Reactor Antineutrino Spectra

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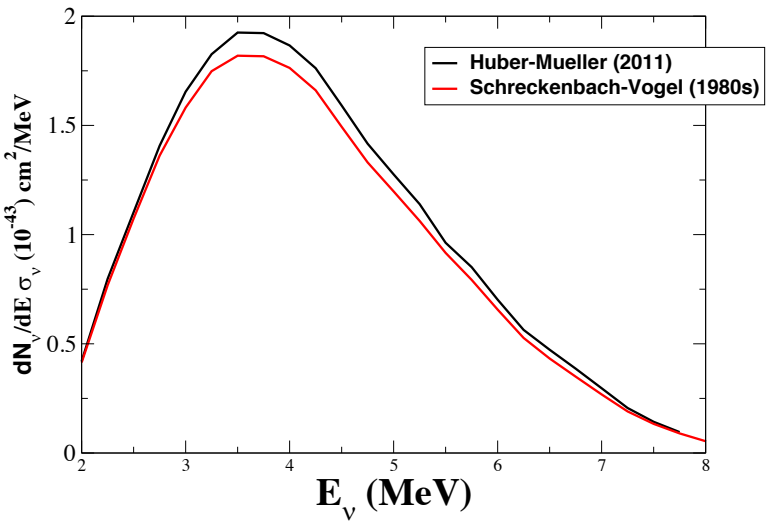
The predicted number of detectable reactor antineutrinos has evolved upward over time

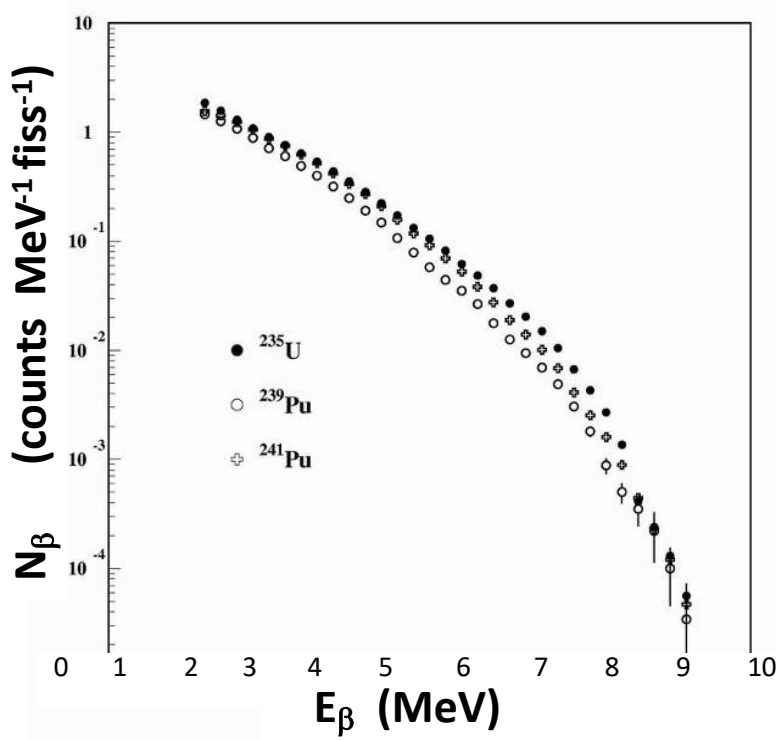
In the 1980s two predictions became the standards for the field:

- Schreckenbach *et al*. converted their measured fission β-spectra for ^{235}U, ^{239}Pu and ^{241}Pu into antineutrino spectra
- Vogel *et al*. used the nuclear databases to predict the spectrum for ^{238}U

In 2011 both Mueller *et al.* and Huber predicted that improvements in the description of the spectra increase the expected number of antineutrinos by 5-6%.



The Original Expected Fluxes were Determined from Measurements of Aggregate Fission β-Spectra (electrons) at the ILL Reactor in the 1980s



K. Schreckenbach et al. PLB118, 162 (1985)

A.A. Hahn et al. PLB160, 325 (1989)

- The thermal fission beta spectra for ^{235}U, ^{239}Pu, ^{241}Pu were measured at ILL.
- These β-spectra were converted to antineutrino spectra by fitting to 30 end-point energies
- ^{238}U requires fast neutrons to fission – difficult to measure at a reactor

⇒ Vogel *et al*. used the ENDF-5 nuclear database to estimate for ^{238}U.

Vogel, et al., Phys. Rev. C24, 1543 (1981).

FIT

Parameterized

$$S_\beta(E) = \sum_{i=1,30} a_i \, S^i(E, E_o^i)$$

$$S^i(E, E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E, Z_{eff})(1 + \delta_{corrections})$$

Two inputs are needed to convert an aggregate β-spectrum to an antineutrino spectrum: (1) the Z of the fission fragments for the Fermi function, and (2) the sub-dominant corrections

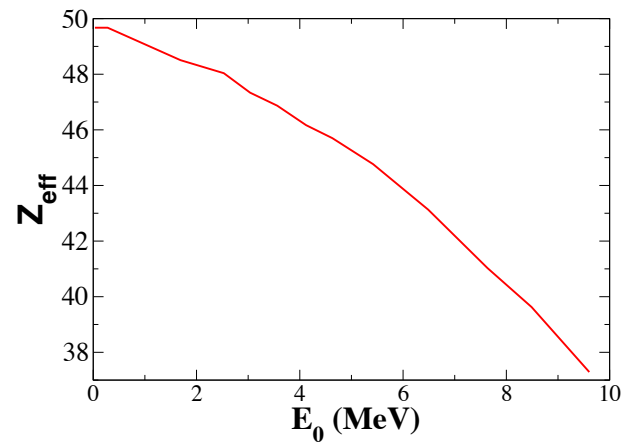
$$S^i(E,E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E,\ Z)(1+\ \delta_{corrections})$$

The Zeff that determines the Fermi function:

On average, higher end-point energy means lower Z.

