Reactor Anomaly - an Overview

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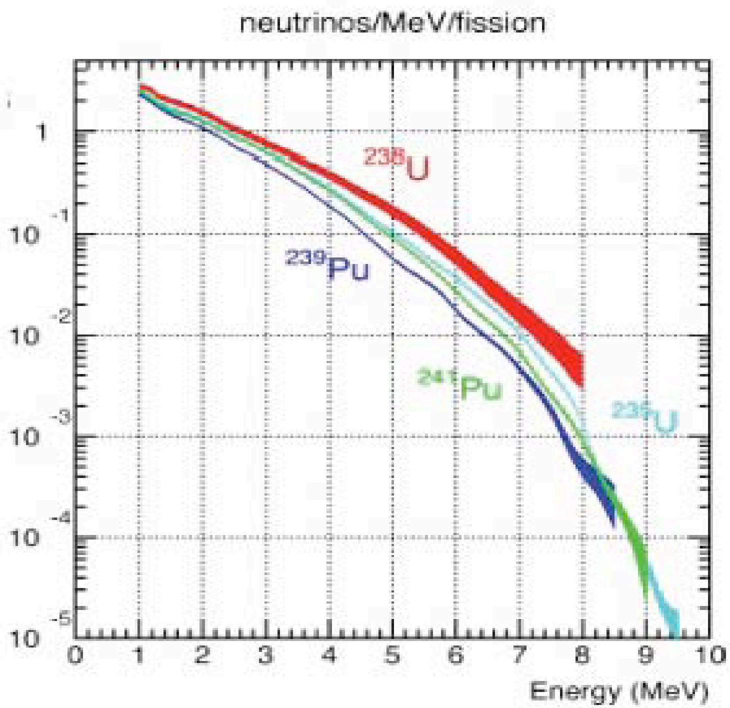
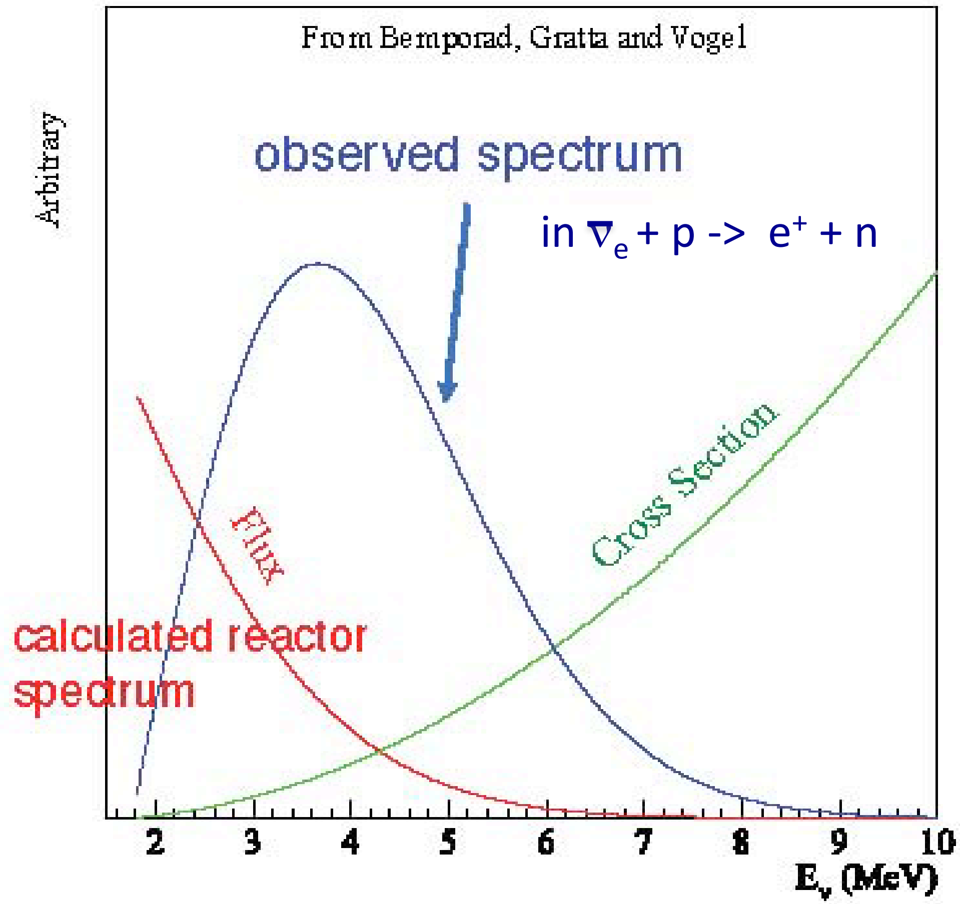
Reactor Antineutrinos





$\bar{\nu}_e$ from n-rich fission products

~ 200 MeV per fission

~ 6 $\bar{\nu}_e$ per fission

~ 2 x 10^{20} $\bar{\nu}_e$/GW_{th}-sec

mean energy of $\bar{\nu}_e$: 3.6 MeV

only disappearance expts possible

cross-section accurate to +/-0.2%

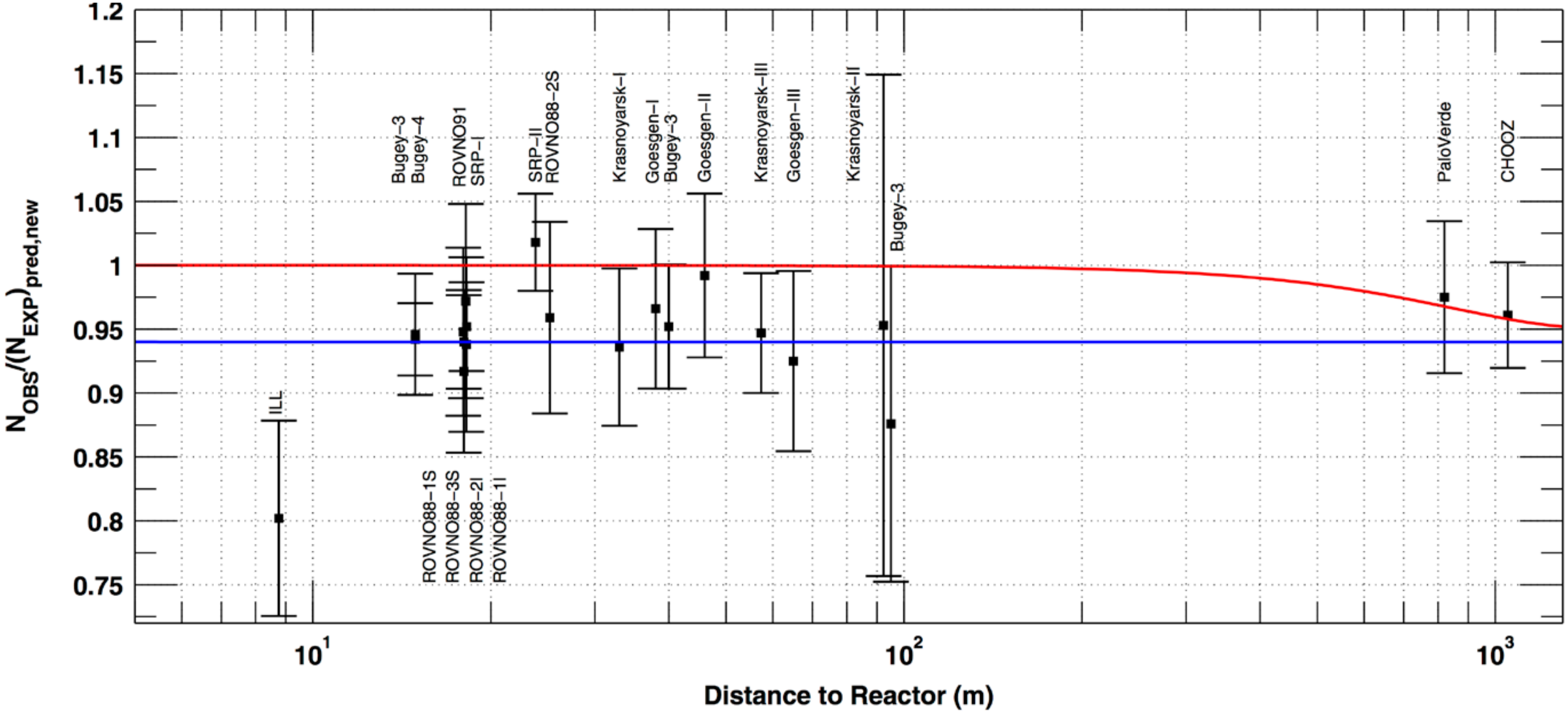


Illustration of the reactor anomaly. Rates in various experiments are compared with the expectations based on the Mueller et al. (2011) spectrum. The mean is 0.943+-0.023.

Possible explanation:

