Neutrino fluxes from nuclear reactors

Patrick Huber

Center for Neutrino Physics – Virginia Tech

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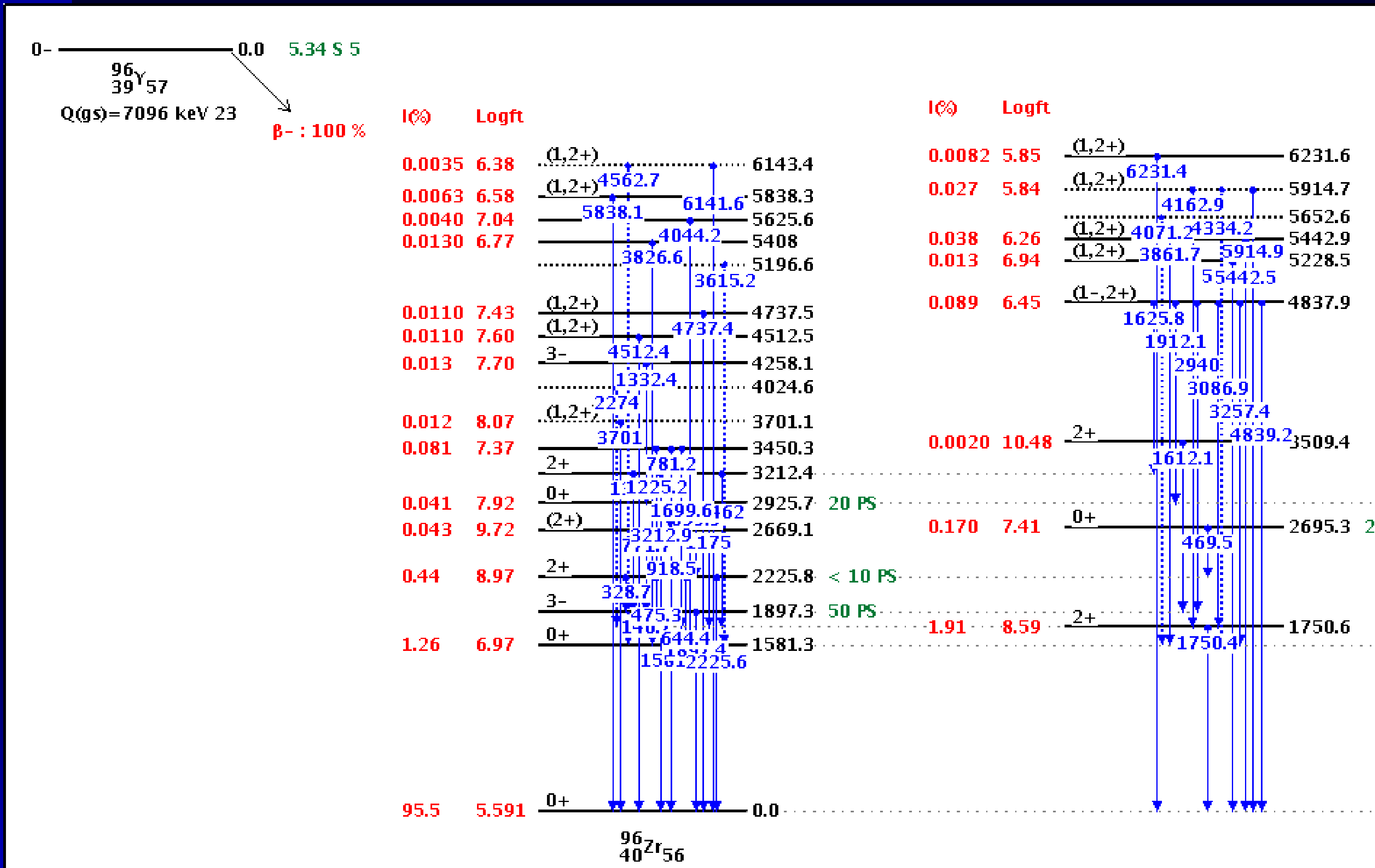
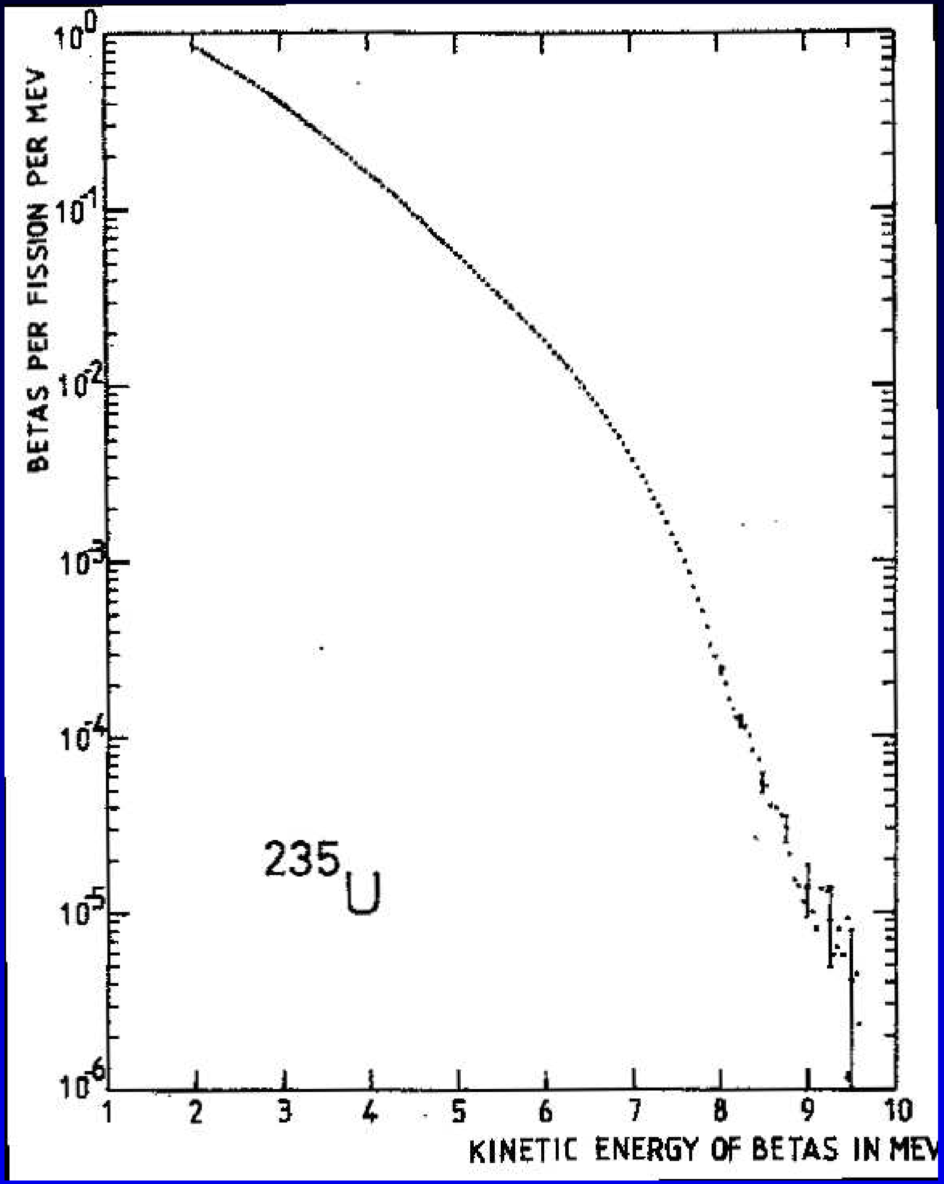
Neutrinos from fission