- Comes from nuclear binding energy differences

$$Z_{eff} \sim a + b\ E_0 + c\ E_0^2$$



The corrections

$$\delta_{correction}(E_e, Z, A) = \delta_{FS} + \delta_{WM} + \delta_R + \delta_{rad}$$

δ_{FS} = Finite size correction to Fermi function

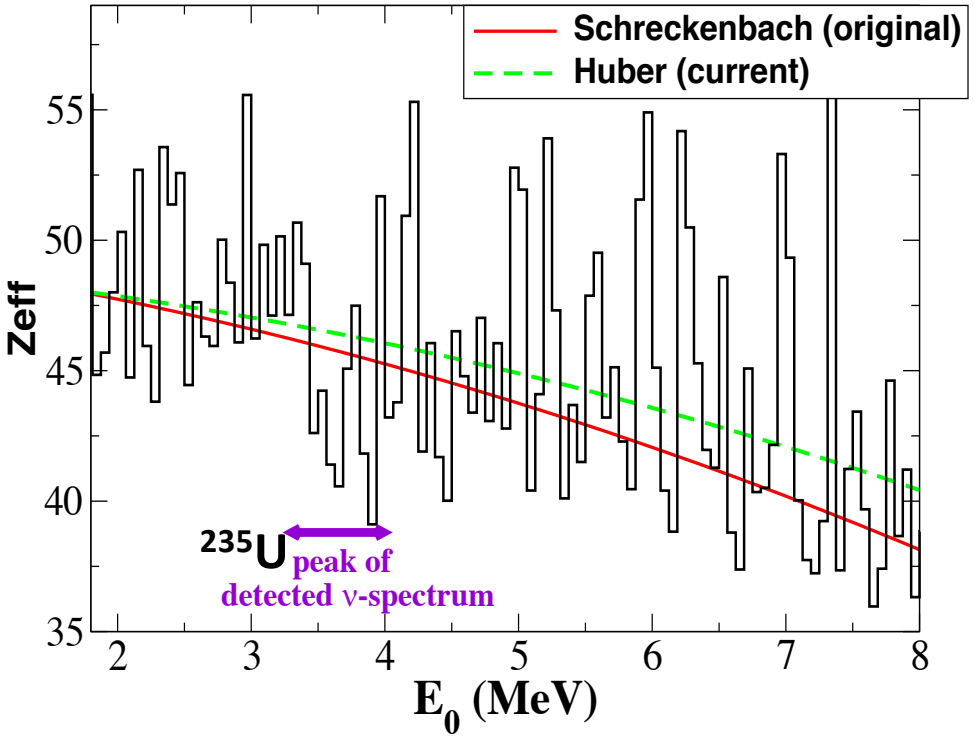
δ_{WM} = Weak magnetism

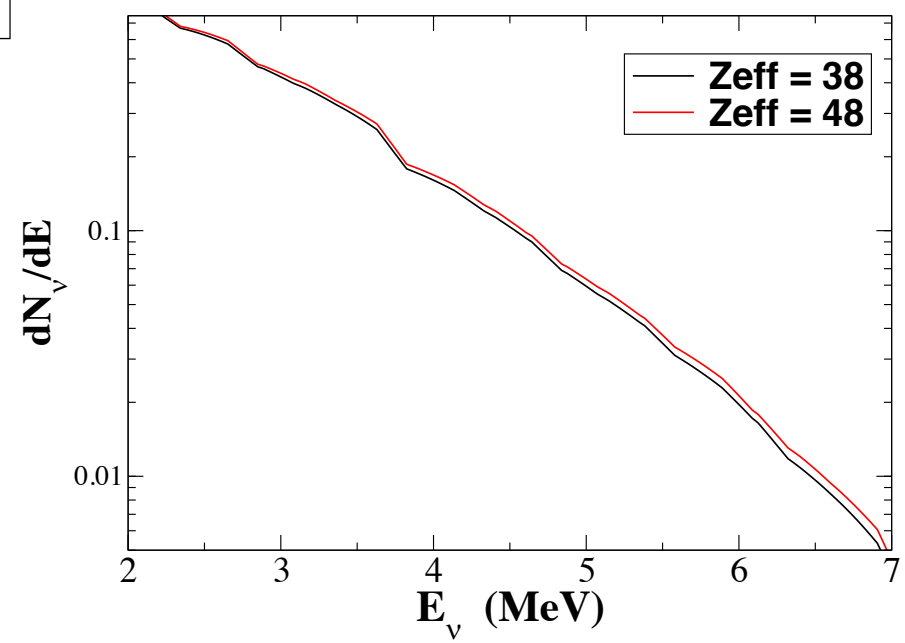
δ_R = Recoil correction

δ_{rad} = Radiative correction

A change to the approximations used for these effects led to the anomaly

The higher the average nuclear charge Zeff in the Fermi function used to convert the β-spectrum, the higher ν–spectrum





$$S^i(E,E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E, Z_{eff}(E_0))(1+\ \delta)$$

- **The new parameterization (P. Huber) of Zeff with end-point energy E_0 changes the Fermi function and accounts for 50% of the current anomaly.**
- **Both fits (original & new) used a quadratic fit** $Z_{eff} = a + b\ E_0 + c\ E_0^2$

The finite size and weak magnetism corrections account for the remainder of the anomaly

$$S(E_e,Z,A) = \frac{G_F^2}{2\pi^3} p_e E_e (E_0 - E_e)^2 F(E_e,Z,A)(1+\delta_{corr}(E_e,Z,A))$$