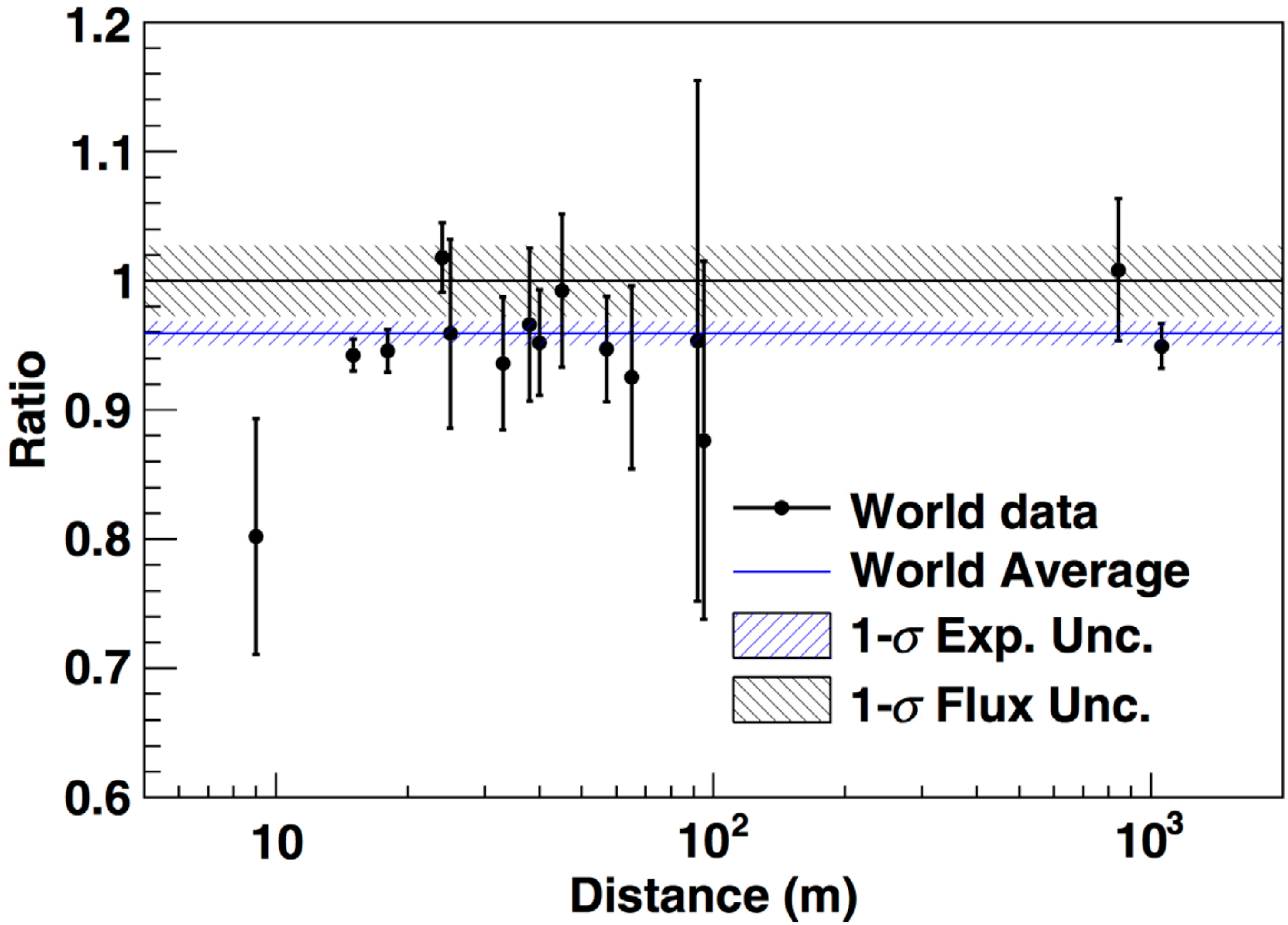
1)Wrong reactor flux or its error

2)Bias in all experiments

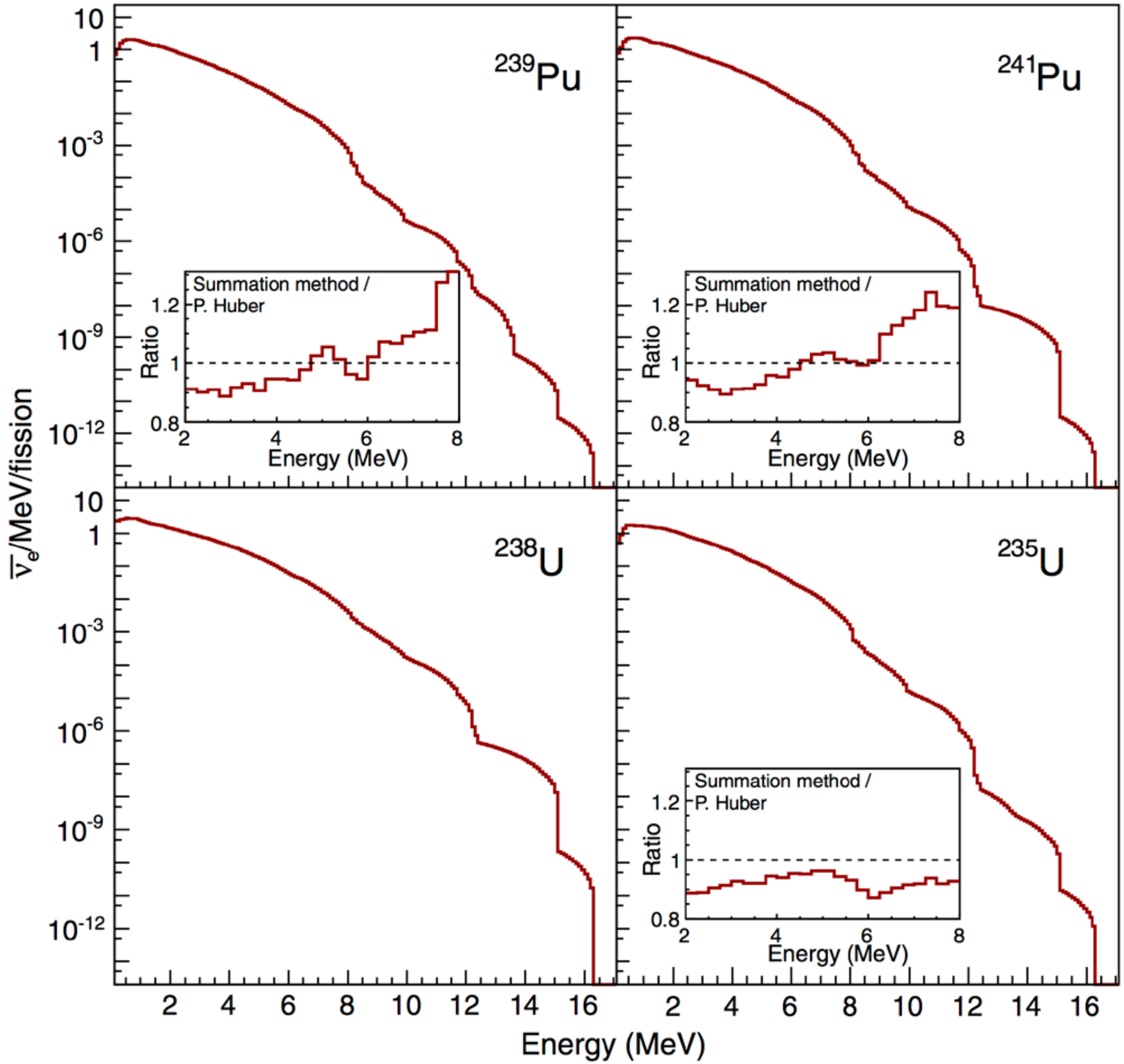
3)New physics at short baseline involving a sterile 4th neutrino

ν_{new} with $\Delta m^2 \sim 1eV^2$ and mixing with ν_e with $\theta_{new} \sim 10^0$

The explanation 3) could be supported by several other, so far unconfirmed anomalies. It would involve unexpected but significant "New Physics"



Reanalysis by Zhang et al. (2013) that includes ~1 km detectors (Chooz, Palo Verde, Double Chooz) corrected for known θ_{13} leads to 0.959+-0.027 i.e. less significant discrepancy. Without the theoretical flux uncertainty we get 0.959 +- 0.009. We are eagerly awaiting the results of absolute rates determined in Daya-Bay and RENO experiments with overwhelming statistics.



Spectra calculated by Fallot et al. 2012. In inserts are the ratios to the spectra of Huber (2011).

When folded with cross sections these spectra result in the yields that are 99.1% (^{235}U), 94.5% (^{239}Pu), 94.8% (^{241}Pu), and 98.1% (^{238}U) of the yields of Huber 2011.

Thus, in my estimate, these spectra would lower the total yield by about 3%.

Of the ~ 800 fission fragments used in the calculation, ~350 have incomplete or totally missing beta decay data.

Here is a list of hints for the existence of sterile neutrinos with ~ eV mass scale. These results (~2-3 σ) are not confirmed but also not ruled out by other experiments.

- LSND
- MiniBooNE ν
- MiniBooNE $\overline{\nu}$
- Reactor Anomaly
- Radioactive Neutrino Source Anomaly

LSND and MiniBoone involve indications for the **appearance** of ν_e or $\overline{\nu}_e$ in the beams that was initially ν_μ or $\overline{\nu}_\mu$ at L/E_ν ~ 1 m/MeV that is incompatible with standard oscillation paradigm.

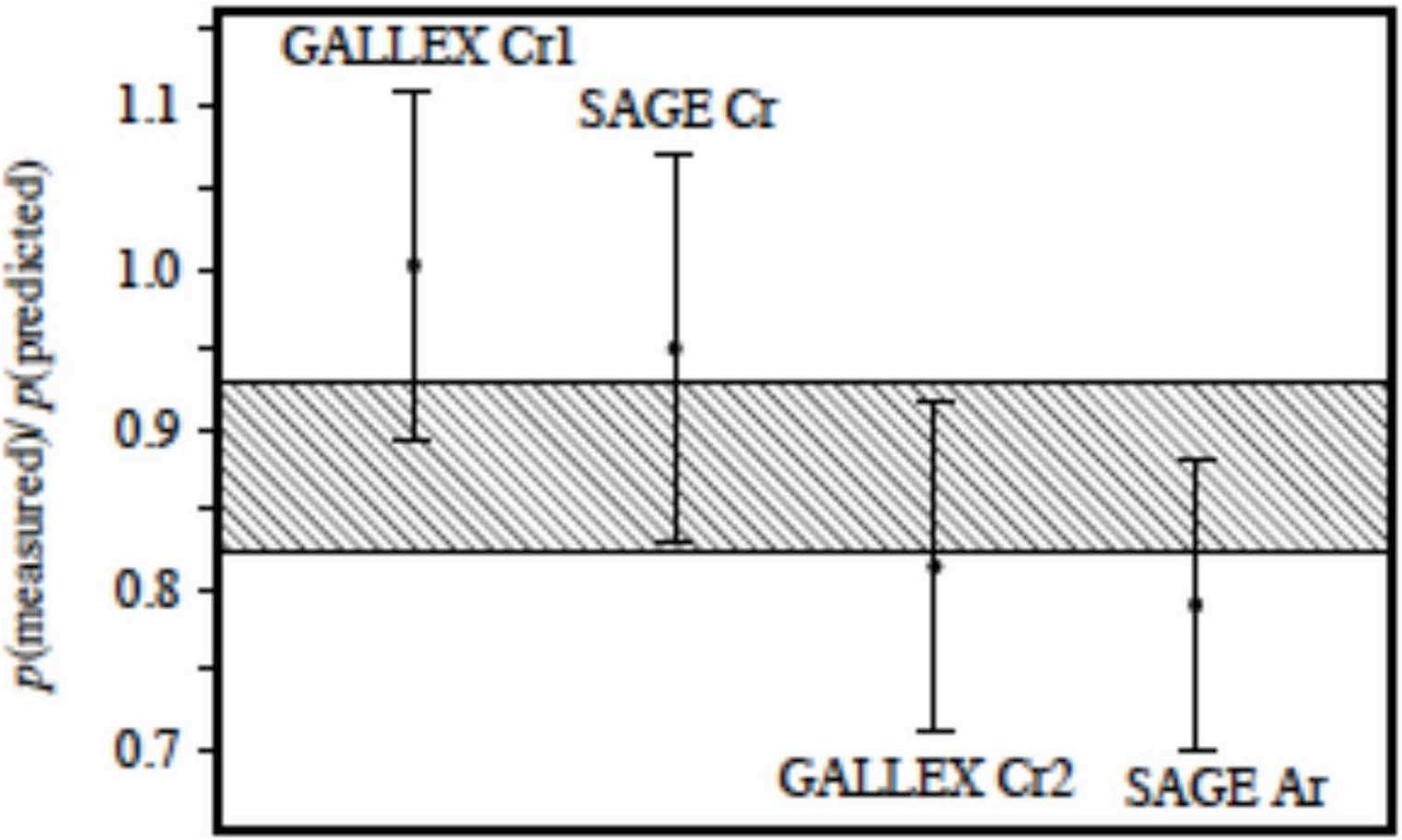
Reactor experiments involve indications of the **disappearance** of $\overline{\nu}_e$ again at L/E_ν ~ 1 m/MeV .

Calibration of the gallium solar neutrino detectors with radioactive sources involve indications of the **disappearance** of ν_e again at L/E_ν ~ 1 m/MeV .

