Reactor Antineutrinos for Basic Science and Engineering

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Snowmass, Reactor Antineutrino workshop

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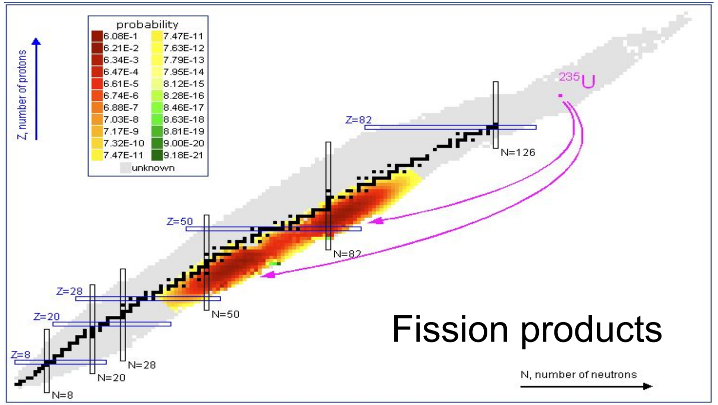
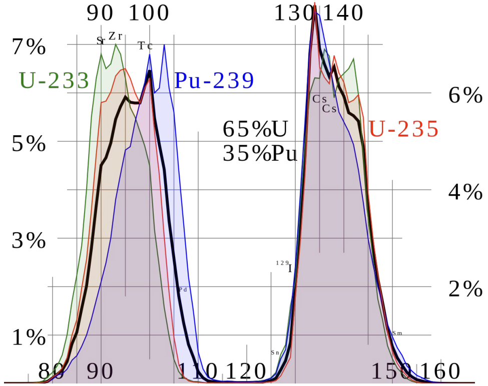
Introduction - Reactor Antineutrinos

- Nuclear fission reactors generate electron antineutrinos in 0-10 MeV range.
- Four main fission isotopes (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) yield different fission products.
- Reactor neutrinos are generated from beta decay of thousands of different fission products.
- Important to understand reactor flux with different isotope compositions.





Neutrinos yielded from fission products for different isotopes.

Achievements with Reactor Neutrinos

Reactor neutrino has been used to investigate:

- **Particle physics:** experimental discovery of the neutrino, precise mixing angle measurement, sterile neutrino searches
- **Nuclear physics and engineering:** reactor neutrino spectrum, reactor isotope assessment, earth-surface measurement

ALSO outstanding topics:

- Flux deviation between experiment and prediction
- Spectral deviation between experiment and prediction
- Wide application of reactor neutrino for nuclear security

Better Characterized RxNeutrino Flux/Spectrum Needed

For basic science:

- Improve model dependent analysis for neutrino physics measurements and beyond standard model (BSM) studies

For nuclear security and engineering:

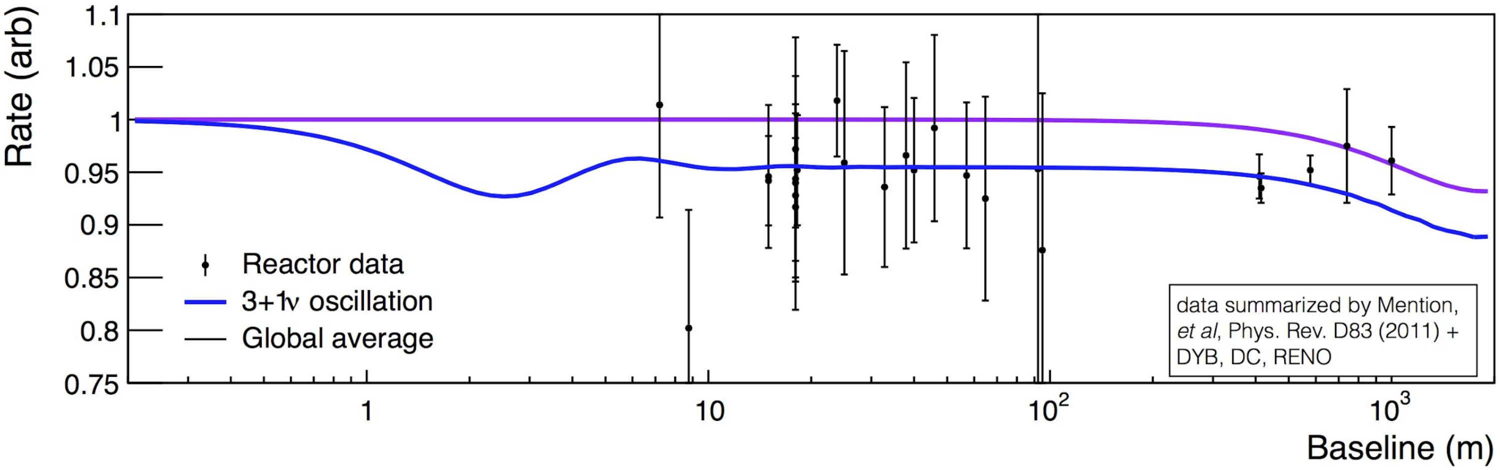
- Improve nuclear data
- Enable remote and advanced nuclear reactor assessment

