Oak Ridge National Laboratory

Nuclear Data for the Reactor Antineutrino Source Term: Introduction

WONDRAM Workshop – June 22, 2021

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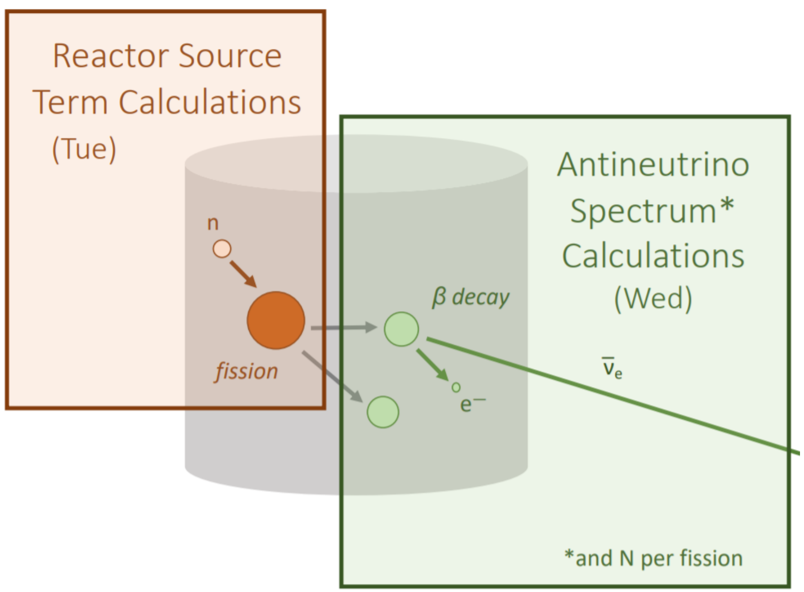
What is part of the source term session?

- We consider effects **up until** the fission process
  - Independent fission product yields (pre-fission fragment decay)
  - Reactor parameters which impacts yields or $\bar{\nu}_e$ spectrum
    - Neutron reaction cross-sections (fission, absorption, etc.)
    - Design and operational considerations
  - **Not** data related to decay, individual β or $\bar{\nu}_e$ spectra
    - Antineutrino Spectrum Calculations (Day 3 – Wednesday)
    - Antineutrino Detector Response (Day 4 – Thursday)

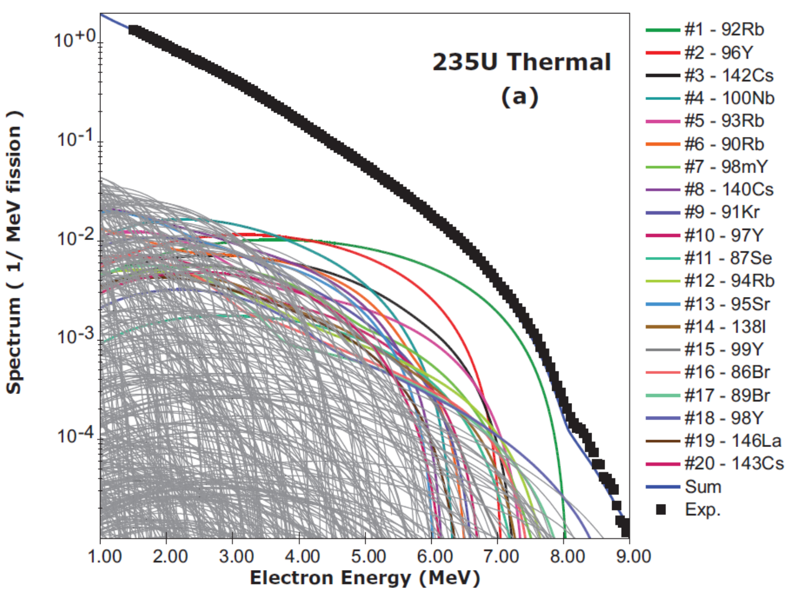


Reactor Source Term: Session Goals

- Fission product yield data
  - What are the uncertainties in the independent fission product yields?
  - What is their dependence on neutron energy?
  - Which fission product yields are most important?
  - What measurements are still needed?
- Fission product absorption cross-section data and uncertainty
  - What are the key fission products with high absorption XS uncertainties?
  - How is this calculated for reactor physics vs. neutrino measurements?
  - What reactor modeling can be done to ameliorate?
- Status of non-equilibrium corrections
  - What are irradiation environment effects on FP concentrations?
  - What are their uncertainties? How are they calculated?
  - What reactor modeling can be done to ameliorate?
- Opportunities/challenges with advanced reactors?
- Streamlining calculations

Fission product yield data

- $\beta/\bar{\nu}_e$ spectra directly related to fission yields:
  - $N_\beta(E_e) = \sum_{F_i} Y_{F_i} S(E_e, Z_i, A_i)$
  - β delayed *n*'s ?
- Which are the most important?
  - MTAS measurements needed?



