STATUS OF THE PREDICTIONS OF REACTOR ANTI-NEUTRINO SPECTRA

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As well as S. Cormon, M. Estienne for their collaboration
And A. Algora, B. Rubio, J.-L. Tain from IFIC/Valencia for the TAS collab.

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Outline

- Introduction
- Summation Method for Antineutrino Energy Spectrum
- New Conversion Method of Integral Beta Spectra and New Converted Spectra
- On the Nuclear Data Side: Synergy with Decay Heat, Pandemonium Effect, Total Absorption Spectroscopy Technique
- New Reactor Antineutrino Spectra With the Summation Method
- New $^{238}$U integral beta spectrum measurement
- New calculation by Hayes et al.: what about forbidden decays?
- Conclusions and Outlooks
Reactor Antineutrinos

<table>
<thead>
<tr>
<th></th>
<th>$^{235}$U</th>
<th>$^{239}$Pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_f$ (MeV)</td>
<td>201.9</td>
<td>210.0</td>
</tr>
<tr>
<td>$&lt;E_\nu&gt;$ (MeV)</td>
<td>1.46</td>
<td>1.32</td>
</tr>
<tr>
<td>$&lt;N_\nu&gt;$ (E&gt;1.8MeV)</td>
<td>5.58 (1.92)</td>
<td>5.09 (1.45)</td>
</tr>
</tbody>
</table>

Most of Fission Products (FP) are neutron-rich nuclei, undergoing $\beta$ - decay

$$^{A}_Z X \rightarrow ^{A}_{Z+1} Y + e^- + \bar{\nu}_e$$

$^{235}$U

$^{239}$Pu

Reactor Antineutrinos
Most of Fission Products (FP) are neutron-rich nuclei, undergoing β - decay

\[
^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + e^{-} + \bar{\nu}_e
\]

⇒ Power Reactors are copious antineutrino emitters => neutrino physics = oscillation parameter search: $\theta_{13}$, search for sterile neutrinos (« reactor anomaly »)
⇒ Use the discrepancy between antineutrino flux and energies from U and Pu isotopes to infer reactor fuel isotopic composition => reactor monitoring, non-proliferation and interest of the IAEA (see IAEA Report SG-EQGNRL-RP-0002 (2012).)
Reactor antineutrinos

- Standard nuclear power plant 900 MWe:

- Usually detection through inverse-β process on quasi-free protons:
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \]

  - Reaction threshold: 1.8 MeV
  - Cross section: \( \langle \sigma \rangle \sim 10^{-43} \text{cm}^2 \)

- Time correlation: \( \tau \sim 30 \mu s \)

- Space correlation: \(< 1 \text{m} \)

\[ \frac{2800 \text{ MW}^{\text{th}}}{200 \text{ MeV}} \times 6 \bar{\nu}_e \sim 5 \times 10^{20} \bar{\nu}_e / s \]

[\text{C. Bemporad et al., Rev. of Mod. Phys., 74 (2002)}]


⇒ The Double Chooz experiment has devoted efforts to new computations of reactor antineutrino spectra

⇒ Two 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}\text{U},^{239}\text{Pu} \text{ and }^{241}\text{Pu} \text{ 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
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Summation Method: Method based on individual fission product beta decay summation

\[ N(E_\nu) = \sum_n Y_n(Z, A, t) \cdot \sum_i b_n, i(E_0^i) P_\nu(E_\nu, E_0^i, Z) \]

- **Core Simulation Evolution Code**: MURE (MCNP Utility for Reactor Evolution)
- **Core geometry**
- **fissile mat. + FY**
- **neutron flux**
- **β-branch**
- **exp. spectrum**
- **models**
- **β-spectra database**: TAGS, Rudstam et al., ENSDF, JEFF, JENDL, ...
- other evaluated nuclear databases

**β^- decay rates**

\[ Y_i(Z, A, t) \]

**Total ν_e and β^- energy spectra**

with possible complete error treatment + off-equilibrium effects
Beta Decay Selection Rules

\[ J_i = J_f + L + S \], with \( J_i \): total angular momentum of mother nucleus, \( J_f \) of the daughter nucleus in populated state, \( L \): angular momentum taken by electron-neutrino pair and \( S \): sum of Spins of electron and neutrino (1/2).