Importance to Basic Science

- **All model dependent analysis can benefit from well characterized reactor neutrino flux and spectra**
- Improve oscillation measurement for sterile neutrino
- Improve precision CEvNS-based physics measurements at reactors
- Performing neutrino-based precision BSM searches at reactors
    - Neutrino magnetic moment measurement
    - Non-standard neutrino interactions
    - Neutrino decoherence
    - Search for axion-like particle (ALP) from reactor
- Improve spectrum-shape-based reactor neutrino measurements:
    - Mass hierarchy measurement
    - Theta_13 measurement

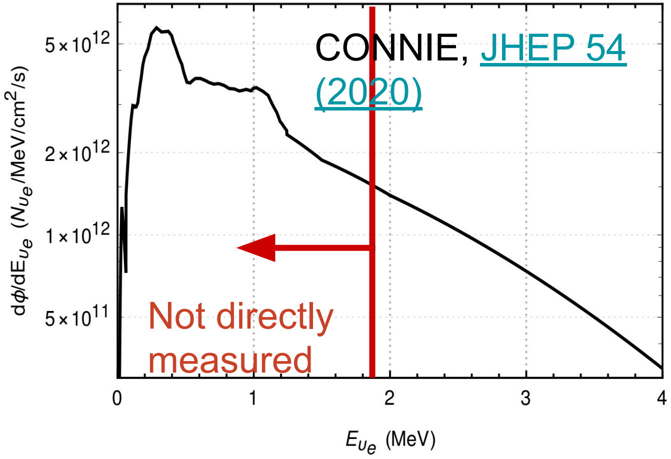
Searching for Sterile Neutrinos

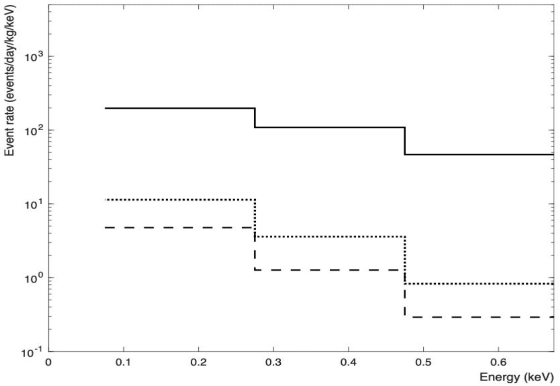
Global reactor neutrino flux analysis to search for sterile.
High precision flux measurement and prediction is needed for reactors with different components.



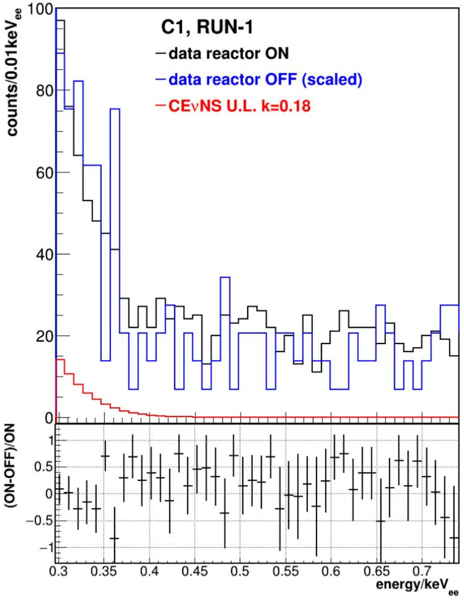
CEvNS Based Reactor Neutrino Research

- Reactor neutrino flux is important to calculate the expected event rate to detect CEvNS
- Neutrino flux for energy below 1.8 MeV is dependent on prediction
- Searching for BSM physics by searching for deficits in precise data to model comparison.





CONNIE, JHEP 54 (2020)



