Antineutrino Energy Spectra and the Summation Method

The Status of Reactor Antineutrino Flux Modelling
2nd Workshop
January 21-23. 2014

fallot@subatech.in2p3.fr

Outline

- 2 Methods to compute Antineutrino Spectra
- Ingredients for Summation Method Spectra
- Conversion Method Revisited
- Update of Summation Method Spectra with TAS data
- News from the field in 2014
- Summation Method Spectra as an explanation of the 4-8MeV distorsion ?
- Conclusions & Outlooks

Outline

- 2 Methods to compute Antineutrino Spectra
- Ingredients for Summation Method Spectra
- Conversion Method Revisited
- Update of Summation Method Spectra with TAS data
- News from the field in 2014
- Summation Method Spectra as an explanation of the 4-8MeV distorsion ?
- Conclusions & Outlooks

Reactor Antineutrino Spectrum

⇒ **Two calculation methods were re-visited:**

- One relying on the conversion of integral beta spectra of reference measured by Schreckenbach et al. in the 1980's at the ILL reactor (thermal fission of ^{235}U, ^{239}Pu and ^{241}Pu integral beta spectra): use of nuclear data for realistic beta branches, Z distribution of the branches…

- The other being the summation method, summing all the contributions of the fission products in a reactor core: only nuclear data : Fission Yields + Beta Decay properties

Outline

- 2 Methods to compute Antineutrino Spectra
- **Ingredients for Summation Method Spectra**
- Conversion Method Revisited
- Update of Summation Method Spectra with TAS data
- News from the field in 2014
- Summation Method Spectra as an explanation of the 4-8MeV distorsion ?
- Conclusions & Outlooks

Summation Method: Method based on individual fission product beta decay summation

$$N(E_\nu) = \sum_n Y_n(Z,A,t) \cdot \sum_i b_{n,i}(E_0^i) P_\nu(E_\nu, E_0^i, Z)$$

fissile mat. + FY

neutron flux

Core geometry

exp. spectrum

β-branch

models

Core Simulation Evolution Code **MURE**
(MCNP Utility for Reactor Evolution)

β-spectra database :
TAS, Rudstam et al.,
ENSDF, JEFF, JENDL, …
other evaluated nuclear databases

β^- decay rates
$Y_i(Z,A,t)$

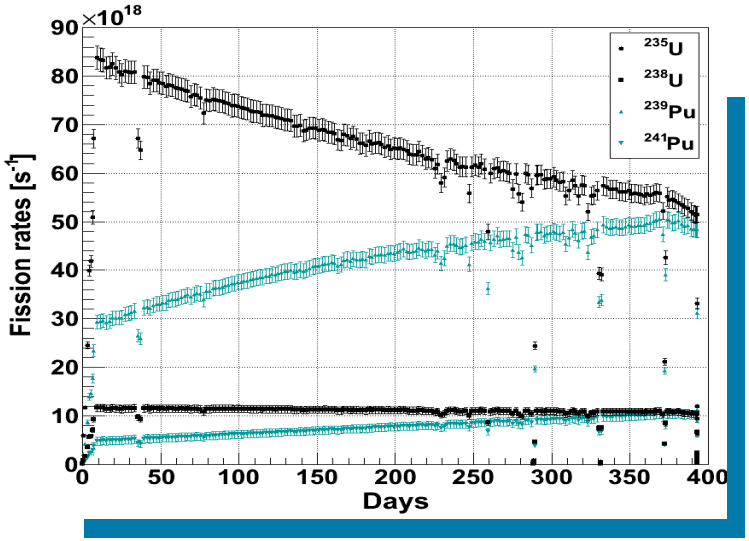
β^- / ν_e spectra
$S_{\bar{\nu},i}(Z,A,E_{\bar{\nu}})$

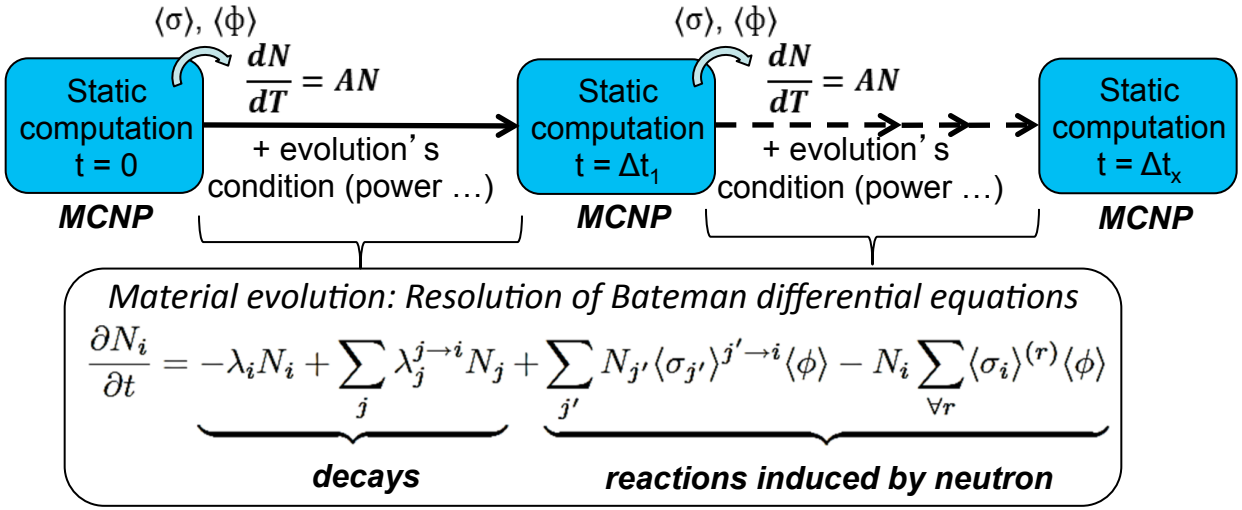
weighted Σ

Total ν_e and β^- energy spectra
with possible error propagation
+off-equilibrium effects

The MURE* Code

- The MURE Code (MCNP Utility for Reactor Evolution) :
  - C++ interface to the Monte Carlo code MCNP (static particle transport code)
  - Open source code available @ NEA: http://www.oecd-nea.org/tools/abstract/detail/nea-1845
  - Used for the 1st phase of the Double Chooz experiment





$$\frac{\partial N_i}{\partial t} = -\lambda_i N_i + \sum_j \lambda_j^{j\to i} N_j + \sum_{j'} N_{j'} \langle \sigma_{j'} \rangle^{j'\to i} \langle \phi \rangle - N_i \sum_{\forall r} \langle \sigma_i \rangle^{(r)} \langle \phi \rangle$$

➡ Outputs provided: keff, neutron flux, inventory, reaction rates + adapted to compute antineutrino spectra

➡ Development of a complete core simulation with a follow up of core operating parameters

➡ Can be used also for simple geometries: ILL spectra computation

From A. Onillon

Ingredients to Build Beta and Antineutrino Spectra

- $N_\beta(W) = K\, pW(W-W_0)^2\, F(Z,W) L_0(Z,W) C(Z,W) S(Z,W) G_\beta(Z,W)(1+\delta_{WM}W)$

Where $W=E/m_ec^2+1$, K = normalization constant,

$pW(W-W_0)^2$ = phase space, to be modified if forbidden transitions

$F(Z,W)$ = „traditional" Fermi function

$L_0(Z,W)$ and $C(Z,W)$ = finite dimension terms (electromagnetic and weak interactions)

$S(Z,W)$ = screening effect (of the Coulomb field of the daughter nucleus by the atomic electrons)

$G_\beta(Z,W)$ = radiative corrections involving real and virtual photons

δ_{WM} = weak magnetism term

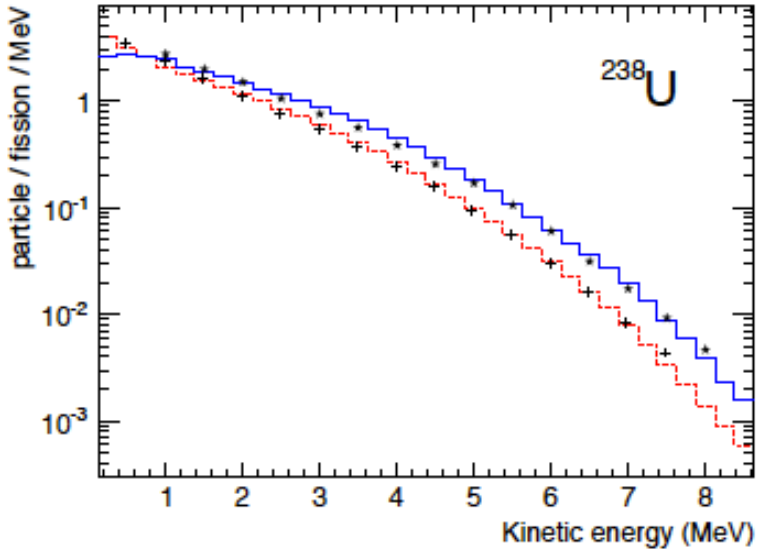
The first results were published in Th.A. Mueller et al, Phys.Rev. C83(2011) 054615:

And only radiative corrections, coulomb and WM corrections were taken into account, following Vogel's prescription

The shape of the actual spectra take care of allowed, and forbidden unique decays but not for forbidden non-unique decays (approx. are made)

Energy conservation for conversion into antineutrino spectrum, for each beta branch of each fission product + realistic Z distribution of the fission products

« Summation » Method with the MURE* code



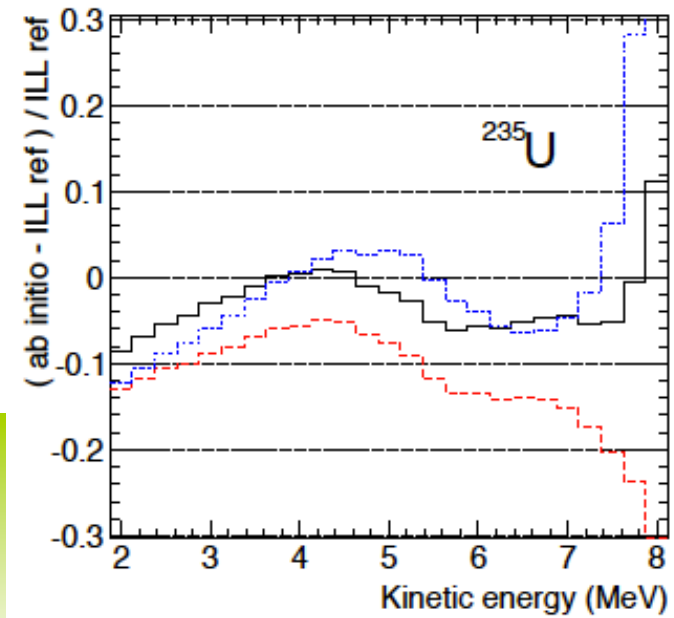
***MCNP Utility for Reactor Evolution:**

- Computes the fission product distributions to couple with beta decay nuclear databases
- Computes off-equilibrium effects
- Prediction of <u>any antineutrino energy spectrum</u> for individual fissible nuclei or full reactor cores, for neutrino physics or non proliferation

But Pandemonium effect:

