Reactor Antineutrinos & Non Proliferation:

- Experimental needs for a better knowledge of the antineutrino spectra from $^{235}\text{U}$, $^{239,241}\text{Pu}$, $^{238}\text{U}$
Outline

- Development of MURE simulation tool for scenario studies...
- Previous measurements of antineutrino energy spectra
- « Dissection » of antineutrino energy spectrum of $^{235}$U : FP contributions
- Interfacing MURE with nuclear databases and using an interface on the Beta-S code
- Conclusions and outlooks
Simulation effort

Fission product proportions vary with the fuel burn-up and with time because of the wide range of half-lives involved.

Aim = Simulation of the anti-neutrino spectrum built from the fission product spectra

For proper translation from beta to antineutrinos: individual end-points and shapes

Need for « dynamical » calculation to simulate the evolution of fuel composition and the decay chains of the fission products

Simulation effort

Developments to obtain a precise calculation of the evolution with time of the antineutrino spectrum in order to have a generic tool for proliferation scenario studies (even for rapid changes).

1 - Simulated spectra of emitted antineutrinos from the fission of $^{239}$Pu and $^{235}$U using MURE:

2 - Folding with the detection cross-section

Threshold: 1.804 MeV

3 - Cumulative spectrum in energy of antineutrinos folded by the detection cross-section
Starting an experimental program...

**Theoretical approach**: Klapdor & Metzinger microscopic calc. of trans. matrix elements (PLB82 + PRL82), Vogel et al. for $^{238}\text{U}$

**Integral $\beta$-spectra** measured by Schreckenbach et al. (at better than 2% until 8 MeV) & Hahn et al. @ILL $^{235}\text{U}$, $^{239,241}\text{Pu}$ targets, but conversion: global fit including 30 arbitrary contributions: global shape uncertainty from 1.3%@3MeV to 9%@8MeV

**FP contributions**: measurements of Tengblad et al. 111 nuclei @ISOLDE and OSIRIS don’t agree with the experimental integral spectra (important errors: 5% at 4MeV, 11% at 5MeV and 20% at 8MeV)

**Chooz and Bugey**: energy spectrum and flux in agreement with Schreckenbach et al. + Vogel et al., 1.9 % error on reactor $\nu_e$ flux

According to Bemporad et al. unknown decays contribute as much as 25% of the antineutrinos at energies $> 4\text{MeV}$ !? (Bemporad et al., Rev. of Mod. Phys.74 2002)

**First list of n-rich nuclei**: $^{86}\text{Ge}$, $^{90-92}\text{Se}$, $^{94}\text{Br}$, $^{94-98}\text{Kr}$, $^{100}\text{Rb}$, $^{100-102}\text{Sr}$, $^{108-112}\text{Mo}$, $^{106-113}\text{Tc}$, $^{113-115}\text{Ru}$, $^{130-131}\text{Cd}$...
Examinating the FP contributions

- Tengblad et al. included 370 nuclides in his spectrum including 111 exp. spectra from short half-lives, but also 177 BR and end-points (spin/parity ?), 25 known β-strengths and 67 extrapolated β-strength !!!

- First step = build back the spectrum obtained that time

  ✓ **Need to read nuclear databases:**

  - ENSDF : BR and endpoints, spin/parities when known!
  - JEFF3.1 : BR and endpoints, spin/parities when known
  - ENDF-B-VI : BR, endpoints, spin/parities + continuous spectra by Gross theory
  - JEF2.2 : contains some of the spectra measured by Tengblad et al.

  ✓ **Beta Decay Theory to have the spectrum shape:**

  Fermi Theory of Beta Decay:
  - Assumes a Weak interaction at a point.
  \[
  \lambda = 2\pi \left| V_{fi} \right|^2 \rho(E_f) \text{ where } V_{fi} = \int \psi_f^* V \psi_i \, dv \\
  \rho(E_f) = \frac{dn}{dE_f} \text{ - no.of states in interval } dE_f
  \]
Beta Decay Theory

The shape of the spectrum goes like:

\[ N(Z, W) dW = g^2 / 2\pi^3 \times F(Z, W) \times \rho W(W_0 - W)^2 \times S_n(W) \, dW \]

- **Weak interaction coupling constant**
- **Fermi Function**
- **Momentum in \( m_e c^2 \) units**
- **Total electron energy in \( m_e c^2 \) units**
- **Shape factor for allowed and nth forbidden transition**
- **Nuclear Matrix element**

\( \sigma \tau \) Gamow-Teller or \( \tau \) Fermi

- **2p 1/2**
- **1f 5/2**
- **2p 3/2**

\( \sigma \tau \)

- **1f 7/2**

\( \sigma \tau \)

- **2p 3/2**
- **1f 5/2**

End point

Total electron energy in \( m_e c^2 \) units

Shape factor for allowed and nth forbidden transition

Nuclear Matrix element

Fermi Function

Momentum in \( m_e c^2 \) units

Weak interaction coupling constant

End point
**β-decay and Classification of β-spectra:**

<table>
<thead>
<tr>
<th>Classification</th>
<th>$\Delta J$</th>
<th>$\Delta \pi$</th>
<th>$\log f t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowed</td>
<td>$0, \pm 1$ (0+ $\leftrightarrow$ 0+)</td>
<td>No</td>
<td>4-6</td>
</tr>
<tr>
<td>1st forbidden non-unique</td>
<td>$0, \pm 1$</td>
<td>Yes</td>
<td>6-10</td>
</tr>
<tr>
<td>1st forbidden unique</td>
<td>$\pm 2$</td>
<td>Yes</td>
<td>7-10</td>
</tr>
<tr>
<td>2nd forbidden non-unique</td>
<td>$\pm 2$</td>
<td>No</td>
<td>11-14</td>
</tr>
<tr>
<td>2nd forbidden unique</td>
<td>$\pm 3$</td>
<td>No</td>
<td>14</td>
</tr>
<tr>
<td>3rd forbidden non-unique</td>
<td>$\pm 3$</td>
<td>Yes</td>
<td>17-19</td>
</tr>
<tr>
<td>3rd forbidden unique</td>
<td>$\pm 4$</td>
<td>Yes</td>
<td>18</td>
</tr>
</tbody>
</table>