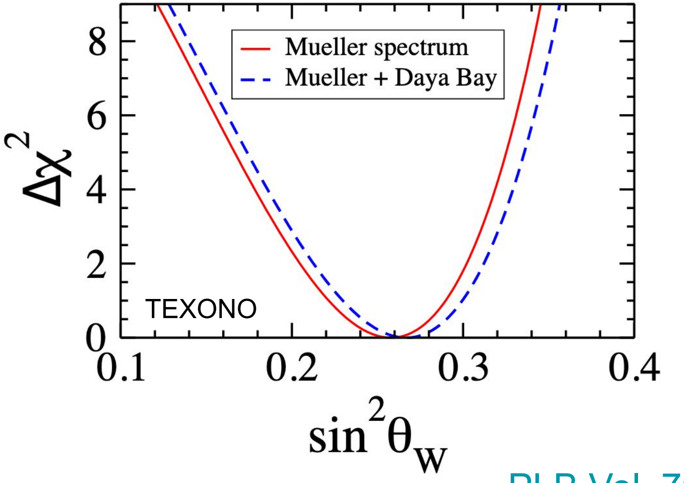
CONUS, arxiv 2011.00210

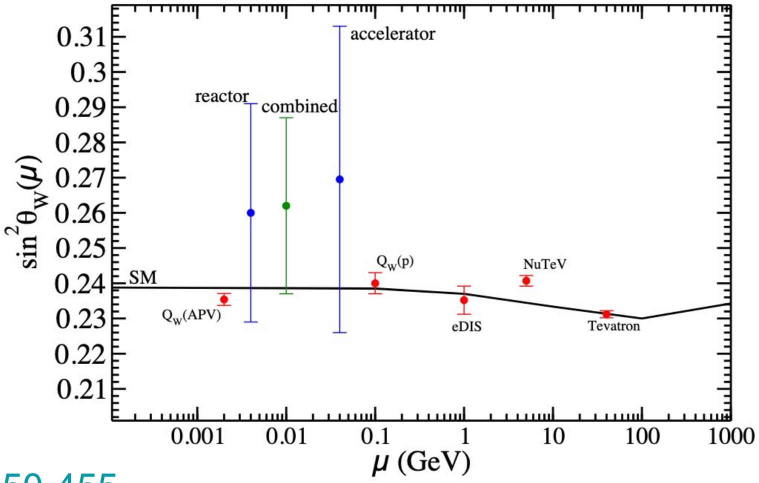
Weak Mixing Angle Measurement

Reactor based neutrino-electron scattering has been used to measure weak mixing angle at low energy.

The analysis requires precise comparison between data and model.

Experiments have shown different best fit results via comparing to different models.

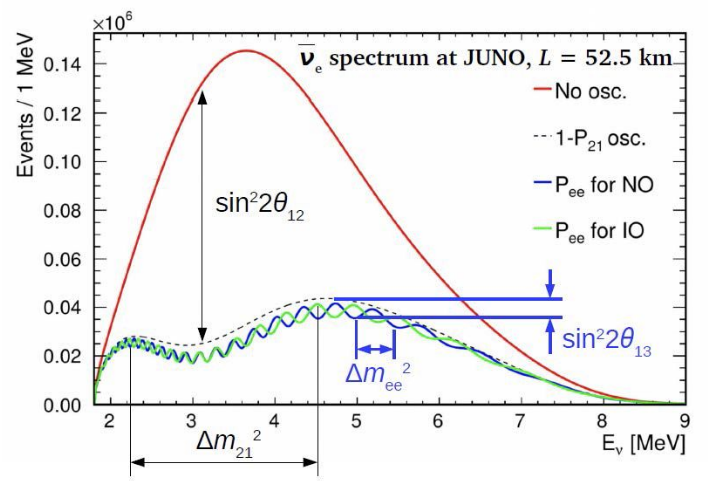




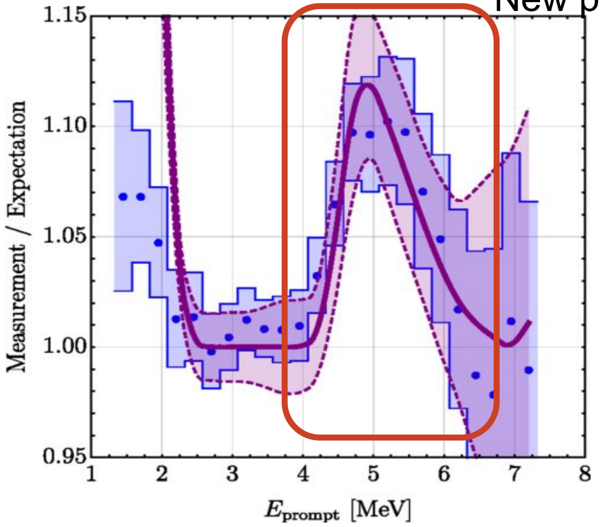
PLB Vol. 761, 450-455

IBD Spectrum Based Measurements

- Model dependent measurement of neutrino mass hierarchy.
- Improved theta_13 measurement at spectral shape level (see this).
- New physics from the bump
  - Check if 13C(v, v'n)12C* interaction is possible Phys. Rev. D 99, 055045

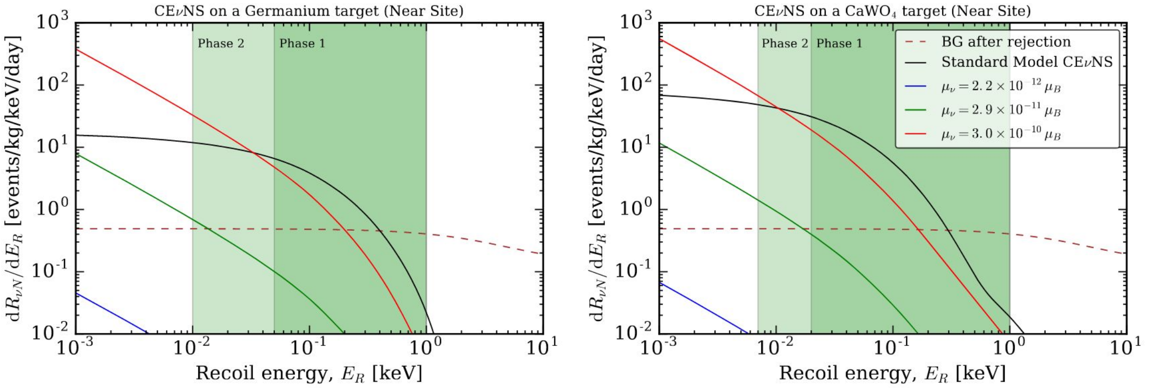


New physics?



