New Insights from Precision Measurements of Reactor Antineutrinos (Part 2)

D. Dwyer, P. Tsang

Feb. 26, 2015

Part 2: Overview

Confusion:

Measurements of the rate and energy spectra of reactor antineutrinos disagree with our traditional predictions.

-> What physics and assumptions underlie these predictions?

Insight:

Can our knowledge of nuclear fission and decay provide any guidance?

-> Look to the sum-total of the past century of nuclear measurements.

Consequences:

What are the consequences of these observations?

What are the prospects for improved understanding of reactor $\overline{\nu}_e$ emission?

Confusion

Prediction: β^- Conversion

Traditional: Use cumulative β^- spectrum to predict $\bar{\nu}_e$ spectrum

Method:

Expose fission parents to thermal neutrons

Measure total outgoing β- energy spectra

Predict corresponding $\bar{\nu}_e$ spectra

Phys. Lett. B160, 325 (1985), Phys. Lett. B118, 162 (1982)
Phys. Lett. B218, 365 (1989), Phys. Rev. Lett. 112, 122501 (2014)
Phys. Rev. C83, 054615 (2011)
Phys. Rev. C84, 024617 (2011)

Results:

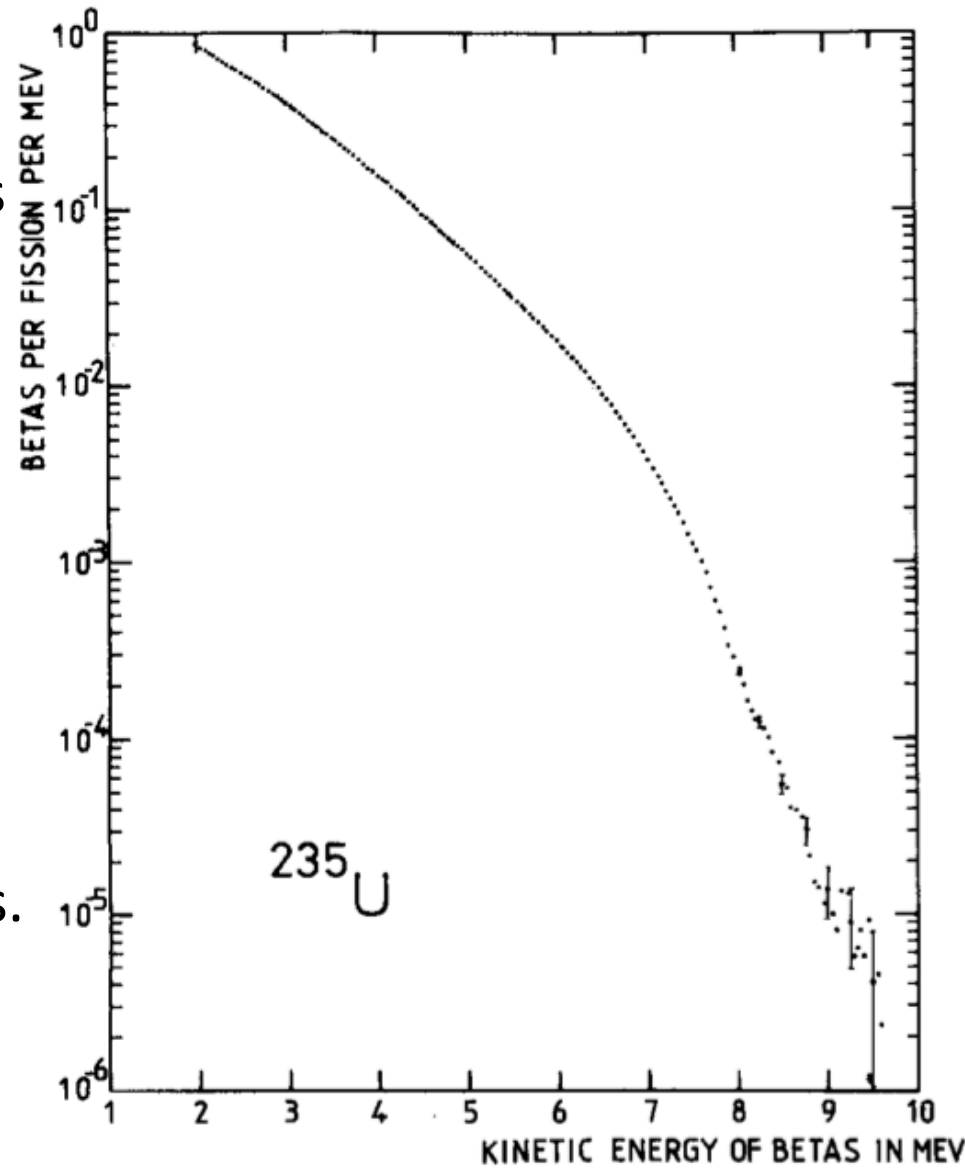
More precise than *summation* predictions

Standard approach for ~30 years

Predicts 6% higher flux than reactor msmts.

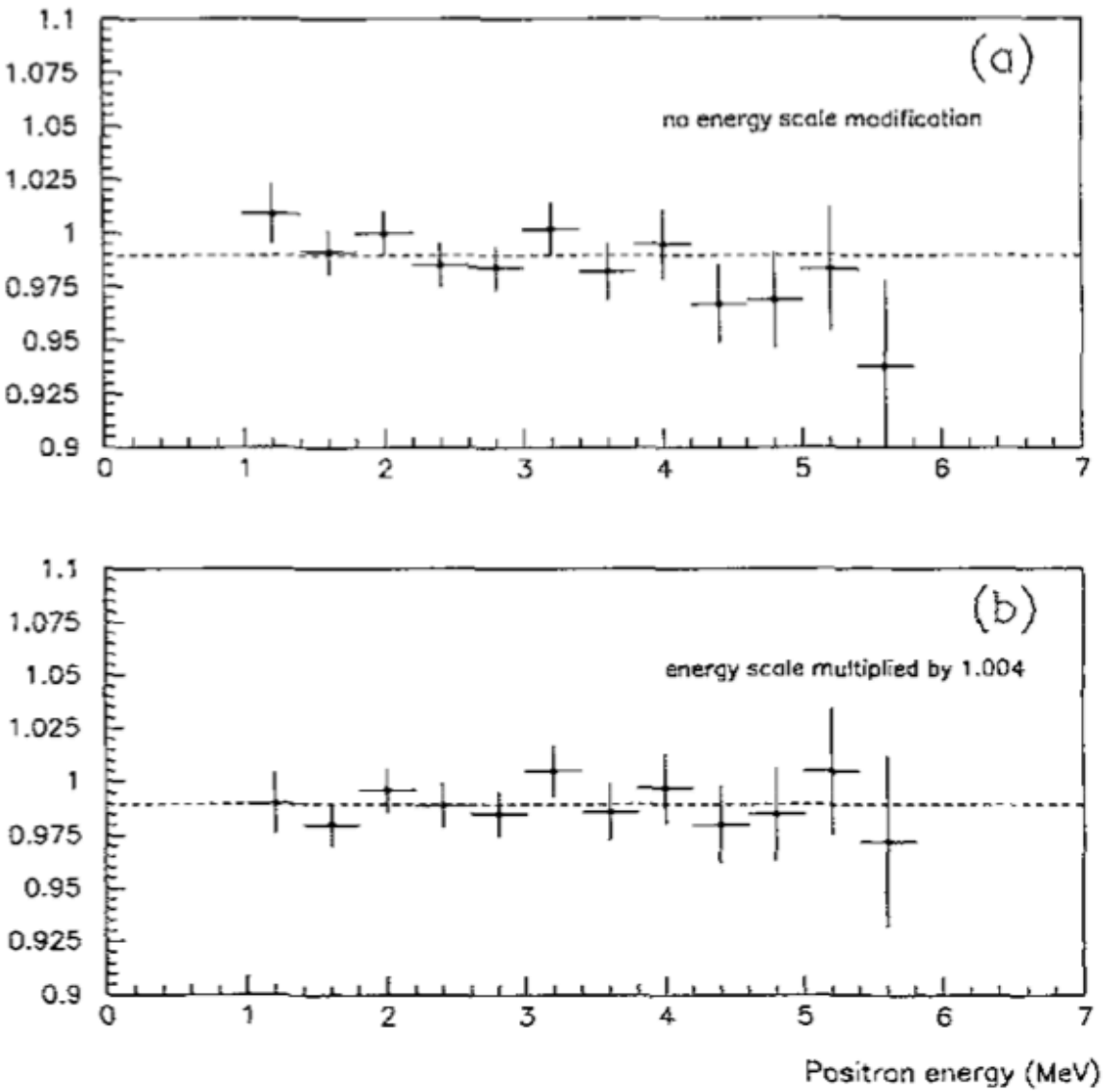
Reactor Anomaly, Sterile Neutrinos?

Phys. Rev. D83, 073006 (2011)



Bugey Measurement

Bugey spectral measurement agreed with β^- conversion model.



Comparison of Bugey 3 spectrum relative to conversion model.
Phys. Lett. B 374, 243 (1996)

No evidence of significant deviation. Measured from 1 to 6 MeV.

Measured spectrum has slightly steeper slope with energy.

A minor (0.4%) shift in detector energy scale improves agreement.

Guidance

Do *summation* models suggest an origin for the 5-7 MeV deviation?

Approach:

Examine tabulated nuclear data to determine antineutrino spectrum composition from 5 to 7 MeV.

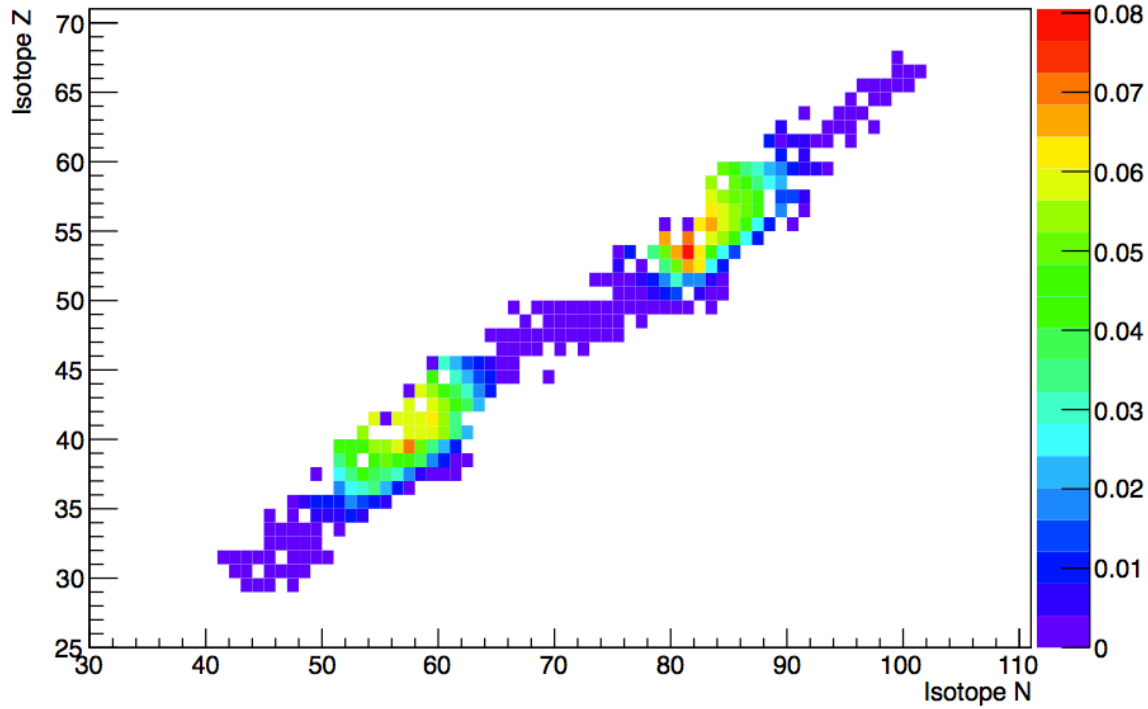
Method:

Cumulative fission yields for >1300 fission daughters provided by ENDF/B.VII.1 database.