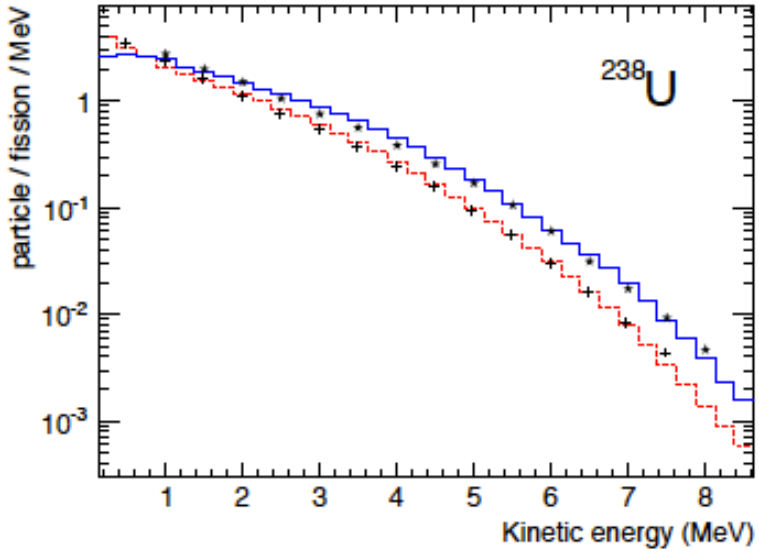
Overestimate of the reference spectra @ high energy + shape distortion

⇒ Requires new measurements of fission product beta decay properties



***MCNP Utility for Reactor Evolution:** http://www.nea.fr/tools/abstract/detail/nea-1845.
Th. Mueller et al. Phys. Rev. C 83, 054615 (2011).,
C. Jones et al. Phys. Rev. D 86 (2012) 012001, arxiv.org/abs/1109.5379

« Summation » Method with the MURE* code



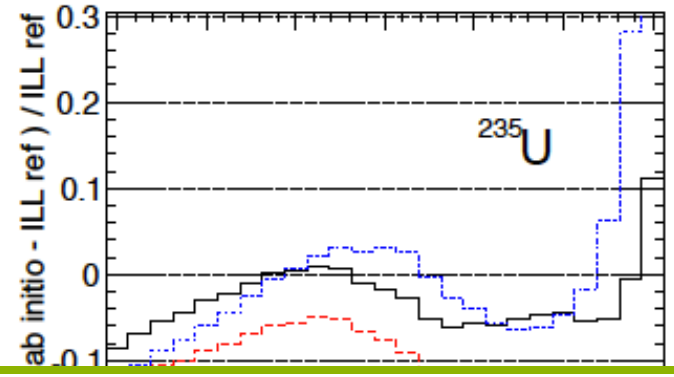
***MCNP Utility for Reactor Evolution:**

- Computes the fission product distributions to couple with beta decay nuclear databases
- Computes off-equilibrium effects
- Prediction of <u>any antineutrino energy spectrum</u> for individual fissible nuclei or full reactor cores, for neutrino physics or non proliferation

But Pandemonium effect:

Overestimate of the reference spectra @ high energy + shape distortion

⇒ Requires new measurements of fission product beta decay properties



The reactor antineutrino estimate is not the only one to suffer from the Pandemonium Effect: Similar problem for Reactor Decay Heat (initiated by Yoshida et al. see Nuclear Science NEA/WPEC-25 (2007), Vol. 25**)**

⇒ TAS experiments as a solution

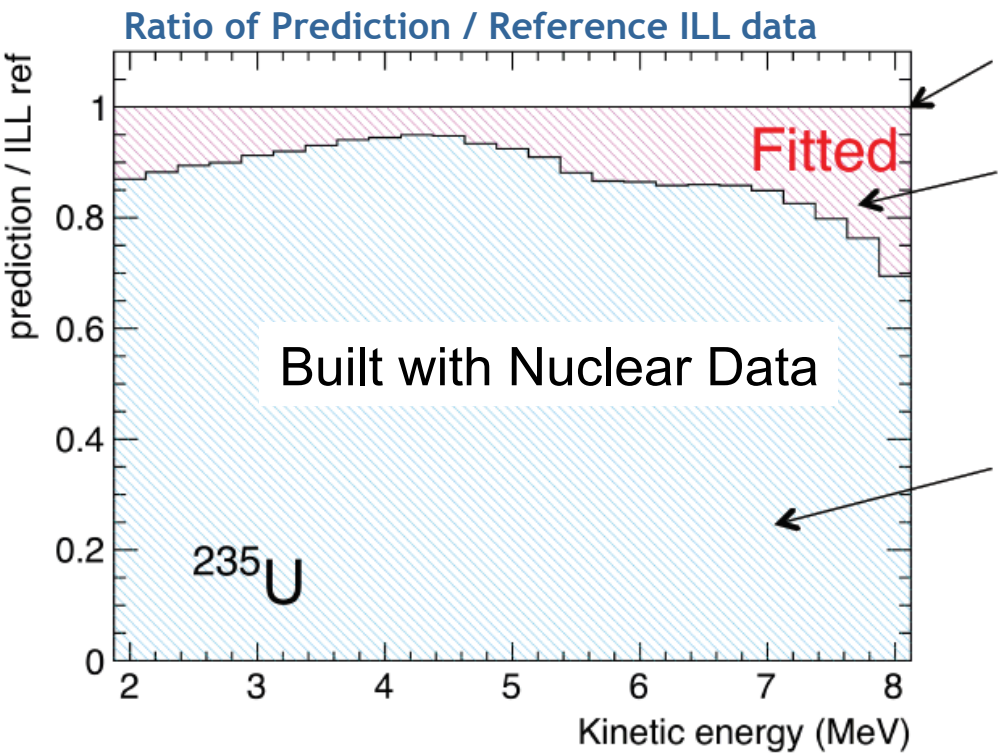
Outline

- 2 Methods to compute Antineutrino Spectra
- Ingredients for Summation Method spectra
- **Conversion Method Revisited**
- Update of Summation Method Spectra with TAS data
- News from the field in 2014
- Summation Method Spectra as an explanation of the 4-8MeV distorsion ?
- Conclusions & Outlooks

Newly Converted Spectra

Th.A. Mueller et al, Phys.Rev. C83(2011) 054615

- **Assume a 10% error on the summation method spectra for all the bins, based on the discrepancy with ILL spectra => no complete error estimate yet**
- **Assuming that summation method not yet precise enough, develop a mixed approach using nuclear databases + fictive branches to reproduce the ILL spectra**

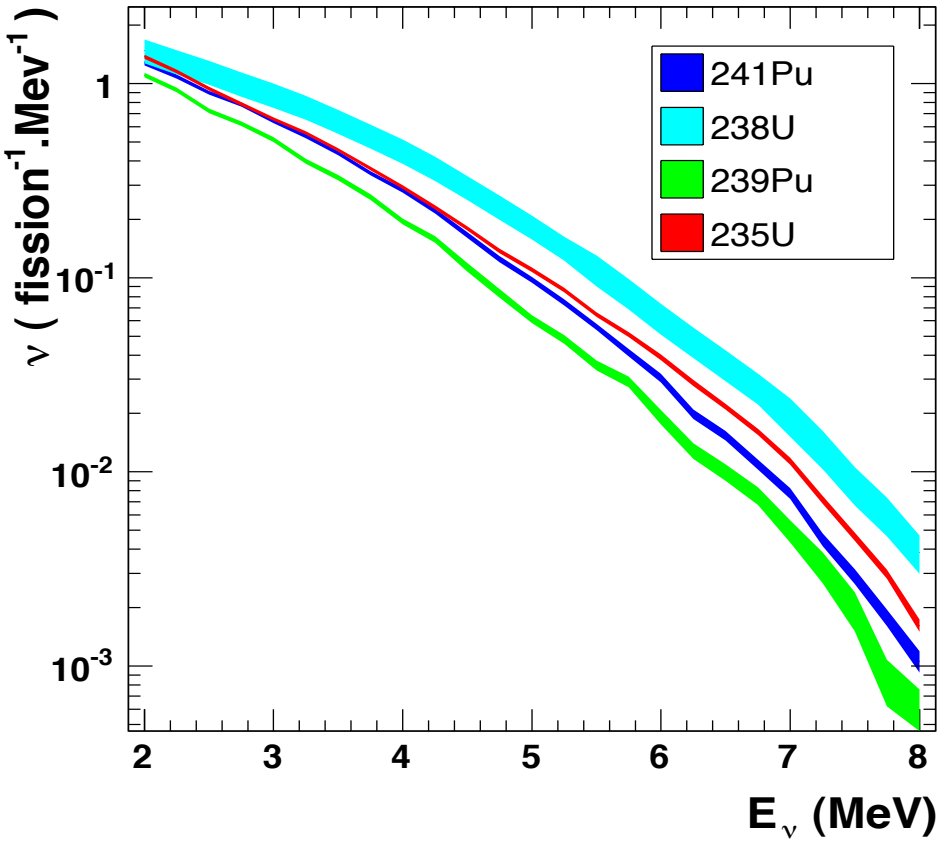


ILL electron data anchor point

- **Fit of residual: five effective branches are fitted to the remaining 10%**
  ⇒ Suppresses error of full Summation Approach, if assumption that ILL data = only reference

- **"true" distribution of all known β- branches describes >90% of ILL e data**
  ⇒ reduces sensitivity to virtual branches approximations

Newly Converted Spectra



- Recent re-evaluations by
  - Th.A. Mueller et al, Phys.Rev. C83(2011) 054615.
  - P. Huber, Phys.Rev. C84 (2011) 024617
- Off-equilibrium corrections included (computed with MURE)
- Summation calculations, database comparisons and fission product distribution= new ^{238}U prediction

These recent works defined a new neutrino flux prediction of reference for neutrino physics

Newly Converted spectra…

- ILL data = unique and precise reference => converted ν spectra = +3% normalization shift with respect to old ν spectra, similar results for all isotopes (^{235}U, ^{239}Pu, ^{241}Pu)

⇒ Origin of the bias identified:

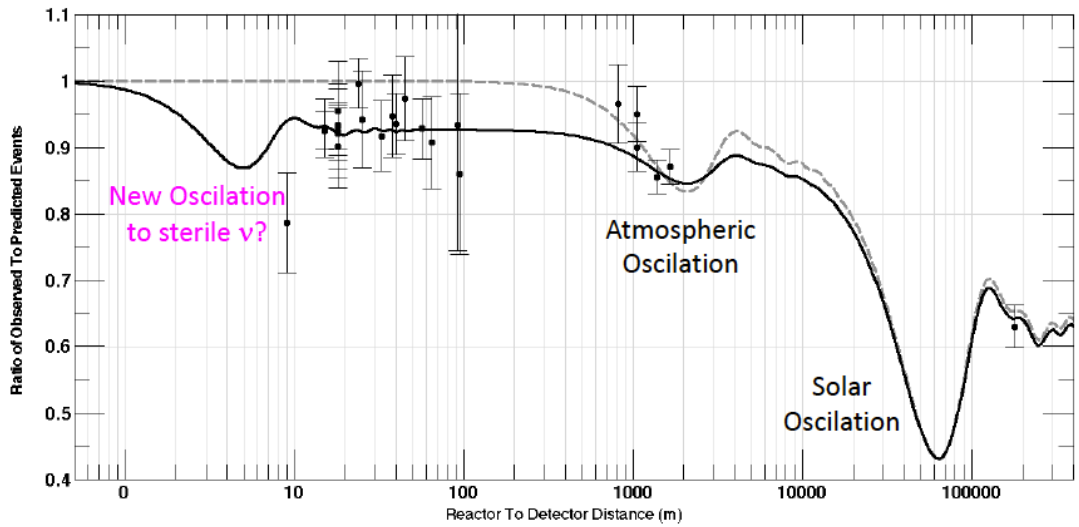
- ILL conversion procedure (only virtual branches): 2 independent biases:
  - Low energy: correction to Fermi theory should be applied at branch level
  - High energy: mean Z fit is not accurate enough.