- Transition rate $\lambda = 0.693$. We introduce $f t_{1/2} \propto \text{Const.}/|M_{fi}|^2$.
- The vast majority of β-transition are classified as allowed type.
- «Shape factors»: emphasize the high energy region of the spectra compared with allowed spectra.
« BESTIOLE » package : interface by D. Lhuillier (CEA/SPhN) on BETA-S code from Oak Ridge*

- Reads ENSDF Branching ratios, End-points and spin/parities

- Allowed, 1st, 2nd and 3rd forbidden unique transitions are explicitly represented

- 1st forbidden non-unique : shape factor $S_1(W)$ independent of energy = idem as allowed transitions

- 2nd and 3rd forbidden non-unique : original approximation = assumed to have an allowed shape

  Modified to take the 1st and 2nd forbidden unique shape instead

*Report COG-96-33-I RC-1564
Results

Tengblad et al. 1 year of irradiation
Compared with BESTIOLE for ~950 nuclei with cumulative yields

Tengblad et al. 20 min. of irradiation
Compared with MURE 20 min. evolution using the spectra from BESTIOLE

No Condition:
~950 nuclei in ENSDF database

Including more nuclei:
among them exotic nuclei, with short half-lives, high endpoints, and more numerous forbidden transitions

Condition: 370 nuclei considered by Tengblad et al.
Results

Tengblad et al. 1 year of irradiation
Compared with BESTIOLE and 75 exp. spectra among the 111 measured by Tengblad et al. for ~950 nuclei with cumulative yields

Tengblad et al. 20 min. of irradiation
Compared with MURE 20 min. evolution for BESTIOLE and 75 exp. spectra

Including exp. spectra:
- Nearly reconstitutes Tengblad spectrum
- We clearly see some more nuclei should be taken into account at high energy + more exp. spectra when forbidden non-unique transition !!!
→ Solving the shape discrepancy with Schreckenbach et al.?
Towards a better understanding of antineutrino spectra: n-rich fission products beta decay

Double-Chooz phase 1: when only far detector, => better precision on the reactor $\nu_e$ spectrum very useful

Double-Chooz phase 2: best measurement of reactor $\nu_e$ spectrum and flux $\sim 10^5$ evts/y

Nuclear reactor physics and safety (decay heat calc.)
/future (Gen. IV) reactors (decay heat + $\beta$-delayed n)

Nuclear structure (exotic nuclei), nuclear astrophysics for the most exotic ones...

Astroparticle physics: future neutrino experiments (relic Supernovae...) $\nu$ spectrum never measured beyond 8 MeV

Muriel Fallot - 26 sept. 2006
Strong common points with measurements for reactor decay heat calculation in nuclear reactors

- Data required-cross-sections, fission yields, decay half-lives, mean beta and gamma energies, neutron capture cross-sections and uncertainties in these data.

The problem of measuring the $\beta$-feeding (if no delayed part. emission)

- We use our Ge detectors to construct the decay scheme
- From the $\gamma$-balance we extract the $\beta$-feeding

Low efficiency of Ge detectors at high energy $\Rightarrow$ Pandemonium effect $=$ displacement of the $\beta$-strength (overestimation of high energies)

« Pandemonium effect » $=$ indication to explain the discrepancy between Tengblad and Schreckenbach?

From W. Gelletly et al.
Test experiment @ Institut Laue-Langevin High Flux Reactor (Grenoble) last summer:

- \( \beta \)-spectra measurements for \( A=90, 94 \):
  - beta singles + \( \beta-\gamma \) coincidences
  - LOHENGRIN Spectrometer : \( A/q \)
  - Target \( ^{235}\text{U}(6\text{mg}) \)
  - 25.8mm Silicon detector

- Test of the simulation of the evolution of beta spectra from isobaric chains \( A=90,94 \)

- Analysis on going..., PhD thesis of S. Cormon

- Propose experiments on the ALTO facility for the next PAC: ex: intensities of Br-Kr-Rb 100 times bigger than ILL.

- Good point: discussions started with collaboration for decay heat related measurements (J.L. Tain, W. gelletly et al.) on ALTO: some nuclei in common

- Measure integral \( \beta \) spectrum from fast \( ^{238}\text{U} \) fission: theoretical calculation from Vogel et al. (89), error \( \leq 10\% \), gives \( \leq 8\% \) of PWR reactor antineutrinos
Conclusions and outlooks

- Possible origins of discrepancies between previous measurements:
  - lack of short half-life nuclei
  - highly forbidden transitions more important at high energy
  - Pandemonium effect in nuclear data basis?

- Comparison between ENSDF and ENDF, JEFF...

- Theoretical point of view: Gross Theory for $\beta$- decay, Microscopic models?

- Isolate the most pertinent nuclei to be measured (forbidden non-unique transitions) that influence the spectrum shape (especially high energy part)

- Proposal to use the ALTO facility, GANIL... $^{238}$U beta spectrum?
  + Moscow-Kurchatov initiative...