- For a single branch energy conservation implies a one-to-one correspondence between β and $\bar{\nu}$ spectrum.
- However, here there are about 500 nuclei and 10 000 individual β-branches involved; many are far away from stability.
- Direct β spectroscopy of single nuclei never will be complete, and even then one has to untangle the various branches
- γ spectroscopy yields energy levels and branching fractions, but with limitations, *cf.* pandemonium effect

β branches



β-spectrum from fission



Schreckenbach, *et al.* 1985.

^{235}U foil inside the High Flux Reactor at ILL

Electron spectroscopy with a magnetic spectrometer

Same method used for ^{239}Pu and ^{241}Pu

For ^{238}U recent measurement by Haag *et al.*, 2013

Extraction of ν-spectrum

The total β-spectrum is a sum of all decay branches

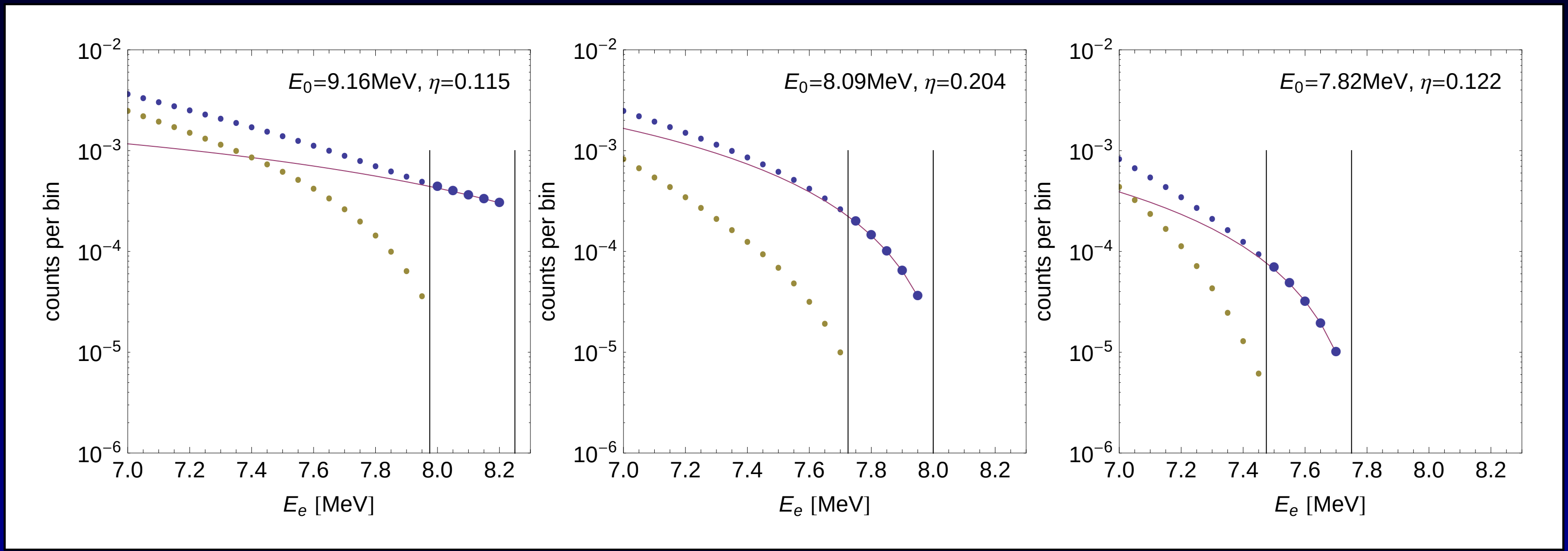
$$\mathcal{N}_\beta(E_e) = \int dE_0 N_\beta(E_e, E_0; \bar{Z})\,\eta(E_0)\,.$$

with $\bar{Z}$ effective nuclear charge and $\eta(E_0)$, the underlying distribution of endpoints

This is a so called Fredholm integral equation of the first kind – mathematically ill-posed, *i.e.* solutions tend to oscillate, needs regulator.

This approach is the basis for "virtual branches" Schreckenbach *et al.*, 1982, 1985, 1989 and is used in the modern calculations as well Mueller *et al.* 2011, Huber 2011

Virtual branches



1 – fit an allowed β-spectrum with free normalization η and endpoint energy E_0 the last s data points