Additional BSM Research

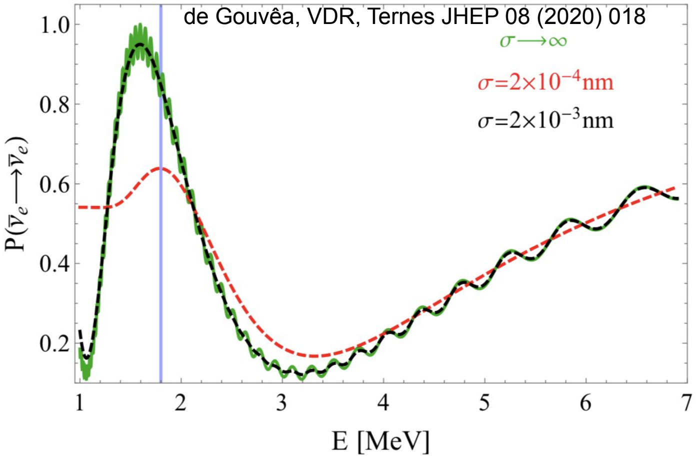
- Many of the BSM concepts involve low energy (<2 MeV) neutrino interactions (cannot be measured with IBD)
- Neutrino magnetic moment measurement:
  - Neutrino-electron elastic scattering data-to-model comparison is necessary.
- Non-standard neutrino interactions:
  - Search for neutrino-nucleus interactions by observing excess events upon reactor CEvNS signals.



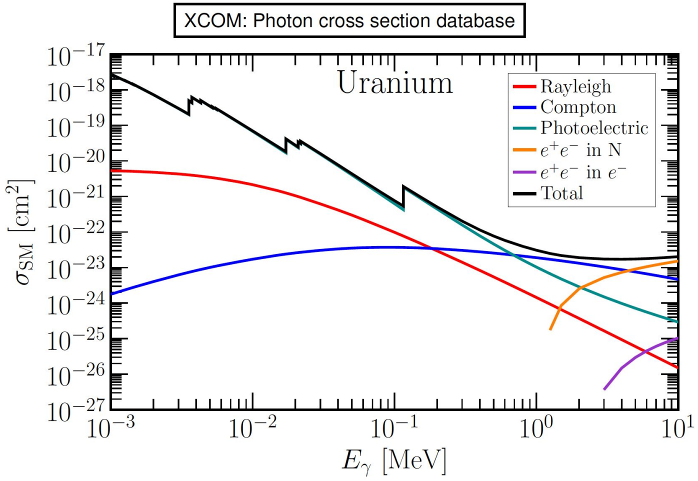
Expected spectrum with different NMM
[Billard et al. JCAP 2018]

Additional BSM Research

- Neutrino decoherence
  - Loss of coherence results into reduced oscillation amplitude.
- Search for axion-like particle (ALP) from reactor
  - Search for ALP induced gamma pairs above SM gamma from reactor.



Reduced oscillation amplitude



Signal channels involving ALP

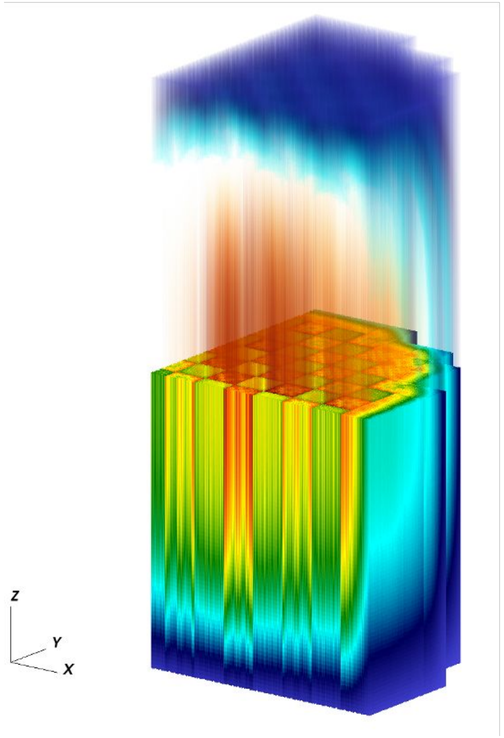
Intersection of Neutrino Spectra and Nuclear Engineering

- Improving nuclear decay data
  a. Beta spectra
  b. Decay heat calculations
  c. Advanced reactor design

- Security and safeguards
  a. Monitoring of nuclear reactors
  b. Open Questions

Nuclear Data For End Users

- Evaluated decay data are essential for reactor safety and fuel cycle analysis
- Decay heat impacts reactor operation, fuel handling, storage, and disposal
- Data for nonproliferation and safeguards applications has had increased focus
- Nuclear data is growing to be the largest contribution of uncertainty for various applications



Workshop for Applied Nuclear Data Activities (2020)

