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Reanalysis of the Reactor Neutrino Anomaly

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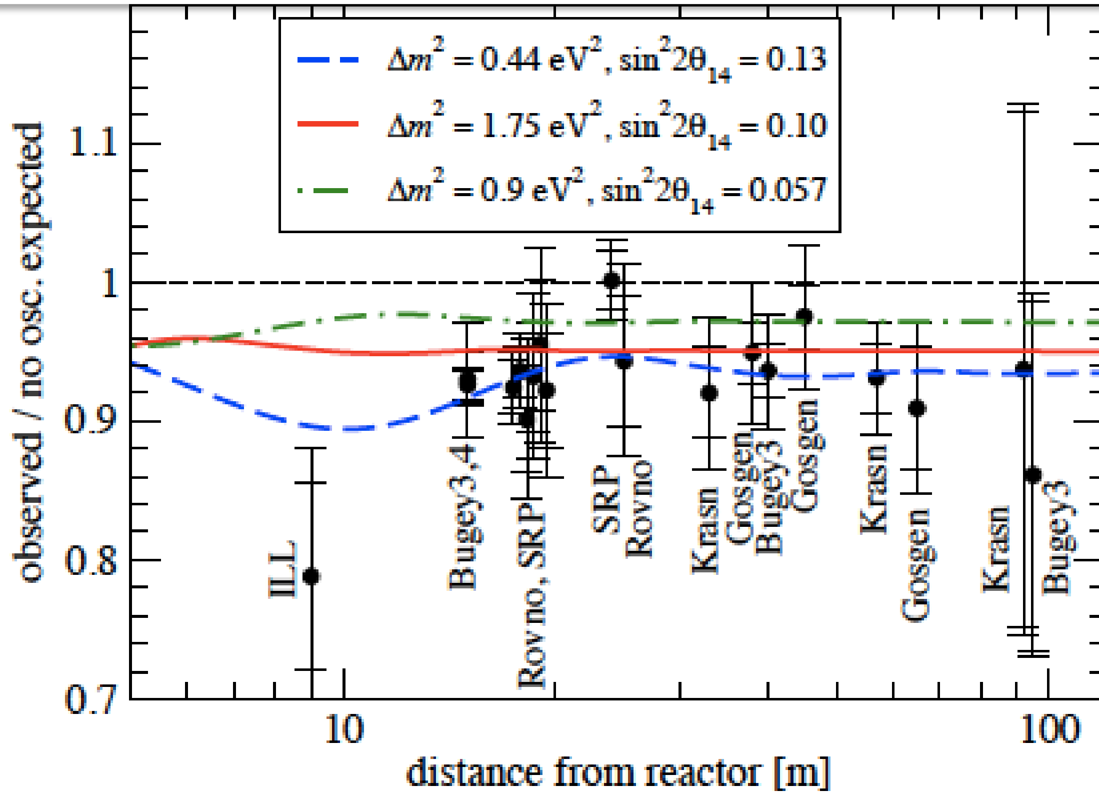
The Reactor Antineutrino Anomaly

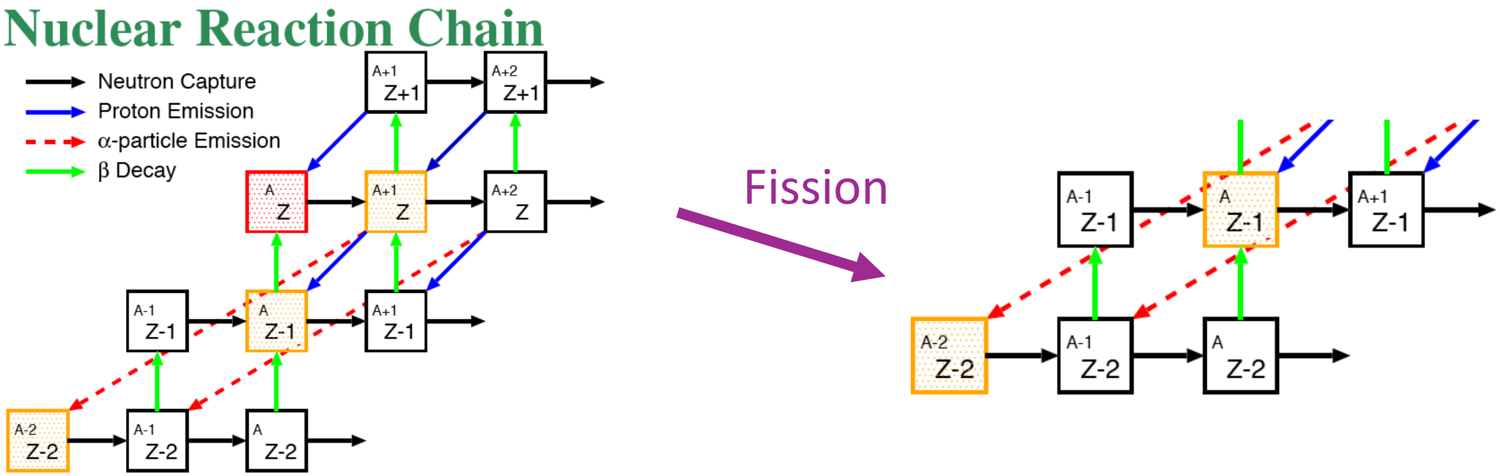
obs/expected=0.936 (~3σ) deficit in the detected antineutrinos from short baseline reactor experiments