2 – delete the last s data points

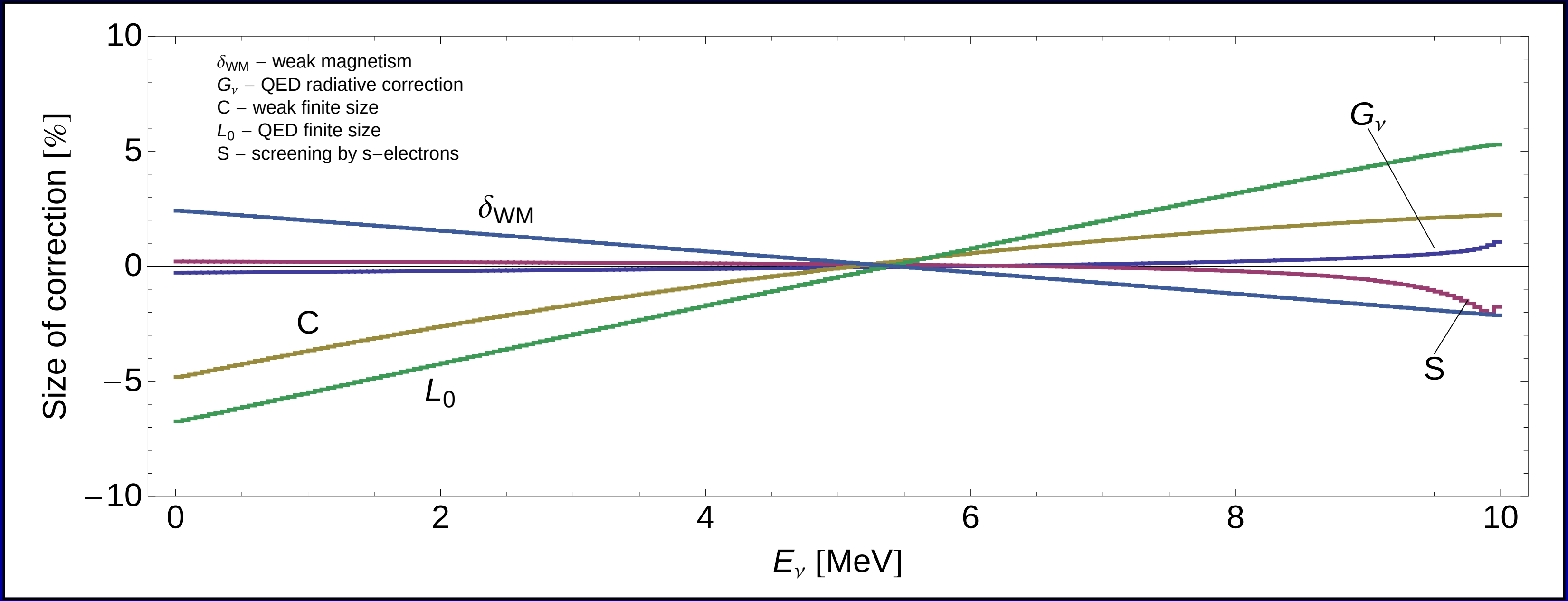
3 – subtract the fitted spectrum from the data

4 – goto 1

Invert each virtual branch using energy conservation into a neutrino spectrum and add them all. *e.g.* Vogel, 2007

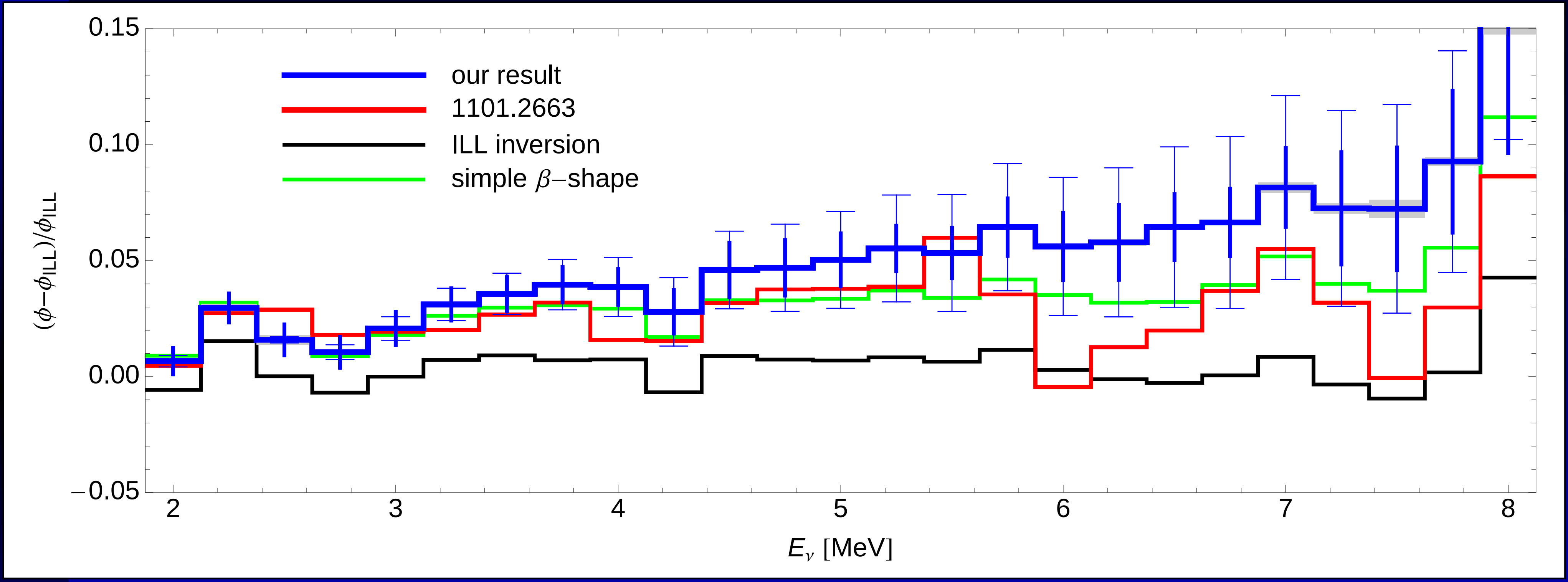
Corrections to β-shape

There are numerous correction to the β-spectrum



Many of these correction depend on the nuclear charge Z, but Z is not determined by the β-spectrum measurement $\Rightarrow$ nuclear databases.