⇒ « Reactor anomaly »: all reactor neutrino experiments are below the prediction (G. Mention et al. Phys. Rev. D83, 073006 (2011)).

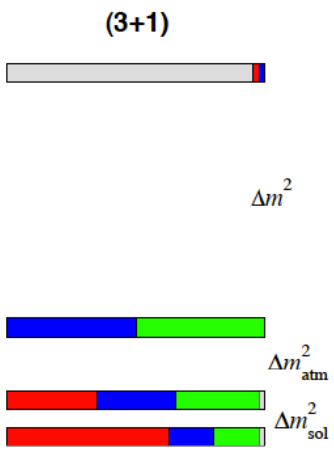
Sterile Neutrino hints ?

- **Reactor Anomaly:**
  - converted ν spectra = ˜+3% normalization shift with respect to old ν spectra, similar results for all isotopes (^{235}U, ^{239}Pu, ^{241}Pu)
  - Neutron life-time
  - Off-equilibrium effects

2 flavour simple scheme :
$P_{Osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2_{[eV2]} L_{[m]}/E_{[MeV]})$



G. Mention et al. Phys. Rev. D83, 073006 (2011)



=> Light sterile neutrino state ? could explain L=10-100m anomalies, $\Delta m^2 \approx 1$ eV²

- candidate can't interact via weak interaction : constrained by LEP result on 3 families

=> so can only exist in sterile form

Newly Converted spectra…

- ILL data = unique and precise reference => converted ν spectra = +3% normalization shift with respect to old ν spectra, similar results for all isotopes (^{235}U, ^{239}Pu, ^{241}Pu)

⇒ Origin of the bias identified:

- ILL conversion procedure (only virtual branches): 2 independent biases:
  - Low energy: correction to Fermi theory should be applied at branch level
  - High energy: mean Z fit is not accurate enough.

⇒ « Reactor anomaly »: all reactor neutrino experiments are below the prediction (G. Mention et al. Phys. Rev. D83, 073006 (2011)).

⇒ Now looking for sterile neutrinos as a potential explanation to the reactor anomaly: Nucifer exp., + numerous projects: SOLiD (UK), STEREO (France), SCRAMM(US-Ca), Neutrino-4 (Russia), DANSS(Russia), + Mega-Curie sources in large ν detector… (white paper: K. N. Abazajian et al., http://arxiv.org/abs/1204.5379.)

⇒ Other explanations still possible: large uncertainty for Weak Magnetism term, treatment of forbidden decays => could change normalization of spectra, or normalization of ILL data

Outline

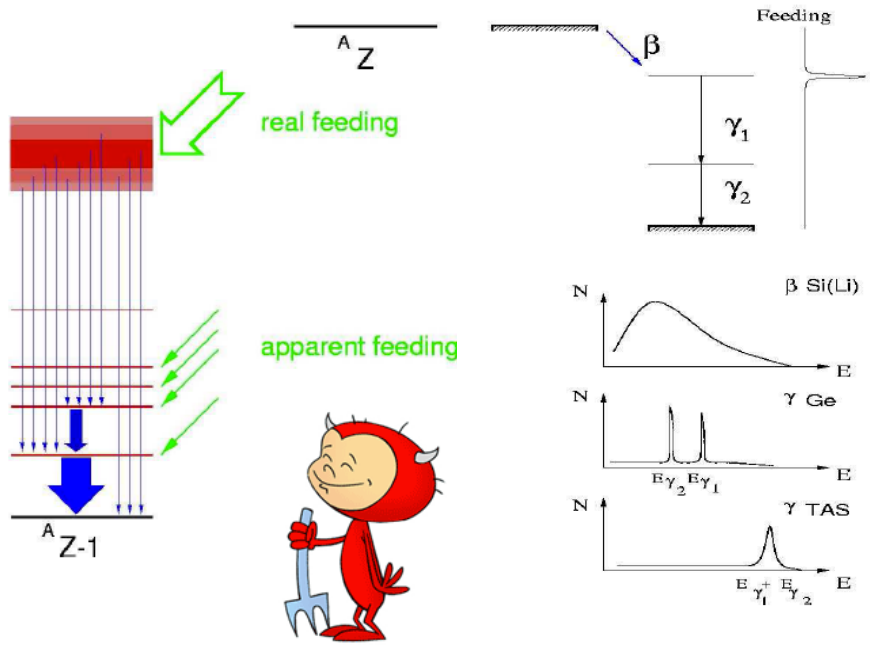
- 2 Methods to compute Antineutrino Spectra
- Ingredients for Summation Method spectra
- Conversion Method Revisited
- **Update of Summation Method Spectra with TAS data**
- News from the field in 2014
- Summation Method Spectra as an explanation of the 4-8MeV distorsion ?
- Conclusions & Outlooks

TAS Technique

Pandemonium effect**:

Due to the use of Ge detectors to measure the decay schemes: lower efficiency at higher energy

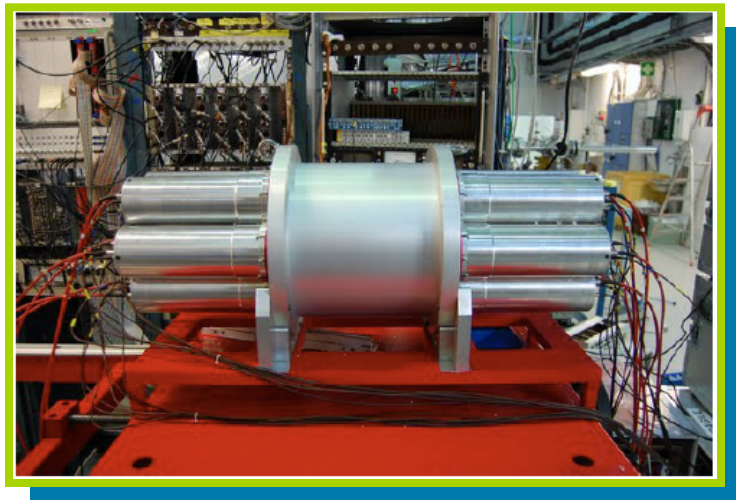
→ underestimate of β branches towards high energy excited states: overestimate of the high energy part of the FP β spectra



Picture from A. Algora

** J.C.Hardy et al., Phys. Lett. B, 71, 307 (1977)

Solution: Total Absorption Spectroscopy (TAS)
Big cristal, 4π => A TAS is a calorimeter !



- 12 BaF_2 covering ~4π
- Detection efficiency of γ ray cascade ~ 100%
- Si detector for β

TAGS developed by the Valencia team (Spain, B. Rubio, J.L. Tain, A. Algora et al.) : Proceedings of the Int. Conf. For nuclear Data for Science and technology (ND2013)

TAS MEASUREMENTS @ JYVÄSKYLÄ UNIV. (JYFL)

- IFIC of Valencia (J.L. Tain et A. Algora et al.)

  Reactor Decay Heat in ^{239}Pu: Solving the γ Discrepancy in the 4-3000-s Cooling Period,

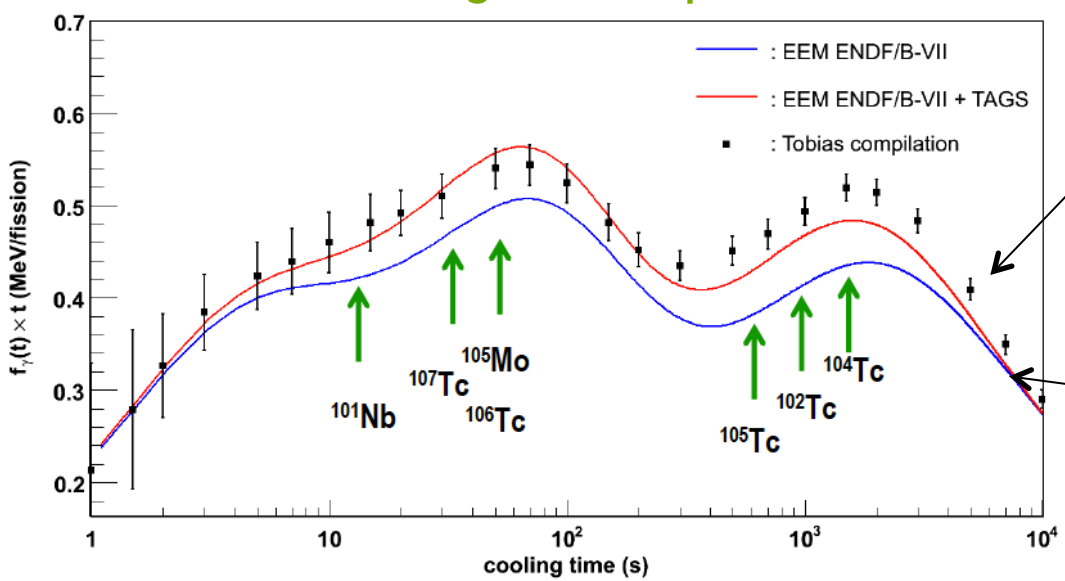
  Algora et al., Phys. Rev. Lett. 105, 202501 (2010),

  D. Jordan, PhD thesis, Univ. Of Valencia 2010

⇒ Taking into consideration the TAS data of the $^{102;104\text{-}107}$Tc, ^{105}Mo, and ^{101}Nb isotopes measured @ Jyväskylä (Nuclei from Nuclear Science NEA/WPEC-25 (2007), Vol. 25)

⇒ i.e. correcting 5 nuclei out of 7 for the Pandemonium effect

Impact of the results for ^{239}Pu: electromagnetic component



Integral measurement of reference

Summation method calculations of the decay heat

D. Jordan, A. Algora et al. Phys. Rev. C 87, 044318 (2013)

Summation Method: Ingredients updated in 2012

- $N_\beta(W) = K\, pW(W-W_0)^2\, F(Z,W)L_0(Z,W)C(Z,W)S(Z,W)G_\beta(Z,W)(1+\delta_{WM}W)$

Where $W=E/m_ec^2$, K = normalization constant,

$pW(W-W_0)^2$ = phase space, to be modified if forbidden transitions

$F(Z,W)$ = Fermi function

$L_0(Z,W)$ and $C(Z,W)$ = finite dimension terms (electromagnetic and weak interactions)

$S(Z,W)$ = screening effect

$G_\beta(Z,W)$ = radiative corrections

δ_{WM} = weak magnetism term (the most uncertain one ! Cf. P. Huber, could change the normalization of the spectra if very different value…)

- Using Huber's prescriptions (formulae and values from PRC84,024617(2011)) + energy conservation for conversion into antineutrino spectrum, for each beta branch of each fission product
- Individual fission yields from the JEFF3.1 database are used

Subatech

Phys. Rev. Lett. 109, 202504 (2012)

Summation Method: Ingredients updated in 2012

- **In order to choose one specific nuclear decay database for one given nucleus, the order in which the bases are read is important: the first one in which the fission product is found is the chosen one:**

The **Greenwood TAS data set** (29 nuclei), the **experimental data measured by Tengblad et al.** (85 nuclei), experimental data from the evaluated nuclear databases: **JEFF3.1** (305, 345, 347, and 318 nuclei, respectively, for ^{235}U, ^{239}Pu, ^{241}Pu, and ^{238}U) **and JENDL2000** (61, 62, 61, and 58 nuclei, respectively), **Evaluated Nuclear Structure Data File nuclei** (94, 106, 109, and 97 nuclei respectively), **Gross theory spectra from JENDL** (214, 215, 227, and 221 nuclei, respectively), and the **"Q_β" approximation** for the remaining unknown nuclei (22, 32, 38, and 33 nuclei, respectively).

