New reactor antineutrino spectra

6th international Workshop on Low energy neutrino physics

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New reactor antineutrino spectra, 2 ref. papers

- Improved predictions of reactor antineutrino spectra.

  Phys. Rev. C83, 054615 (2011)

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- On the determination of anti-neutrino spectra from nuclear reactors.

  Phys. Rev. C84, 024617 (2011)

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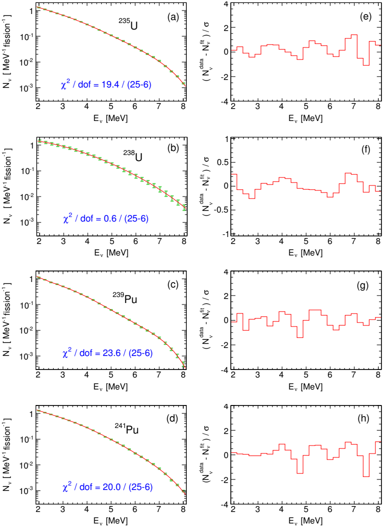
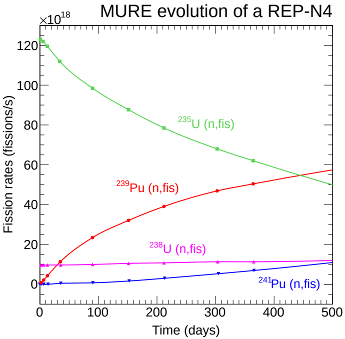


Antineutrino spectrum emitted by a reactor

- The prediction of reactor ν spectrum is the dominant source of systematic error for single detector reactor neutrino experiments

$$\Phi_\nu(E,t) = \frac{P_{\text{th}}}{\sum_k \alpha_k(t) E_k} \times \sum_k \alpha_k(t) S_k(E) \qquad k = {}^{235}\text{U},\ {}^{238}\text{U},\ {}^{239}\text{Pu},\ {}^{241}\text{Pu}$$

- What is needed?
  1. Reactor data: thermal power, $\delta P_{\text{th}} \leq 1\%$
  2. Nuclear databases: E released per fissions of isotope k, $\delta E_k \approx 0.3\%$
  3. Reactor evolution codes: fraction of fissions of isotope k, $\delta\alpha_k \approx \%$ large anti-cor. @ fixed P_{th}
  4. ν spectrum per fission



The guts of $S_k(E)$

- Sum of all fission products' activities:

$$S_k(E) = \sum_{f=1}^{N_f} A_f(t) \times S_f(E)$$

- Sum of all β-branches of each fission product:

$$S_f(E) = \sum_{b=1}^{N_b} BR_f^b \times S_f^b(Z_f, A_f, E_{0,f}^b, E)$$

- Theory of β-decay:

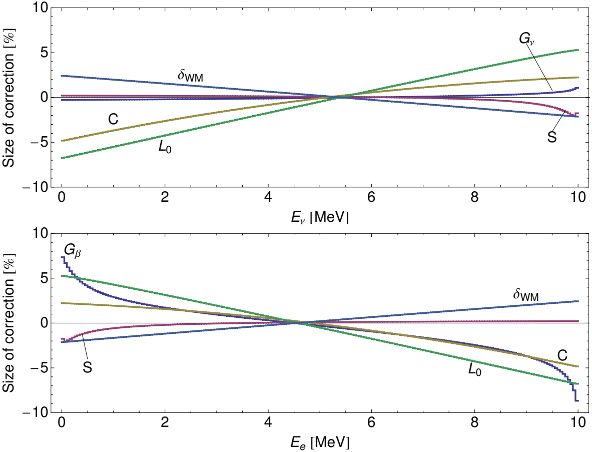
$$\begin{aligned} S_f^b(Z_f, A_f, E_{0,f}^b, E) = \quad & \overbrace{K_f^b}^{\text{Normalization}} \quad \times \quad \overbrace{\mathcal{F}(Z_f, A_f, E)}^{\text{Fermi function}} \\ \times \quad & \underbrace{pE(E - E_{0,f}^b)^2}_{\text{Phase space}} \times \underbrace{C_f^b(E)}_{\text{Shape factor}} \quad \times \quad \big(1 + \underbrace{\delta_f^b(Z_f, A_f, E)}_{\text{Corrections}}\big) \end{aligned}$$