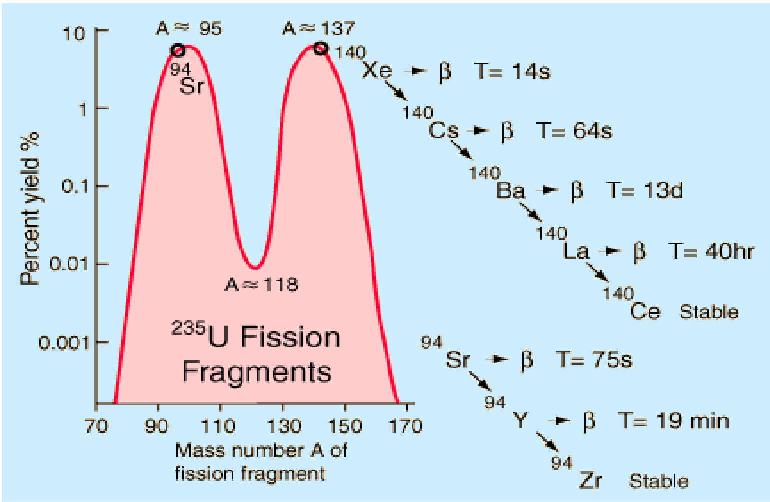


From J. Kopp, et al. JHEP 05 (2013)050

The effect mostly comes from the detailed physics involved in the nuclear beta-decay of fission fragments in the reactor

Beta-decay of fission fragments produce antineutrinos at a rate of ~10^{20} ν/sec for a 1 GW reactor





- Hundreds of fission fragments – all neutron rich
- Most fragments β-decays with several branches

⇒ Approximately 6 ν_e per fission

⇒ Aggregate spectrum made up of about six thousands of end-points

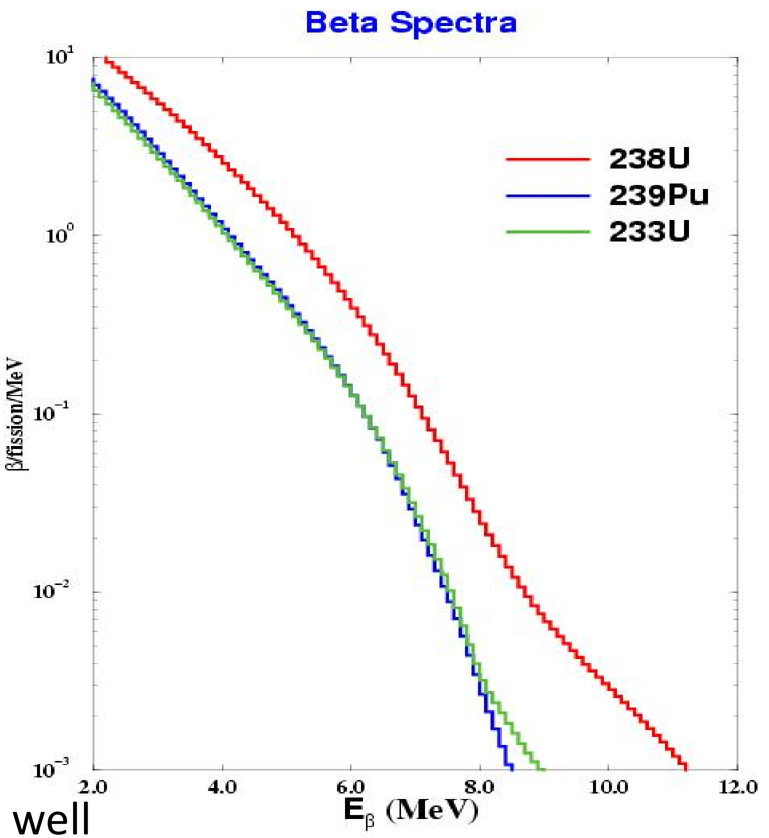
About 1500 of these transitions are so-called forbidden transitions

