Validation of the Monte-Carlo efficiency calculation of the LOENIEv2 long counter for delayed neutron measurements

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LOENIEv2 long counter in calibration at the NPL institue (UK)

Outline

1. **Introduction**
2. **NPL calibration campaign**
3. **TRIPOLI-4® model of the LOENIEv2 long counter**
4. **Calculated vs measured efficiencies**
5. **Conclusions and further works**

1. Introduction

INTRODUCTION
Background and context

- **The simulation of the dynamic behavior of a nuclear system relies on the point kinetics equations**

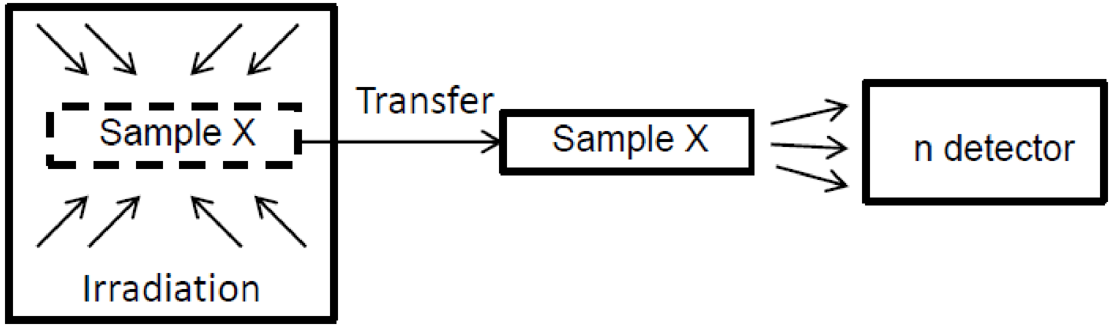
$$\begin{cases} \frac{dn}{dt} & = \frac{\rho-\beta_{eff}}{\Lambda} n(t) + \sum_{i=1}^{G} \lambda_i C_i(t) \\ \frac{\mathrm{d}C_i(t)}{\mathrm{d}t} & = \frac{\beta_{eff,i}}{\Lambda} n(t) - \lambda_i C_i(t). \end{cases}$$

- **$\beta_{eff,i}$ are integral parameters that depend on the following macroscopic delayed neutron (DN) data:**
  - Yield ν_d
  - Group constants (λ_i, a_i)

- **The ALDEN project: accurate measurements of delayed neutron yield ν_d and group constants (λ_i, a_i)**
  - Thermal energy range: ^{233}U, ^{235}U, ^{238}Pu, ^{239}Pu, ^{241}Pu, ^{241}Am, ^{245}Cm
  - Fast energy range: ^{238}U, ^{235}U, ^{239}Pu

- **Work on model for a better description of the energy dependance of these data**
  - Summations calculations
  - Fission yield calculations (GEF)

INTRODUCTION
Equations and definitions



- **Equations for DN yield measurement for a repetition of beam on / beam off sequences**

DN groups

Relative abundances

$$c(t) = b_{off} + \nu_d F_0 \sum_i \varepsilon_{d,i} a_i \frac{(1-e^{-\lambda_k t_{irrad}})e^{-\lambda_i t}}{1-e^{-\lambda_i t_{cycle}}}$$

Detector counting rate

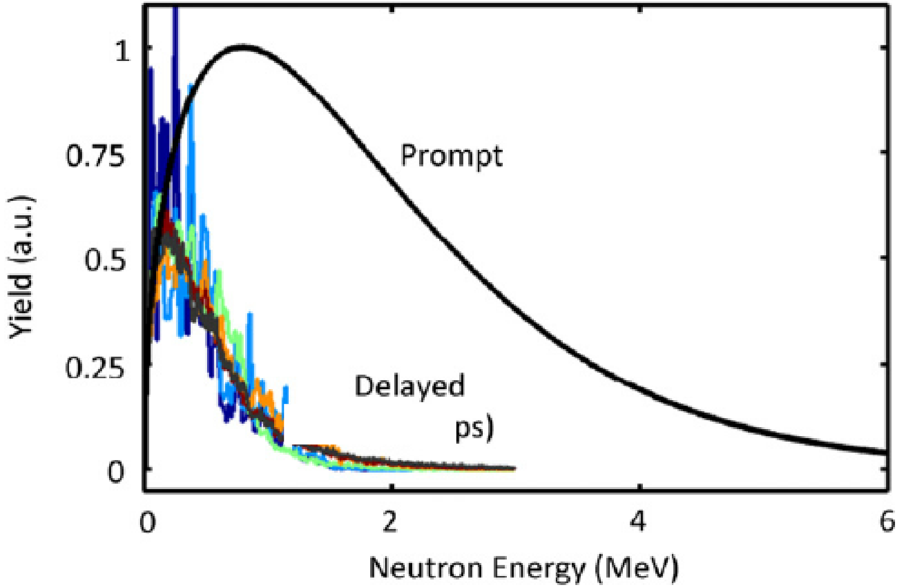
Background

DN yield

Fission rate

Efficiency for DN group *i*

- **Poor knowledge of DN group spectra**
  → The detector should be energy independant over the range [0.1 - 1 MeV] to remove the impact of DN spectra on the determination of ν_d



