Cumhuriyet Science Journal

Cumhuriyet Sci. J., 45(2) (2024) 414-425
DOI: https://doi.org/10.17776/csj.1379874

| csj.cumhuriyet.edu.tr | Founded: 2002 ISSN: 2587-2680 e-ISSN: 2587-246X Publisher: Sivas Cumhuriyet University

Evaluating the Performance of Two NaI(Tl) Detectors Using a Combined Approach of Experiment and Monte Carlo Simulation

Aydın Yıldırım [1,a,*], Gökçe İnal [1,b]

[1] *Physics Department, Science Faculty, Akdeniz University, Antalya, Türkiye*
**Corresponding author*

Research Article

History
Received: 23/10/2023
Accepted: 29/03/2024

ABSTRACT

The aim of this study is to compare two identical NaI(Tl) detectors under the same conditions to reduce potential sources of error in future experiments. To this end, an experimental setup using both detectors was designed to measure the gamma spectrum of point sources. In order to verify the experimental results, the same setup was conducted by Monte Carlo simulations. The characteristics of the detectors, such as resolution and efficiency, were analyzed simultaneously to obtain possible differences. The resolution and efficiency of the detectors were found to be slightly different when their settings were the same, but within the expected range. The fitted data gave a standard deviation of 20.749±0.00693 keV for detector 1 and 19.698±0.00647 keV for detector 2 at 662 keV. The experimental data showed that one detector had a resolution of 6.9% and the other 7.2%. The simulation results and experimental data are in good agreement. In conclusion, it was observed that the high errors in the experimental data are due to the 20% uncertainty of the point sources.

Keywords: Detector, Efficiency, Geant4, Monte Carlo, NaI.

[a] aydinyldrm@gmail.com https://orcid.org/0000-0003-2141-5355
[b] gokcealina@gmail.com https://orcid.org/0000-0003-4660-8532

Introduction

Radioactive sources have been used for various purposes since the late 1800s. There are many areas where these radioactive sources can be used, including medicine, academics, archaeology, agriculture, and industry [1-5]. Also, people may encounter natural radioactive sources during their daily lives, in addition to the areas mentioned above [6]. Although these sources, which are used to simplify life, have many benefits, they can be extremely dangerous. Because radioactive sources are both useful and dangerous, they need to be monitored carefully to prevent harm to people and the environment [7]. Detectors are the main tools used to monitor these types of radiation. To obtain accurate and meaningful readings from detectors and minimize undesirable effects, the characteristics of the detectors must be well known [7–9]. As radioactive sources have a wide range of uses, so do the types of detectors that detect them [10–12]. For some detectors, it is sufficient to detect only the presence of radiation in the environment, while for others, the main purpose of the detector is to detect multiple quantities such as the presence of radiation, the type of radiation, the energy of radiation, the activity of the radiation source. Also, if the activity or dose of a source is to be determined with a gamma spectrometer, the efficiency of the detector must be known as a function of distance and energy. In particular, the detectors used by certified institutes or establishments must often be validated, since these institutes measure the activity and dose of drugs that contain radioisotopes.

Bedir et al. (2020) investigated the characterization of a handheld detector for radioguided surgery. They showed that more than one radiotracer can be used to fully assess the size of the tumor (whole tumor and sentinel lymph nodes). In such cases, a detector must have a resolution of less than 10 keV at energies below 159 keV. To develop such a detector, they chose $LaBr_3$ as the scintillator and studied the characteristics of the developed detector for resolution. As an example of a multiple detector system, Ghosh et al. (2016) studied the PARIS (photon array for the studies with radioactive ions and stable beams) $LaBr_3$(Ce)-NaI(Tl) phoswich detectors. The system consists of two phoswich detectors. Both detectors have 9 LaBr3 and 9 NaI scintillator crystals. Gamma energies up to 22.6 MeV have been measured with this configuration. A resolution of 2.1% at E = 22.6 MeV was achieved in the experiments. In addition, FWHM = 315 ps is measured for time resolution with a 60Co source. Akkurt et al. (2015a) emphasized the importance of the resolution of the detector and investigated a $3' \times 3'$ NaI(Tl) detector, similar to this study. They used photon energies of 511, 662, 835, 1173, 1275, and 1332 keV to characterize the resolution of the detector as a function of distance. Guss et al. (2013) investigated different sizes of scintillators for their properties. $CeBr_3$, $LaBr_3$ and NaI were selected for comparison. Detector resolution and efficiency were compared for different crystal sizes, and it was found that $LaBr_3$ has the best resolution for all sizes compared. They indicated that as the size of the crystal increases, the resolution of all three detectors is reduced but the efficiencies get higher.

In this study, a scintillator type used in gamma spectroscopy is investigated. Gamma spectroscopy is one of the most commonly used techniques for measuring the energy of gamma rays. In gamma spectroscopy, the characterization of the equipment, particularly the characterization of detectors, is crucial for the accuracy of the data taken. NaI(Tl) scintillator detectors have been widely used to measure the activities of low-level radioactive sources in many fields of gamma spectroscopy, especially because of their important characteristics of having high detection efficiency. Nuclear and particle physics experiments today require highly complex setups. Some of the reactions observed during high energy experiments may not be detected with simple detector setups due to their low cross sections. As a solution, research facilities conducting such experiments use a large number of detectors, either of the same type or of different types. In such designs, it is essential to evaluate the readings of each detector separately, as well as the collective readings of all detectors. Also, these high energy reactions produce too much background, and it is very difficult for one detector to handle this background. Increasing the number of detectors reduces the pile-up effect and allows the detector array to make reasonable measurements. Therefore, the thorough examination of the characterization and performance assessment of the systems to be installed is essential due to the extensive usage of comparable systems in research facilities. This is critical to the understanding of the results of the experiments being performed. Accordingly, this investigation will provide valuable insights to research laboratories currently constructing or preparing to construct detector systems that are comparable.