Reactor antineutrino fluxes

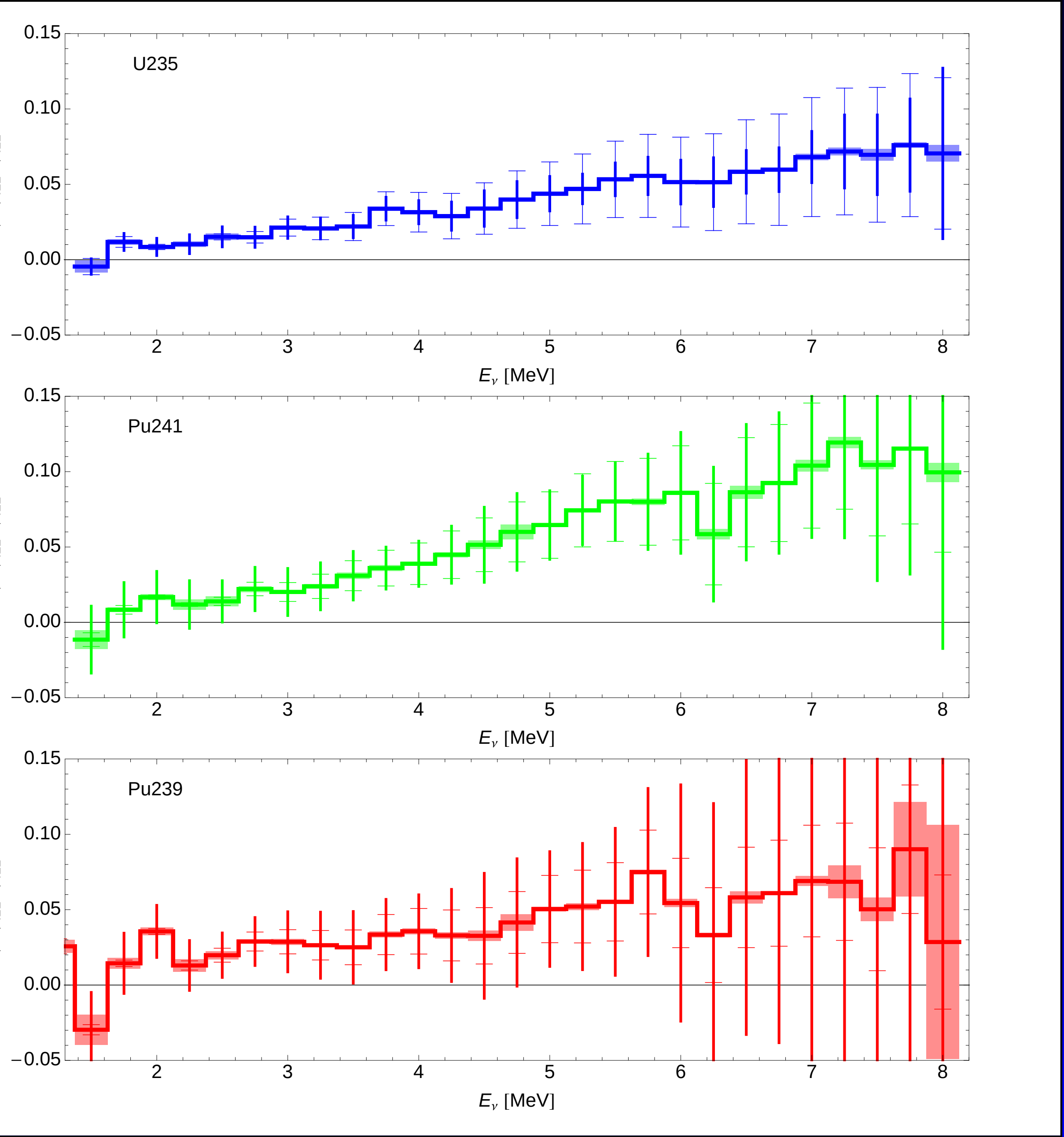


Shift with respect to ILL results, due to

a) different effective nuclear charge distribution

b) branch-by-branch application of shape corrections

Comparison of isotopes

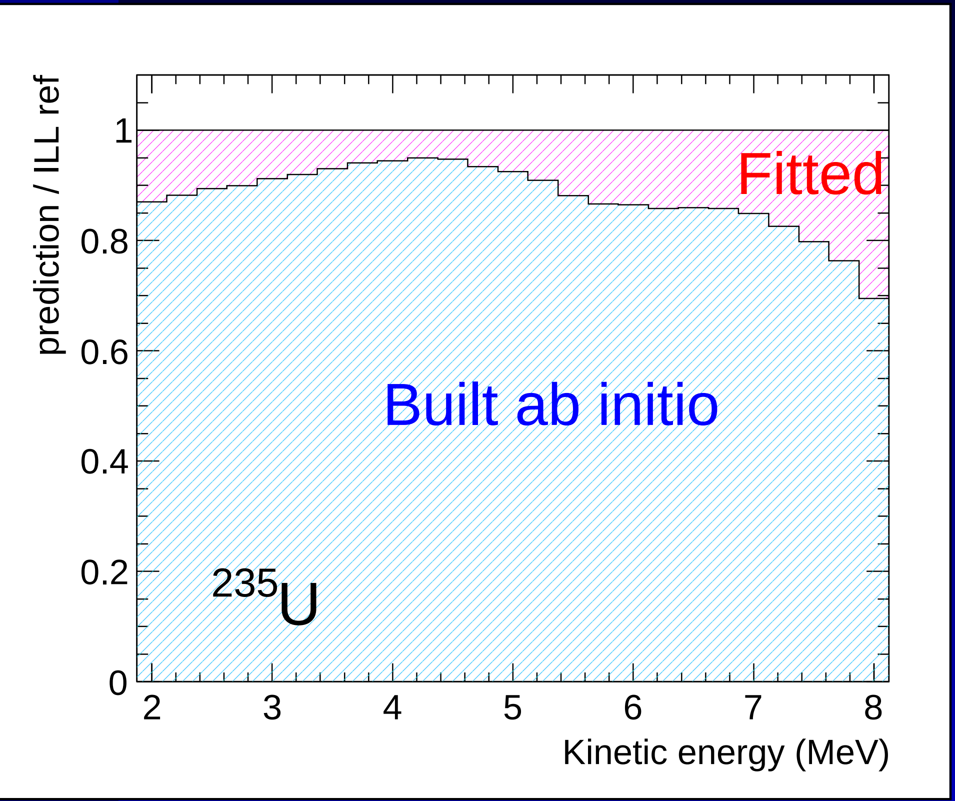


Same shift in all isotopes

Statistical errors of different size, direct consequence of different ILL data quality

^{239}Pu most problematic due to large fission fraction

From first principles?

