Neutrino and Reactor Monitoring

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Safeguard activities:

- Treaty of NonProliferation (and additional protocols):
  - accepted (and unattended) controls
- Detect Diversion from Civil Fuel Cycles to Weapons Programs of Fissile Material (Pu, enriched U)
- Many places to control all around the world:
  - enrichment units, nuclear fuel factories, power and research reactors, reprocessing units, storage waste...

Standard methods used

- mostly checks of input/output declarations
- sampling and analysis (γ-spectroscopy, isotopic content)
- no direct Pu inventory made at the production place, neither power

Seeking for new tools to perform future controls on increasing number of installations: ask physicists
IAEA

Nobel prize for peace in 2005
Physics basis allowing monitoring
Burn-up & Fission

\[ \approx 100 \text{ tons } 3.5\% \, ^{235}\text{U} \, 96.5\% \, ^{238}\text{U} \]

\[ ^{238}\text{U} \, + \, n \rightarrow ^{239}\text{U} \rightarrow ^{239}\text{Np} \rightarrow ^{239}\text{Pu} \]

- Grow up of \(^{239}\text{Pu}\) during operation
  - \(\approx 200 \text{ kg of Pu/y/reactor}\)
- \(^{239}\text{Pu}\) contribute to energy production

Evolution of the fresh fuel

- Mass (g) of the isotope
- Irradiation time (days)

\(<\Phi> = 7 \times 10^{13} \, \text{n/cm}^2 \, \text{s} \)
- \(\text{th}: 33\%\)
- \(\text{ep}: 0.5\%\)
- \(\text{ra}: 42\%\)

Fission fragments from \(^{239}\text{Pu}\) heavier in the light hump
An old idea

Kurchatov's pioneers...

Neutrinos oscillate...

Now a known effect:
- $\text{Prob}(\nu_e \rightarrow \nu_e)$ fnct of $E_\nu$, L

No more unknown between emission and detection

Neutrino: a reliable tool

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MEASURING NUCLEAR PLANT POWER OUTPUT
BY NEUTRINO DETECTION

V. A. Korovkin, S. A. Kodanev,
N. S. Panashchenko, D. A. Sokolov,
O. M. Solov'yanov, N. D. Tverdovskii,
A. D. Yarichin, S. N. Ketov, V. I. Kopeikin,
I. N. Machulin, L. A. Mikaelyan, and V. V. Sinev

Fig. 2. Neutron instrumentation readings for January-August 1986 (a) and average daily reactor power based on data from thermal measurements (b).

Kamland, PRL 90 (2003) 021802

KamLAND

Δ ILL

Savannah River

Bugey

Rovno

† Goesgen

△ Krasnoyarsk

□ Palo Verde

■ Chooz

● KamLAND

Distance to Reactor (m)
Today's effort in the US
3.46 GW\textsubscript{th} reactor @ San Onofre (Ca)

Antineutrino detector in “tendon gallery” with $10^{17}$ $\nu$ / s per m\textsuperscript{2}

0.64 ton Gd doped liquid scintillator readout by 8x 8” PMT

4000 interactions expected per day

SONGS

see N. Bowden's poster
Experimental constraints

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

- Escape energy from neutron capture on Gd
- High background at low energy

- \( \approx 400 \) evts/day
- Signal/noise \( \approx 4 \)
- Stability difficult to keep
- Follow up the reactor power

\( \nu_e + p \rightarrow e^- + n\)
Burn-up sensitivity

![Graph showing burn-up sensitivity with dates and data points.]

1/3 refueling: a 10% effect

- Predicted deficit
- No burnup
- Observed deficit, 30 day average

Date

Reactor Refueling
Today's effort in France
Within

> 500 $\nu_e$ /d

280 m

1051 m

2 x 4270 MWth
A comprehensive effort

- Precise $\nu$ spectrum vs fissile element ($^{235}\text{U}$, $^{239}\text{Pu}$):
  - high statistic with Double Chooz (near): $1.6 \times 10^5$ $\nu$ detected per year
  - correlation with fuel composition, with thermal power
  - At least a valuable database

- Simulations of the fuel evolution
  - use MURE: interface MCNP (static reactor code) and evolution code
  - include diversion scenarios: predict neutrino signature

- Critical evaluation of $\beta$ decays spectrum from fission products
  - concentrate on high energy tails
    - large uncertainties due to multiple excited states
    - place to discriminate $^{235}\text{U}$ vs $^{239}\text{Pu}$ fissions most clearly

- New experimental program at ILL*
  - Lohengrin spectrometer
  - see S. Cormon's poster

* Institut Laue-Langevin (Grenoble)
The high energy limit

- Previous $\nu$ spectrum studies
    - problems in converting $\beta$ to $\nu$ spectrum
    - Above 4 MeV: errors increase (5% at 4 MeV, 20% at 8 MeV)
    - "25% of high energy part due to experimentally unknown exotic neutron-rich nuclei"

- Role of the excited levels
  - Simulation: identification of unknown nuclei of interest: ie contributors and/or discriminating $^{235}\text{U}$/ $^{239}\text{Pu}$
  - Build exact spectrum
  - Include type of transition allowed/forbidden

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**Cumulative plot**

- Cumulative plot for $^{235}\text{U}$ and $^{239}\text{Pu}$

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**$^{94}\text{Sr}$**

- $Q_\beta$ approx
- Exp. data Rudstam et al. 1992
- BR to endpoints ENSDF

**Half life:** 75.3 s

- $J^p$: 0+ → 1+ : 98.1% (allowed)
Fuel composition from $\nu$ recording?

