Validation of a NaI(Tl) detector's model developed with MCNP-X code

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ABSTRACT

The Monte Carlo method was used to calculate the photon detection efficiency and energy resolution curves for a 1.5 x 1 m NaI(Tl) scintillator detector (crystal + housing + photomultiplier tube material equivalent) exposed to gamma rays in the energy range from 20 keV to 662 keV. This work aims to design a precise computational model, based in Monte Carlo simulation, which can be used in practical application. The energy resolution curve was used to improve the response of the mathematical simulation of the detector. The detector was modeled with the MCNP-X code and the results were compared to experimental photopeak efficiency measurements of radiation sources. The results showed good agreement with the experimental data.

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1. Introduction

The Monte Carlo calculation technique can be applied to a wide variety of applications in the radiation field, such as radiological protection, nuclear installations, shielding and detectors modeling among several others purposes. The Monte Carlo technique is a widely used simulation tool for radiation transport, mainly in situations where measurements are inconvenient or impracticable, including gathering data for artificial neural networks input (Salgado et al., 2009, 2010; Moreira et al., 2010).

This work uses the Monte Carlo N-Particle eXtended (MCNPX™) code (Pelowitz, 2005) to simulate the NaI(Tl) scintillation detector and the methodology presented improves the determination of the response function of this type of detector. Even though the computer code does not simulate the scintillation process, but scores the energy deposited in any material, and considering that the photomultiplier tube accounts satisfactorily for the photon interaction within the detector's sensitive volume, the results obtained by the simulation is quite representative of the detector's response, otherwise no match between simulation and experimental would be reached.

Nevertheless, a wide variation in the total number of electron at the output of the photomultiplier tube is expected, which is the cause of the high detection resolution. Therefore, the spread in energy response must be considered in the simulations and is accounted for by experimental measurements.

NaI(Tl) radiation detectors are robust, low cost spectrometric system (detector and associated electronics) for spectra acquisition and is used at room temperature (no refrigeration), therefore, can be used in various applications in field under unfavorable weather conditions. Detection systems based on these scintillators also have high absorption efficiency for high-energy gamma rays detection due to the relatively high atomic number of Iodine (Z = 53) and, due to the crystal’s density, the NaI(Tl) detectors show large absorption efficiency, in other words presents a high photopeak to Compton ratio (Tsoufanidis, 1983). When the gamma radiation interacts with the NaI(Tl) detector it yields scintillation that are transformed into electric signal, using a photomultiplier tube that consists of a photocathode that converts photons in the visible light range produced by radiation interaction within the scintillation crystal into electrons that are properly focused and accelerated by the dynodes with which they collide with enough kinetic energy, resulting in secondary electrons. The electron cascade resulting from this multiplication process produces a current pulse that reach the anode of the tube, which is collected with sufficient intensity to be processed in a gamma-ray spectrometry system.

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The pulse height distribution, which is the output spectrum that reflects the interaction that occurs in the sensitive volume of the detector, does not reflect exactly the true photon flux due to the variation of the detector’s energy response and other physical phenomena, as the occurrence of K-shell X-ray escapes and Compton scattering. Although the pulse height distributions can be measured experimentally with the use of several calibrated monoenergetic radiation sources with energies of emission covering the entire range of interest, the number of these sources can be limited and time consuming. It is also necessary radiation sources with high enough intensity to get a good counting statistics for the desired source-detector distance. Equipment and facilities are also required to ensure accurate positioning of the source, since small variations in distance or source-detector alignment may influence the response of the detector, thus increasing the uncertainty of the measurements. Therefore, to calculate the response at intermediate energies between those obtained by isotopes measurements, either complicated interpolation methods of the experimental spectra or simulation by using Monte Carlo technique should be used (Zerby and Moran, 1962; Weitkamp, 1963; Giannini and Oliva, 1970; Orion and Wilopolski, 2002; Sood and Gardner, 2004).

The Monte Carlo methods make it possible to calculate the response function for detectors with good accurate results (Kovaltchouk and Machrafi, 2011), since precise and sufficient data to describe the various parts constituents of the detector are provided, in good agreement with those obtained experimentally. The photon detection efficiency curve, when calculated by simulation, is not influenced by several parameters, such as uncertainty in the concentration of activity and gamma energy yield, decay correction or peak sum effect (Moss and Stretman, 1990).