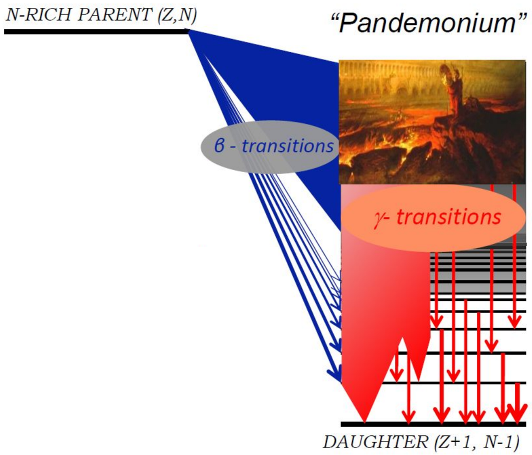
A.2.5 Antineutrino physics

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.*

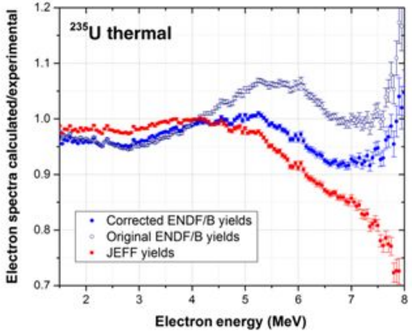
WANDA (2020)

Known: Improving β Spectra Libraries

- Differences between ENDF/JEFF at high energies
- MTAS measurements seem to illuminate differences
  - Significant changes of β/γ/ν energies
  - Account for finer structure in spectra
- Helps answer high-energy, highly-populated states
  - "Pandemonium effect"
- Beta-delayed neutron spectra
  - How well is this known?



Rykaczewski et al. (2015)



Sonzogni (2015)

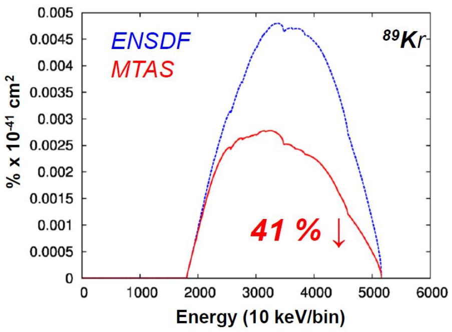
OECD-NEA 2007

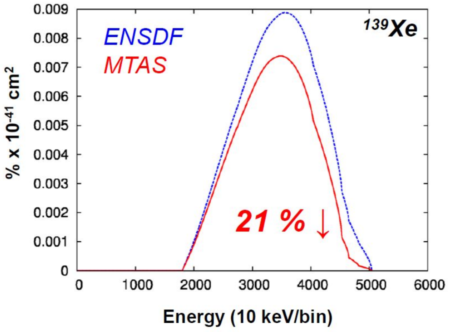
Table 3. Requested TAGS measurements

Radionuclide	Priority	Q_β-value (keV)	Half-life	Comments
35-Br-86	1	7626(11)	55.1 s	
35-Br-87	1	6852(18)	55.65 s	Extremely complex decay scheme with substantial gamma component; large uncertainties in the mean gamma energy arises from significant disagreements between the various discrete gamma-ray measurements. Also (β^-,n) branch.
35-Br-88	1	8960(40)	16.36 s	(β^-,n) branch.
36-Kr-89	1	4990(50)	3.15 min	Incomplete decay scheme.
36-Kr-90	1	4392(17)	32.32 s	Incomplete decay scheme.
37-Rb-90m	2	6690(15)	258 s	Repeat of INL TAGS measurement; data check.
37-Rb-92	2	8096(6)	4.49 s	Small (β^-,n) branch.
38-Sr-89	2	1493(3)	50.53 d	
38-Sr-97	2	7470(16)	0.429 s	Extremely short half-life (0.429 s), and possible (β^-,n) branch.

Opportunities: Beta Spectra Measurements

- TAGS measurements show major improvements
- Several priority isotopes still to be measured
- Neutrino spectra can benefit from these
  - But how much??



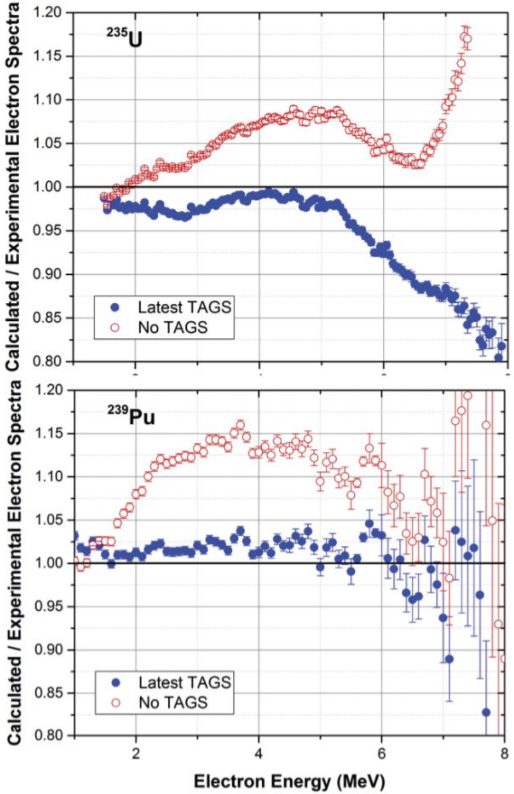


MTAS results for ^{89}Kr and ^{139}Xe decays account for

3 to 2 of the "missing 6 %" difference

in the reactor anti-neutrino anomaly, depending on a burn-up phase.
Here, a reference number of interacting reactor anti-neutrinos is calculated using ENSDF