Decay endpoints and branching fractions provided by ENSDF (kindly tabulated by A. Hayes).

Assume allowed beta decay shapes (including coulomb, radiative, weak magnetism corrections).

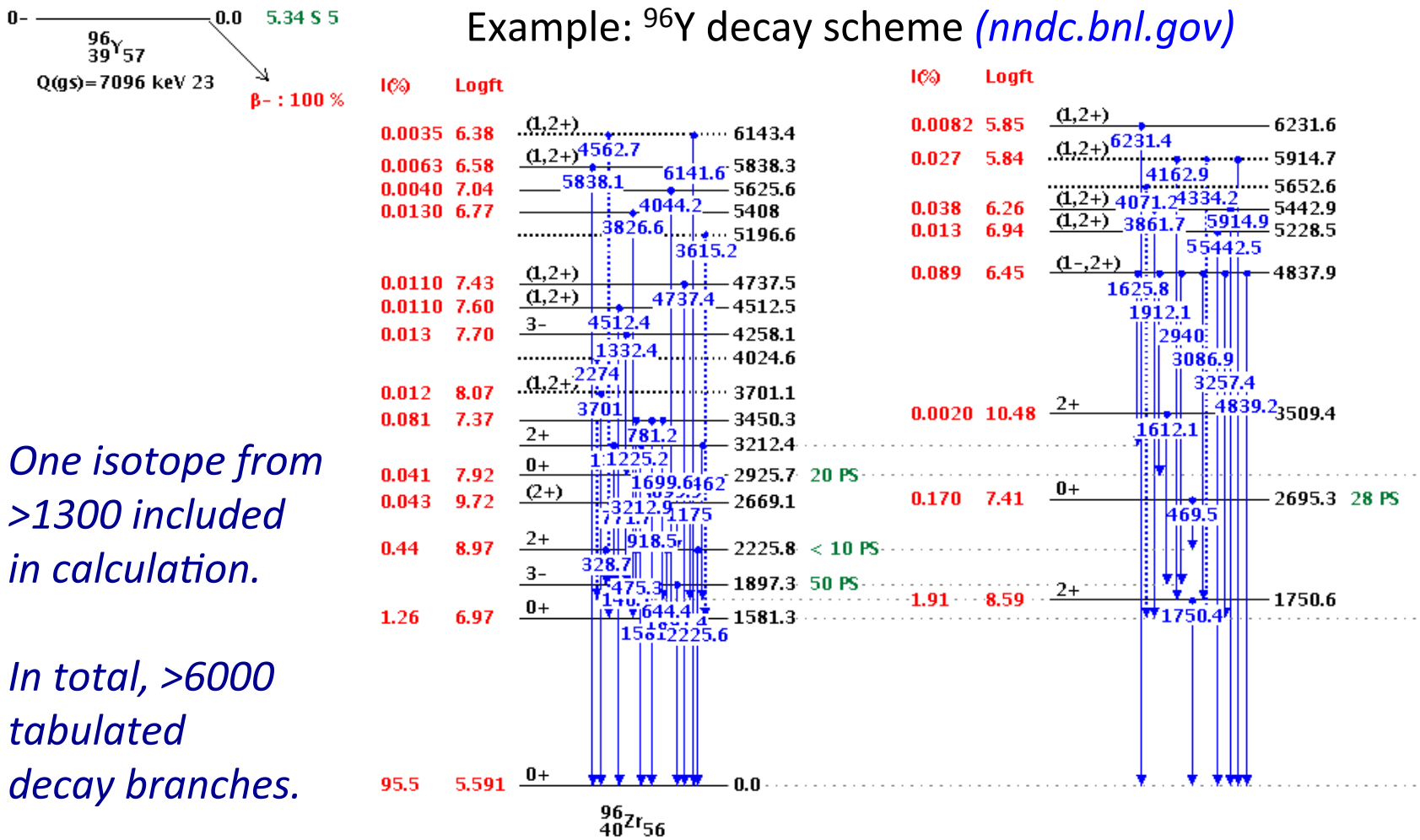
Cumulative fission daughter isotope yields for a nominal reactor



Nuclear Structure

Complex decays of neutron-rich fission daughters.

Example: ^{96}Y decay scheme *(nndc.bnl.gov)*



One isotope from >1300 included in calculation.

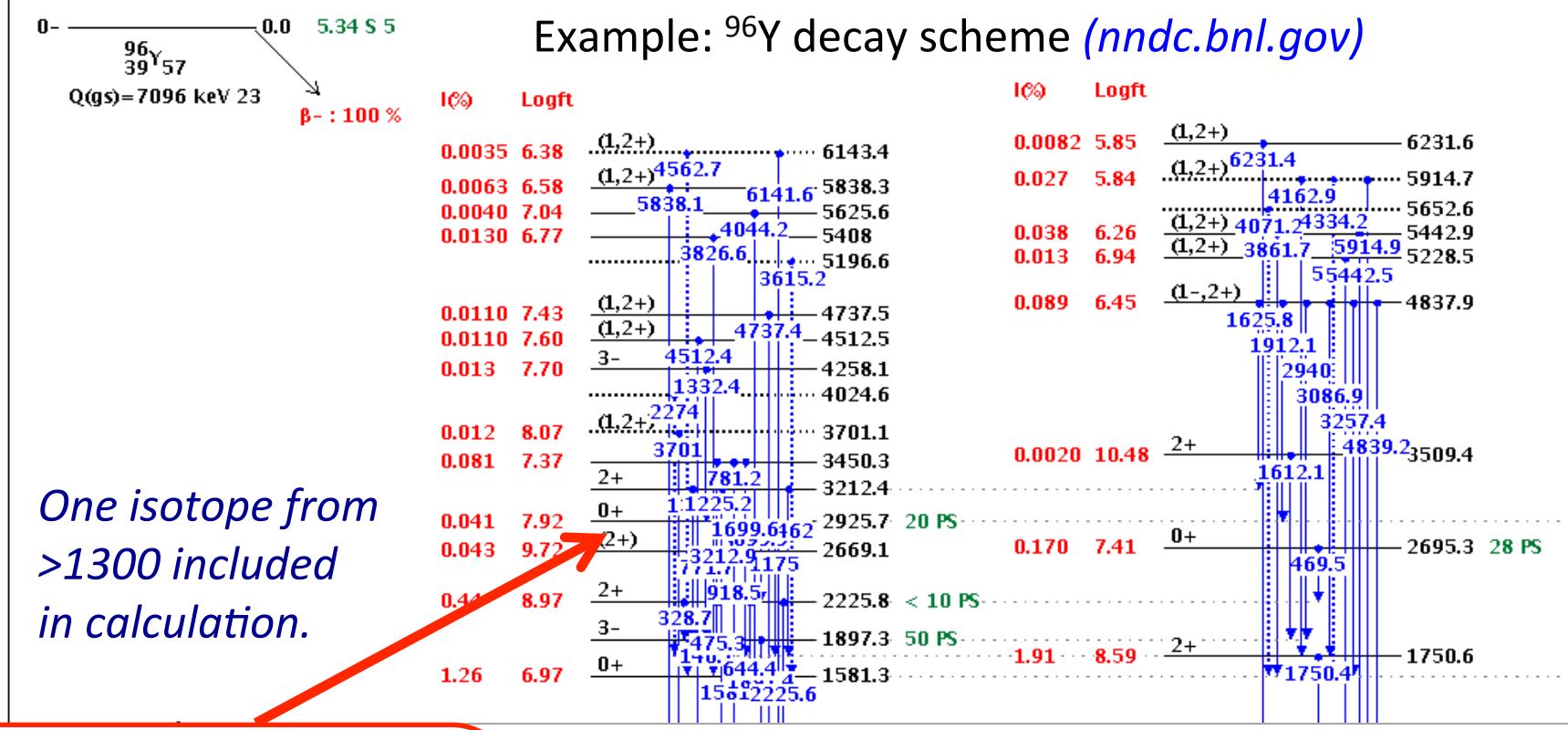
In total, >6000 tabulated decay branches.

Decay branching uncertainties can be considerable, or even unknown.

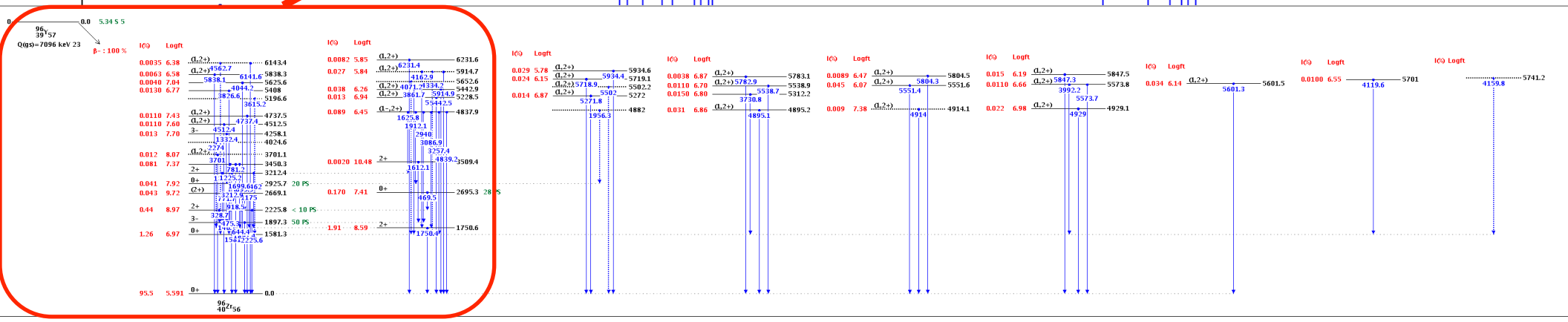
Nuclear Structure

Complex decays of neutron-rich fission daughters.

Example: ^{96}Y decay scheme *(nndc.bnl.gov)*



One isotope from >1300 included in calculation.



Here Be Dragons…

Significant uncertainty when directly calculating energy spectrum.

Missing Details:

Are tabulated fission and decay data comprehensive?

- Fission: What about possible very short-lived unstable daughters?
- Decay: 6% of yield has no corresponding ENDF decay information

eg. Phys. Rev. C24, 1543 (1981)

Biased Data:

Are there systematic biases in the yield or beta decay data?

- Uncertainty from assumption of reactor equilibrium, parent fission rates.
- Pandemonium Effect: Tabulated branches biased toward high-endpoints.

eg. Phys. Rev. Lett. 109, 202504 (2012)

Beta Decay Shape Corrections:

How do forbidden decay corrections impact spectrum?