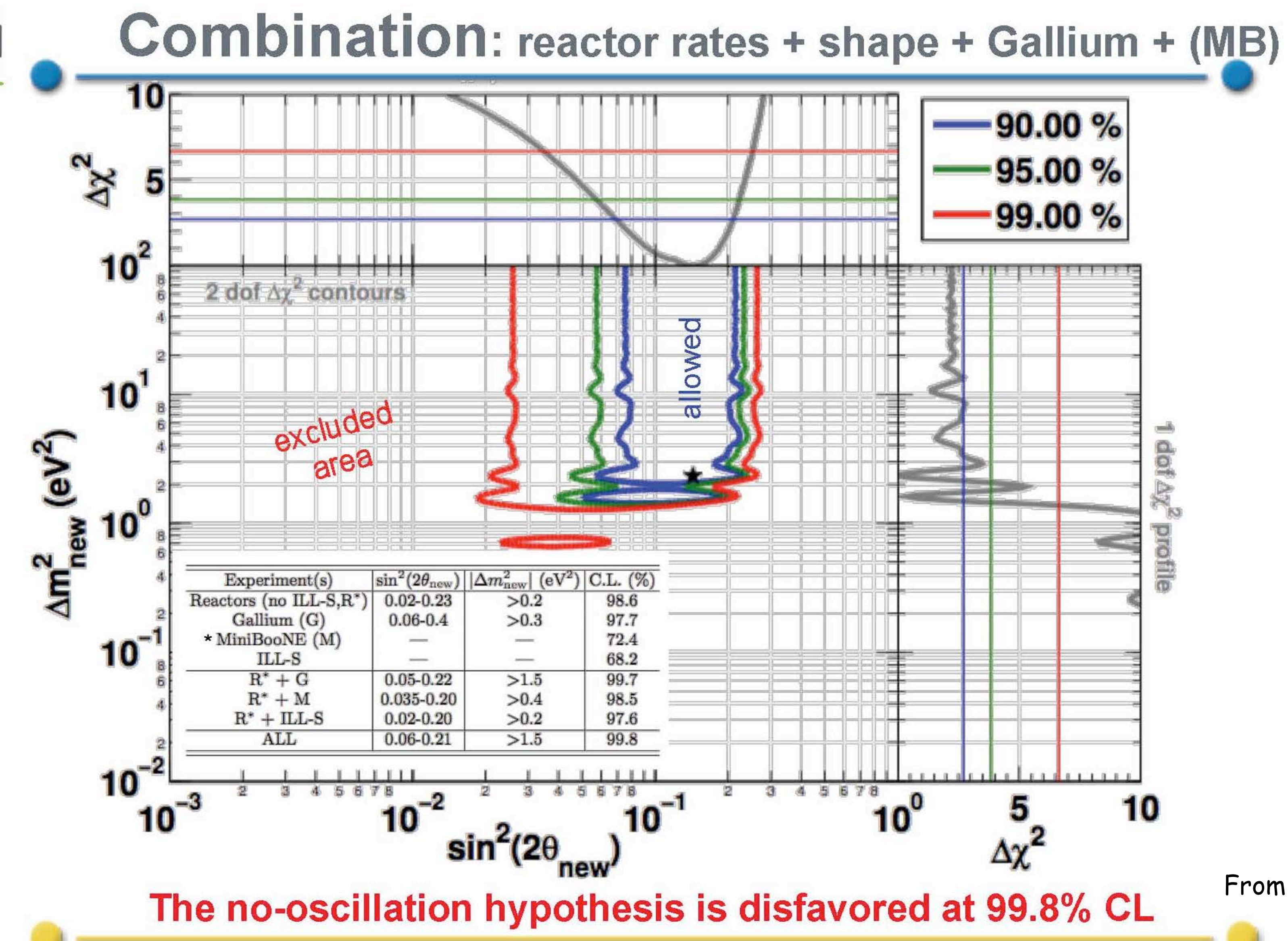
The solar neutrino detectors GALLEX and SAGE based on the ν_e capture on ^{71}Ga leading to ^{71}Ge were tested with strong man-made radioactive sources of ^{51}Cr and ^{37}Ar which were placed inside the detectors. ^{51}Cr and ^{37}Ar produce monoenergetic ν_e by electron capture (Q = 751 and 814 keV).

There were four calibration runs. The corresponding measured/expected ratios are shown below. When averaged they give **$\langle R \rangle = 0.86 \pm 0.05$**

When one tries to explain these ratios as resulting from oscillations, the best fit values are Δm^2 = 2.24 eV^2 and $\sin^2 2\theta$ = 0.50 (Giunti & Lavender, Phys. Rev C**83**,065504(2011)).



Analysis based on $P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{new})\sin^2(\Delta m^2_{new} L/E_\nu)$
Best fit $\Delta m^2_{new} = 2.35 \pm 0.1$ eV^2, $\sin^2(2\theta_{new}) = 0.165 \pm 0.04$



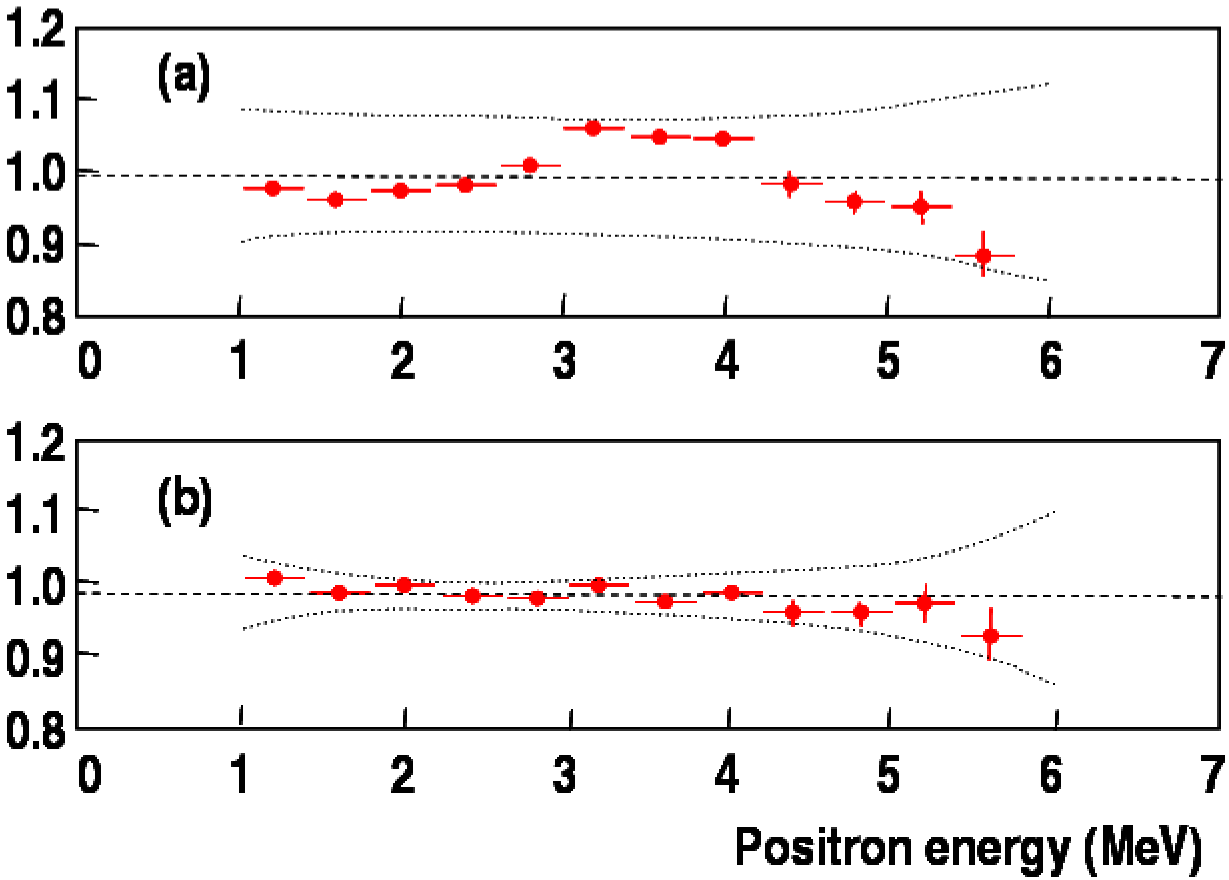
Experiment(s)	$\sin^2(2\theta_{new})$	$\lvert\Delta m^2_{new}\rvert$ (eV^2)	C.L. (%)
Reactors (no ILL-S,R*)	0.02-0.23	>0.2	98.6
Gallium (G)	0.06-0.4	>0.3	97.7
* MiniBooNE (M)	—	—	72.4
ILL-S	—	—	68.2
R* + G	0.05-0.22	>1.5	99.7
R* + M	0.035-0.20	>0.4	98.5
R* + ILL-S	0.02-0.20	>0.2	97.6
ALL	0.06-0.21	>1.5	99.8

From Mention *et al.*

Brief history of the reactor neutrino spectrum determination:

1. First `modern' evaluations were done in late 1970 and early 1980 (Davis et al. 1979, Vogel et al. 1981, Klapdor & Metzinger 1982)
2. During the 1980-1990 a series of measurements of the **electron** spectra associated with the fission of ^{235}U, ^{239}Pu and ^{241}Pu were performed at ILL Grenoble by Schreckenbach et al. These were **converted** into the electron antineutrino spectra by the authors.
3. This is basically what was used until recently, even though some effort was made to measure the β decay of various short lived fission fragments (Tengblad et al, 1989, Rudstam et al. 1990) and new calculations were performed (see e.g. Kopeikin et al, hep-ph/0308186).
4. New evaluation (Mueller et al. 2011, Huber 2012, Fallot et al. 2012) uses a combination of the *ab initio* approach with updated experimental data and the input from the converted electron spectra (see 2) above). **This results in the upward shift by ~3% of the reactor flux (keeping the shape almost unchanged).**
5. Recent reanalysis (Hayes et al. 2013) includes first forbidden decays and claims that the uncertainty is at least 5%, considerably more than previously assumed.