Anti-neutrino Spectrum under Equilibrium Burning Conditions depends the Cumulative Fission Yields

$$S_k(E) = \sum_{FF} Y_{FF}(Z,A,m) S(E,Z,A,m)$$

$$S(E,A,Z,m) = \sum_{i} B^i S(E,Z,A,m,E_0^i)$$

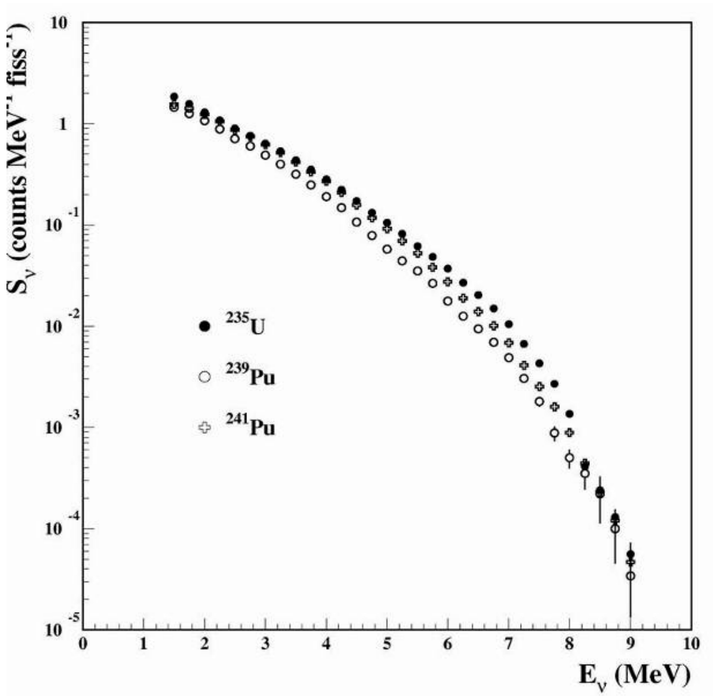
– normalized to unity



- Y_{FF} (cumulative fission yields) known reasonably well
- A few nuclei do not reach equilibrium

- Branching ratios and end-point energies known for about 90% of the decays
- Aggregate β-spectrum measured for ^{235}U, ^{239}Pu and ^{241}Pu

The antineutrino flux used in oscillations experiments is from a conversion of the aggregate beta spectra from ILL



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

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

P. Vogel et al., PRC 24 1543 (1981)

- Measurements at ILL of thermal fission beta spectra for ^{235}U, ^{239}Pu, ^{241}Pu
- Converted to antineutrino spectra by fitting to 30 end-point energies
- Use Vogel *et al*. ENDF estimate for ^{238}U
  ^{238}U ~ 7-8% of fissions =>small error
- All transitions were treated as allowed GT
- An approximate treatment was added for finite size and weak magnetism corrections

FIT

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

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

Known corrections to β-decay are the main source of the anomaly

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

Fractional corrections to the individual beta decay spectra:

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

δ_{rad} = Radiative correction (used formalism of Sirlin)

δ_{FS} = Finite size correction to Fermi function

δ_{WM} = Weak magnetism

Originally approximated as:

$$\delta_{FS}+\delta_{WM}=0.0065(E_\nu-4MeV))$$

The difference between this original treatment and an improved treatment of these corrections is the main source of the anomaly

The finite nuclear size correction

Normal (point-like) Fermi function:
Attractive Coulomb Interaction *increases* electron density at the nucleus
=> beta-decay rate *increases*

Finite size of Nucleus:
Decreases electron density at nucleus (relative to point nucleus Fermi function)
=> Beta decay rate *decreases*

Two contributions: nuclear charge density $\rho_{ch}(r)$ and nuclear weak density $\rho_W(r)$

For Allowed GT transitions:

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

$$< r >_{(2)} = \int r \, d^3 r \int d^3 s \, \rho_W(|\vec{r} - \vec{s}|) \, \rho_{ch}(s)$$

-First moment of convoluted weak and charge densities
= 1st Zemach moment

The weak magnetism correction

Interference between the magnetic moment distribution of the vector current and the spin distribution of the axial current.