INTRODUCTION
LOENIEv2 long counter

LOENIEv2 is an enhancement of the LOENIE long counter used at LOHENGRIN instrument in ILL(1)

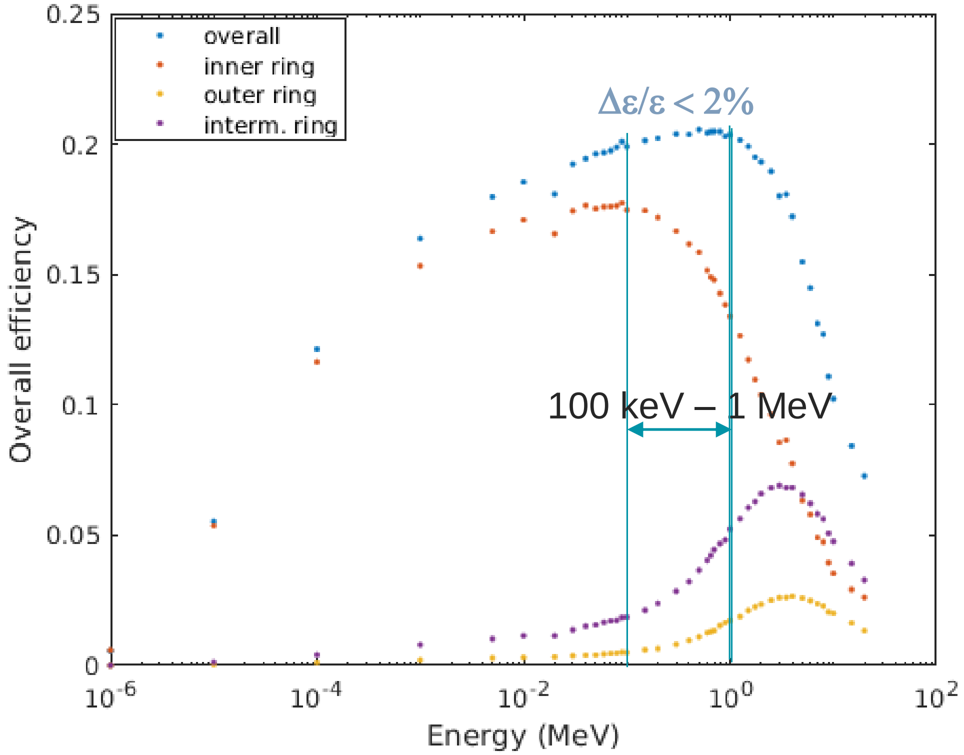
- Higher efficiency
- More energy independant
- Shielded against thermal neutron background

Description

- Cylindrical matrix of HDPE shielded with boron rubber (Flexibore®)
- 16 proportional counters of ^{3}He at P = 10b, arranged in 3 rings

Characteristics

- Overall efficiency ~ 20%
- Relative efficiency variation in [100 keV – 1 MeV]: <2%
- Attenuation to thermal neutrons 10^{-8}



→ Purpose of this study: validate the TRIPOLI-4® model of LOENIEv2 against a set of calibrated neutron sources