This paper is organized as follows. In Section 2, the methodology of the research is described. First, activity of sources was determined with a hybrid model of experiment and simulation. Then, the experimental method will be presented and followed by simulation method. Section 3 presents all the results for experimental and simulation data. Finally, the study is concluded in Section 4.

Material and Method

Point sources were used as gamma generators for this study. The activity of the sources must be known to calculate the efficiency of detectors. The activity of the source and efficiency of the detector are coupled quantities. It is not possible to calculate the activity of the source or the efficiency of the detector without knowing the value of the other one. The sources are labelled with 1 μCi activity however they have 20% uncertainty and are at least two to three years old. Therefore, Monte Carlo simulations were used to calculate the current activity of the sources [13–16]. The Geant4 simulation toolkit, which is used by many researchers, was employed for the simulations. In Geant4 simulations, the selection of event numbers, Monte Carlo parameters, and variance reduction techniques critically impacts simulation accuracy and efficiency. The count of events reflects the total physical occurrences, such as particle interactions or decays, in the simulation. Optimal selection of event numbers is indispensable in balancing computational resources and ensuring statistically valid results. Increasing the number of events may decrease statistical uncertainties, but it also requires additional computational resources and time. Geant4's Monte Carlo parameters include various configurations, such as step sizes, tracking cuts, and production thresholds, which dictate the precision of particle tracking and interactions in the simulation. Proper parameter tuning is essential to strike the right balance between accuracy and computational efficiency for specific applications [17–19]. It must be mentioned that the variance reduction techniques in Geant4 offer users tools to enhance simulation efficiency and minimize statistical fluctuations. These techniques enable users to give priority to specific interactions, divide particle tracks, and modify tracking weights to improve the accuracy and reliability of results. The process of determining the optimal configuration for simulation outcomes requires users to consider their simulation requirements, computational resources, desired level of statistical precision, and the interplay between the number of events, Monte Carlo parameters, and variance reduction techniques. Achieving effective tailoring of these settings for specific applications is a nuanced endeavor, often involving iterative testing and sensitivity analyses to ensure robust and meaningful results. After the calculation of the current activity of the sources, the characterization of the detectors can be carried out. The last part of this study is to validate the experimental results with Geant4 simulations.

The consistency of detection efficiency and resolution for two NaI(Tl) detectors was investigated by experimentally and computationally via Monte Carlo simulations. The reason for considering such a setup is that when both detectors are used for the same measurement at the same time or in a coincidence experiment, there might be unwanted errors due to incorrectly adjusted settings, or it might create accuracy problems. Detectors were kept under consistent conditions to obtain the most accurate evaluation results. The experiment was conducted for different source-detector distances and gamma energies.

Experimental Setup

The detectors in question were $3' \times 3'$ Ortec's 905-4 NaI(Tl) scintillation detectors. These detectors were connected to a CAEN V1725D 8 Ch. 14 bit 250 MS/s Digitizer. The detectors were covered with lead shielding on all sides. The lead thickness was 5 cm. To determine the efficiency and resolution of detector, four gamma sources were used. These gamma sources were ^{22}Na, ^{54}Mn, ^{60}Co, ^{137}Cs. Because of the gamma peaks of the chosen sources, we had the opportunity to look at a wide range in gamma spectroscopy. These peaks are 511, 662, 835, 1173, 1275 and 1332 keV. The design of the experimental setup can be seen in Figures 1-a, 1-b and 1-c. Figure 1-d shows the image of the detectors and one of the sources.

For each source, measurements were performed at five source-detector distances: 1, 2, 3, 5, and 10 cm. The source was placed in the middle of the setup, and the detectors were moved equally to each distance. All measurements lasted 3600 seconds. The optimum bias voltage for these detectors is between 700 and 850 V, and we fixed the bias voltage for both detectors at 750 V. CAEN Compass software was used for data acquisition. In the Compass software, we used the same acquisition parameters for both detectors to determine the differences for identical setups.

Monte Carlo Simulations

For the Monte Carlo simulations, we used the Geant4 Simulation Toolkit. While performing the Geant4 simulations, the "G4EmLivermorePhysics" library was chosen to model the interaction of the electromagnetic radiation and the detectors. The prepared simulation geometry is illustrated in Figure 2. To obtain a realistic result, we added all the necessary components of the experimental setup. The components in the simulation include the two NaI (Tl) detectors, lead blocks, lead sheets, aluminum cap of detectors, and radioactive sources. Unfortunately, the simulations cannot reflect the electronic or other possible effects coming from radiation-matter interactions, which causes broadening at photo-peaks. The simulations give only single lines for the photo-peaks. It is necessary to add the resolution of the detector, which comes from experimental data to the simulations at this point [5]. To reflect the 1 mCi activity of the point sources, 37×10^6 primaries were selected for the simulations. As previously mentioned, the simulations were adjusted for computational efficiency and accuracy. Additionally, the number of primaries is sufficient to minimize statistical fluctuations while maintaining computational efficiency on an ordinary desktop computer. Using only the NaI crystals as sensitive volumes and killing secondary particles that do not affect the study reduces computational time and output file size