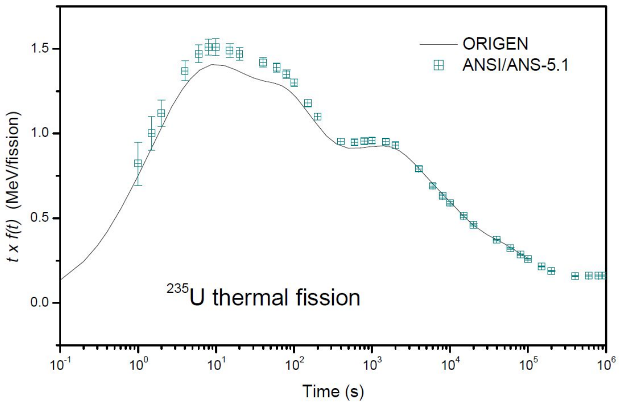
Rykaczewski et al. (2015)



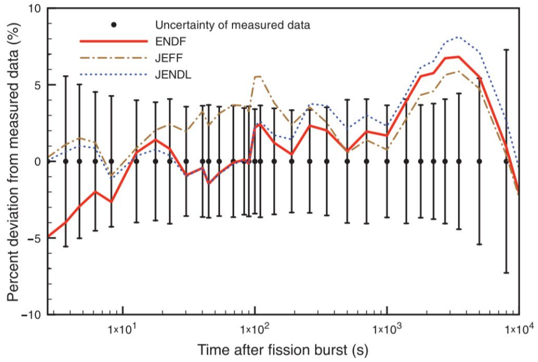
ENDF/B-VIII (2018)

Known: Decay Heat

- Decay heat known to ~ 10%
- Uncertainties in decay energy, half-life, and fission yield important
- Typically standards are used (ANS-5.1-2005 and ISO 10645)
  - Extra conservatism currently built in
- Time-dependence seems to be resolved
  - Except for > 300 years (geological repositories)



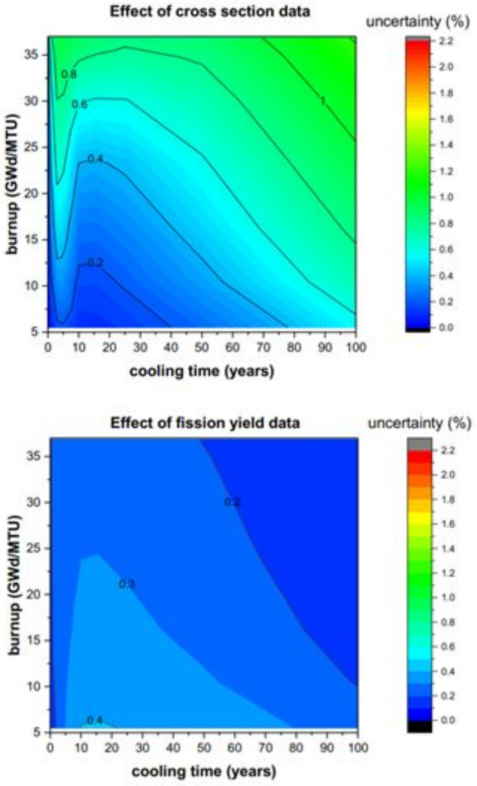
Gauld (2006)

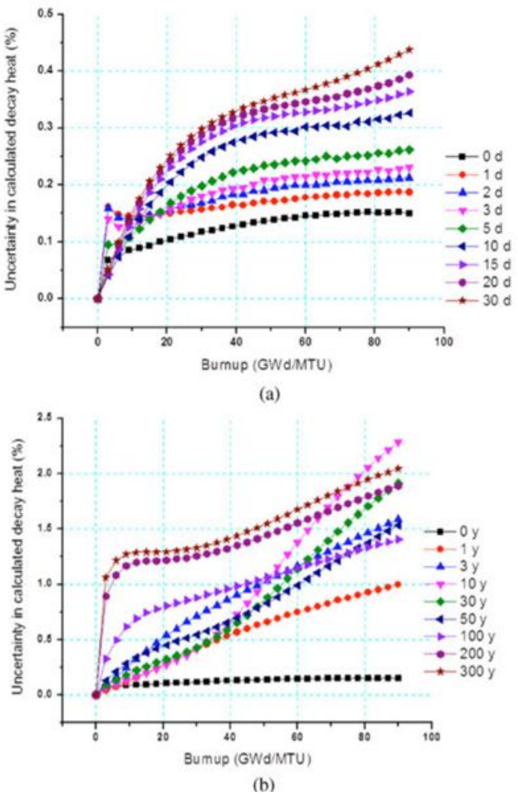


Katakura (2013)