(1) L Mathieu et al 2012 JINST 7 P08029

2. NPL calibration campaign

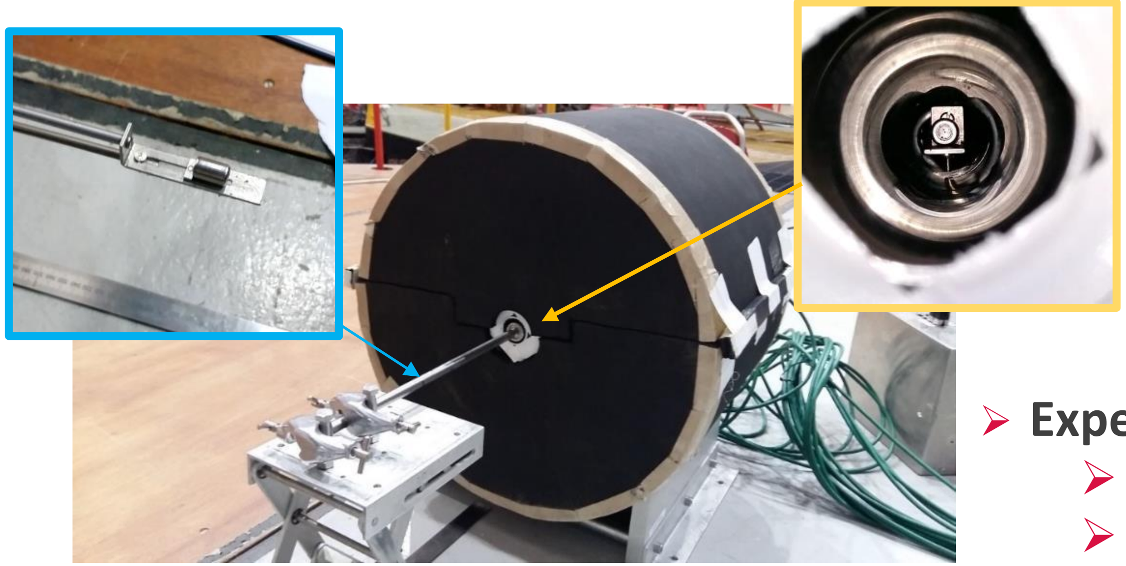
NPL CALIBRATION CAMPAIGN
Description of measurements

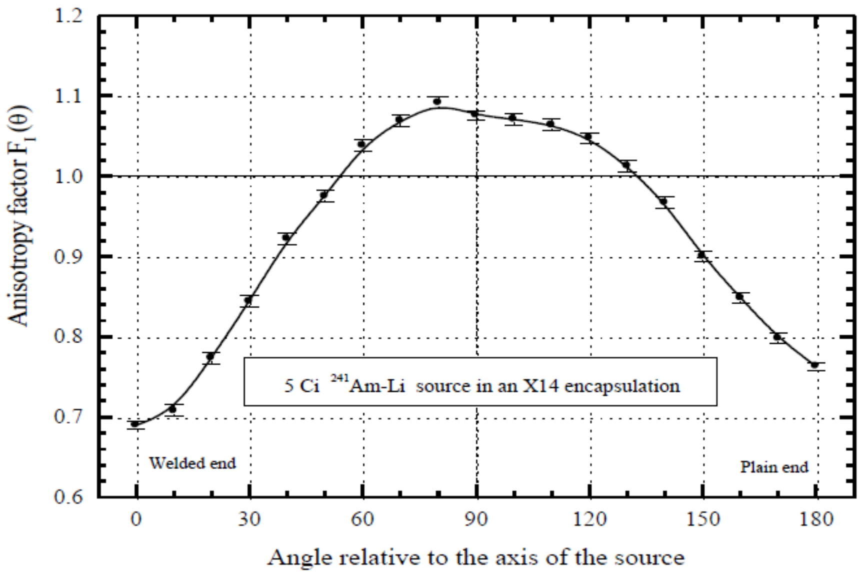
- Use of a set of calibrated neutron sources of various energies and intensities for efficiency calibration

Type of source	Average energy (MeV)	Emission rate at the time of the experiment (n/s in 4π sr.)	Anisotropy factor
AmLi	0.471	$(2.064 \pm 0.0015)\times10^5$	1.075
AmF	1.3	$(1.313 \pm 0.0008)\times10^5$	1.022
Cf	2.13	$(5.870 \pm 0.025)\times10^5$	1.018
AmB	2.72	$(4.222 \pm 0.025)\times10^5$	1.035
AmBe(1)	4.15	$(7.531 \pm 0.064)\times10^4$	1.013
AmBe(2)	4.15	$(2.248 \pm 0.019)\times10^5$	1.014
AmBe(3)	4.15	$(2.362 \pm 0.016)\times10^6$	1.030

Interest to test the robustness of the dead-time correction

- Accurate calibration of the source emission rate with the Mn bath technique (<1%) + anisotropy factor measurements