δ_{FS} = Finite size correction to Fermi function

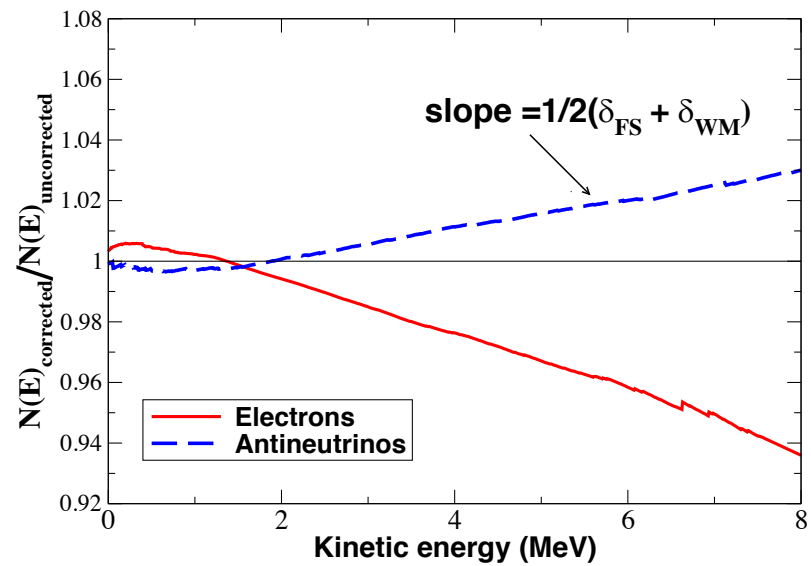
δ_{WM} = Weak magnetism

Originally approximated by a parameterization: $\delta_{FS} + \delta_{WM} = 0.0065(E_\nu - 4MeV))$

In the updated spectra, both corrections were applied on a state-by-state basis
An approximation was used for each:

$$\delta_{FS} = -\frac{10Z\alpha R}{9\hbar c} E_\beta; \;\; R = 1.2A^{1/3}$$

$$\delta_{WM} = +\frac{4(\mu_V - 1/2)}{3M_n} 2E_\beta$$



Led to a systematic increase of in the antineutrino flux above 2 MeV

Uncertainties in the detailed contributions to the total spectra

30% of the beta-decay transitions involved are so-called forbidden
Allowed transitions ΔL=0; Forbidden transitions ΔL=0

Forbidden transitions introduce a shape factor C(E):

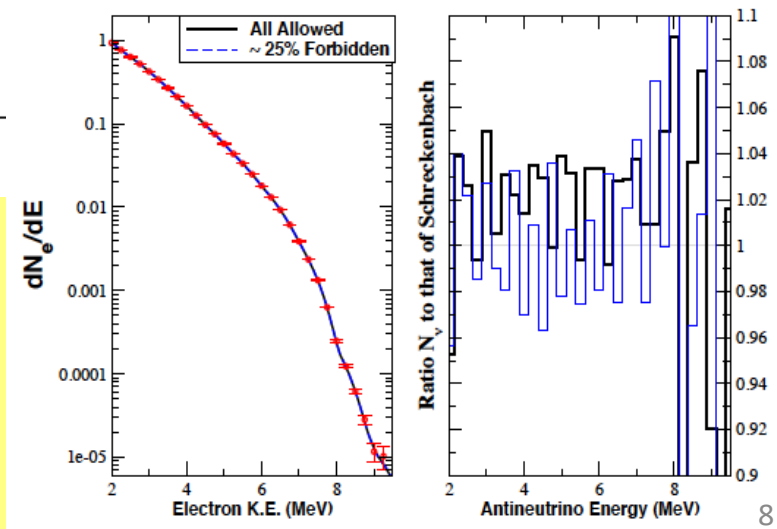
$$S(E_e,Z,A) = \frac{G_F^2}{2\pi^3} p_e E_e (E_0 - E_e)^2 \underline{C(E)} F(E_e,Z,A)(1+\delta_{corr}(E_e,Z,A))$$

The corrections δ for forbidden transitions are also different and sometimes unknown :

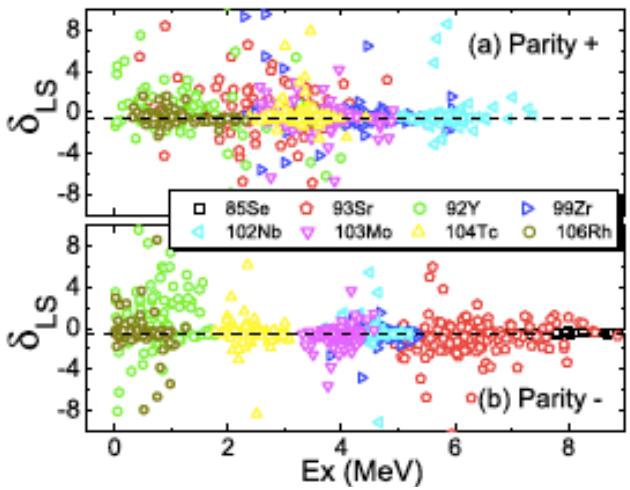
Classification	ΔJ^π	Operator	Shape Factor $C(E)$	Fractional Weak Magnetism Correction $\delta_{WM}(E)$
Allowed GT	1^+	$\Sigma \equiv \sigma\tau$	1	$\frac{2}{3}\left[\frac{\mu_v - 1/2}{M_N g_A}\right](E_e\beta^2 - E_\nu)$
Non-unique 1st Forbidden GT	0^-	$[\Sigma, r]^{0-}$	$p_e^2 + E_\nu^2 + 2\beta^2 E_\nu E_e$	0
Non-unique 1st Forbidden ρ_A	0^-	$[\Sigma, r]^{0-}$	λE_0^2	0
Non-unique 1st Forbidden GT	1^-	$[\Sigma, r]^{1-}$	$p_e^2 + E_\nu^2 - \frac{4}{3}\beta^2 E_\nu E_e$	$\left[\frac{\mu_v - 1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2 E_e - E\nu) + 2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2+E_\nu^2 - 4\beta^2 E_\nu E_e/3)}\right]$
Unique 1st Forbidden GT	2^-	$[\Sigma, r]^{2-}$	$p_e^2 + E_\nu^2$	$\frac{3}{5}\left[\frac{\mu_v - 1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2 E_e - E\nu) + 2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2+E_\nu^2)}\right]$
Allowed F	0^+	τ	1	
Non-unique 1st Forbidden F	1^-	$r\tau$	$p_e^2 + E_\nu^2 + \frac{2}{3}\beta^2 E_\nu E_e$	
Non-unique 1st Forbidden $\vec{J}_V$	1^-	$r\tau$	E_0^2	

The forbidden transitions increase the uncertainty in the expected spectrum.