- Fit the positron spectrum
  - \% $^{235}\text{U}$, $^{239}\text{Pu}$,…as free parameters
  - use known different shapes (paramet.)
  - possible but modest precision $\approx 10$ \% $^{239}\text{Pu}$ content

- Need to reduce errors (1/3) on $\nu$ spectrum to achieve few \% precision on Pu, *P. Huber & T. Schwetz, hep-ph/0407076*
Toward a prototype of monitor

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

- **Songs approach**
  - weak $\nu$ signature
  - not enough rejection of background
  - robust, simple operation
  - automatic
  - cheap
In Brazil: Angra 3

J.C. Anjos et al., "Angra Neutrino Project", hep-ex/0511059
Remote survey

- Movable submarine "KamLAND"
  - only 2 - 5 bigger
- Count at 3 positions:
  - Signal $\approx \frac{P_{th}}{R^2}$
  - Triangulation
- Detection of underground clandestine reactor

- Global survey
  - 10 Mtons units
  - \( \approx 1000 \) units in ocean
  - *J. Learned at Neutrino'04*
Summary

- Non proliferation issues: a tough job!
  - realistic diversion (≈ 50 kg Pu) is a small amount in 100 tons
  - define correct conditions: detector size/positions
  - re-measure/evaluate $\nu$ spectrum emitted in fissions
  - correlation between isotopic content and measured spectrum in Double Chooz (near) detector

- Songs achievements attract interest from a new community
  - efforts towards a real demonstrator/prototype

- An external/independant device to monitor nuclear reactor
  - dissuasive by itself: cannot hide stops or change of power
  - virtually impossible to fake the $\nu$ signal
  - not intrusive

- Thermal power: an intermediate and 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
Personal reflexions

- Physicists worked 50 years to understand the character of this elusive neutrino
  - oscillations are understood quantitatively
- Time has come where this capricious particle will work for us
  - applied neutrino physics has begun
  - 1st use seems to control places where $\nu$ was born:
    - nuclear reactors
      - thermal power; plutonium production in situ
  - long distance control: more futuristics
    - undeclared reactors; clandestine nuclear tests

- A challenging program
Neutrinos for Peace
Fission & ν

Fission products from $^{235}\text{U}$ or $^{239}\text{Pu}$ are different, hence ν are different

<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>Mean energy of ν</td>
<td>2.94 MeV</td>
<td>2.84 MeV</td>
</tr>
<tr>
<td>ν per fission &gt; 1.8 MeV</td>
<td>1.92</td>
<td>1.45</td>
</tr>
<tr>
<td>average inter. cross section</td>
<td>$\approx 3.2 \times 10^{-43} \text{ cm}^2$</td>
<td>$\approx 2.76 \times 10^{-43} \text{ cm}^2$</td>
</tr>
</tbody>
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\[
\frac{\# \text{ int} \ ^{235}\text{U}}{\# \text{ int} \ ^{239}\text{Pu}} = \frac{210.0}{201.7} \times \frac{1.92}{1.45} \times \frac{3.2}{2.76} = 1.60
\]
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
Test experiment @ Institut Laue-Langevin High Flux Reactor (Grenoble)

Facility: High-Flux 58.4 MW Reactor

- Neutron flux ~$5 \times 10^{14}$ n cm$^{-2}$ s$^{-1}$
- Fission rate ~ $10^{12}$ fissions/s at target
- $\sim 300 \, ^{132}\text{Sn}$/s at focal point
- Fission yields depend on target (Np to Cf)

Use of the LOHENGRIN (PN1) online mass spectrometer for unslowed fission products: separates neutron-rich nuclei far from stability

Ions are separated according to their $A/q$ values

- Focal point
- Refocussing magnet (count rate X 7)
- Electric condenser
- Dipole magnet
- Target (thickness X)

Lohengrin data ENDF/B-VI data
Experimental set-up

- $^{235}$U target (6mg)
- 1 HPGe clover (4 crystals D50mm, L80mm)
- 35mm Silicon detector (surface 950mm$^2$) (good energy resolution)
- Tape-transport for $\beta$-decay studies
- Chopper (electric deflection: possible to chop the beam up to ms range)

Measurement of beta spectra: beta singles + $\beta-\gamma$ coincidences
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