Day 3 Summary:
Nuclear Data and Antineutrino Spectra

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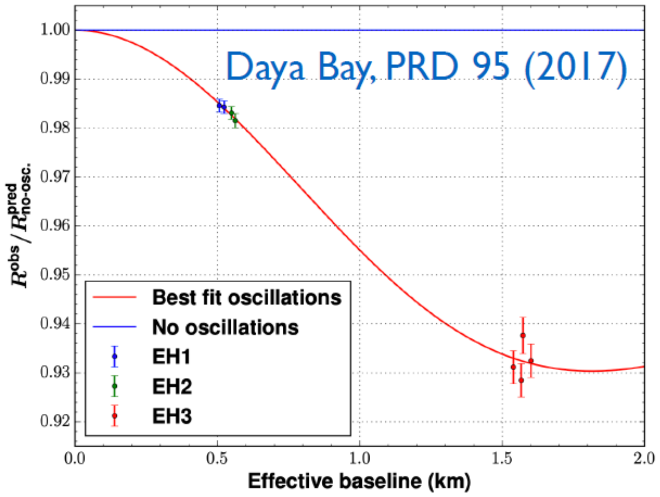
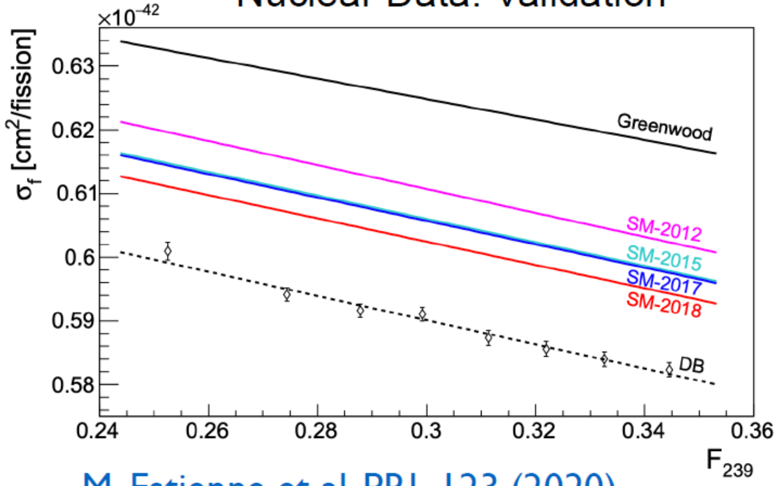
Particle Physics: Oscillations

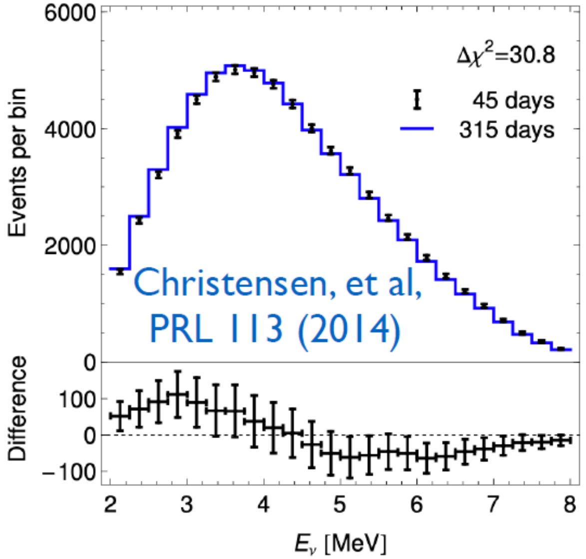


Nuclear Data: Validation

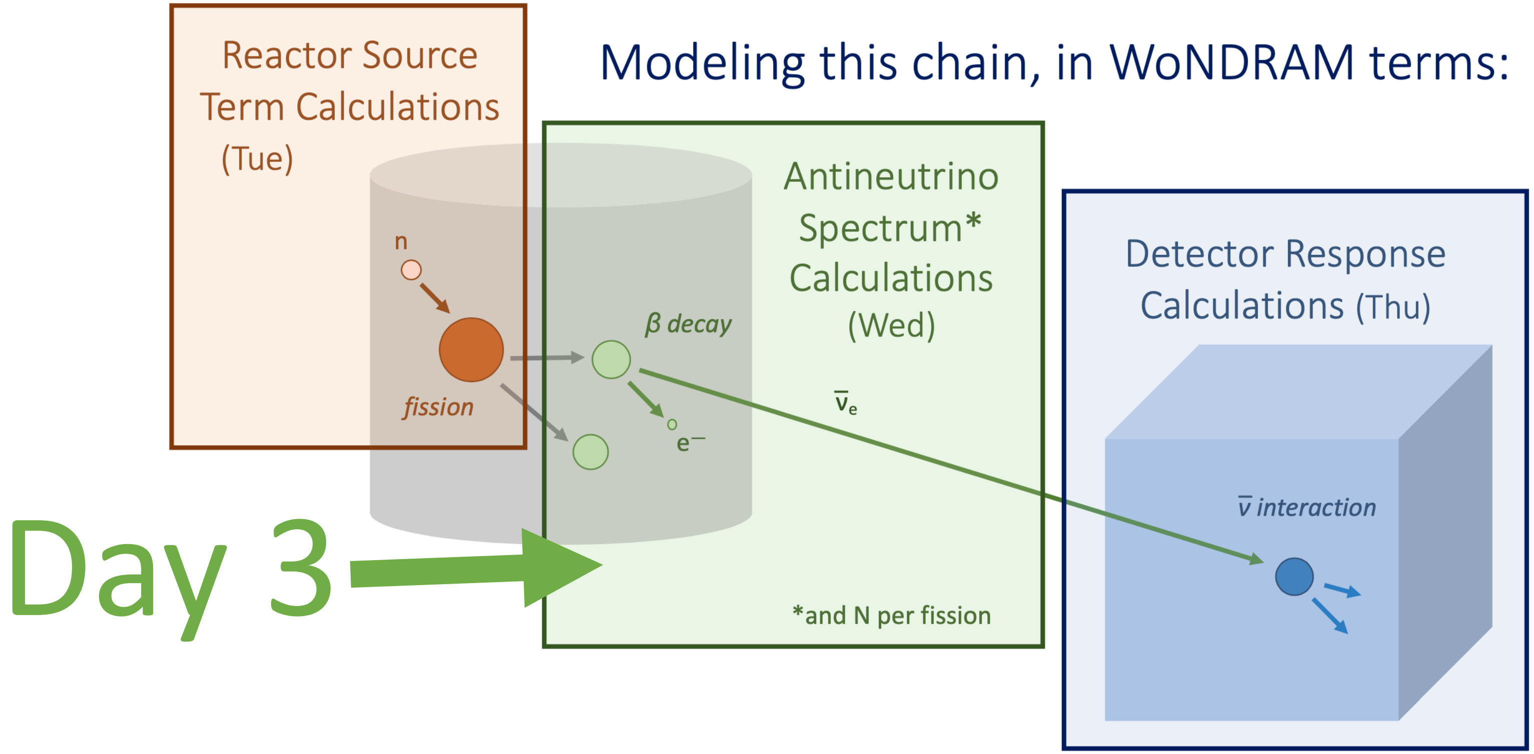


M. Estienne et al, PRL 123 (2020)

Applications: Fuel Content



Day 3 Broad View and Goals



Particle physics, nuclear data, and non-proliferation/monitoring application spheres rely to varying degrees on an accurate and precise understanding of the true aggregate antineutrino energy spectrum generated by each primary fission isotope.

The goals of this session are to identify future experimental, theory and software improvements that can expand understanding of directly-measured and indirectly-predicted antineutrino spectra, and to define the extent to which each of these improvements will benefit the three spheres of application described above.

Day 3 Sub-Sessions and Questions

Sub-Session 1:
Overview

"How will an improvement of X% in my antineutrino spectrum model / measurement improve my ability to do Y?"

Sub-Session 2:
Direct Source Term Measurements

"Reactor neutrino data is nuclear data. What is needed to get it in the pipeline and maximize its utility as nuclear data?"

Sub-Session 3:
Fission Beta Spectra for
Conversion Model Predictions

"Fission beta data is nuclear data. What is needed to get it in the pipeline and maximize its utility as nuclear data?"

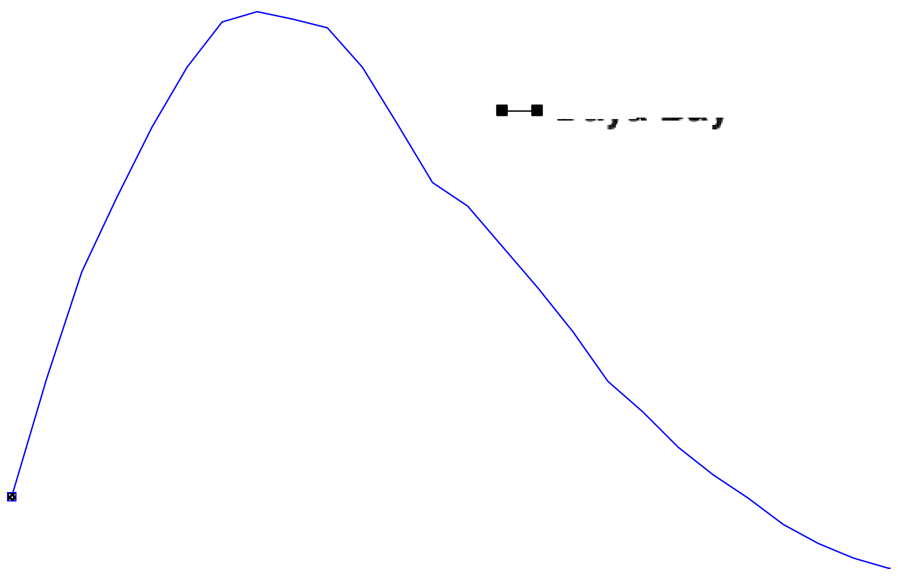
Sub-Session 4:
Prediction Inputs and Software Tools