This *increases* the electron density at the nucleus => beta decay rate *increases*

$$J_V^{\mu} = \left[Q_V,\ \vec{J}_C + \vec{J}_V^{MEC} \right]$$

$$J_A^{\mu} = \left[Q_A + Q_A^{MEC},\ \vec{\Sigma} \right]$$

Affects GT transitions

+

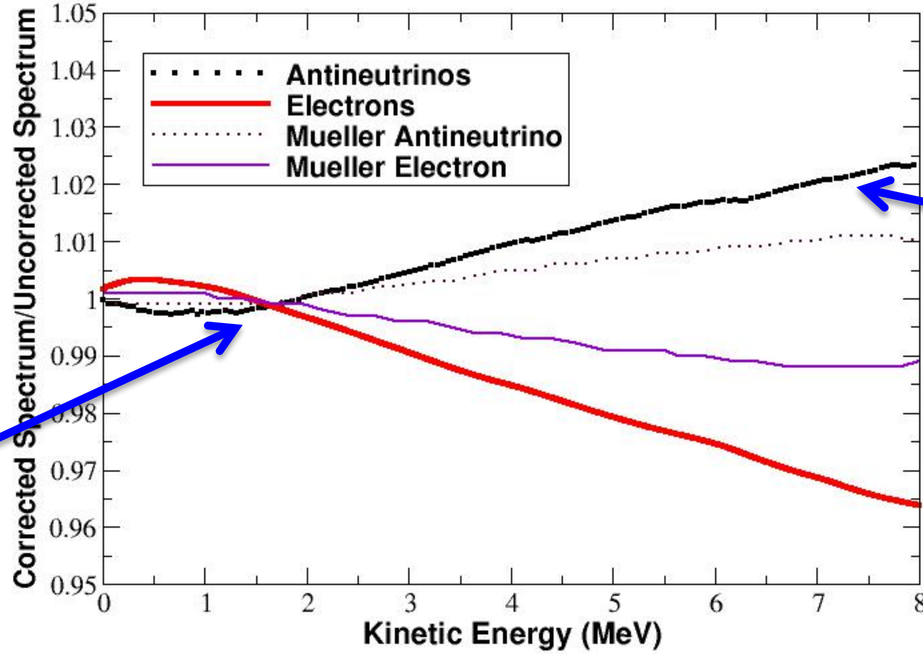
Equivalent correction for spin-flip component of forbidden transitions

The correction is operator dependent:

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

$$\delta_{WM}^{unique1^{st}} = \frac{3(\mu_V - \tfrac{1}{2})}{5 M_N g_A}\left[\frac{(p_e^2 + p_\nu^2)(p_e^2 / E_e - E_\nu) + \frac{2}{3}\frac{p_e^2 E_\nu (E_\nu - E_e)}{E_e}}{(p_e^2 + p_\nu^2)} \right]$$

If all forbidden transitions are treated as allowed GT, the corrections lead to an anomaly - the ν_e spectrum is shifted to higher energy



$\overline{E}_0/2$

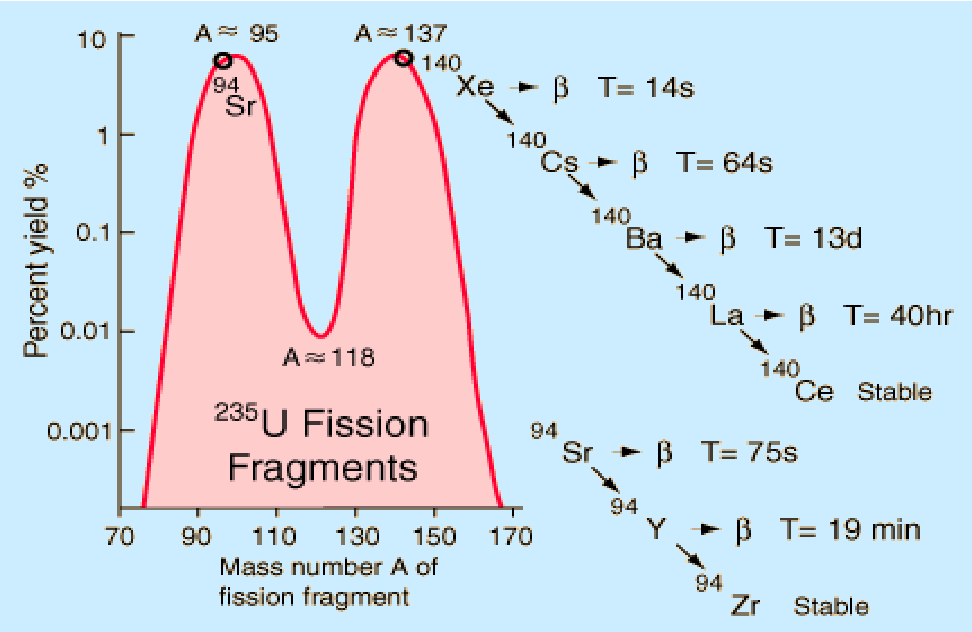
$$\cong \frac{1}{2}\left[\frac{4(\mu_v - \frac{1}{2})}{6M_n g_A} - \frac{3Z\alpha R}{2\hbar c}\right]$$