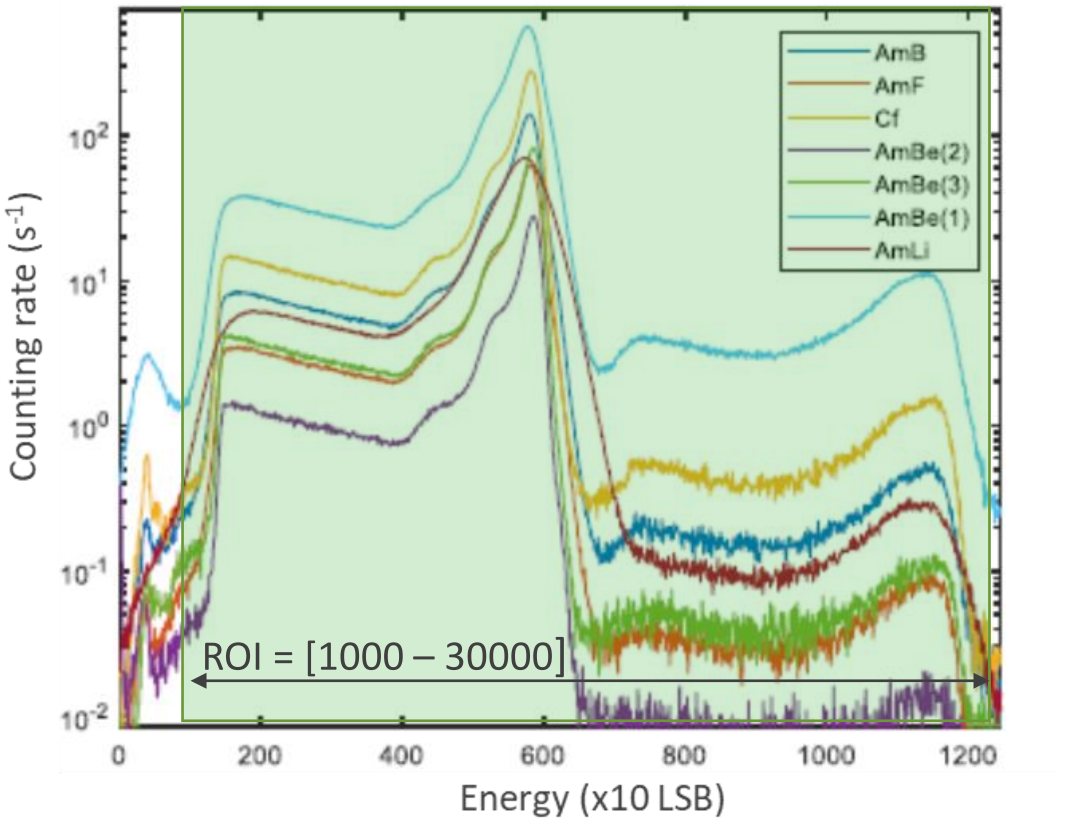


- **Experimental set-up**
  - Source held on a support, mounted on a trolley
  - Central positionning at ±5mm radially and ±2mm axially

NPL CALIBRATION CAMPAIGN
Data processing

- **LST files (pointwise): binary files containing a 3d matrix of the following parameters:**
  - Channel (Tube No.)
  - Energy
  - Time

- **Data processing consists of many steps:**
  - Conversion of LST files into a “mat” format in MATLAB
  - PHA building (histogram in Energy)
  - ROI determination
  - Pulse pile-up and dead time correction
  - MCS building (histogram in Time)
  - Sum over the different channels (^{3}He counters)



- **Overall efficiency:** $\varepsilon(E) = \sum_k \varepsilon_k = \sum_k \frac{c_k}{N(E)}$

Counting rate of tube No. k

Source emission rate

Sum over the 16x ^{3}He tubes

NPL CALIBRATION CAMPAIGN
Overall efficiency results

Type of source	Average energy (MeV)	$\varepsilon(E)$	
		Value (x10^{-2})	Rel. uncertainty
AmLi	0.471	20.17	0.83%
AmF	1.3	19.85	0.70%
Cf	2.13	19.12	0.77%
AmB	2.72	18.41	0.70%
AmBe(2)	4.15	16.63	0.94%
AmBe(3)	4.15	16.57	0.88%
AmBe(1)	4.15	16.59	0.60%

- **Uncertainties include:**
  - Counting statistics (±0.2%)
  - Positioning errors (±0.3%)
  - Source emission rate (±0.4-0.9%)

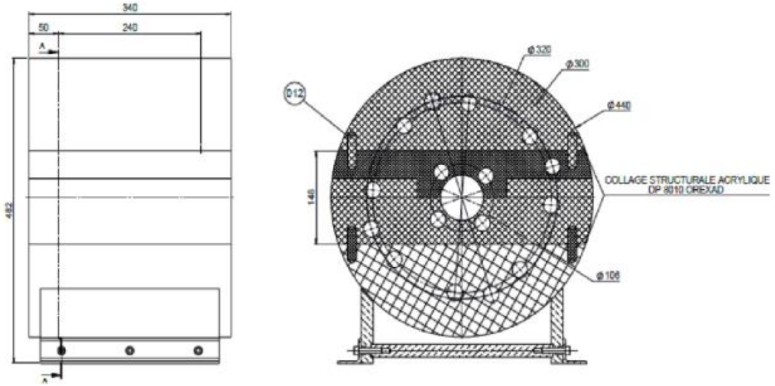
- **Comments on experimental results**
  - Low variation confirmed between AmLi and AmF sources
  - Excellent consistency between the 3 AmBe sources

