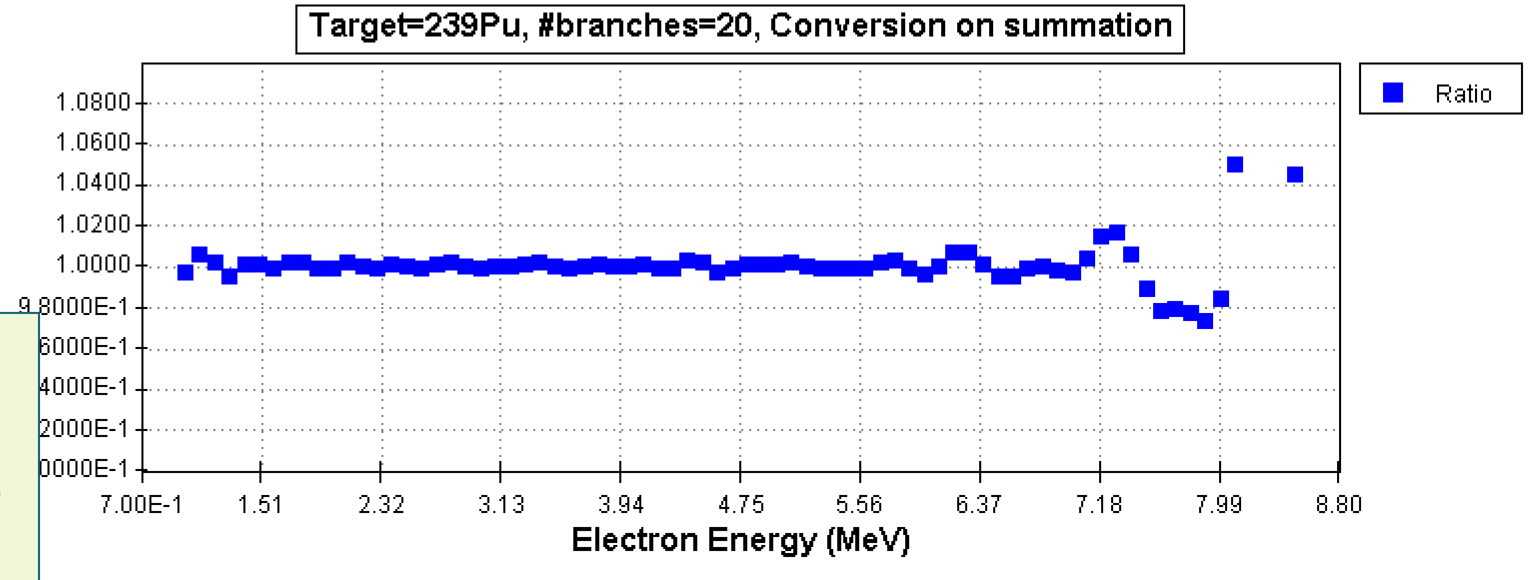


<Zeff>
6.0000E+1
5.6000E+1
5.2000E+1
4.8000E+1
4.4000E+1
4.0000E+1
3.6000E+1
3.2000E+1
2.8000E+1
Target=235U, #branches=31, Conversion on summation
Electron Spectrum (1/MeV Fission)
E+0
E-1
E-2
E-3
Summation
Fit
1.750E0 49 2.61E-1
2.000E0 48 2.77E-1
2.250E0 49 3.29E-1
2.500E0 50 2.74E-1
2.750E0 47 2.46E-1
3.000E0 51 2.79E-1
3.200E0 49 4.51E-2
3.400E0 48 1.90E-1
3.600E0 43 1.73E-1
3.800E0 44 1.32E-1
4.000E0 45 1.13E-1
4.250E0 50 1.67E-1
4.500E0 43 2.53E-1
4.750E0 45 1.23E-1
5.000E0 46 9.52E-2
5.250E0 45 1.26E-1
5.500E0 45 6.61E-2
5.800E0 46 1.00E-1
6.089E0 45 8.81E-2
6.220E0 50 1.05E-2
6.386E0 45 5.98E-2
6.684E0 40 1.88E-2
6.771E0 41 2.72E-2
7.103E0 42 6.02E-2
7.325E0 51 1.67E-2
7.466E0 42 2.25E-2
7.650E0 39 1.08E-2
8.095E0 38 5.92E-2
8.500E0 39 3.22E-3
8.992E0 39 3.94E-3
9.950E0 36 6.76E-4
Target=235U, #branches=31, Conversion on summation
Fit/Data
1.0800
1.0600
1.0400
1.0200
1.0000
9.8000E-1
9.6000E-1
9.4000E-1
9.2000E-1
9.0000E-1
Ratio
1.18
2.04
2.90
3.77
4.63
5.50
6.36
7.22
8.09
8.95
9.82
Electron Energy (MeV)
6.36
7.22
8.09
8.95
9.82
Energy (MeV)

^{96}Y, a=3.98E-2, larger than CFY=2.87E-2. ^{92}Rb a=2.71E-3, smaller than CFY=1.79E-2!

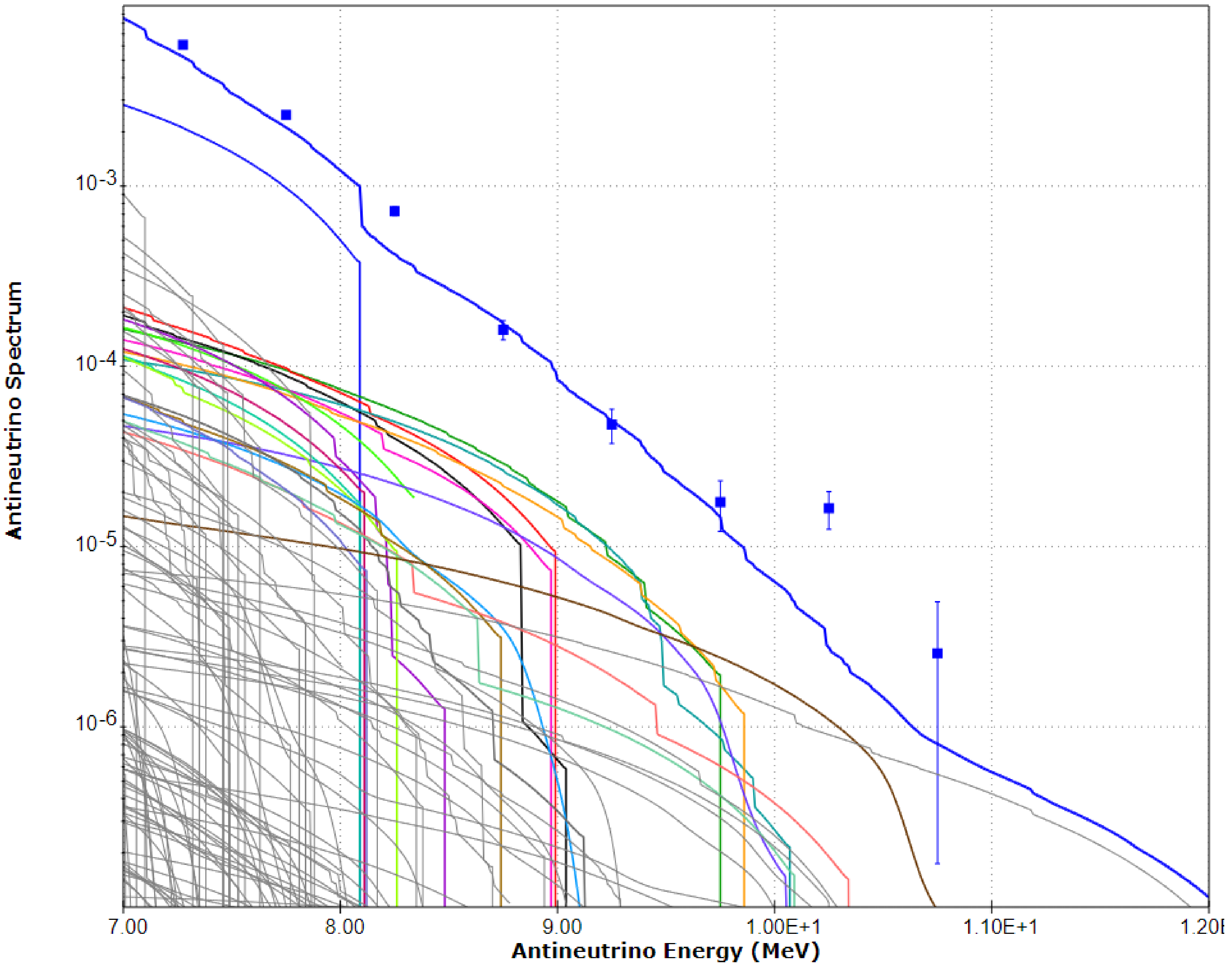






All this work to tell you that we think that the summation method is the more reliable alternative for energies higher than 7 MeV.