Two equally good fits to the Schreckenbach β-spectra, lead to ν-spectra that differ by 4%.

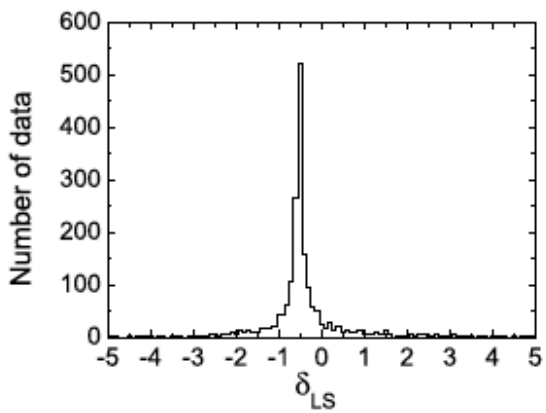


Weak Magnetism has an uncertainty arising from the approximation used for the orbital contribution and from omitted 2-body currents. But, dominant 0+→0- transitions have zero δ_{WM}, with no uncertainty



$$\delta_{WM}^{GT} = \frac{4(\mu_V - 1/2)}{6M_N g_A}(E_e\beta^2 - E_\nu)$$

$$\delta_{LS}^{j_f j_i} \equiv \frac{\langle J_f \,||\, \vec{\Lambda} \,||\, J_i \rangle}{\langle J_f \,||\, \vec{\Sigma} \,||\, J_i \rangle} \simeq -\frac{1}{2}$$



- **Checked for a subset of fission fragments.**
- **A check for all fission fragments, including 2-body terms, requires a large super-computing effort.**

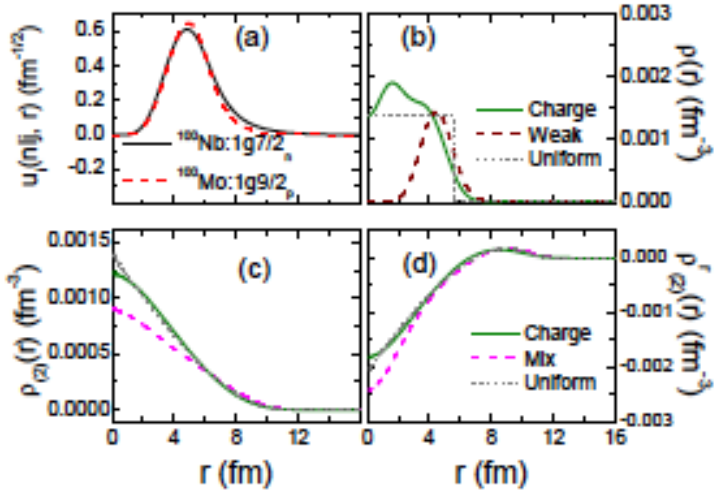
Estimated uncertainty ~ 30% for this 4% correction to the spectra

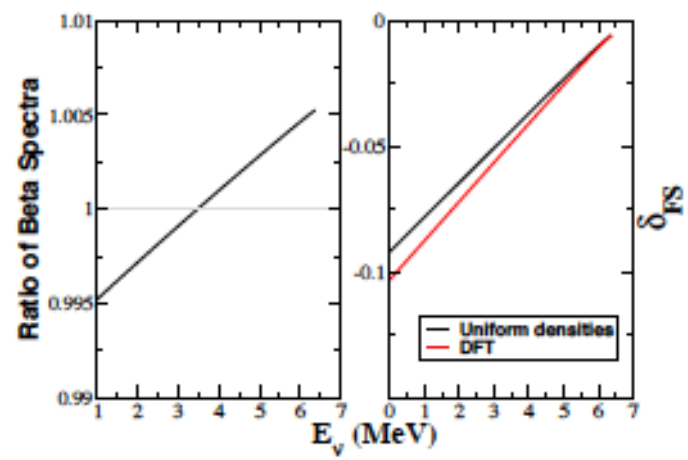
Wang and Hayes, Phys. Rev. C 95, 064313 (2017) .

The Finite Size Correction can be expressed in terms of Zemach moments

$$\delta_{FS} = \Delta F_{\mathrm{REL}}/F_{\mathrm{REL}} = -\frac{Z\,\alpha}{3\hbar c}\left(4E\,\langle r\rangle_{(2)} + E\,\langle r\rangle^{r}_{(2)} - \frac{E_\nu\langle r\rangle^{r}_{(2)}}{3} + \frac{m^2c^4}{E}\left(2\,\langle r\rangle_{(2)} - \langle r\rangle^{r}_{(2)}\right)\right)$$

Approximated as : $$\delta_{FS} = -\frac{3Z\alpha}{2\hbar c} < r >_{(2)} \left(E_e - \frac{E_\nu}{27} + \frac{m^2c^4}{3E_e}\right)$$