⇒ **810, 874, 896 and 841 fission products taken into account respectively**

- **Irradiation times with MURE: 12 h for ^{235}U, 1.5 days for $^{239;241}$Pu, and 450 days for ^{238}U.**

⇒ **Taking into consideration the latest published TAS data of the $^{102;104–107}$Tc, ^{105}Mo, and ^{101}Nb isotopes (A. Algora et al. Phys. Rev. Lett. 105, 202501 (2010)) ?**

⇒ **i.e. correcting 5 nuclei out of 7 for the Pandemonium effect**

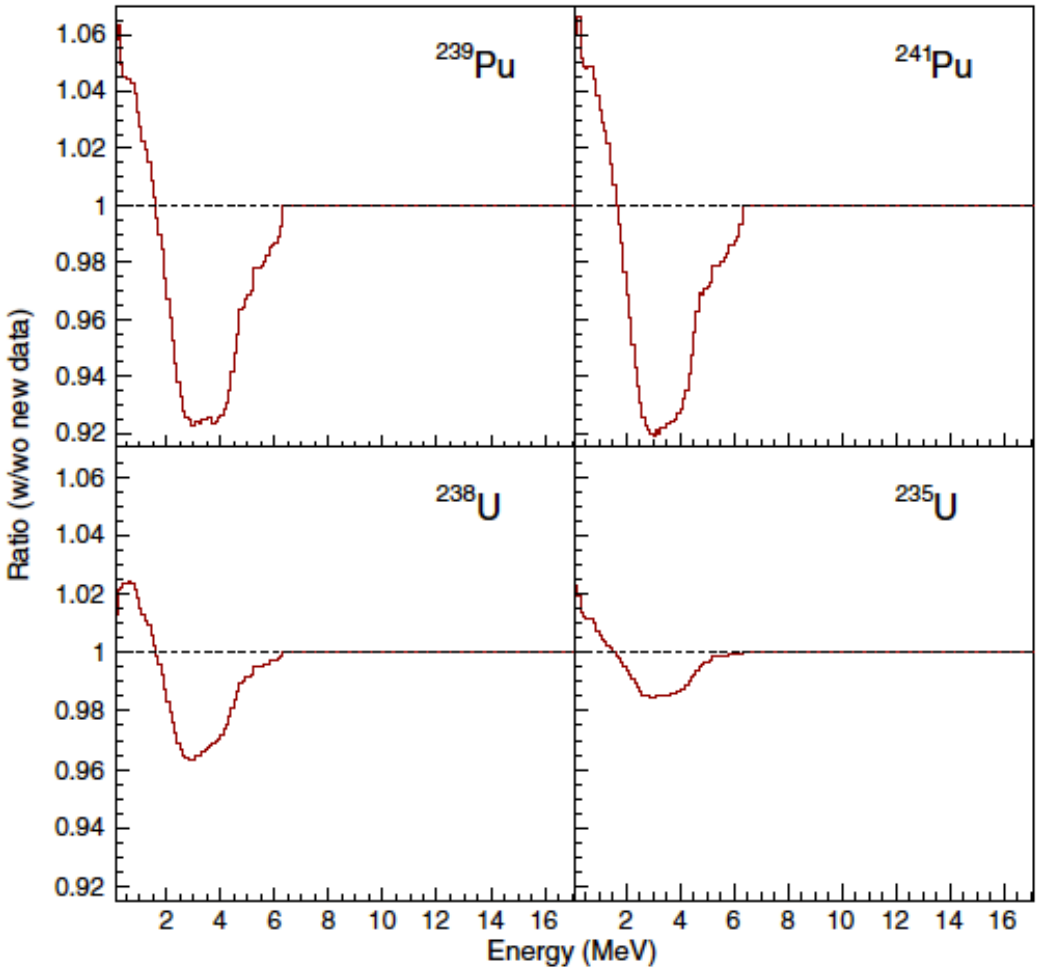
Subatech

Phys. Rev. Lett. 109, 202504 (2012)

Inclusion of the latest TAS data in the Antineutrino Summation Spectra:

Ratios of summation antineutrino spectra including the new TAS data for $^{102;104–107}$Tc, ^{105}Mo, and ^{101}Nb over the same spectra but with the JEFF3.1 data

- $^{239;241}$Pu energy spectra: noticeable deviation from unity observed in the 0–6 MeV energy range reaching an 8% decrease.
- ^{238}U energy spectrum: effect reaches a value of 3.5% at 2.5–3 MeV.
- ^{235}U: 1.5% at 2.5–3.5 MeV, expected since these nuclei are a small contribution to the ^{235}U spectrum.



Phys. Rev. Lett. 109, 202504 (2012)

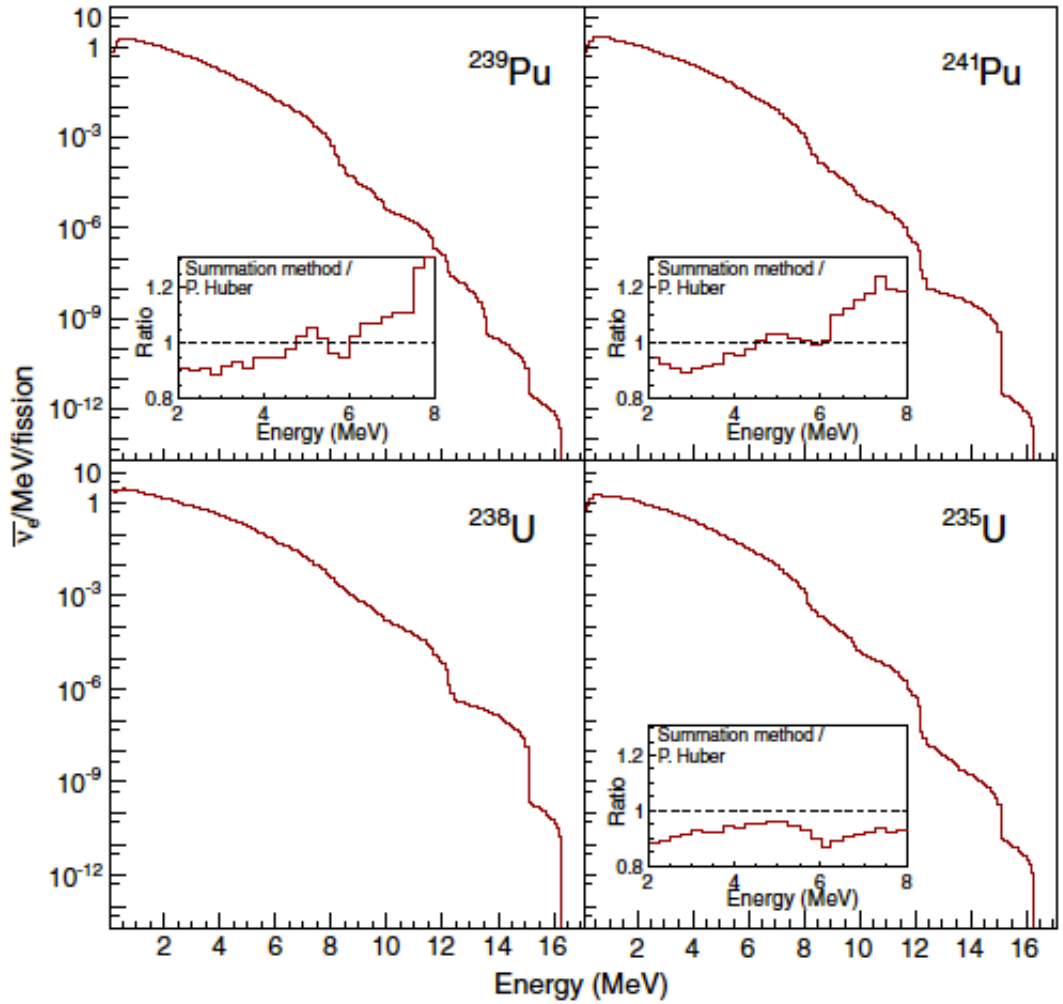
Inclusion of recent TAS data in the Anti-neutrino Summation Spectra:

- **With the TAS data set from Algora et al. Phys. Rev. Lett. 105, 202501 (2010):**

Reconstructed anti-neutrino energy spectra, including the latest TAS data from Algora et al.

In the insets: ratios of the spectra to the ones computed by Huber PRC84,024617(2011) **converted reference spectra from ILL β-spectra**

=> Overall agreement@~10% up to 7 MeV



Phys. Rev. Lett. 109, 202504 (2012)

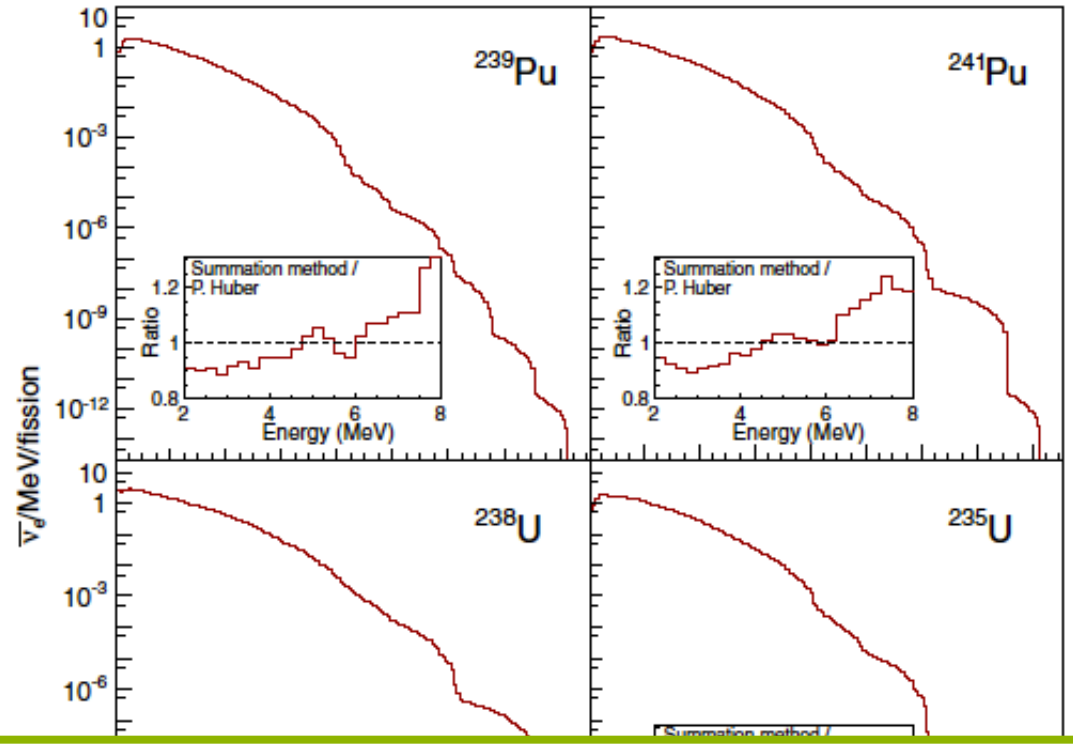
Inclusion of recent TAS data in the Anti-neutrino Summation Spectra:

- **With the TAS data set from Algora et al. Phys. Rev. Lett. 105, 202501 (2010):**

Reconstructed anti-neutrino energy spectra, including the latest TAS data from Algora et al.