Decay Heat Uncertainties Seem Low

Cross-section uncertainty is higher than fission yield (BWR)
[Ilas (2017)](#)

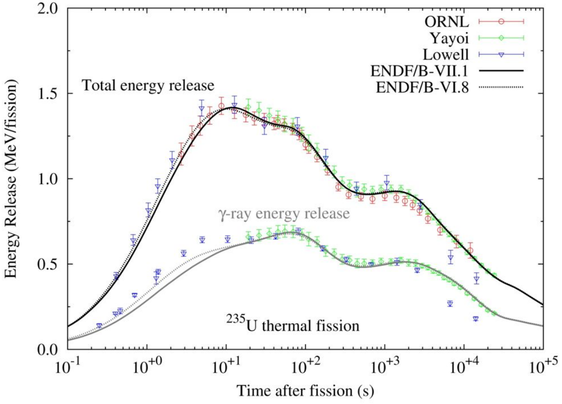




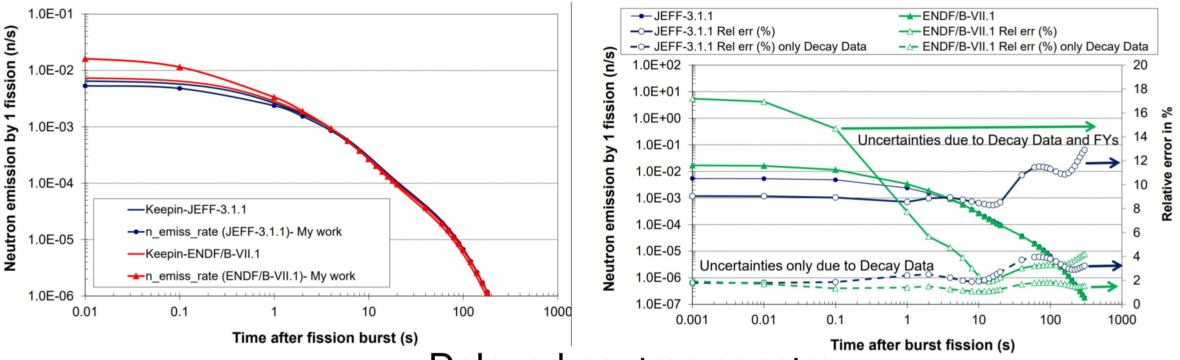
Decay heat uncertainties small, unless they need to be known to better than 1-2% (PWR)
[Williams (2013)](#)

Opportunities: Decay Heat

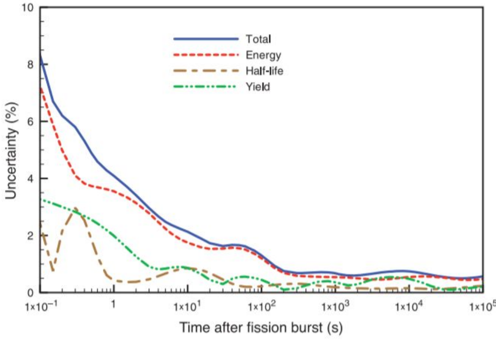
- Higher decay heat uncertainties for JEFF/JENDL
- Beta-delayed neutron emission discrepancies
  - ENDF/JEFF is off by factor of two
  - 10%+ errors in ENDF/JEFF, mostly due to FYs
- Is there a desire for breakdown between γ/β?
  - Energy deposition within a reactor, including during operation
  - Unclear how much neutrinos would benefit from this



Gauld (2010)



Delayed neutron spectra
Cabellos et al. (2013)



(c) ENDF

U-235 Katakura (2013)

Advanced Reactor Data Needs Still Unclear

- Better nuclear data needed (WANDA 2020)
  - Fission product yields
    - Based on incident neutron energy ->
    - This will inform **neutrino** data as well, again how much?
  - Cross-sections
  - Covariance matrices (for cross sections)
- For molten salt reactors (MSRs): (Fredrickson 2018)
  - Beta source term causes radiolysis (Diamond 2018)
  - Minor actinide buildup in the fuel
    - Impacts heat source term
    - Magnitude of the beta spectra component?
  - These seem to be more important for the heat exchanger and storage tanks
    - Rudolph 1997
  - How much of a problem are these?