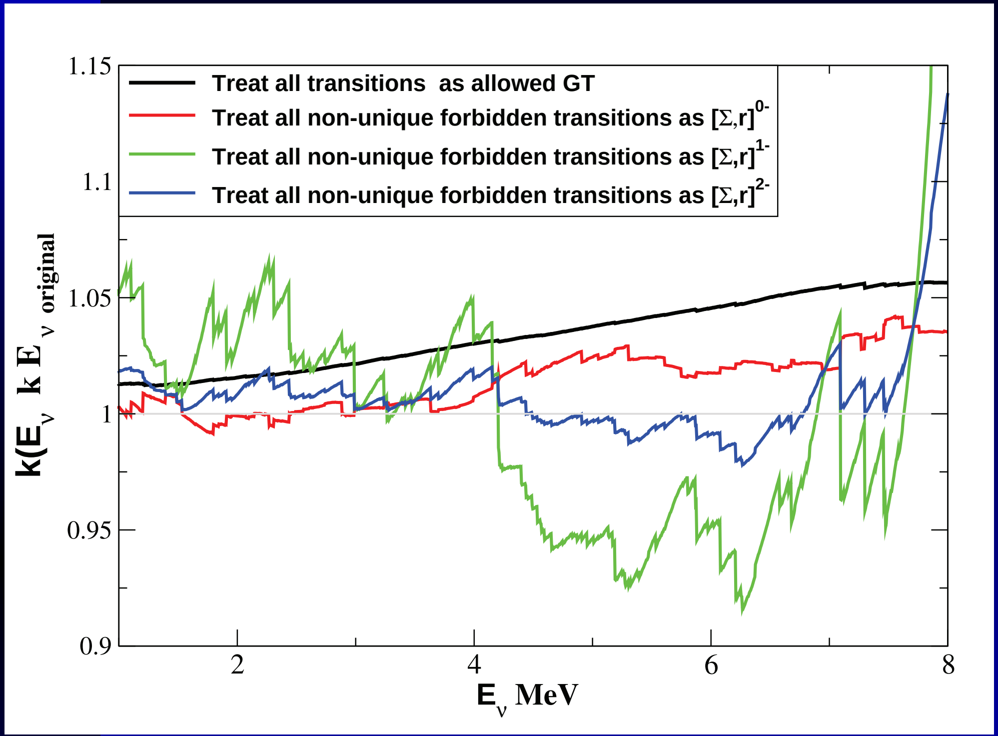


In Mueller *et al.*, Phys.Rev. **C83** (2011) 054615 an attempt was made to compute the neutrino spectrum from fission yields and information on individual β decay branches from databases.

The resulting cumulative β spectrum should match the ILL measurement.

About 10-15% of electrons are missing, Mueller *et al.* use virtual branches for that small remainder.

Forbidden decays



Approximate upper bound for the flux error due to forbidden decays.

Hayes *et. al*, arXiv:1309.4146 point out that in forbidden decays a mixture of different operators are involved, and that while for many of the individual operators the corrections can be computed, the relative contribution of each operator is generally unknown.

Potentially large source of uncertainty.

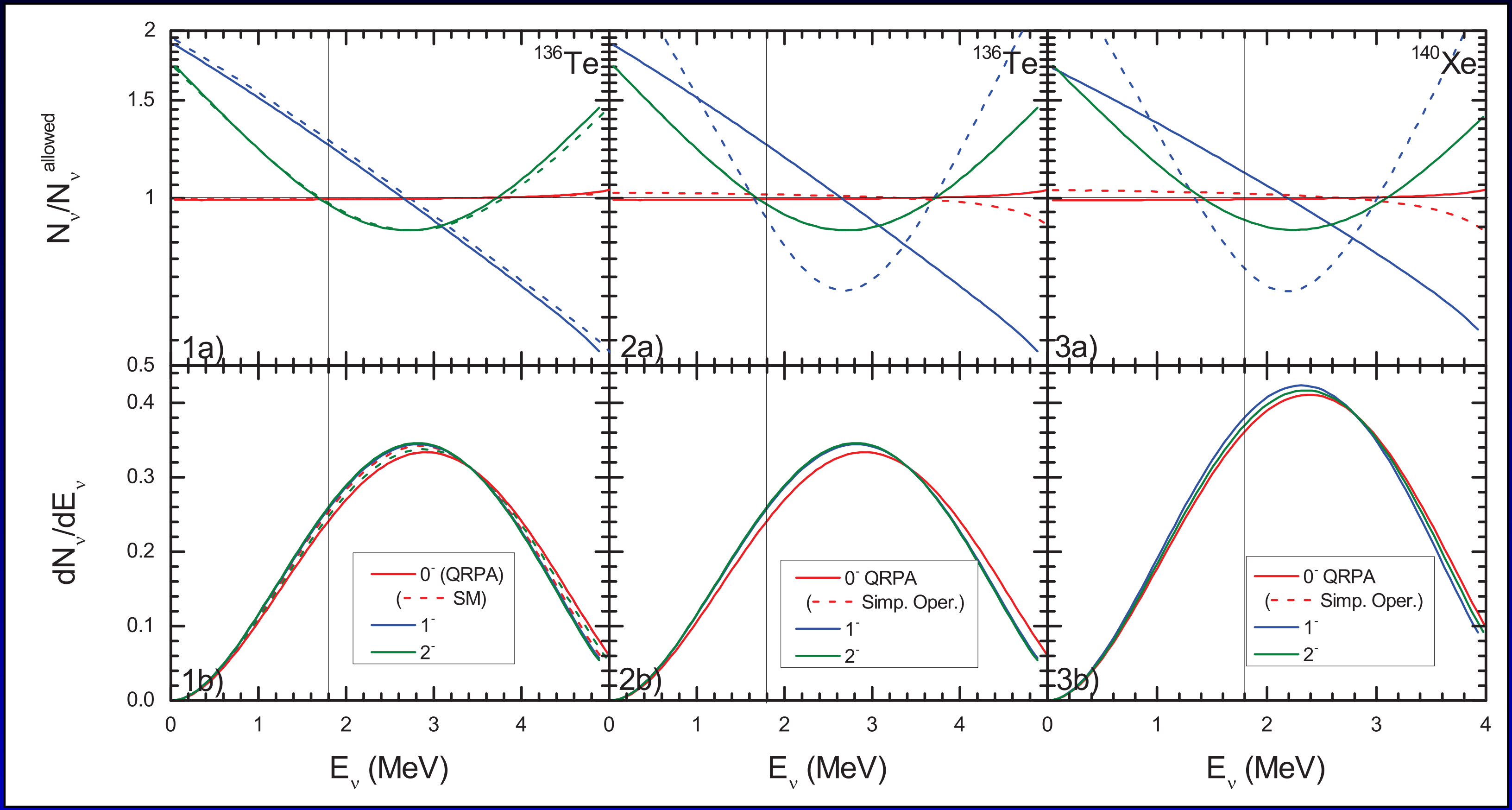
Industrial structure calculations

If we knew the nuclear wave function of parent and daughter we could compute everything we need to know.

On the other hand we do not need to compute the whole β-spectrum from scratch, we just want to know the size of certain corrections like WM. Therefore, an approximate wave function may be all that is needed.

Question: Is there a technology to perform approximate (!) calculations of nuclear wave functions which can be automatized?