- Obtain larger effect & stronger energy dependence than Mueller because the form of our corrections are different

- Linear increase in the number of antineutrinos with E_ν>2 MeV

However, ~30% of the transitions are forbidden

Forbidden:
Not Fermi (0+) or GT (1+)
i.e, $\Delta L > 0$, $\Delta\pi = +/-1$



A~95 Peak
Br, Kr, Rb, Y, Sr, Zr mostly forbidden
Nb, Mo, Tc often allowed GT

A~ 137 Peak
Sb, I, Te, Xe, Cs, Ba, Pr, La
- mostly forbidden

The forbidden transitions tend to dominate the high energy component of spectrum and from the ENDF/B-VII.1 Decay Library these make up 30% of the spectrum

Unique forbidden versus non-unique forbidden transitions

Allowed: Fermi τ and Gamow-Teller $\Sigma=\sigma\tau$

Forbidden: $\Delta L \neq 0$; $(\vec{L} \otimes \vec{\Sigma})^{\Delta J = \Delta L}$, $(\vec{L} \otimes \vec{\Sigma})^{\Delta J = \Delta L - 1}$, $\Delta\pi = (-)^{\Delta L}$

$\vec{r}^{L}\vec{\tau}$, $\frac{\vec{\nabla}\vec{\tau}}{M}$, ...

Unique if $(\vec{L} \otimes \vec{\Sigma})^{\Delta J = \Delta L + 1}$, e.g., 2^-

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

Unique transitions only involve one operator & there is a unique shape change

e.g., 2- the phase space is multiplied by $C(E) = p^2+q^2$

Also, a well defined weak magnetism correction

Non-unique transitions involve several operators

The C(E) shape factor is operator dependent

WM and FS are also operator dependent

Without detailed nuclear structure information there is no method of determining which operators determine the forbidden transitions

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 1^{st} Forbidden GT	0^-	$[\Sigma, r]^{0-}$	$p_e^2 + E_\nu^2 + 2\beta^2 E_\nu E_e$	0
Non-unique 1^{st} Forbidden ρ_A	0^-	$[\Sigma, r]^{0-}$	λE_0^2	0
Non-unique 1^{st} 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 1^{st} 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	0
Non-unique 1^{st} Forbidden F	1^-	$r\tau$	$p_e^2 + E_\nu^2 + \frac{2}{3}\beta^2 E_\nu E_e$	0
Non-unique 1^{st} Forbidden $\vec{J}_V$	1^-	$r\tau$	E_0^2	-

Table lists the situation for 6 operators that enter 1^{st} forbidden transitions

Many transitions are 2^{nd} forbidden, etc.

Have not derived a similar table for the Finite Size corrections

The uncertainty in how to treat the forbidden transitions introduces an uncertainty in the antineutrino flux

- No way to determine what combination of operators and hence corrections to use for this (25%) component of the spectra
- No clear way to estimate the uncertainty due the non-unique forbidden transitions
- Therefore, we examined the uncertainties using several prescriptions.

For different choices of the forbidden operators we examined:

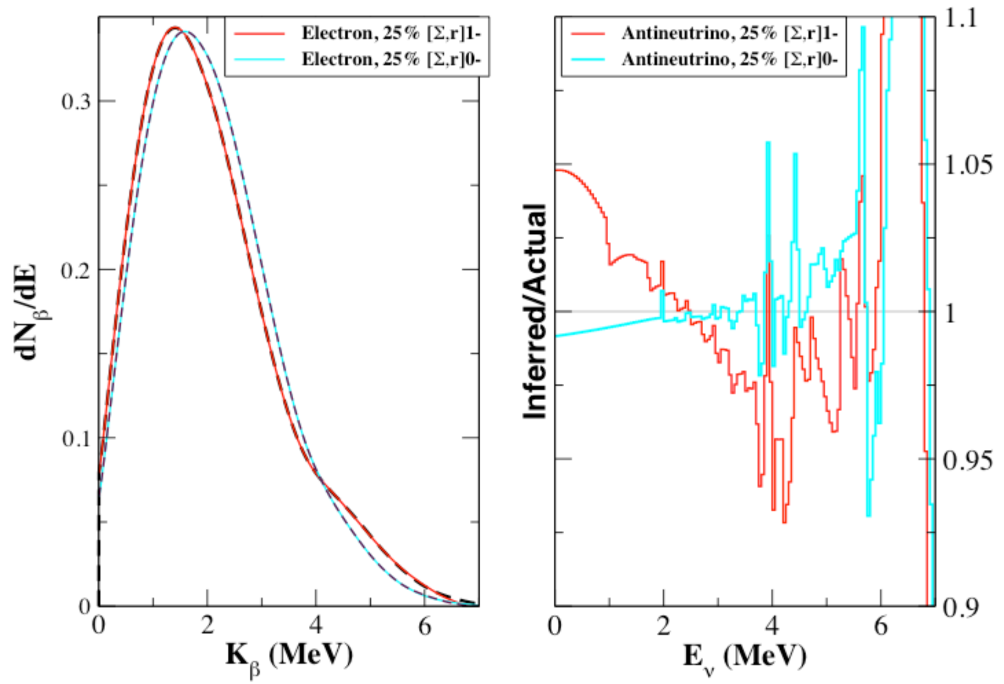
» 1. Inferred antineutrino spectrum from a fit a beta spectrum, without forbidden transitions

» 2. Changes in $k(E_e, E_\nu) = N_\nu(E_\nu)/N_\beta(E_e)$

» 3. Changes in $R \equiv \sum_i \left\lfloor \frac{\partial N_\nu(E_\nu)}{\partial a_i} \right\rfloor / \left\lfloor \frac{\partial N_\beta(E_e)}{\partial a_i} \right\rfloor$

» 4. Change in the predicted antineutrino spectra

1. Examine the inferred antineutrino spectrum from a fitted β-spectrum for fictitious nucleus with 4 - 50 branches



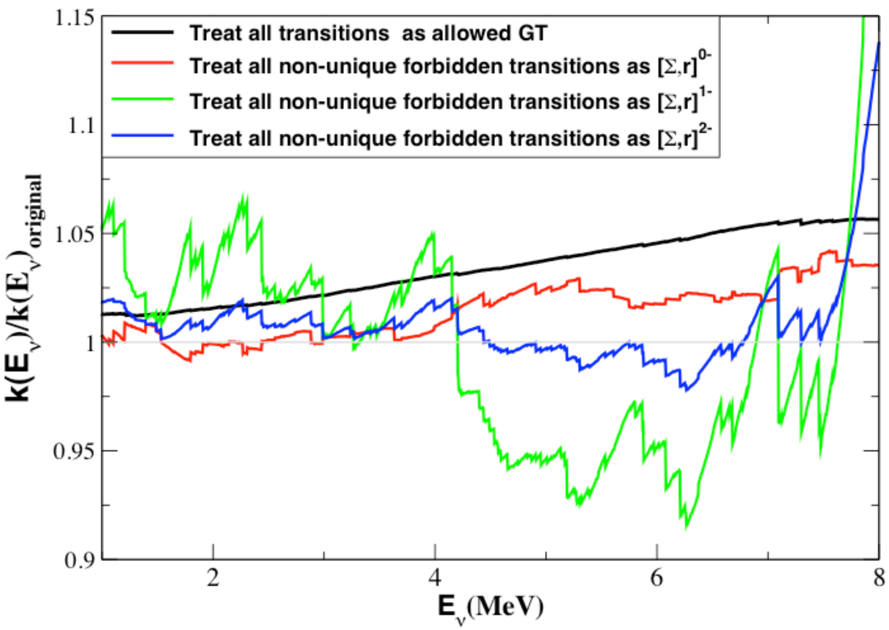
- Actual spectrum involves 30% forbidden transitions and 70% allowed GT
- Fit assumes 100% allowed GT transition
- Inferred $\overline{\nu}_e$ spectrum deviates from the actual $\overline{\nu}_e$ spectrum by ~5%
  - very similar results found for 4, 10 and 50 branches

The problem arises from assuming that the forbidden nature of the transitions can be ignored

2. Examine the bi-variant function $k(E_e, E_\nu) = N_\nu(E_\nu)/N_\beta(E_e)$

If $\boldsymbol{k(E_e, E_\nu)}$ changes by a small percentage for some path in the (E_e, E_ν) plane as we change the operators that determine the forbidden transitions