In the insets: ratios of the spectra to the ones computed by Huber PRC84,024617(2011) **converted reference spectra from ILL β-spectra**

=> Overall agreement@~10% up to 7 MeV



⇒ Shows the important **role of the Pandemonium nuclei in the $\bar{\nu}$ summation spectra**
⇒ The summation spectra are among the only ways to estimate the anti-neutrino spectra **independently** from the still unique ILL integral β-spectra
⇒ **New measurements required, list of nuclei identified should reduce errors significantly**
⇒ **New TAS Measurements done last February in Jyväskylä**

Phys. Rev. Lett. 109, 202504 (2012)

Outline

- 2 Methods to compute Antineutrino Spectra
- Ingredients for Summation Method spectra
- Conversion Method Revisited
- Update of Summation Method Spectra with TAS data
- **News from the field in 2014**
- Summation Method Spectra as an explanation of the 4-8MeV distorsion ?
- Conclusions & Outlooks

INT Workshop in Seattle on Anti-neutrino Spectra

Organized by G. Bertsch, A. Sonzogni and A. Hayes (Nov. 2013)

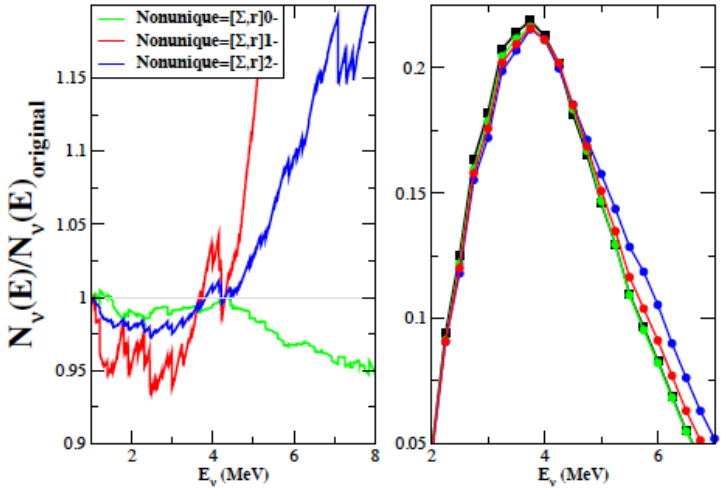
P. Vogel, P. Huber, A. Hayes, A. Sonzogni, L. Mc Cutchan, T. Johnson, A. Algora, N. Haag, H. Pentilla, and al. (sorry that I can't quote everybody)… http://www.int.washington.edu/talks/WorkShops/int_13_3/

Converted spectra:

⇒Large log(ft) contribute importantly to the spectra (~30%) but we don't know how many of them are forbidden non-unique transitions, nor the spin/parity of the transitions

⇒Need inputs from Nuclear Physics

A. Hayes et al. Phys. Rev. Lett. 112, 202501 (2014)

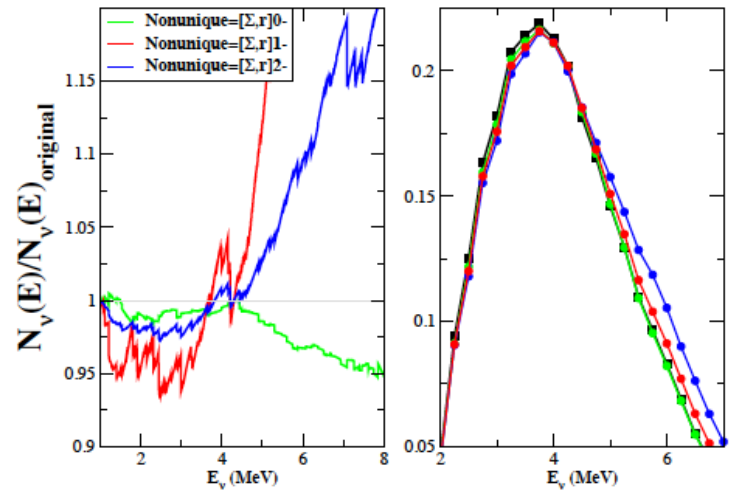


INT Workshop in Seattle on Anti-neutrino Spectra

Organized by G. Bertsch, A. Sonzogni and A. Hayes (Nov. 2013)

P. Vogel, P. Huber, A. Hayes, A. Sonzogni, L. Mc Cutchan, T. Johnson, A. Algora, N. Haag, H. Pentilla, and al. (sorry that I can't quote everybody)… http://www.int.washington.edu/talks/WorkShops/int_13_3/

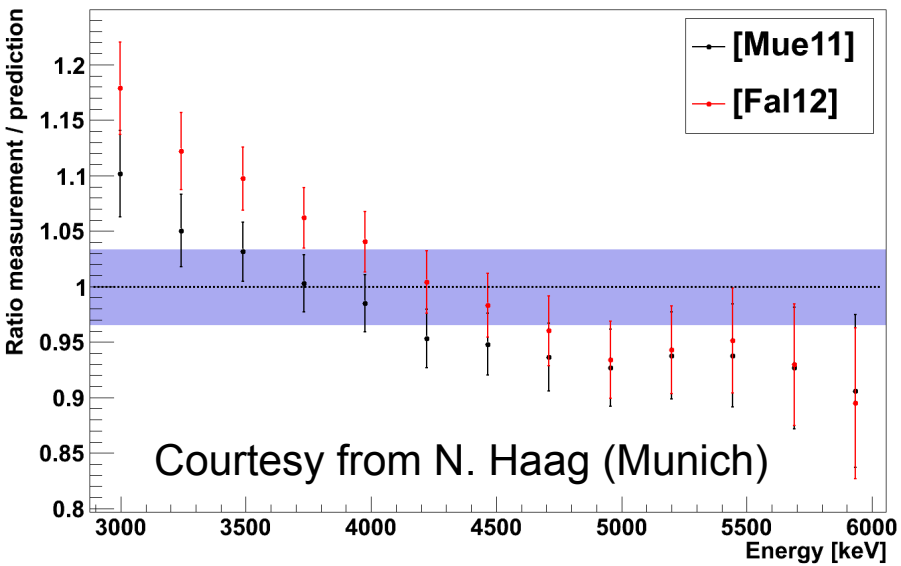
A. Hayes et al. Phys. Rev. Lett. 112, 202501 (2014)



Converted spectra:

⇒Large log(ft) contribute importantly to the spectra (~30%) but we don't know how many of them are forbidden non-unique transitions, nor the spin/parity of the transitions

⇒Need inputs from Nuclear Physics



N. Haag et al., Phys. Rev. Lett., 112, 12 (2014).

Summation Method Spectra:

⇒ Agreement on a short list of important Pandemonium nuclei to re-measure, experiments on-going

⇒ Fission Yields status ?

⇒ Tentative error envelop calculation (?)

⇒ But overall good agreement with Nils Haag's measurement of ^{238}U integral beta spectrum reassuring !

Latest News from Reactor Neutrino Experiments in 2014

Reactor ν

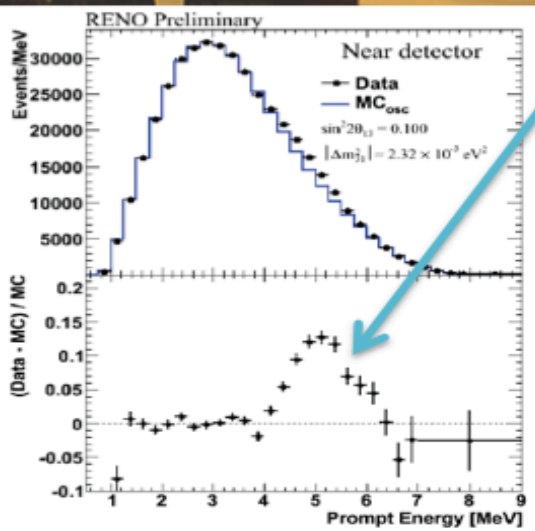
What is this?!?

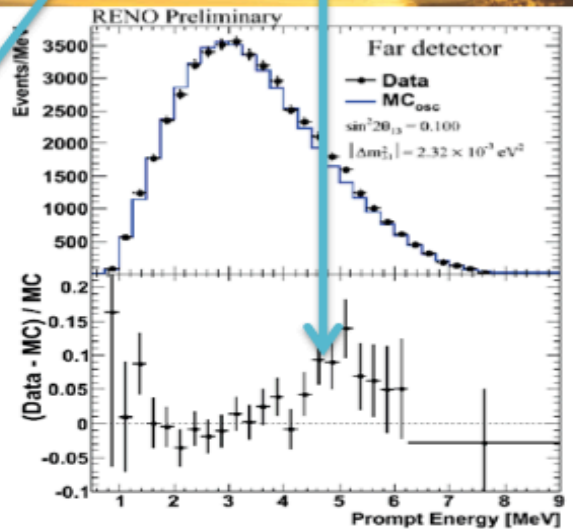
Semi - Double Chooz

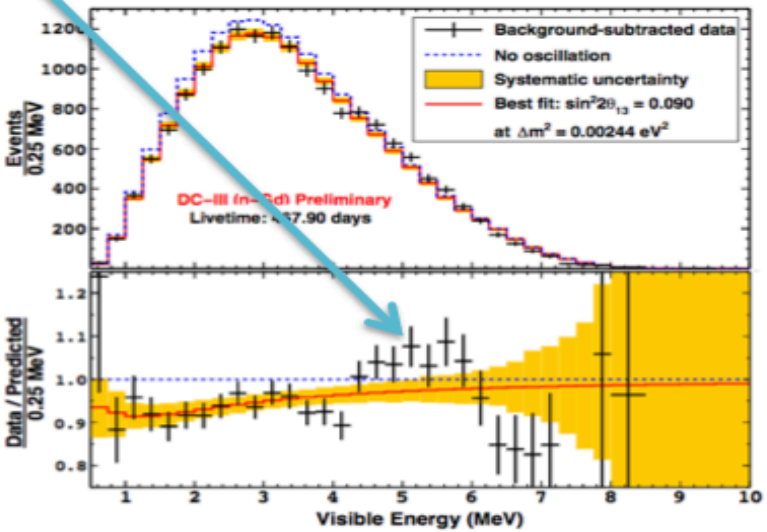
XXVI International Conference on Neutrino Ph hysics

New Results from RENO

June 2-7 U.S.A.