The MCNP-X code is a general purpose Monte Carlo radiation transport code developed at the Los Alamos National Laboratory and designed to track different types of particles (neutrons, electrons, gamma rays, etc.) over a broad range of energies. The code rather obtains the solution of the problem by simulating individual particle trajectories and recording some aspects of their average behavior (it does not solve the Boltzmann particle transport equation). The individual probabilistic events that comprise a process of interaction of nuclear particle with material are simulated sequentially. The probability distributions governing these events are statistically sampled to describe the total phenomenon and the sampling process is based on the selection of pseudo-random numbers. The process consists of following each of many particles since its emission from a source until it reaches an energy threshold; the particle energy is transferred to the medium by absorption, escape, physical cut-off, etc. Probability distributions are randomly sampled using transport data to determine the outcome at each step of its trajectory. The quantities of interest are tallied, along with estimates of the statistical precision of the results. The MCNP-X code can be used, as in the case of this work, to simulate gamma-rays interactions which comprise: i) incoherent and coherent scattering; ii) the possibility of fluorescent emission after photoelectric absorption; iii) pair production with local emission of annihilation radiation and Bremsstrahlung effect (Pelowitz, 2005). Additionally, electron trajectories were tracked.

When performing the mathematical simulation (using the MCNP code) of NaI(Tl) detectors (Jehouani et al., 2000; Vitorelli et al., 2005; Hadizadeh Yazdi et al., 2004), in order to obtain their response curves, some corrections should be made to improve the simulation in order the approach to the real case. Two of the main corrections are essential: the determination of the photon detection efficiency to quantify the radiation field and; the energy resolution, \( \Delta E/E \), which is related to distinguish between different peaks very close to each other in the energy spectrum, their determination is of great importance when performing the identification of radionuclides or when simulating detectors that approximate of the real case: For NaI(Tl) detectors coupled to the photomultiplier tube, it is due mainly to the following factors:

- Variations of the response of the detector’s active volume (crystal\(^2\)); fluctuation in light generation in the crystal due to gamma-ray absorption of same energy; due to (Poisson) distribution of the number of scintillation photons produced.
- Statistical fluctuation\(^3\) in the number of collected charges in the anode of the photomultiplier tube: variation on light collection at the photocathode, photoelectron production at the photocathode, photoelectron collection at the first dynode and multiplication by the photomultiplier tube dynodes.
- Electronic noise: both the electronics and the detector (current leakage).

The listed factors introduce a broadening of the photopeak (Moszyński et al., 2002). Therefore, the spectral line refers to the total absorption peak that broadens to a Gaussian\(^4\) function.

In practice the energy resolution \( R_E \), as shown in Equation (1), of a detector is given by the full width at one-half of the maximum height (FWHM) of the Gaussian peak (pulses per channel) \( H \) for a given energy \( E_0 \), after subtraction of the background and the contributions due to interactions by Compton effect (Debertin and Helmer, 1988), which already includes all effects that cause broadening of the photopeak.

\[
R_E = \frac{\text{FWHM}}{E_0} \quad (1)
\]

Where: \( R_E \): energy resolution; FWHM: width at half maximum of the photopeak; \( E_0 \): energy central of photopeak.

The measurement of the energy resolution of the detector is performed in the photopeak as shown in Fig. 1 for the energy of 50 keV.

The energy resolution of a NaI(Tl) detector is usually reported for 662 keV gamma rays emitted by the \(^{137}\)Cs source. For 3” × 3” cylindrical detectors, the resolution varies from 7.5 to 8.5%, such values can be easily obtained from commercially available detectors (Heath, 1997).

The spectrum obtained by the simulation of a NaI(Tl) detector using the MCNP-X computer code (Pelowitz, 2005), when applying the pulse height distribution\(^5\) which does not consider the effects of broadening the photopeak and neither the response functions of the detector, is shown in Fig. 2.

Some of the effects that broaden the photopeak are inherent to the electronic circuit of the spectrometric system which are also not simulated. Thus, to optimize the detector response and

\(^2\) The intrinsic resolution of the crystal is connected with many effects such as inhomogeneities in the scintillator causing local variations in the light output, non-uniform reflectivity of the reflecting cover of the crystal, as well as the non-proportional response of the scintillator.

