Beta-delayed neutron measurements for nuclear technologies

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CIEMAT-IFIC-UPC collaboration
\[ B_{GT}^i = \frac{K}{f_{T_{1/2}}^i (Z, Q_\beta)} = K \frac{1}{f_{T_{1/2}}^i (Z, Q_\beta)} \]
Beta decay knowledge (on neutron rich nuclei) is needed as input for nucleosynthesis calculations, and in particular for the r-process to explain the cosmological abundance of the elements.
Main reactions in a nuclear reactor (or transmutation device)

- n-induced fission (energy + waste)
- neutron capture (activation + breeding)
- elastic and inelastic neutron scattering
- radioactive decay
- (n,xn), (n, charged particle), ...

Calculations involving a large amount of data:
- Standard reactor 1500 isotopes
- ADS with spallation 3000 isotopes
The delayed neutrons and the reactor control

A small fraction of the fission fragments are neutron precursors and neutron emission proceeds after their $\beta$-decay. The times associated to the process range from 100 ms to minutes (excluding photofission neutrons).

$$v_{\text{total}} = v_{\text{prompt}} + v_{\text{delayed}} (\beta \sim 0.6\%)$$

Such neutrons are essential for the control of the reactor!
Table 1 Typical precursor coefficients.

For the values in table 1, $\beta = \sum_{i=1}^{6} \beta_i = 0.0065$. So the delayed precursors only account for 0.65%
The delayed neutron energy spectra (left) have a mean energy of 500 keV (below the 2 MeV for the fission spectrum).

Delayed neutrons have a much lower probability of causing fast fissions than prompt neutrons because their average energy is less than the minimum required for fast fission to occur.

Delayed neutrons have a lower probability of leaking out of the core while they are at fast energies, because they are born at lower energies and subsequently travel a shorter distance as fast neutrons. Larger probability of being absorbed!
Nuclear Reactor Kinetics (without delayed neutrons)

• Average generation time” $\Lambda \equiv$ average time between the birth of two fission neutrons in successive generations
• $N(t)$ = neutron population at time $t$.

$$N(t + \Lambda) = k_{eff}N(t)$$

If we identify $\Lambda$ as $\Delta t$, or as $dt$ in the limit, we can write

$$\frac{N(t + \Lambda) - N(t)}{\Lambda} = \frac{k_{eff}N(t) - N(t)}{\Lambda} = \frac{k_{eff} - 1}{\Lambda}N(t)$$

$$\frac{dN(t)}{dt} = \frac{k_{eff} - 1}{\Lambda}N(t) \quad \Rightarrow \quad N(t) = N(0)\exp\left(\frac{k_{eff} - 1}{\Lambda}t\right)$$


**Prompt critical reactor**

\[ k_{\text{eff}} = 1.001 \text{ (i.e., a reactivity } \equiv 1 \text{ mk) and } \Lambda = 1 \text{ ms } = 10^{-3} \text{ s}, \]

\[ N(t) = N(0) \exp\left(\frac{1.001 - 1}{0.001 s} t\right) = N(0) \exp(t) \]

Thus, the neutron population (and also the power) would multiply:

- by a factor \( \exp(1) = 2.718 \) in 1 s
- by a factor \( \exp(2) = 2.718^2 = 7.389 \) in 2 s
- by a factor \( \exp(3) = 2.718^3 = 20.1 \) in 3 s!

This is a **very** fast rate of increase in the fission power, and it is impossible to control such a fast power increase with mechanical shutdown systems.
Critical reactor with delayed neutrons

For 99.4% of neutrons, take average generation time = $10^{-3}$ s. For the other 0.6% (the delayed neutrons) take $10^{-3}$ s + (say) the half-life of the precursor group (this requires a 6-term)

Using again $k_{eff} = 1.001$, we now find in the exponential equation

$$N(t) = N(0) \exp \left( \frac{1.001 - 1}{0.1 s} t \right) = N(0) \exp(0.01t)$$

Thus, the neutron population (and also the power) would multiply
- by a factor $\exp(0.01) \cong 1.01$ in 1 s
- by a factor $\exp(0.02) \cong 1.02$ in 2 s
- **by a factor $\exp(0.03) \cong 1.03$ in 3 s**!

The delayed neutrons have reduced the rate of increase of fission power dramatically. It is now very achievable to control the power transient with mechanical shutdown systems.
Individual precursors are responsible for a large number of the $v_d$

<table>
<thead>
<tr>
<th>Iodine model</th>
<th>Precursor</th>
<th>Half-life, s</th>
<th>Bromine model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{gr}$</td>
<td>Group period, s</td>
<td>$^{137}$I</td>
<td>$N_{gr}$</td>
</tr>
<tr>
<td>1</td>
<td>55.69</td>
<td>$^{87}$Br</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>24.50</td>
<td>$^{137}$I</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>16.30</td>
<td>$^{88}$Br</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>6.46</td>
<td>$^{138}$I</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>4.67</td>
<td>$^{93}$Rb</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>2.76</td>
<td>$^{89}$Br</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>2.30</td>
<td>$^{94}$Rb</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>2.056</td>
<td>$^{85}$As</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>1.119</td>
<td>$^{93}$Kr</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>0.860</td>
<td>$^{140}$I</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>0.443</td>
<td>$^{91}$Br</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>0.195</td>
<td>$^{96}$Rb</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{97}$Rb</td>
<td></td>
</tr>
</tbody>
</table>
Status of the delayed neutron data

The delayed neutron precursor groups seem to work reasonably well for a wide set of calculations. There are however significant discrepancies between the "evaluated/experimental results" and the results from summation calculations starting from microscopic data.