We are unable to reproduce the Daya Bay high energy segment of the spectrum with our current summation calculations



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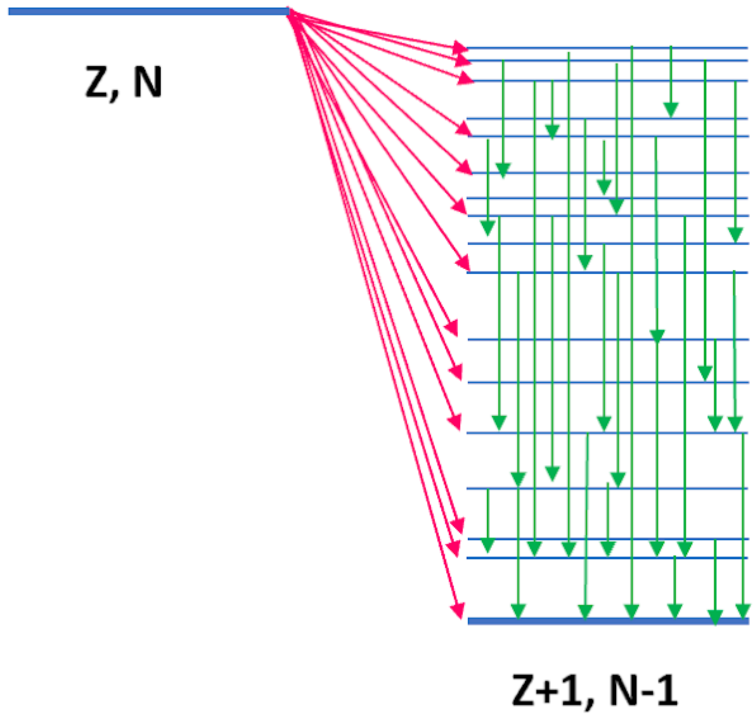
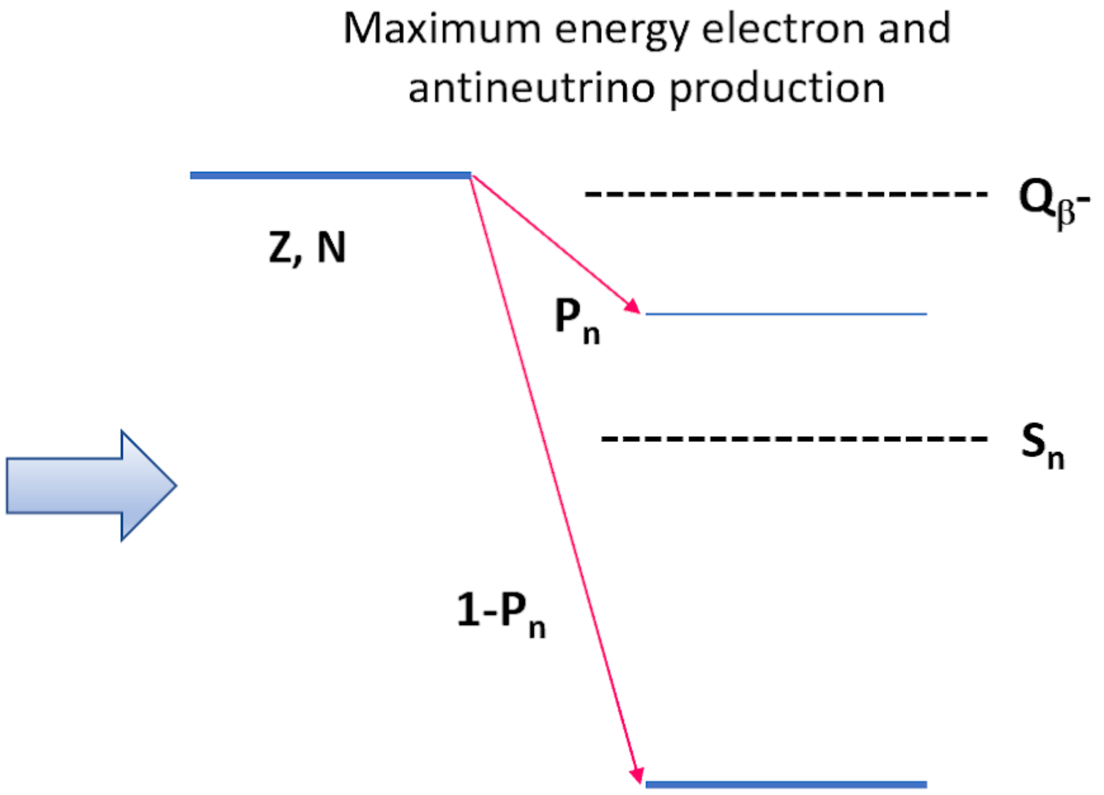
What's the maximum antineutrino spectrum a beta-minus decaying nucleus can have?

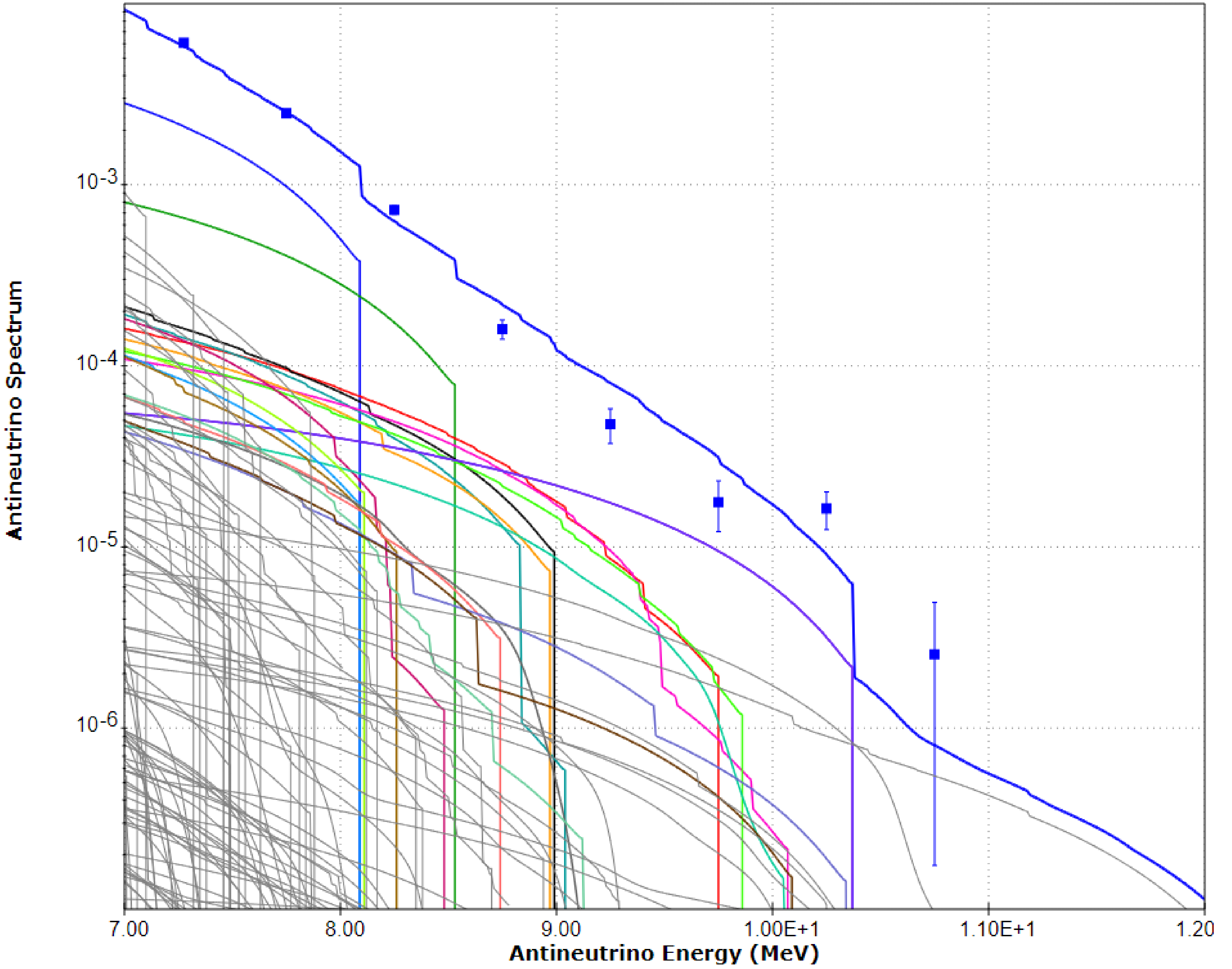




Sensitivity study: We will replace the ENDF/B theoretical antineutrino spectra with this parameterization to find out the most likely contributors.

We are able to better reproduce by adjusting $^{102g,m}Y$ and ^{104}Nb

Other important cases are $^{92,93}Br$, ^{86}As, ^{140}I, ^{144}Cs, ^{104}Y



Fine structure, yes? no? may be? who knows?