- Corrections to Fermi theory of β-decay :

$$\delta_f^b(Z_f, A_f, E) = G_{\nu(\text{QED})} + L_{0(\text{coulomb size})} + C_{(\text{weak size})} + S_{(\text{screening})} + \delta_{\text{WM(weak magnetism)}}$$

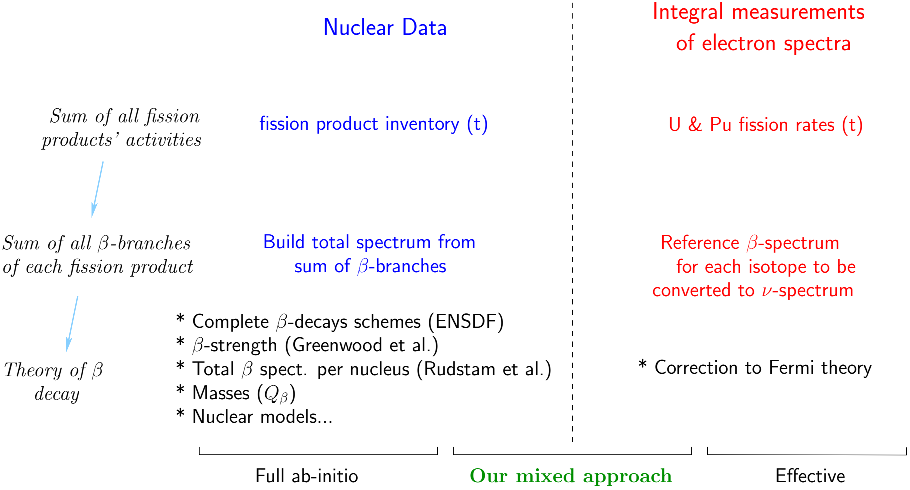
Corrections to Fermi Theory

Example with $Z = 46$, $A = 117$, $E_0 = 10$ MeV



taken from P. Huber *Phys. Rev. C84, 024617 (2011)*

Complementary approaches to compute the ν flux



Nuclear Data

Integral measurements of electron spectra

Sum of all fission products' activities

fission product inventory (t)

U & Pu fission rates (t)

Sum of all β-branches of each fission product

Build total spectrum from sum of β-branches

Reference β-spectrum for each isotope to be converted to ν-spectrum

Theory of β decay

* Complete β-decays schemes (ENSDF)
* β-strength (Greenwood et al.)
* Total β spect. per nucleus (Rudstam et al.)
* Masses (Q_β)
* Nuclear models...

* Correction to Fermi theory

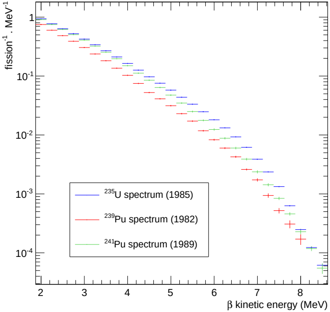
Full ab-initio

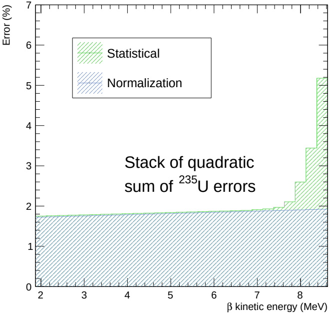
Our mixed approach

Effective

The ILL electron data anchorage

- Accurate electron spectra measurements @ ILL (1980-89)
  1. High resolution electromagnetic spectrometer
  2. Intense and pure thermal n spectrum from the core
  3. Extensive use of reference internal conversion electron lines $\Rightarrow$ normalization $\pm 1.8\%$