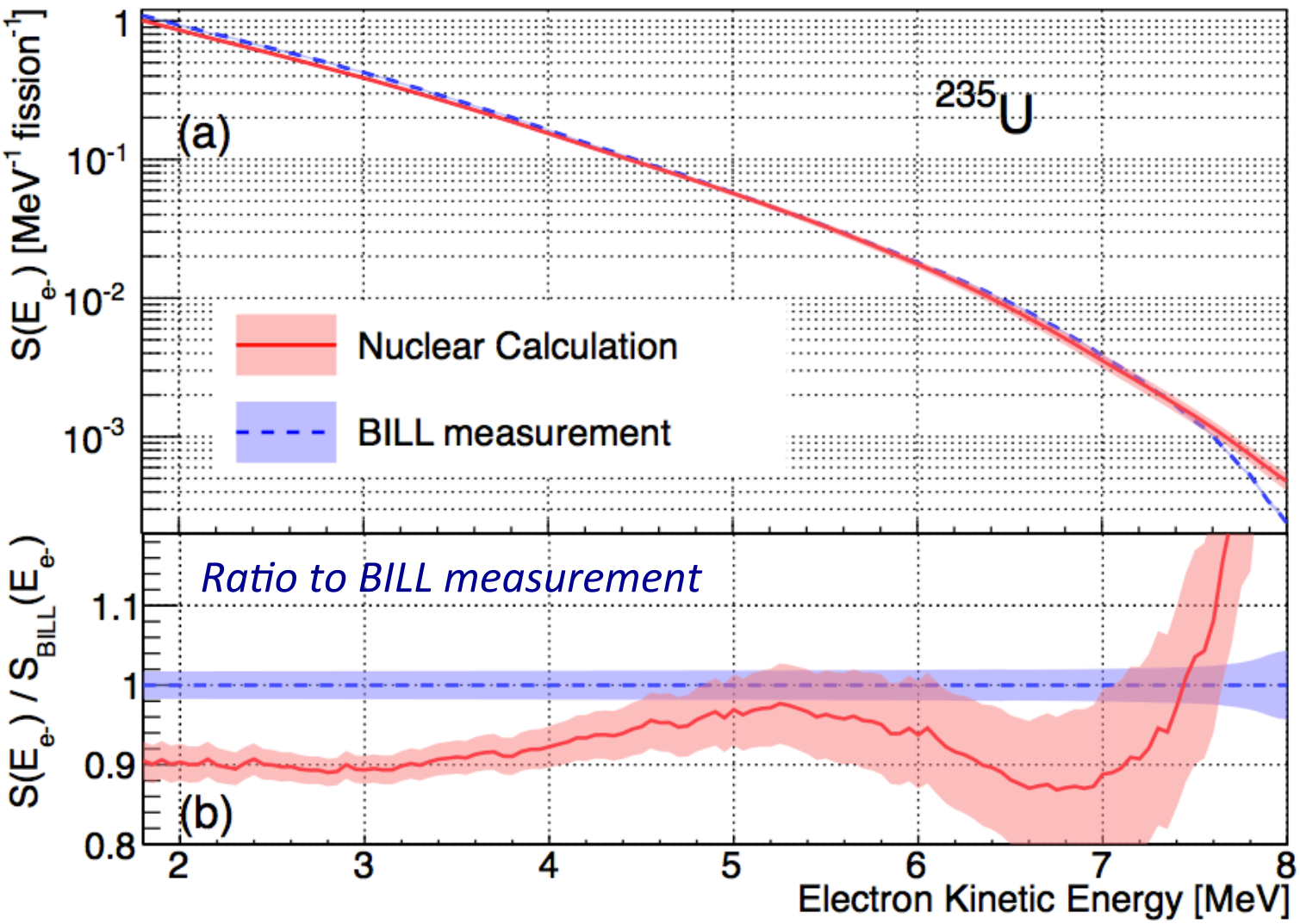
- Mismatch of decay initial-final spin and parity can distort spectrum

eg. Phys. Rev. Lett. 112, 202501 (2014)

Approach: Choose simplest assumption at each step (all allowed shapes, etc.)

β^- Spectrum Disagreement

Direct calculation of ^{235}U β^- spectrum disagrees with BILL msmt.



Note:
Uncertainty band for calc. is a lower bound.

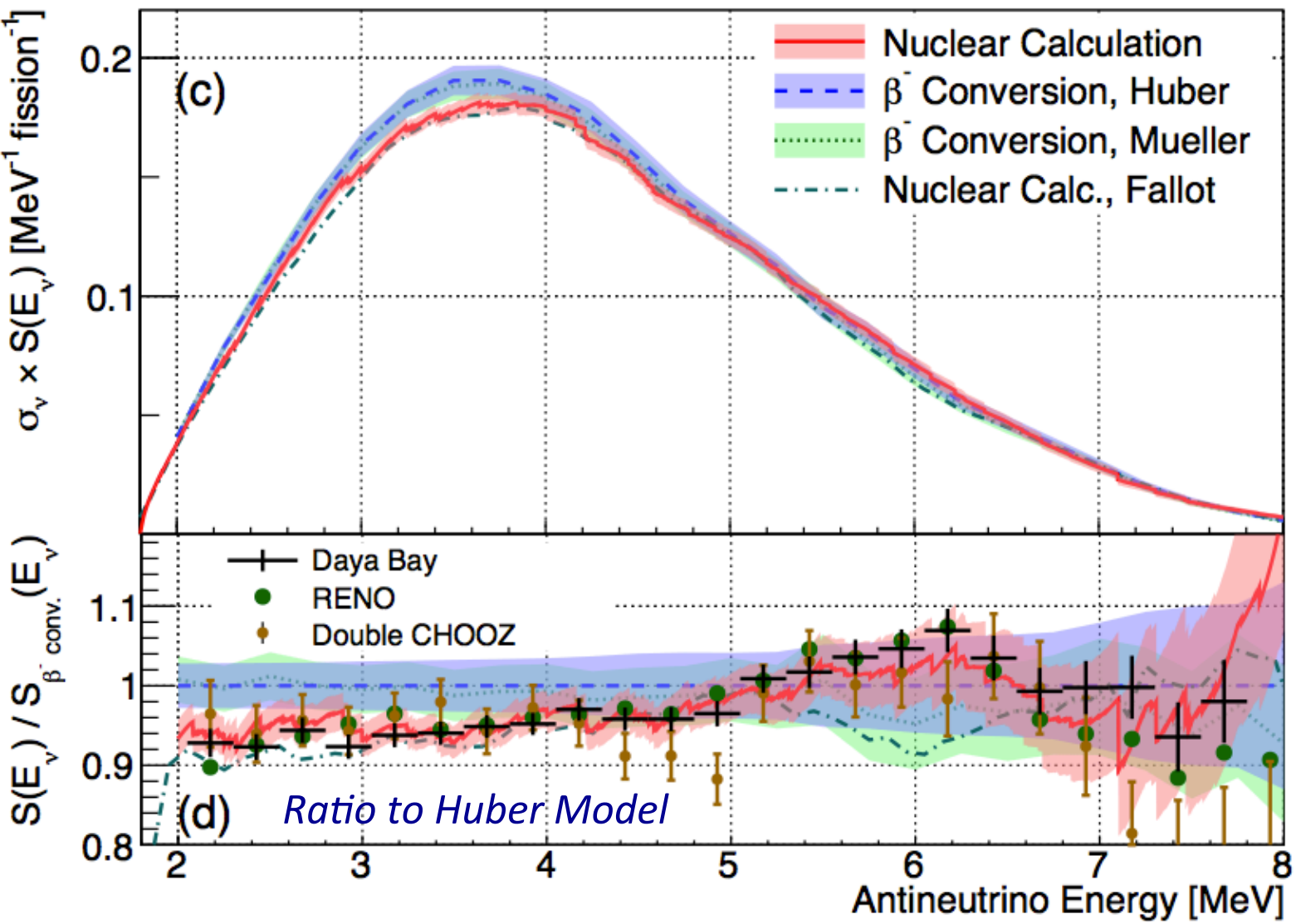
Only includes tabulated yield+branch uncertainties.

Occam's razor:
Something wrong with calculation?

D.Dwyer, T.Langford
PRL 114, 012502 (2015)

Reactor $\bar{\nu}_e$ Spectrum

Summation calculation unexpectedly agrees with preliminary msmts.



Note:
Preliminary data compared using approx.
$E_\nu \approx E_{e+} + 0.8$ MeV

Data normalization adjusted to accurately compare shape.

How do large calc. uncertainties not cause more tension with measurements?

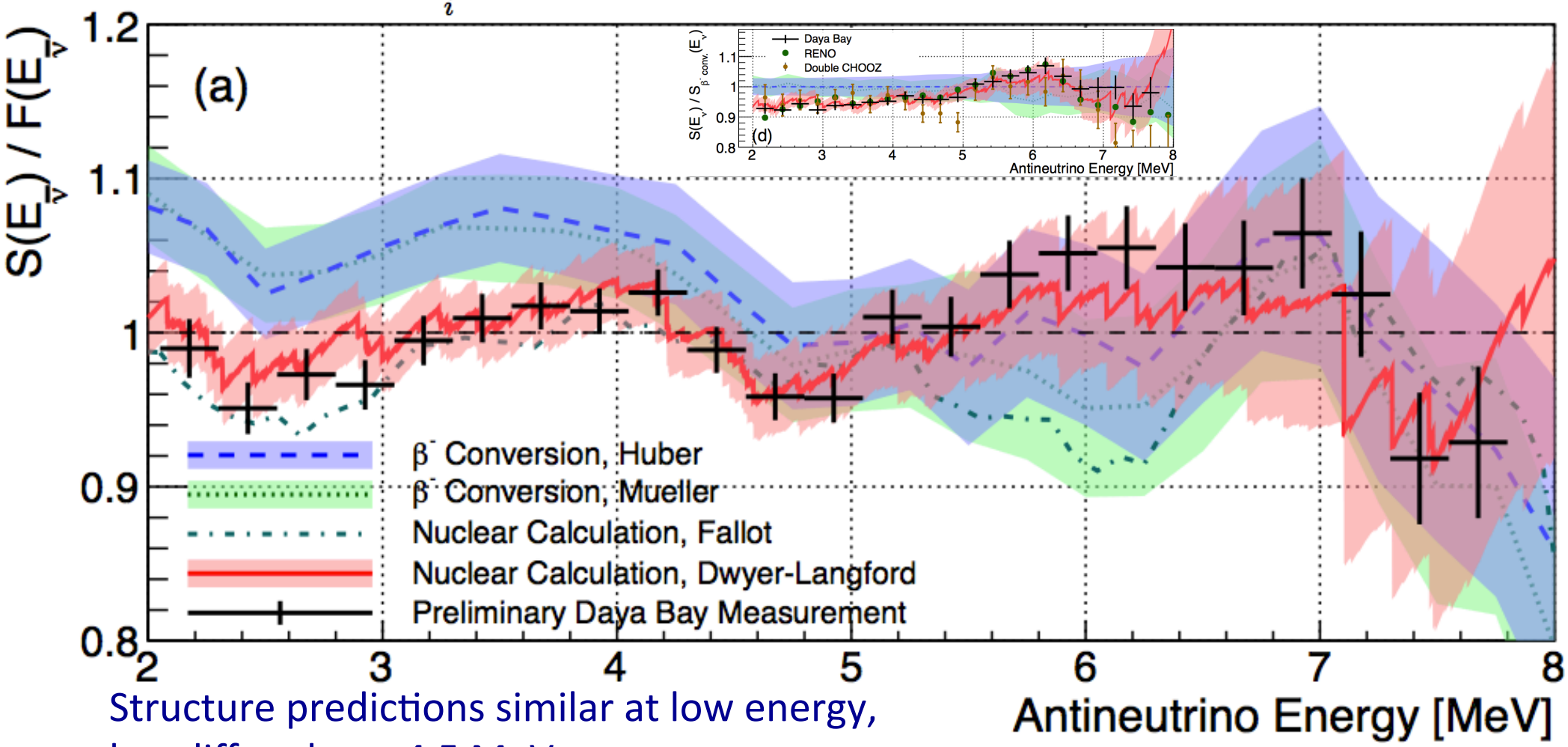
D.Dwyer, T.Langford
PRL 114, 012502 (2015)

Detailed $\bar{\nu}_e$ Spectrum Shape

Structure clearer when compared with smooth approximation *F(E)*

$$F(E_{\bar{\nu}}) = \exp\left(\sum_i \alpha_i E_{\bar{\nu}}^{i-1}\right)$$

α = {0.4739, 0.3877, −0.3619, 0.04972, −0.002991}



Structure predictions similar at low energy, but differ above 4.5 MeV

Insight

Dominant Branches

Eight decay branches dominate 5-7 MeV shape in the calculation.

