ν spectrum emitted by a reactor

The prediction of reactor ν spectrum is the dominant source of systematic error for single detector experiments

Reactor data
Thermal power, \( \delta P_{th} \leq 1\% \)

\[
\Phi_{\nu}(E,t) = \frac{P_{th}(t)}{\sum_k \alpha_k(t) E_k} \times \sum_k \alpha_k(t) S_k(E)
\]

Reactor evolution codes
Fraction of fissions from isotope \( k \), \( \delta \alpha_k \approx \text{few \%} \) but large anti-correl @ fixed \( P_{th} \)

Nuclear databases
E released per fissions of isotope \( k \), \( \delta E_k \approx 0.3\% \)

\( \nu \) spectrum per fission
This work!

\[
k = \frac{235U}{238U}, \frac{239Pu}{241Pu}
\]

# of fissions

\( \times 10^{18} \)

\( \times 10^{18} \)

Time (days)

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The guts of $S_k(E)$

$$S_k(E) = \sum_{f_p=1}^{N_{fp}} \mathcal{A}_{fp}(T) \times S_{fp}(E)$$

$$S_{fp}(E) = \sum_{b=1}^{N_b} BR_{fp}^{b} \times S_{fp}^{b}(Z_{fp}, A_{fp}, E_{0fp}^{b}, E)$$

$$S_{fp}^{b} = K_{fp}^{b} \times \mathcal{F}(Z_{fp}, A_{fp}, E) \times pE(E - E_{0fp}^{b})^2 \times C_{fp}^{b}(E) \times \left(1 + \delta_{fp}^{b}(Z_{fp}, A_{fp}, E)\right)$$

$$\delta_{fp}^{b}(Z_{fp}, A_{fp}, E) = \delta_{QED}(E) + A_C(Z_{fp}, A_{fp}) \times E + A_W \times E$$
• Exact conversion requires complete knowledge from fission yield down to β-transition between parent ground (or isomeric)-state and daughter states

• Lot of relevant quantities: Z, A, End-points, J^π, nuclear matrix elements, branching ratios, fission yields, life time... but scarce data as E₀ increases → integral electron spectra.
Accurate measurements @ ILL in the 80’s:

- High resolution magn. spectrometer
- Intense and pure thermal neutron spectrum from the core.
- Extensive use of reference internal conversion electron lines
  → Normalization
  → Shape via $\varepsilon_{\text{det}}(E)$

**Unique reference to be met by any other measurement or calculation**
ILL data: conversion to $\nu$ spectra

Lost info of single $\beta$-branches $\rightarrow$ fit $e^-$ (50 keV bins) spectrum with a sum of 30 effective branches

- All theory included in these effective branches but:
  - What $Z$? : Mean fit on nuclear data $Z = f(E0)$
    \[ Z(E_0) = 49.5 - 0.7E_0 - 0.09E_0^2, \quad Z \geq 34 \]
  - What $A_{CW}$? : effective correction
    \[ \Delta N^C_w(E_\nu) \approx 0.65 \times (E_\nu - 4 MeV) \% \]

- Conversion error from envelop of all numerical studies

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Ab initio approach… do we have the guts?

MURE evolution code: core composition and off equilibrium effects

(Subatech Nantes)

\[ S_k(E) = \sum_{fp=1}^{N_{fp}} A_{fp}(T) \times S_{fp}(E) \]

- Full simulation of reactor core  
  → absolute prediction of isotopes inventory.

- Relative off-equilibrium effect: close to beta-inverse threshold, a significant fraction of the \( \nu \) spectrum takes weeks to reach equilibrium  
  → Sizeable correction in the \( \nu \) oscillation range that depends on the exact chronology of ILL data taking.

Relative change of \( \nu \) spectrum w.r.t. infinite irradiation time

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Improved conversion
Deviation from ILL converted spectrum

- ~+3% normalization shift with respect to ILL converted $\nu$ spectrum
- Similar result for all isotopes.
Origin of the 3% shift

- **E <4 MeV**: deviation from effective linear $A_{C,W}$ correction of ILL data

  $$\Delta N_{v}^{C,W}(E_{v}) \approx 0.65 \times (E_{v} - 4 \text{MeV}) \%$$

- **E >4 MeV**: mean fit of $Z(E_{0})$ doesn’t take into account the very large dispersion of $Z$ around the mean curve

  $$Z(E_{0}) \approx 49.5 - 0.7E_{0} - 0.09E_{0}^{2}, \quad Z \geq 34$$
Error budget

Stack of quadratic sum of $^{238}$U errors

$^{235}$U bin-to-bin correlation matrix
(25x25 bins, 2-8 MeV)

(100% bin to bin correl from norm and $A_{cw}$)
• More refined treatment of normalization error (impact on global fit of reactor experiments).

• Exploit ILL $e^-$ data in 50 keV bins (reduce conversion error)

• Better estimate of $A_{c,w}$ corrections and associated error?

• Details on chronology of ILL measurement for more accurate off-equilibrium effects.
Pandemonium

Bias of $\beta$-decay scheme deduced from $(e^-, \gamma)$ coincidence:

- Underestimation of the low $E$ part of the spectrum
- Overestimation of the high $E$ part
- Missed $\gamma$ are attributed to GS transition.

Solution is Total Absorption Gamma Spectrometers (detect total $E$ of $\gamma$ chain)
$Z = 53.4 - 1.3E0 - 0.026E0^2$