Validation of the Monte Carlo model of the LOENIEv2 long counter for absolute efficiency calculation

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Abstract. LOENIEv2 is a long counter detector used for delayed neutron (DN) measurements. It is composed of sixteen $^3$He tubes embedded in a cylindrical high-density polyethylene (HDPE) matrix. Thanks to a special arrangement of the $^3$He tubes in three concentric rings, relative variations of the total efficiency as low as 2% can be reached over the $[0.1 - 1 \text{ MeV}]$ energy range. This paper addresses the development of a Monte-Carlo model of the detector and its validation thanks to calibrated neutron source measurements, performed at the NPL institute. These sources are in the form of small cylinders containing either a spontaneous fission material ($^{252}$Cf) or a radioactive material producing neutron through ($\alpha$,n) reactions (AmLi, AmB, AmF, AmBe). These sources are well characterized in emission rate, spectrum and anisotropy so that they can used as standards for efficiency calibration. Using the JEFF-3.3 nuclear data library, the calculation of the detector absolute efficiency is validated within experimental uncertainties. The averaging of $[C/E-1]$ values between the different sources end up to an estimated bias of $-0.3\%$ with an uncertainty of $\pm0.6\%$ (1σ) over the range $[0.5 - 4.1 \text{ MeV}]$.

1 Introduction

The LOENIEv2 [1] is a long counter detector designed and built par CEA/DES for delayed neutron measurements, in the framework of the ALDEN project [2]. The derivation of the absolute delayed neutron yield of actinide requires the determination of the detector efficiency for delayed neutron emission. The standard method consists in using calibrated neutron sources of well-known activities and spectra. This is the purpose of the experimental campaign conducted at NPL in November 2021.

This paper presents the construction of a TRIPOLI-4® [3] model of the LOENIEv2 detector and its validation against calibrated source measurements. The first part reminds the background and context of the study, the second one provides the key elements of the experimental campaign, the third one describes the Monte-Carlo model of the LOENIEv2 long counter and the fourth part its validation against experimental data.

2 Background and context

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2.1 Equations for delayed neutron measurements

The determination of the absolute delayed neutron yield by the macroscopic technique consists in counting the integral emission rate of all the delayed neutron precursors, after a sufficient long irradiation time, so that they reach an asymptotic behavior. The measurement consists of a repetition of cycles, each of them being composed of an irradiation phase followed by a counting phase.

After a repetition of cycle for at least 10 minutes, so that the different delayed neutron precursors can reach a steady-state behavior, the counting rate \( c(t) \) of the detector during the cooling phase can be written as follows [1]:

\[
c(t) = b_{off} + v_d \varepsilon_d F_0 \sum_k a_k f_k \frac{(1 - e^{-\lambda_k t_{irr}}) e^{-\lambda_k t}}{1 - e^{-\lambda_k t_m}}
\]

With the following definitions:
- \( t \) is the measurement time (\( t = 0 \) at the end of the irradiation),
- \( t_{irr} \) is the irradiation time,
- \( t_m \) is the cycle time (irradiation + counting time),
- \( \nu_d \) is the delayed neutron yield,
- \( (a_k, \lambda_k) \) the delayed neutron group constants,
- \( F_0 \) is the fission rate during the irradiation phase (assumed to be constant),
- \( \varepsilon_d \) is the efficiency for the equilibrium delayed neutron spectrum,
- \( f_k = \frac{\varepsilon_{d,k}}{\varepsilon_d} \) is the ratio between the efficiency for the delayed neutron spectrum associated to group \( k \), over the efficiency computed for the equilibrium neutron spectrum,
- \( b_{off} \) is the background counting rate with the irradiation beam being off.

This equation requires the determination of the absolute efficiency for delayed neutron emission. Note that in the above equations, \( c(t) \) can refer either to a single or to the sum of several proportional counters. If we note ‘\( i \)’ the index for each counter of the neutron detector, then we can define the overall counting rate for delayed neutrons:

\[
C(t) = \sum_i c_i(t) = \sum_i \left[ b_{off,i} + \nu_d \varepsilon_{d,i} F_0 \sum_k a_k f_k \frac{(1 - e^{-\lambda_k t_{irr}}) e^{-\lambda_k t}}{1 - e^{-\lambda_k t_m}} \right]
\]

Afterwards, we will refer to the efficiency as the overall efficiency, i.e. summed over the different counters of the detector:

\[
\varepsilon_d = \sum_i \varepsilon_{d,i}
\]

2.2 LOENIEv2: a long counter with energy independent efficiency

In equations (1) and (2), the \( f_k \) parameters quantify the variation of delayed neutron spectra with time. As these nuclear data are very complex to measure, due to the limited count rate statistics, the neutron detector is designed in such a way that \( f_k \) are all close to unity so that the sensitivity to uncertainties on the spectrum remains low (<0.2% according to [1]).