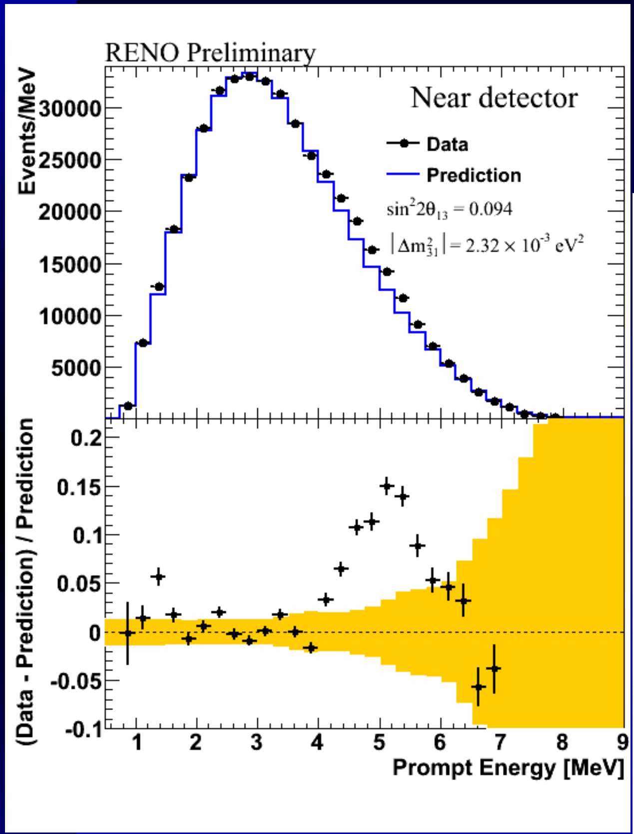
Nuclear structure calculation

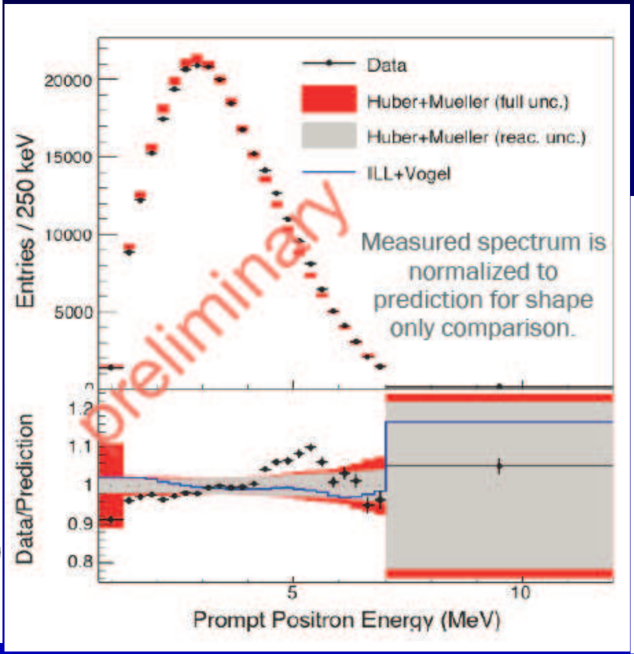


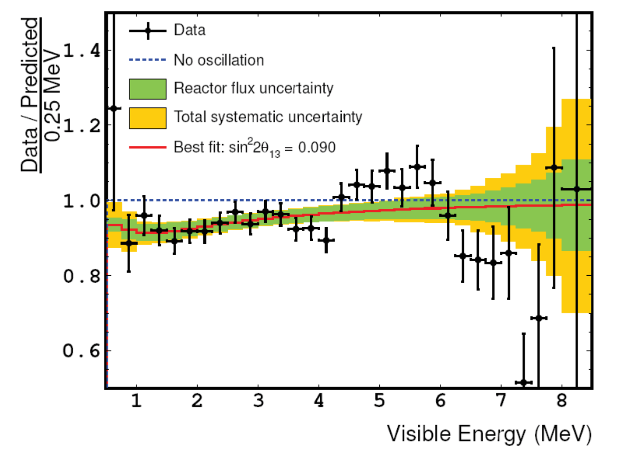
Fang, Brown, 2015

These are detailed calculations for the nuclei in question and indicate an overall 1-2% effect, smaller than the expansion by Hayes et al.

The 5 MeV bump







Seen by all three reactor experiments

Tracks reactor power

Seems independent of burn-up

see J. Haser's talk

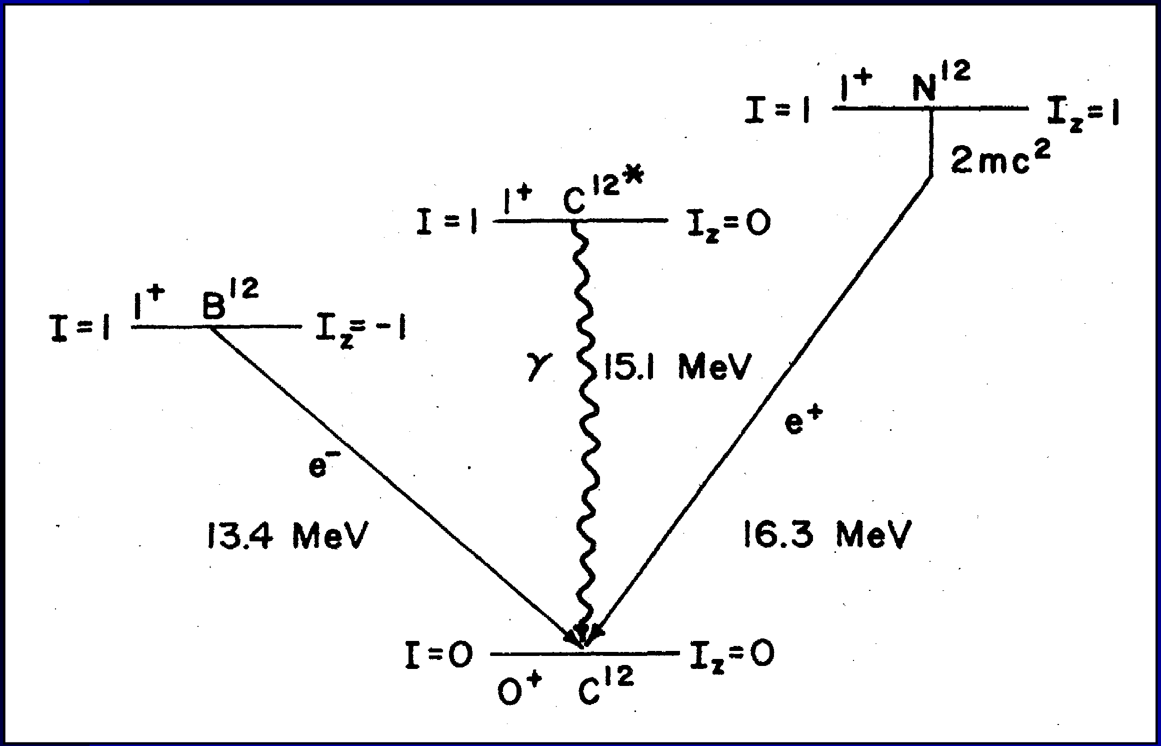
Pausible causes

Hayes *et al.* (arXiv:1506.00583) point to following suspects:

1. Beta decay of non-fissionable material in the reactor
2. Shape of the beta and neutrino spectrum for $\Delta J^{\Delta\pi} = 0^-$ first forbidden decays
3. Beta decay of the daughters of the fast fission of ^{238}U
4. Beta decay of daughters of the epithermal fission of ^{235}U, ^{239}Pu and/or ^{241}Pu
5. Errors in Schreckenbach's ILL beta spectra

I believe 1 and 5 are very unlikely, but what about 2?