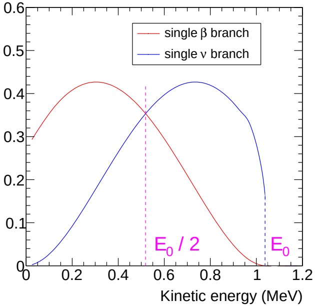


Unique reference to be met by any other measurement and/or calculation

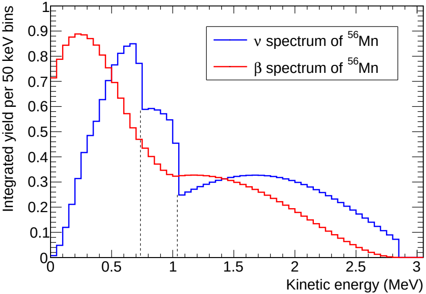
$\beta \rightarrow \nu$ conversion

- Exact conversion requires complete knowledge from fission yield down to β-transition between parent ground (or isomeric) state and daughter states

β-branch level



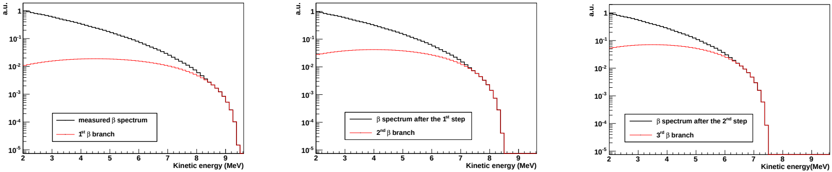
fission product level



- Lot of relevant quantities: Z, A, endpoints, J^{π}, nuclear matrix element, branching ratios, fission yields, lifetime... but scarce data as E_0 increases

ILL data: conversion to ν spectra

- Fit total β spectrum with a sum of 30 effective branches determined by iterative method (instead of ≈ 10000 real branches)

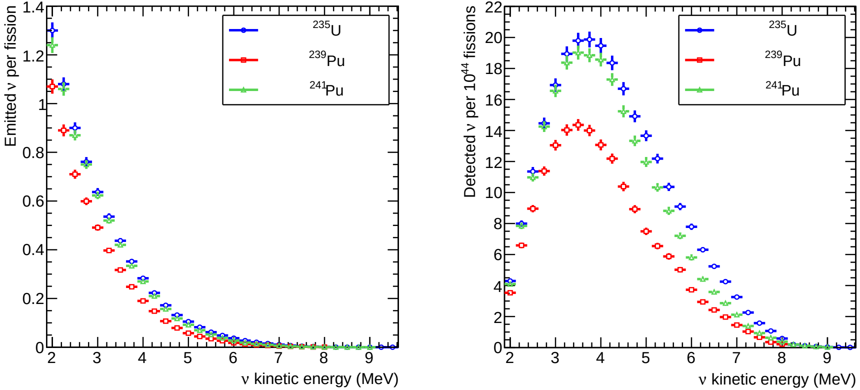


- Convert each effective β branch to ν branch of through energy conservation

- Sum all ν branches to get total ν spectrum

K. Schreckenbach et al. *Phys. Lett. B99, 251 (1981)*

ILL antineutrino spectra



Emitted

Detected

Reference spectra over the last 25 years

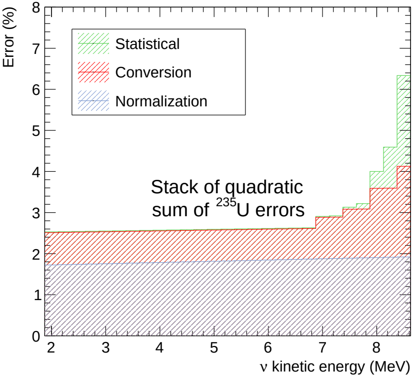
ILL ν spectra (cont'd)