The LOENIEv2 (reminder: LOnge counter with Energy Independent Efficiency) was specifically designed to meet this objective. It is composed of a High Density PolyEthylene
(HDPE) matrix of diameter 44 cm and length 34 cm, with a central cavity of diameter 7.2 cm. It is covered by a 1 cm thick boron rubber on its outer surface and by a 6 mm thick boron rubber in its inner channel. 16 holes were drilled in the HDPE to receive 1 inch proportional counters filled with $^3$He (internal pressure : 7600 Torr).

In order to minimize the variation of efficiency with neutron energy over the range of delayed neutron emission (typically 0.1 - 1 MeV), a suitable arrangement was designed between $^3$He counters: 3 rings were positioned at different distances from the position of the sample (centered in the inner cavity). Indeed, the closest $^3$He tubes are sensitive to low energy neutrons while the farthest ones are sensitive to high energy neutrons (see Fig. 1).

![Fig. 1. Cross section of the detection setup (in green : inner ring of radius 5.3 cm; in blue intermediate ring of radius 15 cm ; in red outer ring of radius 16 cm)](image)

Thanks to TRIPOLI-4®+JEFF3[4] design calculations, input parameters like the position and number of $^3$He tubes were iteratively modified until a maximum deviation (max/min-1) lower than 2% can be reached for neutron energies between 200 and 600 keV. Calculations of the delayed neutron spectrum averaged efficiency were reported in [1], confirming a maximum variation of 1% between the lowest energy group No. 1 ($E_{\text{mean}} = 211$ keV) and the highest energy group No. 2 ($E_{\text{mean}} = 612$ keV).

### 3 NPL calibration campaign

Performing the calibration campaign in NPL is motivated by the availability of low energy neutron sources like AmLi, with an average energy similar to the one of delayed neutrons (~500 keV). The diversity of higher energy sources allows to cover a range from 1.3 to 4.2 MeV. Several units of the same source (AmBe) but with different emission rates can be used to test the robustness of the dead-time corrections. We summarized in the Table 1 the characteristics of the neutron sources used for the NPL campaign. Note that the uncertainties reported in this document are given for one standard deviation ($\sigma$).

The anisotropy factor represents the deviation from the isotropic emission, due to the variable attenuation of neutron through the inner nuclear material and through the capsule. The values are provided in a NPL report [5] and are validated against MCNP simulations.

<p>| Table 1. Neutron source characteristics |</p>
<table>
<thead>
<tr>
<th>Type of source</th>
<th>Average energy (MeV)</th>
<th>Reference</th>
<th>Geometry type</th>
<th>Emission rate at the time of the experiment (n/s in $4\pi$ sr.)</th>
<th>Anisotropy factor(*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AmLi</td>
<td>0.471</td>
<td>3250Li</td>
<td>X14</td>
<td>$(2.064 \pm 0.0015) \times 10^5$</td>
<td>1.075</td>
</tr>
<tr>
<td>AmF</td>
<td>1.3</td>
<td>7582</td>
<td>X3</td>
<td>$(1.313 \pm 0.0008) \times 10^5$</td>
<td>1.022</td>
</tr>
<tr>
<td>Cf</td>
<td>2.13</td>
<td>4774</td>
<td>X224</td>
<td>$(5.870 \pm 0.025) \times 10^5$</td>
<td>1.018</td>
</tr>
<tr>
<td>AmB</td>
<td>2.72</td>
<td>7584B</td>
<td>X3X3</td>
<td>$(4.222 \pm 0.025) \times 10^5$</td>
<td>1.035</td>
</tr>
<tr>
<td>AmBe(3)</td>
<td>4.15</td>
<td>1679</td>
<td>X2</td>
<td>$(7.531 \pm 0.064) \times 10^4$</td>
<td>1.013</td>
</tr>
<tr>
<td>AmBe(2)</td>
<td>4.15</td>
<td>1152</td>
<td>X2</td>
<td>$(2.248 \pm 0.019) \times 10^5$</td>
<td>1.014</td>
</tr>
<tr>
<td>AmBe(1)</td>
<td>4.15</td>
<td>1095</td>
<td>X3</td>
<td>$(2.362 \pm 0.016) \times 10^6$</td>
<td>1.030</td>
</tr>
</tbody>
</table>

(*) counting rate ratio for the 0° and 90° angular position, 0° being the direction of the source container upper plug.