**Allowed Transition: \( L=0 \),**
If \( S=0 \): electron and neutrino have their spin anti-parallel (Fermi decay) : singlet state 0
IF \( S=1 \): parallel spins, triplet state 0, +1 ou -1 : Gamow-Teller transitions, and 0+ -> 0+ not possible.

\[ \begin{align*}
\text{n, } &+1/2 \rightarrow \text{p, } +1/2 + \text{e, } \nu \rightarrow 0, \\
\text{singlet, spin 0} &
\end{align*} \]
Beta Decay Selection Rules

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Forbidden transitions: \( L \neq 0 \), \( L=1 \) first forbidden, \( L=2 \) second forbidden... can be of Fermi or G-T type.
Electron + neutrino wave function parity : \((-1)^L\).
If \( S=0 \) et \( L=1 \) : \( \Delta J = |J_f - J_i| =0, +/-1 \) (no 0->0),
If \( S=1 \) et \( L=1 \) : \( \Delta J = |J_f - J_i| =0, +/-1 , +/-2 \) (no 0->0) and \( \Delta \pi = \text{yes} \).

These transitions have a weaker rate than allowed ones.
1st forbidden transitions: can be a mix of F and GT, except : \( \Delta J = +/-2 \) which are only GT =>
1st forbidden unique transitions.
=> General case for a given \( L \): transitions with \( \Delta J = L+1 \) are only GT and called "unique".
**β-decay and Classification of β-spectra:**

<table>
<thead>
<tr>
<th>Classification</th>
<th>ΔJ</th>
<th>Δπ</th>
<th>logft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowed</td>
<td>0,±1 (0+ → 0+)</td>
<td>No</td>
<td>4-6</td>
</tr>
<tr>
<td>1st forbidden non-unique</td>
<td>0, ± 1</td>
<td>Yes</td>
<td>6-10</td>
</tr>
<tr>
<td>1st forbidden unique</td>
<td>± 2</td>
<td>Yes</td>
<td>7-10</td>
</tr>
<tr>
<td>2nd forbidden non-unique</td>
<td>± 2</td>
<td>No</td>
<td>11-14</td>
</tr>
<tr>
<td>2nd forbidden unique</td>
<td>± 3</td>
<td>No</td>
<td>14</td>
</tr>
<tr>
<td>3rd forbidden non-unique</td>
<td>± 3</td>
<td>Yes</td>
<td>17-19</td>
</tr>
<tr>
<td>3rd forbidden unique</td>
<td>± 4</td>
<td>Yes</td>
<td>18</td>
</tr>
</tbody>
</table>

- Transition rate \( \lambda = 0.693/T_{1/2} \)

Commonly is introduced the quantity \( f_t \propto \text{Const.}/ |M_{fi}|^2 \), allows to compare decay probabilities, only due to the nuclear matrix elements and how forbidden it is.

- The majority of β-transition are classified as allowed type.
Ingredients to Build Beta and Antineutrino Spectra

N_β (W) = K \ pW(W-W_0)^2 \ F(Z,W)L_0(Z,W)C(Z,W)S(Z,W)G_β (Z,W) (1+δ_{WM} W)

Where W=E/m_e c^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_β (Z,W) = radiative corrections involving real and virtual photons

δ_{WM} = weak magnetism term
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- \( G_\beta (Z,W) = \text{radiative corrections involving real and virtual photons} \)
- \( \delta_{WM} = \text{weak magnetism term (decaying quark is bound in the nucleon)} \)

- **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
But Discrepancy with ILL spectra:
Overestimate of the reference spectra @ high energy + shape distortion
⇒ Requires new measurements of fission product beta decay properties
⇒ 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
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Newly Converted Spectra


- Antineutrino flux used in oscillation exp. = from conversion of integral beta spectra from ILL (A.A. Hahn et al. PLB160, 325(1989) and ref. incl.): converted to antineutrino spectrum by fitting to 30 end-point energies (30 virtual branches)

- Develop a mixed approach using nuclear databases + virtual branches to reproduce the ILL spectra

\[
\text{Ratio of Prediction / Reference ILL data}
\]

- 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

Built with Nuclear Data
Recent re-evaluations by
- P. Huber, Phys.Rev. C84 (2011) 024617

- Off-equilibrium corrections included
  (computed with MURE)

- Summation calculations, database comparisons and fission product
distribution= new $^{238}\text{U}$ prediction

Recent works defining new reference on the neutrino flux prediction 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 $\nu$ spectra = $\sim +3\%$ normalization shift with respect to old $\nu$ spectra, similar results for all isotopes ($^{235}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$)
  - Neutron life-time
  - Off-equilibrium effects

2 flavour simple scheme:
$$P_{\text{Osc}} = \sin^2 2\theta \sin^2 (1.27 \Delta m^2_{\text{atm}} L / E_{\text{MeV}})$$

=> Light sterile neutrino state? could explain $L=10-100$ m anomalies, $\Delta m^2 \approx 1$ eV$^2$
- candidate can’t interact via weak interaction: constrained by LEP result on 3 families
=> so can only exist in sterile form
Newly Converted spectra...