3. TRIPOLI-4® model of the LOENIEv2

TRIPOLI-4® MODEL OF THE LOENIEv2
Geometrical model

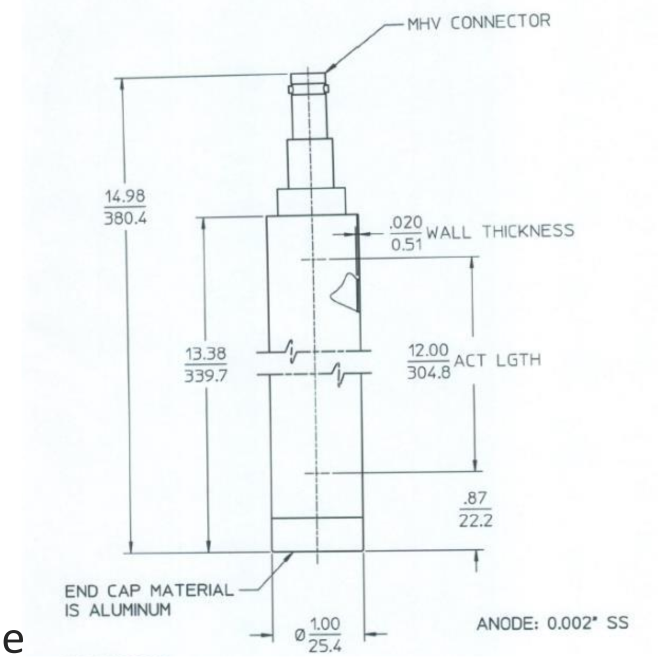
- **Geometry**

« As built » model as close as possible to technical drawings of the LOENIEv2, ^{3}He tube specification sheet and source container IAEA certificate$^{(1)}$