\(^3\) The photomultiplier tube contribution can be determined experimentally based on the measured number of photoelectrons and it depends on the light output of the crystal being studied, quantum efficiency of the photocathode and efficiency of photoelectron collection at the first dynode.

\(^4\) When it represents the number of pulses in function of energy in a monoenergetic beam, we observe a Gaussian peak, centered on the energy of beam called the total absorption peak, whereas the generation of charges in the detector obeys the Poisson law whose mean depends on the number of charges collected and the nature of the detector material.

\(^5\) The interaction of the gamma or X-rays beam with NaI(Tl) detectors provides a pulse height distribution that does not represent the true spectrum of the incident photons due to the presence of photons escape-X and energy resolution and Compton scattering, and the fact that the efficiency of detection decrease rapidly with the increase of the photon energy.
consider these physical effects in the simulation it is necessary to obtain experimentally adjustment parameters of the energy resolution of detector and apply the function provided by the MCNP-X code that fits a Gaussian to the spectrum to make the proper corrections.

2. Methodology

The methodology consists in mathematical modeling of the NaI(Tl) detector and simulation by the Monte Carlo method. The relationship between resolution and energy was determined experimentally for the correction of the spectra obtained by the MCNP-X code that should be modeled with the best possible accuracy in the simulation and variations of the height and diameter of the crystal were slightly modified until the energy resolution of detector and apply the function provided by the MCNP-X code that fits a Gaussian to the spectrum to make the proper corrections.

2.1. Radiation sources and equipment

The spectrometer system specification and the radiation sources used in this work is: Spectrometry system, model: MS-4031, assembled by the Institute of Nuclear Engineering (IEN), consists of a preamplifier from ORTEC, model 113, multi channel analyzer, integral line type $1^{1/4} \times 1^{1/4}$ NaI(Tl) detector with a resolution of 10.44% for 662 keV (measured experimentally). The dimensions of the NaI(Tl) detector were determined by an industrial gammagraphy machine with a $^{137}$Cs source.

The spectrometric system response on energy resolution and efficiency curves was determined by measuring the maximum number of secondary standard sources available which were supplied and certified either by the Institute of Radioprotection and Dosimetry (IRD) or the International Atomic Energy Agency (IAEA). The available sources used in this work are presented in Table 1.

2.2. Experimental validation

To simulate the response functions for NaI(Tl) detector by the MCNP-X code it should be modeled with the best possible accuracy because variations of the detector’s crystal and surrounding materials dimension influence the photon detection efficiency (Nakamura, 1983; Sima, 1990). The detector's physical data for the mathematical model was obtained by gammagraphy technique and the crystal dimension was obtained by the relation between simulation and measurement of two point sources at several positions around the detector.

Two sources were used to determine the actual dimensions of the detector's crystal, $^{241}$Am and $^{137}$Cs, low and high–energy emitter respectively. The sources were measured with the NaI(Tl) detector under well-defined distances, positioned toward the longitudinal axis and laterally around the detector’s crystal. Four measurements were performed with the two sources on the longitudinal axis (source-detector distance: 5.45 cm) of the detector and the other with the sources positioned laterally (source-detector distance: 4.78 cm), to determine experimentally detector's response for a known radiation field. This geometry was reproduced by simulation and the results were compared with the experimental values.

The procedure consists of an interactive process between counts in the simulation and variations of the height and diameter of the crystal cylinder. The calculations were started with the value obtained by gammagraphy, which were 31.75 mm in diameter and 19.05 mm high, showing relatively higher counts than those obtained experimentally. New calculations were performed, gradually decreasing the height and diameter of the crystal until the value of the total count was in agreement with the experimental value for longitudinal irradiation. Then, again the height and diameter of the crystal were slightly modified until the variation of the count was small for the simulated response of the detector to approach the expected value for lateral irradiation. This procedure was repeated successively until the value by

![Fig. 1. Energy resolution measurement for the 50 keV photopeak energy.](image1)

![Fig. 2. The pulse height distribution obtained by the MCNP-X code. Presents the effects of escape peak and Compton interactions, besides the photopeak (the photopeak was reduced by a factor of 100 for better viewing).](image2)