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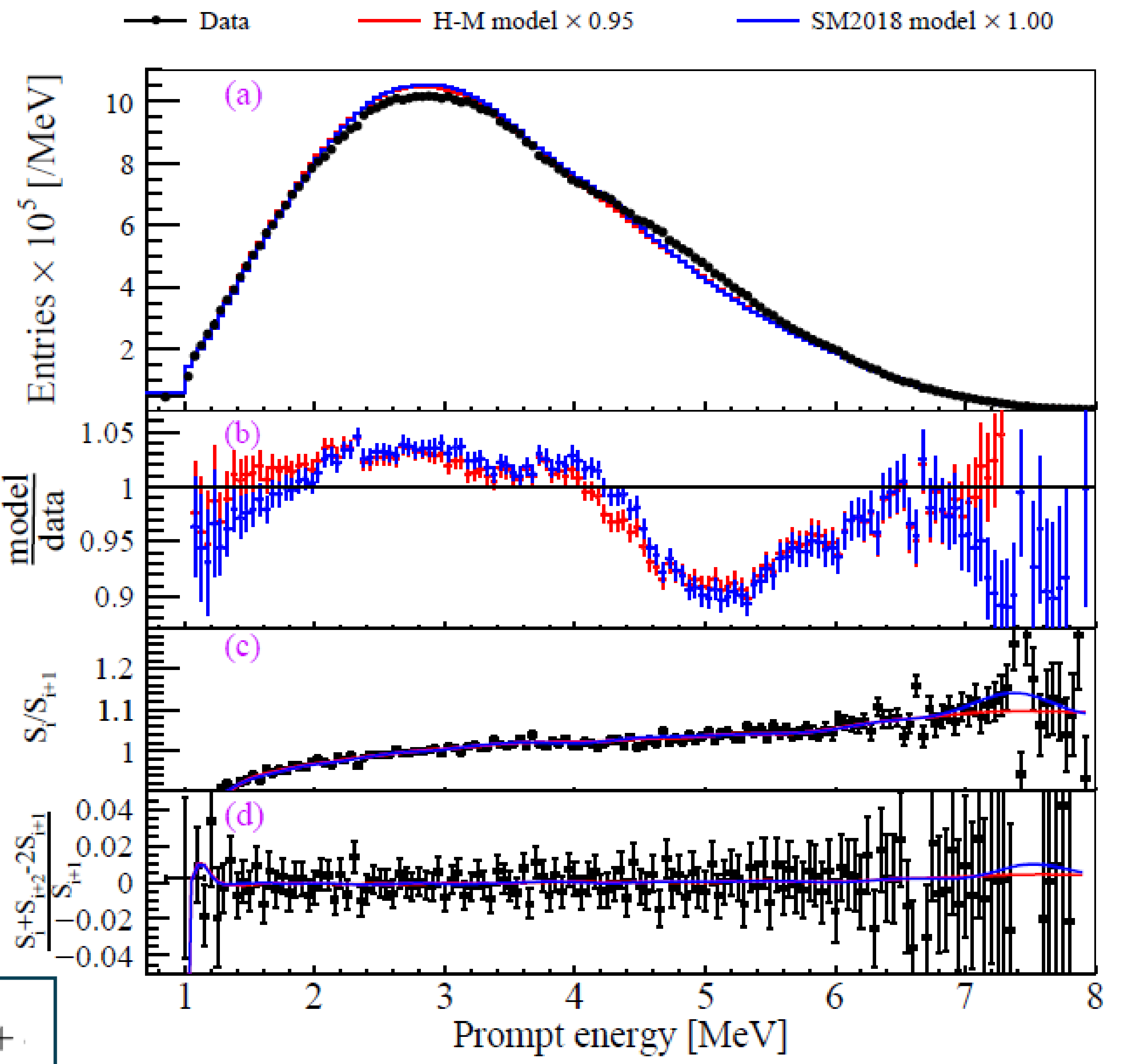
Analysis of Daya Bay's arXiv:2102.04614v2 data

Spectrum and its covariance given with 50 keV prompt energy bin.



We will re-bin the data and obtain new covariance matrices using:

$$\mathrm{cov}(aX+bY, cW+dV) = ac\ \mathrm{cov}(X,W) + ad\ \mathrm{cov}(X,V) + bc\ \mathrm{cov}(Y,W) + bd\ \mathrm{cov}(Y,V)$$

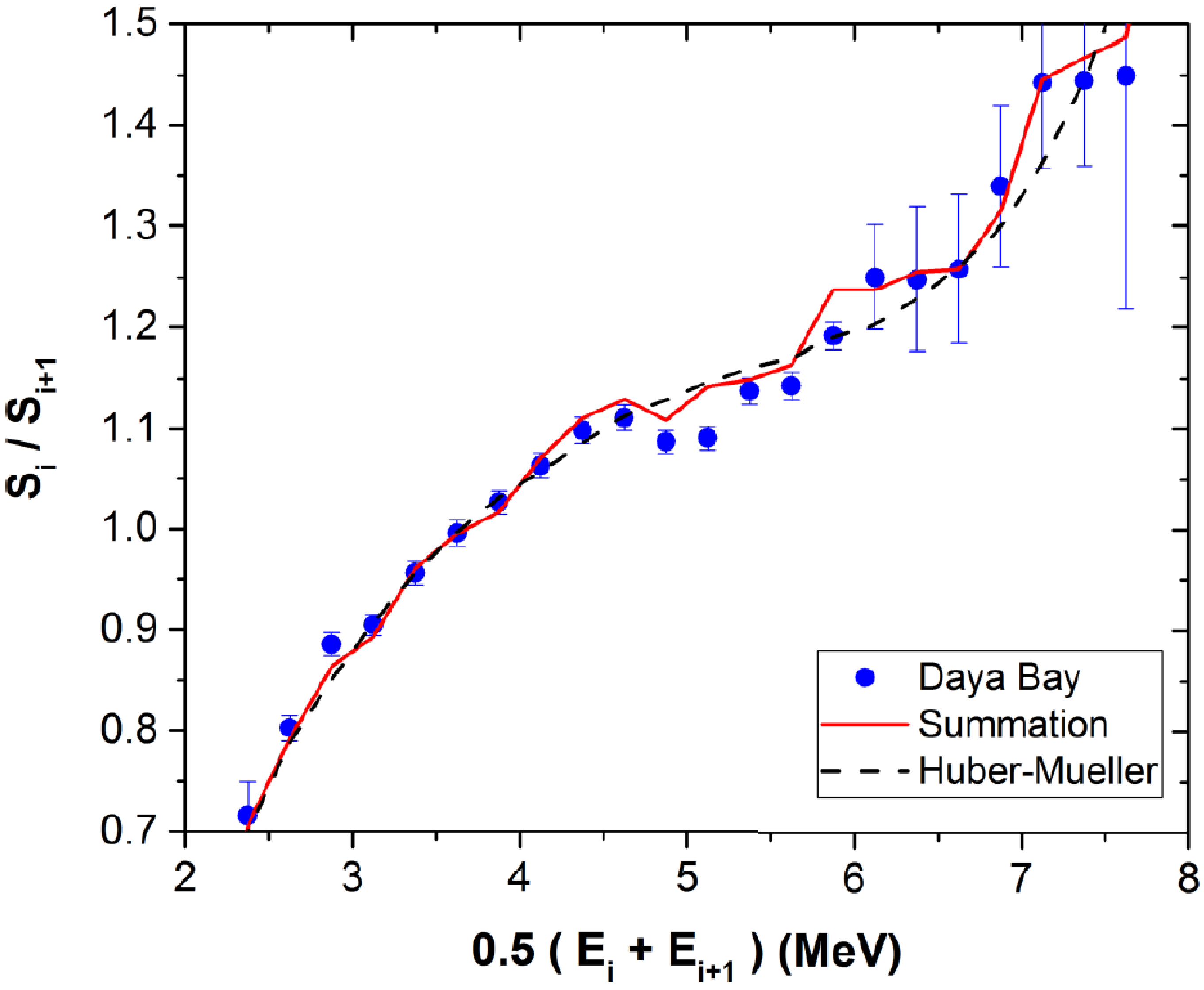
The presence of individual fission products (Fine Structure) is revealed using the ratio of adjacent spectrum values:

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

with uncertainty given by:

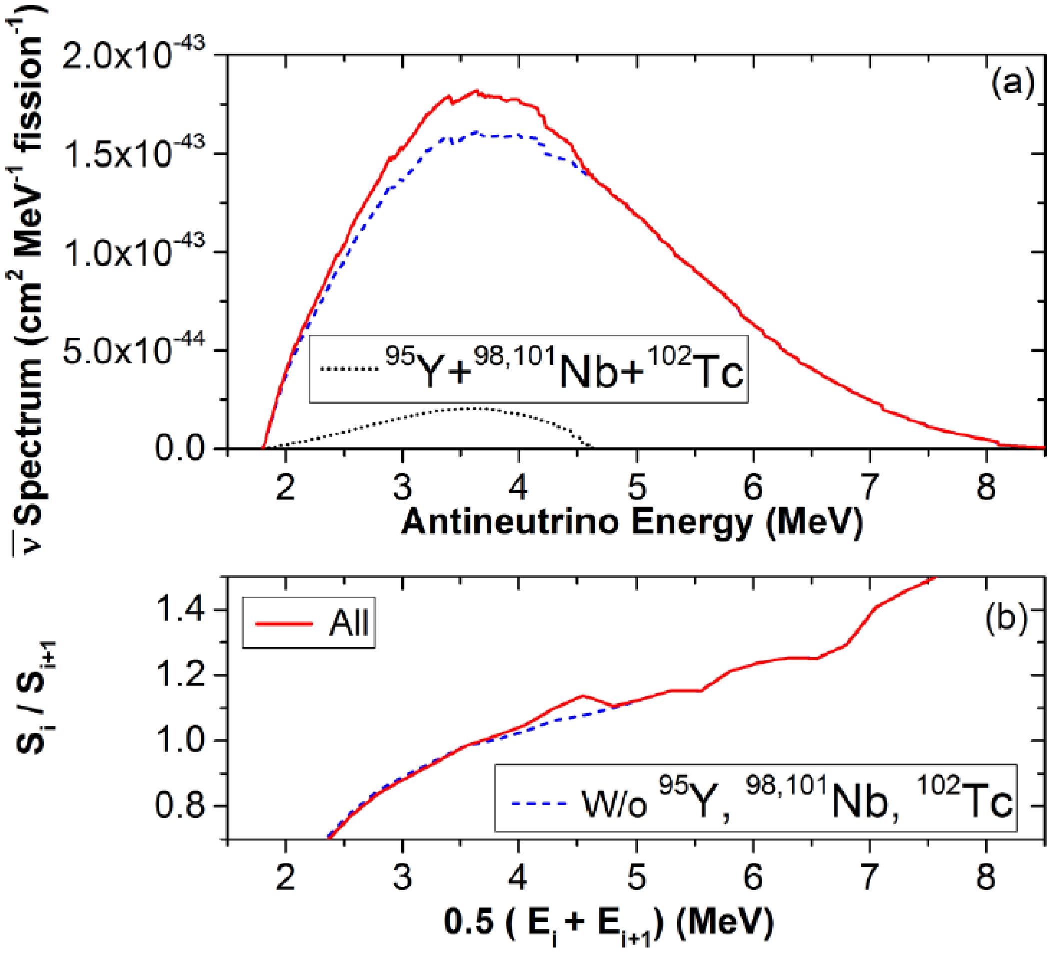
$$\Delta^2 R_i = S_{i+1}^{-2}\sigma_{i,i} + S_i^2 S_{i+1}^{-4}\sigma_{i+1,i+1} - 2 S_i S_{i+1}^{-3}\sigma_{i,i+1},$$