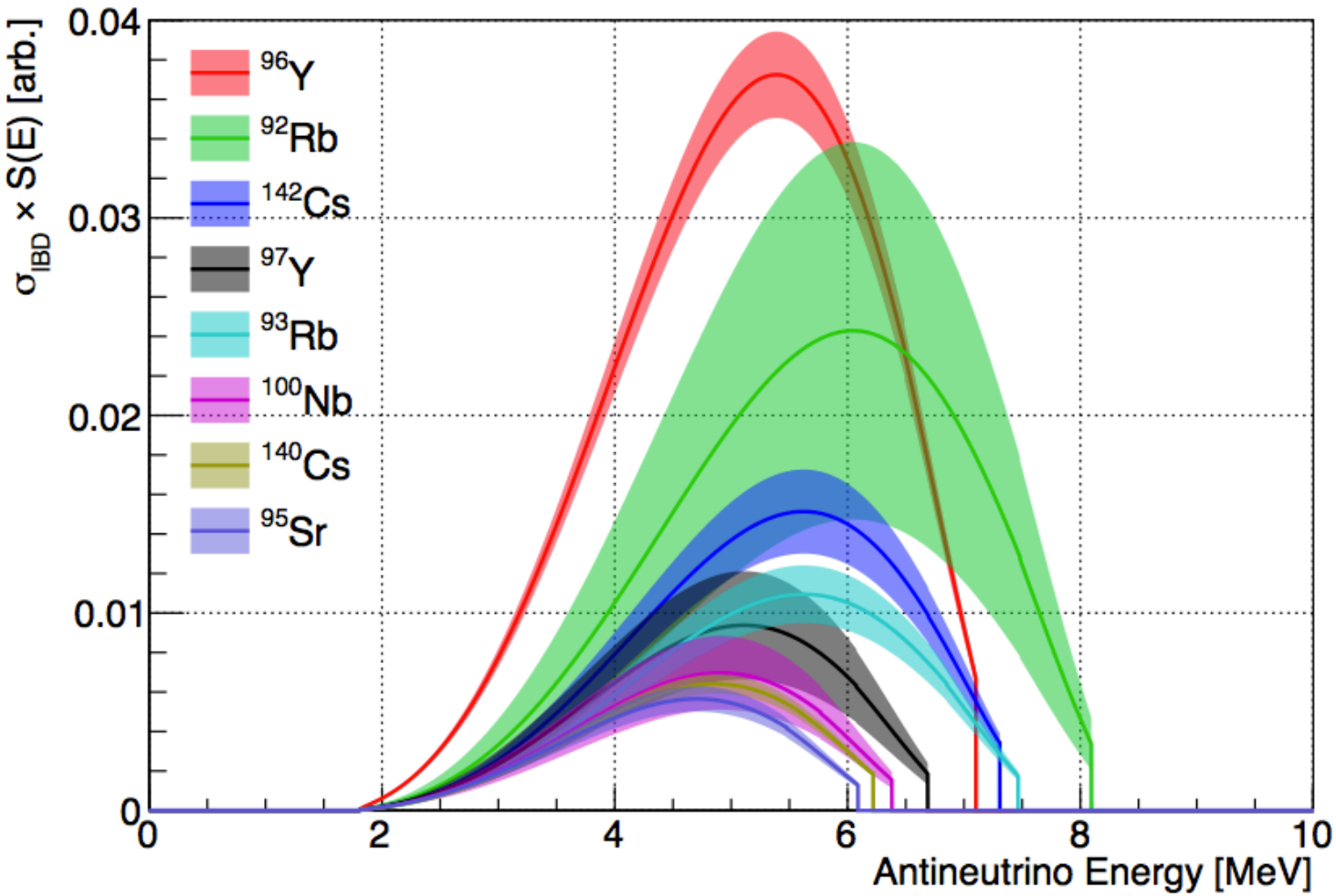
Isotope	Q[MeV]	$t_{1/2}$[s]	$\log(ft)$	Decay Type	N[%]	σ_N[%]
^{96}Y	7.103	5.34	5.59	$0^- \rightarrow 0^+$	13.6	0.8
^{92}Rb	8.095	4.48	5.75	$0^- \rightarrow 0^+$	7.4	2.9
^{142}Cs	7.308	1.68	5.59	$0^- \rightarrow 0^+$	5.0	0.7
^{97}Y	6.689	3.75	5.70	$1/2^- \rightarrow 1/2^+$	3.8	1.1
^{93}Rb	7.466	5.84	6.14	$5/2^- \rightarrow 5/2^+$	3.7	0.5
^{100}Nb	6.381	1.5	5.1	$1^+ \rightarrow 0^-$	3.0	0.8
^{140}Cs	6.220	63.7	7.05	$1^- \rightarrow 0^+$	2.7	0.2
^{95}Sr	6.090	23.9	6.16	$1/2^+ \rightarrow 1/2^-$	2.6	0.3

Calculation predicts ~42% of rate in 5-7 MeV caused by these 8 beta decay branches.

Are the fission yields and branching fractions accurate for these dominant branches?

Dominant Branches

Eight decay branches dominate 5-7 MeV shape in the calculation.



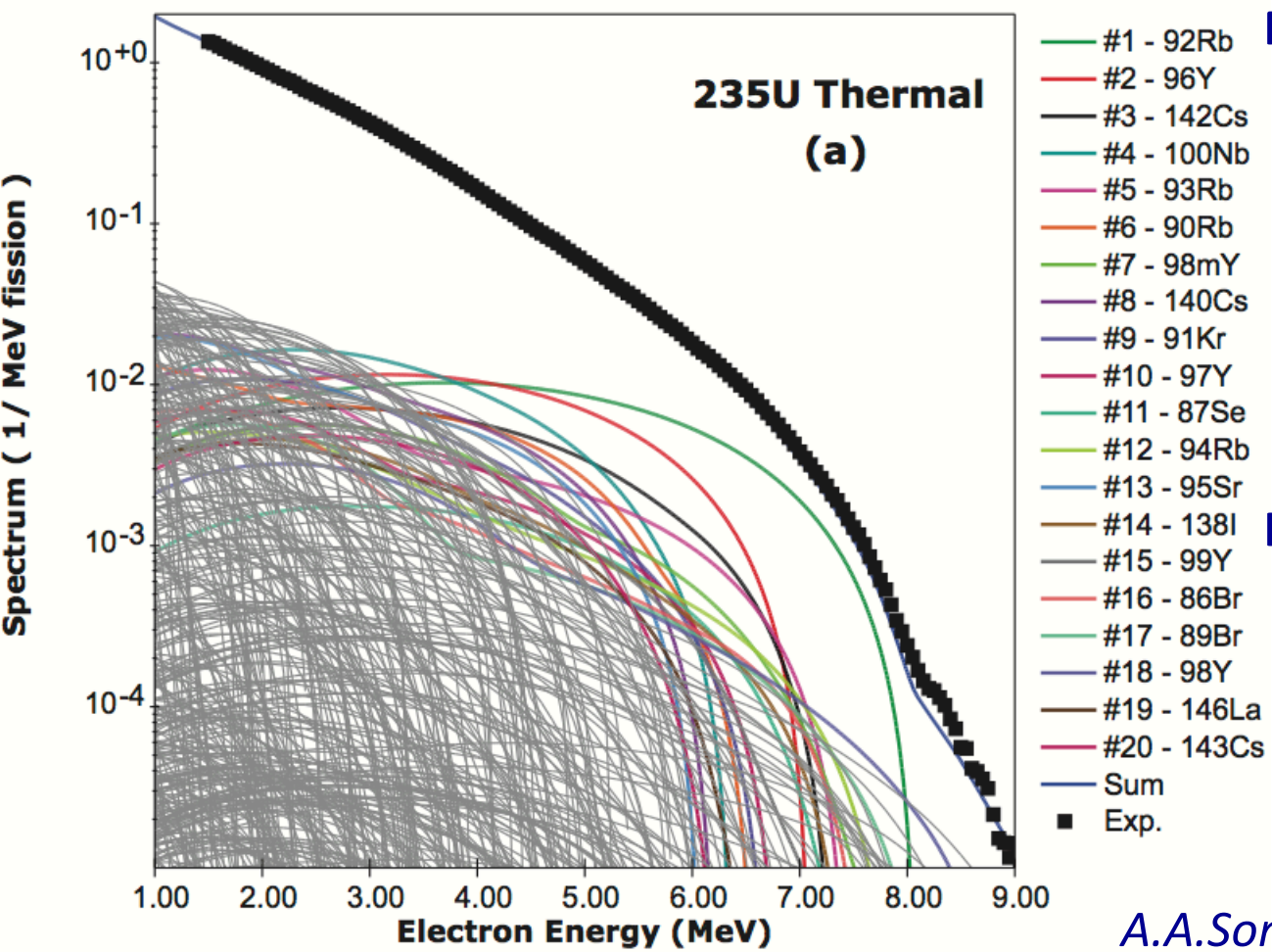
Energy Spectra:
Allowed shape
+ IBD cross-section

Uncertainties:
Fission Yield
Branch fraction
^{92}Rb most significant

If nuclear data accurate, calculated 5-7 MeV excess seems robust.

Dominant Branches

Recent calculations also identify the same prominent branches.



