Neutrino Sciences 2005

Neutrinos & Non-proliferation in Europe

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Physics principles allowing monitoring
Fission with two humps

235U

239Pu

Atomic mass of fission fragments
A complex physic to predict emitted $\beta$ spectrum

a simple example

$$Q_\beta = 6490$$

$$Q_\beta = 4950$$

$$Q_\beta = 3640$$

$$Q_\beta = 1917$$

$$Q_\beta = 567$$

Cooling time
### Few basic numbers

<table>
<thead>
<tr>
<th></th>
<th>$^{235}\text{U}$</th>
<th>$^{239}\text{Pu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>released energy per fission</td>
<td>201.7 MeV</td>
<td>210.0 MeV</td>
</tr>
<tr>
<td>maximum energy of $\nu$</td>
<td>9.0 MeV</td>
<td>7.4 MeV</td>
</tr>
<tr>
<td>$\nu$ per fission $&gt;1.8$ MeV</td>
<td>1.92</td>
<td>1.45</td>
</tr>
<tr>
<td>average inter. cross section</td>
<td>$\approx 3.2 \times 10^{-43}$ cm$^2$</td>
<td>$\approx 2.76 \times 10^{-43}$ cm$^2$</td>
</tr>
</tbody>
</table>

\[
\frac{\# \text{int}^{235}\text{U}}{\# \text{int}^{235}\text{Pu}} = \frac{210.0}{201.7} \times \frac{1.92}{1.45} \times \frac{3.2}{2.76} = 1.60
\]
A toy model
of a nuclear power plant

- Order of magnitudes of the effects
- A very simplified view of the core
  - homogeneous neutron flux
  - $\langle \Phi \sigma \rangle$
- Allow to size the difficulty of the question
The burn-up

\[ \beta(n, \gamma) \text{ fission} \]
The 1st cycle

110 tons of U @ 3.5% in $^{235}$U

Evolution of the fuel over the 1st cycle

Mass (g) of the isotope vs. Irradiation time (days)

$\langle \Phi \rangle = 7 \times 10^{13} \text{n/cm}^2 \text{s}$

th : 33% ; ep : 0.5% ; ra : 42%
A normal cycle

107 tons of $^{238}\text{U}$
225 kg of $^{235}\text{U}$
50 kf of Pu

Evolution of the fuel over one normal cycle

$<\Phi> = 7 \times 10^{13} \text{ n/cm}^2 \text{ s}$
$th: 33\%; ep: 1\%; ra: 42\%$
Thermal power

Evolution of the power over one normal cycle

\[ \langle \Phi \rangle = 7 \times 10^{13} \text{ n/cm}^2 \text{ s} \]

th : 33% ; ep : 1% ; ra : 45%
Neutrino Spectrum : 1-5 d

"Double Chooz detector" @ 150 m

Recorded spectrum between 0 and 5 days

3545 evts
Neutrino Spectrum : 100-105 d

only 1 reactor
"Double Chooz detector"
@ 150 m

Recorded spectrum between 100 and 105 days

Visible Energy in MeV

dN/dE

3401 evts
Neutrino Spectrum: 350-355 d

only 1 reactor
"Double Chooz detector"
@ 150 m

Recorded spectrum between 350 and 355 days

Visible Energy in MeV

3029 events
A diversion…
…without stop

Diversion signature
in a 12.7 m$^3$ $\nu$ detector @ 50 m

Remove 20 kg of $^{239}$Pu
Add 28.4 kg of $^{235}$U

$\nu$ counting in 10 days:
- normal: 61160 ± 250
- diversion: 61410 ± 250

a $\pm$ $\sigma$ effect
More sophisticated simulations

- Professional reactors codes
  - MCNP, Appolo, determinist codes
  - Evolution: Mure, Origen
  - Emission of antineutrinos
    - in time, in energy
  - Coupling with detector simulation and backgrounds

- Study of diversion scenarios
  - simplist: invented by physicists
  - realist: interaction with AIEA

- Neutrino monitors for control
  - masse, performances, place
  - simplification needed
  - what can be really controled? Is it needed?
What is MURE*? 

*Mure : Blackberry in french

MCNP Utility for Reactor Evolution
C++ code interfacing MCNP and an Evolution code.

**Principle**

- MCNP: Monte Carlo code designed for calculations of neutron flux inside a reactor.

- MURE runs MCNP to evaluate production of nuclei
- Evolution code to follow transmutation of these nuclei
Evolution

- MCNP = photography of core at given time
- Build a « Base of links » between all potential nuclei in material
- Then, solve Bateman equations:

\[
\frac{dN_i}{dt} = \sum_j \lambda_j^{\to i} N_j - \lambda_i N_i + \sum_j N_j \sigma_j^{\to i} \langle \phi \rangle - N_i \sum_r \sigma_i^{\to r} \langle \phi \rangle
\]

...which is done in time steps (Bsteps):

\[\Delta t_{MCNP} = N_B \delta t_B\]
Approximations

- Optimize computation time
  - by-pass short half lived nuclei (the ones that β-decay…)
- Reaction rate $<\sigma \phi>$ extrapolation between 2 MCNP runs
Could we deduce isotopic composition from neutrino measurements?

Recorded positron spectrum

A different spectrum by fissile isotope
What is the precision required?