Rate only analysis ➔

Preliminary result

C data set (~800 days)

$\sin^2(2\,\theta_{13}) = 0.101 \pm 0.008$ (stat.) $\pm$ 0.010 (sys.)

Rate + shape analysis ➔

$\sin^2(2\,\theta_{13}) = (0.09 \pm 0.03)$

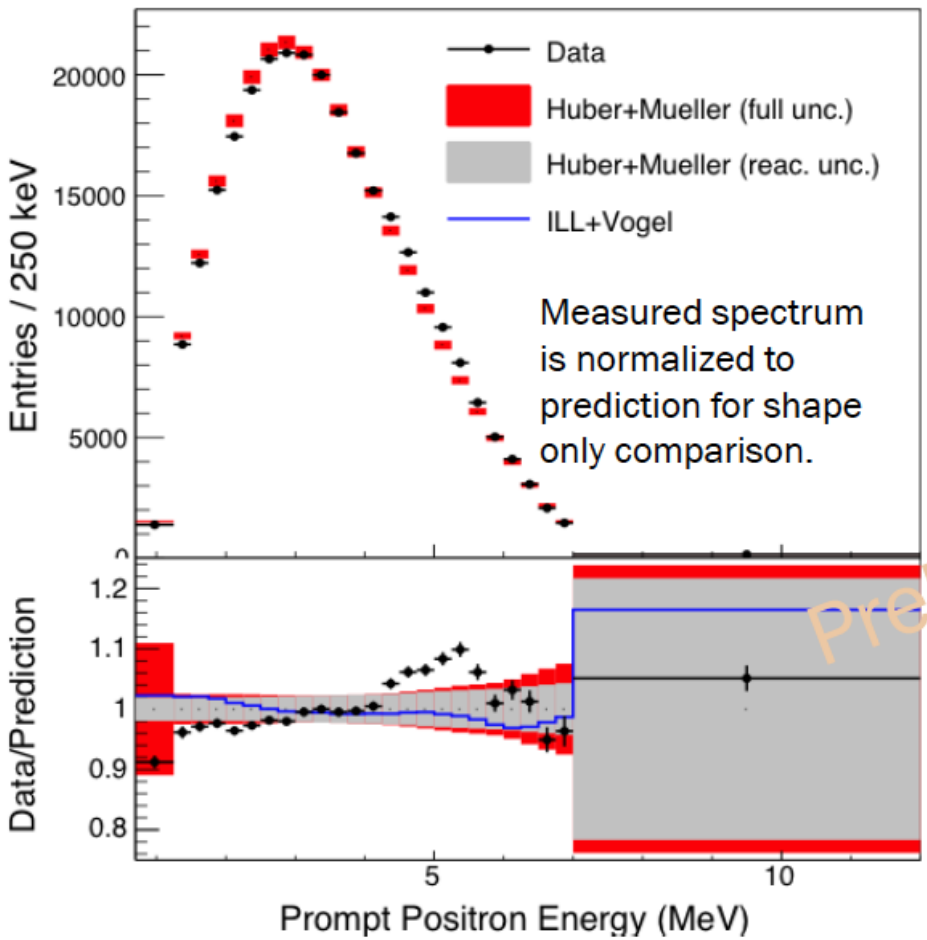
(χ^2/n.d.f. = 51.4/40)

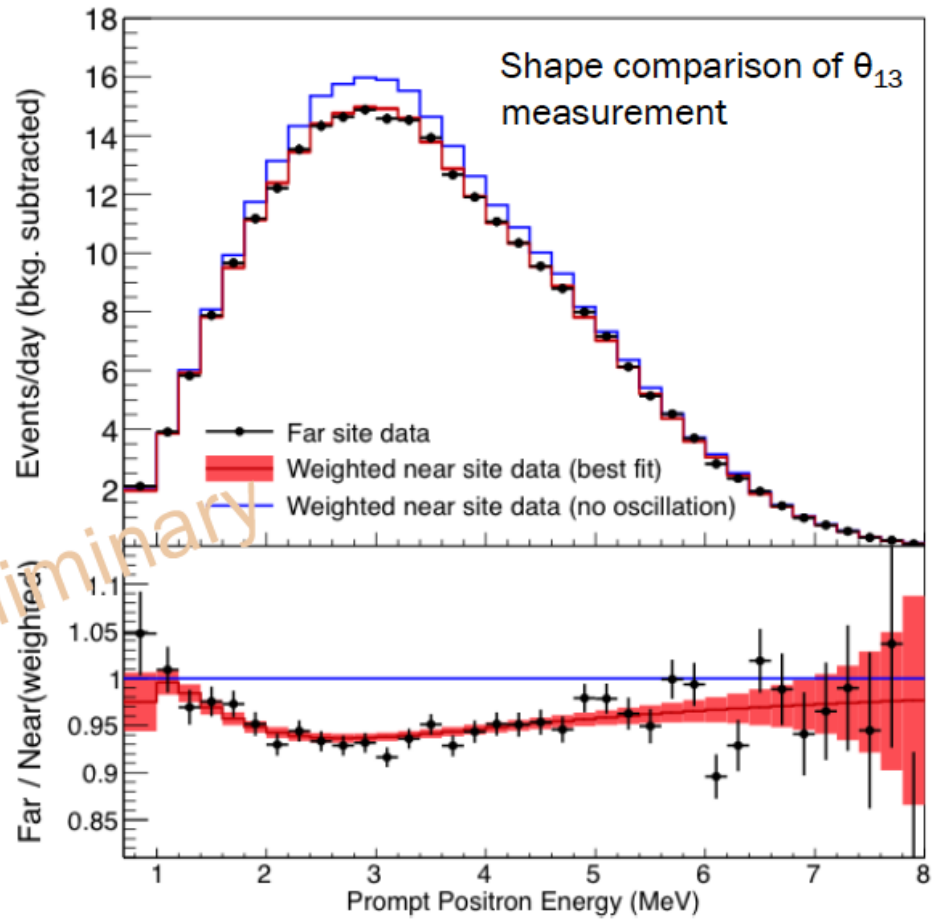
background substracted

The field benefits greatly from 3 exps!

ABSOLUTE SPECTRUM MEASUREMENT

- Absolute shape comparison of data and prediction: $\chi^2/ndf = 41.8/21$
- Primarily relative shape comparison among detectors: $\chi^2/ndf = 134.7/146$





Outline

- 2 Methods to compute Antineutrino Spectra
- Ingredients for Summation Method spectra
- Conversion Method Revisited
- Update of Summation Method Spectra with TAS data
- News from the field in 2014
- **Summation Method Spectra as an explanation of the 4-8MeV distorsion ?**
- Summary & Conclusion

Main contributors to Reactor Antineutrino Spectrum [4-8 MeV]

« Spectral Structure of Electron Antineutrinos from Nuclear Reactors » by Dwyer and Langford:

Phys. Rev. Lett. 114, 012502

Isotope	Q[MeV]	$t_{1/2}$[s]	log(ft)	Decay Type	N[%]	σ_N[%]
^{96}Y	7.103	5.34	5.59	$0^- \rightarrow 0^+$	13.6	0.8
^{92}Rb	8.095	4.48	5.75	$0^- \rightarrow 0^+$	7.4	2.9
^{142}Cs	7.308	1.68	5.59	$0^- \rightarrow 0^+$	5.0	0.7
^{97}Y	6.689	3.75	5.70	$1/2^- \rightarrow 1/2^+$	3.8	1.1
^{93}Rb	7.466	5.84	6.14	$5/2^- \rightarrow 5/2^+$	3.7	0.5
^{100}Nb	6.381	1.5	5.1	$1^+ \rightarrow 0^-$	3.0	0.8
^{140}Cs	6.220	63.7	7.05	$1^- \rightarrow 0^+$	2.7	0.2
^{95}Sr	6.090	23.9	6.16	$1/2^+ \rightarrow 1/2^-$	2.6	0.3

TABLE I. Most prominent beta decay branches in the region of $E_{\bar{\nu}}$=5–7 MeV. The table presents the decay parent, end-point energy, half-life, and decay ft value. The decay type describes the parent and daughter states. The moderate ft values and lack of significant change of J^π suggest that all but possibly ^{140}Cs decay with allowed spectral shapes. The rate each branch contributes to the total between 5–7 MeV is N, accounting for the inverse beta decay cross section. The 1-σ uncertainty due to the fission yield and branching fraction is σ_N.

The calculation from M. Fallot et al., PRL 109, 20254 (2012) gives the following table: (Z. Issoufou et al. in preparation)

TABLE I. Main Contributors to a standard PWR antineutrino energy spectrum computed using the summation method described in [12].

	4 - 5 MeV	5 - 6 MeV	6 - 7 MeV	7 - 8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	-
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	-	-
^{93}Rb	2.34%	4.17%	6.78%	4.21%
^{98m}Y	2.43%	3.16%	4.57%	4.95%
^{135}Te	4.01%	3.58%	-	-
^{104m}Nb	0.72%	1.82%	4.15%	7.76%
^{90}Rb	1.90%	2.59%	1.40%	-
^{95}Sr	2.65%	2.96%	-	-
^{94}Rb	1.32%	2.06%	2.84%	3.96%

Main contributors to Reactor Antineutrino Spectrum [4-8 MeV]

« Spectral Structure of Electron Antineutrinos from Nuclear Reactors » by Dwyer and Langford:
Phys. Rev. Lett. 114, 012502

Isotope	Q[MeV]	$t_{1/2}$[s]	log(ft)	Decay Type	N[%]	σ_N[%]
^{96}Y	7.103	5.34	5.59	$0^- \to 0^+$	13.6	0.8
^{92}Rb	8.095	4.48	5.75	$0^- \to 0^+$	7.4	2.9
^{142}Cs	7.308	1.68	5.59	$0^- \to 0^+$	5.0	0.7
^{97}Y	6.689	3.75	5.70	$1/2^- \to 1/2^+$	3.8	1.1
^{93}Rb	7.466	5.84	6.14	$5/2^- \to 5/2^+$	3.7	0.5
^{100}Nb	6.381	1.5	5.1	$1^+ \to 0^-$	3.0	0.8
^{140}Cs	6.220	63.7	7.05	$1^- \to 0^+$	2.7	0.2
^{95}Sr	6.090	23.9	6.16	$1/2^+ \to 1/2^-$	2.6	0.3

TABLE I. Most prominent beta decay branches in the region of $E_{\bar{\nu}}$=5–7 MeV. The table presents the decay parent, end-point energy, half-life, and decay ft value. The decay type describes the parent and daughter states. The moderate ft values and lack of significant change of J^π suggest that all but possibly ^{140}Cs decay with allowed spectral shapes. The rate each branch contributes to the total between 5–7 MeV is N, accounting for the inverse beta decay cross section. The 1-σ uncertainty due to the fission yield and branching fraction is σ_N.

