Response Function Simulation of Labr3 (Ce) Scintillation Detector

M A Fida¹, Fang Liu¹*, Min Li¹, Tianze Jiang¹, Xiaoxue Fan¹
¹ Beijing Key Laboratory of Passive Safety Technology for Nuclear Energy, North China Electric Power University, No.2, Beinong Road, Huilongguan, Changping District, Beijing 102206, China
Email: liuf@ncepu.edu.cn

Abstract. In Nuclear physics, gamma detection techniques are the most common ones being used for spectroscopy. Scintillation detectors find their applications in a large number of fields. The most commonly used and famous scintillation detector was NaI(Tl) that has been in use since the last 50 years. Recently, several new detectors have also been introduced commercially and they include lanthanum-based detectors. This study focuses on the response function simulation of the LaBr3(Ce) detector crystal. This is accomplished by developing a model that calculates various key properties for the detector crystal. This is done by using the Monte Carlo N-Particle (MCNP) transport code. A complete model for the detector is developed to simulate the lab setup. The simulation is then used to obtain the energy distribution of pulses that are created in the detector. Several gamma sources are used to obtain the pulse height spectra to calculate our properties of interest. The effect of distance on the spectra is also simulated. For Cs137 (662KeV), the energy resolution comes out to be 3.447% and FWHM is 22.12 KeV. An increase in the incident gamma energy results in increased FWHM whereas energy resolution and detection efficiency show a decreasing trend. After simulations, the crystal was also studied experimentally. In this case, both the simulation and experimental coincided. This proves the validity of the model developed.

Keywords: Scintillation Detectors, Lanthanum Detectors, Response Function, FWHM, Monte Carlo Transport Code

1. Introduction
Scintillation detectors have been in use in a wide range of applications ranging from health physics to industrial applications [1]. These detectors use gamma detection techniques to detect radiation. The most widely used scintillation detector is NaI(Tl) that has been in use since the last 50 years. During recent years, new detectors based on lanthanum have also become available. Several studies have already been done on the LaBr3 (Ce) detector. The light yield of Ø19×19 mm³ of LaBr3 (Ce) was found out to be 61000 photons per MeV (ph/MeV), and the energy resolution at 662 KeV was observed to be 3.4% experimentally [2]. However, the results obtained from these studies have not yet been justified by the simulations. The already conducted studies on the LaBr3 (Ce) detector show that its scintillation properties are better as compared to the two most widely used detectors previously, i.e., NaI(Tl) and HPGe. A comparison between Ø3"×3" of the LaBr3 (Ce) and NaI(Tl) scintillation detectors found out that the energy resolution of LaBr3 (Ce) was 2.9% whereas NaI(Tl) showed an energy resolution of 7% [2].
The technique used for simulations is called the MCNP. It is used in various applications like radiation detection, radiological protection, nuclear sites, shielding, and several other purposes. The same technique is used in this research to simulate the response function of the detector crystal and calculate various properties. Previously, utilizing this technique, another research was carried out to determine the various properties of NaI(Tl) scintillation detector [3]. The properties were calculated and also correlated with experimental values at varying distance between detector and radiation source.

The performance of a scintillation detector depends significantly on its full-energy peak detection efficiency [3]. This study focuses on the response function simulation of the LaBr₃(Ce) detector crystal through simulations as well as experimentally by developing a detector model in MCNP to verify the experimental results. Several radionuclides were used to obtain the properties of interest i.e., energy resolution and detection efficiency at different energy levels. The distance of the radioactive source was also changed to investigate its effect on the scintillation properties. After simulations, the results were also verified using a detector crystal of the same size experimentally.

2. Methods

2.1. MCNP Simulation Model

MCNP is a general-purpose N-Particle transport code that can be used to perform simulations for several types of particle transport. MCNP can be used to simulate particles with energies ranging from 0.001MeV to 100 MeV [4]. The detector model that is used to perform the simulations is shown below in figure 1. The model consists of a lead shield that is the biggest cylinder. Another cylinder is used to represent the PMT and also the detector crystal. The glass window of the detector and the reflecting material are represented by thin cylinders.

![Figure 1. MCNP Simulation Model.](image)

The MCNP code can be modified according to our needs to specify the radionuclide by giving its energy and also its distance from the detector. Proper materials were also defined using the MCNP material database. The code uses the F8 tally to record the energy distribution of pulses detected by the detector [5].