10^6 evts : 10 tons @ 10m in 10d
Power determ. in 1d @ 3%
Pu content poorly determ. @ > 10% in 10d with present knowledge of flux

Improve flux determ.

P. Huber & T. Schwetz, hep-ph/0407076,
*Precision spectroscopy with reactor antineutrinos*
Related experimental effort in France

O. Bringer\textsuperscript{1}, S. Chabod\textsuperscript{1}, S. Cormon\textsuperscript{2}, M. Fallot\textsuperscript{2}, H. Faust\textsuperscript{3}, Y. Foucher\textsuperscript{2}, U. Kayser\textsuperscript{4}, A. Letourneau\textsuperscript{1}, P. Mutti\textsuperscript{3}, Y. Tall\textsuperscript{2}, K. Zbiri\textsuperscript{2}

\textsuperscript{1}CEA Saclay (SPhN) \hspace{1cm} \textsuperscript{2}Subatech (Nantes) \hspace{1cm} \textsuperscript{3}ILL Grenoble \hspace{1cm} \textsuperscript{4}Univ. Braunschweig
Experiments at ILL

- H9 beam channel (98% thermal spectrum) (6 $10^{14}$ n/s/cm²)
- Mini-Inca chamber
- $\alpha, \gamma, \beta$ spectroscopy
- D$_2$O tank
- Lohengrin mass separator
- Samples automatically transported
  Irradiations $<=$ Measurements

December 16, 2005
Michel Cribier
Individual β spectrum of short life fission products

- Fission rate $\approx 10^{12}/s$ at target
- Several target: Np $\rightarrow$ Cf
  - thus explore fission humps
- The Lohengrin spectrometer at ILL
  - selection in A/q
- On line selection by isobar
  - access to FP $\approx \mu$s
- Measure $Q_\beta$ important for detected $\nu$
An ambitious experimental programme

- **A fact** (quoted by C. Bemporad)
  - unknown decays contribute as much as 25% of the antineutrinos at energies > 4MeV!

- **Integral spectra** measured by Schreckenbach et al.
  - precision better than 2% up to 8 MeV

- **Fission products contributions to neutrino spectra**
  - measurements of Tengblad et al.
  - disagreement with experimental integral spectra
    - important errors: 5% at 4MeV, 11% at 5MeV and 20%

- **Focus on n-rich nuclei**
  - with yields very different in $^{239}$Pu and $^{235}$U fission:
    - $^{86}$Ge, $^{90-92}$Se, $^{96-98}$Kr, $^{100}$Rb, $^{100-102}$Sr, $^{108-112}$Mo, $^{106-113}$Tc, $^{113-115}$Ru...

- **Irradiation tests last summer. Analysis in progress**
Yields dominated by Kr and Rb.
Integral $\beta$ spectrum

ILL high flux : 1 day (H9) $\approx 20d$ PWR
Fast measurements of decays products
$\beta$ spectrum study for :
- $^{235}$U, $^{239}$Pu...
- different irradiation time : burn-up
- different cooling time

to install
Within

The near detector @ 200 m from cores
What is planned?

- Wonderful overlap with Double Chooz oscillation ($\theta_{13}$) experiment
  - need to improve neutrino spectrum
  - need to improve knowledge of burn-up
  - no new equipment required

- Precise $\nu$ spectrum vs fissile element ($^{235}\text{U}, ^{239}\text{Pu}$):
  - high statistic with Double Chooz (near): $5 \times 10^5 \nu$ detected per year
  - correlation with fuel composition
  - correlation with thermal power

- Good exchange with EDF needed
  - history of the fuel rods, position

- At least a valuable database

- Project: install a smaller detector closer from cores
Toward a prototype of monitor

- **Double Chooz approach**
  - good energy measurement
  - good signal/noise
  - too sophisticated
  - expensive

- **Sands approach**
  - weak ν signature
  - not enough rejection of background
  - robust, simple
  - automatic
  - cheap
Interest?

- Closer cooperation with LLNL
- Combine mutual experience of detectors
- Test/measure at ILL: core of $\approx$ pure $^{235}$U
  - very pure $\nu$ signal vs burn-up
  - calibration of the $\nu$ vs thermal power
  - simple simulation of the nuclear core
- A demonstrator to be shown at AIEA
- An already usable tool to measure the thermal power
Conclusions

- **Non prolif. issues : a tough job !**
  - realistic diversion (~50 kg Pu) is a small effect
  - define correct conditions : detector size/positions
  - re-measure \( \nu \) spectrum emitted in fissions
  - correlation between isotopic content and measured spectrum in Double Chooz (near) detector

- **Thermal power : a less difficult job**
  - a new tool to monitor/measure the thermal power
    - not so well known (> 2 % ?) apparently thru temp. and flow measurement
  - effort also needed on \( \nu \) spectrum from fissions

- **An external/independant device to monitor nuclear reactor**
  - disuasive by itself : cannot hide stops or change of power
  - virtually impossible to fake the \( \nu \) signal
An (even) more difficult demand

- An interest in remote detection of \( \approx \) kton atomic test
  - neutrino is an unambiguous signature
- An extremely weak signature
  - 1 kton atomic test @ 100 km...
    \[ \Rightarrow 3 \text{ interactions in a } 1.7 \text{ Mton detector } \approx (120 \text{m})^3 \]
- Geoneutrinos detectors paved the way for a global network of survey