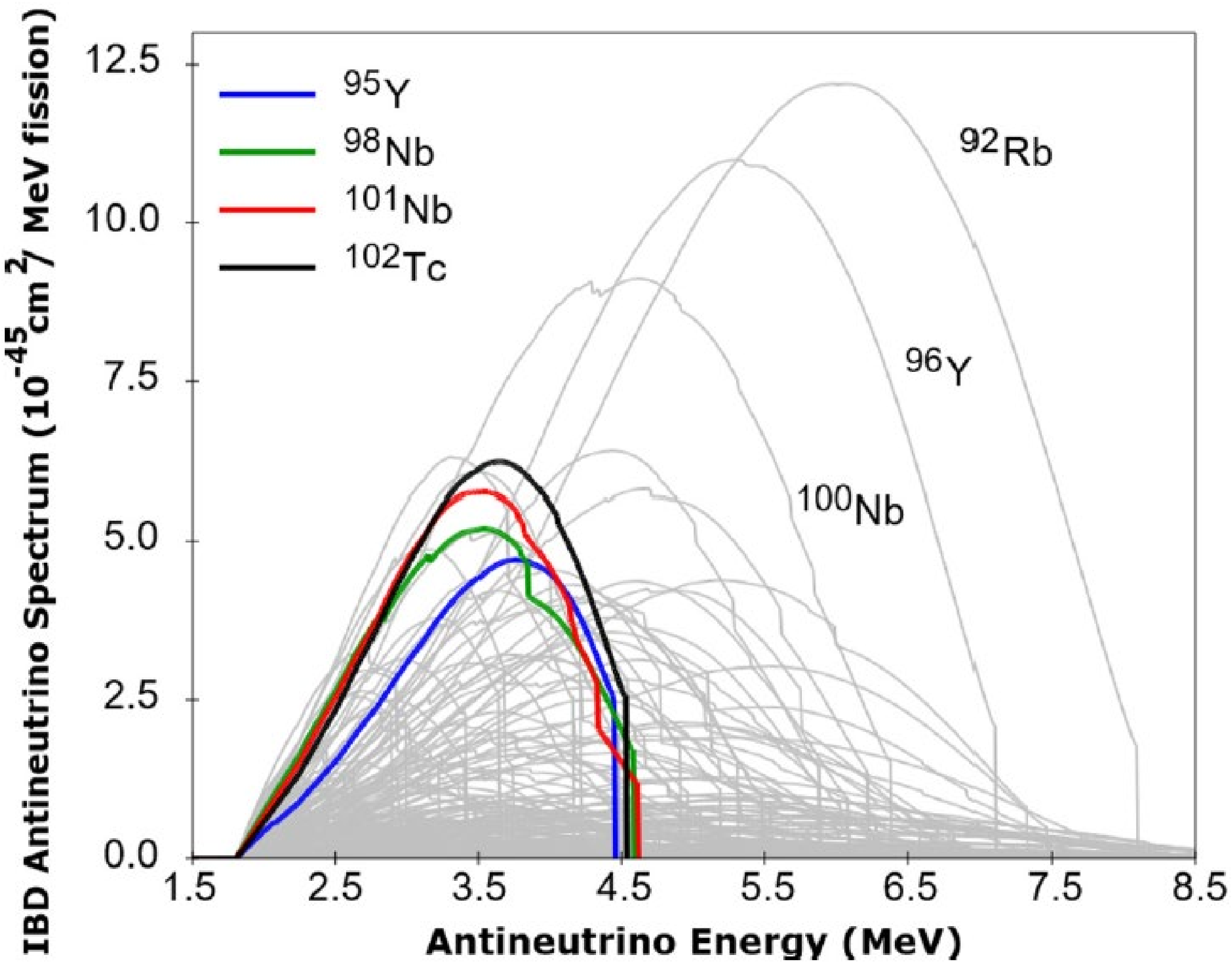
With **σ** the covariance matrix.



To better reveal fine structure you need to reduce the spectrum uncertainty and increase the adjacent spectrum points correlation!

Our 2018 analysis





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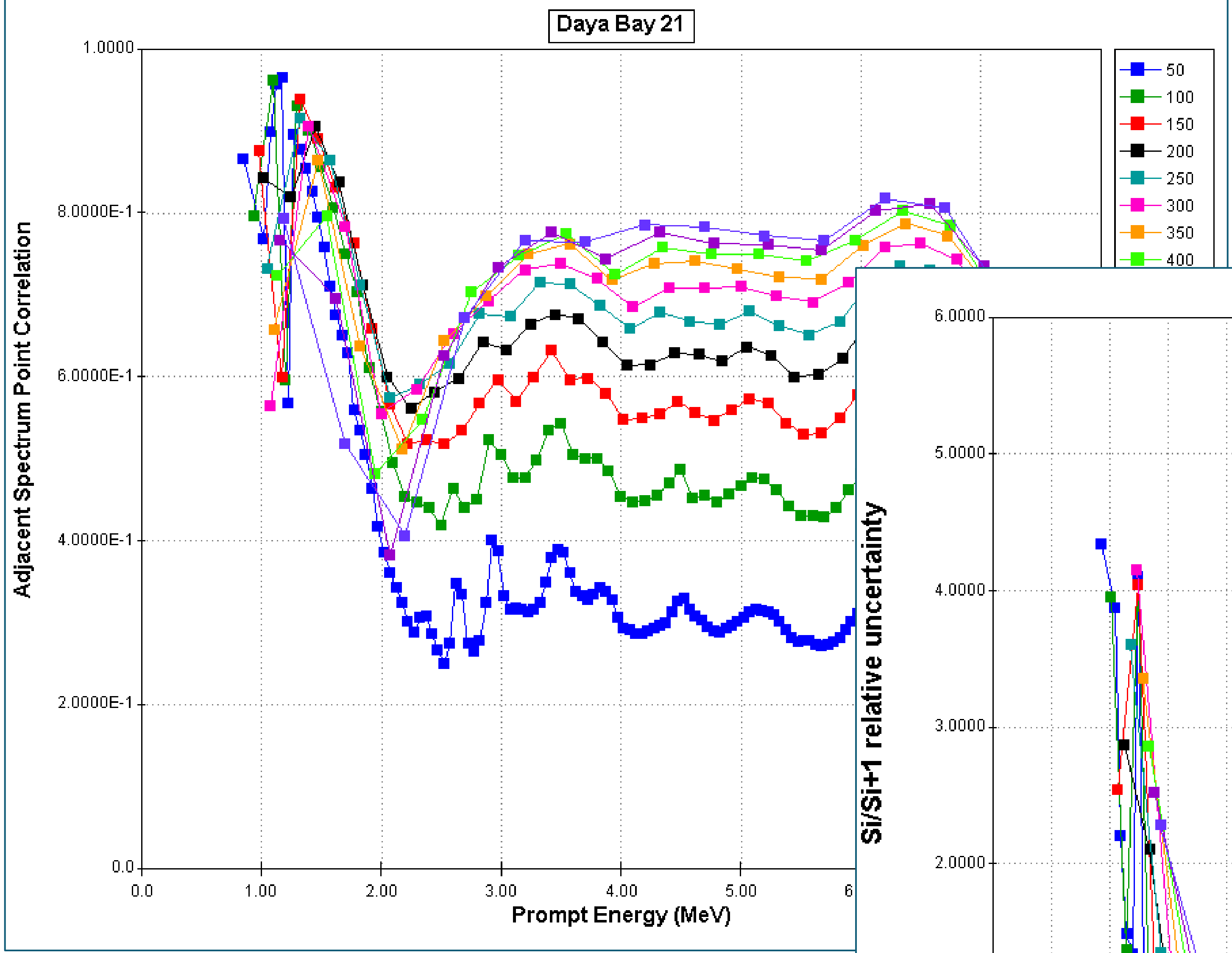
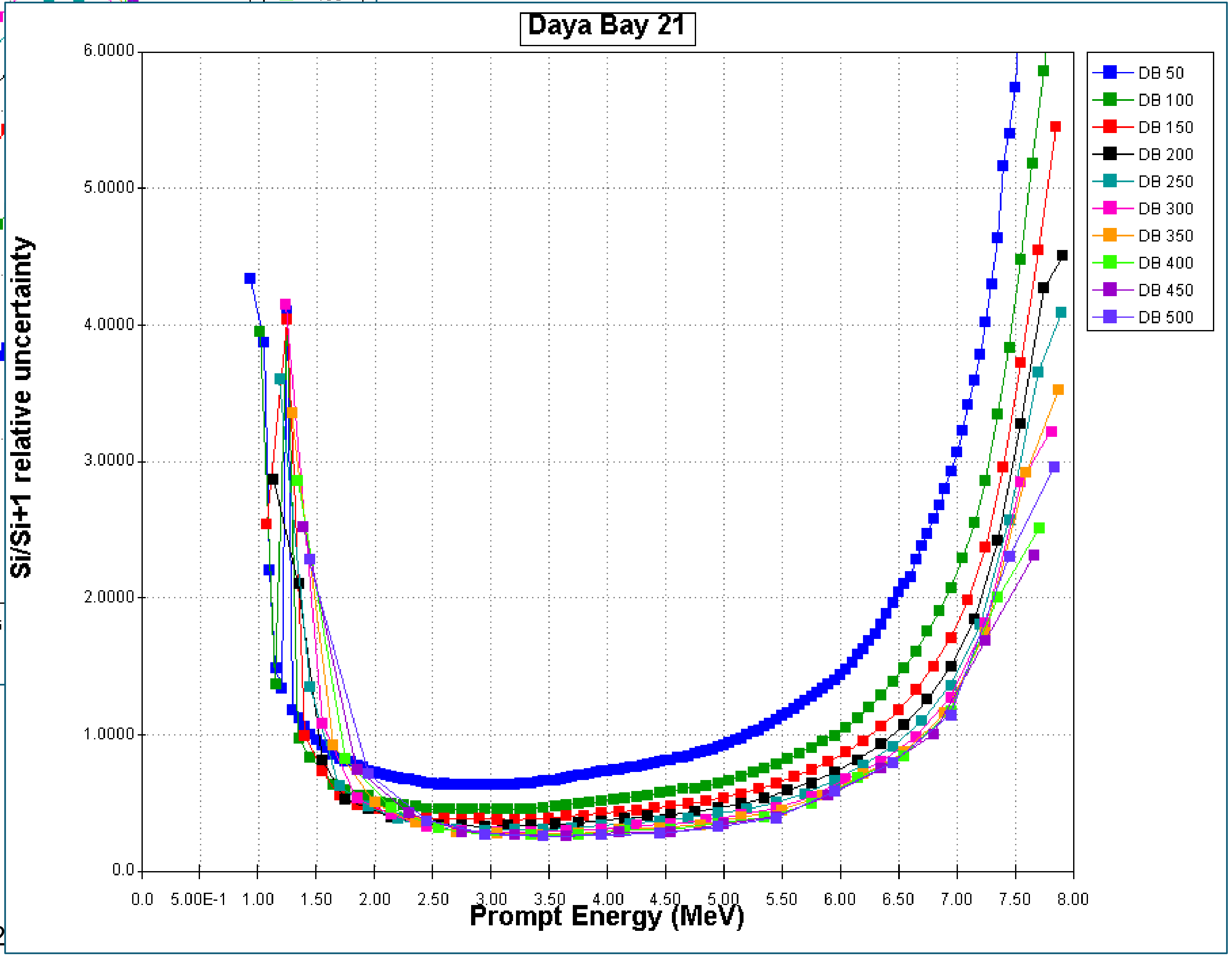
Binning Results