Isospin analog γ-decays



B. Holstein, Rev. Mod. Phys. **46**, 789, 1974.

$$\Gamma(C^{12*} - C^{12})_{M1} = \frac{\alpha E_\gamma^3}{3M^2}\left|\sqrt{2}\mu(0)\right|^2$$

$$b := \sqrt{2}\mu(0) = F_M^N(0)$$

Gamow-Teller matrix element c

$$c = F_A^N(0) = \sqrt{\frac{2ft_{\mathrm{Fermi}}}{ft}}$$

and thanks to CVC $ft_{\mathrm{Fermi}} \simeq 3080\,\mathrm{s}$ is universal.

CVC at work

Collect all nuclei for which we

- can identify the isospin analog energy level
- and know Γ_{M1}

then, compute the resulting δ_{WM}. This exercise has been done in Calaprice, Holstein, Nucl. Phys. **A273** (1976) 301. and they find for nuclei with $ft < 10^6$

$$\delta_{WM} = 0.82 \pm 0.4\%\,\mathrm{MeV}^{-1}$$

which is in reasonable agreement with the impulse approximated value of $\delta_{WM} = 0.5\%\mathrm{MeV}^{-1}$. Our result for $ft < 10^6$ is $\delta_{WM} = (0.67 \pm 0.26)\,\%\,\mathrm{MeV}^{-1}$.

CVC at work

Decay	$J_i \to J_f$	E_γ (keV)	Γ_{M1} (eV)	b_γ	ft (s)	c	b_γ/Ac	$\lvert dN/dE\rvert$ (% MeV^{-1})
^{6}He $\to^{6}$ Li	$0^+ \to 1^+$	3563	8.2	71.8	805.2	2.76	4.33	0.646
^{12}B $\to^{12}$ C	$1^+ \to 0^+$	15110	43.6	37.9	11640.	0.726	4.35	0.62
^{12}N $\to^{12}$ C	$1^+ \to 0^+$	15110	43.6	37.9	13120.	0.684	4.62	0.6
^{18}Ne $\to^{18}$ F	$0^+ \to 1^+$	1042	0.258	242.	1233.	2.23	6.02	0.8
^{20}F $\to^{20}$ Ne	$2^+ \to 2^+$	8640	4.26	45.7	93260.	0.257	8.9	1.23
^{22}Mg $\to^{22}$ Na	$0^+ \to 1^+$	74	0.0000233	148.	4365.	1.19	5.67	0.757
^{24}Al $\to^{24}$ Mg	$4^+ \to 4^+$	1077	0.046	129.	8511.	0.85	6.35	0.85
^{26}Si $\to^{26}$ Al	$0^+ \to 1^+$	829	0.018	130.	3548.	1.32	3.79	0.503
^{28}Al $\to^{28}$ Si	$3^+ \to 2^+$	7537	0.3	20.8	73280.	0.29	2.57	0.362
^{28}P $\to^{28}$ Si	$3^+ \to 2^+$	7537	0.3	20.8	70790.	0.295	2.53	0.331
^{14}C $\to^{14}$ N	$0^+ \to 1^+$	2313	0.0067	9.16	1.096×10^9	0.00237	276.	37.6
^{14}O $\to^{14}$ N	$0^+ \to 1^+$	2313	0.0067	9.16	1.901×10^7	0.018	36.4	4.92
^{32}P $\to^{32}$ S	$1^+ \to 0^+$	7002	0.3	26.6	7.943×10^7	0.00879	94.4	12.9

None of this is anywhere close to A=90. . .

What happens for large ft?

Decay	$J_i \to J_f$	E_γ (keV)	Γ_{M1} (eV)	b_γ	ft (s)	c	b_γ/Ac	$\lvert dN/dE\rvert$ (% MeV^{-1})
$^{14}\mathrm{C} \to ^{14}\mathrm{N}$	$0^+ \to 1^+$	2313	0.0067	9.16	1.096×10^9	0.00237	276.	37.6
$^{14}\mathrm{O} \to ^{14}\mathrm{N}$	$0^+ \to 1^+$	2313	0.0067	9.16	1.901×10^7	0.018	36.4	4.92
$^{32}\mathrm{P} \to ^{32}\mathrm{S}$	$1^+ \to 0^+$	7002	0.3	26.6	7.943×10^7	0.00879	94.4	12.9

Including these large ft nuclei, we have

$$\delta_{WM} = (4.78 \pm 10.5)\,\%\,\mathrm{MeV}^{-1}$$

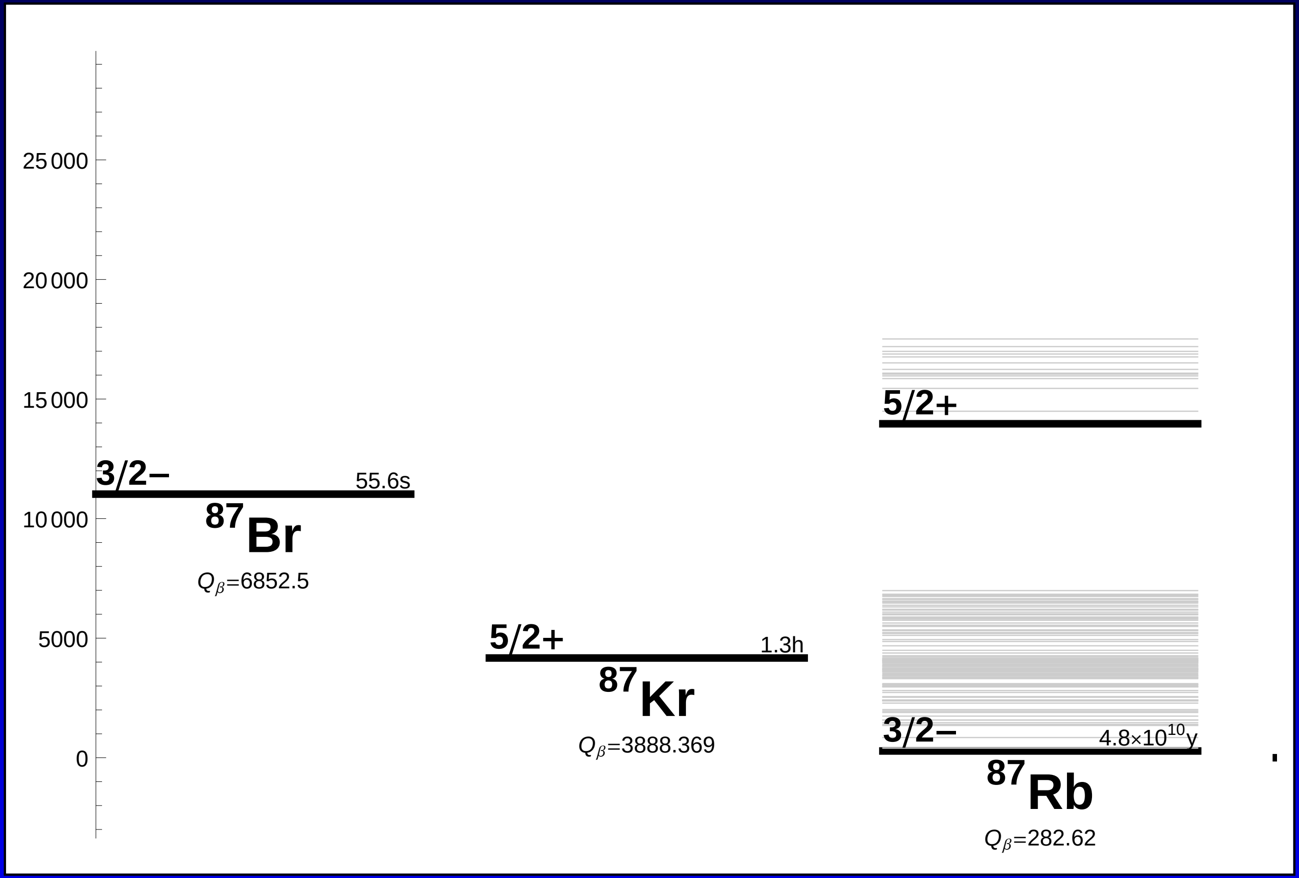
which is about 10 times the impulse approximated value and this are about 3 nuclei out of 10-20...