The whole simulation model is made in accordance with the physical detector package available in the laboratory. This is done in order to ensure as much similarity between the simulation and experimental setups. To improve the simulation results, the F8 tally was given a better Gaussian energy distribution. This was accomplished by providing the GEB parameters as input to MCNP. This gives the results of the simulation a Gaussian shape by using the GEB parameters to solve the 1 equation 1.

\[
f(E) = Ce^{-\frac{(E-E_0)^2}{\sigma^2}}
\]  

(1)
Where \( E \) and \( E_o \) represent the broadened and the unbroadened energy respectively, \( C \) is a constant used for normalization, and \( A \) is known as Gaussian Width that can be written in terms of FWHM as,

\[
A = \frac{FWHM}{\sqrt{2\ln 2}}
\]  

(2)

The GEB parameters are related to the experimental FWHM as given by equation 3. These are specified by the user as input to the GEB tally,

\[
FWHM = a + b\sqrt{E} + cE^2
\]

(3)

Here, the energy of the incident gamma-ray is being used [6]. The GEB parameters were calculated by using the FWHM data from the experiments and then performing a least square approximation [7]. The accuracy of the GEB parameters increases if the number of gamma sources is increased. These parameters are distance-dependent, so they have to be recalculated if the distance is varied between the source and the detector crystal. In simulations, four different gamma sources (Co\(^{60}\), Mn\(^{54}\), Eu\(^{152}\), and Cs\(^{137}\)) were used. The energy of the gamma photons generated by these sources was 344 KeV, 662 KeV, 1173 KeV, and 1332 KeV, respectively. The distance was also varied for each simulation to see its effect on the scintillation properties. The simulation is performed with a large number of source particles to make sure that error stays within acceptable limits.

2.2. Experimental Setup

In our experiments, the detector crystal that was used is manufactured by Saint Gobain company. The crystal is packed in an aluminum case with glass that acts as entrance window [3]. The flowchart diagram of the experimental setup is shown in figure 2.

![Figure 2. Experimental Setup.](image)

The detector is placed at a distance from the radionuclide at which the results are to be obtained. The glass window is facing the source. The detector is coupled with a photomultiplier tube that converts the input light signals to electrical signals which are then amplified. A variable high voltage is supplied to the PMT and its value can be changed from the computer. The amplified signal is then fed into the multichannel analyzer that feeds the results to a computer where the energy calibration is done, and the results are analyzed.

During the experiment, it is desired to keep the outside interference minimal. To achieve this, the experiment is performed in a dark environment so that the visible light doesn’t interfere with the results obtained. The experiment is performed separately from each radionuclide available to us. The distance is also varied by suspending the radionuclide in the air at a distance from the detector i.e., 25 cm, 20 cm, and 15 cm.

3. Results and Discussion

Each of the performance parameters of the detector crystal is discussed below.

3.1. Full Width at Half Maximum (FWHM)

Full Width at Half Maximum (FWHM) is the width of a function taken at a point that is half of the maximum value of ordinate. As the width of the function becomes smaller, the accuracy of the results improves [8]. The results of FWHM obtained from simulation and experiment are shown below.
Figure 3. Simulated Gamma-ray Spectrum of Cs137 (Point A: 662KeV).

Figure 4. Experimental Gamma-ray Spectrum of Cs137 (Point A: 662KeV).

Figure 5. Experimental Gamma-ray Spectrum of Co60 (Point A: 1173KeV, Point B: 1330KeV).

Figure 3 shows the spectrum of Cs$^{137}$ obtained from MCNP Simulations. As we can see that we have a single peak at 662KeV. This spectrum was analyzed in Origin Pro software to obtain the simulated FWHM for Cs$^{137}$ and it comes out to be 22.82KeV. A similar simulation was also done for Co60 having two peaks at 1173KeV and 1330KeV and the simulated FWHM came out to be 31.56KeV and 32.61KeV respectively.

After the simulations, the same radionuclides were used to perform the experiment and the values of the experimental FWHM were calculated. The experimental spectra of both the radionuclides can be seen in figure 4 and figure 5 respectively. Here we can see that experimental counts are less than
those in the simulation for Cs\textsuperscript{137}. The reason for this being because the number of counts can be amplified by the high voltage that is being supplied to the PMT. In this case, the experiment was done at 550V. If a higher voltage is applied, the number of counts will be also increased.