Measured ν_e spectrum shape and normalization agreed with calculated predictions to ~10% and with converted electron spectra even better

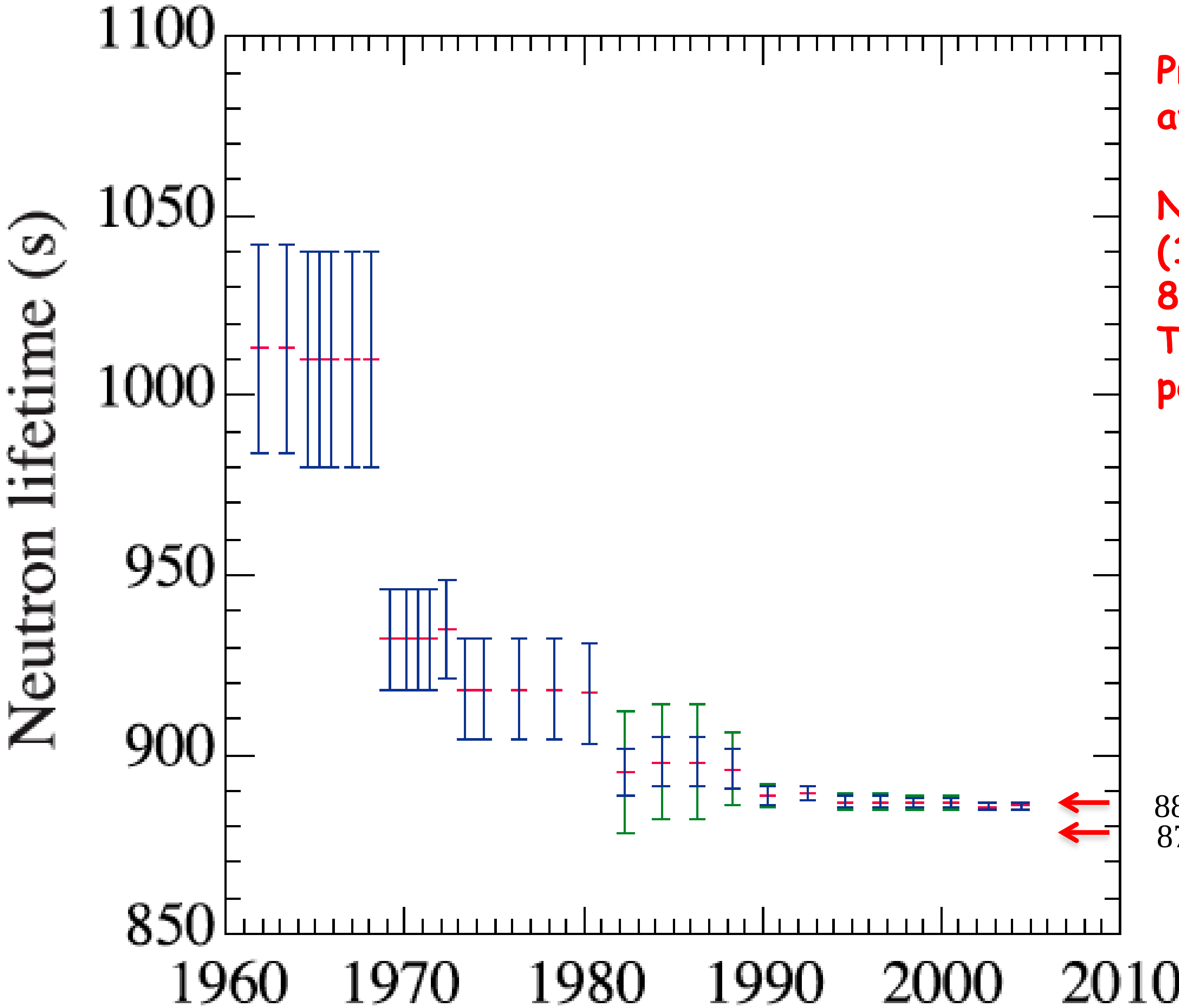


Calculation only
Klapdor and Metzinger, 1982

Beta calibrated
Schreckenbach, 1985
Hahn, 1989

Results of Bugey experiment (1996)

History of neutron lifetime measurement. Rather recent result differs from the previous ones by ~6.5 σ. There is a persistent discrepancy between the bottle and beam measurements.

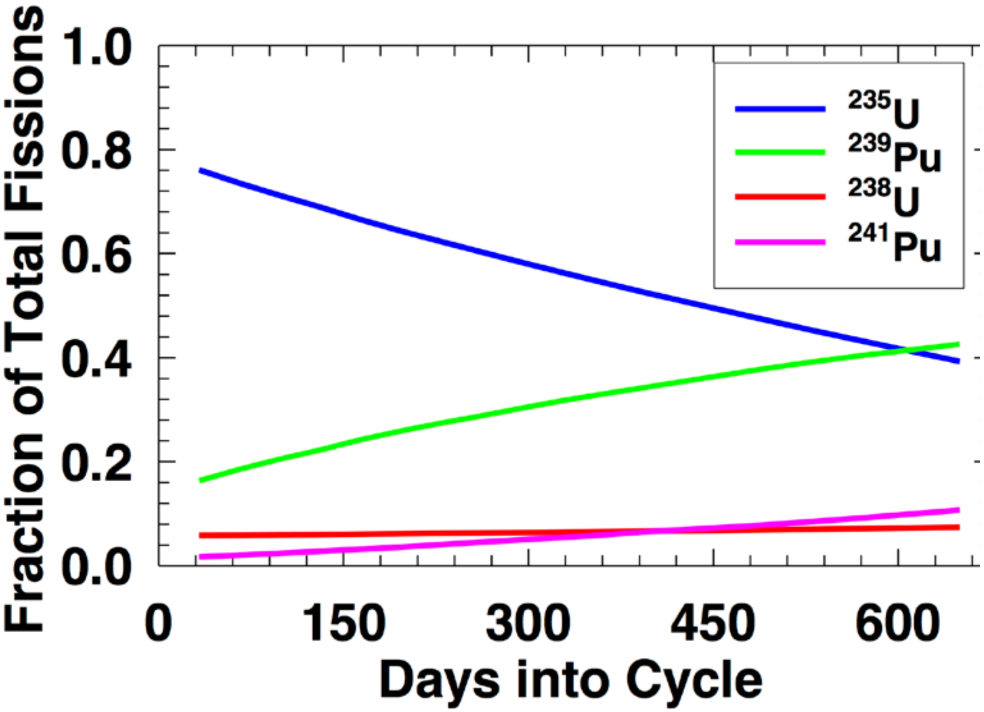


Present official average 880.1+-1.1

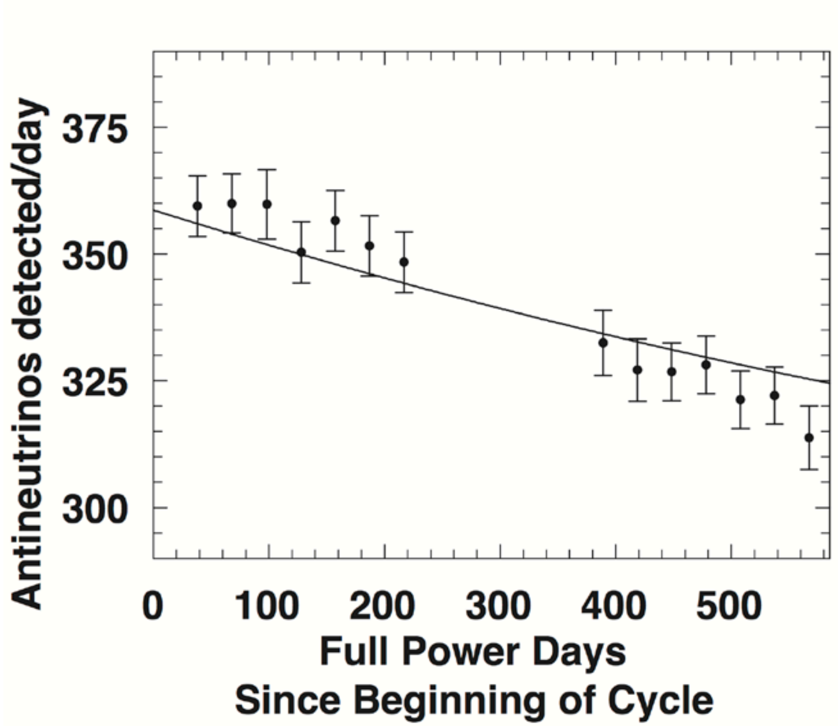
New measurement (1309.2623) gives 887.7+-1.2+-1.9. The discrepancy persists.

885.7 +-0.8 previous average
878 +-0.8 Serebrov 2005

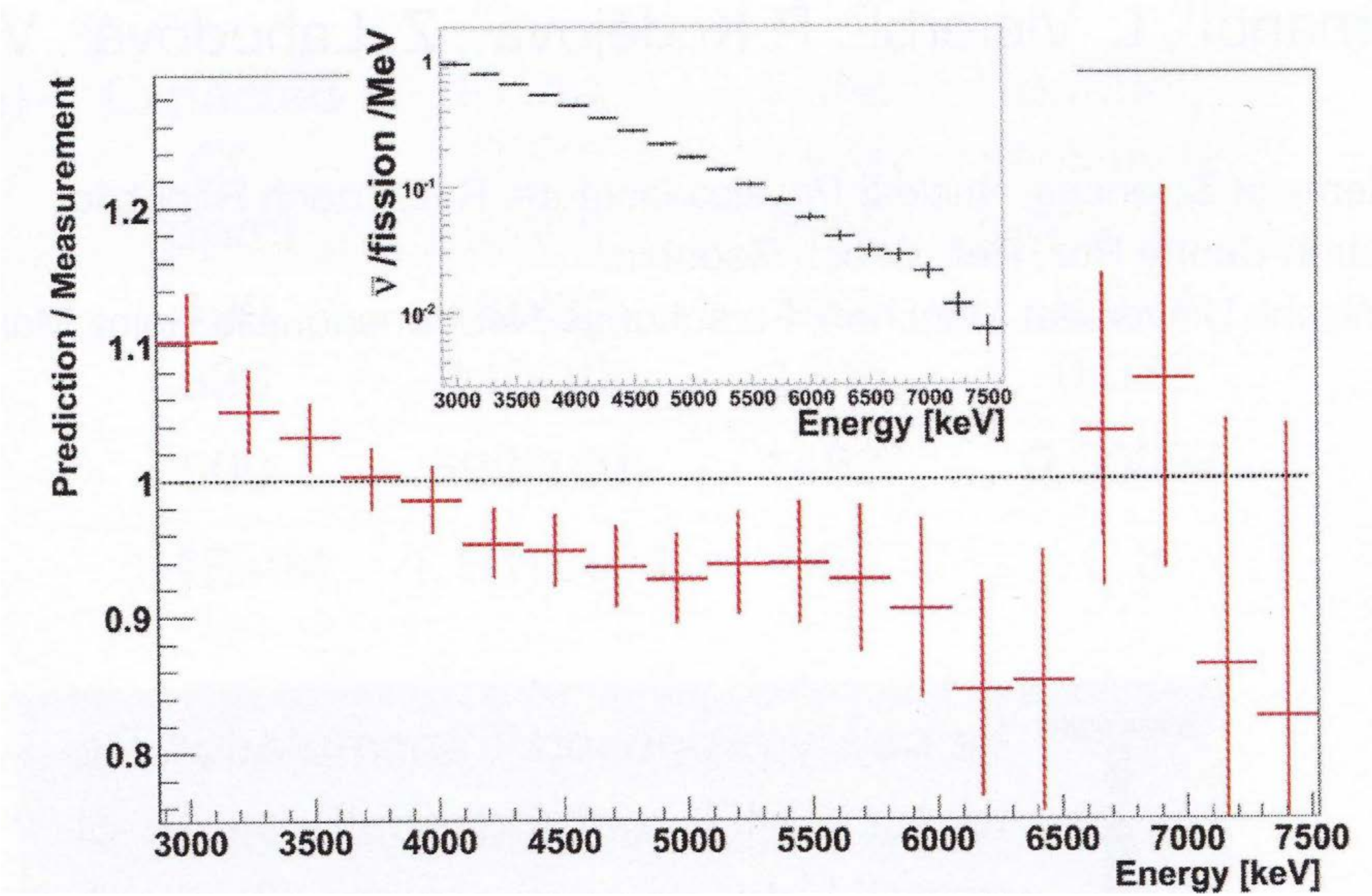
Changes in the fuel composition in a typical light water reactor



Changes in the daily antineutrino rate during the fuel cycle. (Bowden et al. 2009)



The ^{238}U spectrum has been missing until now. The calculations were used instead. The corresponding electron spectrum was determined at TU Munich recently, and converted into the antineutrino spectrum. The ratio to the Mueller et al. is plotted. (K. Schreckenbach and N. Haag, in TU annual report 2012)