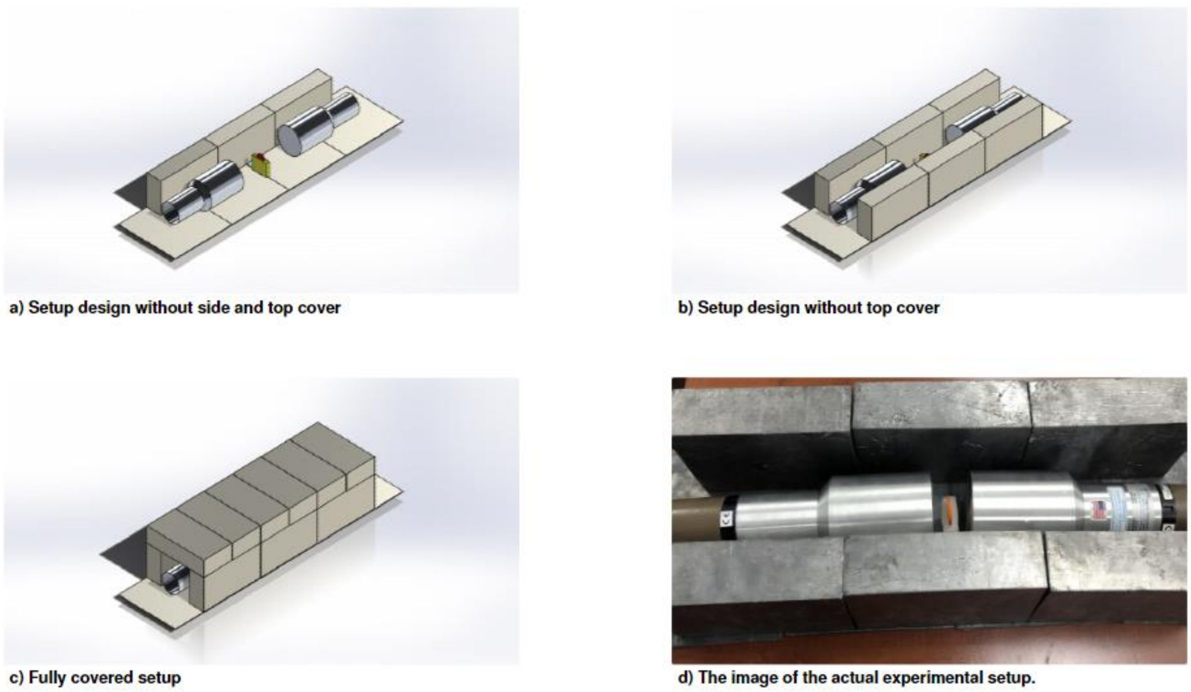

Figure 1. The lead blocks are 5 cm thick, and they covered both detectors and the source. The top blocks were put after the image was taken. The orange disk between the detectors is the gamma source.

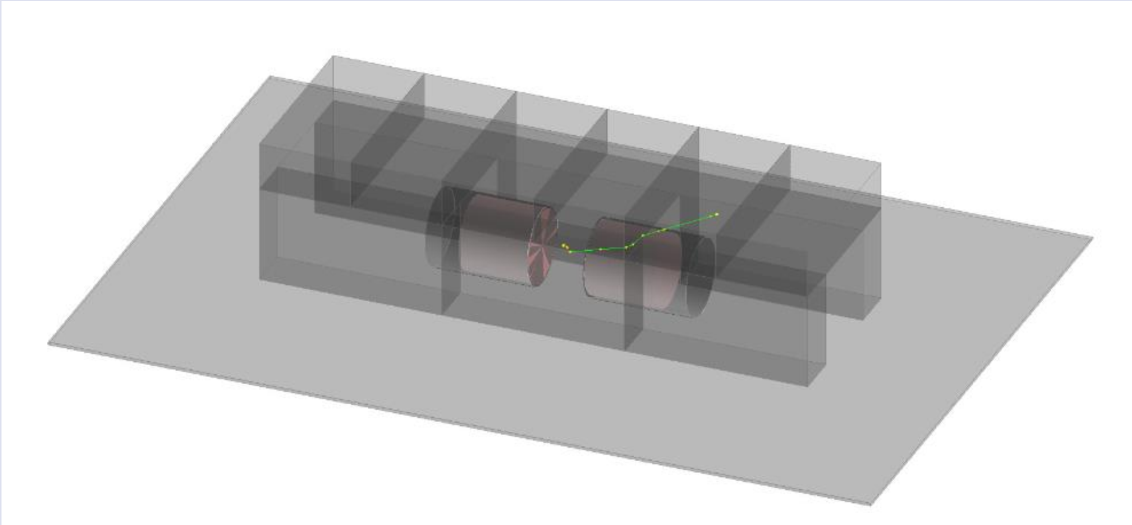

Figure 2. The Geant4 simulation includes lead blocks, lead sheets under the detectors, aluminum covers of the scintillation crystals and the NaI crystals (red cylinders). One gamma was released between two detectors.

Results

We began with the calculation of activity of the sources by using a hybrid model, which includes experiment and simulation. First, we calculated the efficiency of a single NaI (Tl) detector with Monte Carlo method. The next step was to create the same setup in the laboratory environment. The activity of a point source can be calculated with the equation given below [10];

$$A = \frac{N_p}{\epsilon \times \gamma \times t} \quad (1)$$

where A is the activity of the point source, N_p is the total area (or the total counts) under the interested peak, ϵ is the efficiency of the detector for the specific gamma peak of the source, γ is the probability of the source for emitting a gamma photon and t is the time of measurement in second. The current activities of the point sources were given in Table 1.

.**Table 1.** The radioactive sources that were used in this study and their calculated activities. The gamma energies and their emission probabilities are also given in the table.