Nuclide	Q_β (MeV)	GS BR (%)	$J^\pi_{gs} \rightarrow J^\pi_{gs}$	Contr. (%)
^{96}Y	7.1	95.5(5)	$0^- \rightarrow 0^+$	6.3
^{92}Rb	8.1	95.2(7)	$0^- \rightarrow 0^+$	6.1
^{100}Nb	6.4	50(7)	$1^+ \rightarrow 0^+$	5.5
^{135}Te	5.9	62(3)	$(7/2^-) \rightarrow 7/2^+$	3.7
^{142}Cs	7.3	56(5)	$0^- \rightarrow 0^+$	3.5
^{140}Cs	6.2	36(2)	$1^- \rightarrow 0^+$	3.4
^{90}Rb	6.6	33(4)	$0^- \rightarrow 0^+$	3.4
^{95}Sr	6.1	56(3)	$1/2^+ \rightarrow 1/2^-$	3.0
^{88}Rb	5.3	77(1)	$2^- \rightarrow 0^+$	2.9

^{235}U 4 MeV

Nuclide	Q_β (MeV)	GS BR (%)	$J^\pi_{gs} \rightarrow J^\pi_{gs}$	Contr. (%)
^{92}Rb	8.1	95.2(7)	$0^- \rightarrow 0^+$	21.6
^{96}Y	7.1	95.5(5)	$0^- \rightarrow 0^+$	14.5
^{142}Cs	7.3	56(5)	$0^- \rightarrow 0^+$	6.8
^{100}Nb	6.4	50(7)	$1^+ \rightarrow 0^+$	4.7
^{93}Rb	7.5	35(3)	$5/2^- \rightarrow 7/2^+$	4.6
^{90}Rb	6.6	33(4)	$0^- \rightarrow 0^+$	3.4
^{98m}Y	9.0	12(5)[a]	$(4,5) \rightarrow 4^+$	2.8
^{140}Cs	6.2	36(2)	$1^- \rightarrow 0^+$	2.4
^{91}Kr	6.8	18(3)[b]	$5/2^{(+)} \rightarrow (5/2^-)$	2.4

^{235}U 5.5 MeV

Sonzogni, Phys. Rev. C. (2015)