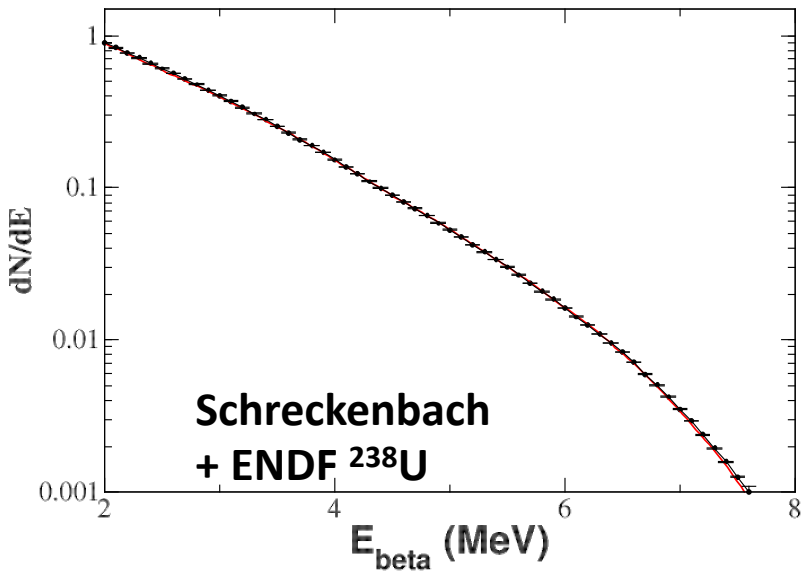


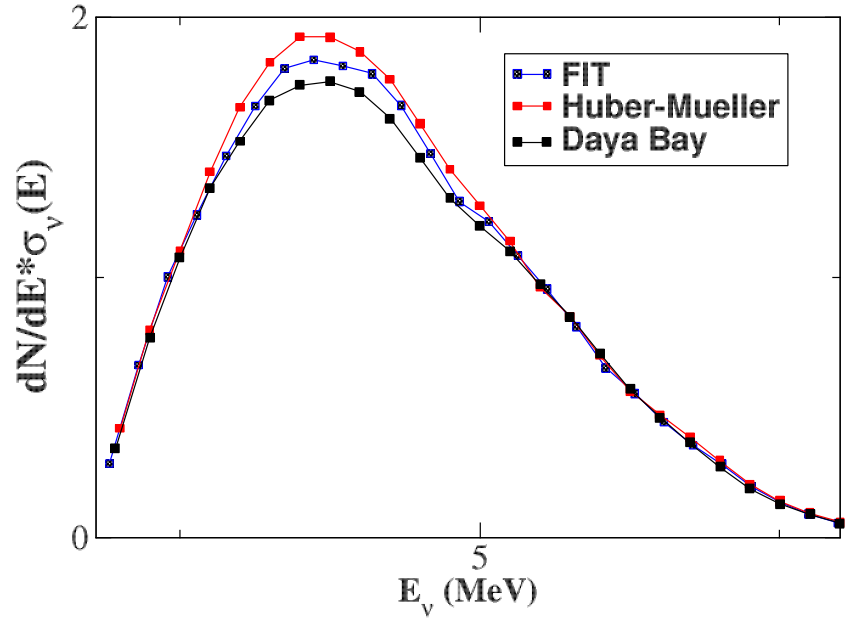
- **Found to be a good approximation for allowed transitions.**
- **Not checked for forbidden transitions.**

Estimated uncertainty ~ 20% for this 5% correction to the spectra

Wang, *et al.* PRC, 94, 034314 (2016)

Simultaneous fit of the Daya Bay antineutrino spectrum and the equivalent aggregate β–spectrum with (1) point-wise Z_{eff} and (2)improved descriptions of forbidden transitions reduces the anomaly from 5% to 2.5%