Nuclide	Energy (keV)	Emission Probability (%)	Current Activity (kBq)
^{22}Na	511.0	179.91	8.85∓1.77
	1274.537	99.940	
^{60}Co	1173.228	99.85	14.7∓2.94
	1332.492	99.9826	
^{137}Cs	661.657	85.10	37.4∓7.48
^{54}Mn	834.848	99.9760	0.80∓0.16

After obtaining the current activities, we proceeded to our intended study. To perform the experiments, we carefully measured each of the distances and fixed the points where the detectors and sources were located. Here, it is essential to prevent extra uncertainties which may arise from miscalculated distances or solid angles.

The Root analysis program was used for all calculations and analyses in the study (see also “ROOT” [software], Release v6.24/06) [20,21]. First, the resolution of the detectors was calculated for the 662 keV gamma peak. The distance of the source-detector was 3 cm for each detector. The spectra which belong to ^{137}Cs for both detectors were given in Figure 3 and these spectra are given for 16384 channels. The Compass software was set to measure between 0 and 2500 keV in 16384 channels.

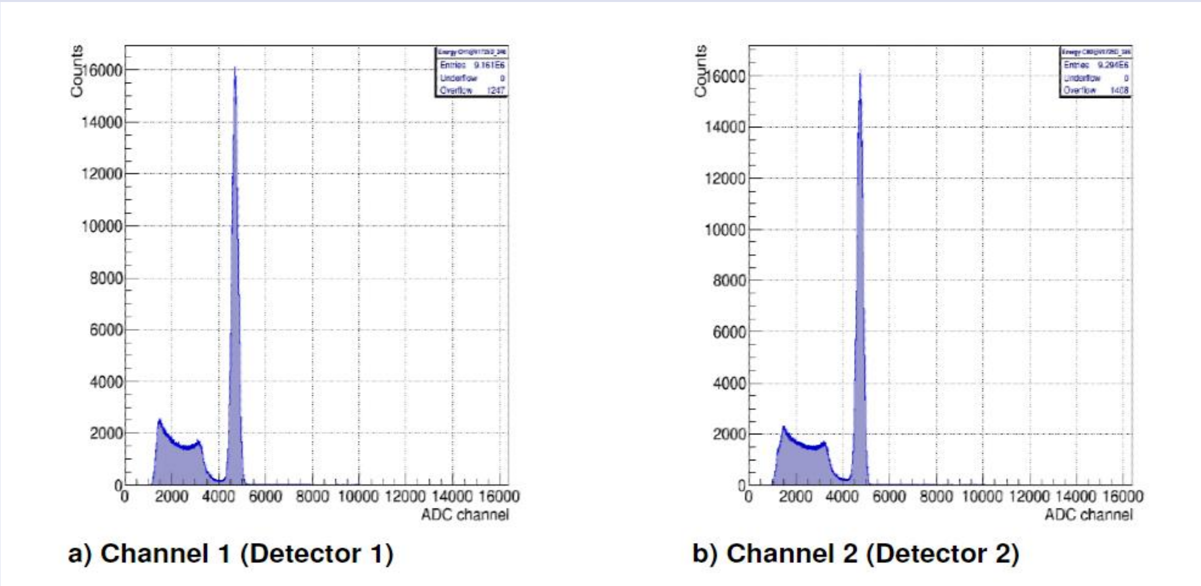

Figure 3. Spectrum of ^{137}Cs at 3 cm source-detector distance. Figure 3-a shows the spectrum of detector 1 and Figure 3-b shows the spectrum of detector 2. The spectra were taken by CAEN's Compass software..

The peaks were fitted using a Gaussian function, and the standard deviation (σ) of the fit function was calculated. Then, using the standard deviations from the fit, the full width at half maximum (FWHM) of the Gaussian was calculated, and the resolutions of the detectors were evaluated. Detector 1 (the detector on the left in Fig. 1) has 7.2% resolution at 662 keV, whereas Detector 2 (the detector on the right in Fig. 1) has 6.9% resolution at 662 keV. The relationship between the σ, FWHM, and the resolution (R) is given by Equation (2) [22].

$$2.335\sigma = FWHM$$
$$R = \frac{FWHM}{E_0} \times 100 \quad (2)$$

As shown in Figure 4, the shape of the fitted data was clearly Gaussian. Therefore, the standard relation given in Equation (2) can be used for the resolution calculations. Although the resolutions were 7.2% and 6.9% for detectors 1 and 2, respectively, it cannot be concluded that there is a difference in the resolution under same conditions since both detectors, photomultipliers (PMTs) and scintillation crystals, are sealed and cannot be opened. An additional analysis of PMT response to single photoelectron (SER) is required to conclude the real difference in resolution [23].

The measured resolutions for both detectors are comparable with those reported in previous works. The resolution values obtained for both detectors were close to 7%, but slightly worse than the datasheet values at 662 keV and at a detector-source distance of 3 cm. Akkurt et al. (2014) used a $3' \times 3'$ NaI(Tl) detector to determine the detector resolution for 5 different gamma energies at a detector-source distance of 0.5 cm. Their study found that the resolution for 662 keV was approximately 7%. Demir et al. (2021) conducted a study on a $3' \times 3'$ NaI(Tl) detector using Fluka Monte Carlo code. They calculated the energy resolution for the ^{137}Cs gamma peak (662 keV), which is traditionally used for resolution determination in NaI(Tl) detectors, as 6.48% [24]. Similarly, Tam et al. (2017) characterized NaI(Tl) both experimentally and using Geant4 Monte Carlo code and found the energy resolution for 662 keV at 20 cm detector-source distance to be 6.44% and 6.54%, respectively. Moszynski et al. (2003) conducted a study on pure crystals of NaI at both room temperature and liquid nitrogen (LN_2) temperature [25]. For their study, three pure NaI crystals were utilized, and the energy resolutions were measured. The resolutions at room temperature were approximately 16%, whereas at LN_2 temperatures, they ranged from 3.8% to 6.2%. The research demonstrates that NaI detectors, when pure, can achieve a resolution similar to that of $LaBr_3$ detectors at LN_2 temperatures.