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⇒ « 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 => could change normalization of spectra, or normalization of ILL data
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Antineutrino spectrum calculations independent from ILL data would be desirable...

The reactor antineutrino spectrum built with nuclear data suffers from the Pandemonium Effect:
⇒ TAS experiments
Total Absorption gamma-ray Spectroscopy 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

**Solution**: Total Absorption Spectroscopy (TAS)

Big cristal, $4\pi \Rightarrow$ A TAS is a calorimeter!

- 12 BaF$_2$ covering $\sim 4\pi$
- Detection efficiency of γ ray cascade $\sim 80\% @ 5$MeV
- 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)


Picture from A. Algora
TAS MEASUREMENTS @ JYVÄSKYLÄ UNIV. (JYFL)

- IFIC of Valencia (J.L. Tain et A. Algora et al.)
  Reactor Decay Heat in $^{239}$Pu: Solving the $\gamma$ Discrepancy in the 4-3000-s Cooling Period,

⇒ Taking into consideration the TAS data of the $^{102,104-107}$Tc, $^{105}$Mo, and $^{101}$Nb isotopes measured @ Jyväskylä
⇒ 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 (~850 nuclei !!!!)

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Summation Method: New Spectra


- **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, all FP taken into account

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

- Careful choice of nuclear databases, privileging TAS data to avoid Pandemonium as much as possible

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

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

⇒ i.e. **correcting 5 nuclei out of 7 for the Pandemonium effect, among ~850 Fission Products !!!**
Inclusion of the latest TAS data in the Antineutrino Summation Spectra:

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

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

⇒ 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 antineutrino spectra independently from the still unique ILL integral $\beta$-spectra
⇒ New measurements required, list of nuclei identified should reduce errors significantly
⇒ Measurements are programmed next year in Jyväskylä and in Argonne in 2014
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$^{238}$U integral beta energy spectrum measured!

Antineutrino spectrum of the fission products of $^{238}$U: N. Haag PhD thesis, TU Muenchen

Total relative error 6% at 4 MeV (regime interesting for current experiments)

Spectral distortions of ~10% with summation method spectra
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What about forbidden decays?

- A. Hayes et al. arXiv:1309.4146v2:
  - Out of ~6000 beta decay transitions ~1500 are forbidden transitions
  - Phase space factor and Weak Magnetism expressions have to be modified for Forbidden non-unique transitions, and the corrections are not the same for beta and antineutrinos (= what really matters as the beta spectrum is fixed to the ILL data in the conversion method):