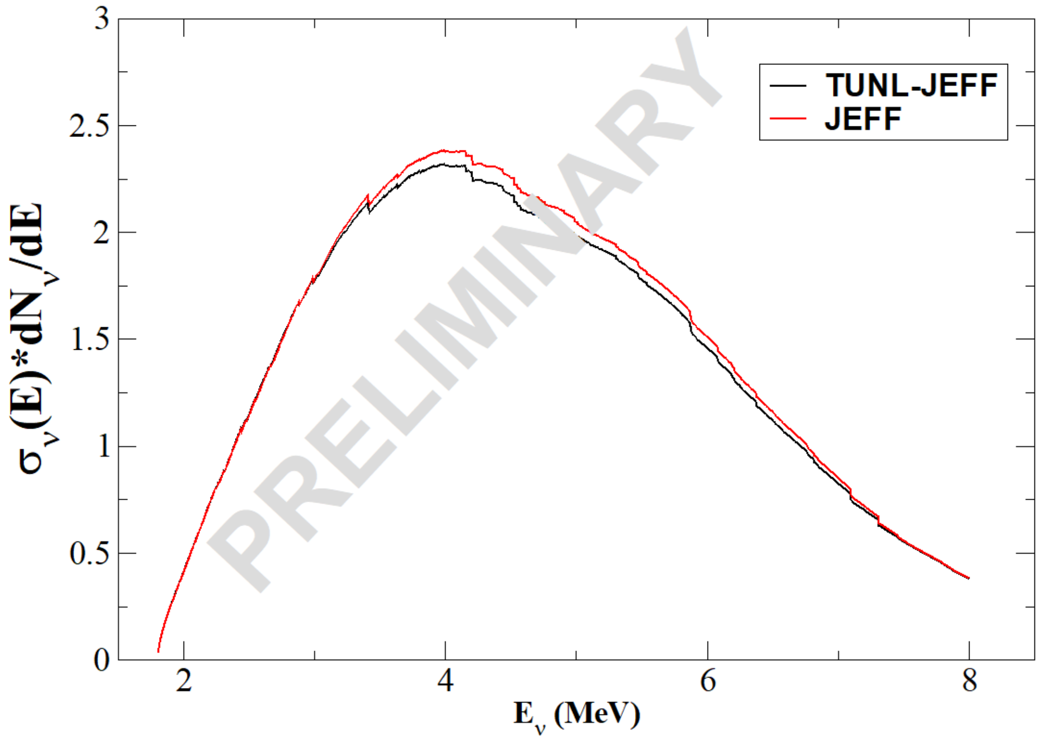
"What other prediction inputs can be improved?"
"How can we make neutrino models/data more accessible?"

The goals of this session are to identify future experimental, theory and software improvements that can expand understanding of directly-measured and indirectly-predicted antineutrino spectra, and to define the extent to which each of these improvements will benefit the three spheres of application described above.

Anna Hayes (LANL)

- Described in detail the conversion and summation methods to calculate antineutrino spectra.
- Some of the data input, for instance Zeffective in conversion, and sub-dominant corrections needed were presented.





- Also presented the effect of fission yields, in particular, the impact of new data for ^{238}U measured at TUNL.
- Explained in detail how the Schreckenbach 235U/239Pu ratio appears to be inconsistent with reactor burnup measurements.

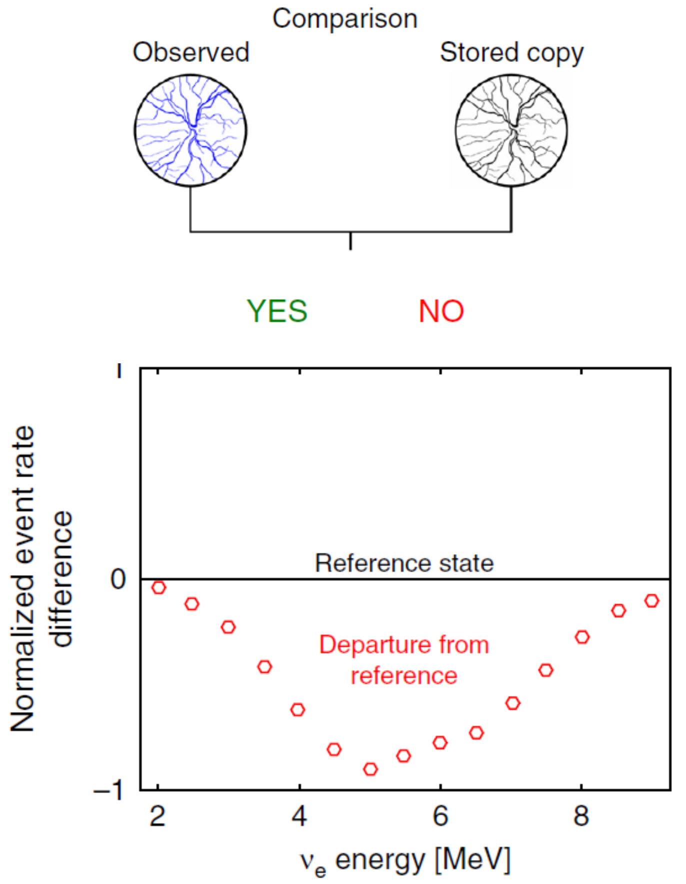
Anna Erickson (GA Tech)

- Presented on the feasibility of using antineutrino spectrum measurements to determine diversion of special nuclear material (SNM) from the reactor core.

- The use of antineutrino spectrum measurements for two advanced fast reactors, UCFR and AFR were presented.

- In particular, plutonium diversion scenarios such as changes in antineutrino spectrum response by removing plutonium assemblies from different locations in the core was reported.
  - Different response rates were recorded for removal from the center of the core, as opposed to the core periphery

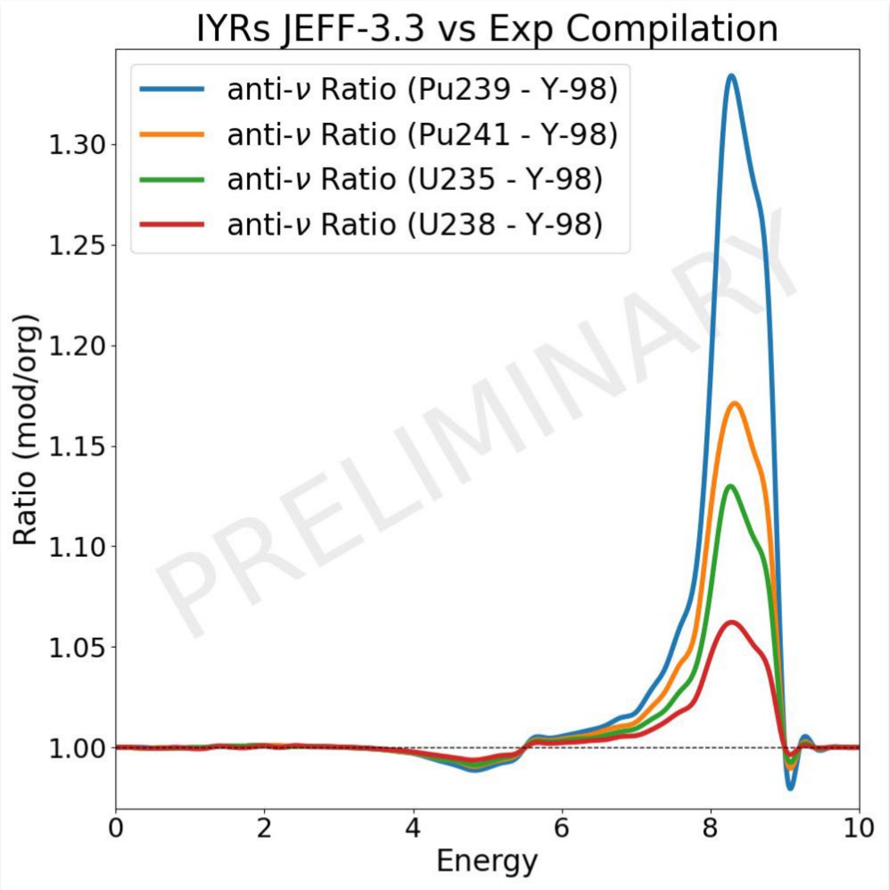
- Extremely long antineutrino spectrum measurement times for detection of SNM with an IBD response model was reported (in the context of IAEA framework).