National Nuclear Data Center Group

'Optimized' data sources

- ENDF/B.VII.1 decay library
  & latest TAGS measurements
  & direct β-spectrum msmts.
  & theoretical calc. for missing data
- JEFF 3.1 fission library (OECD-NEA)

Interesting observations

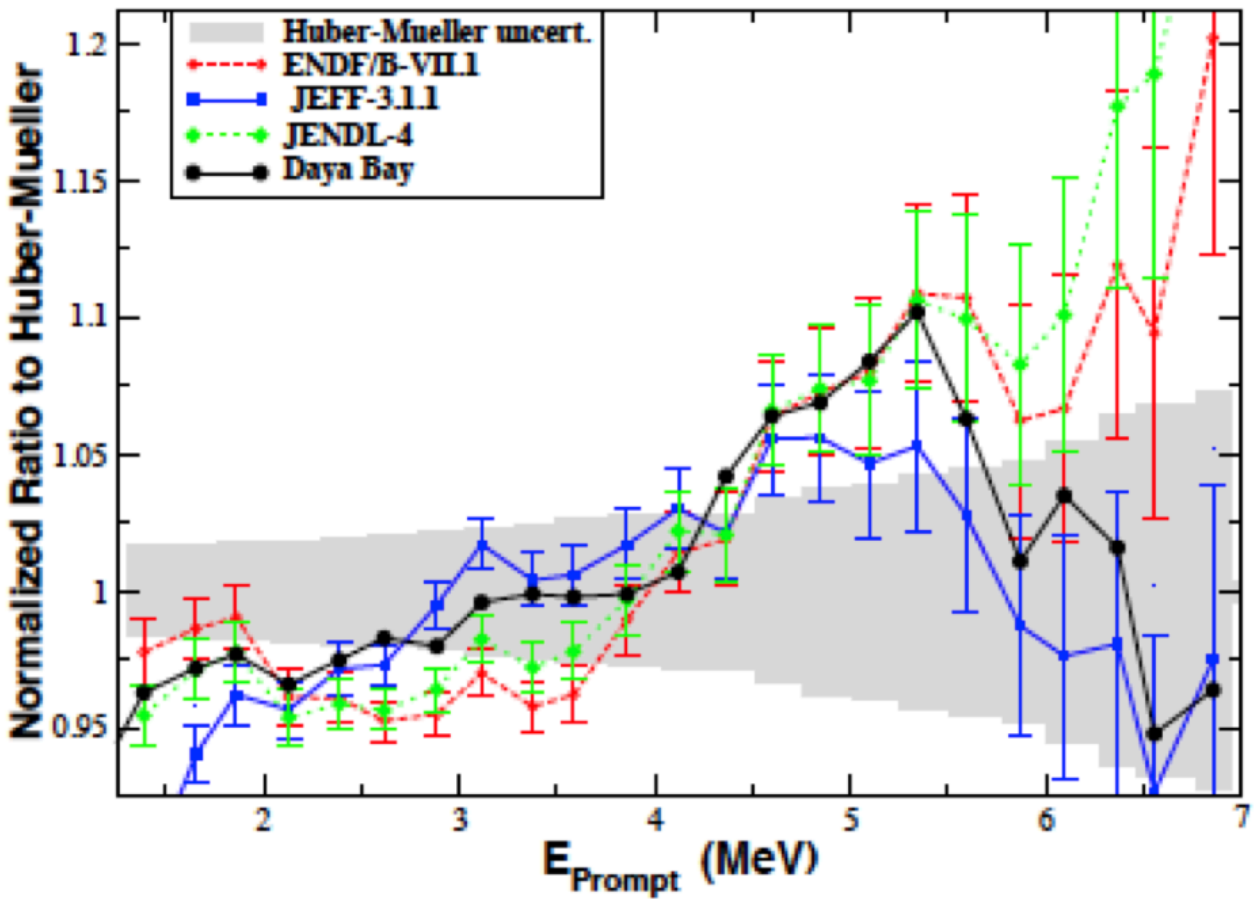
Reactor antineutrino spectra dominated by:

- Light fission fragments (~70%)
- Odd-Z, odd-N nuclides (~50%)

A.A.Sonzogni, T.D.Johnson,E.A.McCutchan
PRC 91, 011301(R) (2015)

Nuclear Databases

All nuclear databases show similar tension with β^- conversion



Standard Databases:

ENDF: USA

JEFF: OECD-NEA (Europe)

JENDL: Japan

Interesting observations:

- All databases show similar structure below 6 MeV.
- Variations between databases larger than claimed uncertainties.

A.Hayes, Presented at the Workshop on the Intermediate Neutrino Program (BNL, Feb. 4-6, 2015)

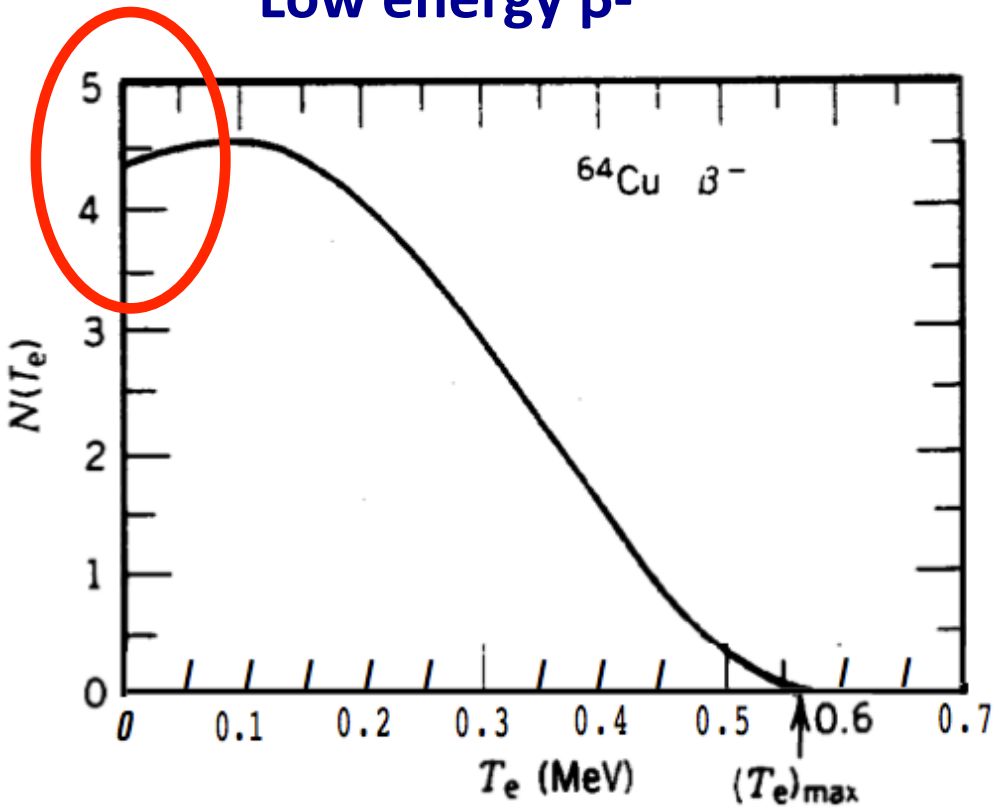
Detailed $\bar{\nu}_e$ Spectrum Shape

Calculation predicts significant discontinuities in spectrum.

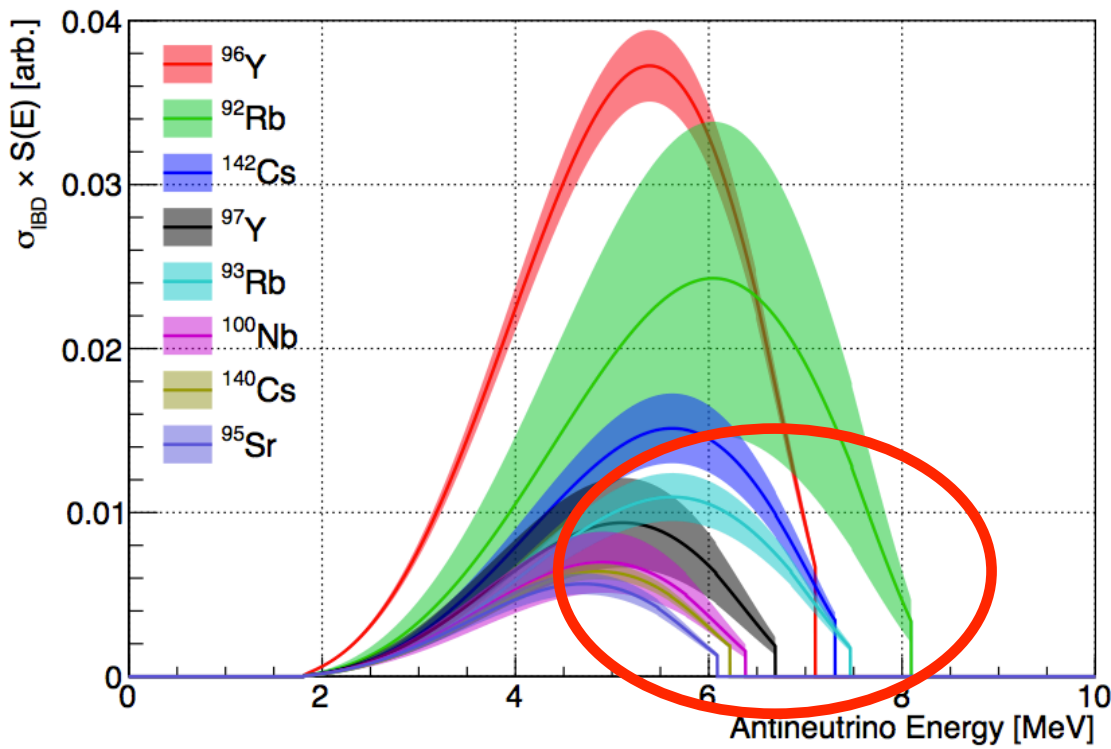
Coulomb correction:

Nuclear charge enhances production of:

Low energy β-



High-energy $\bar{\nu}_e$

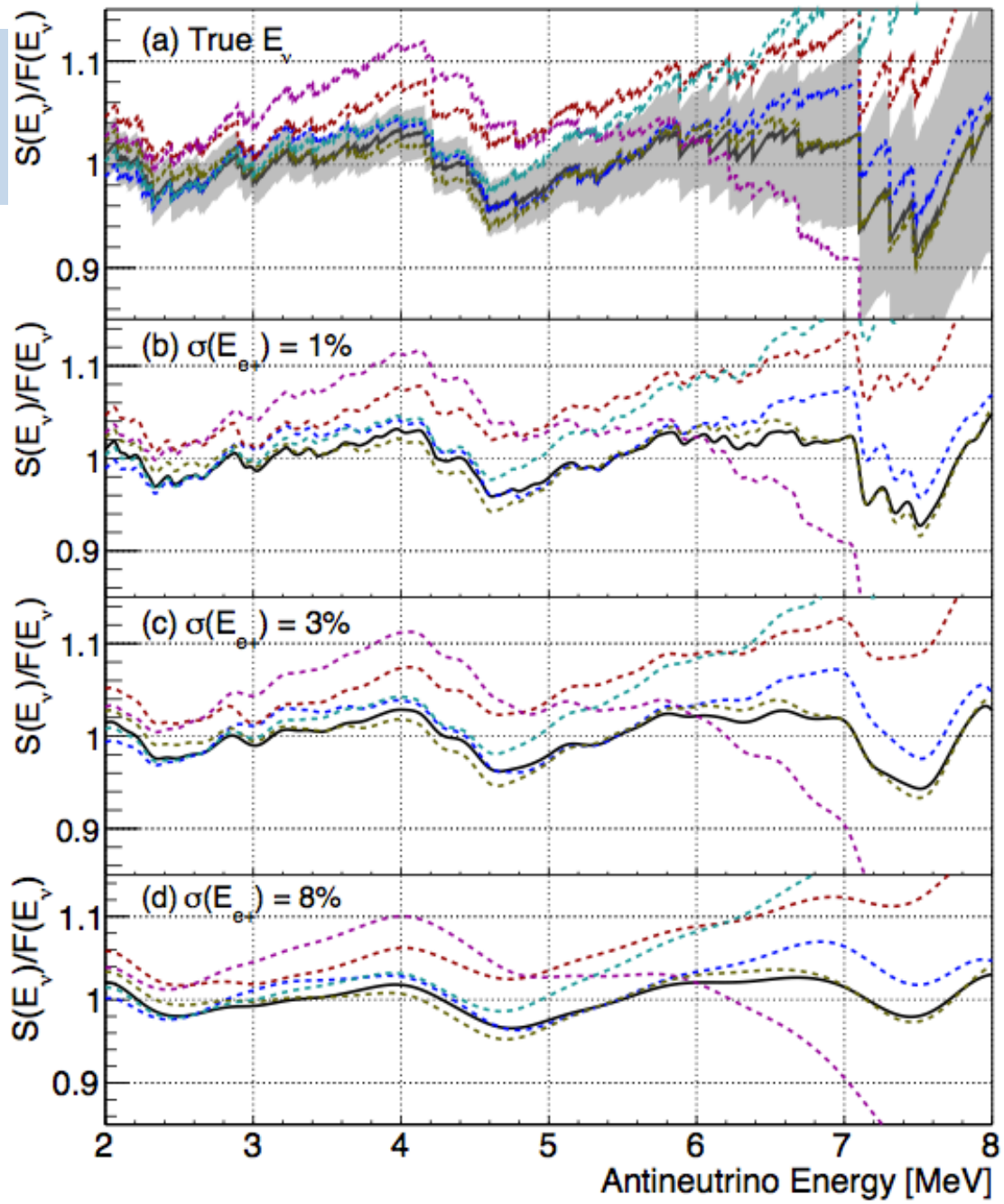


Pronounced example from
R. D. Evans, The Atomic Nucleus

Detailed $\bar{\nu}_e$ Spectrum Shape

Calculation predicts significant discontinuities in spectrum.

Solid: Nominal calc. *Dashed: Varying uncertainties*



Reactor Spectroscopy?

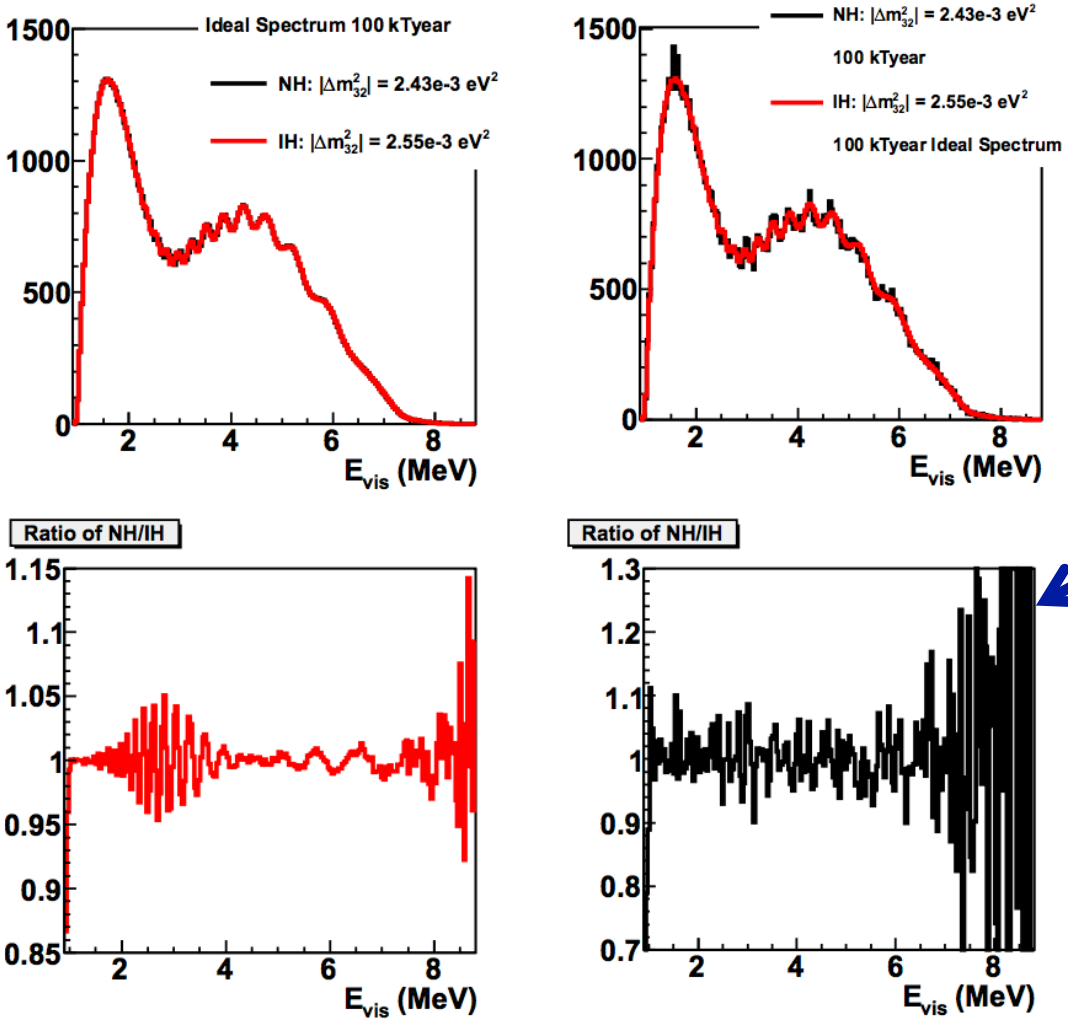
Each edge identifies one significant decay branch.

Current detectors (~8% resolution) unlikely to see details.

Consequences

Neutrino Mass Ordering

Spectral structure complicates determination of the mass ordering



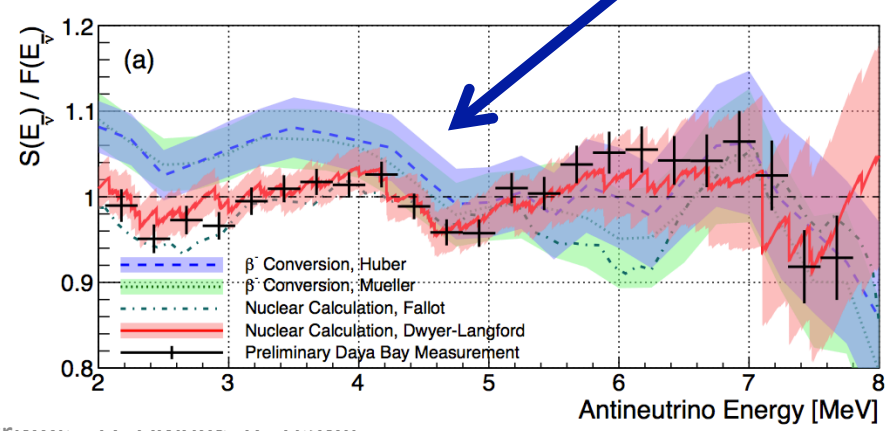
X.Qian, D.Dwyer, et al. PRD 87, 033005 (2013)

Detailed structure in spectrum:

In principle, not a show-stopper for measurement, but it adds difficult to quantify systematic uncertainty

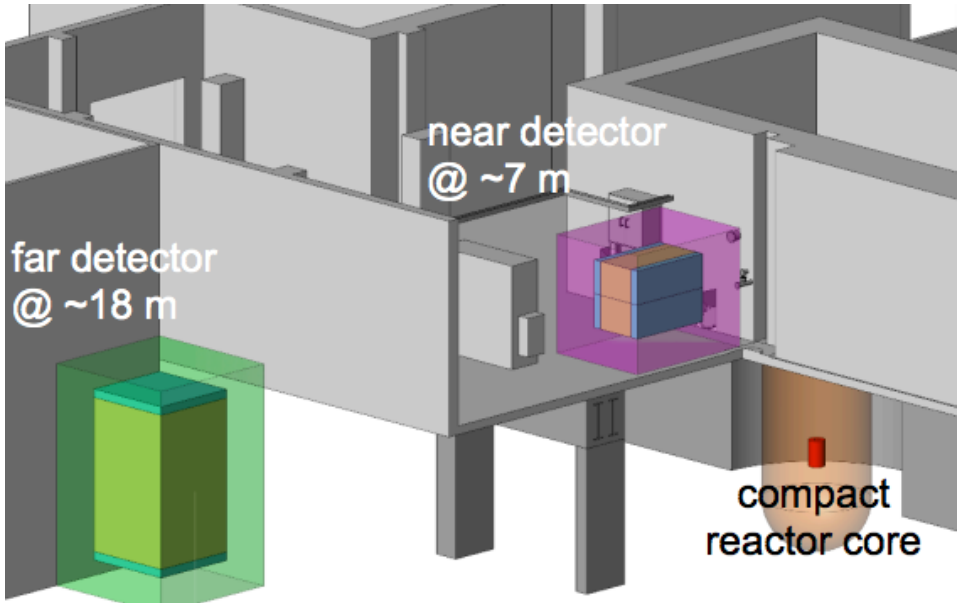
Example measurement assuming true spectrum is smooth

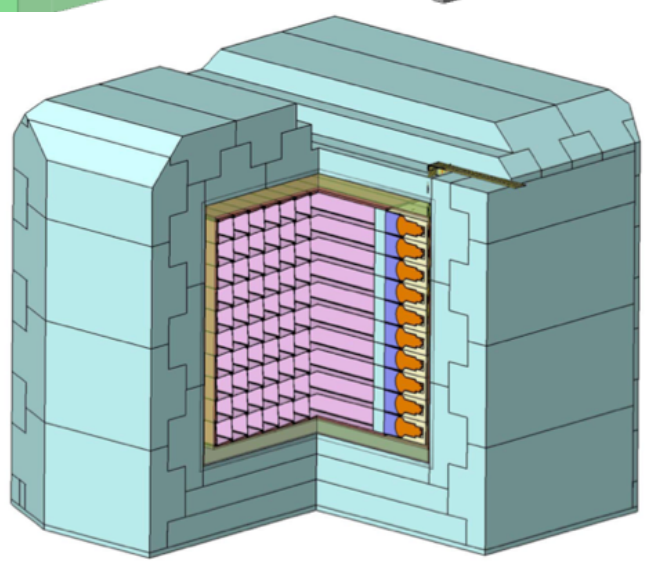
Example measured and calculated structure relative to smooth shape



PROSPECT

Precision reactor $\bar{\nu}_e$ measurements can elucidate these questions.