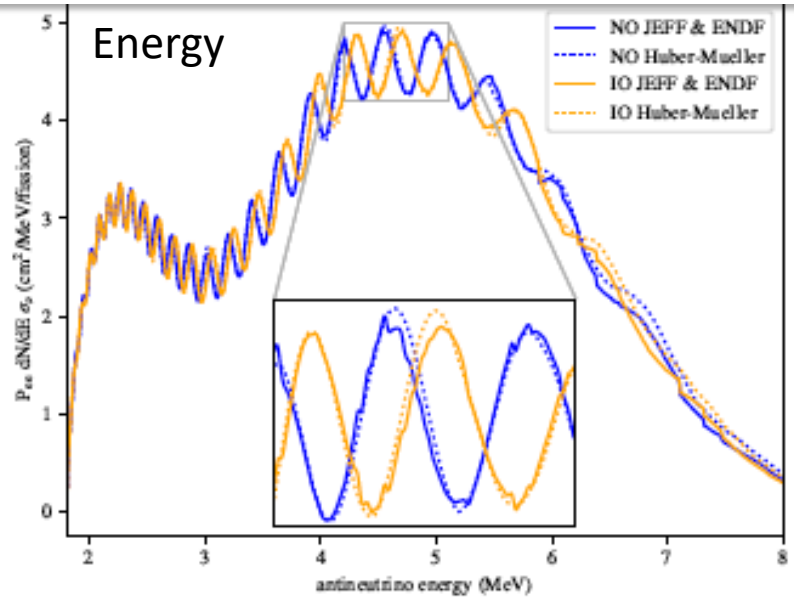


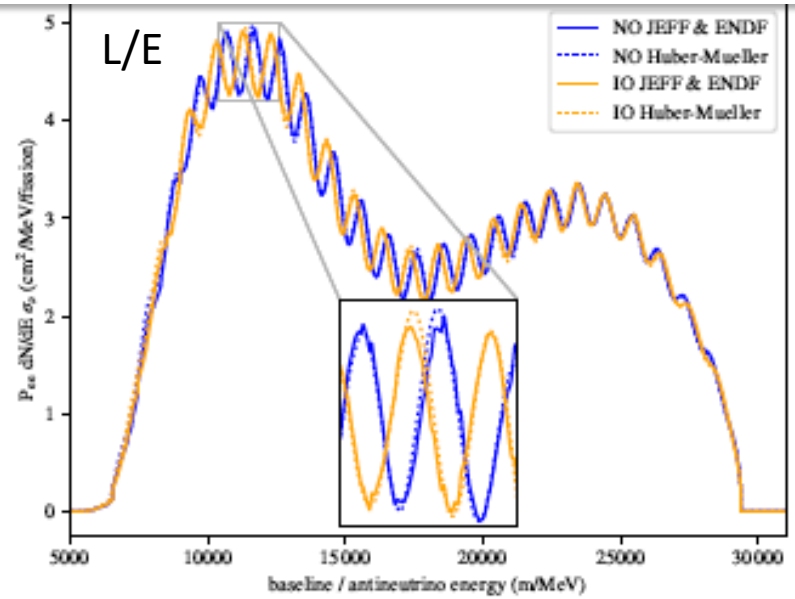


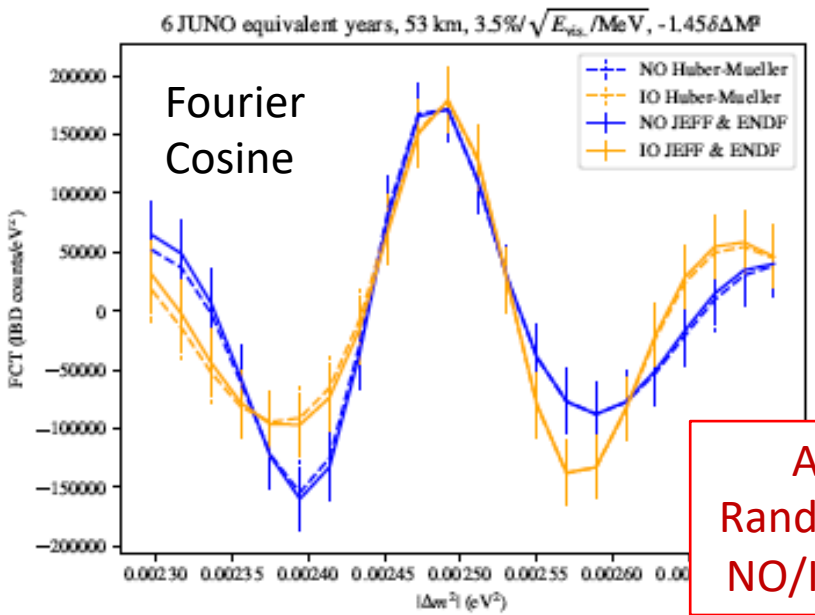
The magnitude of the IBD cross sections change, depending on assumptions, but not the ratio of one isotope to another

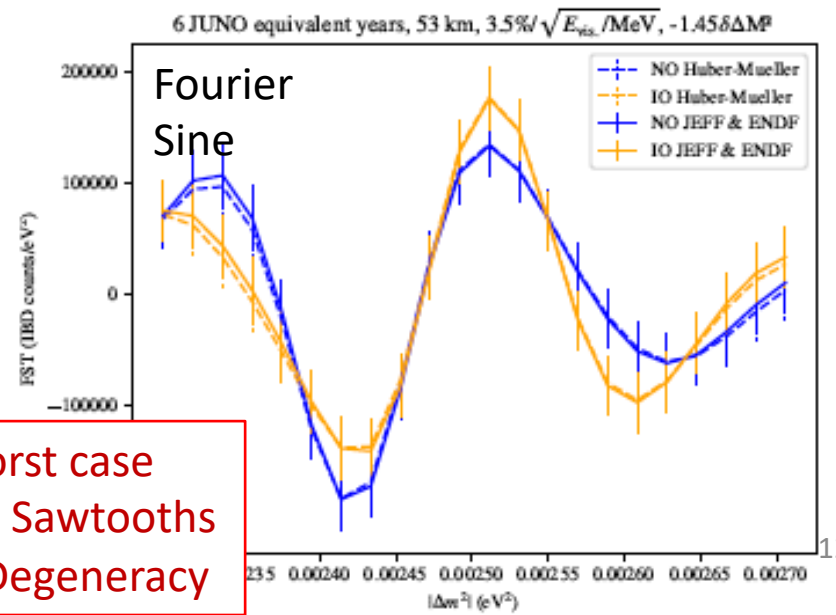
	all allowed $Z_{\rm eff}^{\rm Huber}$	all allowed $Z_{\rm eff}$	allow.+forbid. $Z_{\rm eff}$	allow.+forbid. $(Z_{\rm eff}^2)^{1/2}$
^{235}U	6.69	6.58	6.47	6.48
^{239}Pu	4.36	4.3	4.22	4.23
ratio	1.534	1.530	1.533	1.532

Uncertainties due to Sawtooth Fine Structures in the antineutrino spectra unlikely to affect JUNO's ability to extract the mass hierarchy <u>if</u> a Fourier analysis is possible