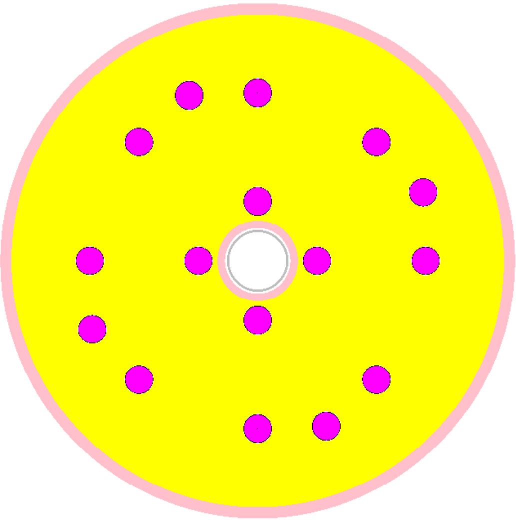


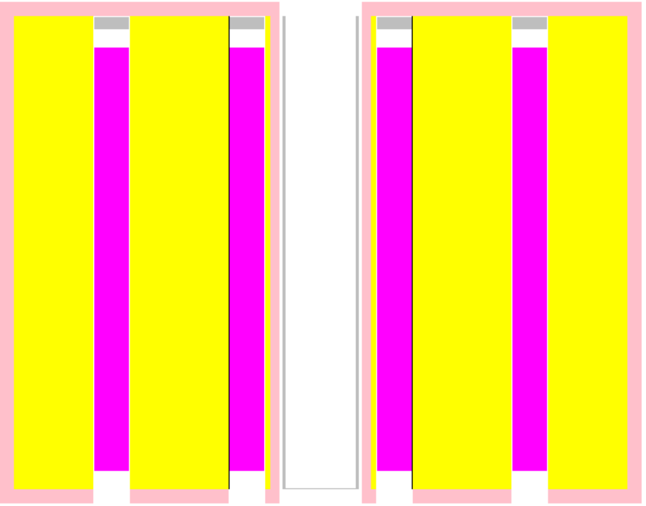
HDPE matrix of LOENIEv2

X3 container for AmBe source



^{3}He tube drawing





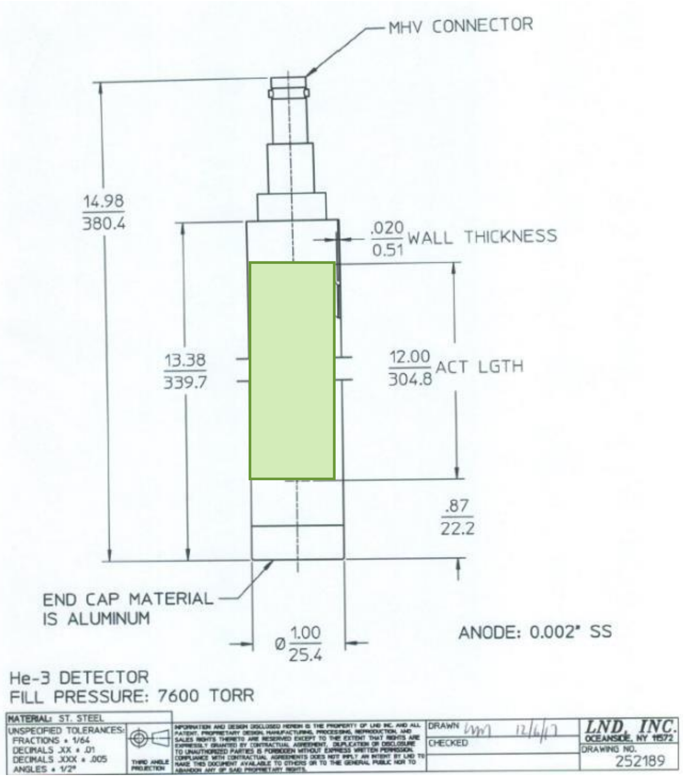
- **Materials**
  - ^{3}He is mixed with 3% CO_2 (quencher)
  - It follows the ideal gas law $pV = Nk_BT$

9.7 bar ^{3}He at 20° → n_{He} = 2.421 x 10^{20} at/cm^{3}

0.3 bar CO_2 at 20° → n_{CO2} = 7.488 x 10^{18} at/cm^{3}

(1) https://www.qsa-global.com/industrial-ambe-neutron-sources

TRIPOLI-4® MODEL OF THE LOENIEv2
Simulation parameters



➢ Source definition

- Spatial distribution over the inner container volume
- Energy distribution provided by NPL (ISO-8529 standard values$^{(1)}$)
- Angular distribution based on anisotropy measurements

➢ Tally definition

- ^{3}He(n,p) reaction rate
- Score over the “active” ^{3}He volume

➢ Simulation parameters

- 10^3 batches of 10^4 particles
- 1.5 hours on a personal computer (Intel(R) Xeon(R) CPU E5-2620 v4 @ 2.10GHz)
- Nuclear data libraries: JEFF-3.1.1, JEFF-3.3, ENDF/BVIII.0, JENDL-4.0

→ Statistical uncertainties are ranging from 0.2% to 0.8% on individual tube reaction rate resulting in ±0.2% on $\varepsilon(\boldsymbol{E})$

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(1) *International Standard ISO 8529, Neutron reference Radiations for Calibrating Neutron-Measuring Devices used for Radiation Protection Purposes and for Determining their Response as a Function of Neutron Energy, International Organization for Standardization, Geneva, Switzerland, 1989.*

4. Calculated vs measured efficiencies

CALCULATED VS MEASURED EFFICIENCIES
Reference values

- **C vs E with the JEFF-3.3 library**

Type of source	Average energy (MeV)	$\varepsilon_d(E)$	
		[C/E-1]	$\pm 1\sigma$
AmLi	0.471	**-0.28%**	0.83%
AmF	1.3	**0.27%**	0.70%
Cf	2.13	**-1.27%**	0.77%
AmB	2.72	**0.42%**	0.70%
AmBe(2)	4.15	**-0.53%**	0.94%
AmBe(3)	4.15	**-0.21%**	0.88%
AmBe(1)	4.15	**-0.07%**	0.61%
Average value		**-0.24%**	0.56%(*)

(*) standard deviation of the [C/E-1] values

- **Comments**
  - Calculated $\varepsilon(\boldsymbol{E})$ are 2σ consistent with the measured values

CALCULATED VS MEASURED EFFICIENCIES
Impact of anisotropy factors

Type of source	Average energy (MeV)	$\varepsilon_d(E)$	
		[C/E-1]	±1σ
AmLi	0.471	**-0.28%**	0.83%
AmF	1.3	**0.27%**	0.70%
Cf	2.13	**-1.27%**	0.77%
AmB	2.72	**0.42%**	0.70%
AmBe(2)	4.15	**-0.53%**	0.94%
AmBe(3)	4.15	**-0.21%**	0.88%
AmBe(1)	4.15	**-0.07%**	0.61%
Average value		**-0.24%**	0.56%(*)

(*) standard deviation of the [C/E-1] values

Removal of anisotropy factors →

Type of source	Average energy (MeV)	$\varepsilon_d(E)$	
		[C/E-1]	±1σ
AmLi	0.471	**-1.37%**	0.83%
AmF	1.3	**-0.17%**	0.70%
Cf	2.13	**-1.55%**	0.77%
AmB	2.72	**0.09%**	0.70%
AmBe(2)	4.15	**-0.77%**	0.94%
AmBe(3)	4.15	**-0.23%**	0.88%
AmBe(1)	4.15	**-0.30%**	0.61%
Average value		**-0.89%**	0.63%(*)