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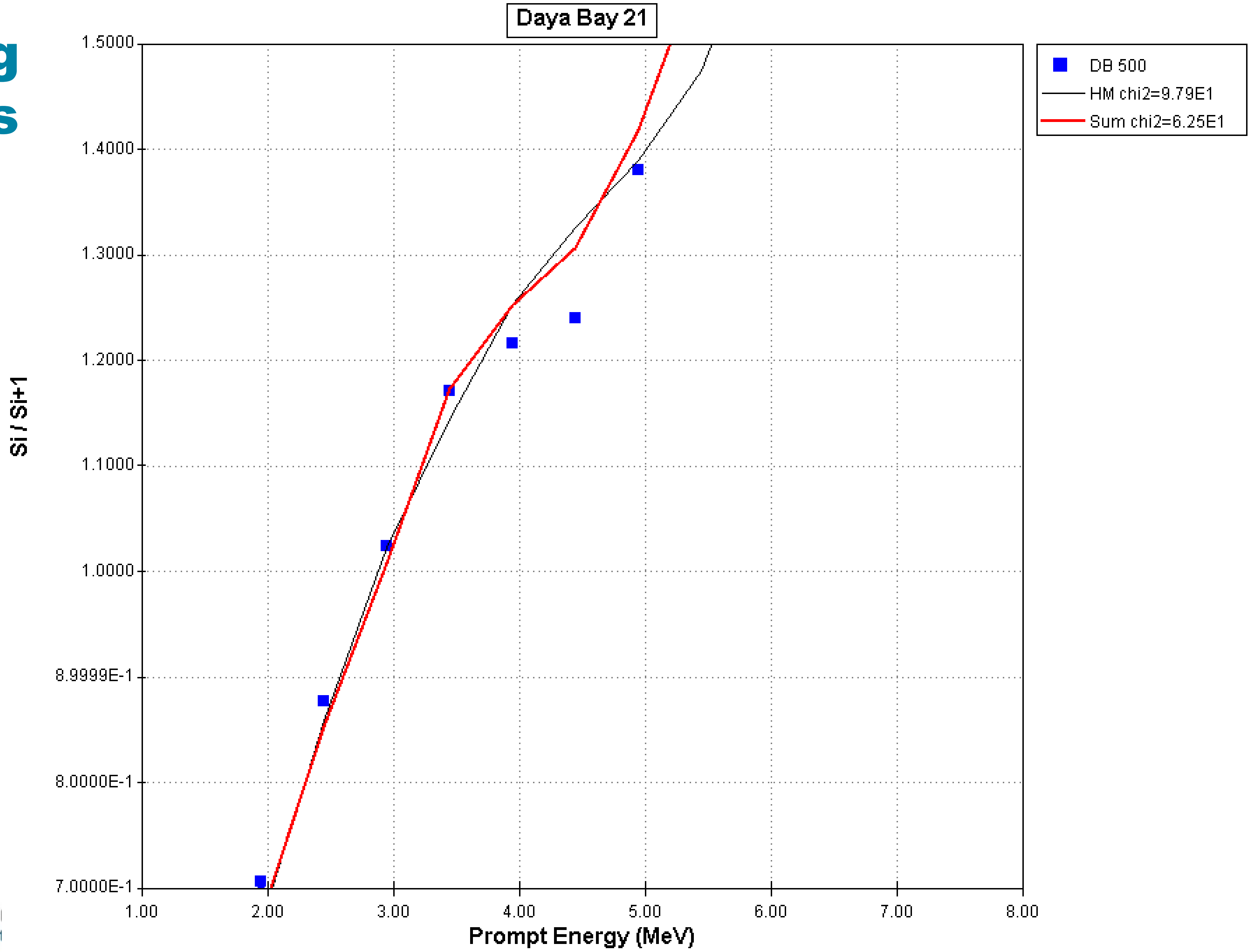
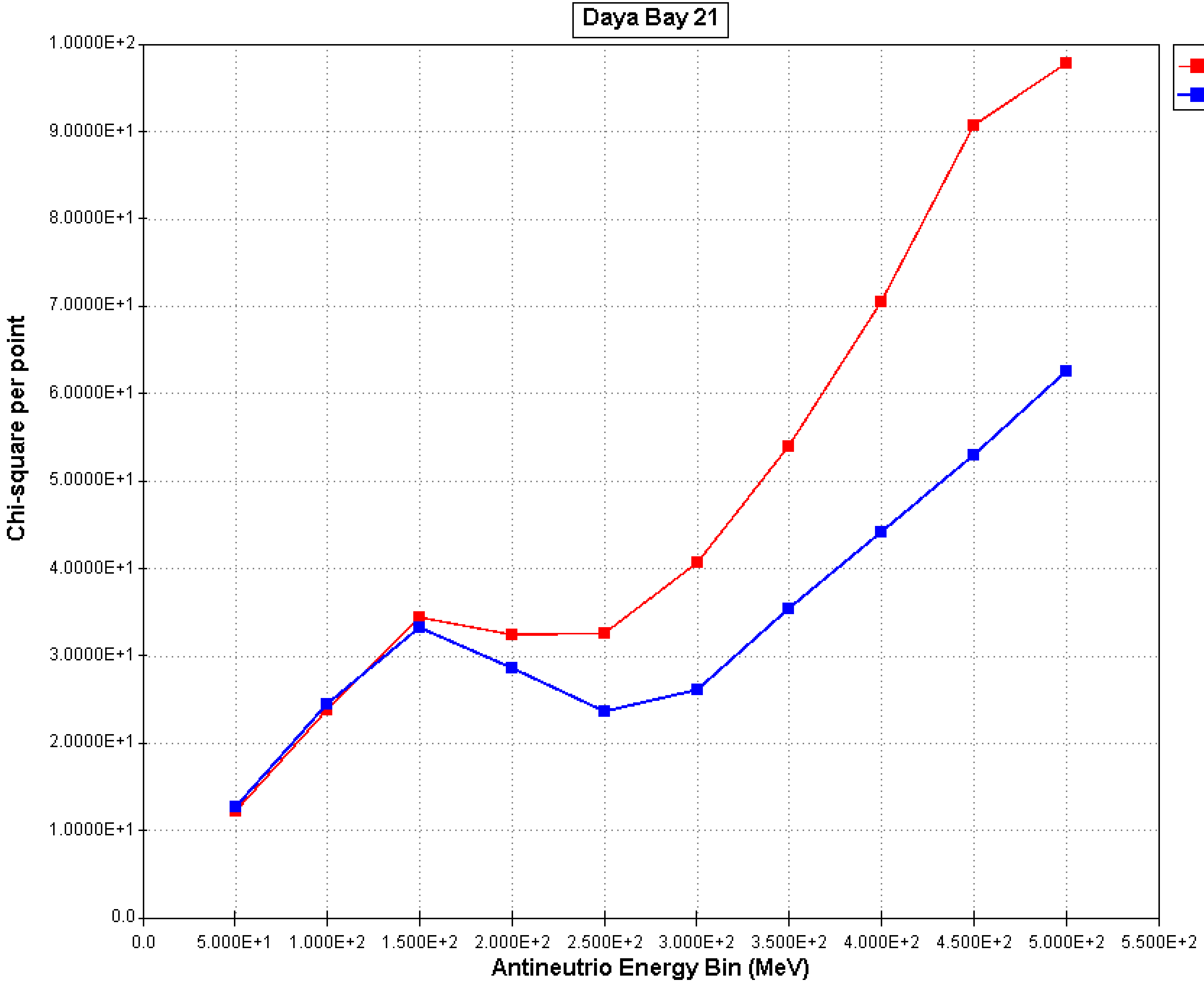
Binning Results