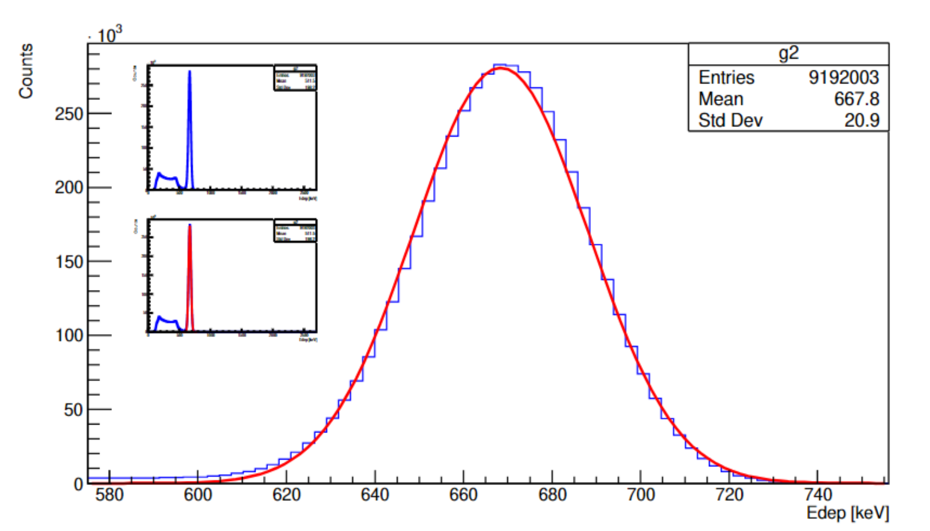

Figure 4. The experimental spectrum of the ^{137}Cs that belongs to one of the detectors. It shows the photo-peak at 662 keV and the gaussian function.

After getting the resolution of detectors, we proceeded to efficiency calculations. We analyzed each photo-peak with ROOT and calculated net area under the peak. By putting the count numbers in the Equation (1), we calculated the efficiencies for both detectors. The solid angles that the detectors saw were also calculated for each source-detector distance. This information is useful for determining the scaling factor for efficiency. The calculated solid angle fractions and scaling factor, or in other words, interaction probabilities are given in Table 2.

Table 2. Calculated interaction probabilities for Detector 1 and 2 from the experimental data.

	Interaction Probability											
Distance (cm)	511 keV		662 keV		835 keV		1173 keV		1275 keV		1332 keV	
	Det.1	Det.2	Det.1	Det.2	Det.1	Det.2	Det.1	Det.2	Det.1	Det.2	Det.1	Det.2
1	0.66	0.58	0.23	0.21	0.26	0.23	0.18	0.16	0.13	0.13	0.15	0.14
2	0.68	0.57	0.22	0.18	0.23	0.21	0.18	0.15	0.14	0.14	0.15	0.13
3	0.65	0.65	0.20	0.19	0.23	0.20	0.18	0.16	0.14	0.15	0.15	0.13
5	0.65	0.76	0.19	0.23	0.22	0.25	0.17	0.20	0.15	0.16	0.15	0.17
10	0.95	0.76	0.24	0.22	0.27	0.27	0.22	0.22	0.19	0.19	0.19	0.19

In following figures (Figures 5 and 6), a comparison of the experimental data and simulation data is given for Detector 1 and Detector 2, respectively. These figures show the change in efficiency with increasing source-detector distance. We also compared the efficiencies with increasing gamma energies. These comparisons are shown in Figures 7 and 8 for detectors 1 and 2, respectively. Figures 5 - 8 show similarities with previous studies and are in good agreement with literature and simulations [8, 13]. Although there are few results that do not agree with the simulations, these results may be due to the large uncertainty of the sources. The main purpose of this study is to determine the differences between two identical detectors with the same settings. We have already mentioned the difference in resolution. Figures 5 - 8 show the differences in terms of efficiency. In particular, the difference in the efficiency of 511 keV for 1 cm is clearly visible for these detectors. As the energy increases, this difference decreases, and this is true for increasing source-detector distance.