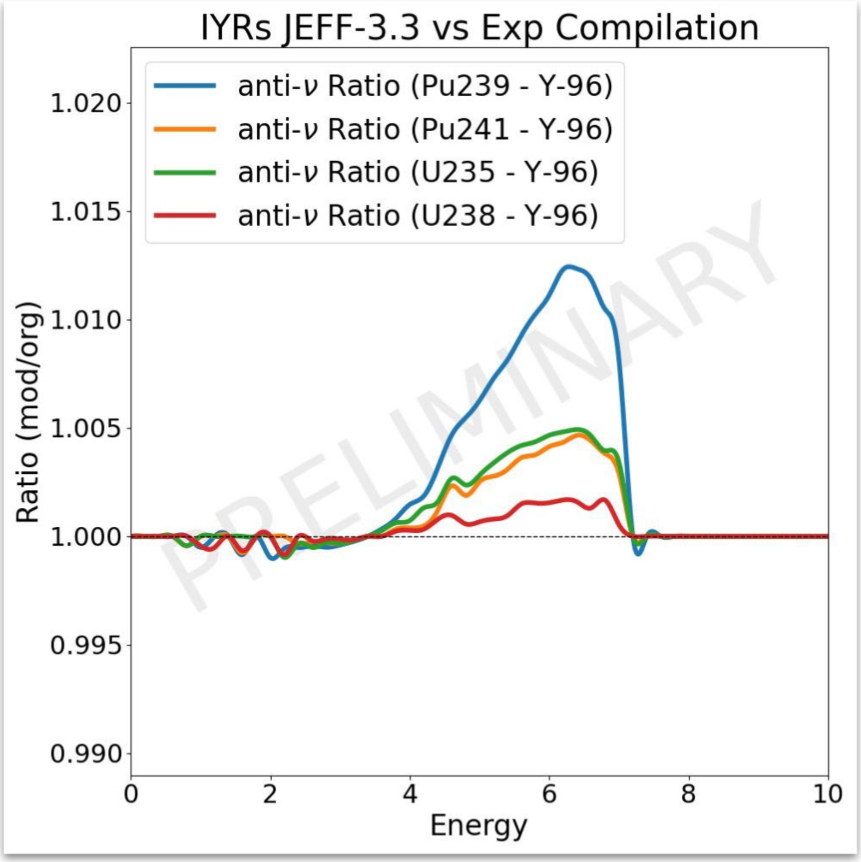


Christopher Stewart, Abdalla Abou-Jaoude & Anna Erickson, *Nature Communications*, (2019) 10:3527

Andrea Mattera (BNL)

- Presented a new evaluation of fission yield isomeric ratios.
- Effect of isomeric ratios on antineutrino summation calculations was discussed.
- For 96Y, isomeric ratio data comes from a proton-induced reaction experiment, an experiment using a neutron beam is needed.



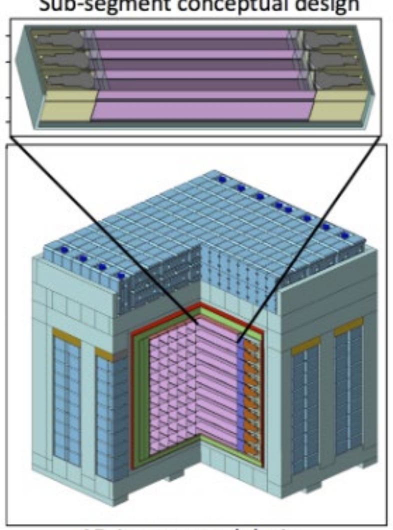


Compilation and Evaluation of Isomeric Fission Yield Ratios

C.J. Sears,[1,2] A. Mattera,[1,*] E.A. McCutchan,[1] A.A. Sonzogni,[1] D.A. Brown,[1] and D. Potemkin[1,3,4]

J. Pedro Ochoa-Ricoux (UC Irvine)

- Showed several examples of oscillation experiments – no need for improved fluxes
- New physics searches could in principle benefit from better flux models, but very high reliability of error bars would be needed.



Works when oscillation length is comparable with the size of the detector

The lack of precise enough reactor antineutrino predictions has not been a show stopper for neutrino oscillation measurements

Strategy: make a relative measurement

1) Between near and far detectors

Example: Daya Bay

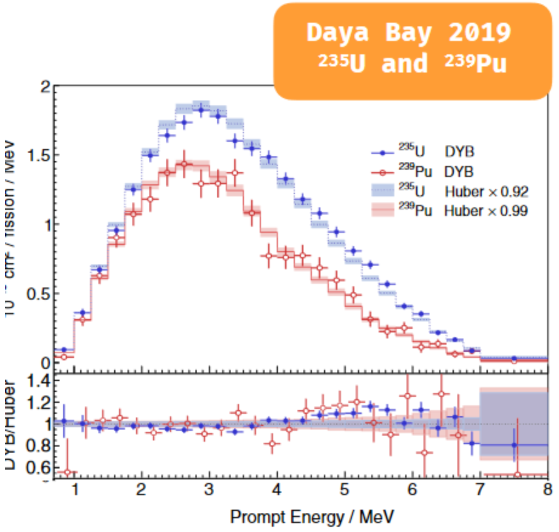
$$\frac{R_{Far}}{R_{Near}} = \left(\frac{\Phi_{Far}}{\Phi_{Near}}\right)\left(\frac{L_{Near}}{L_{Far}}\right)^2\left(\frac{N_{Far}}{N_{Near}}\right)\left(\frac{\epsilon_{Far}}{\epsilon_{Near}}\right)\left(\frac{P^{osc}_{Far}}{P^{osc}_{Near}}\right)$$

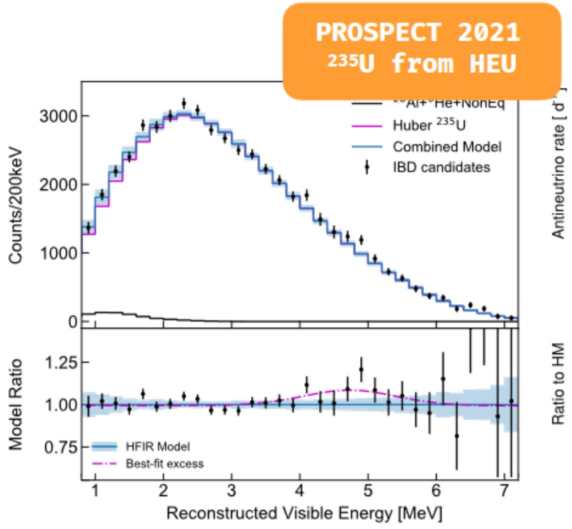
bserved $\bar{\nu}_e$ ratio | $\bar{\nu}_e$ flux | baseline | # of protons | detection efficiency | oscillation

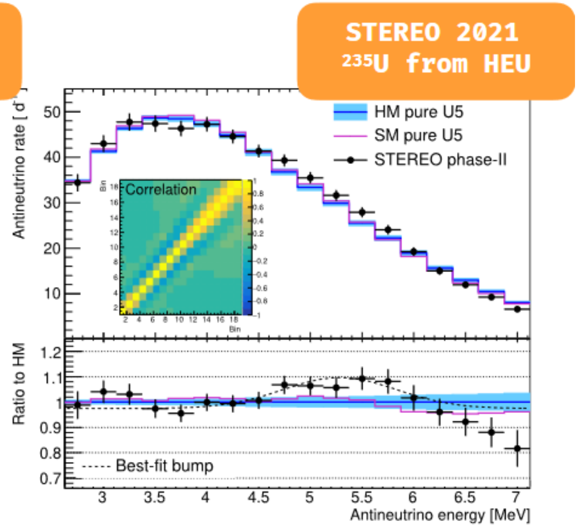
Size of near-far flux difference due to oscillations in Daya Bay: ~6%

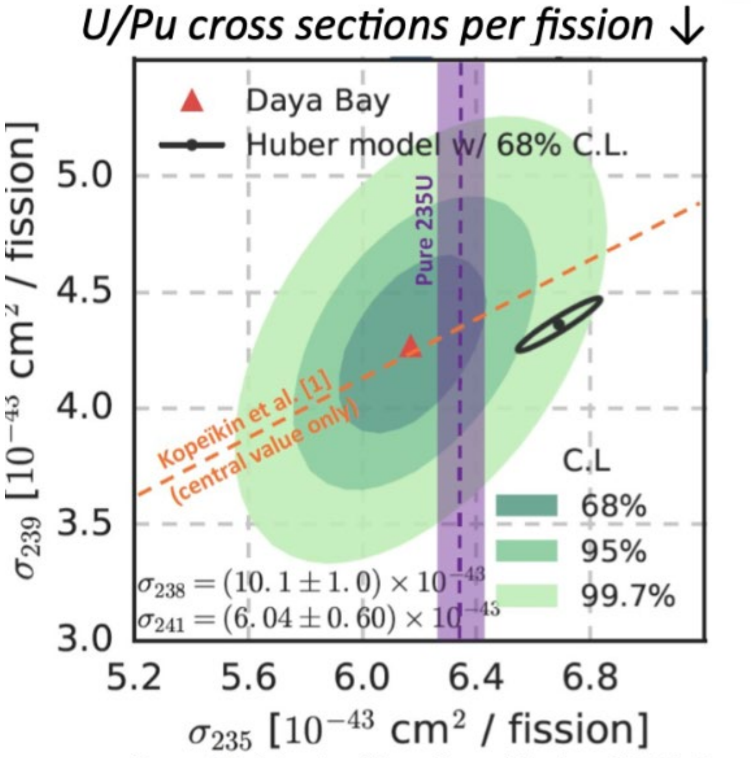
This difference is proportional to $\sin^2 2\theta_{13}$, which is measured to ~3.5%

Thomas Langford (Yale)