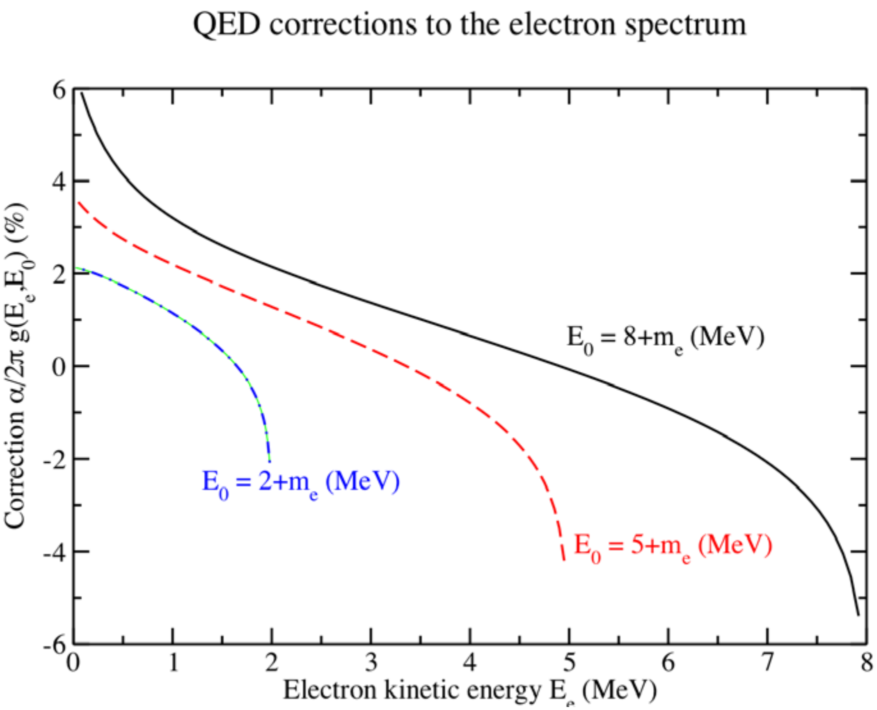
Reactor spectrum evaluation:

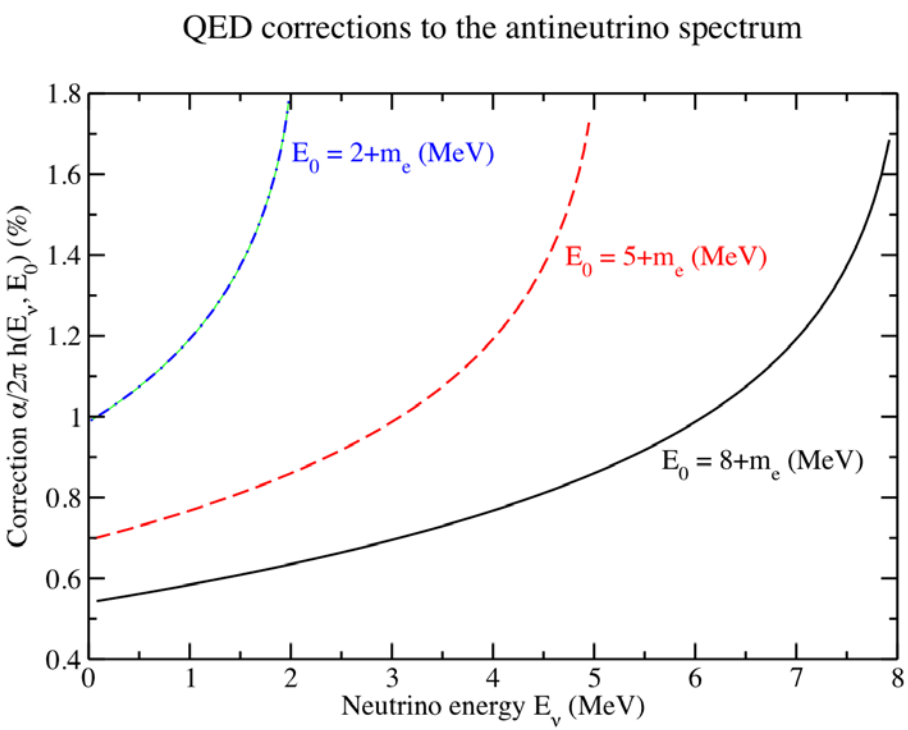
1) Fission yields $Y(Z,A,t)$, essentially all known with sufficient accuracy
2) β decay branching ratios $b_{n,i}(E_0^i)$ for decay branch *i*, with endpoint E_0^i and spins I_i , some known but some (particularly for the very short-lived and hence high Q-value) unknown or known only in part.
3) β decay shape, if allowed shape is assumed, is known $P(E_\nu,E_0^i,Z)$ or for electrons $E_e = E_0 - E_\nu$.

Then: $dN/dE = \Sigma_n Y_n(Z,A,t)\, \Sigma_i\, b_{n,i}(E_0^i)\, P(E_\nu,E_0^i,Z)$
and a similar formula for electrons.

4)However, for detailed evaluation we need to include several small corrections $P(E_\nu,E_0^i,Z)\,(1 + \delta_{qed} + \delta_{WM} + \delta_C)$ as well as the effects of the forbidden decays.

If the electron spectrum is known, it can be `converted' into the antineutrino spectrum, because in each branch $E_\nu = E_0 - E_e$. Uncertainty associated with this procedure need be carefully evaluated..





QED corrections of the order $\alpha/2\pi$ are different for the electrons and antineutrinos. It is not enough to take the known correction to the electron spectrum and substitute $E_\nu = E_0 - E_e$.

The antineutrino correction was evaluated by Batkin and Sundaresan (1995) And a simpler analytic formula was derived and published by Sirlin (2011). **Remarkably** the expression by Sirlin was used already earlier in Mueller et al. (2011).

Weak magnetism correction $1 + \delta_{WM} E_e$

$\delta_{WM} = 4/3[(\mu_v - 1/2)/Mg_A]$(Vogel 84) or $4/3[(\mu_v - 1/2)/Mg_A](1 - m_e^2/2E_e^2)$ (Hayes 13)

Using CVC $\delta_{WM} = 4/3[6\Gamma_{M1}^3/\alpha E_\gamma^3]^{1/2}\ m_e$ for M1 transition of the analog state.
The table below shows available data, the average δ_{WM} = 0.67(0.26) % MeV^{-1} while the formula above gives ~0.5% MeV^{-1}. In calculations 100% error was assumed.

decay	$J_i \to J_f$	E_γ [keV]	Γ_{M1} [eV]	b_γ	ft [s]	c	b_γ/Ac	$\|dN/dE\|$ [% MeV^{-1}]	Ref.
$^6He \to {}^6Li$	$0^+ \to 1^+$	3563	8.2	71.8	805.2	2.76	4.33	0.646	[28]
$^{12}B \to {}^{12}C$	$1^+ \to 0^+$	15110	43.6	37.9	11640.	0.726	4.35	0.62	[29]
$^{12}N \to {}^{12}C$	$1^+ \to 0^+$	15110	43.6	37.9	13120.	0.684	4.62	0.6	[30]
$^{18}Ne \to {}^{18}F$	$0^+ \to 1^+$	1042	0.258	242.	1233.	2.23	6.02	0.8	[31]
$^{20}F \to {}^{20}Ne$	$2^+ \to 2^+$	8640	4.26	45.7	93260.	0.257	8.9	1.23	[32]
$^{22}Mg \to {}^{22}Na$	$0^+ \to 1^+$	74	0.0000233	148.	4365.	1.19	5.67	0.757	[33]
$^{24}Al \to {}^{24}Mg$	$4^+ \to 4^+$	1077	0.046	129.	8511.	0.85	6.35	0.85	[34]
$^{26}Si \to {}^{26}Al$	$0^+ \to 1^+$	829	0.018	130.	3548.	1.32	3.79	0.503	[35]
$^{28}Al \to {}^{28}Si$	$3^+ \to 2^+$	7537	0.3	20.8	73280.	0.29	2.57	0.362	[36]
$^{28}P \to {}^{28}Si$	$3^+ \to 2^+$	7537	0.3	20.8	70790.	0.295	2.53	0.331	[36]
$^{14}C \to {}^{14}N$	$0^+ \to 1^+$	2313	0.0067	9.16	1.096×10^9	0.00237	276.	37.6	[29]
$^{14}O \to {}^{14}N$	$0^+ \to 1^+$	2313	0.0067	9.16	1.901×10^7	0.018	36.4	4.92	[26]
$^{32}P \to {}^{32}S$	$1^+ \to 0^+$	7002	0.3	26.6	7.943×10^7	0.00879	94.4	12.9	[37]

Table from P. Huber, Phys. Rev. C**84**, 024617(erratum C**85**, 02990(E) (2012)

Correction term A_C, convolution of the lepton and nucleon wavefunctions. Correction is generally in the form const*$Z\alpha RE_e = A_C E_e$

A simple analytic formula has been worked out for the j=1/2 electron waves, i.e. for the **allowed** transitions. The simple expression, used previously is

$A_C = -$ **9/10** $Z\alpha R/hc \ \langle\sigma r^2\rangle/R^2$, with $\langle\sigma r^2\rangle = k\langle\sigma\rangle R^2$,
k = **1(3/5)** for surface(volume) spin distribution (Vogel 1984).
(*Mueller et al use -9/10*)

Analogous formula was obtain earlier by Holstein and Calaprice (1976)
A_C = **-11/15**$Z\alpha R/hc$ (*close to average of the two possibilities above)*

On the other hand, Wilkinson in 1990 has a formula that contains also a quadratic term in energy
A_C = **-3/5**$Z\alpha R/hc + 4/9R^2E_\nu/(hc)^2$ (*close to the volume distribution above*)
(This was used by Huber and claimed to be a new or forgotten correction)