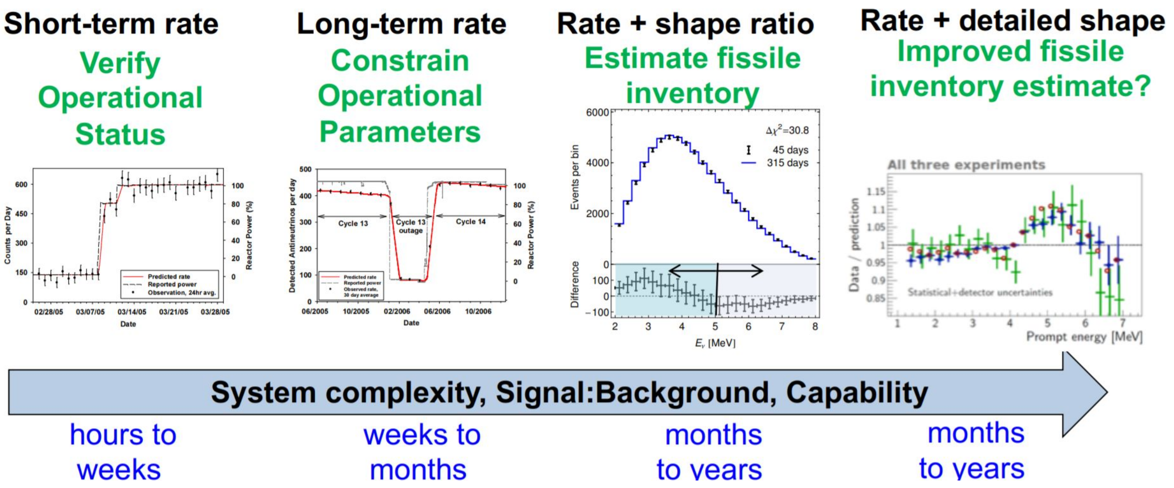
TABLE IV. Thermal fission yields Y_t^c and thermal-fast yield differences, $Y_t^c - Y_f^c$, for isotopes with the largest contribution to the ^{235}U and ^{239}Pu 5-7 MeV antineutrino flux. Values of $Y_t^c - Y_f^c$ are provided for the JEFF and ENDF fission yield databases, as well as Q-value and N, the relative flux contribution to the 5-7 MeV range of antineutrino energy, in percent. A '*' denotes a metastable state for that isotope, while a '^' indicates that JEFF fission yield values are used in place of ENDF fission yield values, for reasons described in the text.

Isotope	Y_t^c (JEFF)	$Y_t^c - Y_f^c$ (JEFF)	$Y_t^c - Y_f^c$ (ENDF)	N(5-7) (%)	Q-Value (MeV)
^{235}U					
Y-96	0.047	-0.0004	-0.0004^	10.66	7.10
Rb-92	0.048	-0.0032	+0.0064	9.63	8.10
Cs-142	0.029	-0.0025	-0.0012	5.77	7.32
Nb-100	0.056	- 0.0036	-0.0003	4.61	6.38
Rb-93	0.035	-0.0064	-0.0021	3.92	7.47
Cs-140	0.060	+0.0034	-0.0002	3.26	6.22
I-138	0.015	+0.0009	+0.0013	3.09	7.99
Y-99	0.019	-0.0103	-0.0038	3.05	6.97
Rb-90	0.044	+0.0051	+0.0023	3.03	6.58
Sr-95	0.053	-0.0004	+0.0003	3.01	6.09
^{239}Pu					
Y-96	0.029	-0.0015	-0.0015^	10.86	7.10
Nb-100	0.052	+1.6e-5	+1.6e-5^	7.16	6.38
Nb-102*	0.016	-0.0039	-0.0039^	6.85	7.26
Rb-92	0.020	-0.0035	-0.0009	6.73	8.10
Cs-142	0.016	+0.0043	+0.0019	5.35	7.32
Cs-140	0.044	+0.0026	-0.0047	4.02	6.22
Y-99	0.013	-0.0045	+0.0017	3.60	6.97
Rb-93	0.017	-0.0050	-0.0015	3.11	7.47
Y-98*	0.019	-0.0051	+0.0014	3.08	9.40
Sr-95	0.032	-0.0003	-0.0021	3.07	6.09

Littlejohn (2018)

Known: Nonproliferation & Safeguards

- Demonstrated capability to monitor reactors
- Some use cases have been identified and/or limited
  - Unlikely: power reactor monitoring
  - Unlikely: far-field reactor discovery w/o directional information (Bernstein 2020)
  - Likely: compact reactor monitoring, above-ground deployment (Bowden 2014)
  - Potentially: near-field cooperative, scientific cooperation (Carr 2019)



Bowden (2019)

Open Questions for Nuclear Energy and Engineering

1. How well do safeguards quantities rely on spectrum knowledge?
    a. What about the timescales and sensitivities?
2. How can you monitor without knowing what is inside the reactor?
3. How can coherent scattering (CEvNS) help reactor measurements?
4. What would a standardized nuclear data product for neutrinos look like?

More utility insight to come from the NuTools study in 2021

Summary

- Reactor neutrino flux/spectrum prediction is important input for particle physics, nuclear physics and nuclear engineering.
- A well characterized and/or predicted neutrino flux contributes to scientific research by:
  - Improving the precision of basic science measurements
  - Providing models essential for experiments to probing potential new physics
- For nuclear physics and engineering, precise neutrino flux predictions benefit:
  - Efforts to improve nuclear data
  - Nuclear reactor monitoring
- Still lots of unanswered questions!

Forward looking

Experimental improvements:

- Neutrino physics measurements
- Nuclear physics measurements

Prediction improvements:

- Conversion
- Summation
- Database
- Systematic