Neutron sources are radially and axially centered with respect to the HDPE matrix of LOENIEv2 for the calibration of the detector efficiency (see Fig. 2).

Fig. 2. Positioning of neutron sources inside the LOENIEv2 detector for efficiency calibration

The data processing consists in a series of actions mastered by MATLAB scripts:
- Conversion of pointwise data (even by even) into MATLAB structure-type data,
- Building energy and time histograms,
- Energy calibration of the Pulse Height Amplitude (PHA) spectra and definition of a Region Of Interest (ROI) associated to the neutron interaction with $^3$He [6],
- Dead time correction per event with a non-parallel model ($\tau = 7.61 \pm 0.07 \mu$s / event),
- Counting rate estimation for each channel and quadrant.

Background counting rate is estimated to be less than 1 c/s. It is neglected, as it is several orders of magnitude lower than the source counting rates.

The absolute efficiency for the source of mean energy $E$ is derived from the following equation:

$$
\varepsilon_d(E) = \frac{1}{N(E)} \sum_{k=1}^{16} \frac{c_k(E)}{1 - r c_k(E)}
$$

Where $N(E)$ denotes the total emission rate of the used source at the time of the experiment, $c_k$ the count rate of k-th $^3$He tube.
Another way to validate the change of efficiency with 3He position is the determination of the Ring Ratio (RR), obtained through:

$$RR(E) = \frac{\sum_{k \in \text{internal tubes}} \frac{\epsilon_k(E)}{1-\epsilon_k(E)} \sum_{E \in \text{internal tubes}} \epsilon_k(E)}{\sum_{k \in \text{outer tubes}} \frac{\epsilon_k(E)}{1-\epsilon_k(E)} \sum_{E \in \text{outer tubes}} \epsilon_k(E)}$$

Due to the strong difference in neutron sensitivity between the 3He of the inner and outer rings, this ratio has a strong energy dependence that is worth

Experimental uncertainties on the determination of the efficiency and RR account for:
- Statistics uncertainty due to the counts,
- Source emission rates,
- Positioning errors.

The statistics uncertainty is very low (typically < 0.1%) as a minimum of hundreds of thousands counts are recorded for each run, even for the lowest efficient tubes.

For the activities of the neutron sources emission rates are provided by NPL, the uncertainties range from 0.4% to 0.9%. This uncertainty cancels in the determination of the RR.

The axial positioning of the different sources is assumed to be at ±2mm and the radial one at ±5mm. The impact of these positioning errors is estimated by computing sensitivity coefficients to the positioning errors with the TRIPOLI-4 Monte-Carlo model of the long counter (see section 4).

The final experimental data and associated uncertainties are reported in Table 1.

<table>
<thead>
<tr>
<th>Type of source</th>
<th>Average energy (MeV)</th>
<th>$\varepsilon_d(E)$ (absolute in %)</th>
<th>RR($E$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>Rel. uncertainty</td>
<td>Value</td>
</tr>
<tr>
<td>AmLi</td>
<td>0.471</td>
<td>20.17</td>
<td>0.78%</td>
</tr>
<tr>
<td>AmF</td>
<td>1.3</td>
<td>19.85</td>
<td>0.67%</td>
</tr>
<tr>
<td>Cf</td>
<td>2.13</td>
<td>19.12</td>
<td>0.77%</td>
</tr>
<tr>
<td>AmB</td>
<td>2.72</td>
<td>18.41</td>
<td>0.70%</td>
</tr>
<tr>
<td>AmBe(2)</td>
<td>4.15</td>
<td>16.63</td>
<td>0.94%</td>
</tr>
<tr>
<td>AmBe(3)</td>
<td>4.15</td>
<td>16.57</td>
<td>0.88%</td>
</tr>
<tr>
<td>AmBe(1)</td>
<td>4.15</td>
<td>16.59</td>
<td>0.60%</td>
</tr>
</tbody>
</table>

4 TRIPOLI-4® model of the LOENIEv2 long counter

The TRIPOLI-4® model of the LOENIEv2 is constructed based on the mechanical drawings of the HDPE block and $^3$He tubes from the LNE manufacturer. Radial and axial views of the model are plotted in Fig. 3.

Additional information have been supplied by LNE on our request: the tubes contain 3% CO$_2$ and the pressure refer to the compound mixture ($^3$He+CO$_2$). The atomic density of $^3$He is obtained from the ideal gas law:
\[ pV = Nk_B T \]  

\( p \) is the absolute pressure of the gas, \( V \) is the volume of the gas, \( k_B \) is the Boltzmann constant \( (1.380649 \times 10^{-23} \text{ J} \cdot \text{K}^{-1}) \), \( T \) is the absolute temperature of the gas.