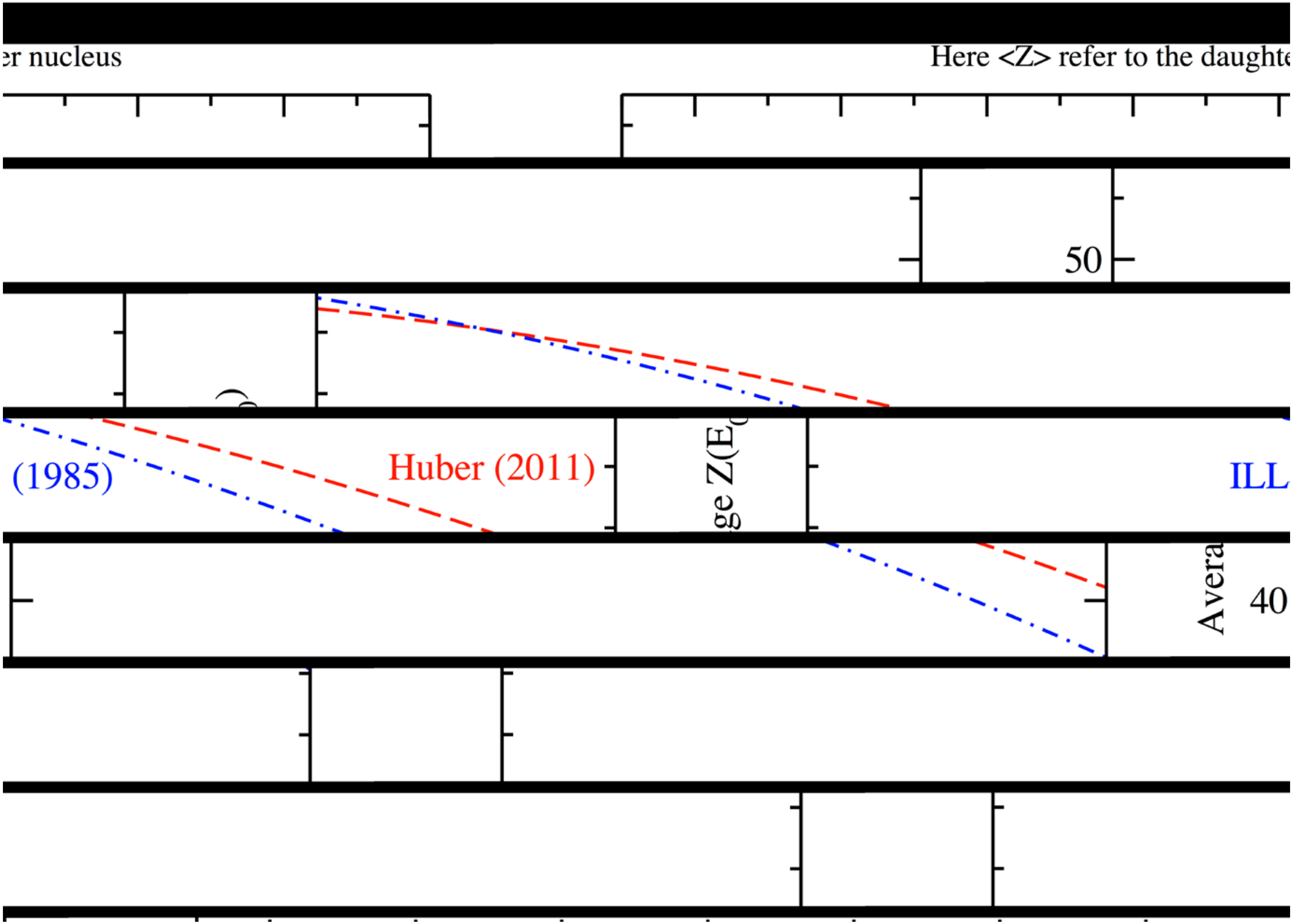
A_C = **-8/5**$Z\alpha R/hc\ (1 + m_e^2/2E_e^2)$ used by Hayes(2013) is similar but considerably larger. However, safely within the 100% error bar previously assumed.

Thus, while the basic form of A_C is the same in all cases, there is a rather wide variation of the numerical coefficients and it is not clear how the formula should be modified for forbidden decays

How the conversion of the electron spectrum into the ν works?

a) For a single β decay it is trivial: $E_\nu = E_0 - E_e$ where E_0 is the decay energy
b) For a decay with many known allowed decay branches
$Y(E_e) = \Sigma_i\, b_i\, k(E_0^i,Z)\, p_e\, E_e\, (E_0^i - E_e)^2\, F(E_e,Z)$ where $k(E_0^i,Z)$ is a normalization and b_i are the branching ratios
Once b_i and E_0^i are known, $Y(E_\nu)$ can be easily calculated
c) Now suppose that b_i and E_0^i are unknown, but $Y(E_e)$ is measured. One then can *assume* that E_0^i are e.g. equidistantly distributed, and fit for b_i.
By varying the number of branches, one can check that the result is convergent. (30 branches were used in Schreckenbach et al.)
d) In the actual case Z is also unknown. Some procedure for choosing Z, or Z(E) must be chosen and tested.
e) The error associated with the procedure must be determined.

Average charge <Z> for ^{235}U fission



Forbidden β decays:

Until now we considered only the **allowed** β decays, in which the nuclear spin is changed by no more than one unit, $|\Delta I| \leq 1$, and the parity is not changed. Such decays have the shape $dN/dE = pE(E_0-E)^2F(Z,E)(1 + \delta_{qed} + \delta_{WM} + \delta_C)$.

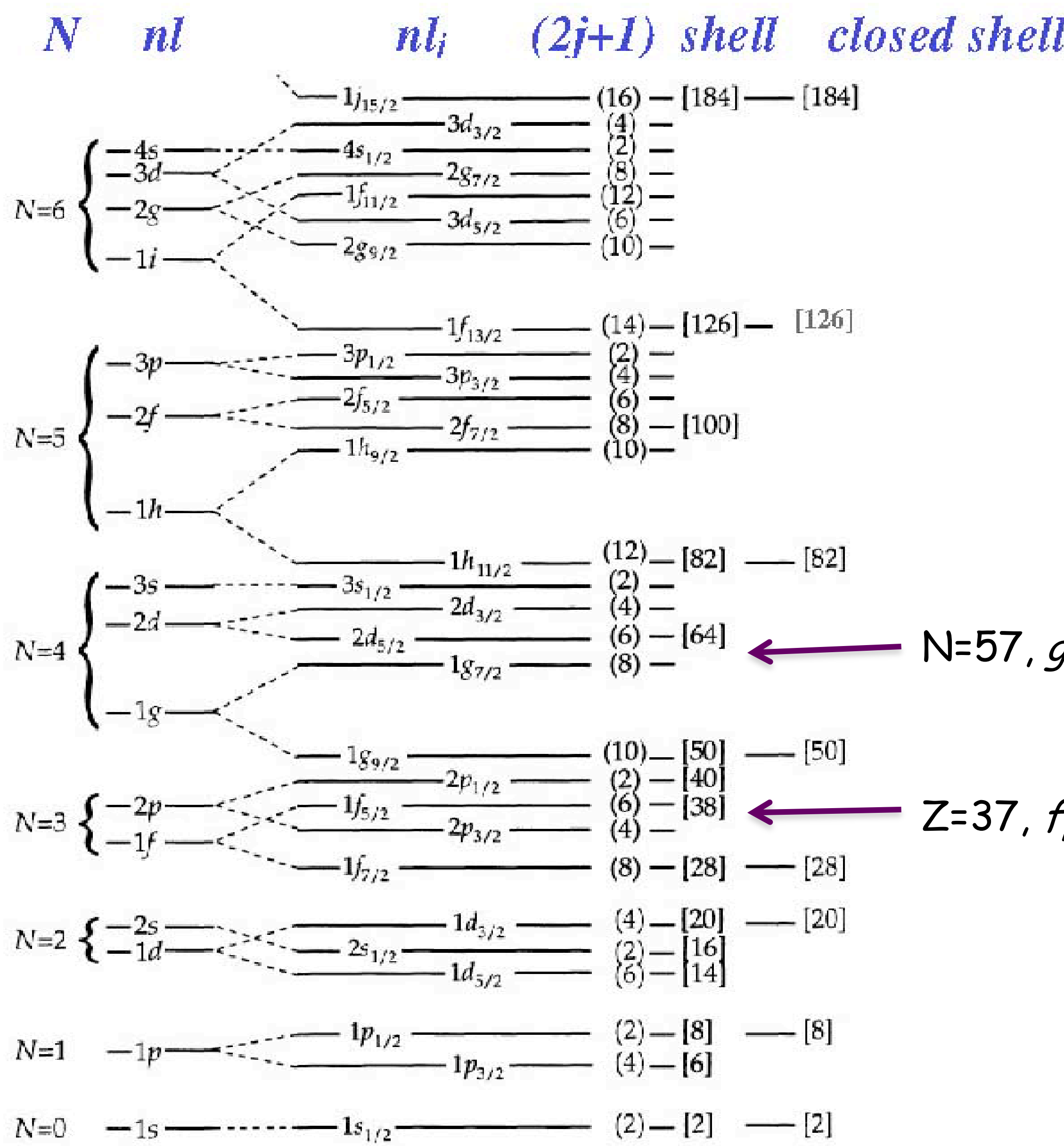
However, when these selection rules are not fulfilled the decay proceeds anyway, but the decay rate is reduced usually by $\sim(pR)^2 \ll 1$ for each order. Note that for a typical fission fragment A~120, $pR \sim E_0(MeV)/30 \ll 1$.
For our application we need to consider essentially only the first forbidden decays, with $|\Delta I| \leq 2$ and $\Delta\pi$ = yes.

The transitions with $|\Delta I| = 0,1$ and $\Delta\pi$ = yes are governed by several nuclear matrix elements each, and might have complicated spectrum shape (the decay of RaE = Bi^{210} is a textbook example). However, many of such decays have approximately allowed shape due to a combination of the Coulomb and relativistic effects. This *quasi-allowed* (ξ) approximation is valid if

$$\xi = Z\alpha/E_0R \gg 1, \quad \text{for } Z=46 \text{ this means } (11/E_0(MeV)) \gg 1$$

which is barely fulfilled. **Thus, for the first-forbidden β decays we can use the allowed shape with caution, and the corrections δ_{WM} and δ_C are not applicable. It is difficult to estimate the error this causes.**

First forbidden β decays are common in fission fragments

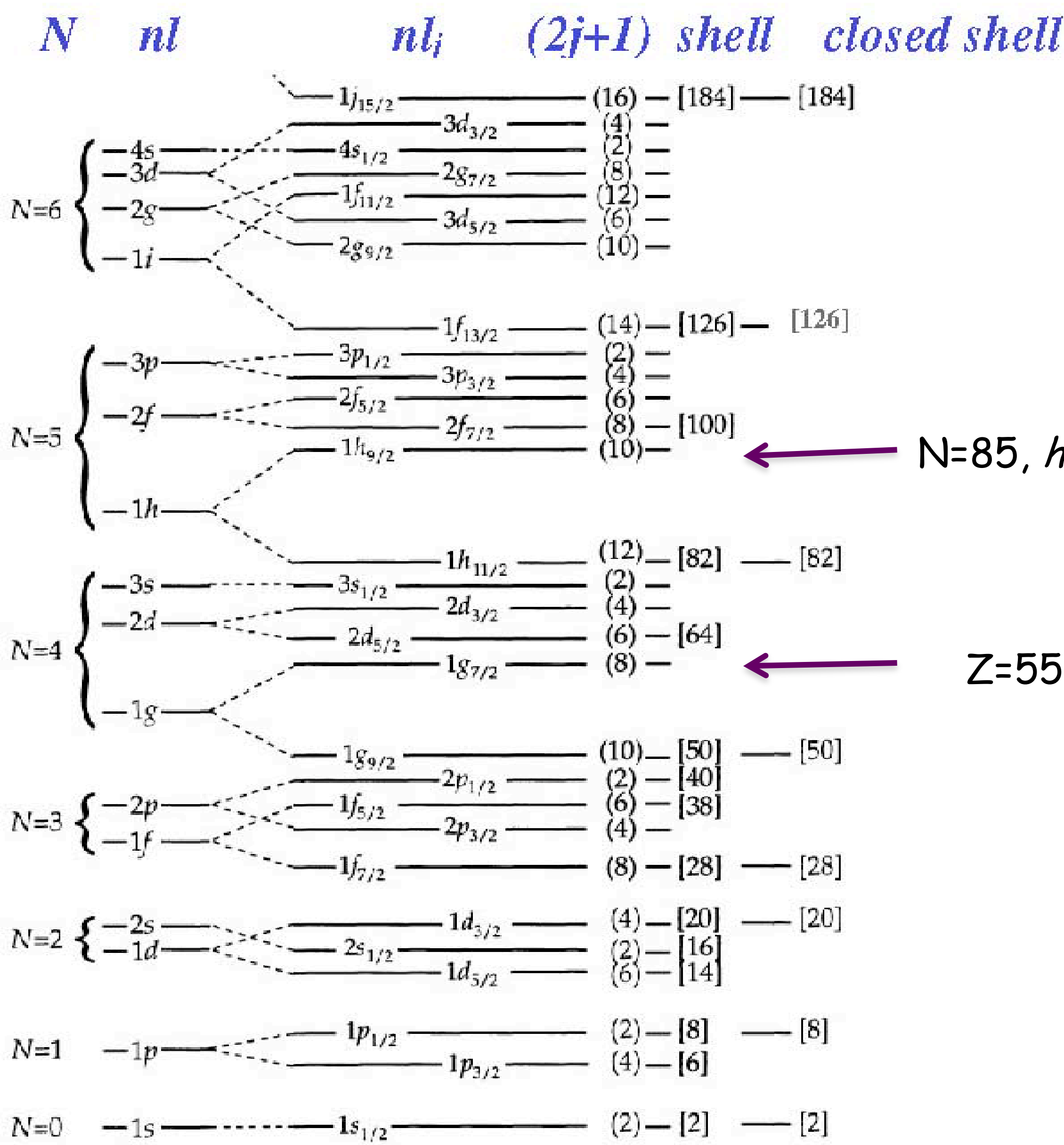


N=57, *gds* shell, π=+

Z=37, *fp* shell, π=-

In the lighter peak of the fission yields, A ~ 90-100, take as an example $_{37}Rb^{94}$, near its maximum. Protons and neutrons near the Fermi level are in states of opposite parity.