Table 1. FWHM values of available radionuclides.

| Nuclide       | Experimental FWHM (KeV) | Simulated FWHM (KeV) |
|---------------|-------------------------|----------------------|
| Co\textsuperscript{60}(1173KeV) | 32.94                   | 31.56                |
| Co\textsuperscript{60}(1330KeV) | 33.33                   | 32.61                |
| Cs\textsuperscript{137}(662KeV)  | 22.12                   | 22.82                |

Table 1 shows the experimental as well as simulated FWHMs for the radionuclides that are available to us in the laboratory. Here it can be seen although there is a slight difference between the simulated and experimental values due to the non-consideration of PMT in our MCNP model, the values are still in good agreement with experimental results. The simulations were also carried out for three other radionuclides that were not available in the laboratory and the results are presented below in table 2.

Table 2. Simulated FWHM values for radionuclides not available

| Nuclide | Photopeak Energy (KeV) | Simulated FWHM (KeV) |
|---------|------------------------|----------------------|
| Eu\textsuperscript{152} | 344                    | 15.12                |
| Mn\textsuperscript{54}  | 834                    | 25.98                |

Figure 6. Detector FWHM vs Incident Gamma Energy.

Figure 6 shows both the experimental and simulation results obtained for FWHM of various radionuclides. It can be seen that as the incident energy increases, the FWHM also increases. The reason being that with an increase in the source energy the effects like Compton scattering, and pair production modes become dominant so not all incident gamma rays are included in the full-energy photpeak and it decreases. It is also observed that FWHM is not dependent on the distance between
the source and the detector as the results obtained were the same after performing the experiment by changing the distance.

3.2. Energy Resolution
The energy resolution of a detector crystal is its ability to differentiate between two gamma rays having photopeaks close to each other. The better the energy resolution, the clearer it can separate two adjacent energy peaks. The energy resolution is given by the equation 4,

\[ R = \frac{FWHM}{E} \times 100 \]  

(4)

Once we have the FWHM values for various radionuclides the energy resolution values can be simply calculated by using the equation 4. The energy resolution values of the sources available in the laboratory are given below in table 3. They have been calculated from both the experimental and simulated data.

| Nuclide | Experimental Energy R (%) | Simulated Energy R (%) |
|---------|---------------------------|------------------------|
| Cs\(^{137}\)(662KeV) | 3.447 | 3.341 |
| Co\(^{60}\)(1173KeV) | 2.808 | 2.691 |
| Co\(^{60}\)(1330KeV) | 2.506 | 2.452 |

The energy resolution is also calculated for the other radionuclides which were not available in the laboratory and only the simulations were performed for them. The simulated energy resolution for these is shown below in table 4.

| Nuclide | Photopeak Energy (KeV) | Simulated Energy R (%) |
|---------|------------------------|------------------------|
| Eu\(^{152}\) | 344 | 4.385 |
| Mn\(^{54}\) | 834 | 3.115 |

It can be seen that the energy resolution of Cs\(^{137}\) comes out to be 3.447%. In literature, the value is reported to be 3.2%. The difference might be due to the experimental setup and different crystal packaging. However, the values for other sources are comparable to the ones already reported. This could be caused by some minor errors such as the energy linearity of PMT. As the light yield of LaBr\(_3\) (Ce) crystal is quite high, combining that with a fast decay time, the peak current through the PMT is also high [9]. Thus, the PMT available to us in the laboratory was not suitable for this experiment. This is also a reason for deviation from already reported literature values.

| Nuclide | Detector Crystal | Simulated Energy R (%) |
|---------|------------------|------------------------|
| Cs137   | NaI(Tl)          | 6.29                   |
| Cs137   | LaBr3(Ce)        | 3.34                   |

Table 3. Energy Resolution Values of available radionuclides.

Table 4. Simulated Energy Resolution Values of sources not available.

Table 5. Energy Resolution Comparison (MCNP Simulation).
Table 5 shows the comparison of energy resolution values between the commonly used NaI(Tl) and LaBr3(Ce) by using a single radionuclide Cs\textsuperscript{137}. It can be seen that energy resolution is approximately 50% better in the case of LaBr3(Ce).

Figure 7 shows both the simulation and experimental results. It can be seen with the increase of energy of the incident gamma-ray, the energy resolution is decreased. It was also observed that energy resolution doesn’t depend on the distance between the source and the detector. Also, in MCNP simulations, the effect of PMT is ignored; this can also result in errors. The error was also there due to inaccuracy in the calculation of GEB parameters. This can be mitigated by using an increased number of gamma sources. However, it can still be seen that both simulation and experimental results are in good agreement.