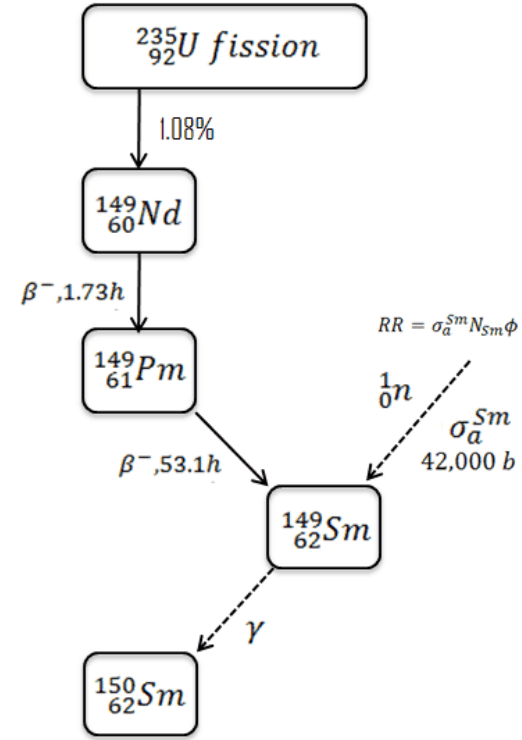
FPY uncertainties for LWR systems

Fission-able nuclide *i*	Fission product *j*	Thermal incident neutron energy		Intermediate incident neutron energy		Fast incident neutron energy	
		Mean (-)	Standard deviation (%)	Mean (-)	Standard deviation (%)	Mean (-)	Standard deviation (%)
^{235}U	^{135}Te	3.23E-02	2.11	2.48E-02	9.93	1.05E-02	18.05
	^{135}I	2.92E-02	2.28	3.59E-02	6.58	3.13E-02	6.14
	^{135}Xe	7.97E-04	1.11	1.20E-03	10.86	4.54E-03	6.17
	^{149}Nd	6.87E-05	48.53	3.50E-05	48.39	6.98E-04	48.36
	^{149}Pm	3.93E-08	47.81	1.63E-08	49.60	1.31E-05	50.00
	^{149}Sm	1.75E-12	48.07	5.68E-13	48.57	2.67E-08	47.72
^{238}U	^{135}Te	-	-	4.61E-02	9.01	2.65E-02	9.18
	^{135}I	-	-	1.36E-02	28.92	2.59E-02	28.78
	^{135}Xe	-	-	1.23E-04	2.45	1.33E-03	2.54
	^{149}Nd	-	-	4.99E-06	47.71	6.30E-05	47.71
	^{149}Pm	-	-	1.19E-09	46.92	1.57E-07	46.92
	^{149}Sm	-	-	1.55E-14	50.35	2.27E-11	50.41
^{239}Pu	^{135}Te	2.19E-02	9.62	2.12E-02	28.11	6.87E-03	45.20
	^{135}I	4.28E-02	4.94	3.92E-02	9.97	3.25E-02	24.16
	^{135}Xe	3.14E-03	3.43	6.11E-03	6.14	8.54E-03	47.60
	^{149}Nd	4.99E-04	48.45	5.89E-04	49.10	2.37E-03	46.64
	^{149}Pm	2.38E-06	50.82	2.55E-06	48.70	1.39E-04	47.55
	^{149}Sm	8.22E-10	48.13	9.57E-10	48.52	9.81E-07	49.94

Wieselquist, NRC Report (2017)

Fission yield data of "non-equilibrium" isotopes

- Long time to reach equilibrium of certain FP
  - ^{135}Xe builds up over ~ hours/days
  - ^{149}Sm builds up over ~ month
  - Impacts neutron flux and fission distributions
- Isotopes previously identified
  - **^{97}Zr, ^{132}I, ^{93}Y, ^{106}Ru, ^{144}Ce, ^{90}Sr**
  - (*Hayes, Rev. Mod. Phys. (2016)*)
- Is better modeling needed?

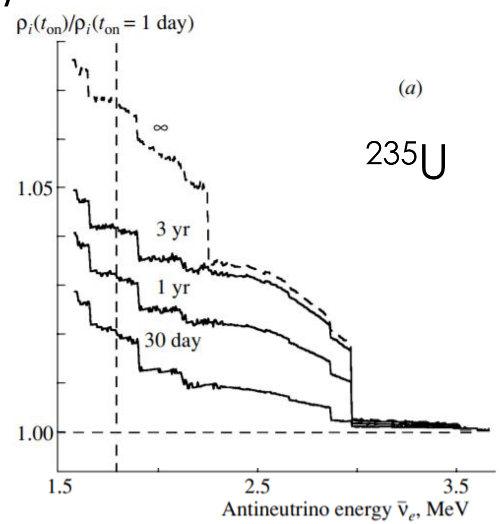


Source: www.nuclear-power.net
Data: JANIS 4.0 / NEA

$$^{106}\text{Ru} \xrightarrow[E_{\max} = 0.04\ \text{MeV}]{T_{1/2} = 372\ \text{day}} \text{Rh} \xrightarrow[E_{\max} = 3.541\ \text{MeV}]{T_{1/2} = 30\ \text{s}} \text{Pd (stab)},$$

$$^{144}\text{Ce} \xrightarrow[E_{\max} = 0.32\ \text{MeV}]{T_{1/2} = 285\ \text{day}} \text{Pr} \xrightarrow[E_{\max} = 2.996\ \text{MeV}]{T_{1/2} = 17\ \text{min}} \text{Nd}(T_{1/2} = 3 \times 10^{15})\ \text{yr}.$$