=> A prescription for inferring $N_\nu(E_\nu)$ from known $N_\beta(E_e)$



Found no path in the (E_ν, E_e) plane that left the function **$k(E_\nu, E_e)$** unchanged by 5%

=> Uncertainty in $N_\nu(E_\nu)$ is ~5%

3. Examine change in the antineutrino spectrum with respect to the β-spectrum

Examine the function R:

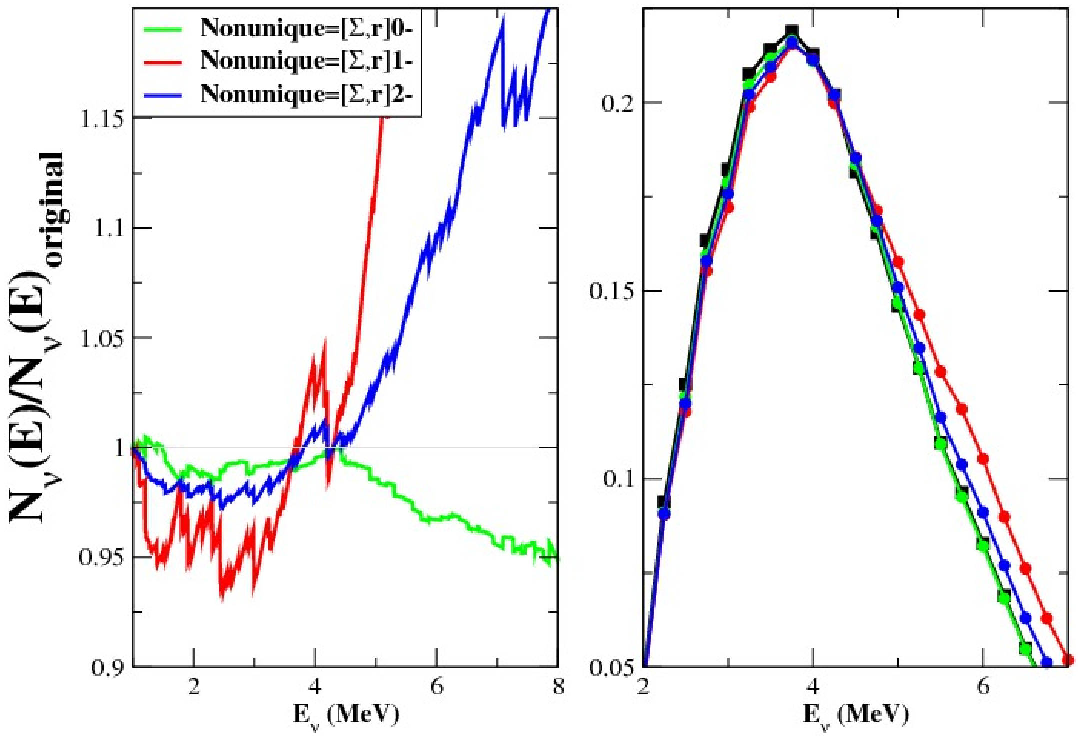
$$R \equiv \sum_i \left[\frac{\partial N_\nu(E_\nu)}{\partial a_i} \right] / \left[\frac{\partial N_\beta(E_e)}{\partial a_i} \right],$$

$$N_\nu(E_\nu) = \sum_i a_i S(E_\nu, E_{0i}) \;\; ; \;\; N_\beta(E_\beta) = \sum_i a_i S(E_\beta, E_{0i})$$

As we changed the operators determining the forbidden transitions there was no path in the (E_e, E_ν) plane such that ***R*** changed by as little as 5%

=> Uncertainty in $N_\nu(E_\nu)$ is ~5%

4. Examine the ratio of antineutrino spectra for different treatments of the forbidden transitions



Ratio of antineutrino spectrum to the original ILL spectrum allowing different operators to dominate the non-unique forbidden transitions