Table 1

<table>
<thead>
<tr>
<th>Source</th>
<th>Half-life</th>
<th>Energy (keV)</th>
<th>Emission probability (%)</th>
<th>Activity (kBq)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{241}$Am</td>
<td>432.7 ± 0.4 year</td>
<td>59.54 ± 0.001</td>
<td>36.0 ± 0.3</td>
<td>190.49 ± 1.5%</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>1525.2 ± 4.0 day</td>
<td>4.0000 ± 0.000</td>
<td>35.0 ± 0.5</td>
<td>396.30 ± 1.0%</td>
</tr>
<tr>
<td>$^{132}$Eu</td>
<td>13.53 ± 0.03 year</td>
<td>121.78 ± 0.000</td>
<td>55.0 ± 0.1</td>
<td>150.42 ± 1.5%</td>
</tr>
<tr>
<td>$^{22}$Na</td>
<td>2.602 year</td>
<td>511 ± 1.0</td>
<td>100 ± 1.0</td>
<td>364.60 ± 1.0%</td>
</tr>
<tr>
<td>$^{152}$Eu</td>
<td>11.009 ± 0.001</td>
<td>661.65 ± 0.009</td>
<td>84.5 ± 0.5</td>
<td>329.39 ± 1.0%</td>
</tr>
</tbody>
</table>

* For a reliable interval of 95.45%: k = 2.

b Annihilation radiation.
simulation approached the experimental values, thus defining the actual volume of the crystal (Conti, 1999; Conti et al., 1999).

2.3. Resolution energetic curve

In the experimental spectra, the data has a Gaussian distribution shape for the energy lines. However, the MCNP-X code does not simulate physical effects leading to the broadening of the spectrum, but it uses a fitting technique to take into account the resolution of the real detector, measured experimentally, and provided in the input file of this code. Thus, for more realistic results obtained by simulation, it is necessary to consider the spectrum resolution by applying a Gaussian function. The technique consists of using a “FT8 GEB” card and calculating the full width at half maximum (FWHM) of the peak. For this purpose, the experimental FWHM curve as a function of energy was determined by measuring the radioactive sources in the energy range of 59.45–662 keV, listed in Table 1. The tallied energy is broadened by sampling from the Gaussian which is done by Equation (2).

\[ f(E) = Ce^{-\frac{(2\pi ln 2/E-E_0)^2}{FWHM}} \]  

(2)

Where: \( E \): the broadened energy; \( E_0 \): the unbroadened energy of the tally; \( C \): normalization constant.

A non-linear function adjusted by least-squares procedure was applied to calculate the values of the “\( a \), “\( b \)" and “\( c \)" coefficients, which will be used as input to the MCNP-X code, using a fitting function shown in Equation (3) (Pelowitz, 2005). These parameters should be used with the Gaussian Energy Broadening (GEB) command in order to consider the energy resolution of the detector in the simulation (Hashem et al., 2007). GEB is a special treatment for tallies to better simulate a physical radiation detector in which the energy from the photopeak area, the photon intensity and the activity, respectively, and \( N \) denotes the number of full absorbed photons in the MCNP calculations.

2.4. Efficiency curve

The experimental absolute efficiency measurements for point sources listed in Table 1 were compared with the simulated results under the same conditions of the experimental setup to validate the simulation of the NaI(Tl) detector (Ewa et al., 2001). In order to avoid the sum effect, improve the counting statistics and consider the source as point, these sources were measured at a well-defined position source-detector distance of 5.45 cm, located on the longitudinal axis of the detector’s crystal. The measurement time of 12 h and source-detector distance were chosen so that the associated errors due counting uncertainties were kept below 5%.

The detector’s crystal and the surrounding materials dimension must be considered for a well characterized detector, especially for photons below 300 keV (Heath; Ewa et al., 2001; Nakamura, 1983).

The equation used to calculate the absolute photopeak efficiency (\( \varepsilon \)) of a detector at energy “\( E \)” is given by Equation (4):

\[ \varepsilon(E) = \frac{S}{A.P.t.k_c} \]  

(4)

Where: \( \varepsilon \): Efficiency (cps by \( \gamma \) cm \(^{-2}\)); \( S \): Net peak area (counts) in the photopeak of absorption total at energy “\( E \)” (cps); \( A \): Activity of the source (Bq); \( P \): Emission probability for gamma rays at energy “\( E \)” ; \( t \): Live time of counting (s), is the time during which the spectrum was acquired taking into account the analyzer counting losses; \( k_c \): Decay factor.