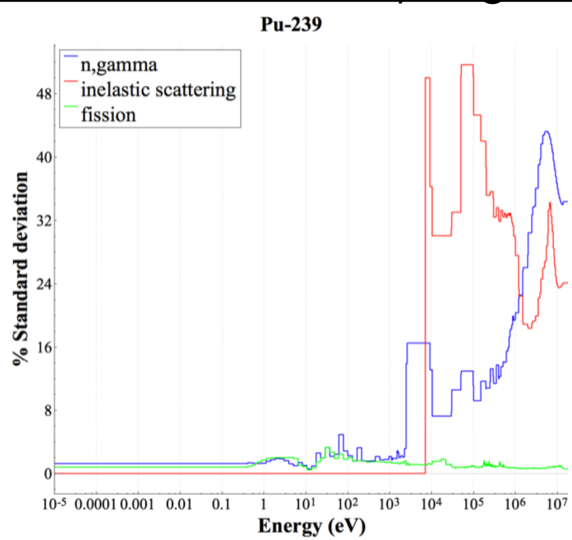
Kopeikin, Phys. At. Nuc. (2001)

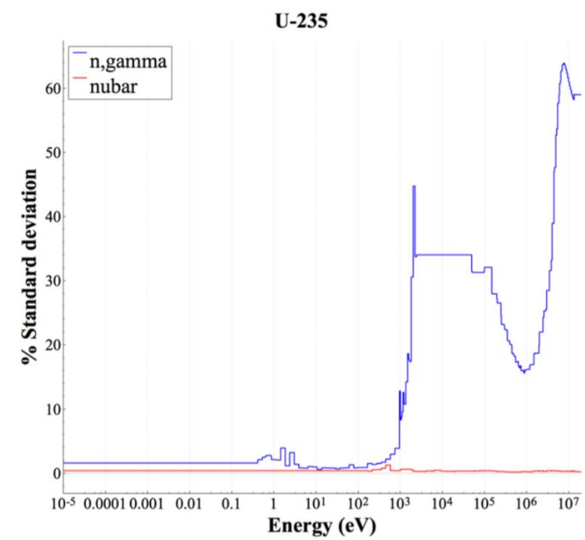


Ratio of $\bar{\nu}_e$ to t=1 day

Cross-section data for better modeling

- For current and advanced reactors:
  - $^{235}U(n,f)$ fast
  - $^{239}Pu(n,f)$ – fast
  - $^{135m}Xe(n,X)$
  - Various scattering (graphite, salt, FLiBe, iron, etc.)
- How has CIELO helped improve?
  - Collaborative International Evaluation Library Organization
  - k_{eff} in nuclear tech.
  - $^{235,236,238}U$
  - ^{239}Pu
  - ^{16}O, ^{56}Fe, ^{1}H
- What about?
  - Sensitivities
  - Uncertainties





Bostelmann, ORNL report (2019)

Key cross-section data uncertainties

Nuclide, *i*	Neutron reaction type, *x*	Cross section, $\sigma_{i,x}$ (barns)	Uncertainty with correlation (%)	Uncertainty without correlation (%)	Uncertainty weighted average (%)
^{235}U	fission (f)	3.73E+01	0.32	0.10	0.40
	gamma (γ)	8.68E+00	1.26	0.48	2.15
	$\bar{\nu}$	2.54E+00	0.11	0.05	0.26
^{238}U	fission (f)	1.27E-01	0.52	0.29	0.64
	gamma (γ)	2.12E+00	1.17	0.72	2.50
	scattering (sIN)	1.24E+00	14.08	6.49	16.10
^{239}Pu	fission (f)	8.20E+01	0.77	0.31	1.10
	gamma (γ)	4.42E+01	1.13	0.49	1.53
	$\bar{\nu}$	3.01E+00	0.07	0.05	0.22
^{240}Pu	gamma (γ)	2.16E+02	0.25	0.08	0.27
^{135}I	gamma (γ)	5.16E+00	3.65	3.65	13.24
^{135}Xe	gamma (γ)	1.63E+05	4.15	1.48	4.15
^{149}Pm	gamma (γ)	1.13E+02	16.14	5.53	21.43
^{149}Sm	gamma (γ)	4.44E+03	1.47	0.59	1.58
^{10}B	alpha (α)	2.50E+02	0.08	0.02	0.08
^{155}Gd	gamma (γ)	2.14E+03	3.27	1.76	4.95
^{90}Zr	gamma (γ)	9.53E-03	11.72	5.25	16.97
^{1}H	scattering (sEL)	1.21E+01	0.20	0.04	0.20
	gamma (γ)	2.16E-02	1.07	0.29	1.08
^{2}H	scattering (sEL)	3.03E+00	1.67	0.40	1.97
	gamma (γ)	3.63E-05	5.66	2.41	8.10
^{16}O	scattering (sEL)	3.41E+00	1.91	0.42	1.97
	gamma (γ)	7.62E-05	32.22	10.70	34.84
^{232}Th	gamma (γ)	2.80E+00	1.64	1.59	4.07