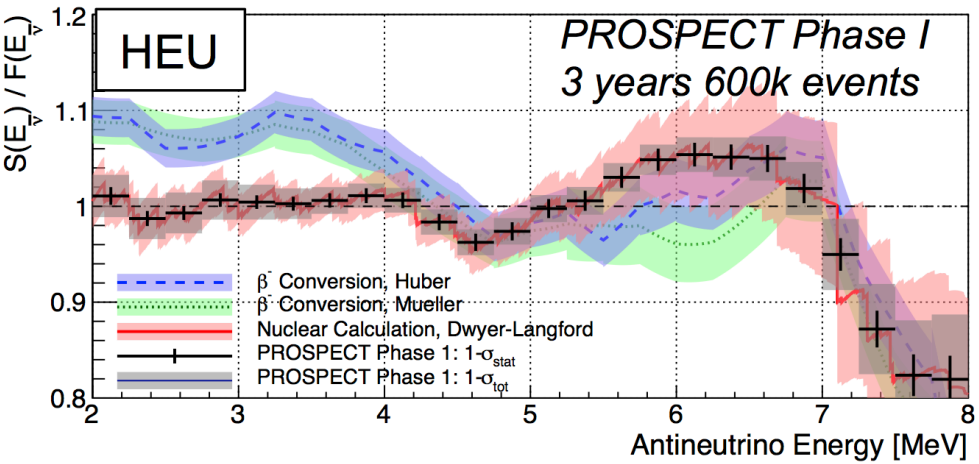
PROSPECT:
A Precision Oscillation and Spectrum Measurement

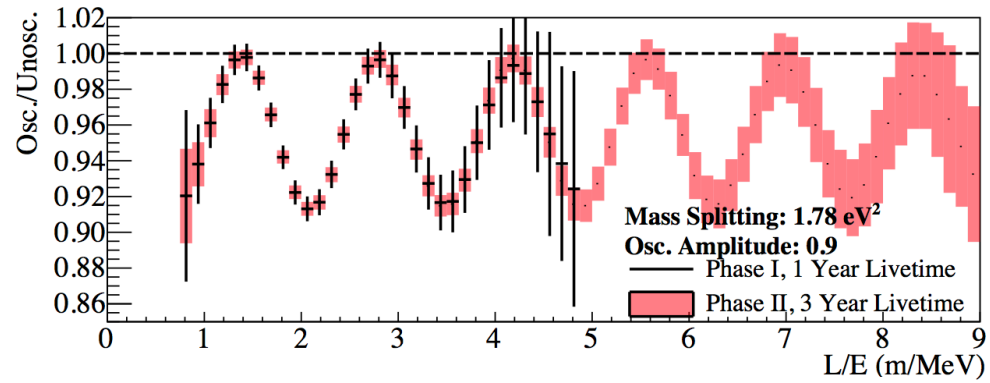
Design: (Phase 1)

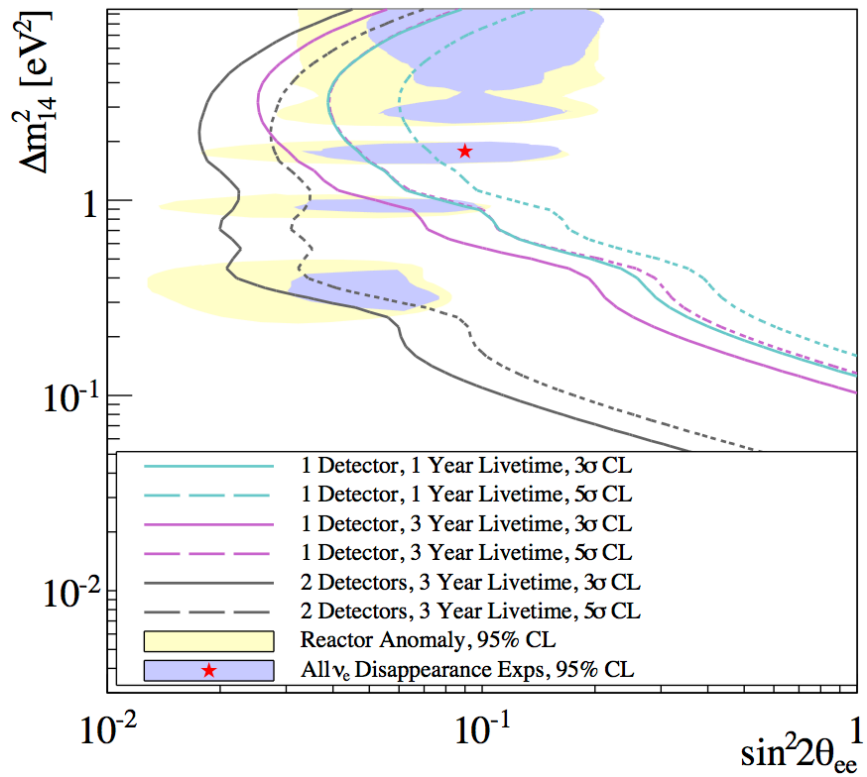
- 2-ton highly-segmented scintillator detector
- Compact (~40cm), intense HFIR reactor at ORNL
- ~7 m from core, probes short-distance effects
- ~10^6 antineutrino interactions per year
- Energy resolution: 4.5%

PROSPECT

Precision reactor $\bar{\nu}_e$ measurements can elucidate these questions.







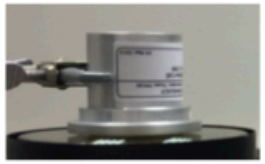
Goals:

Precision measurement of ^{235}U $\bar{\nu}_e$ spectrum
- Strong constraint of models of emission

Short-baseline oscillation search
- Segmentation provides direct test of oscillation hypothesis.

PROSPECT: Progress

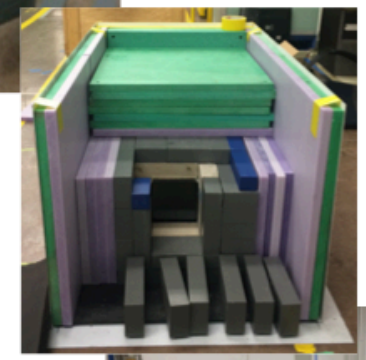
PROSPECT 0.1
Aug. 2014



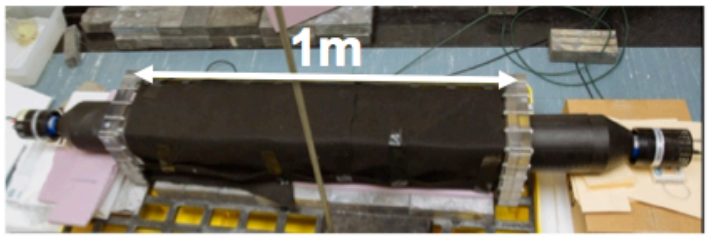
5cm
0.1 liter
LS cell

PROSPECT 2
Dec. '14/Jan. '15

12.5cm
2 liter
LS cell

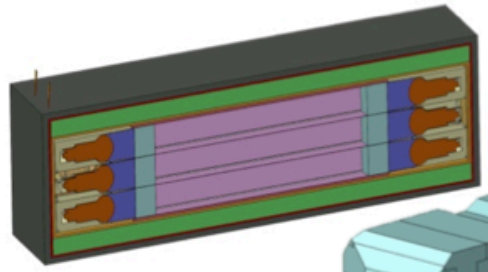


PROSPECT 20
Early 2015

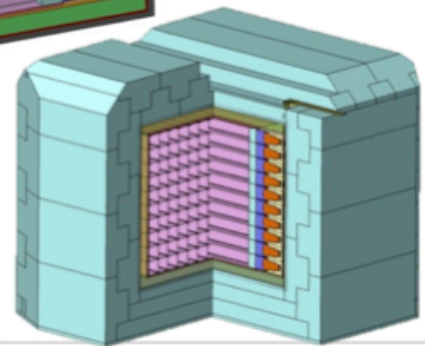


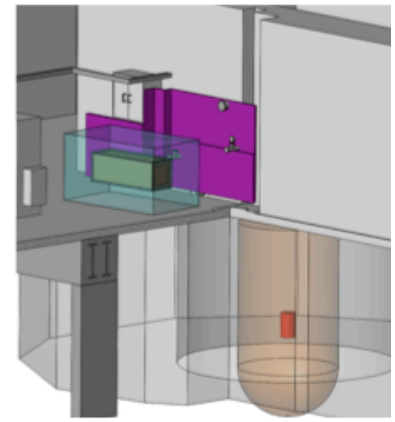
1m
20 liter
LS cell

PROSPECT N×20
Summer 2015*



N×20 liter
LS segments



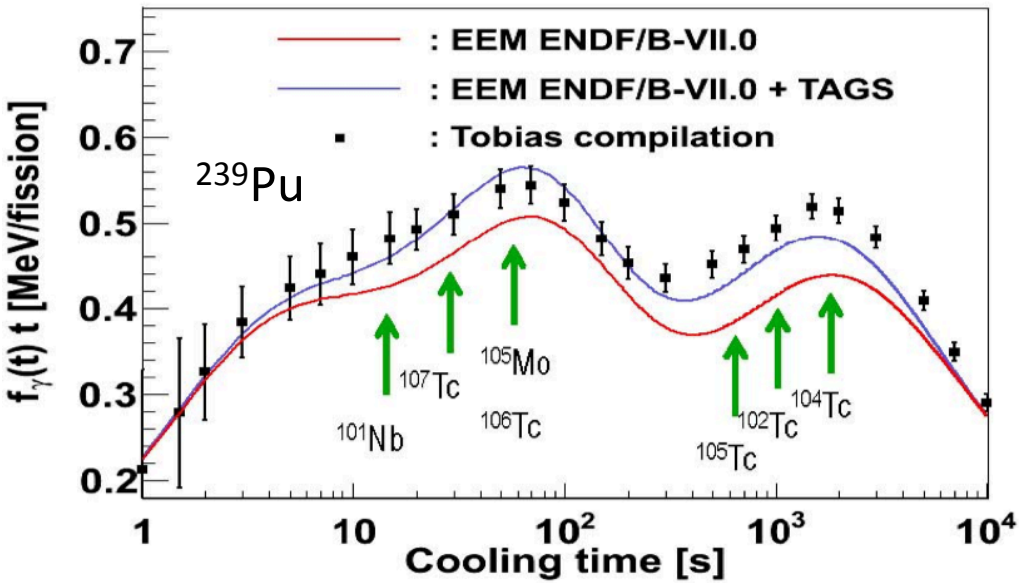


PROSPECT 2ton
Summer 2016*

* Technically driven schedule

Consequences: Nuclear Physics

Decay Heat: Current benchmark of nuclear fission and decay



- Valencia & Nantes collaboration

Date	Facility	Radionuclides	Status	Group
2006-2008	IGISOL (JYFL)	^{101}Nb, ^{105}Mo, ^{102,104,105,106,107}Tc	Published and included in ENDF/B VII.1	Valencia
2009	IGISOL (JYFL)	^{86,87,88}Br, ^{91,92,93,94}Rb	Ready to be published	Valencia
2014	IGISOL (JYFL)	^{95}Sr, ^{95}Rb, ^{99}Y, ^{98,98m,100,100m}Nb, ^{137,138}I, ^{137}Xe, ^{140,142}Cs	Early stages of analysis	Valencia-Nantes

- Oak Ridge National Laboratory + Univ. Warsaw collaboration

Date	Facility	Radionuclides	Status: under analysis	By Group:
2014	HRIBF-ORNL	^{85,86,87}Br, ^{87,89,90}Kr, ^{92}Rb, ^{137}I, ^{137,139}Xe, ^{142}La, ^{142}Ba, plus some daughter products	^{86}Br, ^{89}Kr, ^{139}Xe ^{137}I ^{142}La, ^{142}Ba ^{85}Se, ^{85}Br	Univ. Warsaw Luisiana State University Univ. Warsaw Univ.Tennesse-ORNL

State-of-the-art:
Comparison of fission heat emission versus time.