The relative standard uncertainties, \( u_{exp}, u_{sim} \), respectively for experimental and calculated (by the MCNP-X code) efficiency are given by Equation (5) and Equation (6).

\[ u_{exp} = \sqrt{(u_s)^2+(u_p)^2+(u_A)^2} \]  

(5)

\[ u_{sim} = \frac{\sqrt{N}}{N} \]  

(6)

Where \( u_s, u_p \) and \( u_A \) denote the relative standard uncertainties of the photopeak area, the photon intensity and the activity, respectively.

2.5. NaI(Tl) detector’s simulation

The detector’s simulation was based on information obtained from the gammagraphy technique. Both dimensions and materials were used for the calculation with the MCNP-X code. The NaI(Tl) crystal density used was 3.667 g cm \(^{-3}\), the MgO powder density used was 2.0 g cm \(^{-3}\) (Saito and Moriuchi, 1981) and the aluminum...
density was 2.7 g cm$^{-3}$. The photomultiplier tube on the back of the crystal was treated as a 30 mm thick aluminum disk to account for backscattering (Shi et al., 2002).

The energy resolution of the full energy peak of a scintillator coupled to a photomultiplier tube depends of the intrinsic resolution of the crystal itself, the transfer resolution and photomultiplier tube contribution due to the spread in the final number of electrons at its output (Moszyński et al., 2002). A set of measurements were performed in order to determine the energy resolution curve of the NaI(Tl) scintillator detector (crystal + housing + photomultiplier tube material equivalent) used for this work, and the curve’s coefficients were introduced in the function provided by the MCNP-X code that fits a Gaussian to the spectrum to make the proper corrections.

A pulse height distribution estimate (F8 tally), available in the code MCNP-X, was used to obtain the deposited energy distribution per incident photon on the considered detector volume. This tally accumulates, for each individual starting history, the kinetic energy lost by local photon-induced secondary electrons in their multi-step Coulomb interactions with the surrounding atoms.

In order to get good statistics due to the counts in each energy range of the spectrum, the history number (2E10$^8$) was selected to obtain 3% or less relative statistical uncertainties in the Compton continuum region and smaller than 1% under the photopeak regions. The energy bins of the output pulse height distributions were 1 keV width.

3. Discussions and results

3.1. Simulation of NaI(Tl) detector

The detector’s simulation was validated both qualitatively by the energy resolution curve and quantitatively by the photon detection efficiency.

The gammagramy technique showed to be an important tool to estimate, with some precision, the detector’s dimensions used in this work. Fig. 3 shows the result from the gammagramy.

The aluminum disk at the base of the simulated detector takes into account the effect of all the materials of the photomultiplier tube located under the crystal. The volume sensitive dimensions of the NaI(Tl) detector that showed better agreement was 30.10 ± 1 mm height and 17.20 ± 1 mm diameter. For the process of determining the volume of crystal, the difference between the measured and calculated values for point sources of $^{241}$Am and $^{137}$Cs were kept as small as possible with an estimated uncertainty smaller than 5%.

Fig. 4 shows the schematic representation of the detector used for the simulation.

3.2. Energy resolution curve

Fig. 5a shows the energy resolution curve expressed by a Power law relation ($xE^y$) (Berger and Seltzer, 1972, the coefficient $x = -0.54698$ and $y = 0.26204$, were calculated by least-squares fitting.

Fig. 5b shows the FWHM curve as a function of energy expressed by the function represented by Equation (3) in order to get the parameters to be used in the GEB command of the MCNP-X code.

The adjustment coefficients of energy resolution for the NaI(Tl) detector, $a = -0.0024$, $b = 0.05165$ and $c = 2.85838$, were obtained after adjusting a function provided by Equation (3).

The effect of energy resolution on the pulse height distribution obtained by MCNP-X code for a bare NaI(Tl) crystal under the energy of 662 keV with and without resolution correction is shown in Fig. 6.