Wieselquist, NRC Report (2017)

E_n impact on ^{235}U fission mass distributions

Region No.	Energy range (eV)	V_{ratio}
1	<0.1	1
2	0.29–0.46	1.12 ± 0.34
3	0.78–1.29	1.13 ± 0.35
4	2.38–3.37	0.47 ± 0.21
5	7.71–9.53	1.36 ± 0.42
6	17.34–21.37	0.78 ± 0.26
7	43.4–60.24	0.87 ± 0.26
8	225–275	0.54 ± 0.21
9	511–675	1.40 ± 0.44
10	675–1400	1.13 ± 0.30

V_{ratio} = ratio of resonance to thermal yields

Changes in shape of ^{235}U fission mass distributions as a function of incident neutron energy

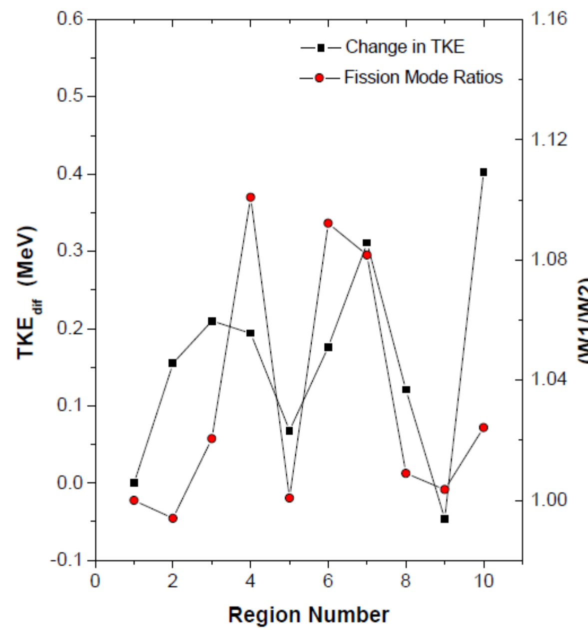


Figure 5.26 - Comparison of TKE trends and Fission Mode Ratio trends in each resonance region.

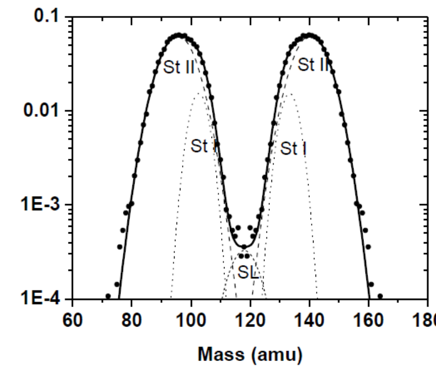
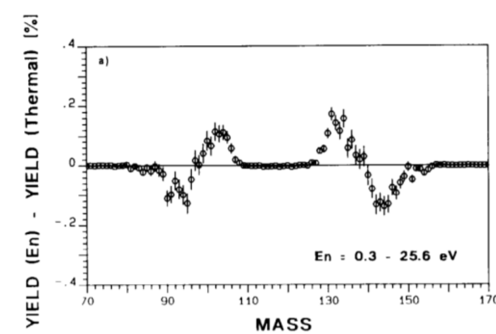


Figure 5.22 - Five Gaussian fit describing the three fission modes for ^{235}U. The points are the data and the solid line is the sum of the three modes.