For this particular case, the sweet spot to reveal fine structure seems to be a 250 keV binning.

<u>Note:</u>

To understand the possible individual fission product effects, we really need the spectrum as function of the antineutrino energy.

Conclusions

- ❑ We really need to remeasure the big 4's electron spectra with modern techniques and 25 keV bins.

- ❑ We absolutely need TAGS data to predict decay heat and nuclear reactors antineutrino spectrum. There are still approx. 20 nuclides waiting for a measurement.

- ❑ Keep in mind that most relevant fission yields have not been measured directly, isomers can be a problem.

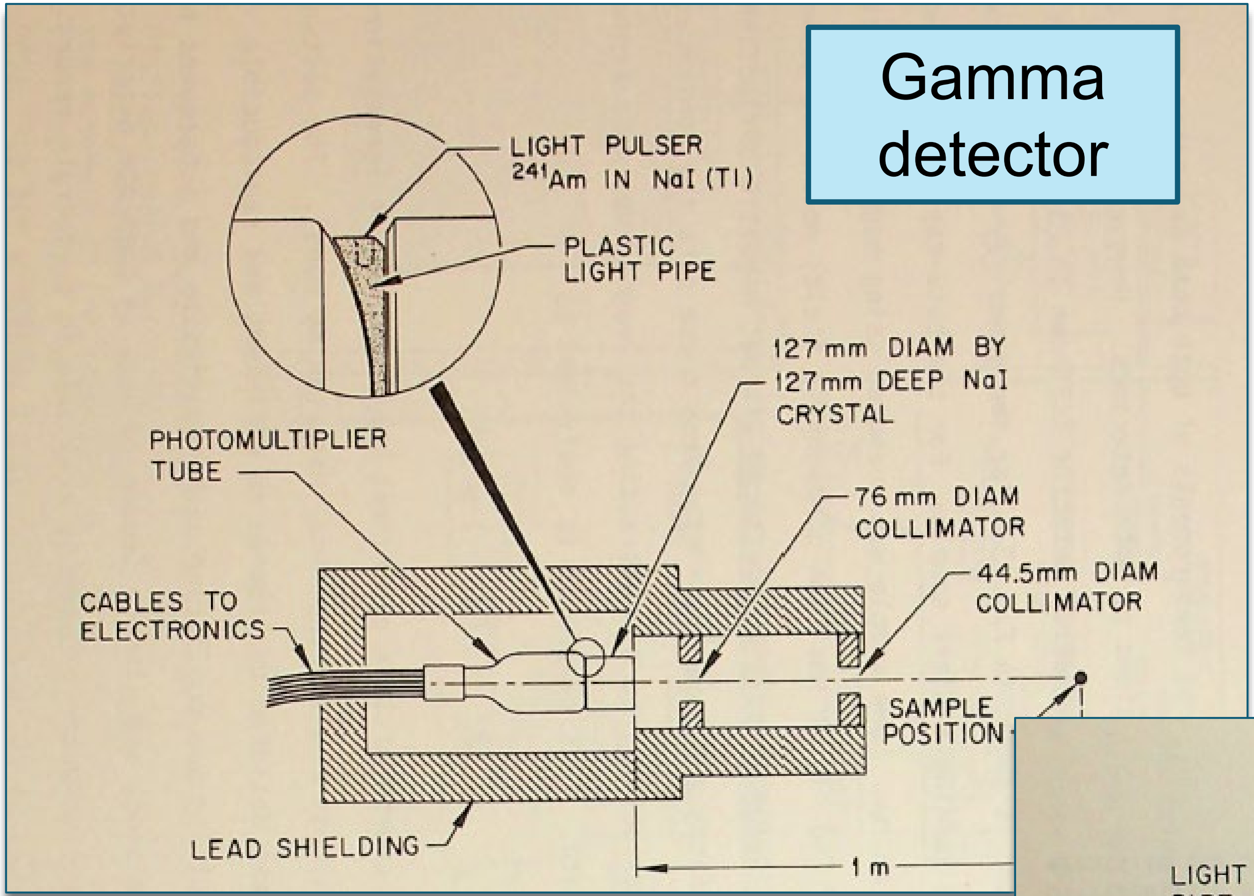
Acknowledgements:

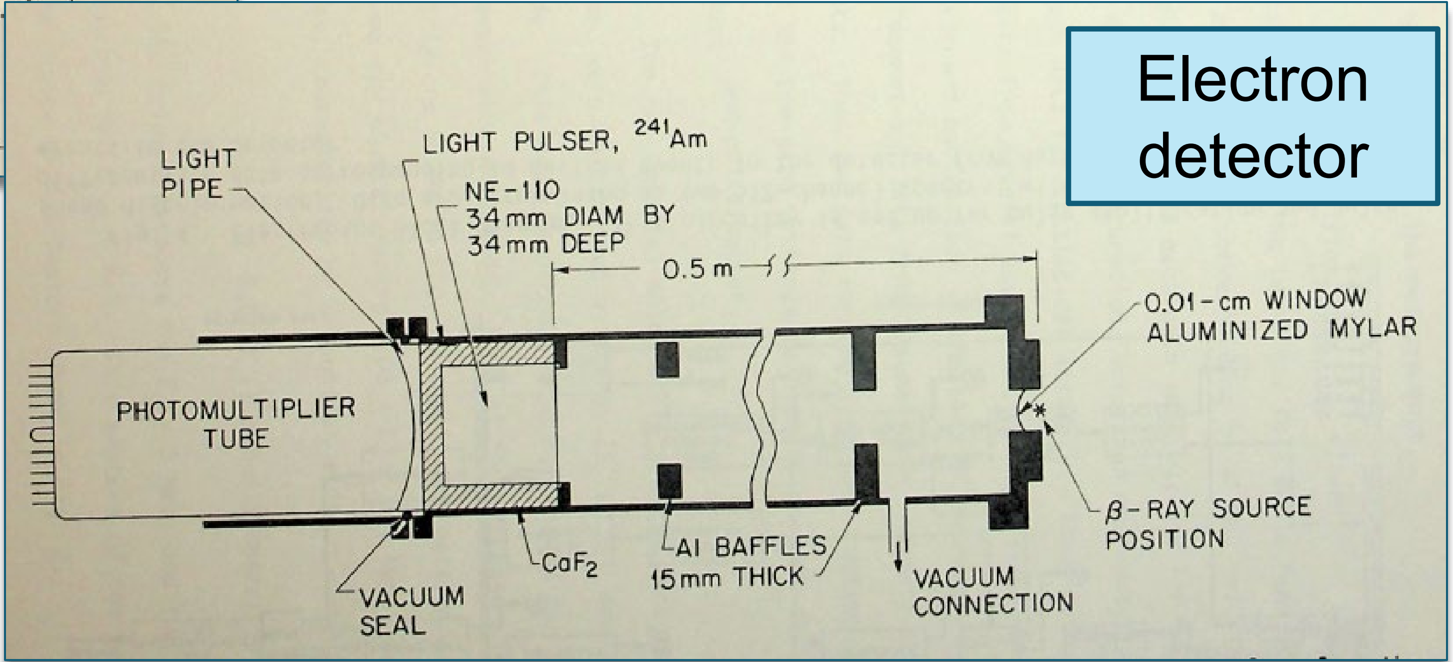
Work at Brookhaven National Laboratory was sponsored by the Office of Nuclear Physics, Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-98CH10886 as well as by the U.S. Department of Energy, National Nuclear Security Administration, Office of Defense Nuclear Nonproliferation Research and Development (DNN R\&D).

We are grateful to the Daya Bay collaboration for sharing their data, including a full documentation and spectrum covariance matrix.