Fig. 7a and b show the comparison between the experimental and simulated data by MCNP-X code.

It is important to emphasize that the pulse height distribution shown in Fig. 7a and b represents the radiation sources spectra with...
background subtraction and, for the simulated spectra, peak broadening treatment was considered. It can be noticed an acceptable agreement on the photopeak from both sources, but for \(^{137}\text{Cs}\) source the Compton continuum below 400 keV, all the calculated results are a little lower than the experimental data due to the photons scattered on the detector’s shielding, support and surrounding materials (Berger and Seltzer, 1972). The technique of the “shadow shield” can minimize these differences (Sima, 1990; Conti, 1999). For \(^{241}\text{Am}\), in comparison with the experimental data, a small discrepancy can be seen because the effect of the scintillation efficiency increase in low-energy region where the scintillation efficiency is non-linear and is not considered in MCNP-X code.

All the calculated pulse height distributions were normalized to the experimental data by the counting number in the maximum height of the photopeak and also that the X-ray K-shell of \(^{137}\text{Ba}\) (BaK\(_{\alpha}\)) (Heath, 1997) was not simulated and, for this reason, does not appear in pulse height distribution obtained by the MCNP-X code.

3.3. Photopeak efficiency curve

The photon detection efficiency values obtained by Monte Carlo calculation were compared with experimental data aiming to validate the detector’s simulation. The estimated uncertainties, given the fluctuating counts, the source activity and the emission probability remained below 5% (for a confidence interval of 95.45% k = 2).

Fig. 8 shows the experimental absolute photopeak efficiency and the simulation curves as a function of the energy. Energies other than the measured ones were simulated in order to obtain a curve fitted by Equation (7) in the energy range from 59.45 to 662 keV, for the geometry described in section 2.2. Fig. 8 shows the same measured and the simulated energies for comparison purposes.

The experimental and simulated data showed good agreement. The largest discrepancy of 5.54% was found to be for the energy of 59.45 keV from \(^{241}\text{Am}\).

The adjustment coefficients of the efficiency curve for the NaI(Tl) detector of Equation (7) were obtained by the method of least squares and the values are: \(a = 0.93226, b = 0.00888, c = -8.60811E-5, d = 2.56056E-7, e = -3.28954E-10, f = 1.56801E-13\), the correlation coefficient \((r^2)\) was 0.9987.

\[
\varepsilon = a + bE + cE^2 + dE^3 + eE^4 + fE^5
\]  
(7)

Where: \(\varepsilon\): photon detection efficiency (counts/photons number); \(E\): energy (keV); \(a, b, c, d, e, f\): adjustment coefficient.

4. Conclusions

A procedure for simulation of a NaI(Tl) detector has been presented in this work with the MCNP-X computer code. It consists of measuring two point sources at different locations around the detector and compared to the simulation results; the crystal dimensions was then adjusted accordingly until a match between the experimental and simulated results. It was considered a match when the difference between the results was less than 5%.

The crystal’s dimension determined by the proposed procedure are slightly different from the ones determined by gammagraphy. As the efficiency curves comparison showed better agreement with the dimensions determined by the two point sources methodology, it is clear that some distortions might have occurred in the gammagraphy procedure. Nevertheless, it showed to be effective as a starting point.

It became clear that it is necessary to consider, in the simulation, the parameters of the real energy resolution of the detector obtained by experimental measurements.

The photon detection efficiency curve was used for the validation of the mathematical model developed in the code. The efficiency curve was obtained both experimentally and by simulation;
the results were compared and showed a good agreement. The largest discrepancy of 5.54% was found to be for the energy of 59.45 keV from $^{241}\text{Am}$.

The methodology using two radioactive sources, a low and one high-energy photon, was found to be satisfactory to fit the dimensions of the crystal to be used in the detector’s simulation.

It is important mentioning that, depending on the degree of accuracy required, it is necessary to improve the curve fitting of the FWHM for low energy, in order to reduce the differences in energy resolution for the $^{241}\text{Am}$ photopeak.

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References


Ewa, I.O.B., Bodizs, D., Czifrus, S.Z., Molnar, Z.S., 2005. Improving curve fitting of the FWHM for low energy in order to reduce differences in energy resolution for the $^{241}\text{Am}$ photopeak.