First forbidden β decays are common in fission fragments



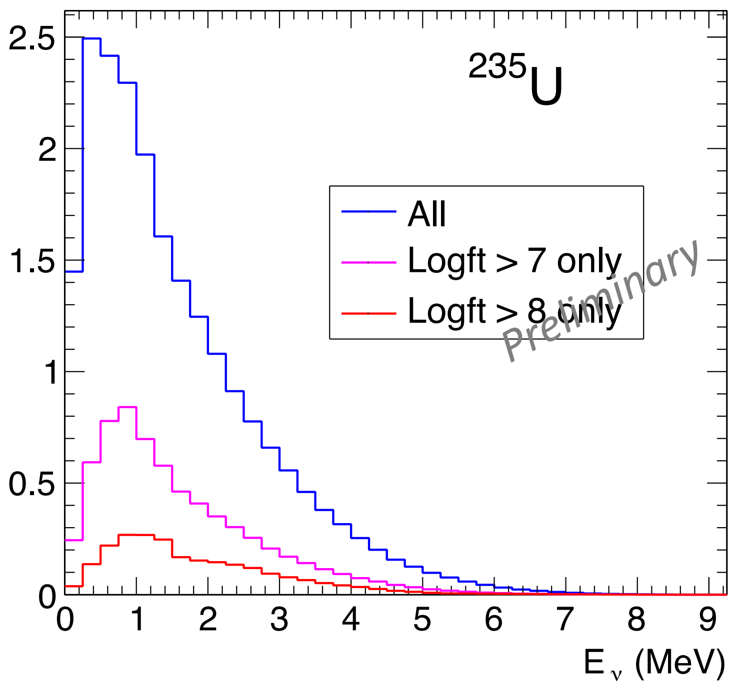
In the heavier peak of the fission yields, A ~ 132-145, take as an Example $_{55}Cs^{140}$, near its maximum. Protons and neutrons near the Fermi level are in states of opposite parity.

N=85, *hfp* shell, π=-

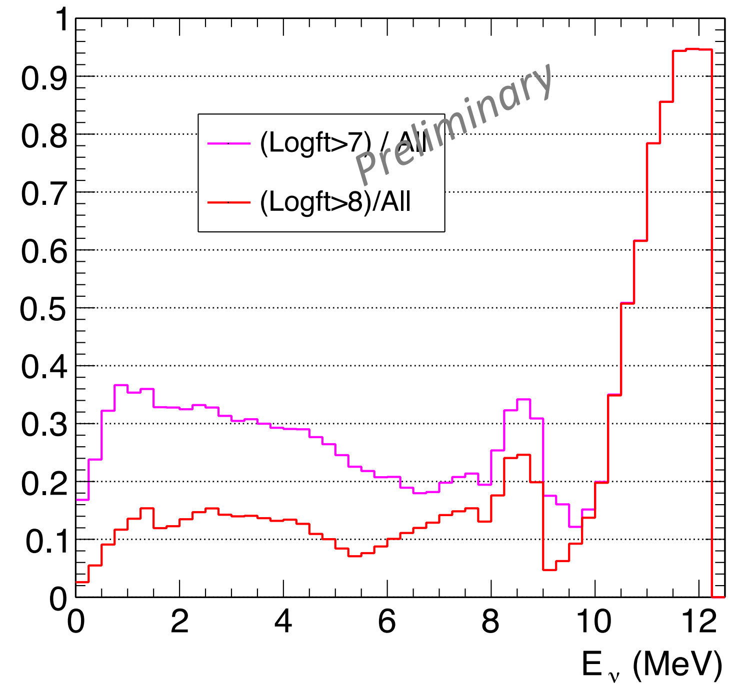
Z=55, *gds* shell, π=+

One can estimate the contribution of forbidden decays by using the fact that the allowed decays have typically log(ft)=5-6 while the first forbidden decay have log(ft)=7-8. Such decays contribute about 30-40% of the spectrum.

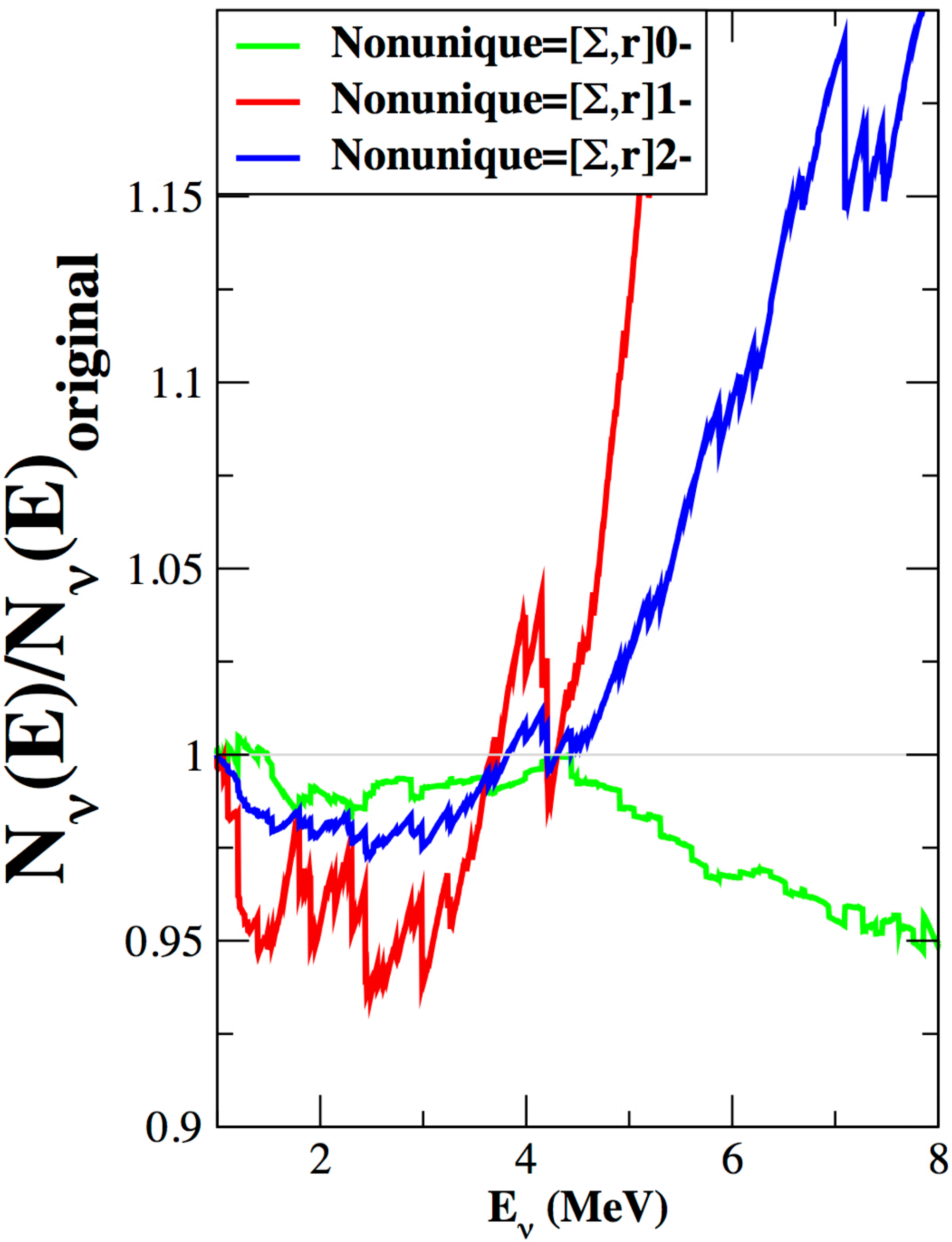
Slide by D. Lhuillier



Relative contribution



This estimate agrees with the statement in Hayes et al (2013) that out of ~6000 beta decay transitions ~1500 are forbidden transitions.



Ratio of the summed antineutrino spectra with different treatment of forbidden decays to the treatment used by Schreckenbach et al. Different colors correspond to using different operators exclusively.
In reality there will be a mixture of these and other operators.
(figure from Hayes et al. 2013)

Summary:

1) The average rate of the $\bar{\nu}_e$ capture on protons has been measured to ~1% accuracy for distances 10-2000 m from the reactor core. Even more data on that rate will be available soon (Daya-Bay, RENO, DoubleChooz)
2) A number of experiments has been proposed to convincingly test whether additional neutrinos with $\Delta m^2 \sim 1$ eV^2 that mix with the standard neutrinos exist. However, no results are expected for several years.
3) In that context reliable determination of the reactor $\bar{\nu}_e$ spectrum and its uncertainty is extremely important.
4) The main difficulty appears to be the treatment of the first forbidden β decays.
5) Additional smaller effects are related to the determination of the neutron lifetime that affects the detection cross section and to the treatment of corrections to the β decays shape for the allowed and forbidden decays.

spares

Weak magnetism correction A_{WM}, in spectrum as $\delta_{WM} E_e$

Weak charged current has a simple form for quarks, but need be generalized for the nucleons. The vector part is

$$\langle p|V^\alpha|n\rangle = \cos\theta_C \exp(iqx)\, u' [f_1(q^2)\,\gamma^\alpha + i f_2(q^2)\,\sigma^{\alpha\nu} q_\nu] t_+ u$$

In the case of β decay we need the form factors just for $q^2 = 0$.
The CVC requires that

$$f_1(0) = 1 \quad \text{and} \quad f_2(0) = [\mu_p - \mu_n]/2m_p$$

Where $\mu_p - \mu_n = 3.7$ is the anomalous isovector magnetic moment.