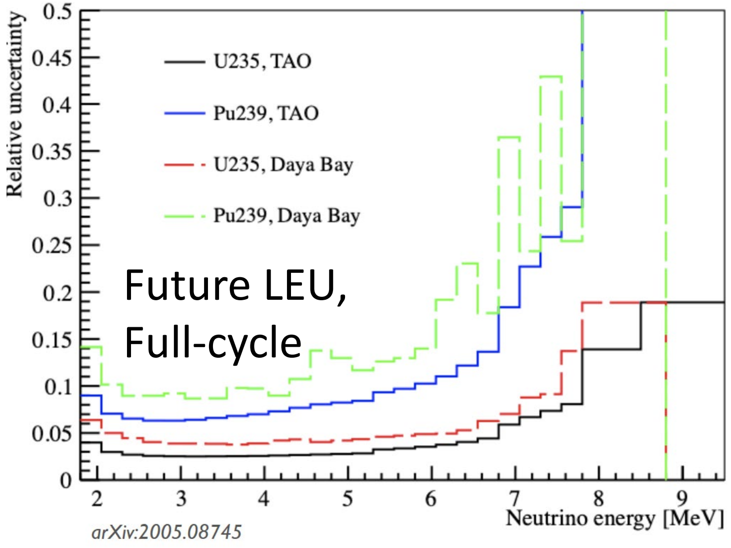


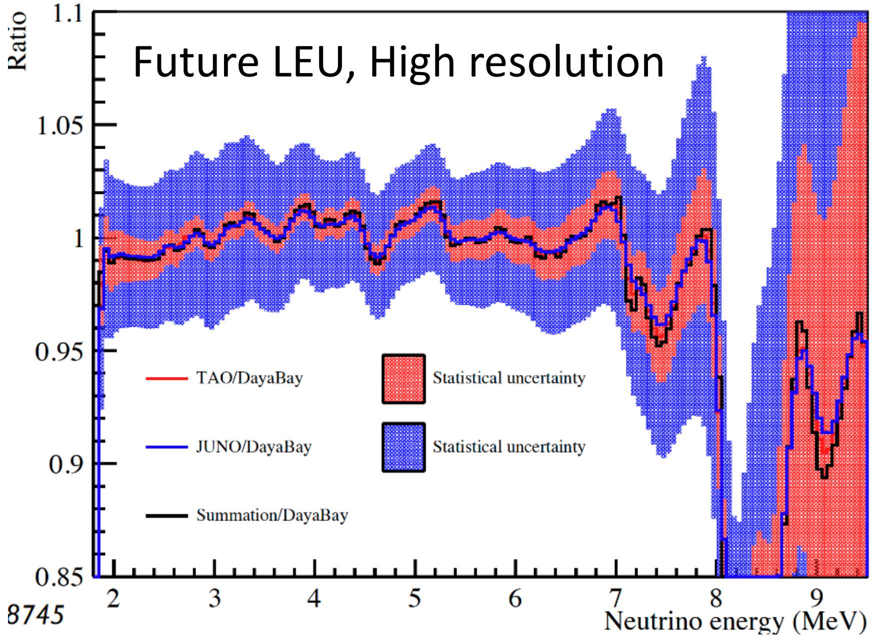
(from M. Licciardi's talk at Moriond 2021)

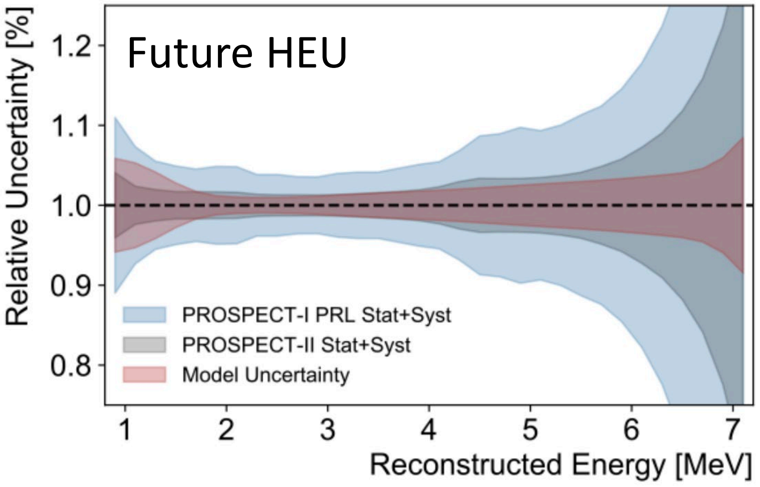
- Summary of current reactor neutrino data
- We now can have isotopic spectral neutrino yields for U235 and Pu239
- Future HEU measurements could improve statistics
- Well understood technology and clear path to improved fluxed
- Rate & spectral discrepancies with respect to both summation and conversion fluxes

Pranava Surukuchi (Yale)

- JUNO TAO will provide excellent spectra, separated by isotope (1.5% resolution at 1MeV)
- Short-baseline HEU-based measurements can provide most precise U235 source term
- Future measurements at a range of reactors with a single detector can deliver per-cent level neutrino yields per isotope







Adapted from PRD 97, 013003

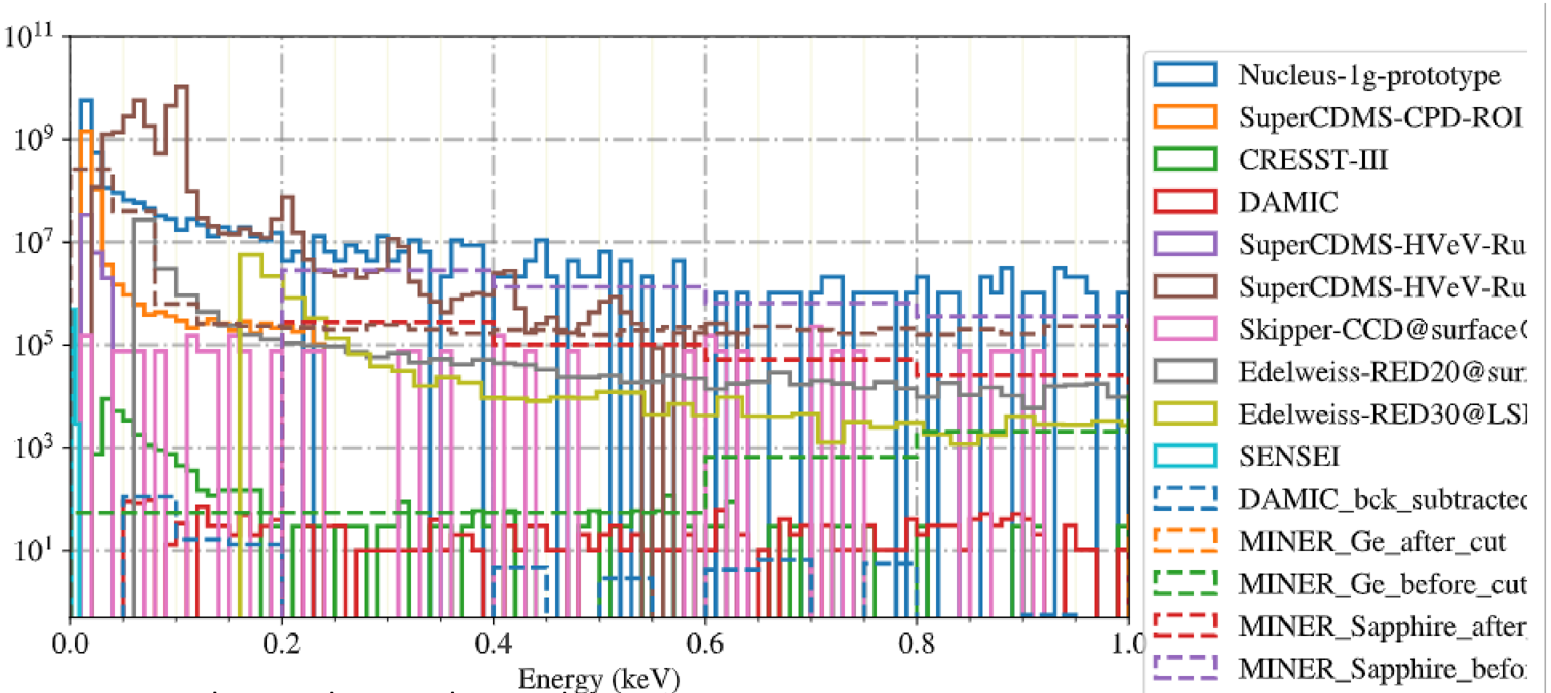
Case	Description	Precision on σ_i (%) ^{235}U	^{239}Pu	^{238}U
1	Daya Bay-like LEU	2.8	5.9	10.0
2	Daya Bay-like LEU + new HEU	1.3	5.3	9.2
3	Improved Daya Bay-like LEU + HEU	1.3	4.8	8.9
4	Short-Baseline LEU + HEU	1.2	3.7	8.8
→ 5	Short-Baseline LEU + HEU, Correlated	1.5	3.8	6.7
	urrent theoretical uncertainties	2.1	2.5	11.2

"Reactor neutrino data <u>is</u> nuclear data. What is needed to get it in the pipeline and maximize its utility as nuclear data?"

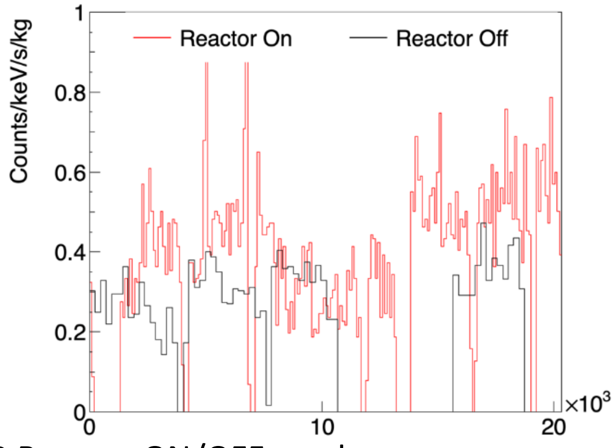
B. Littlejohn

Rupak Mahapatra (Texas A&M)

- Presented on coherent-elastic-neutrino-nucleus-scatter (CEvNS) as a detection mechanism for reactor antineutrinos spectrum measurements.
  - Scintillator CEvNS detectors
  - Semiconductor CEvNS detectors
- Can provide lower thresholds, and better precision for spectroscopy
- Severely crippled by the high, nonlinear background rates



Background rates observed in various CEvNS measurements, 2021-EXCESS Workshop



MINER Reactor ON/OFF results

Light (quenched)	Ionization (quenched)	Phonon(no quenching)
Lindhard=.1-.2	.15 (Ge), .05 (Si)	No Quenching!
Req E_{th} =20 eV	30eV(Ge),10(Si)	200 eV
Resol. σ=4 eV	5 eV (Ge), 2 (Si)	40 eV
CRESST (10 gm)	CDMS(kg), CONNIE(gm)	CRESST, CDMS

Pieter Mumm (NIST)

- Presented a thorough analysis of the recently published Kopeikin et al results.
- Effects arising from targets, background, neutron flux discussed.
- Advantage of ratio measurement to cancel efficiency effects.
- Implies IBD yields are (5.4±0.2)% lower.
- σ5/σ9 = **1.45±0.03**, in a good agreement w/ Daya Bay (**1.44 ± 0.10**) and RENO.