(*) standard deviation of the [C/E-1] values

- **Comments**
  - Maximum change in the calculated $\varepsilon(\boldsymbol{E})$ for AmLi (-1.5%)
  - Other sources: -0.1% → 0.4%

CALCULATED VS MEASURED EFFICIENCIES
Impact of nuclear data

Type of source	Average energy (MeV)	JEFF-3.3		JEFF-3.1.1		JENDL-4.0		ENDF/B-VII.1		ENDF/B-VIII.0	
		[C/E-1]	±1σ	[C/E-1]	±1σ	[C/E-1]	±1σ	[C/E-1]	±1σ	[C/E-1]	±1σ
AmLi	0.471	**-0.28%**	0.83%	**-0.04%**	0.83%	**-0.04%**	0.83%	**-0.06%**	0.83%	**-0.80%**	0.83%
AmF	1.3	**0.27%**	0.70%	**0.11%**	0.70%	**0.41%**	0.70%	**0.32%**	0.70%	**-0.61%**	0.70%
Cf	2.13	**-1.27%**	0.77%	**-1.38%**	0.77%	**-1.19%**	0.77%	**-1.15%**	0.77%	**-1.88%**	0.77%
AmB	2.72	**0.42%**	0.70%	**0.46%**	0.70%	**0.38%**	0.70%	**0.51%**	0.70%	**-0.45%**	0.70%
AmBe(2)	4.15	**-0.53%**	0.94%	**-0.67%**	0.94%	**-0.69%**	0.94%	**-0.52%**	0.94%	**-1.43%**	0.94%
AmBe(3)	4.15	**-0.21%**	0.88%	**-0.11%**	0.88%	**-0.07%**	0.88%	**0.18%**	0.88%	**-0.83%**	0.88%
AmBe(1)	4.15	**-0.07%**	0.61%	**0.16%**	0.61%	**0.14%**	0.61%	**0.37%**	0.61%	**-0.68%**	0.61%
Average value		**-0.24%**	0.56%(*)	**-0.21%**	0.62%(*)	**-0.15%**	0.59%(*)	**-0.05%**	0.59%(*)	**-0.96%**	0.51%(*)

(*) standard deviation of the [C/E-1] values

- **Comments**
  - Best C/E agreement are obtained for ENDF/B-VII.1 results
  - Best consistency between neutron sources is obtained for ENDF/B-VIII.0

5. Conclusions and further works

CONCLUSIONS AND FURTHER WORKS

- **Our TRIPOLI-4® Monte-Carlo model of LOENIEv2 using the JEFF-3.3 nuclear data library is validated for the computation of the overall efficiency $\varepsilon(E)$ under these conditions:**
  - Range of validation: 0.47-4.1 MeV
  - **Average bias +/- uncertainty: -0.2% ± 0.6%**
  - Maximum deviation : 1.3%
- **The change of nuclear data does not exhibit changes higher than 1%**
- **JENDL-4 and ENDF/B-VII.1 provide the best C/E agreement**

- **Efficiency spatial dependance from z=0 to z=117 cm still to be analyzed (AmBe source axial profile)**
- **This model will be applied to finalize the analysis of the ALDEN experiment and to publish new DN data values for ^{235}U, ^{239}Pu, ^{233}U by the end of 2023**

6. Appendix

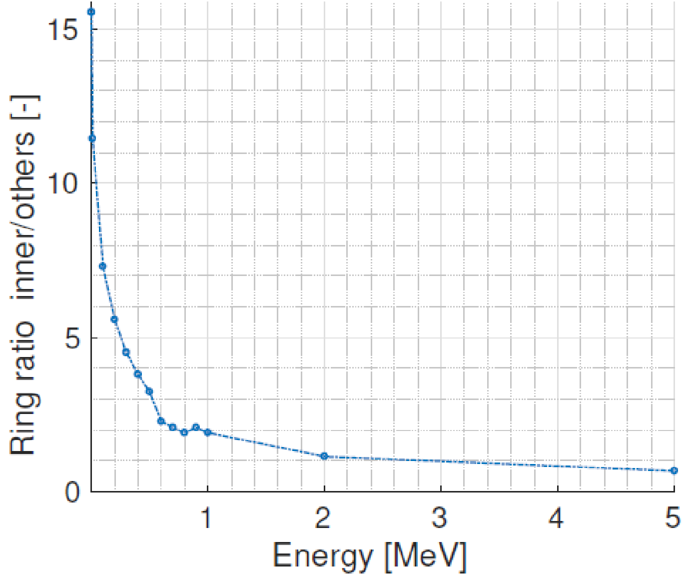
NPL CALIBRATION CAMPAIGN
Ring Ratio results