Knowing that \( p = 7600 \text{ torr} \ (1013 \text{ kPa}) \), the \(^3\text{He} \) partial pressure is estimated to be 982.85 kPa. Assuming \( T = 294 \text{K} \), we end up with the following atomic densities:
- \(^3\text{He} \): \( 2.421 \times 10^{20} \text{ at/cm}^3 \)
- \( \text{CO}_2 \): \( 7.487 \times 10^{18} \text{ at/cm}^3 \)

**Fig. 3.** Radial and axial cuts of the LOENIEv2 long counter model in TRIPOLI-4®

The neutron source is homogeneously distributed in a void volume, with the dimensions corresponding to the inner volume of the source container. Dimensions of the source container can be found from the manufacturer website [7] which provides the reference types of the IAEA certificate for X2, X3, X224 and X14 containers. As the anisotropy factor is already provided by NPL, the container is not described in the simulation. The energy spectra of the different sources are taken from the reference [5], based on an ISO standard (AmBe, AmB, AmF Cf sources) or from NPL spectrum measurement (AmLi source).

The environment of the detector is not described, assuming that the probability of room return effect for the source located inside the HDPE matrix is negligible.

The calculation computes the \(^3\text{He}(n,p) \) reaction rate in the active volume of each of the \(^3\text{He} \) tubes. The latter are post-processed to produce absolute efficiency and ring ratio values.

The calculation is run with 1000 batches of 10000 particles, taking 1.5h on a personal computer (Intel(R) Xeon(R) CPU E5-2620 v4 @ 2.10GHz). The statistical uncertainties are ranging from 0.2 to 0.8% on each tube, corresponding to a combined uncertainty of 0.1% on \( \varepsilon_d(E) \) and 0.2% on \( RR(E) \).

### 5 Comparison of calculated and measured efficiency

#### 5.1 Reference values with JEFF-3.3

We present in Fig. 4 the differences between the simulated and measured efficiency and ring ratio values for the neutron sources placed at the central position inside the LOENIEv2 long counter. The calculations are performed with the JEFF-3.3 nuclear data library.
The calculated efficiencies $\varepsilon_d(E)$ compare very well with the measured values. The standard deviation of [C/E-1] values is close to the [C/E-1] uncertainties, mostly due to the source emission rate calibration.

The calculated ring ratio $RR(E)$ are well predicted as well with a mean 0.6% bias compared with the measurements. We observe more discrepant [C/E-1] values, some of which are beyond $3\sigma$ uncertainty. It is possible that the experimental uncertainties are underestimated due to missing influent parameters.

### 5.2 Impact of nuclear data

Nuclear data from the JEFF-3.1.1, JENDL-4, END/B-VII.1 and ENDF/B-VIII.0 libraries are tested and compared with the JEFF-3.1.1 used in the previous subsections. Results are presented in Fig. 5.

The nuclear data library change, in comparison with JEFF-3.3, results in a negligible effect on the calculated efficiency $\varepsilon_d(E)$ for JEFF-3.1.1, ENDF/B-VII.1 and JENDL-4.0 (maximum 0.2% on the average). The most significant change concerns the ENDF/B-VIII.0 library where the efficiency is reduced by 0.7% on the average (see Fig. 5 left).
For the RR values, the results are reduced by 0.8% for the JENDL-4.0 library and 0.5% for the ENDF/B-VII.1 library, while they are almost unchanged for the other libraries.

6 Conclusions and outlooks

A TRIPOLI4® Monte-Carlo model was built for the LOENIEv2 long counter used in delayed neutron measurements. It was validated against calibrated source measurements performed at NPL, with uncertainty values on the emission rate of the order of 0.5-0.8% (1σ). The model performs well to reproduce both the absolute efficiency associated to the sum of the sixteen 3He counters, as well as the ring ratio defined as the counting rate of the inner ring to the one of the outer ring.

Sensitivity studies were conducted to study the influence of nuclear data library. Their impacts are limited to less than 1% and remain in the range of experimental uncertainties.

As a final recommendation to this study, we may consider the following modeling bias $b$ and uncertainties $\sigma$ on the efficiency determination over the range [0.5 – 4.1 MeV], based on the JEFF-3.3 nuclear data library:

$$b = -0.3\% \quad ; \quad \sigma = 0.6\%$$

These values result from the weighted mean of [C/E-1] values and on the minimal uncertainty value among the different used sources.

7 References


8 Acknowledgments

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