Backgrounds

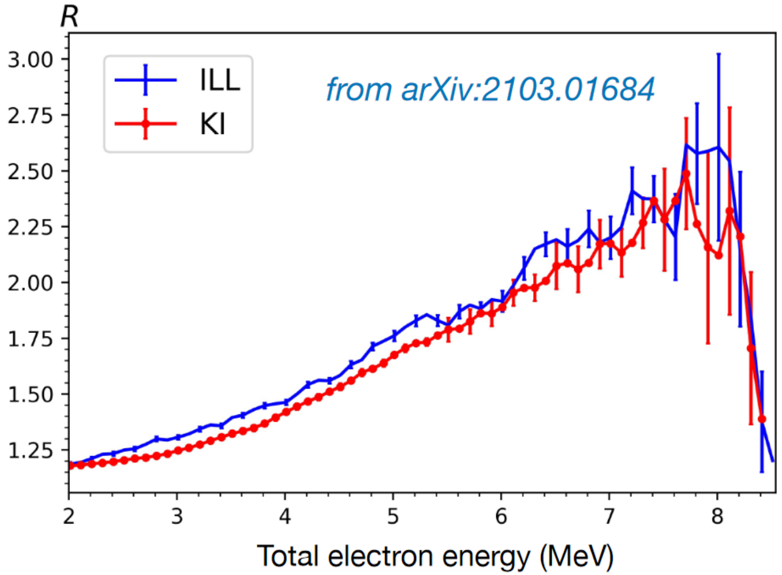
- Signal to background 15-20 at 2 MeV decreasing to unity at 7.7 MeV
- Getting background right is important

Systematics

- Attenuation in air/windows calculated (small) - benchmarked against ^{252}Cf
- Attenuation in target: identical propagation for both isotopes (mounting, masses near identical)
- Various beta sources (^{207}Bi, ^{56}Mn, ^{144}Ce-^{144}Pr, ^{42}K, ^{38}Cl, ^{252}Cf) placed between 2 lead foils to mimic targets
- Thick/thin nearly identical for each source
- Correction ratio ranges from x1.22 (2 MeV) to x1.03 (4 MeV)

$$\frac{\rho_\beta^5}{\rho_\beta^9} = \frac{\sigma^9}{\sigma^5} \cdot \frac{N^9}{N^5} \cdot \frac{n_\beta^5}{n_\beta^9}$$

- The *neutron beam flux and beta detection efficiency cancels* in the ratio.
- N determined by the target foil masses

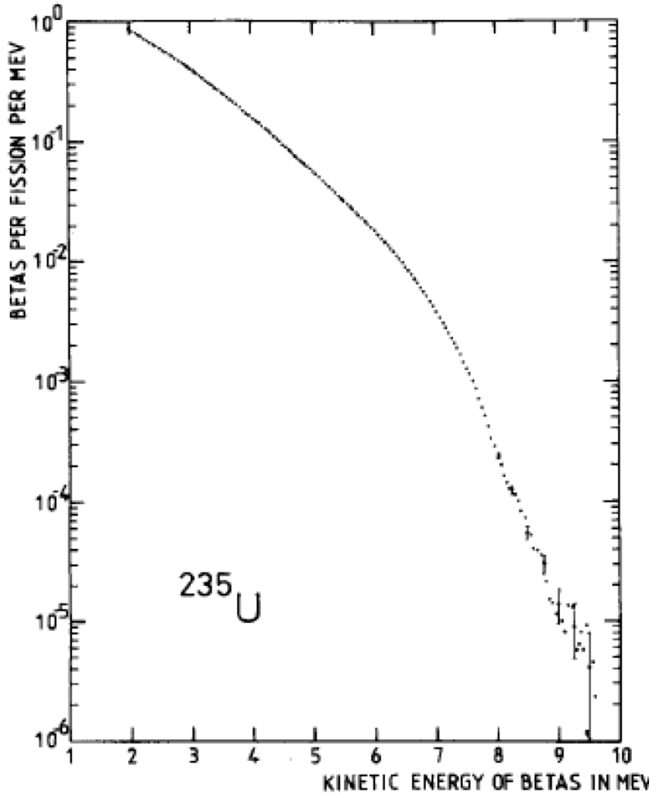


$\rho_\beta^5/\rho_\beta^9$ = 1.197 @ 2 MeV (data)

$\rho_\beta^5/\rho_\beta^9$ = 1.20 ±1.5% @ 2 MeV (calc)

Krzysztof Rykaczewski (ORNL)

- Presented a plan to measured the $^{233,235}U$ and $^{239,241}Pu$ electron spectra.
- Labs and Universities collaboration: ORNL, BNL, ANU, UTK.
- Goal is to obtain the highest quality datasets.
- More detailed technical presentations by Lowell Crow, Tibor Kibedi and Mitch Allmond followed.

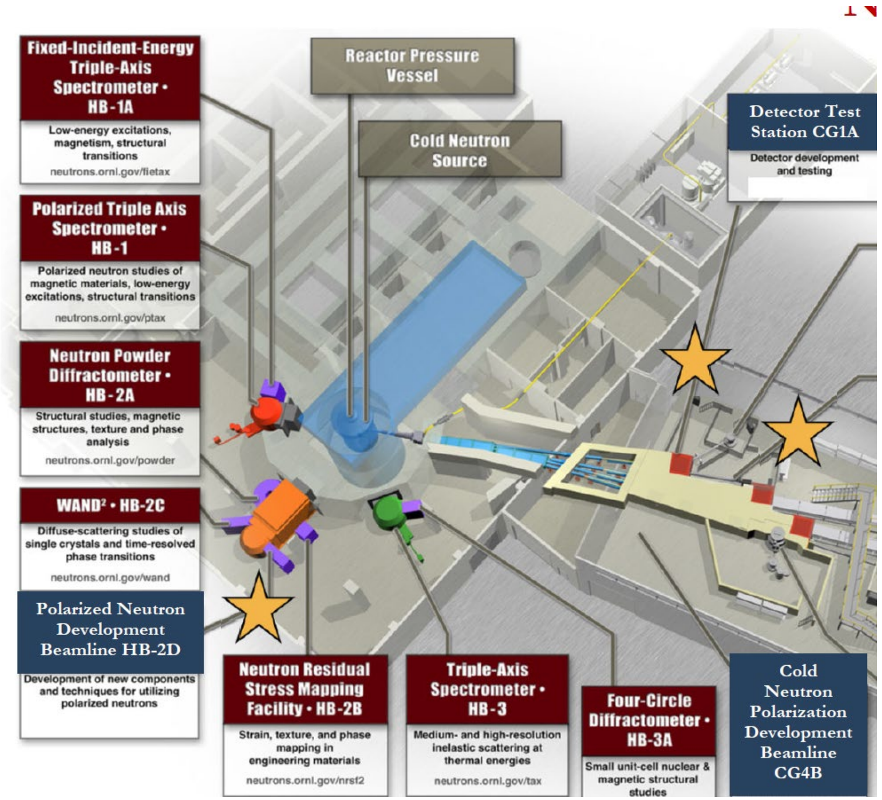


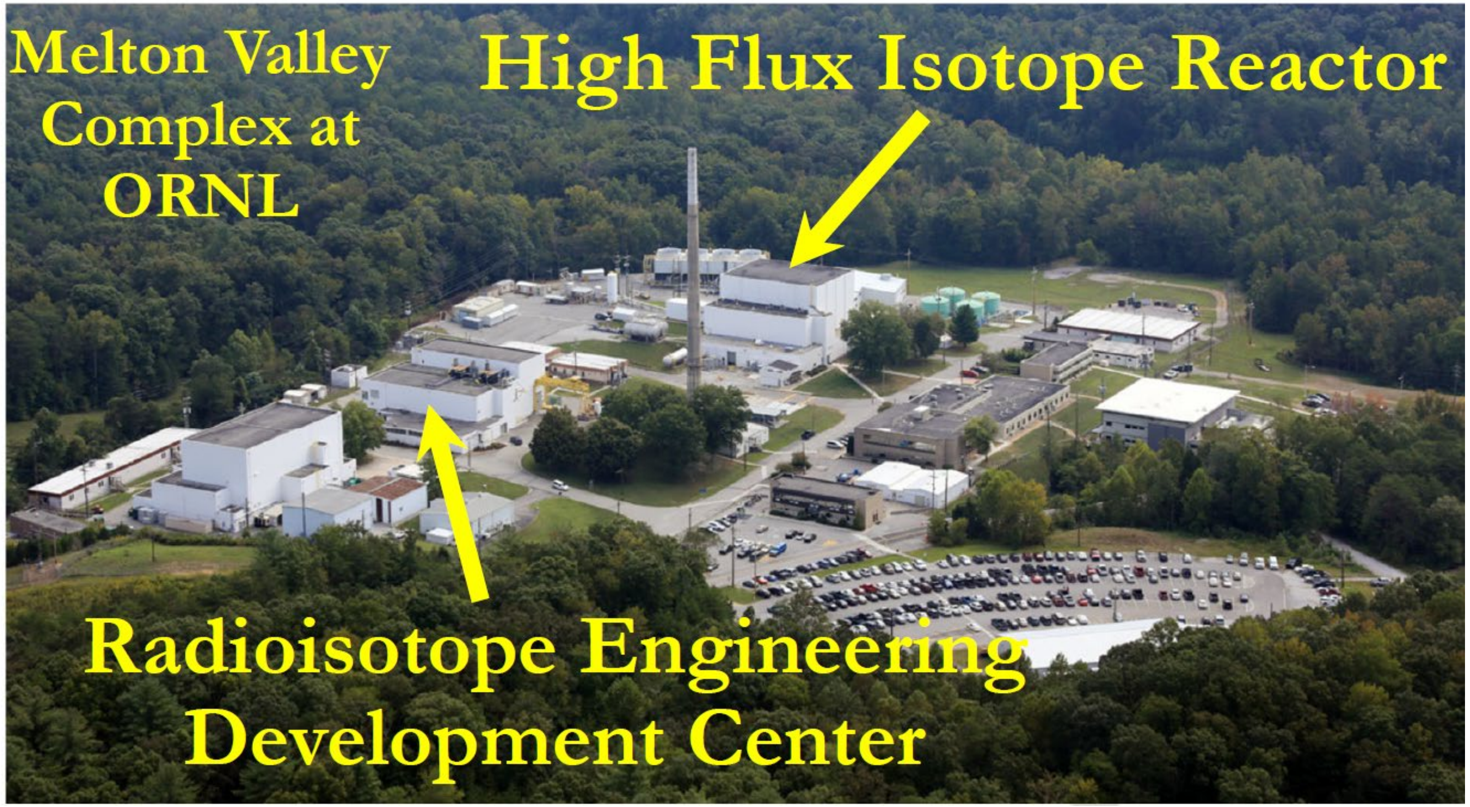
(a) at least 10^7 n/cm2/s neutron flux, one HFIR cycle per year, proper fission rate normalization
(b) optimized targets with thin backing (stop fission fragments, let electrons out with minimal energy losses)
(c) two e-spectrometers, for monitoring at a fixed energy (~3 MeV), and a larger one scanning the electron energies
(d) good energy resolution (~ ten keV) and transmission (~%), 25 keV bins for the electron spectra
(e) meaningful high statistics of electron spectra, up to 9 MeV
(d) gamma detectors for gamma-gamma coincidences and normalization, later TAS for the integral decay heat
(f) radiation background reduction/passive shielding