- Conversion error from envelop of numerical studies
- Corrections to Fermi theory in the effective branches:
    - What Z? $\rightarrow$ mean fit on nuclear data $Z = f(E_0)$

$$Z(E_0) = 49.5 - 0.7E_0 - 0.09E_0^2,$$
$$Z \geq 34$$

    - Effective $L_0 + \delta_{\mathrm{WM}}$ corrections

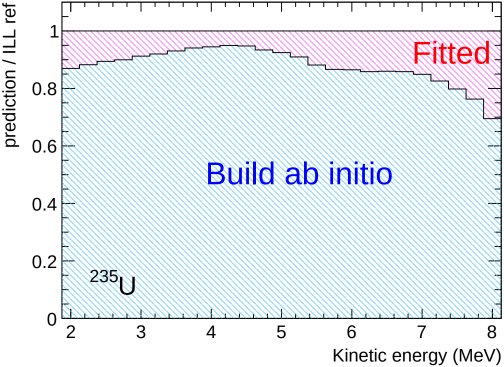
$$\Delta N_\nu^{L_0,\mathrm{WM}}(E_\nu) = 0.65\times(E_\nu - 4\ \mathrm{MeV})\%$$



Can we do better?

New mixed approach

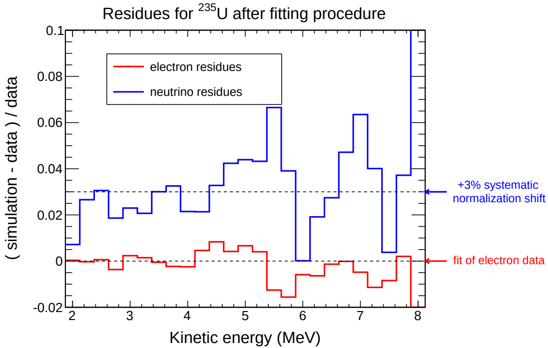
Ratio of prediction / reference ILL data



- ILL β data anchor point
- Fit of residual: five effective branches are fitted to the remaining 10%
  → suppresses error of full ab initio approach
- "True" distribution of all known β-branches describes $> 90\%$ of ILL electron data
  → reduces sensitivity to virtual branches approx.

New mixed approach (cont'd)

Residuals to ref. ILL data

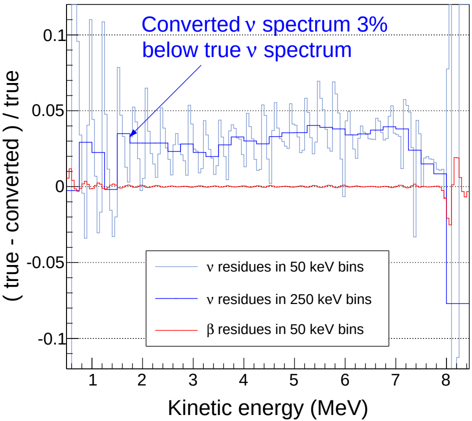


- Corrected Fermi theory applied on all β-branches
- $+3\%$ normalization shift with respect to old ν spectrum
- Similar result for all isotopes (^{235}U, ^{239}Pu, ^{241}Pu)
- Stringent tests performed, origin of the biais identified

NB: this $+3\%$ shift is above the IBD threshold, the total integral of emitted spectrum remains unchanged (1 β and 1 ν per decay)

Consistency check

1. Define "true" β and ν spectra from reduced set of well-known branches from ENSDF nuclei database. "Perfect knowledge" of both β and ν spectra.
2. Apply exact same OLD conversion procedure to true β spectrum
3. Compare converted ν spectrum to the true one