Hambsch (1989)

C. Romano, Y. Danon, R. Block, J. Thompson, E. Blain, and E. Bond, **Fission fragment mass and energy distributions as a function of incident neutron energy measured in a lead slowing-down spectrometer,** PHYSICAL REVIEW C **81**, 014607 (2010)

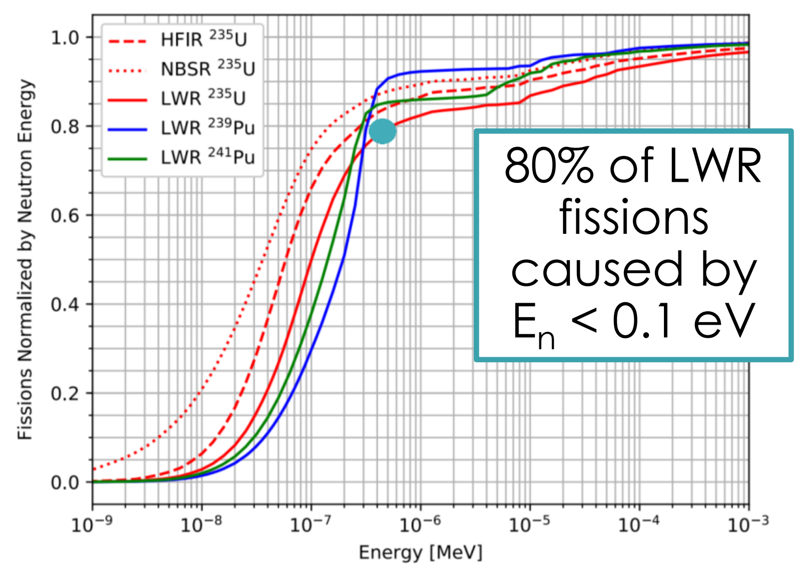
Neutron energy dependence on FPY

- ENDF/B-VIII.0 has changed no fission yield data
- Reactor yields only for thermal, intermediate, and fast
- ***Does this need to be better understood?***

^{235}U E = 0.0253 eV

Material	Quantity	ENDF/B-VIII.0 (current)	ENDF/B-VIII.0 (mod)	Ratio (current/mod)
^{90g}Y	ΔCY	3.7004E-02	5.7819E-04	6.4000E+01
^{90g}Zr	ΔCY	3.7004E-02	5.7819E-04	6.4000E+01
^{91g}Y	ΔCY	3.7298E-02	5.8275E-04	6.4003E+01
^{91m}Y	ΔCY	2.1633E-02	1.3275E-03	1.6296E+01
^{93g}Y	ΔCY	4.0616E-02	7.9430E-04	5.1134E+01
^{93m}Y	ΔCY	1.4160E-02	1.3719E-03	1.0321E+01
^{109g}Ru	IY	8.5644E-06	1.7129E-05	5.0000E-01
^{109g}Ru	ΔIY	5.4812E-06	1.0962E-05	5.0000E-01
^{109g}Ru	CY	3.0360E-04	3.1146E-04	9.7475E-01
^{109g}Ru	ΔCY	1.9431E-04	6.8580E-05	2.8333E+00
^{109g}Rh	IY	2.0599E-08	4.1197E-08	5.0000E-01
^{109g}Rh	ΔIY	1.3183E-08	2.6366E-08	5.0000E-01
^{109g}Rh	CY	3.1220E-04	3.1150E-04	1.0023E+00
^{109g}Rh	ΔCY	1.9981E-04	6.8580E-05	2.9136E+00
^{109g}Pd	ΔCY	1.9981E-04	6.8580E-05	2.9136E+00
^{109g}Ag	ΔCY	1.9982E-04	6.8580E-05	2.9137E+00
^{109m}Ag	ΔCY	1.9970E-04	6.8540E-05	2.9137E+00
^{132g}I	ΔCY	2.7596E-02	6.0619E-04	4.5523E+01
^{133g}I	ΔCY	4.2858E-02	1.9754E-03	2.1695E+01
^{133g}Xe	ΔCY	4.2874E-02	3.4287E-03	1.2504E+01
^{135g}Cs	ΔCY	4.1849E-02	4.5770E-04	9.1434E+01
^{135g}Ba	ΔCY	4.1849E-02	4.5770E-04	9.1434E+01
^{148g}Pr	ΔCY	1.0456E-02	1.2999E-03	8.0435E+00

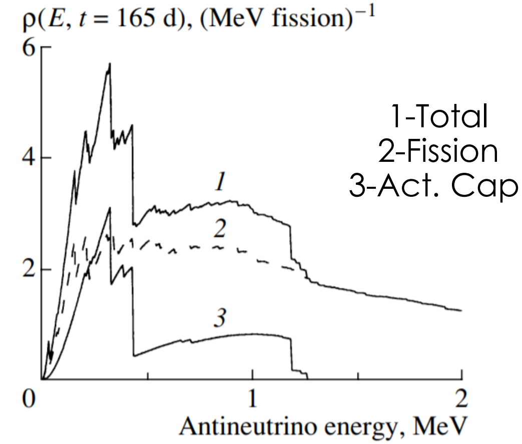
Mattera, BNL Report (2021)