3.3. Absolute Detection Efficiency

The absolute detection efficiency is defined as the ratio between the counts recorded by the detector to the total gamma rays emitted by the radionuclide in all directions [10]. It can be calculated for MCNP simulations by the equation 5 given below,

\[ \varepsilon_{MC} = \frac{N_C}{N_S} \]  \hspace{1cm} (5)

Where \( N_C \) is the number of the counts and \( N_S \) is the number of photons. In the case of the experiment, the equation 5 is modified to be,

\[ \varepsilon_{exp} = \frac{N}{A_t P} \]  \hspace{1cm} (6)

Where \( N \) is the number of counts, \( A \) is the activity of the radionuclide, \( t \) is the time, and \( P \) is the probability of emission. The efficiency of the detector is influenced by various factors such as its shape, volume, material, and attenuation layers and also the distance between source and detector [11].

In our experiment, the distance was also varied to see its effect on efficiency. First, the distance was kept constant and gamma energy was varied to see its effect. Then the distance was varied. The results are shown below in figure 8 and figure 9.
Figure 8. Detector Efficiency vs Incident Gamma Energy.

Figure 9. Detector Efficiency vs Distance from source (Cs\textsuperscript{137}).

It can be seen from figure 8 that when the distance is kept constant, an increase in gamma ray incident energy results in decrease of the efficiency. This is due to the fact that at higher energies, all gamma rays do not add to full energy peak because of Compton scattering and pair production [12]. It is also evident from figure 9 that as the distance from the source to detector increases that detection efficiency decreases.

4. Conclusion
In this study, we developed a model for Ø1"×1" LaBr\textsubscript{3} (Ce) detector to simulate its response function and calculate its scintillation properties using MCNP Simulations. Various properties like FWHM, energy resolution and detection efficiency were recorded experimentally as well as calculated through simulations. The distance between the source and crystal was also varied to see its effect on these properties.

If we look at the energy resolution values, it can be seen that for Cs\textsuperscript{137} it came out to be 3.447% experimentally. This value is already much better than the commonly used NaI(Tl) based detector. Hence, LaBr\textsubscript{3} (Ce) exhibits better detection capabilities than the previously used detectors. Further, it was observed that the FWHM and energy resolution is independent of the distance between the detector and the source radionuclide. However, detection efficiency still changes when the distance is changed.
A strong agreement was established between simulation and experimental findings. However, there were still some minor errors. These could be due to several reasons. First and foremost being the light yield of the lanthanum bromide detector is high and the decay time is fast. This results in very high peak currents flowing in the PMT that cause a nonlinearity in the results. One other reason is the inaccuracy in the calculation of GEB parameters. This can be mitigated by using more radionuclides to calculate these parameters which will ultimately result in reduced errors.

Acknowledgments

This work was supported by the Project of National Natural Science Foundation of China (Grant No. 11405055) and the Fundamental Research Funds for the Central Universities (Grant No. 2018ZD10).

References

[1] Knol G E 2000 Radiation Detection and Measurement John Wiley & Sons.
[2] Casanovas R 2012 Energy and Resolution Calibration of NaI(Tl) and LaBr3(Ce) Scintillators and Validation of an EGS5 Monte Carlo User Code for Efficiency Calculations Elsevier 675 78-83.
[3] BrilLanCeTM Scintillators Performance Summary 2004-2016 [Online] Available: https://www.crystals.saint-gobain.com/sites/imdf.crystals.com/files/documents/brillance380-material-data-sheet_69765.pdf.
[4] Briesmeister F 2010 MCNP–A General Monte Carlo New Mexico: Los Alamos National Laboratory.
[5] Salgado C M 2012 Validation of a NaI(Tl) detector’s model developed with MCNP-X code Progress in Nuclear Energy 59: 19-25.
[6] Navarro J 2015 Gamma-Ray Simulated Spectra Deconvolution of a LaBr3 1-in. x 1-in Scintillator Nuclear Technology 190(2): 183-192.
[7] ORIGINLAB [Online] Available: http://www.originlab.com/
[8] Dorenbos P 2004 Gamma ray spectroscopy with a 19*19 mm3 LaBr3: 0.5% Ce3+ scintillator IEEE Transactions on Nuclear Science 51(3).
[9] Quarati F G A 2013 Scintillation and detection characteristics of high-sensitivity CeBr3 gamma-ray spectrometers Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 729: 596-604.
[10] Akkurt I 2014 Detection efficiency of NaI (Tl) detector in 511–1332 keV energy range Science and Technology of Nuclear Installations 2014(1).
[11] Akkurt I 2015 Calculation of detection efficiency for the gamma detector using MCNPX Acta Phys. Pol. A 128(2-B): 332-334.
[12] Bizarri G 2006 Scintillation properties of Ø 1 1 inch IEEE Transactions on Nuclear Science 53(2): 615.