Interesting observations:
Significant differences between model and msmt.

Improved by program of targeted isotope msmts.

Strong overlap of heat generation with dominant antineutrino emitters

Antineutrino spectral msmts are more precise, particularly at early times

P.Dimitriou, Report on the IAEA TAGS meeting (Vienna, Dec. 15-17, 2014), INDC(NDS)-0676

IAEA Report

Reactor antineutrino physics overlaps with existing IAEA efforts

P.Dimitriou, Report on the IAEA TAGS meeting (Vienna, Dec. 15-17, 2014), INDC(NDS)-0676

Specific Recommendations for anti-neutrino spectra

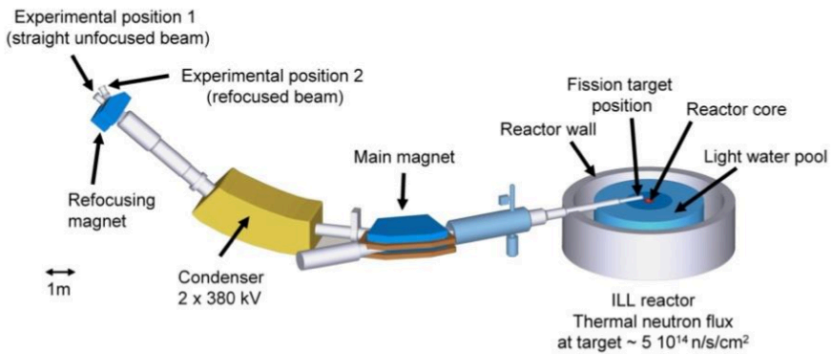
- Precision measurements (with accuracies < 1%) of the beta-shape for radionuclides that are major contributors to antineutrino spectra to help resolve the discrepancies observed in the shapes of measured and calculated beta spectra.

- New integral measurements of the beta spectra for 235U, 239Pu, 233U, 241Pu thermal fission, 232Th, 238U fast fission, and 252Cf spontaneous fission (All comparisons are currently made with only a single set of reference data for 235U and 239Pu measured by Schreckenbach et al.)

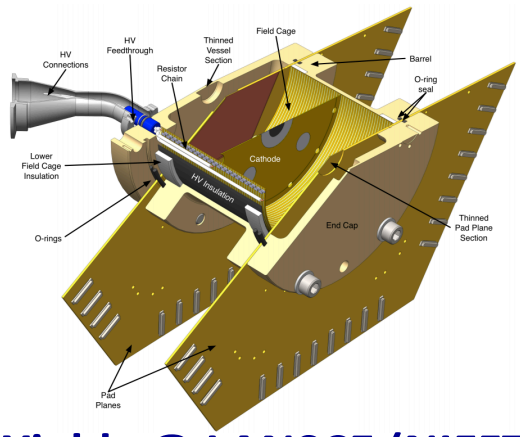
- A thorough investigation of the impact of decay data, fission product yields and their uncertainties on summation calculations producing antineutrino spectra.

Upcoming Measurements

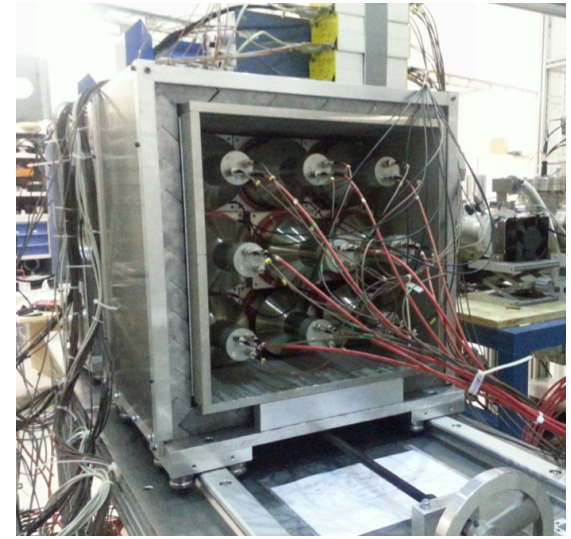
Fission Yields @ ILL (Lohengrin)



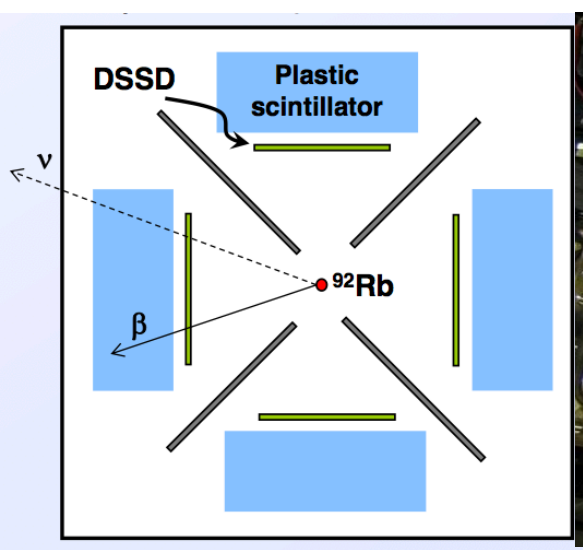
Total Absorp. Spec. @ IGISOL (DTAS)

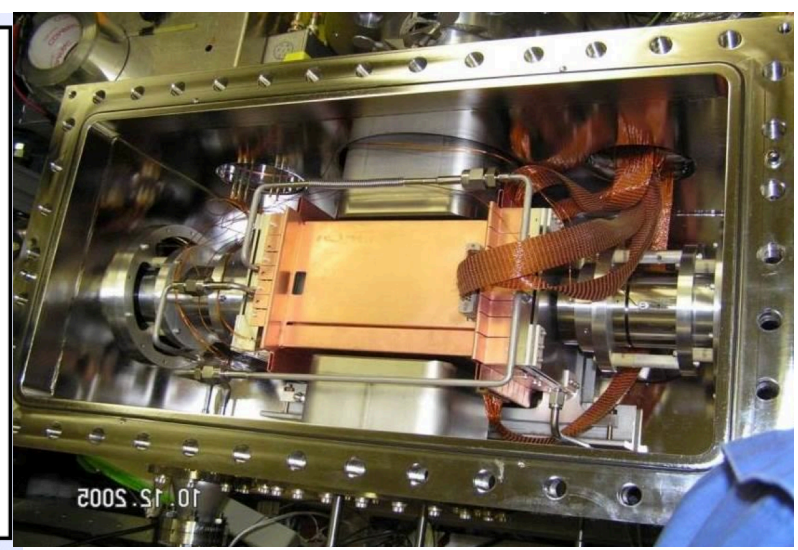


Fission Yields @ LANSCE (NIFFTE)



Precision β⁻ Spec. with Trapped Ions @ ANL/CARIBU





Total Absorp. Spec. @ ORNL (MTAS)

Conclusions

Confusion:

Precise measurements of absolute flux and energy spectrum by the Daya Bay experiment (and others) disagree with traditional predictions.

Insight:

Nuclear physics suggests an origin for observed $\bar{\nu}_e$ energy spectrum.
Also predicts significant discontinuities should be present in spectrum.

Consequences:

Precise $\bar{\nu}_e$ measurements can:

- Test fundamental neutrino properties
- Elucidate spectral structure for use in future measurements
- Interplay with nuclear physics and applied fields:
  * Stringent benchmark for models of nuclear fission and decay.
  * Complement dedicated measurements of specific dominant isotopes.
  * Assist non-proliferation activities.

Backup

Nuclear Pandemonium

Systematic bias present in tabulated nuclear data.

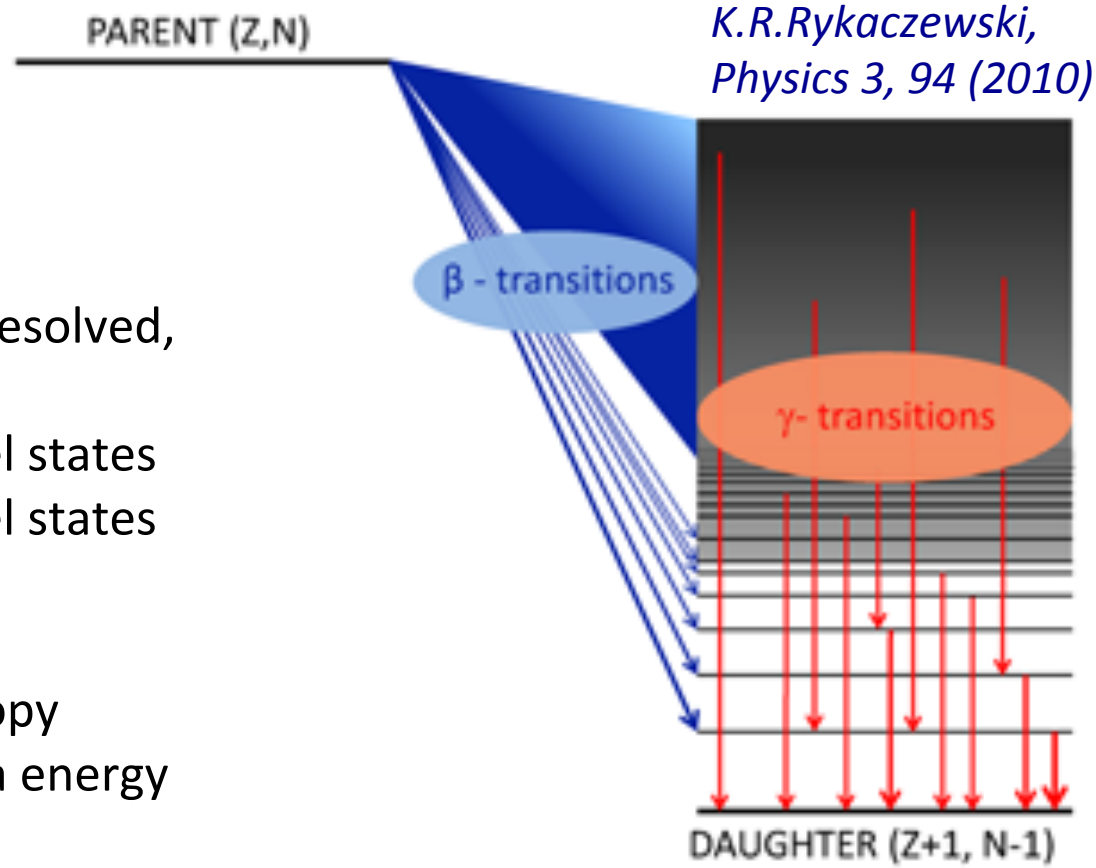
J.C.Hardy et al., Phys. Lett. B71, 307 (1977)

Standard Technique:
Measure gamma emission intensities to determine beta decay branching fractions.

Problem:
Continuum of high-energy gammas is not resolved, resulting in biased measurement:
- Underestimate of branching to high-level states
- Underestimate of branching to high-level states

Solution:
TAGS: Total Absorption Gamma Spectroscopy
- High-efficiency detection of total gamma energy

K.R.Rykaczewski, Physics 3, 94 (2010)



Fission and the R-Process