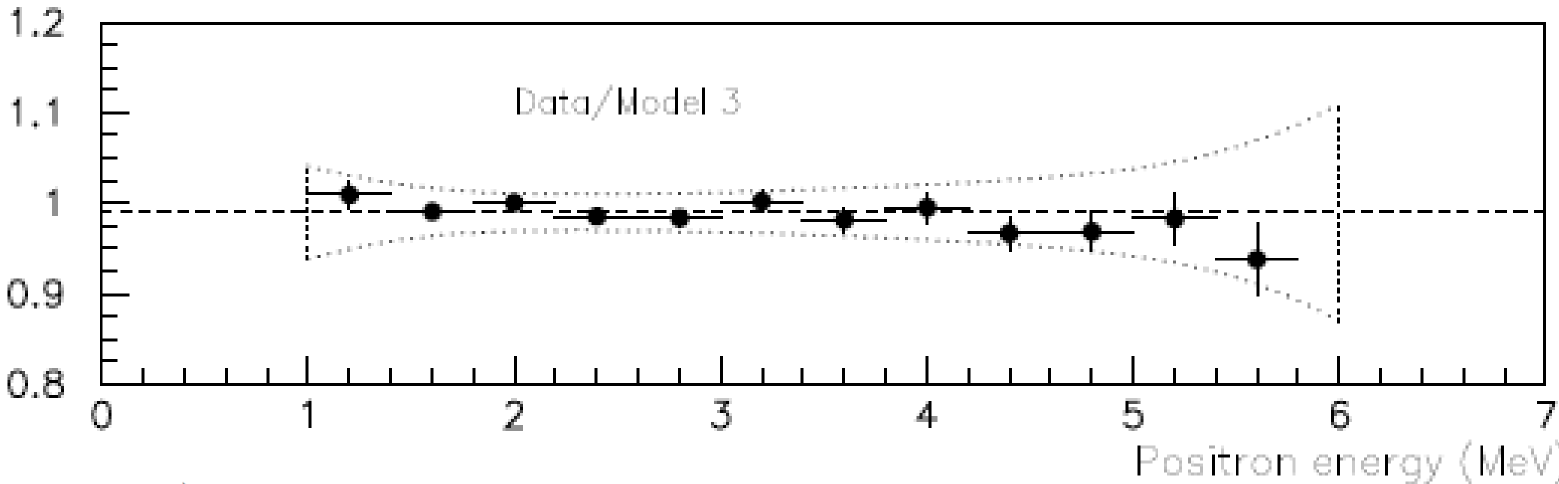
The forbidden transitions introduce an operator-dependent distortion of spectrum
A purely theoretical analysis is unlikely to reduce the uncertainties in a model-independent way

=> Need direct measurement of the shape of the spectrum to reduce the uncertainties

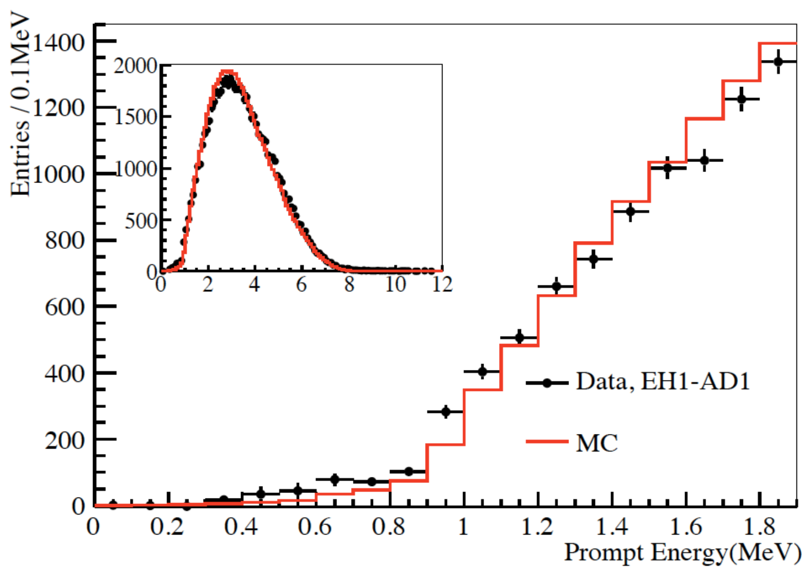
What does experiment say?

Bugey 3 did not report any significant distortions

Do Double Chooz, Daya Bay, Reno see distortions in the near detectors?



Bugey



Daya Bay

- See talk by Karsten Heeger Friday

Summary

- The weak magnetism and finite size corrections are the main effects that led to the anomaly
- These corrections increase the antineutrino spectrum above 2 MeV **if** all transitions can be treated as allowed
- Forbidden transitions ~30% - tend distort the shape of the spectrum
- Uncertainty in how to treat non-unique forbidden transitions outweighs the size of the anomaly
- **<u>Requires</u>:**

  Direct measurement of the antineutrino spectrum

  Or a measurement of the dominant forbidden β-decay spectra