Deconvolution methods used for the development of a neutron spectrometer

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Introduction

• « Ratemeter / spectrometer »:
  • Detection threshold : $H^*(10) = 1 \mu Sv/h – 10 mSv/h$ in <5-10 minutes
  • 0 – 20 MeV neutron spectrometer
  • Transportable < 15 kg

• Optimize a unique multi-detectors Bonner sphere:
  • Simulations with GEANT4
  • Unfolding methods to pre-validate the model
Introduction

- **Idea: multi-detectors Bonner sphere**
  - PE sphere to moderate neutrons (Ø = 25 cm)
  - LiF Detectors at different depths to be sensitive to different energies:
    - $^6\text{Li}(n,\alpha)^3\text{H}, \ Q = +4.78 \text{ MeV}, \ \sigma = 937 \text{ barns}$
    - 1.0 cm x 1.0 cm x 0.04 cm
    - $\rho_{\text{LiF}} = 2.64 \text{ g.cm}^{-3}$
    - 14.3% $^6\text{Li}$ (8.8\,$\cdot$10$^{21}$ cm$^{-3}$) and 85.7% $^7\text{Li}$

→ **Select the most appropriate geometry and unfolding method**

Beam of monoenergetic neutrons from 10⁻⁹ to 10² MeV
Introduction: unfolding, general idea

Matrix equation RX = M, with vector X unknown.

- X: neutron source vector to be retrieved (cm\(^{-2}\)) : m energy groups
- M: measure vector (no unit) : n detectors
- R: response matrix, obtained with GEANT4 (cm\(^{2}\)) : size : n x m
  - n: number of detectors or groups of detectors
  - m: number of groups of energies
1. GEANT4 simulations

To build the measure vectors $M$:

- 4 reference spectra
- $4 \times 10^8$ neutrons
- Surf. Fluence $\Phi = 141\ 471\ \text{cm}^{-2}$

- $X_{\text{AmBe}}$ (bare $^{241}\text{AmBe}) \rightarrow M_{\text{AmBe}}$
- $X_{\text{Cf}}$ (bare $^{252}\text{Cf}) \rightarrow M_{\text{Cf}}$
- $X_{\text{AmBe}_\text{mod}}$ (mod. AmBe) $\rightarrow M_{\text{AmBe}_\text{mod}}$
- $X_{\text{Cf}_\text{mod}}$ (mod. Cf) $\rightarrow M_{\text{Cf}_\text{mod}}$

(6 cm PE)
1. GEANT4 simulations

To build the response matrix $R$:

- $56 \times 10^8$ neutrons from $10^{-9}$ to $10^2$ MeV
- Surface fluence: $\Phi = 141\ 471\ \text{cm}^{-2}$
- Simulation n°j with j from 0 to 55:
  - Neutrons energy: $E_j = 10^{-9+0.2j}$ MeV
  - Parallel monoenergetic neutrons: $R_{\text{parallel}}$ (done)
  - Isotropic monoenergetic neutrons: $R_{\text{isotropic}}$ (to do)
1. R matrix construction

- Multi-detectors Bonner sphere
  - Parallel monoenergetic beams: $10^{-9}$ to $10^2$ MeV
  - Start with one detector each cm along x, y, z
  - Then: try to optimize the layout of the detectors
    $\rightarrow$ new R matrix
1. Responses (r constant)

Response (cm$^2$) for detector distances to center between 0 and 12 cm.

Position optimization:
- Simulations to determine responses, function of depth
- Very sensitive next to the surface
  - More detectors to put next to the surface
  - Less detectors to put next to the center
1. Responses (r constant)

From the previous histogram:
- 6 selected depths
- 6 groups of detectors
(Still to be optimized)
2. Unfolding methods

- **UMG 3.3 (NEA):**
  - GRAVEL: iterative algorithm (SAND-II modified)
  - MAXED: maximum of entropy algorithm
  - 6 groups of 6 equidistant detectors (= 36 detectors)

- **1 “personal”* method:**
  - Maximum of {likelihood and entropy}
  - Detectors taken one by one

3. Unfolding results for Cf $\left( H^*(10) \sim 50 \, \mu Sv \right)$

For the first iteration of the algorithm, it is important to define a guess spectrum: Flat, bare or moderated spectrum, etc.

Conversion into $H^*(10)$
3. Results for moderated AmBe ($H^*(10) \sim 50 \mu Sv$)

If moderated awaited spectrum, it is very important to have at least a moderated guess spectrum.
3. Results of unfolding \((H^*(10) \sim 0.5 \, \mu \text{Sv})\)

Conversion into \(H^*(10)\)

Conversion into \(H^*(10)\)
4. Preliminary tests on ZnS:LiF detectors

**AmBe source:** \( \sim 3 \mu \text{Sv/h} \)

Detectors behind 3.6 cm of paraffine

\( \sim 0.4 \) detected neutrons / cm\(^2\)

*First encouraging results*

Could give sufficient statistics

\( \rightarrow \) tests behind different thicknesses of paraffine to try to unfold
Conclusion

- Better to have a guess of the spectrum before unfolding
- If not, it is better to pre-define
  - A rapid component
  - An epithermal component?
  - A thermal component
- One can imagine an automatisation
  - Comparison of the $\chi^2$ of many different guess spectra at the first iteration
  - The spectrum which gives the minimum $\chi^2$ could be adopted
  - Then, the algorithm could start
- Why a personal unfolding method?
  - For a faster acquisition on a PC (MAXED/GRAVEL on older versions of Windows)
  - But some convergence parameters are still to optimize
Conclusion

• General simulation results with 36 detectors:
  • < 15% from reference spectra
  • Even with low ambient dose equivalent $H^*(10) \approx 1 \mu Sv/h$ in ~10 minutes

• To validate the multi-detectors Bonner sphere concept:
  • More accurate modelization of LiF detectors: ZnS(Ag) + epoxy to add to the material composition
  • 45 degrees parallel-beam + isotropic-beam-response matrices to build

• Next steps:
  • prototype to develop and test
  • perhaps machine learning could help