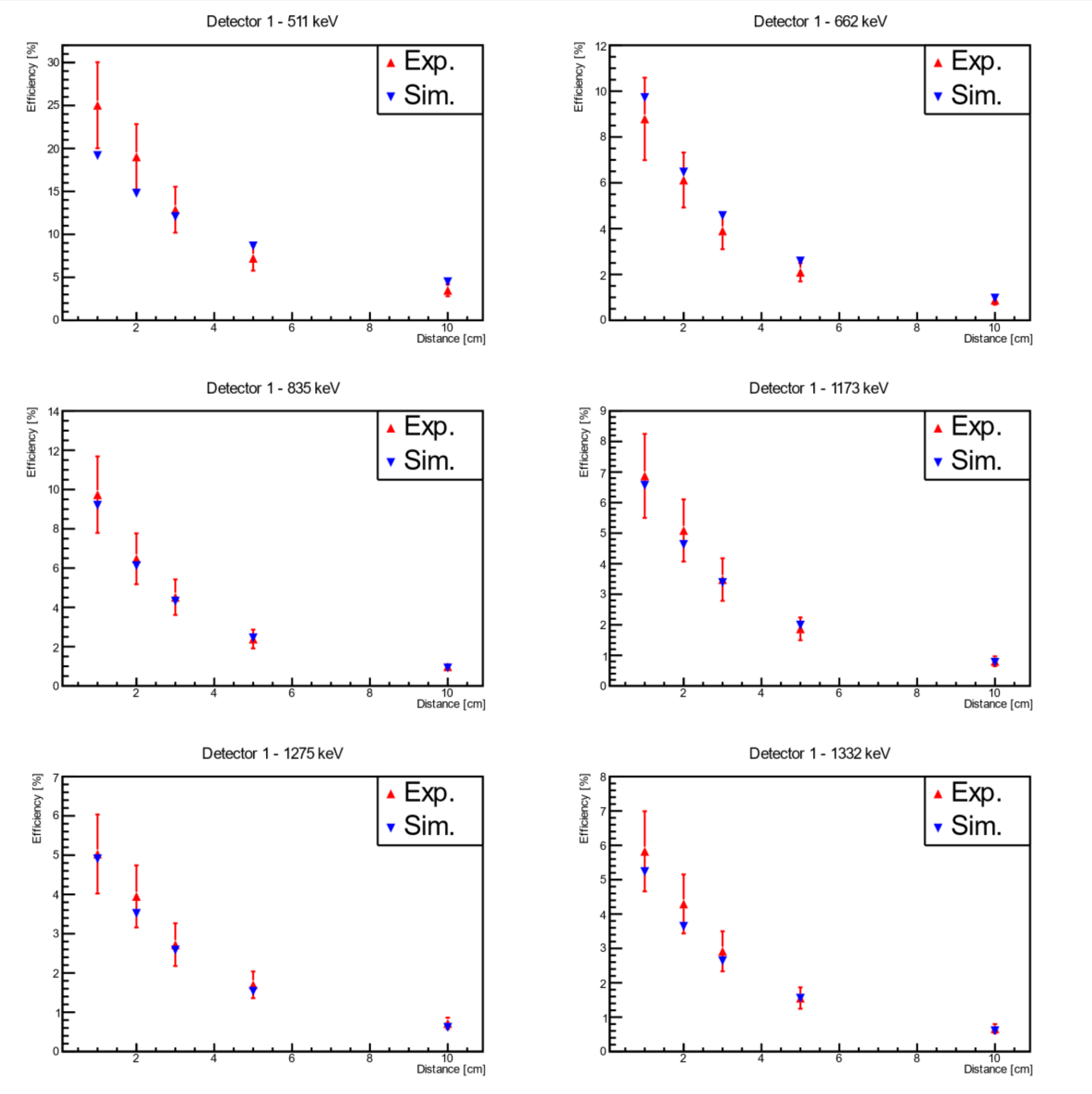

Figure 5. The efficiency graph of the Detector 1 with increasing distance in the x-axis. The simulation results are also in the graphs.