Backup material

ORNL detectors





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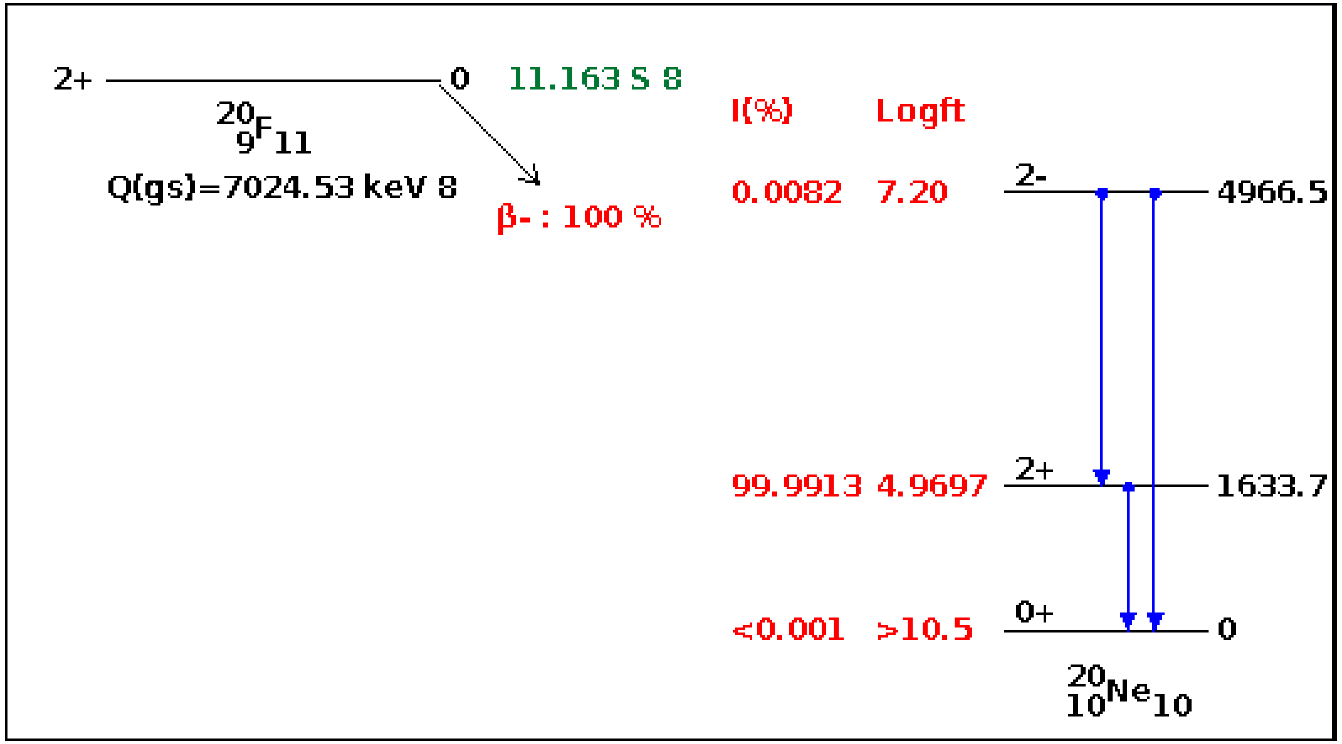
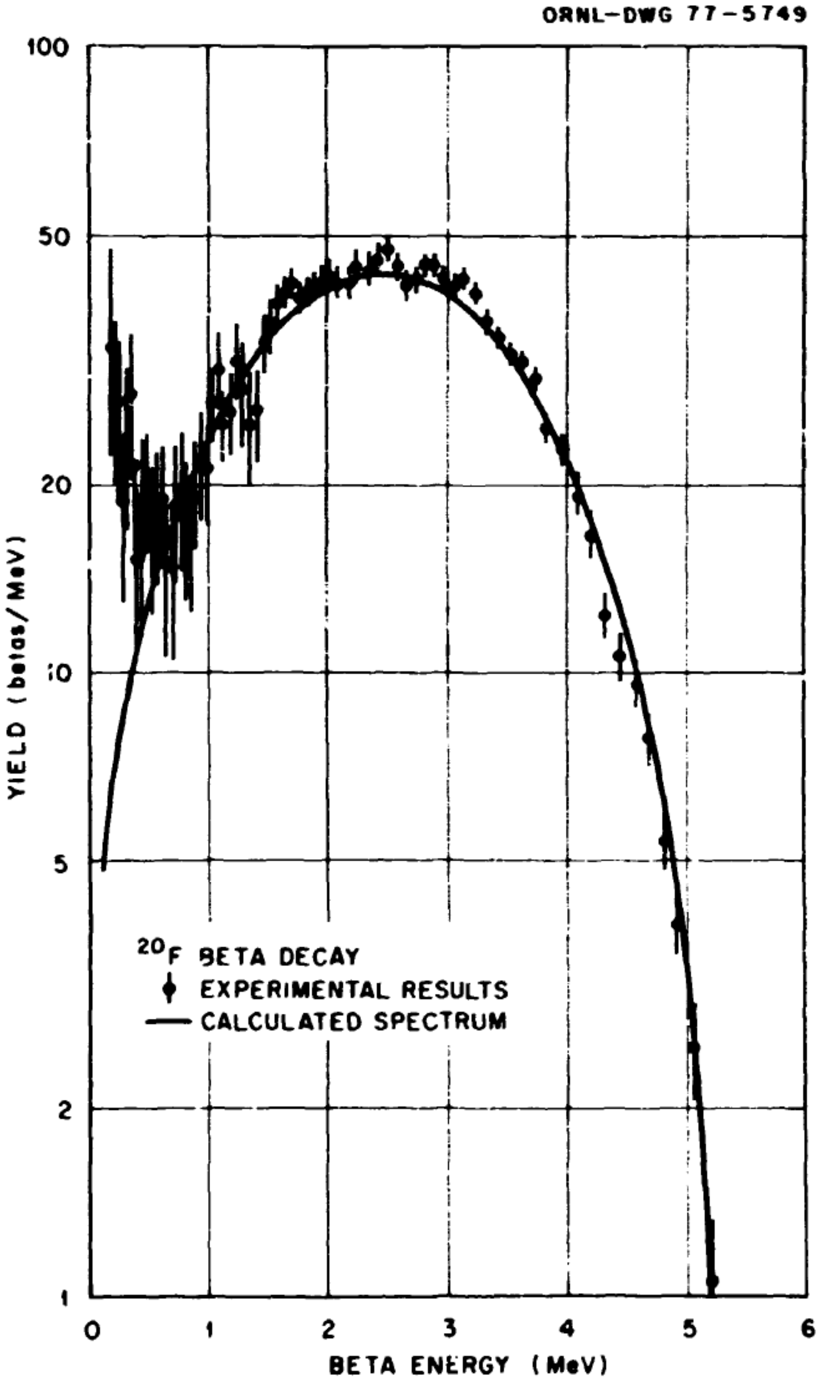
Electron spectra

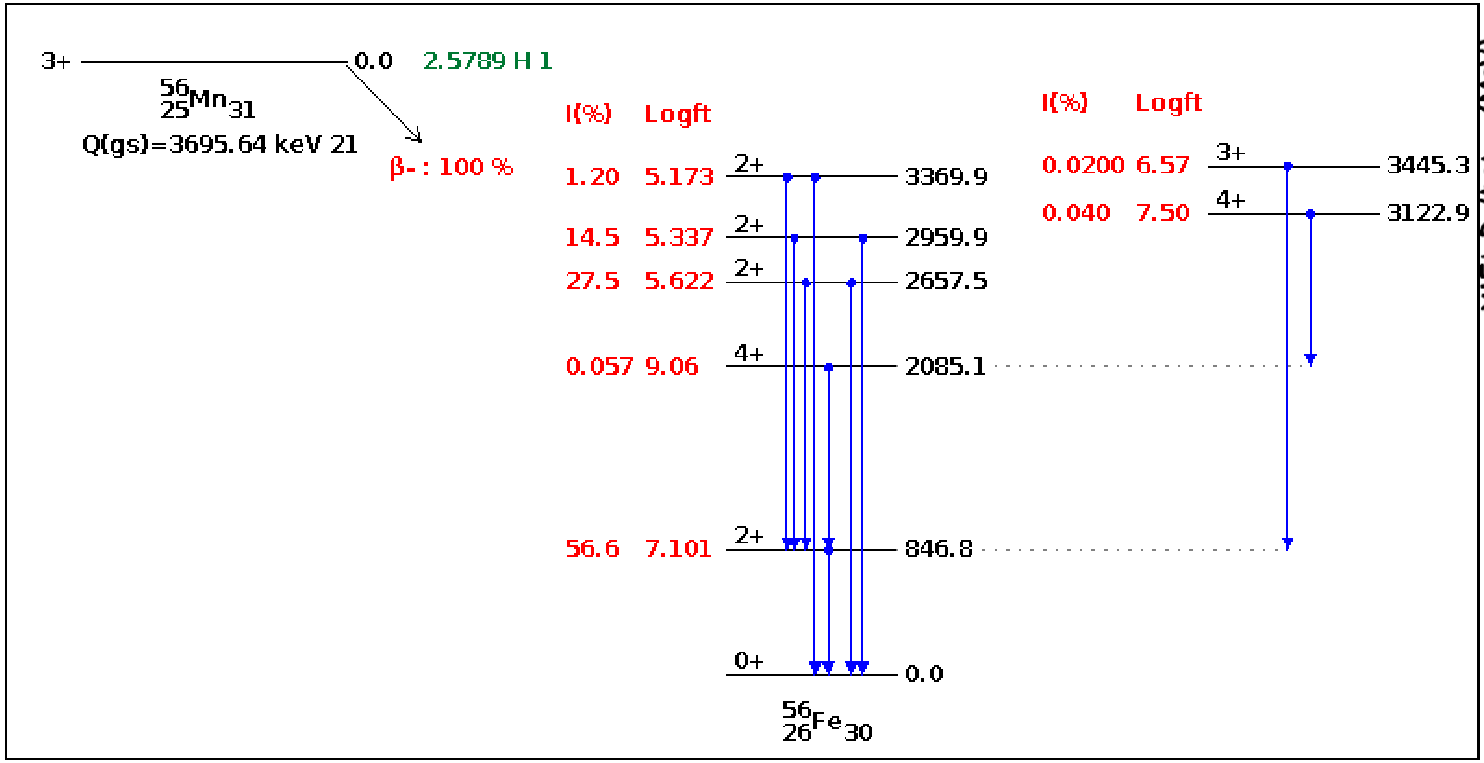
- ❑ Electron spectra measurements were benchmarked with the well-known beta-minus decay of $^{19}F(n,\gamma)^{20}F$.