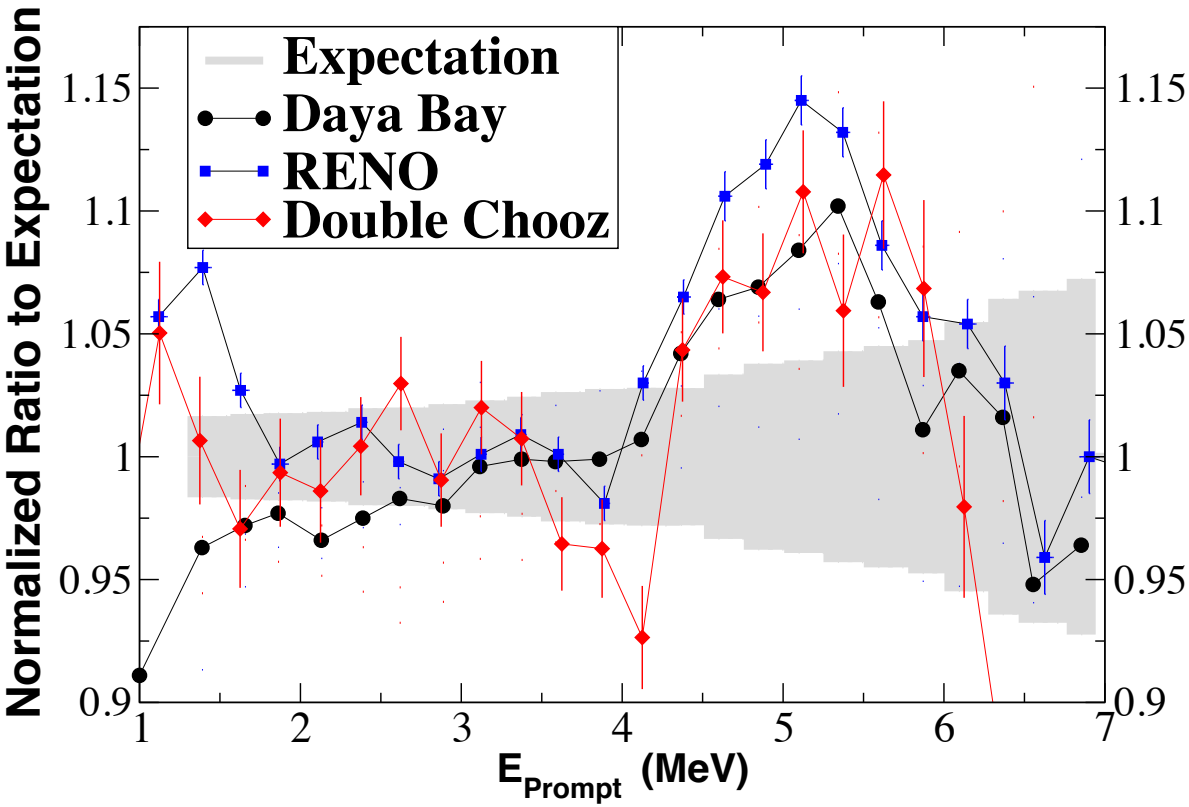






A worst case
Random Sawtooths
NO/IO Degeneracy

The Reactor Neutrino 'BUMP'



All recent reactor neutrino experiments observed a shoulder at 4-6 MeV, relative to expectations.

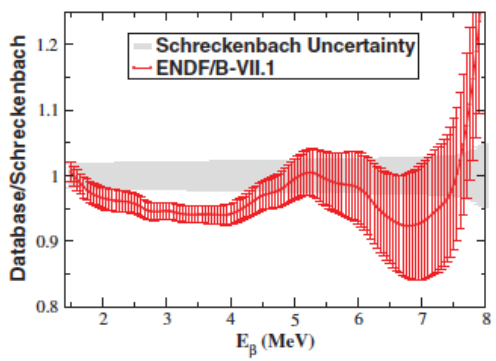
- **The current expectations are Huber (^{235}U,$^{239,241}Pu$) and Mueller (^{238}U)**
- **RENO observed the largest bump**
- **Double-Chooz used Huber and Haag (^{238}U) for expected flux**

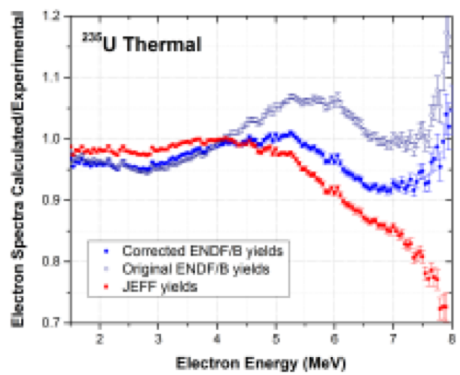
P. Huber, Phys. Rev. C 84, 024617 (2011); Th. A. Mueller et al., Phys. Rev. C 83, 054615 (2011); N. Haag, Phys. Rev. Lett. 112, 122501 (2014).

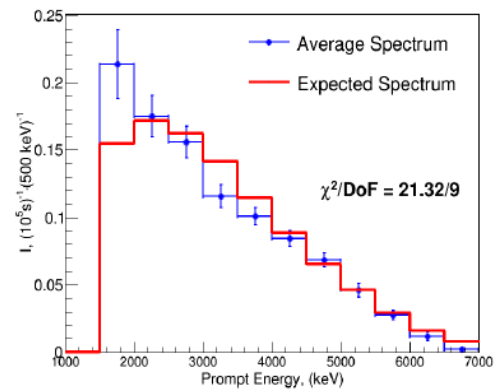
Possible Origins of the 'Bump'

- ^{238}U as a source of the shoulder
  – Possible because ^{238}U has a hard spectrum and contributes significantly in the Bump energy region. It is also the most uncertain actinide.
  But the BUMP is reported by Neutrino-4, which requires that it is in ^{235}U.

- A possible error in the ILL β-decay measurements
  - True if the Neutrino-4 spectrum shape is confirmed .
  - Dwyer and Langford pointed to BUMP in the beta spectrum relative to ENDF/B-VII.1
  - Not predicted by BNL updated ENDF nuclear database, nor by the JEFF database.