$$\bar{V}_d = \sum_i C_i \cdot P_n^i$$
The amount and energy of the delayed neutrons depends on the fissioning system

<table>
<thead>
<tr>
<th>Fissioning Nuclide</th>
<th>Fractional Group Yield</th>
<th>Decay Constant $\lambda$ (s$^{-1}$)</th>
<th>Direct Delayed Neutron Yield ($\nu_d$) and Fraction ($\beta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}\text{U}$</td>
<td>0.0380, 0.1918, 0.1638, 0.3431, 0.1744, 0.0890</td>
<td>0.0133, 0.0325, 0.1219, 0.3169, 0.9886, 2.9544</td>
<td>$\nu_d = 0.0166 \pm 3%$, $\beta = 0.00682 \pm 3%$</td>
</tr>
<tr>
<td>Thermal Fission</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>0.0139, 0.1128, 0.1310, 0.3851, 0.2540, 0.1031</td>
<td>0.0136, 0.0313, 0.1233, 0.3237, 0.9060, 3.0487</td>
<td>$\nu_d = 0.0450 \pm 4.4%$, $\beta = 0.01584 \pm 4.4%$</td>
</tr>
<tr>
<td>Fast Fission</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
New nuclear data are necessary for the innovative nuclear technologies

Nuclear data are also necessary for the design of nuclear systems. Hot topics in the field are:

- Higher burnup
- New critical reactors (Gen IV): liquid metal Na-cooled reactor, Pb-cooled reactor and gas cooled reactor.
- Accelerator Driven Systems (ADS) for the transmutation of the nuclear waste (MYRRHA project)

An ADS is a subcritical nuclear system ($K_{eff} = 0.95-0.98$) whose power is sustained by an external high intensity neutron source. Usually the neutrons are produced by spallation in heavy nuclides (Pb) by high energy neutrons (~1 GeV). **It is designed for burning Minor Actinides.**
I. Fast Na-cooled critical reactor

Core: 300 fuel elements of MOX: 14% - 16% $^{239}$Pu + depleted U (0.25% $^{235}$U)
Blanquet: a) depleted U + 10-20% Minor Actinides for waste transmutation, b) MOX

$$\beta_{\text{eff}} = 4.5 \times 10^{-3} \text{ vs } \beta_{\text{eff}} = 6.8 \times 10^{-3} \text{ for a }^{235}\text{U LWR}$$

For the licensing of a critical reactor, it is important to determine with a good accuracy (a few hundred pcm/s) the design parameters. Otherwise, the control mechanisms will have to be over dimensioned (i.e. install more control rods)!

II. Accelerator Driven System

The ADS is intrinsically subcritical, even though a value close to criticality is desired for holding a sustained transmutation. For its licensing, however, one has to guarantee that the criticality will be never reached

$$\delta k_{\text{eff}} = \delta k_{\text{prompt}} + \delta k_{\text{delayed}} + \delta k_{\text{void}} + \ldots$$
How to measure microscopic data on delayed neutrons?

\[ P_n \text{ values} \rightarrow 4\pi \text{ detector (talks by Yu. Penionzhkevich - TETRA and B. Gómez – BELEN detector)} \]

\[ P_n \text{ values (depending on the threshold and energy spectrum) and energy spectrum} \rightarrow \text{ToF spectrometers (this talk and F. Delaunay)} \]
The CIEMAT ToF spectrometer
30 cells of BC501A, 20cm x 5cm

CIEimat – Madrid
IFIC – Valencia
LPC – Caen
UPC - Pol. Univ. Barcelona
Univ. Surrey
Neutron Time Of Flight Spectrometer

IGISOL facility
Purification trap \( \Delta M/M < 10^{-5} \)

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Purification trap \( \Delta M/M < 10^{-5} \)

Isobar spectrum of \( A=101 \)
fission products measured at spectroscopy setup

D. Cano-Ott
Leuven, 26th-28th of May 2010
The power of digital electronics

Data taking with digital electronics is limited only by the scientist’s imagination.

A 12 bit (14 bit) flash ADC with 1 Gsample/s is a nearly universal digitiser:

- Fast and high resolution pulse sampling.
- Large dynamic range.

Mounted on an FPGA on board pulse shape analysis data reduction.

Guerrero et al. NIMA 597(2008)212
CIEMAT’s high performance flash ADC

Resolution: 12 bits @ 1 Gsample/s or 14 bits @ 800 Msamples/s (1 GHz bandwidth) and 2 V p2p ADCs
FPGA for trigger decision and preprocessing.
DSP for pulse shape analysis.
2 Gbytes DDR2 for waveform storage.

Trigger in/out, external clock synchronisation, various input ranges (500 mV-1-2-5 V)
Possible locations for the neutron spectroscopy setups.

http://www.cenbg.in2p3.fr/desir/
Summary and conclusions

Conclusions of the NEA WPEC Subgroup 6 on delayed neutron data: there is a need for a continuing effort on delayed neutron data [...] mainly directed at satisfying new requirements emerging from current trends in reactor technology, such as:

- the use of high burn-up fuel
- the burning of plutonium stocks
- fuel recycling strategies
- actinide burners (ADS)

Possible (?) day 1 experiments: the main Rb, I, Br, As, Ge, Y, Sb... delayed neutron precursors should be measured with better accuracy. Pₙ values and neutron energy spectra.

DESIR is an excellent place for measuring several of these isotopes due to its high yields and combined instrumentation: 4π detector and ToF spectrometer.

The construction of a large ToF spectrometer with sufficient efficiency implies a significant financial effort that very likely will have to be shared between various partners.