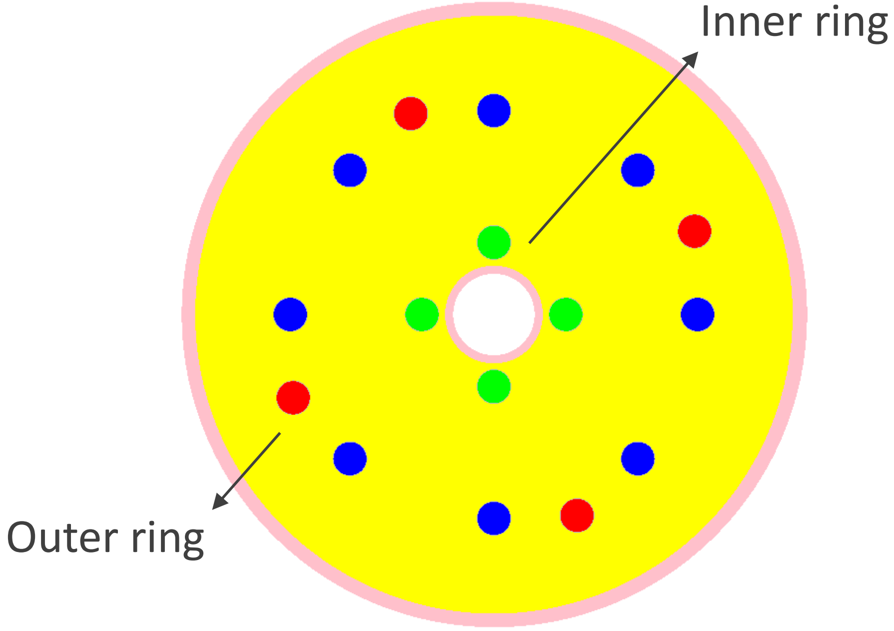
- **Ring ratio:** $\mathbf{R} = \frac{\sum_{k}^{inner\ ring} \varepsilon_k}{\sum_{k}^{outer\ ring} \varepsilon_k}$

  → Highly energy dependent parameter, for validation purpose
  → Independent of the source emission rate

Type of source	Average energy (MeV)
AmLi	0.471
AmF	1.3
Cf	2.13
AmB	2.72
AmBe(2)	4.15
AmBe(3)	4.15
AmBe(1)	4.15

$RR(E)$	
[C/E-1]	±1σ
0.62%	0.51%
-1.34%	0.51%
-1.93%	0.53%
1.82%	0.51%
0.70%	0.52%
1.00%	0.52%
2.30%	0.52%
0.45%	1.56%(*)





- **Uncertainties include:**
  - Counting statistics (±0.1%)
  - Positioning errors (±0.4-0.5%)

CALCULATED VS MEASURED EFFICIENCIES
Comparison of RR calculated vs measured values

Type of source	Average energy (MeV)	**JEFF-3.3**		JEFF-3.1.1		JENDL-4.0		ENDF/B-VII.1		ENDF/B-VIII.0	
		[C/E-1]	±1σ	**[C/E-1]**	±1σ	**[C/E-1]**	±1σ	**[C/E-1]**	±1σ	**[C/E-1]**	±1σ
AmLi	0.471	**0.62%**	0.51%	**1.14%**	0.59%	**0.13%**	0.59%	**0.10%**	0.59%	**1.24%**	0.59%
AmF	1.3	**-1.34%**	0.51%	**-1.15%**	0.58%	**-2.13%**	0.58%	**-1.47%**	0.58%	**-1.30%**	0.58%
Cf	2.13	**-1.93%**	0.53%	**-1.32%**	0.79%	**-2.45%**	0.79%	**-1.94%**	0.79%	**-1.66%**	0.79%
AmB	2.72	**1.82%**	0.51%	**2.58%**	0.65%	**1.58%**	0.65%	**1.85%**	0.65%	**2.04%**	0.65%
AmBe(2)	4.15	**0.70%**	0.52%	**1.09%**	0.66%	**0.56%**	0.66%	**0.92%**	0.66%	**1.22%**	0.66%
AmBe(3)	4.15	**1.00%**	0.52%	**1.53%**	0.66%	**0.70%**	0.66%	**0.94%**	0.66%	**1.23%**	0.66%
AmBe(1)	4.15	**2.30%**	0.52%	**2.25%**	0.66%	**2.02%**	0.66%	**2.28%**	0.66%	**2.15%**	0.66%
Average value		**0.45%**	1.56%(*)	**0.88%**	1.54%(*)	**0.06%**	1.73%(*)	**0.38%**	1.59%(*)	**0.70%**	1.54%(*)

(*) standard deviation of the [C/E-1] value

- **Comments**
  - Best C/E agreement is obtained for ENDF/B-VIII.0 and JEFF-3.3 results
  - Best consistency between neutron sources is obtained for ENDF/B-VIII.0