NB, a shift of δ_{WM} by $1\%\mathrm{MeV}^{-1}$ shifts the total neutrino flux above inverse β-decay threshold by $\sim 2\%$.

Example

There is significant information on isobaric analog states (IAS) through all mass.

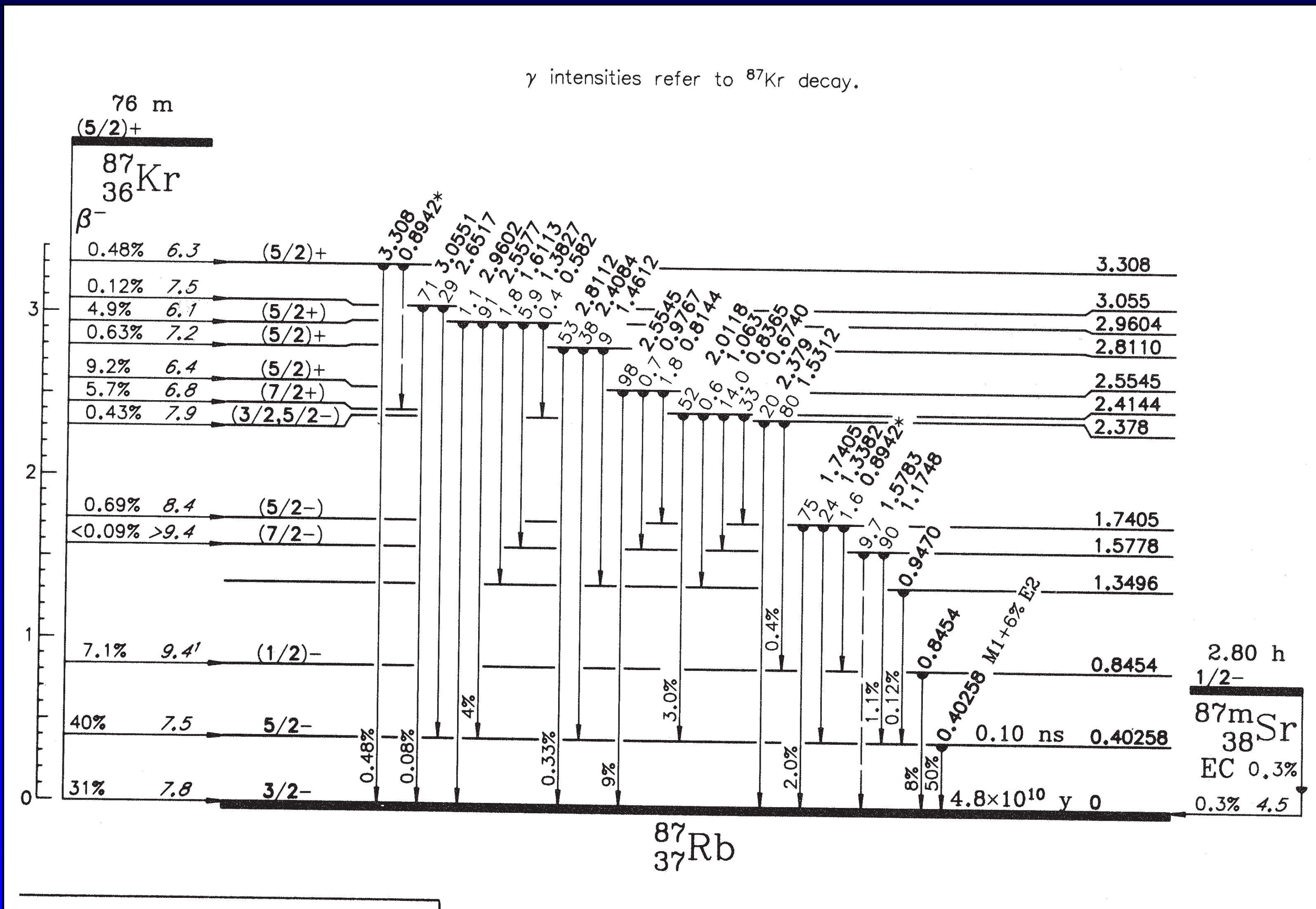
87Kr, with a fission yield of about 0.5%



Ongoing experimental effort at TUNL.

But…

There are nearly no pure GS to GS allowed decays to be found, also 87Kr has a complicated decay scheme



Summary

- Reactors are complex neutrino sources – our current understanding is at the 2-5% level
- New neutrino data will have to have systematics around 1% or better to make a real difference
- The Daya Bay data set will remain a benchmark which we need to exploit to its fullest
- $\Delta J^{\Delta\pi} = 0^-$ beta shape is our main theoretical obstacle, since it does depend on nuclear structure
- Can CVC together with dedicated gamma spectroscopy shed light on the problem?

Questions?