After some algebra one finds (**for the allowed GT transitions**)

$$\text{Amplitude} \sim \; g_A\langle\sigma\rangle + \iota[(\mu_p - \mu_n + 1)\langle\sigma\rangle + \langle L\rangle] \times q/2m_p$$

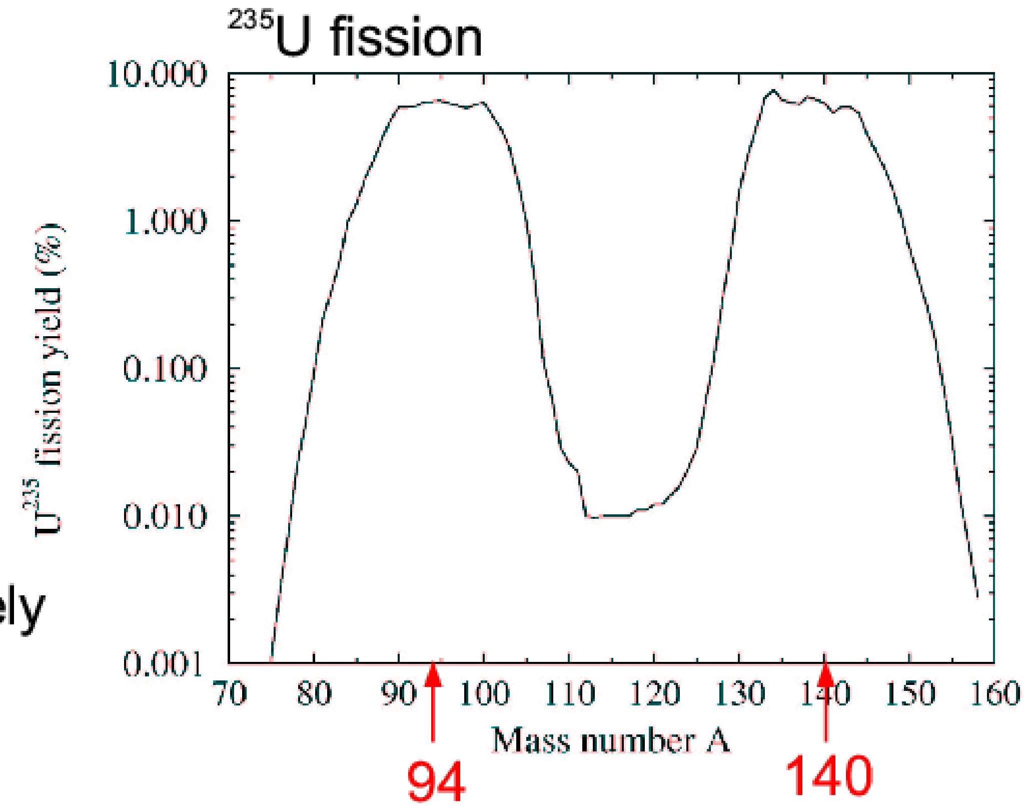
In the decays rate the two terms interfere, Often the orbital momentum $\langle L\rangle$ is neglected. I used instead for $j_i = j_f \pm 1$ and $\ell_i = \ell_f$ $\langle L\rangle = -\langle\sigma\rangle/2$.
Thus finally

$$\delta_{WM} = 4/3 \times [(\mu_p + 1) - \mu_n - \tfrac{1}{2}] \,/\, g_A\, m_p \;\cong\; 0.47\%/\text{MeV}$$

For the allowed GT decays δ_{WM} is independent of the GT matrix element.

Electron antineutrinos are produced by the β decay of fission fragments

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

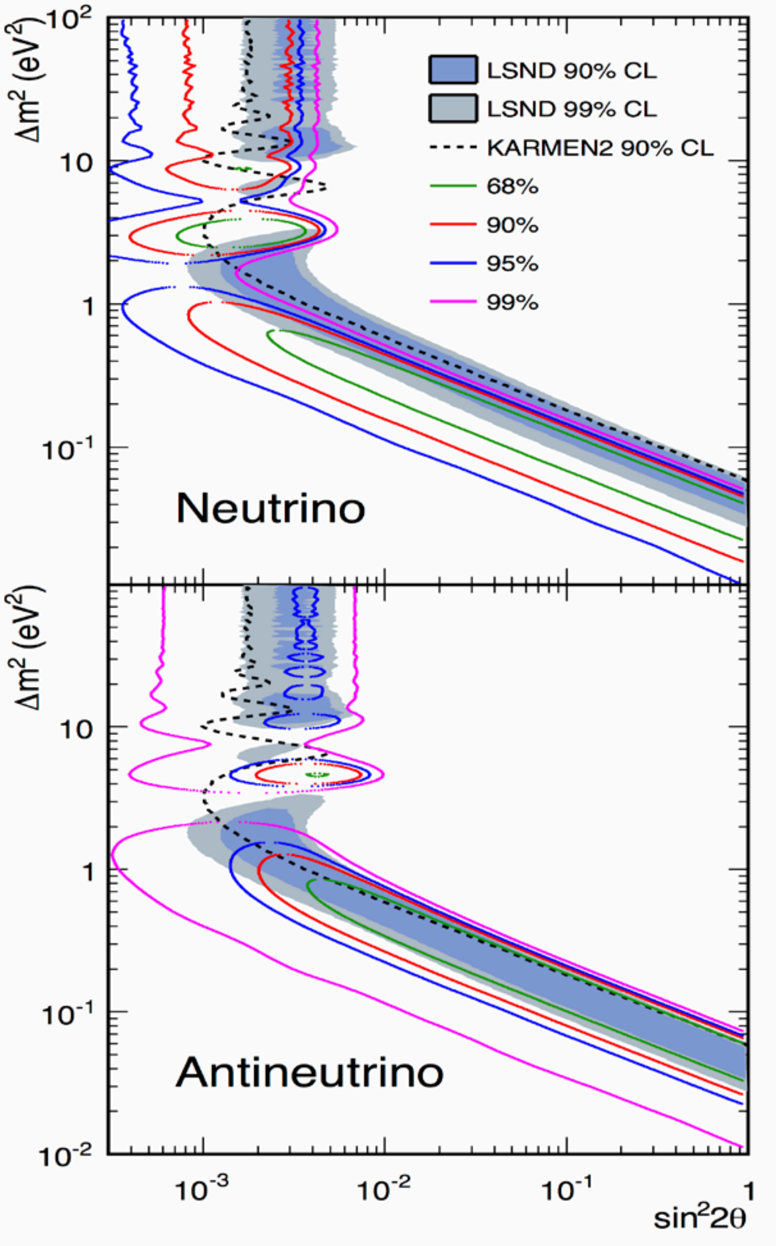


The stable products most likely from Uranium fission:

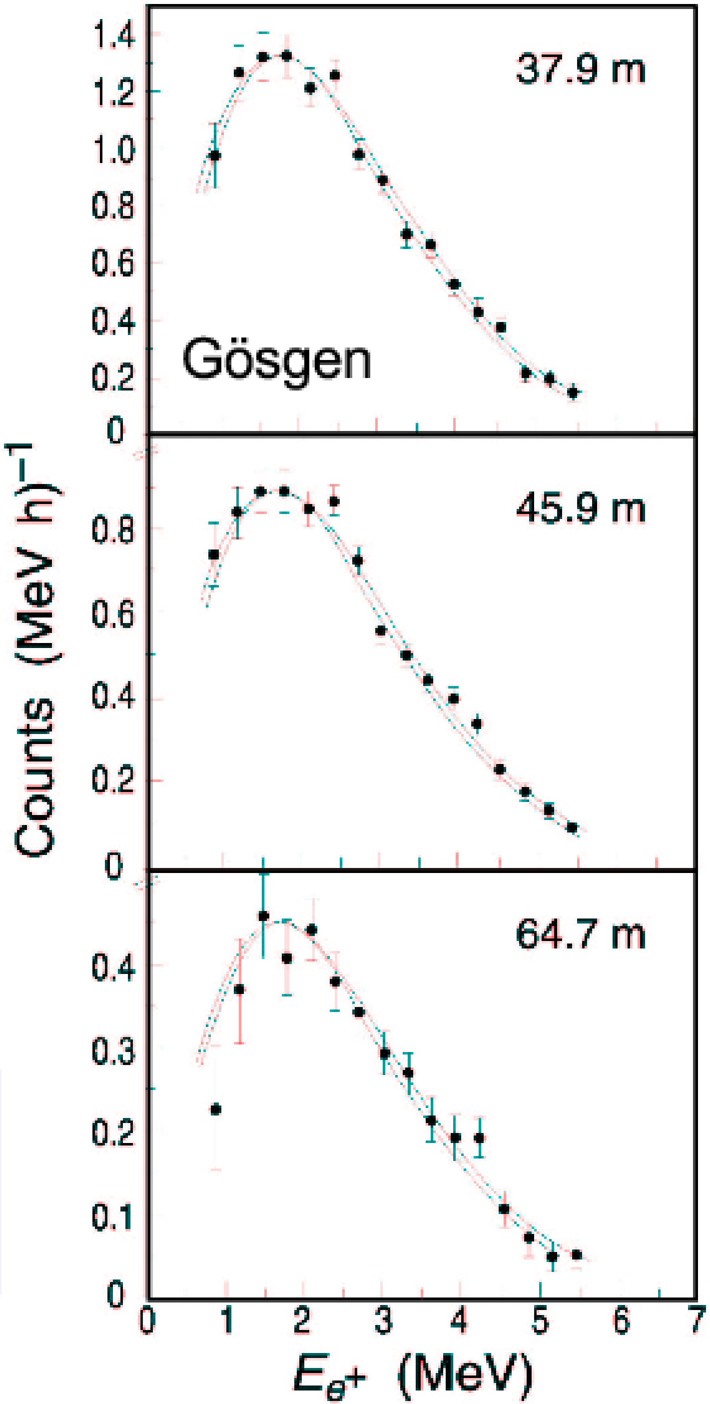
$^{94}_{40}Zr$ $\quad$ $^{140}_{58}Ce$

Together 98 protons and 136 neutrons

6 neutrons have to β-decay to reach stable matter: $6\overline{\nu}_e$ / fission



Allowed regions in the two-neutrino oscillation space for the 3+1 model. The lines are for MiniBoone, the shaded are for LSND. The excluded region by Karmen is to the right of the dashed lines.



The measured spectra at several distances in Goesgen (1986) also agreed well in shape and normalization.

Transforming thermal power into fission rate
(all energies in MeV/fission)

^{235}U	202.7 +-0.1	192.9 +- 0.5	201.7 +- 0.6	201.9+-0.5
^{238}U	205.9 +-0.3	193.9 +- 0.8	205.0 +- 0.9	205.5+-1.0
^{239}Pu	207.2 +-0.3	198.5 +- 0.8	210.0 +- 0.9	210.0+-0.6
^{241}Pu	210.6 +-0.3	200.3 +- 0.8	212.4 +- 1.0	213.6+-0.6
	Energy per fission from the mass excesses	Energy per fission without neutrinos and long lived fragments (E_ν ~ 9 MeV)	Energy per fission without neutrinos and long lived fragments but including the energy associated with the neutron captures, (See M.F. James 1969)	From Kopeikin et al. 2004

Corrections for the allowed beta decays: In the evaluation 100% error was assumed. Initially, the corrections were treated crudely as an overall additional energy dependence. In the more recent works, they are applied to each branch. Most of the difference of the older and newer spectra stems from these corrections.

$$\delta(E_e, Z) = \delta_{QED} + \delta_{WM} E_e + \delta_{finite\ size}$$