The calculation from M. Fallot et al., PRL 109, 20254 (2012) gives the following table: (Z. Issoufou et al. in preparation)

TABLE I. Main Contributors to a standard PWR antineutrino energy spectrum computed using the summation method described in [12].

	4 - 5 MeV	5 - 6 MeV	6 - 7 MeV	7 - 8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	-
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	-	-
^{93}Rb	2.34%	4.17%	6.78%	4.21%
^{98m}Y	2.43%	3.16%	4.57%	4.95%
^{135}Te	4.01%	3.58%	-	-
^{104m}Nb	0.72%	1.82%	4.15%	7.76%
^{90}Rb	1.90%	2.59%	1.40%	-
^{95}Sr	2.65%	2.96%	-	-
^{94}Rb	1.32%	2.06%	2.84%	3.96%

Discrepancies due to the choice of nuclear data:

⇒ Example: **D. Dwyer and T. Langford chose the previous ENSDF value of GS feeding of 50% for ^{92}Rb, whereas we have chosen Rudstam's data to try to avoid Pandemonium effect => different decay data**

⇒ **Different fission yields (CFY ENDF-B/VII.1 vs Indep FY JEFF3.1 + evolution code)**

Main contributors to Reactor Antineutrino Spectrum [4-8 MeV]

« Nuclear structure insights into reactor antineutrino spectra » by Sonzogni et al.: PHYSICAL REVIEW C 91, 011301(R) (2015)

TABLE II. Strongest contributors to the antineutrino spectrum from ^{235}U in the energy range around 4.0 MeV. Included are the β-decay Q value, the ground-state to ground-state β-feeding intensity (GS BR), the initial and final J^{π} of the ground states (all from Ref. [32]), and the percent contribution to the antineutrino spectra (Contr.).

Nuclide	Q_β (MeV)	GS BR (%)	$J^{\pi}_{gs} \rightarrow J^{\pi}_{gs}$	Contr. (%)
^{96}Y	7.1	95.5(5)	$0^- \rightarrow 0^+$	6.3
^{92}Rb	8.1	95.2(7)	$0^- \rightarrow 0^+$	6.1
^{100}Nb	6.4	50(7)	$1^+ \rightarrow 0^+$	5.5
^{135}Te	5.9	62(3)	$(7/2^-) \rightarrow 7/2^+$	3.7
^{142}Cs	7.3	56(5)	$0^- \rightarrow 0^+$	3.5
^{140}Cs	6.2	36(2)	$1^- \rightarrow 0^+$	3.4
^{90}Rb	6.6	33(4)	$0^- \rightarrow 0^+$	3.4
^{95}Sr	6.1	56(3)	$1/2^+ \rightarrow 1/2^-$	3.0
^{88}Rb	5.3	77(1)	$2^- \rightarrow 0^+$	2.9

The calculation from M. Fallot et al., PRL 109, 20254 (2012) gives the following table: (Z. Issoufou et al. in preparation)

TABLE I. Main Contributors to a standard PWR antineutrino energy spectrum computed using the summation method described in [12].

	4 - 5 MeV	5 - 6 MeV	6 - 7 MeV	7 - 8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	-
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	-	-
^{93}Rb	2.34%	4.17%	6.78%	4.21%
^{98m}Y	2.43%	3.16%	4.57%	4.95%
^{135}Te	4.01%	3.58%	-	-
^{104m}Nb	0.72%	1.82%	4.15%	7.76%
^{90}Rb	1.90%	2.59%	1.40%	-
^{95}Sr	2.65%	2.96%	-	-
^{94}Rb	1.32%	2.06%	2.84%	3.96%

Main contributors to Reactor Antineutrino Spectrum [4-8 MeV]

« Nuclear structure insights into reactor antineutrino spectra » by A. Sonzogni et al.: PHYSICAL REVIEW C 91, 011301(R) (2015)

TABLE II. Strongest contributors to the antineutrino spectrum from ^{235}U in the energy range around 4.0 MeV. Included are the β-decay Q value, the ground-state to ground-state β-feeding intensity (GS BR), the initial and final J^π of the ground states (all from Ref. [32]), and the percent contribution to the antineutrino spectra (Contr.).

Nuclide	Q_β (MeV)	GS BR (%)	$J^\pi_{gs} \rightarrow J^\pi_{gs}$	Contr. (%)
^{96}Y	7.1	95.5(5)	$0^- \rightarrow 0^+$	6.3
^{92}Rb	8.1	95.2(7)	$0^- \rightarrow 0^+$	6.1
^{100}Nb	6.4	50(7)	$1^+ \rightarrow 0^+$	5.5
^{135}Te	5.9	62(3)	$(7/2^-) \rightarrow 7/2^+$	3.7
^{142}Cs	7.3	56(5)	$0^- \rightarrow 0^+$	3.5
^{140}Cs	6.2	36(2)	$1^- \rightarrow 0^+$	3.4
^{90}Rb	6.6	33(4)	$0^- \rightarrow 0^+$	3.4
^{95}Sr	6.1	56(3)	$1/2^+ \rightarrow 1/2^-$	3.0
^{88}Rb	5.3	77(1)	$2^- \rightarrow 0^+$	2.9

The calculation from M. Fallot et al., PRL 109, 20254 (2012) gives the following table: (Z. Issoufou et al. in preparation)

TABLE I. Main Contributors to a standard PWR antineutrino energy spectrum computed using the summation method described in [12].

	4 - 5 MeV	5 - 6 MeV	6 - 7 MeV	7 - 8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	-
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	-	-
^{93}Rb	2.34%	4.17%	6.78%	4.21%
^{98m}Y	2.43%	3.16%	4.57%	4.95%
^{135}Te	4.01%	3.58%	-	-
^{104m}Nb	0.72%	1.82%	4.15%	7.76%
^{90}Rb	1.90%	2.59%	1.40%	-
^{95}Sr	2.65%	2.96%	-	-
^{94}Rb	1.32%	2.06%	2.84%	3.96%

⇒ **Small discrepancies because very similar ingredients:** same library for fission yields (though CFY vs Indep FY + evolution code), very similar choice of decay data (minimizing Pandemonium)

⇒ **Remaining discrepancies:** hypothesis: could come from the (non-)taking into account of the most exotic nuclei at high energy

Outline

- 2 Methods to compute Antineutrino Spectra
- Ingredients for Summation Method spectra
- Conversion Method Revisited
- Update of Summation Method Spectra with TAS data
- News from the field in 2014
- Summation Method Spectra as an explanation of the 4-8MeV distorsion ?
- **Conclusions & Outlooks**

Conclusions & Outlooks

⇒Recent results from reactor neutrino experiments show a substantial deformation of the predictions made with converted ILL data w.r.t. direcly measured antineutrino energy spectra (Double Chooz, Daya Bay, Reno, see this afternoon's talks)

⇒ Summation Method Spectra highly depend on the ingredients coming from the nuclear databases: careful choices should be done

⇒ Associated Systematic Errors are still to be assessed

⇒ Pandemonium Effect is large and difficult to predict the associated error: could explain the bumpy shape quoted by D. Dwyer and T. Langford

⇒ Rudstam set of data is of tremendous importance in this calculation (see J.-L. Tain's talk), and the high energy part changes drastically without them

⇒ The main contributors to the 4 to 8 MeV energy region have been measured with the TAS technique (independent from Pandemonium effect):

⇒ New results will be presented today (see A. Porta's talk)

⇒ Measurements performed in 2014 in Jyväskylä (see A. Algora's talk)

Summary & Conclusions

✓ Can we agree on the best ingredients to use to compute antineutrino spectra with the summation method (state of the art) and provide the community with this piece of information (cf. work done in the frame of IAEA CRP and WPECs) ?

✓ Still additional nuclear uncertainties affecting the converted spectra: forbidden non-unique decays, Weak Magnetism

⇒ BUT Converted Spectra are still the most precise by now

✓ Reactor neutrino experiments still keep them as a reference but try the Summation Method spectra « just to see », and to try to think about potential explanation of the [5-7] MeV bump

⇒ why not ? If used nuclear data are carefully chosen

⇒ BUT Summation Method spectra cannot replace converted spectra by now (maybe in the future with proper systematic errors ?)

✓ Can we agree on the required nuclear information (theory & experiment) to help improving converted spectra ?

THANK YOU

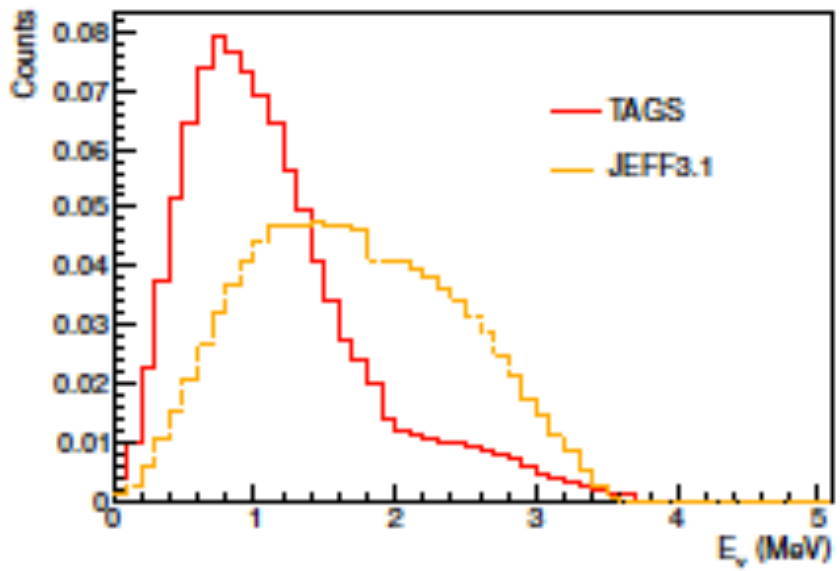


FIG. 1. Illustration of the Pandemonium effect on the ^{105}Mo nucleus anti-ν energy spectrum presents in the JEFF3.1 data base and corrected in the TAS data.