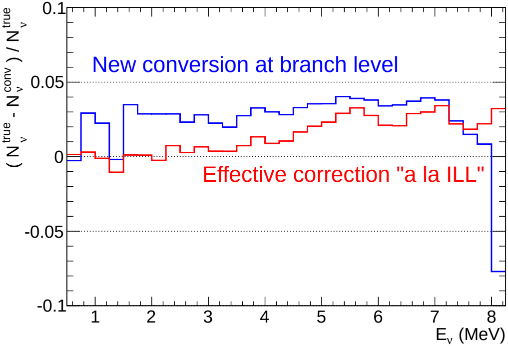


⇒ OLD technique leads to a -3% bias w.r.t the true ν spectrum

Origin of the 3% shift - $E < 4$ MeV

- Effective linear correction $\Delta N_\nu^{L_0,\text{WM}}(E_\nu) = 0.65 \times (E_\nu - 4\ \text{MeV})\%$ of ILL data replaced by correction at β-branch level:

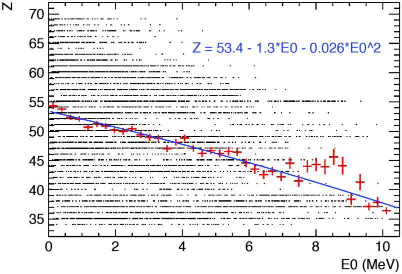
$$L_0 \approx -\frac{10Z\alpha R}{9\hbar c} \times E \text{ and } \delta_{\text{WM}} \approx \frac{4}{3}\frac{\mu_p - \mu_n}{M_N}\left|\frac{G_V}{G_A}\right| \times E$$

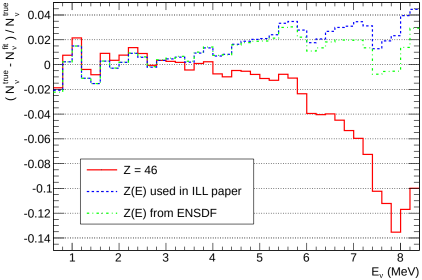


- Correct a bias. Assume 100% syst. error
- Still the correction at branch level neglects all effects of nuclear structure Uncertainty could be larger than 100%?

Origin of the 3% shift - $E > 4$ MeV

- Mean fit of nuclear charge $Z(E_0) = 49.5 - 0.7E_0 - 0.09E_0^2, \quad Z \geq 34$ doesn't reflect accurately enough the Z distribution





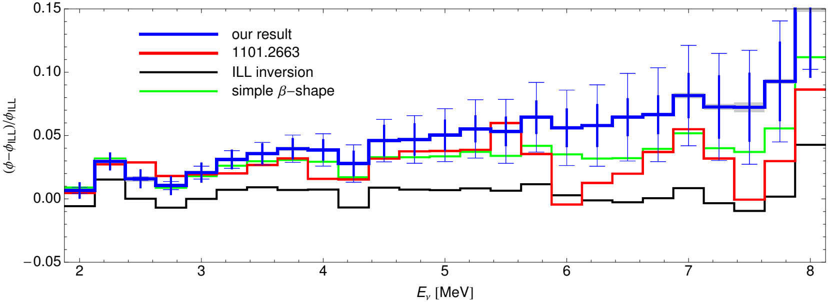
What we learned

- Mixed approach:
  - ILL conversion procedure have 2 independent biases ($\approx 1.5\%$ each in total detected rate):

    - Low energy: correction to Fermi theory should be applied at branch level
    - High energy: mean Z fit is not accurate enough
  - Combination of all "well known" nuclear data can provide a good proxy for neutrino spectra ($\approx 90\%$ of experimental spectrum described)
- Revisit conversion procedure:
  - Apply all above
  - Complementary approach, minimizing the use of nuclear data

→ P. Huber, Phys. Rev. C84, 024617 (2011)

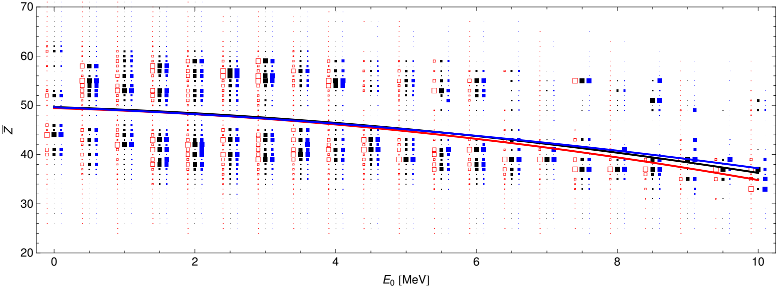
Well established deviation from ILL spectra