Littlejohn, *Phys. Rev. D.* (2018)

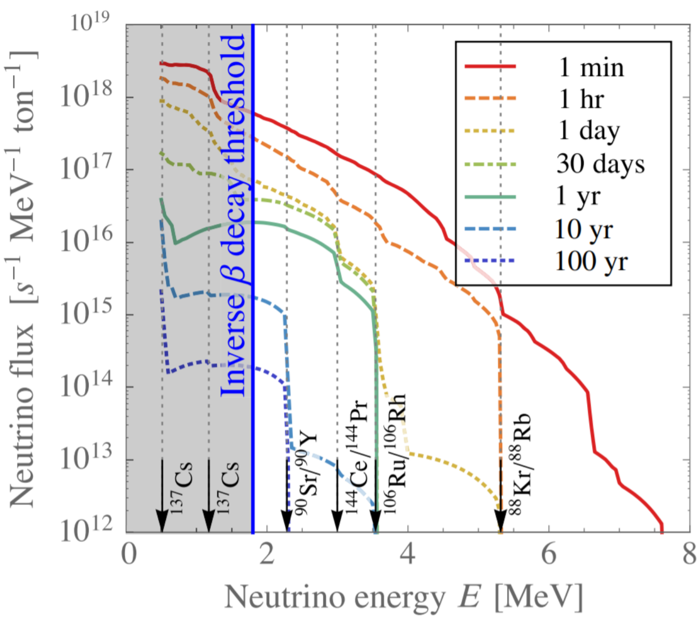
Other contributions?

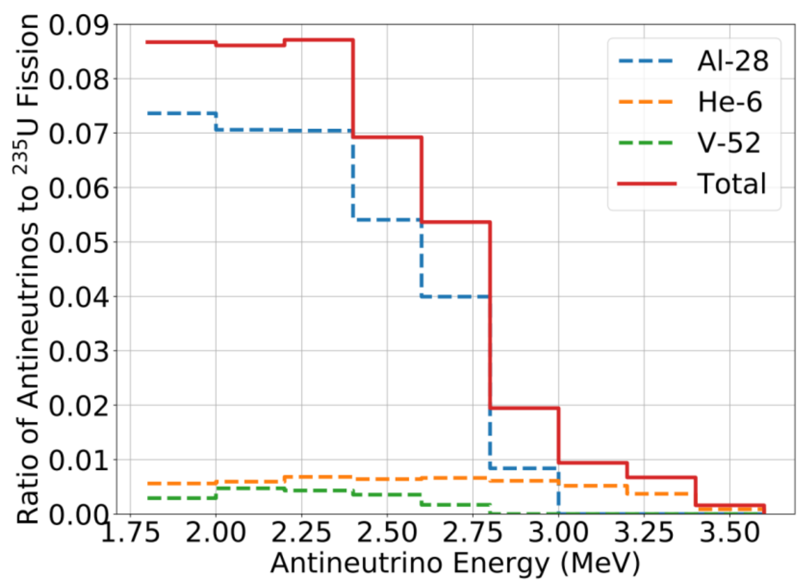
- Used nuclear fuel
  – ^{244}Cm SF > 90% of high energy β in PWR
  – ^{240}Pu SF > 90% of high energy β in breeder blanket
- Nonfuel (capture, activation, etc.)



Kopeikin, *Phs. At. Nuc.* (2003)

$$\frac{d^2\phi(E_{\overline{\nu}_e},t)}{dE_{\overline{\nu}_e}dt} = \sum_i f_i(t)\frac{dN_i}{dE_{\overline{\nu}_e}}c_i^{\mathrm{ne}}(E_{\overline{\nu}_e},t) + s_{\mathrm{SNF}}(E_{\overline{\nu}_e},t) + a_{\mathrm{NF}}(E_{\overline{\nu}_e},t)$$





PROSPECT @ HFIR

Brdar, *Phys. Rev. App.* (2017)