Lowell Crow (ORNL)

- Presented a technical description of ORNL's High Flux Isotope Reactor (HFIR).

- Possible locations for superconducting solenoid were discussed, including beam intensity and profile, as well as bacground.

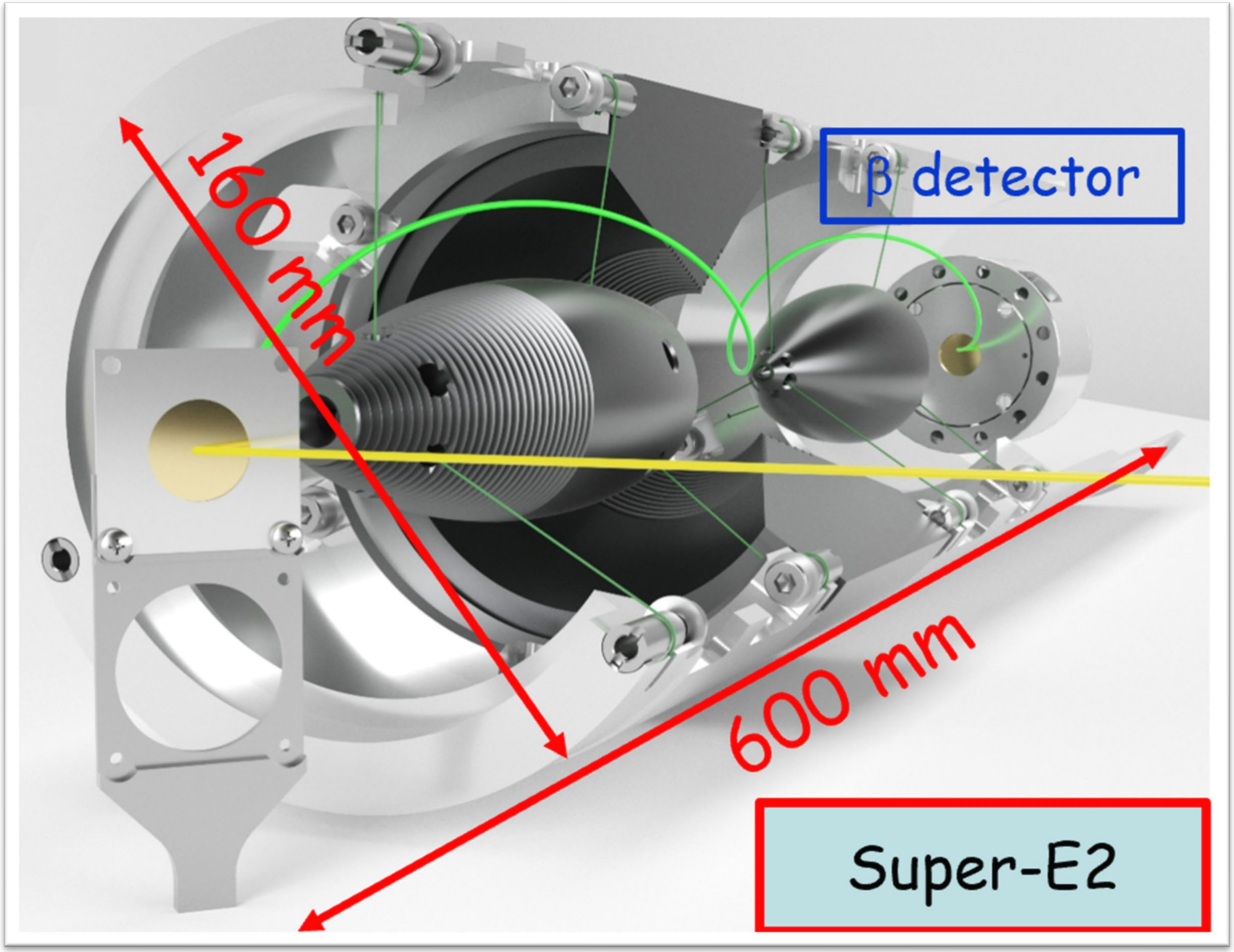




- The possibility of also using the NIST reactor was raised by Pieter Mumm and was briefly discussed.

Tibor Kibedi (Australian National University)

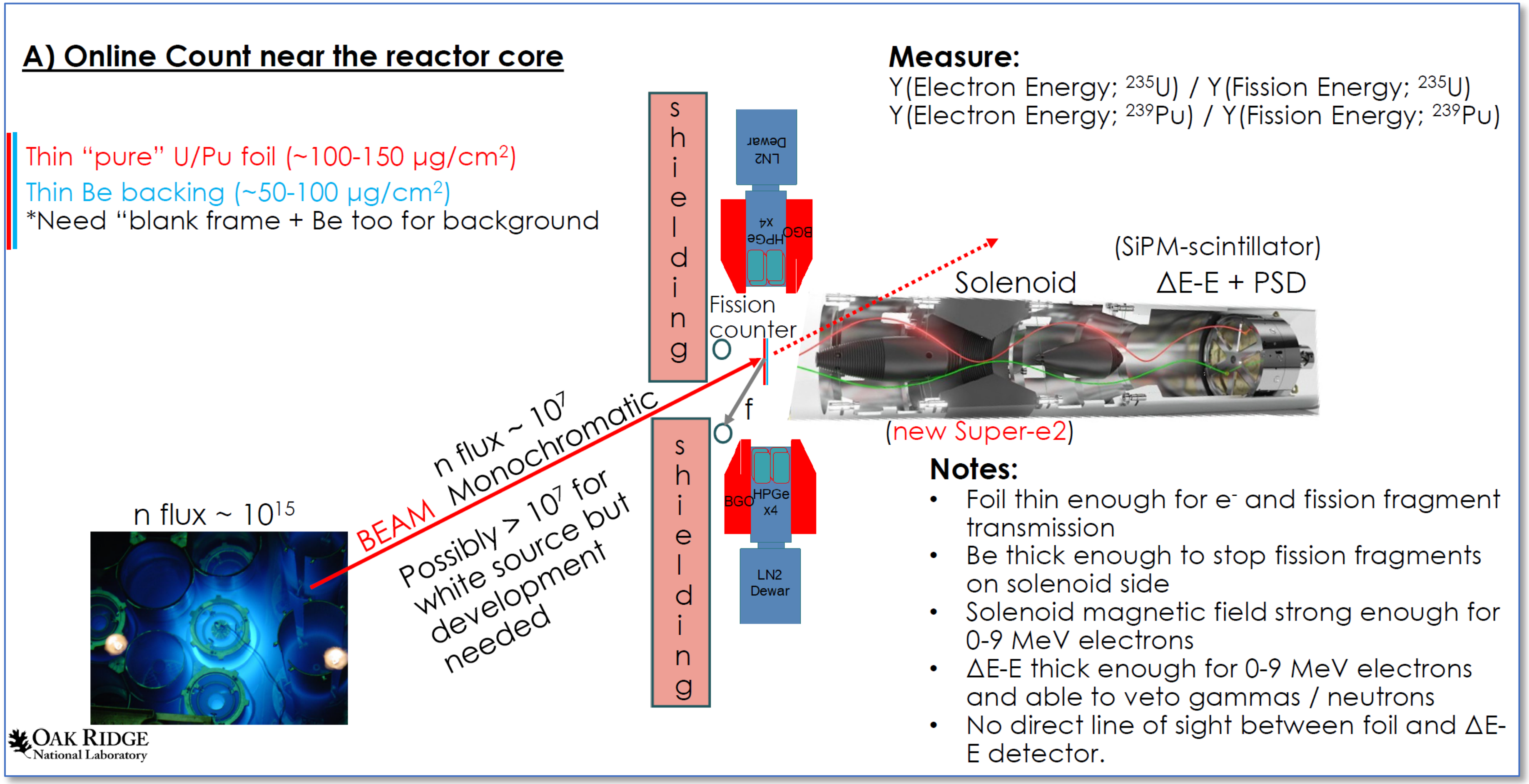
- Described use of superconducting solenoid to measured electron spectra.
- Based on existing detector with plenty of experience in conversion electrons and E0 transitions.
- Low background, great resolution, compact, high efficiency.
- 1 Tesla solenoid, HPG detector at focal plane, system in vacuum.
- About $1M.