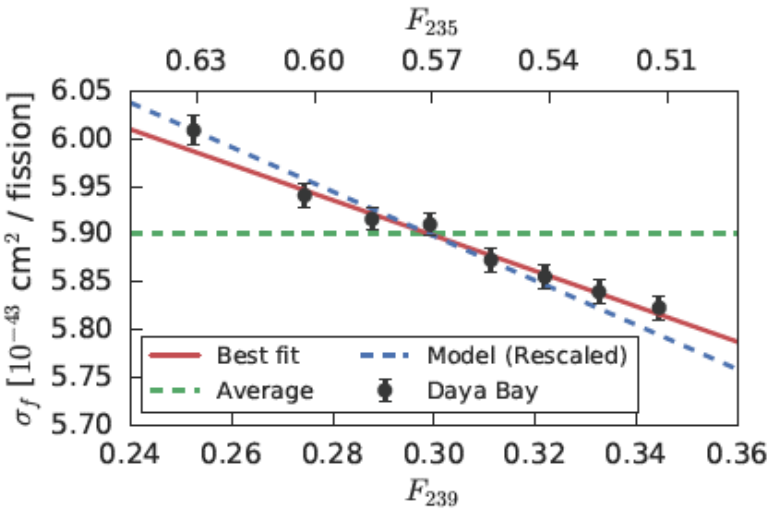


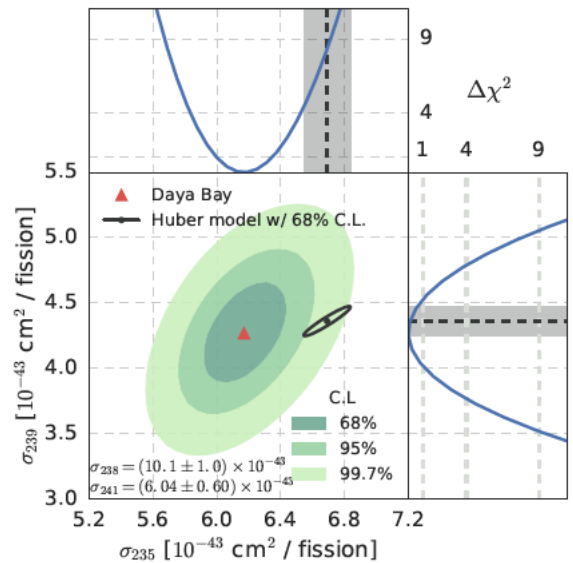
All are nuclear physics explanations pointing to a problem with the 'expected spectra'.

Changes in the Antineutrino Spectra with the Reactor Fuel Burnup

Suggest a problem with the $^{235}U/^{239}Pu$ ratio

The Total Number of Antineutrinos Decreases with Burnup, but the Huber-Mueller Model does not agree with the measured slope





$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}}(F_{239} - \overline{F}_{239})$$

$$d\sigma_f/dF_{239} = (-1.86 \pm 0.18) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$

$$(-2.46 \pm 0.06) \times 10^{-43}\mathrm{cm}^2/\mathrm{fission}$$

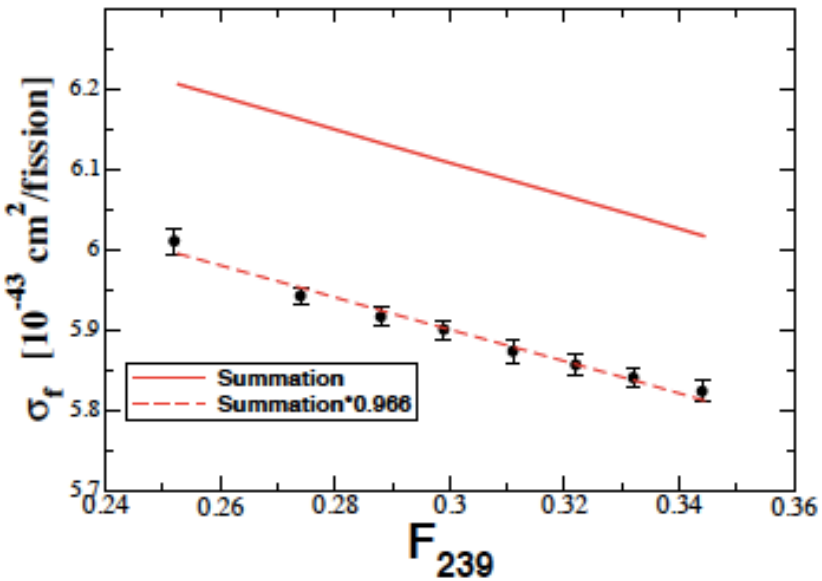
-1.86×10^{-43} cm^2/fission

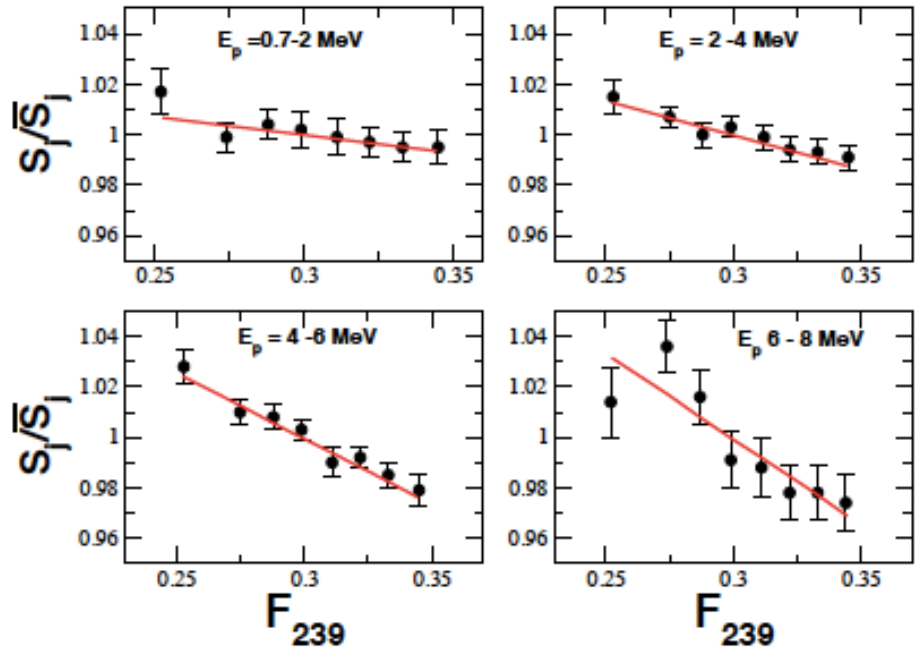
Experiment

Huber-Muller

JEFF+ENDF

The Nuclear database explains the Daya Bay fuel evolution data, but still allows for a (smaller) anomaly





- **The IBD yield is predicted to change with the correct slope.**
- **But the absolute predicted value is high by 3.5%.**
- **This anomaly is not statistically significant.**

Summary

- Changes in the treatment (1) the Fermi Function Zeff, (2) the sub-dominant corrections to beta-decay led to the reactor anomaly.

- Improved treatments reduce the size of the anomaly.

- Uncertainties remain in the spectra, but they are unlikely to affect JUNO, <u>if</u> a Fourier transform analysis is possible.

- The BUMP is due to standard nuclear physics issues that need to be tracked down. Neutrino-4 suggest that it is due to the ^{235}U spectrum.

- The Daya Bay fuel evolution data suggest that the Schreckenbach $^{235}U/^{239}Pu$ ratio is also incorrect.