- Confirms global increase of predicted spectrum
- Extra deviation at high energy from more complete correction to Fermi theory (weak interaction in the finite volume of the parent nucleus)
- Fixes remaining oscillations of mixed-approach prediction

Mean nuclear charge

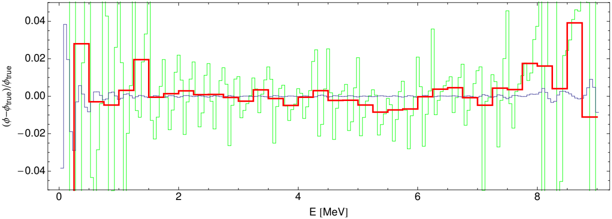
- Demonstrate that proper weighting by fission yield and by branching ratio when fitting the mean nuclear charge cures the conversion bias at high energy



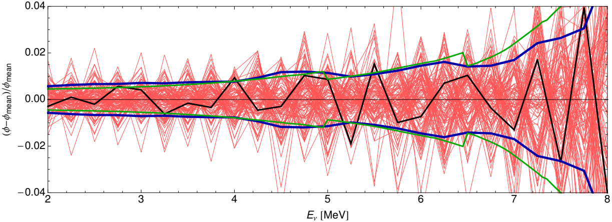
- Quite robust with respect to approx of poorly known nuclei

Conversion with virtual branches: bias and uncertainties

- Total spectra built from JEFF (fission yields) and ENSDF (β-spectra) nuclear databases $\Rightarrow$ proxy for real reference spectra



- Complete numerical studies of the conversion procedure to determine the size of bias as well as the uncertainty for a given data set and number of branches



Weak magnetism

$$\delta_{\mathsf{WM}} \approx \frac{4}{3}\frac{\mu_p-\mu_n}{M_N}\left|\frac{g_V}{g_A}\right| \times E \approx 0.48\%/\mathsf{MeV} \times E$$

assume 100% error

decay	$J_i \rightarrow J_f$	E_γ [keV]	Γ_{M1} [eV]	b_γ	ft [s]	c	b_γ/Ac	$\lvert dN/dE \rvert$ [$\%\mathsf{MeV}^{-1}$]
^{6}He → ^{6}Li	$0^+ \rightarrow 1^+$	3560	8.2	72	805	2.77	4.33	0.65
^{12}N → ^{12}C	$1^+ \rightarrow 0^+$	15110	43.6	38	13100	0.685	4.61	0.60
^{12}B → ^{12}C	$1^+ \rightarrow 0^+$	15110	43.6	38	11600	0.727	4.34	0.62
^{18}Ne → ^{18}F	$0^+ \rightarrow 1^+$	1040	0.268	247	1230	2.24	6.13	0.81
^{20}F → ^{20}Ne	$2^+ \rightarrow 2^+$	5790	2.55	64.5	93300	0.257	12.5	1.72
^{26}Si → ^{26}Al	$0^+ \rightarrow 1^+$	2700	0.0950	50.9	3550	1.32	1.48	0.19
^{34}P → ^{34}S	$1^+ \rightarrow 0^+$	5380	0.00494	5.38	145000	0.206	0.766	0.11
^{58}Cu → ^{58}Ni	$1^+ \rightarrow 0^+$	7390	0.475	55.9	74100	0.288	3.34	0.45
^{64}Cu → ^{64}Zn	$1^+ \rightarrow 0^+$	3187	0.000147	3.83	200000	0.176	0.341	0.05
^{66}Cu → ^{66}Zn	$1^+ \rightarrow 0^+$	3230	0.00112	10.7	214000	0.17	0.955	0.14
^{142}Pm → ^{142}Nd	$1^+ \rightarrow 0^+$	2590	0.000587	23.2	31600	0.441	0.371	0.05
^{144}Eu → ^{144}Sm	$1^+ \rightarrow 0^+$	3970	0.0950	158	31500	0.442	2.48	0.33
^{14}O → ^{14}N	$0^+ \rightarrow 1^+$	2310	0.0067	9.16	1.9×10^7	0.018	36.3	4.97
^{14}C → ^{14}N	$0^+ \rightarrow 1^+$	2310	0.0067	9.16	1.1×10^9	0.00237	276	37.6
^{32}Si → ^{32}P	$0^+ \rightarrow 1^+$	513	0.000264	39.8	1.55×10^8	0.00631	197	26.8
^{32}P → ^{32}S	$1^+ \rightarrow 0^+$	4700	0.00171	3.66	7.94×10^7	0.00881	13	1.78