Mitch Allmond (ORNL)

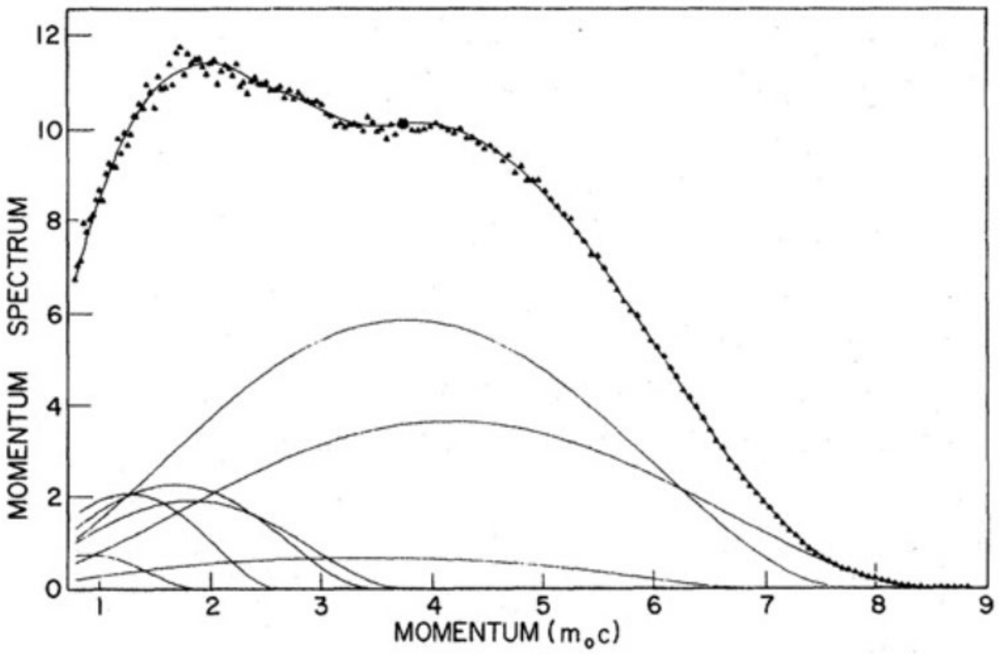
- Presented different possible concepts to perform electron measurement at HFIR, in-core rabit system or using a beam line.

- About $10-15 M, 5-6 years campaign.



Charlie Rasco (ORNL)

- Described need to accurately measure the shape of electron spectra following beta decay.
- Needed to understand effect of sub-dominant corrections and an input in summation calculations.



^{87}Kr Integral β Spectrum
Wohn, *et al.*, PRC 7, 160 (1973)

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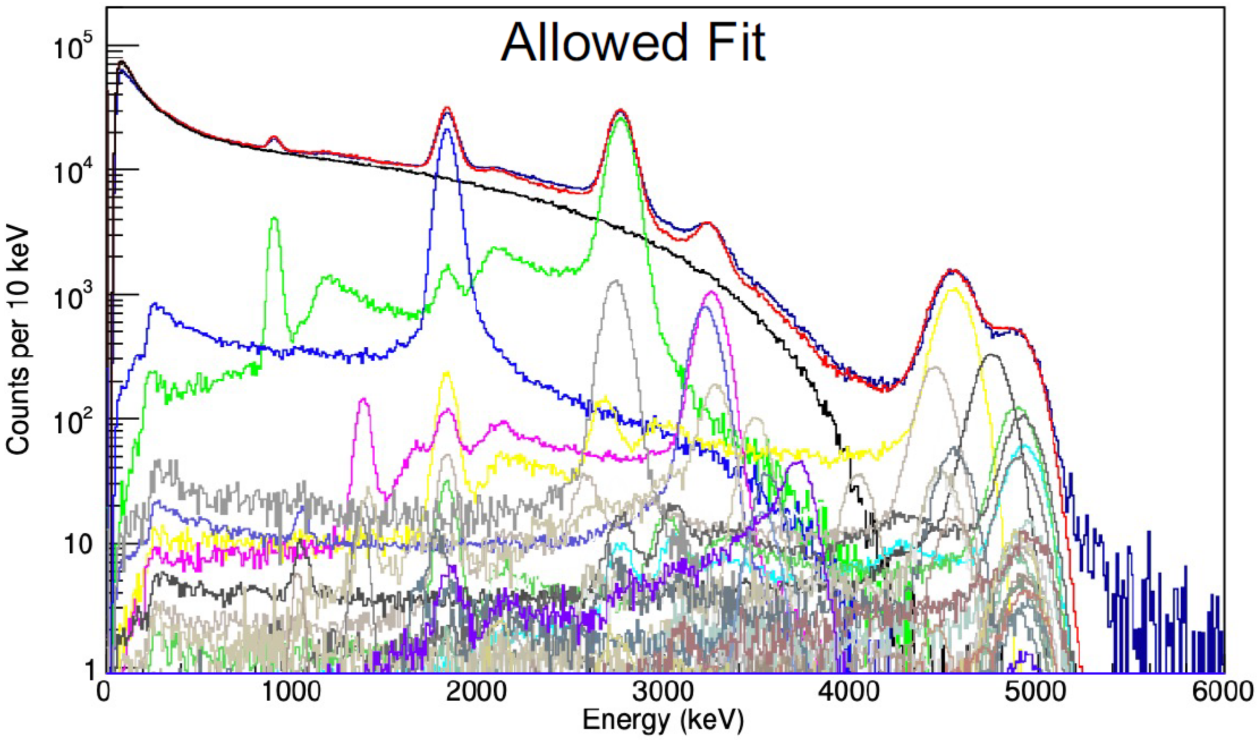
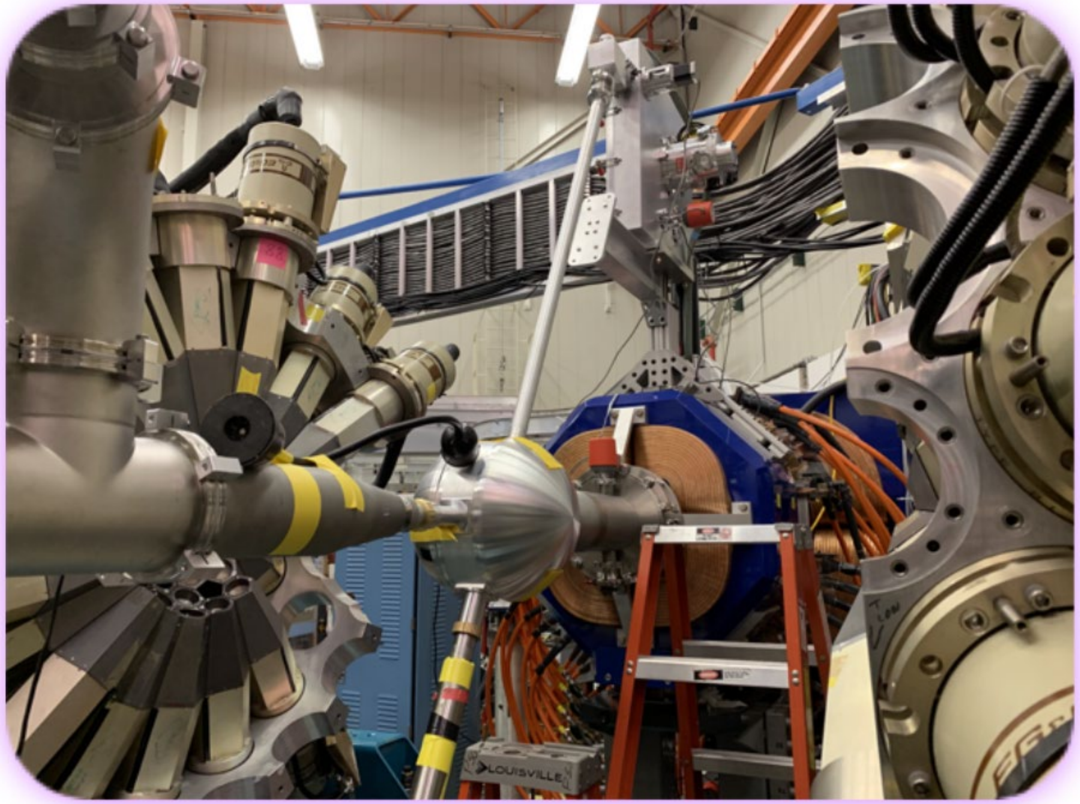


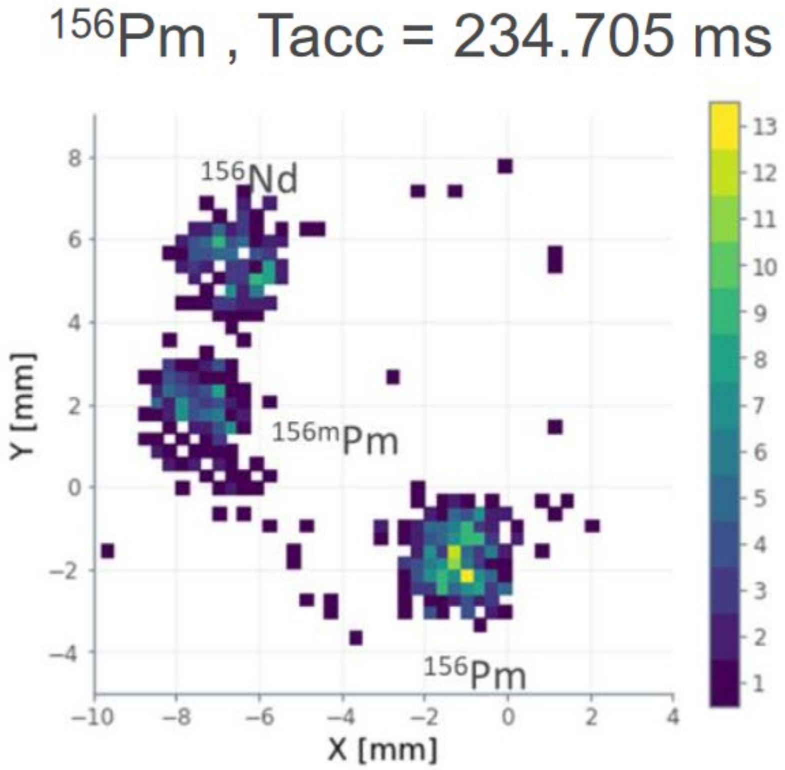
- For high-Q values, the shape of the sum electron spectrum includes a number of relevant contributions.
- Integration with current MTAS setup to allow for more efficient identification of the β component from complex β decays.
- Approved beamtime for testing prototype at ANL.