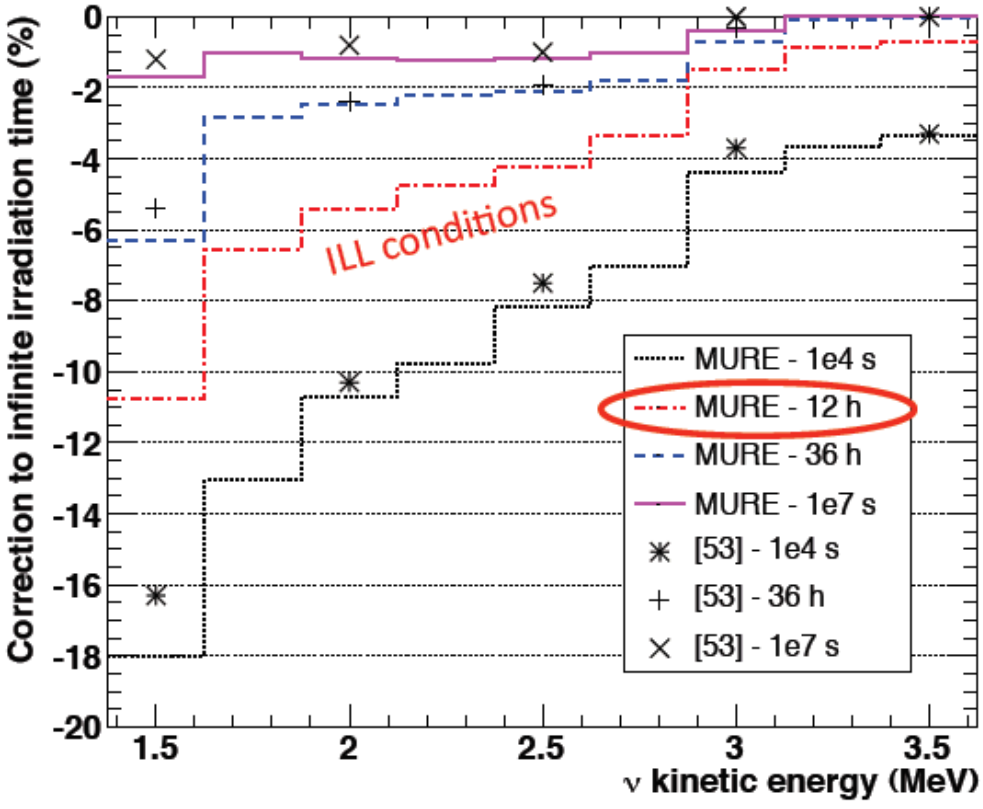
Extracted from M.Estienne's ND2013 proceedings

Off-equilibrium effects

MURE code: core composition and off-equilibrium effects

Relative Off-equilibrium Effect:
close to beta-inverse threshold, a significant fraction of the ν spectrum takes weeks to reach equilibrium
⇒ Sizeable correction of ILL data in the low E range.

Relative change of ν spectrum w.r.t infinite irradiation time



Weak Magnetism

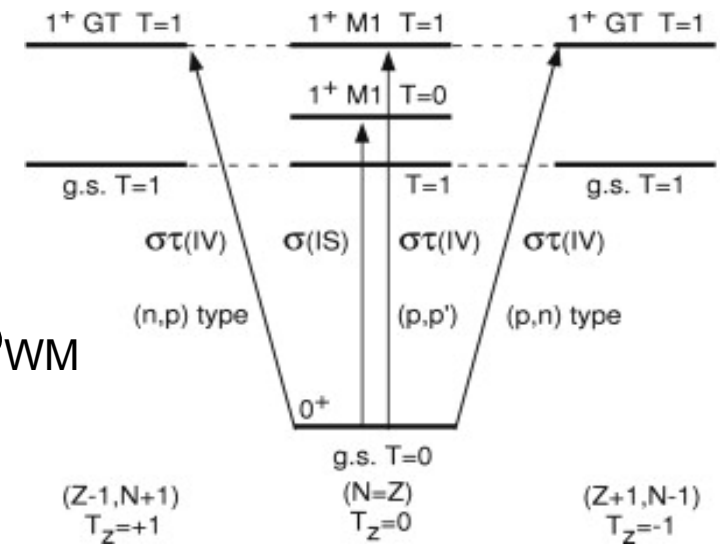
Approximate expression neglecting nuclear structure:

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

Measurement of δ_{WM} through transitions in isobaric analog states:

CVC symmetry

Magnetic dipole M1 γ decay width $\longleftrightarrow$ δ_{WM}



Weak Magnetism

$$1 + \delta_{\mathrm{WM}} W \quad \text{with} \quad \delta_{\mathrm{WM}} = \frac{4}{3} \underbrace{\frac{b}{M\,c}}_{=w} m_e \,,$$

where c is the Gamow-Teller matrix element, b = 2 $\sqrt{\mu}$, with μ the magnetic transition moment and M = AM_N the mass of the nucleus. Experimentally, the transition magnetic moment or b can be determined by measuring the magnetic dipole M1 γ decay width, Γ_{M1} , of the corresponding isovector transition of the isobaric analog state (CVC hypothesis)

$$b = \left(\frac{6\Gamma_{\mathrm{M1}}\, M^2}{\alpha\, E_\gamma^3} \right)^{\frac{1}{2}}$$

Weak magnetism

From P. Huber's PRC

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}]	Ref.
^{6}He $\to$ ^{6}Li	$0^+ \to 1^+$	3560	8.2	72	805	2.77	4.33	0.65	[28]
^{12}N $\to$ ^{12}C	$1^+ \to 0^+$	15110	43.6	38	13100	0.685	4.61	0.60	[29]
^{12}B $\to$ ^{12}C	$1^+ \to 0^+$	15110	43.6	38	11600	0.727	4.34	0.62	[29]
^{18}Ne $\to$ ^{18}F	$0^+ \to 1^+$	1040	0.268	247	1230	2.24	6.13	0.81	[30]
^{20}F $\to$ ^{20}Ne	$2^+ \to 2^+$	5790	2.55	64.5	93300	0.257	12.5	1.72	[31]
^{26}Si $\to$ ^{26}Al	$0^+ \to 1^+$	2700	0.0950	50.9	3550	1.32	1.48	0.19	[32]
^{34}P $\to$ ^{34}S	$1^+ \to 0^+$	5380	0.00494	5.38	145000	0.206	0.766	0.11	[32]
^{58}Cu $\to$ ^{58}Ni	$1^+ \to 0^+$	7390	0.475	55.9	74100	0.288	3.34	0.45	[33]
^{64}Cu $\to$ ^{64}Zn	$1^+ \to 0^+$	3187	0.000147	3.83	200000	0.176	0.341	0.05	[34]
^{66}Cu $\to$ ^{66}Zn	$1^+ \to 0^+$	3230	0.00112	10.7	214000	0.17	0.955	0.14	[35]
^{142}Pm $\to$ ^{142}Nd	$1^+ \to 0^+$	2590	0.000587	23.2	31600	0.441	0.371	0.05	[36]
^{144}Eu $\to$ ^{144}Sm	$1^+ \to 0^+$	3970	0.0950	158	31500	0.442	2.48	0.33	[37]
^{14}O $\to$ ^{14}N	$0^+ \to 1^+$	2310	0.0067	9.16	1.9×10^7	0.018	36.3	4.97	[26]
^{14}C $\to$ ^{14}N	$0^+ \to 1^+$	2310	0.0067	9.16	1.1×10^9	0.00237	276	37.6	[38]
^{32}Si $\to$ ^{32}P	$0^+ \to 1^+$	513	0.000264	39.8	1.55×10^8	0.00631	197	26.8	[32]
^{32}P $\to$ ^{32}S	$1^+ \to 0^+$	4700	0.00171	3.66	7.94×10^7	0.00881	13	1.78	[39]

Experimental slope in good agreement for transitions with low ft values

Contribution of large ft's in fission neutrino spectra ?

⇒ Yes: high log(ft) values have a sizeable contribution to fission ν spectra across all E range (reflects the large contribution of forbidden decays), cf. Lhuillier AAP2012

⇒ No obvious argument can reject a substantially larger WM contribution or error

Error budget in Mueller's paper

Th.A. Mueller et al, Phys.Rev. C83(2011) 054615

Column 2: global effect of the errors quoted in ENSDF at the 1 sigma level.

Columns 3 and 4: impact of the theoretical assumptions used to describe the shape of the β -branches

⇒ Effect of assuming all branches as allowed

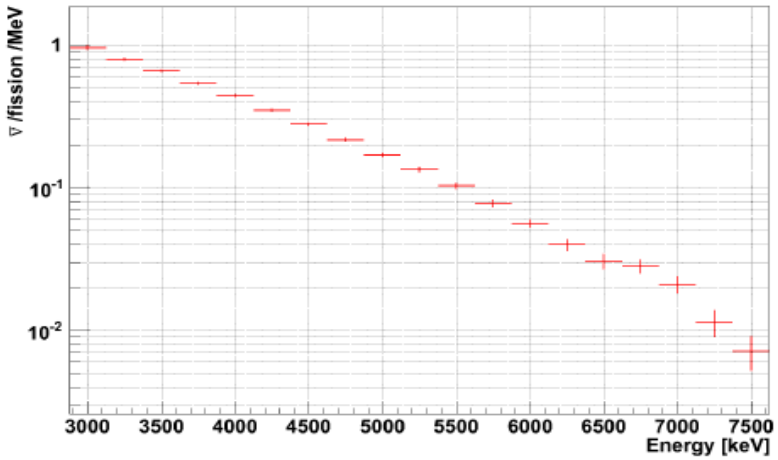
⇒ Effect of Coulomb and WM terms by Vogel

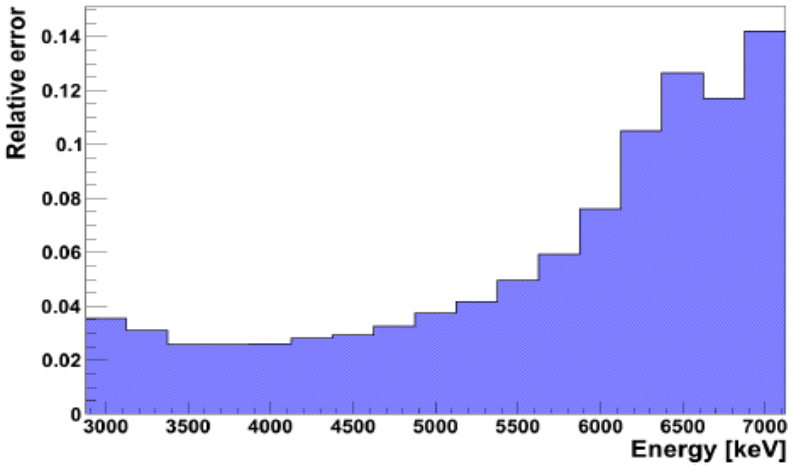
Kinetic E (MeV)	Nuclear databases	Forbid. treatment	$A_{C,W}$ corrections	Missing info.
2.00	1.2	0.2	0.1	10
2.25	1.3	0.2	0.2	10
2.50	1.3	0.1	0.3	10
2.75	1.3	0.1	0.3	10
3.00	1.4	0.4	0.4	10
3.25	1.6	0.7	0.5	10
3.50	1.7	0.1	0.5	10
3.75	1.9	1.3	0.6	10
4.00	2.2	1.6	0.6	10
4.25	2.5	1.6	0.7	10
4.50	2.8	1.4	0.8	10
4.75	3.2	1.0	0.8	10
5.00	3.8	0.5	0.9	10
5.25	4.4	0.2	0.9	10
5.50	5.2	0.2	0.9	15
5.75	6.1	0.2	0.9	15
6.00	7.1	0.2	1.0	15
6.25	8.0	0.3	1.0	15
6.50	9.0	0.4	1.1	15
6.75	10.1	0.4	1.1	15
7.00	10.9	0.5	1.1	20
7.25	11.0	0.7	1.1	20
7.50	10.7	0.8	1.1	> 20
7.75	11.1	0.8	1.2	> 20
8.00	13.3	1.2	1.3	> 20

TABLE II. Sources of errors in the ^{235}U electron spectrum as predicted by the *ab initio* approach. All errors are given in percent at 1σ (68% CL).

The final $\bar{\nu}_e$-spectrum

Antineutrino spectrum of the fission products of ^{238}U:





- Total relative error $\sim 6\,\%$ at 4 MeV (regime interesting for current experiments)
- Spectral distortions of $\sim 10\,\%$