Experimental slope in good agreement for transitions with low ft values

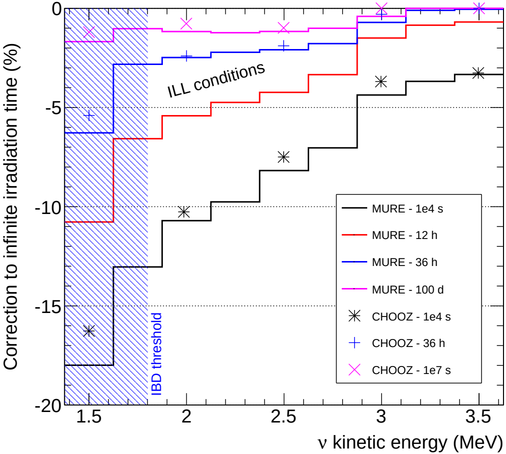
Contribution of large ft's in fission neutrino spectra?

Gamow-Teller decays and the associated parameters needed for a computation of the weak magnetism slope parameter using the CVC hypothesis.

Ab-initio approach

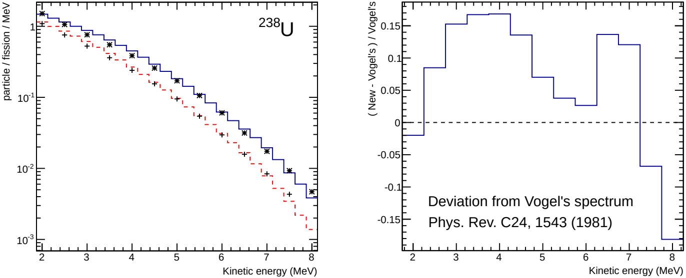
MURE evolution code: core composition & off-equilibrium effects
(see `http://www.oecd-nea.org/tools/abstract/detail/nea-1845`)

- Full simulation of reactor core for absolute prediction of isotopes inventory
  → 10-20% accuracy, not enough for osc. analysis
- Relative off-equilibrium effect: close to inverse β-decay threshold, a significant fraction of the ν spectrum takes week to reach equilibrium
  → sizeable correction of ILL data



^{238}U reference spectrum

- No measurement of total β-spectrum available yet
- Updated prediction using the ab-initio approach $\approx 10\%$ above previous calculations, with uncertainties in the 10-20% range



- Upcoming results from ^{238}U irradiation in fast neutron flux of FRM-II reactor (München) by N. Haag & K. Schreckenbach → New conversion procedure to be appplied on β data

Conclusions and perspectives

- ILL electron data are high quality data
- Their conversion to antineutrino was biased at the few % level by the way the corrections to Fermi theory were implemented
- Current normalization and shape errors are not fully under control
  $\Rightarrow$ *Size and uncertainty of the weak magnetism correction might be under-estimated*
- Normalization and shape of ^{235}U and Pu isotopes are highly correlated
  ILL data normalization is common to all spectra, correction term are basically common to all spectra

Upcoming spectral data collected at reactors might bring stringent enough constraint on the shape to confirm/update our error budget