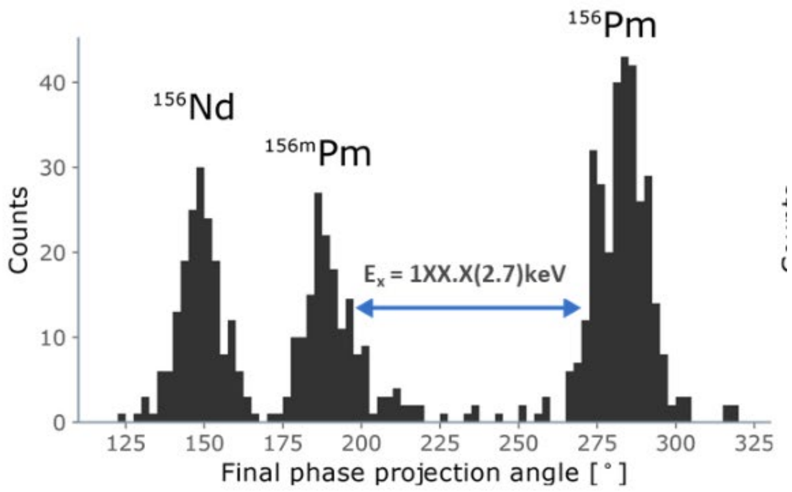
Guy Savard (ANL)

- Gave a presentation of current CARIBU facility capabilities as well as upcoming upgrades.

- Presented selected results, including the use of Gammasphere as a powerful decay station as well as separation of isomers and ground state levels for isomeric ratio measurements.

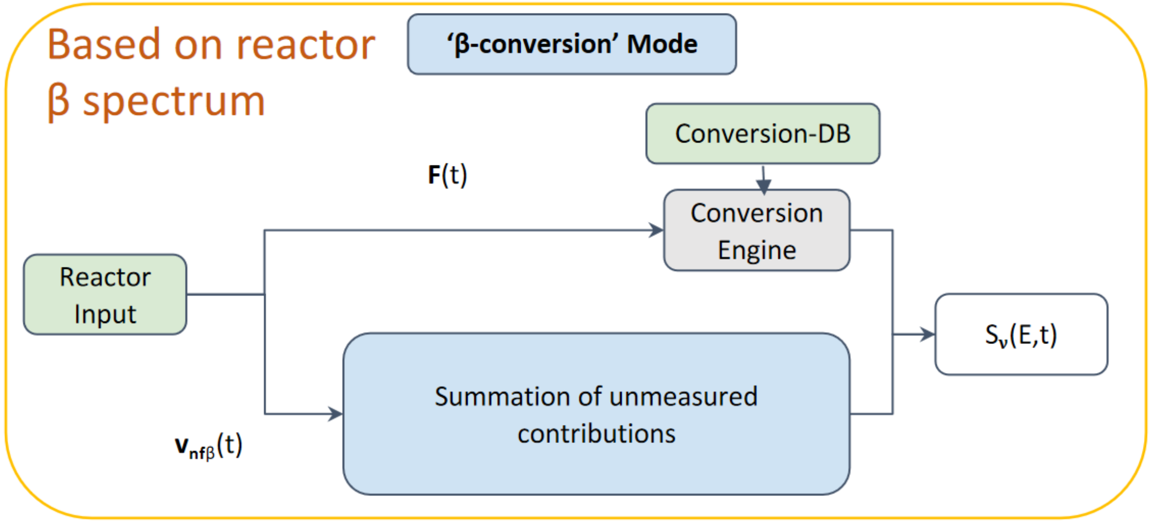


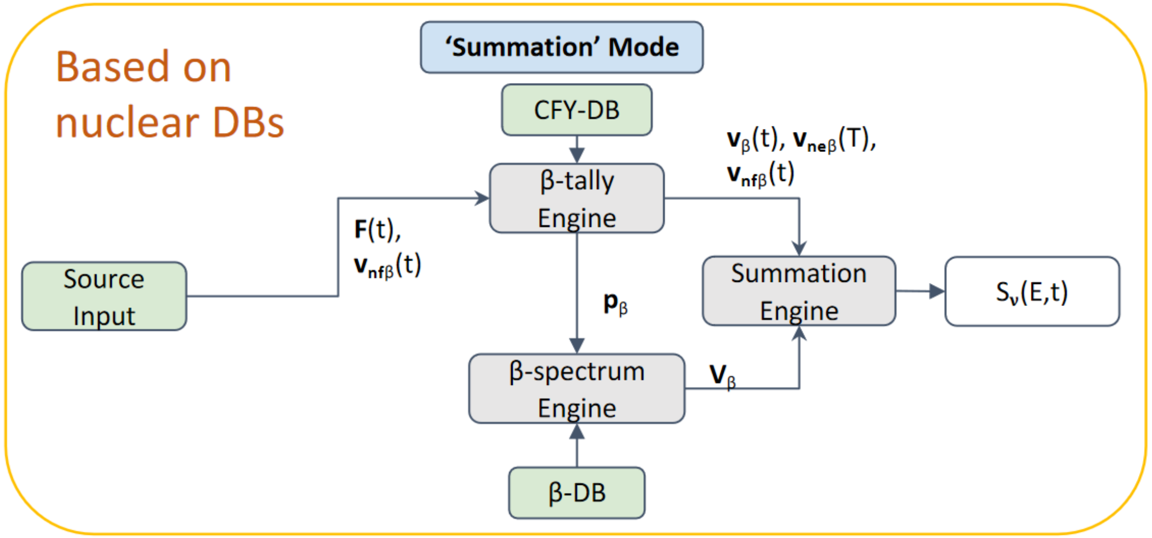


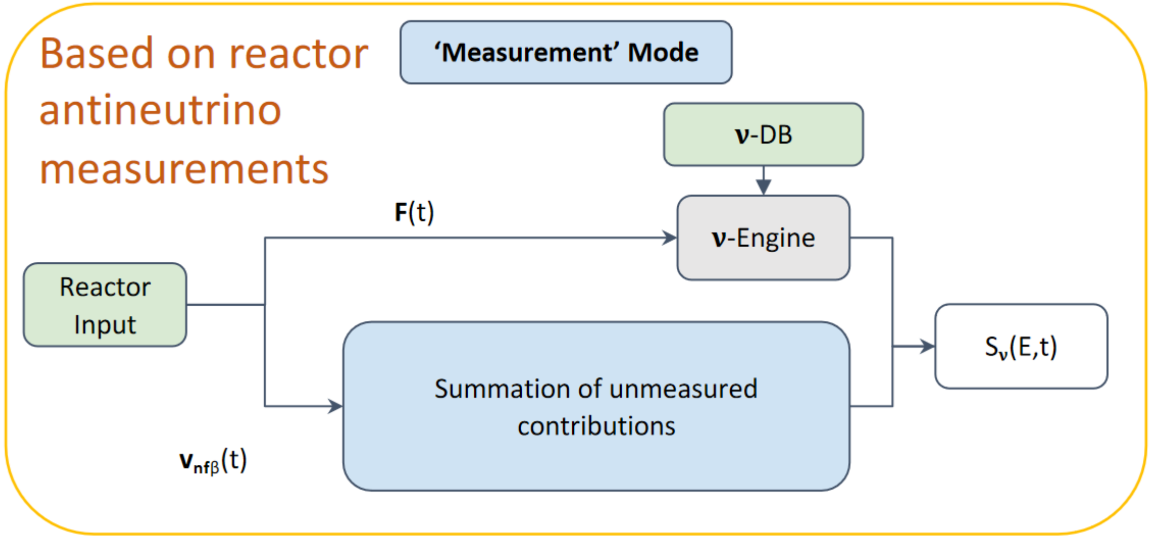


Xianyi Zhang (LLNL)

- Presented CONFLUX a framework for calculating antineutrino spectra in three different modes.
- IIT, LLNL, UT, VT collaboration







Summary

Identified the following actionable improvements related to the antineutrino spectrum:

Improvements to aggregate fission beta measurements

- New high-precision, US-based fission beta spectrum using ORNL HFIR neutron beamlines, or possibly at other reactor facilities such as NIST's.

Improvements to other summation and conversion model inputs

- Beta shape factor and feeding strength measurements for key isotopes
- Isomeric yield ratio measurements

Direct antineutrino source term measurement improvement

- Improved high-statistics U235 flux and spectrum measurement at an HEU reactor
- High-energy-resolution, full-cycle measurement of a single LEU core
- Further development of reactor CEvNS detectors for measuring LEU low-energy source term
- Joint analyses of HEU and LEU IBD data; correlated LEU+HEU measurements with one detector

Improvements in antineutrino spectrum software tools

- Data pipeline development for extraction, evaluation, and public access of neutrino data
- Same, for summation and conversion predictions