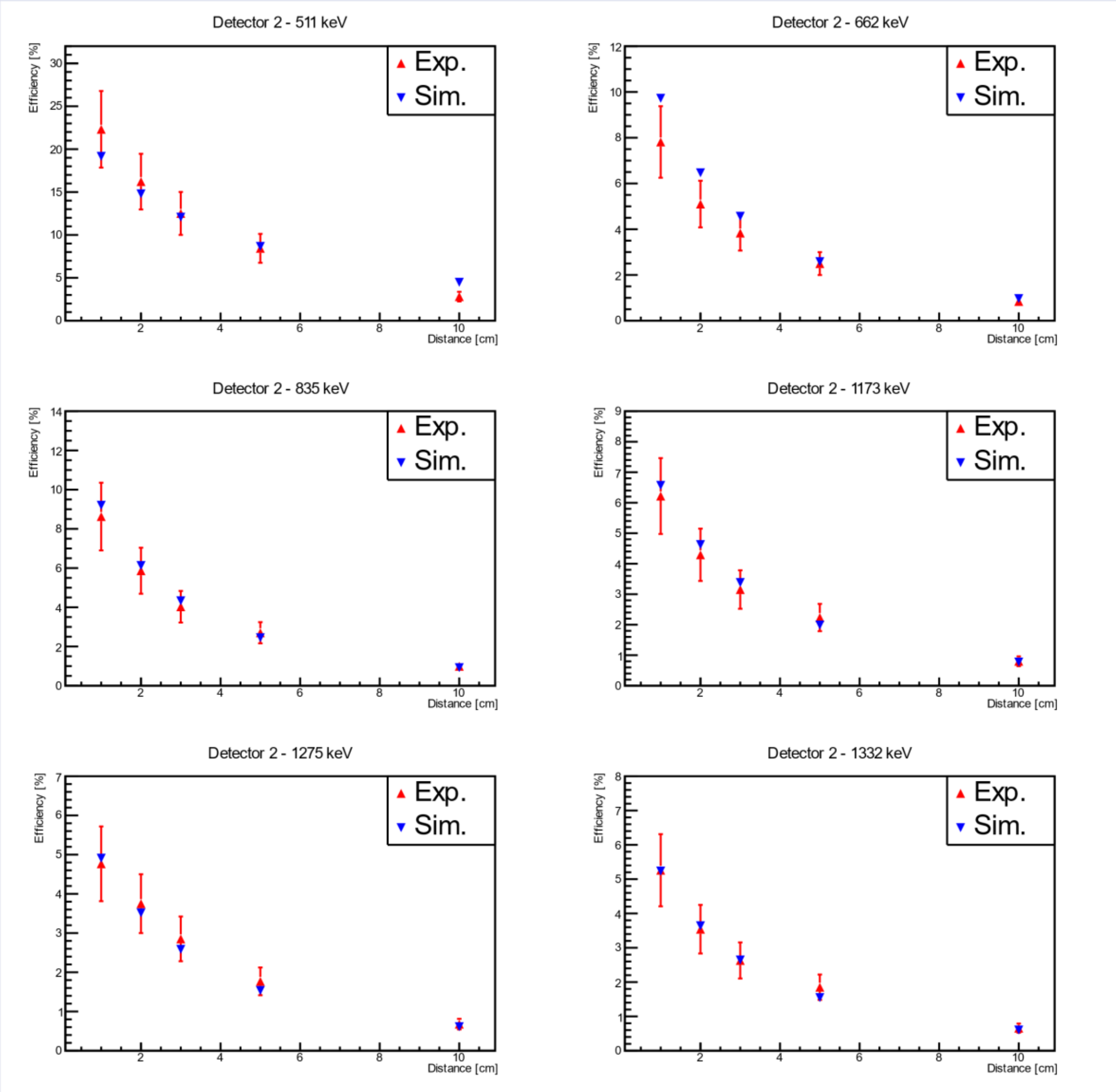

Figure 6. The efficiency graph of the Detector 2 with increasing distance in the x-axis. The simulation results are also in the graphs.

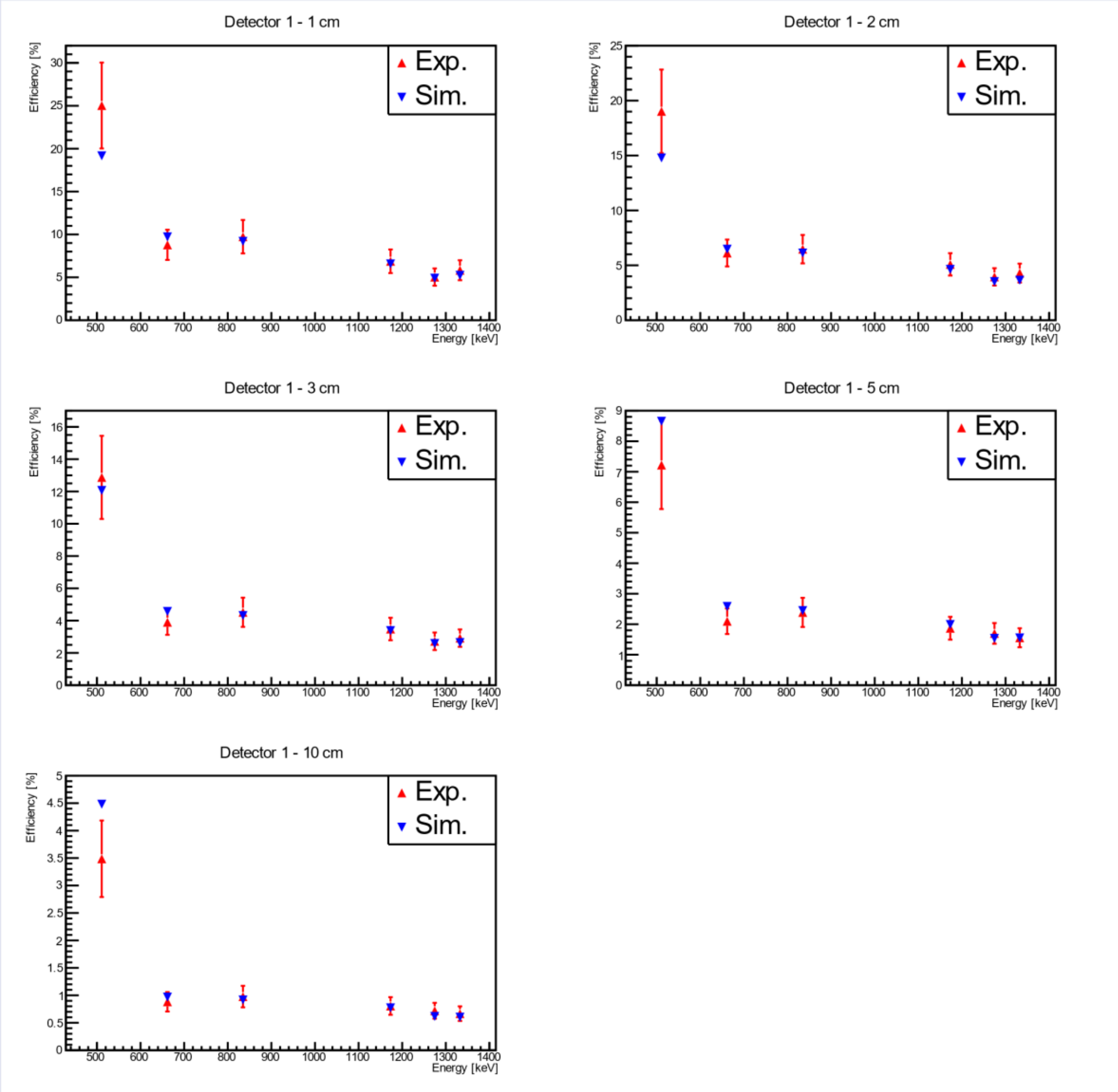

Figure 7. The efficiency graph of the Detector 1 with increasing energy in the x-axis. The simulation results are also in the graphs.