<table>
<thead>
<tr>
<th>Classification</th>
<th>$\Delta J^\pi$</th>
<th>Operator</th>
<th>Shape Factor $C(E_e)$</th>
<th>Fractional Weak Magnetism Correction $\delta_{WM}(E_e)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowed GT</td>
<td>$1^+$</td>
<td>$\Sigma \equiv \sigma \tau$</td>
<td>1</td>
<td>$\frac{2}{3} \left( \frac{\mu_{\nu} - 1/2}{M_{NGA}} \right) (E_e\beta^2 - E_{\nu})$</td>
</tr>
<tr>
<td>Non-unique 1$^\text{st}$ Forbidden GT</td>
<td>$0^-$</td>
<td>$[\Sigma, r]^{0-}$</td>
<td>$p_e^2 + E_{\nu}^2 + 2\beta^2 E_{\nu} E_e$</td>
<td>0</td>
</tr>
<tr>
<td>Non-unique 1$^\text{st}$ Forbidden $\rho_A$</td>
<td>$0^-$</td>
<td>$[\Sigma, r]^{0-}$</td>
<td>$\lambda E_0^2$</td>
<td>0</td>
</tr>
<tr>
<td>Non-unique 1$^\text{st}$ Forbidden GT</td>
<td>$1^-$</td>
<td>$[\Sigma, r]^{1-}$</td>
<td>$p_e^2 + E_{\nu}^2 - \frac{4}{3} \beta^2 E_{\nu} E_e$</td>
<td>$\frac{\mu_{\nu} - 1/2}{M_{NGA}} \left( \frac{(p_e^2 + E_{\nu}^2)(\beta^2 E_{\nu} - E_e) + 2\beta^2 E_e E_{\nu}(E_{\nu} - E_e)/3}{(p_e^2 + E_{\nu}^2 - 4\beta^2 E_{\nu} E_e/3)} \right)$</td>
</tr>
<tr>
<td>Unique 1$^\text{st}$ Forbidden GT</td>
<td>$2^-$</td>
<td>$[\Sigma, r]^{2-}$</td>
<td>$p_e^2 + E_{\nu}^2$</td>
<td>$\frac{3}{5} \left( \frac{\mu_{\nu} - 1/2}{M_{NGA}} \right) \left( \frac{(p_e^2 + E_{\nu}^2)(\beta^2 E_{\nu} - E_e) + 2\beta^2 E_e E_{\nu}(E_{\nu} - E_e)/3}{(p_e^2 + E_{\nu}^2 - 4\beta^2 E_{\nu} E_e/3)} \right)$</td>
</tr>
<tr>
<td>Allowed F</td>
<td>$0^+$</td>
<td>$\tau$</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Non-unique 1$^\text{st}$ Forbidden F</td>
<td>$1^-$</td>
<td>$r \tau$</td>
<td>$p_e^2 + E_{\nu}^2 + \frac{2}{3} \beta^2 E_{\nu} E_e$</td>
<td>0</td>
</tr>
<tr>
<td>Non-unique 1$^\text{st}$ Forbidden $\bar{\nu}$</td>
<td>$1^-$</td>
<td>$r \tau$</td>
<td>$E_0^2$</td>
<td>-</td>
</tr>
</tbody>
</table>

- Without detailed nuclear structure information there is no method of determining which operators determine the 1500 forbidden transitions
- If significant contribution for forbidden non-unique transitions in the decays of the fission products => uncertainty associated to the conversion may be greater than 5% over the whole energy range.
What about forbidden decays?

A. Hayes et al. arXiv:1309.4146v2

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

Different colors correspond to each single operator => The forbidden transitions introduce an operator-dependent distortion of spectrum.

In reality there will be a mixture of these and other operators.
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INT Workshop in Seattle on Antineutrino Spectra

Organized by G. Bertsch, A. Sonzogni and A. Hayes

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)...

Talks can be found there: http://www.int.washington.edu/talks/WorkShops/int_13_3/

Converted spectra:

⇒ The largest uncertainty (cf. Huber PRC84,024617(2011)) comes from the weak magnetism term (too few experimental values that would allow to compute it for fission products): constraints from precised reactor antineutrino experiments (DB, DC, Reno)

⇒ 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

⇒ Potential effects of compensation in the full conversion of the ILL spectra not computed yet?

⇒ Toward an agreement on the expressions of the corrections to Fermi theory
Nuclear Data for Summation Method Spectra

⇒ Agreement on a short list of important contributors (Subatech, BNL) to re-measure to correct from the Pandemonium bias in the databases is established, experiments are on-going

⇒ Pandemonium bias distorts largely the Summation Method spectra: needs to be corrected before using them

⇒ A survey of forbidden non-unique cases for which the shape of the beta spectra were measured will be performed

⇒ Fission Yields status

⇒ Tentative error envelop calculation (?)

⇒ But overall good agreement with Nils Haag’s measurement of 238U integral beta spectrum reassuring!
Conclusions & Outlooks

- The ILL data are still the only and most precise measurements, considered as a reference in neutrino physics. Newly converted ν spectra => normalization shift w.r.t previous ν spectra => « reactor anomaly »

- Independent evaluations of the reactor spectra could provide new constraints on the existence of light sterile neutrinos. A possible alternative = spectra built with the summation method

- Pandemonium nuclei play a major role in the estimate of the antineutrino spectra using the summation method and TAS measurements of these nuclei could allow us to improve drastically the predictiveness of these spectra (analysis on-going and new experiment planned in 2014).

- The inclusion of the shape distortion due to first forbidden non-unique transitions should be tested in the ILL data conversion procedure before drawing any definite conclusions

- INT workshop on antineutrino spectra: an effort to provide a summary of the situation to the neutrino and nuclear communities

- Interest for safeguards: ESARDA WG + IAEA Ad-Hoc WG;