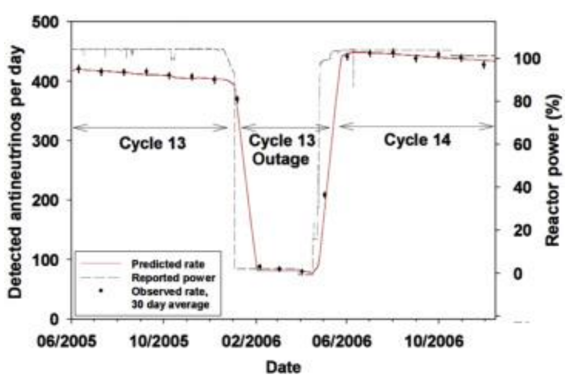
Conant, *Phys. Rev. C* (2020)

Reactor Power and Energy Uncertainties

$$\frac{dN(E,t)}{dEdt} = \frac{P_{th}(t)}{\overline{E_f}(t)} \sum_{i=1}^{4} f_i(t)\, s_i(E)\, c_i^{ne}(E)$$

Source	Power Uncertainty (%)
Daya Bay	0.5
PROSPECT	2.1

Daya Bay, CPC (2017)



Bowden (2008)

Precision depends on application!

TABLE XII: Prompt fission Q-values in MeV obtained with ENDF/B-VI.8 data[a]. To get total energy deposition, add the incident energy to total Q-values tabulated here.

Nuclide	Incident energy e_n	ENDF/B VI.8	Madland[b]	NJOY (old [c])	NJOY (Eq. 36)
^{235}U	0.0253 eV	180.88	180.57	180.89	180.89
	1.0 MeV	180.42	179.68	180.08	180.43
	14.0 MeV	169.31	168.14	164.49	169.39
^{238}U	0.0253 eV	181.31	181.04	181.33	181.33
	1.0 MeV	181.04	180.15	180.71	181.06
	14.0 MeV	169.62	169.37	164.88	169.78
^{239}Pu	0.0253 eV	189.45	188.42	189.44	189.44
	1.0 MeV	188.65	187.42	188.30	188.65
	14.0 MeV	177.07	174.12	172.19	177.09

Prompt E release, ENDF/B-VII.0

isotope	energy per fission/MeV
^{235}U	202.36 ± 0.26
^{238}U	205.99 ± 0.52
^{239}Pu	211.12 ± 0.34
^{241}Pu	214.26 ± 0.33

What tools can be used for reactor analysis?

Workshop on Applied Nuclear Data (2020)
[Proceedings from 2020 iteration]

A.2.5 Antineutrino physics

To address the reactor antineutrino anomaly and foster the development of applied antineutrino physics technologies, new nuclear physics measurements, neutrino-centered nuclear data infrastructure, and advances in modeling and simulation for antineutrino sources are required. For nuclear physics measurements, improved accuracy and uncertainty are needed in beta energy spectrum shape functions, beta decay level feeding, fission product yields, and relevant covariance data for short-lived, high Q-value fission products.[9] Simultaneous effort is needed towards integrating diverse neutrino datasets and models into a common standardized format and repository with provisions for public access. In addition to basic nuclear physics inquiry, these data provide benefits for broadening the scope of the validation stage of the nuclear data pipeline (i.e., as an "integral benchmark" for illuminating errors in nuclear data measurements and processing)[10] and for developing capabilities for remote measurement of fissile material inventory in nuclear reactor monitoring applications. *Recommended actionable tasks include direct measurements of beta energy spectra for high-yield, high Q-value fission products, related neutrino modeling to assess impacts of new datasets, and development of standardized nuclear data products for existing reactor antineutrino data.*

NNDC National Nuclear Data Center

scale

νfit www.nu-fit.org

mcnp

sMURE

GEANT4 A SIMULATION TOOLKIT

Speakers for today's session

Speaker	Topic	Time
Amy Lovell (LANL)	Overview of fission yield evaluations	11:20
Muriel Fallot (U. of Nantes)	Non-equilibrium corrections and the MURE utility for neutrinos	11:40
Anna Erickson (GT)	Reactor Operational Uncertainties and Effect on Detection Precision	12:00
Steve Skutnik (ORNL)	Uncertainty in fission product yields and absorption	12:20
Robert Mills (UK NNL)	Modeling of Neutrino Production and Spectra From a Magnox Reactor	12:40
Break		1:00
Nick Smith (INL)	Advanced reactor instrumentation at NRIC and potential for neutrino measurements	1:15
Discussion		1:35

Thank you

Be prepared for an open discussion following the presentations and break

Backup Slides