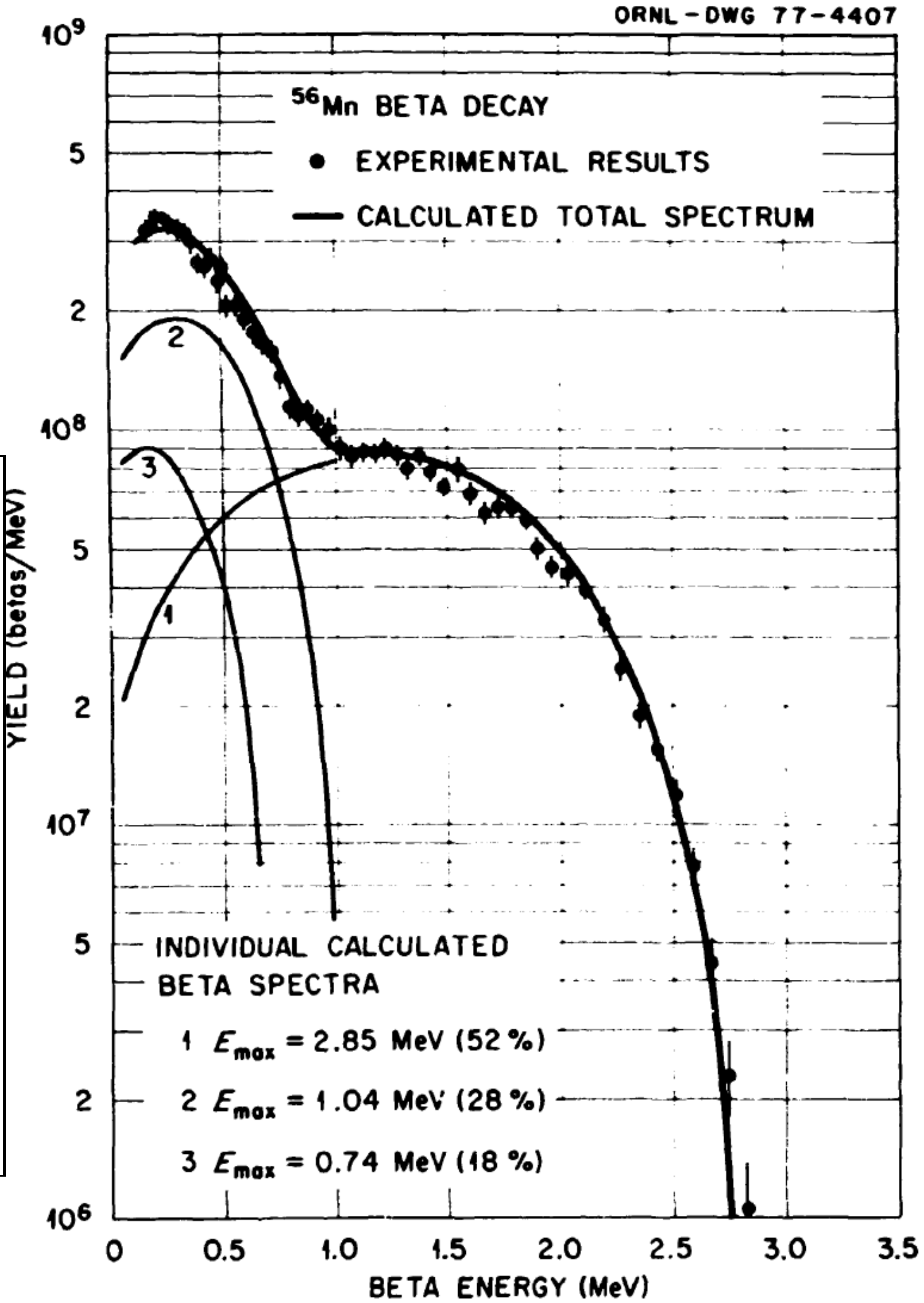




Electron spectra

- Electron spectra measurements were benchmarked with the well-known beta-minus decay of $^{55}Mn(n,\gamma)^{56}Mn$.

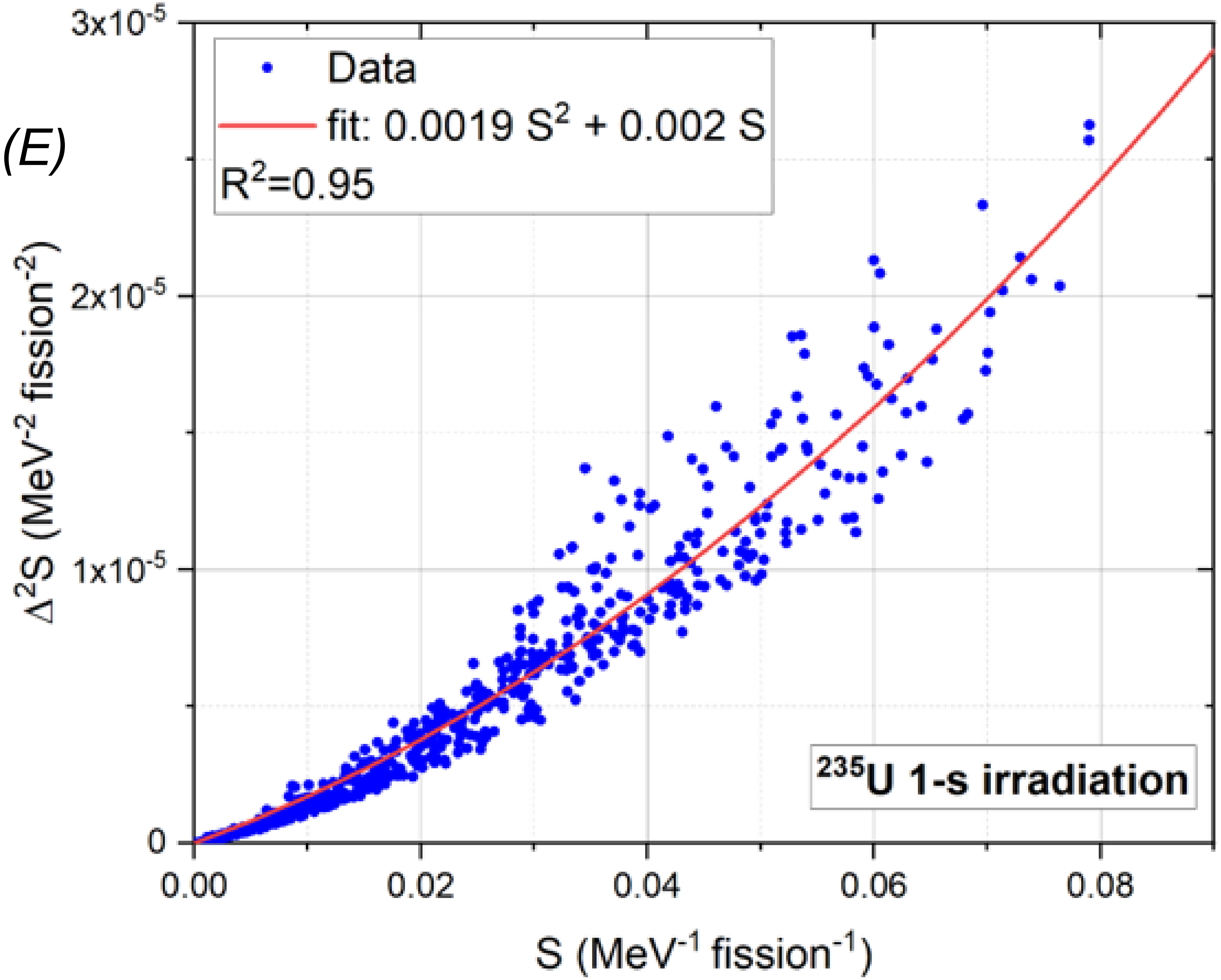




$$\Delta^2 S_{stat}(E) = \Delta^2 S_{stat}(E) + \Delta^2 S_{sys}(E)$$

$$\Delta\, S_{stat}(E) = c_{stat} S^{1/2}(E)$$

$$\Delta\, S_{sys}(E) = c_{sys} S(E)$$



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