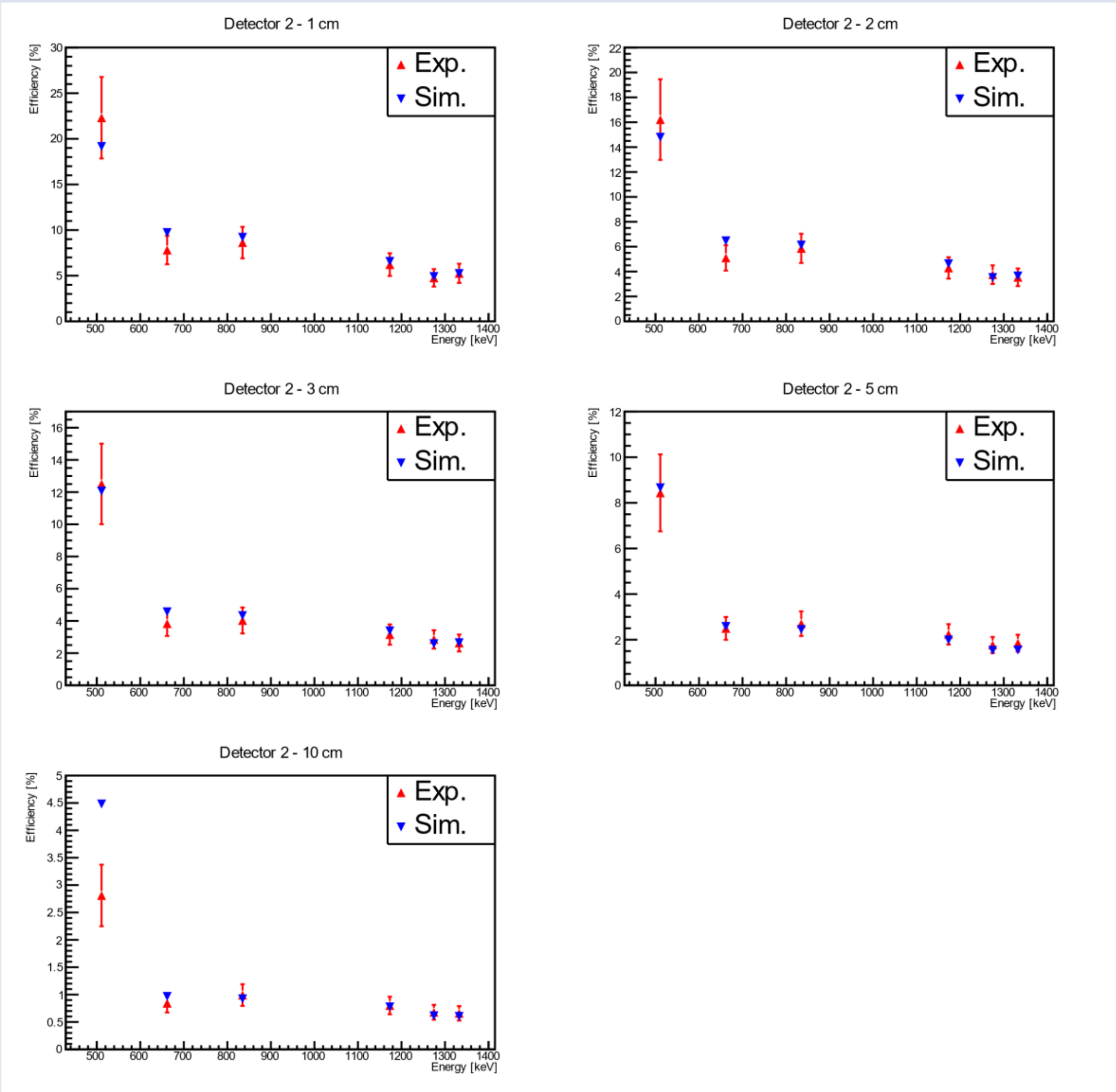

Figure 8. The efficiency graph of the Detector 2 with increasing energy in the x-axis. The simulation results are also in the graphs..

Looking at Figures 5-8, it is clear that Detector 1 has the highest efficiency of 25% and the lowest efficiency of 0.7%, while Detector 2 has the highest efficiency of 22% and the lowest efficiency of 0.7%. However, it is difficult to conclude that the difference in efficiencies at low energies is due to the same detector settings. The error bars indicate that both detectors may have the same efficiency for this setup. It is worth noting that Akkurt et al. (2014) demonstrated that a similar detector has a maximum efficiency of approximately 16% for 511 keV. Both of the detectors investigated in this study have a higher efficiency at lower energy levels. The study indicates that optimizing detector settings can lead to maximum efficiency and improved resolution. It was found that even with two identical detectors, the same performance values could not be achieved at the same settings. Compared to the literature, some similar detectors provided better resolution, but not greater efficiency. However, in high-budget experiments that use multi-gamma detector systems, increasing detection efficiency becomes more important when the detector resolution is deemed sufficient. The efficiency of the detector can also be improved by increasing the number of detectors surrounding the source, which will cover a larger solid angle. Measurements on a smaller scale with a larger number of detectors are more convenient for obtaining data from experiments, as covering a larger solid angle with a single detector leads to pile-up in the spectrum, especially in experiments with high fluxes [26, 27].

Discussion and Conclusion

We studied two identical NaI(Tl) scintillator detectors with the same settings as the bias voltages and software parameters to observe the differences in resolution and efficiency. We also performed Geant4 simulations using the exact experimental setup. While the results of the experiment are in good agreement with the literature values, we have observed some differences with the simulation data. In addition, there are certain differences in the resolution and efficiency with the same settings for both detectors. The first detector had a 7.2% resolution at 662 keV, while the second detector had a 6.9% resolution at 662 keV for a 3 cm source-detector distance. However, as stated in the previous section, this difference in resolution cannot be verified without SER measurements. The source of this difference is therefore not verified. Another difference worth noting is the efficiency of the two detectors. Detector 1 is clearly more efficient than detector 2 for small source-detector distances and low energies. The study's findings will make a valuable contribution to the literature, particularly regarding the use of multi-gamma detectors and effective coincidence/anticoincidence experimental setups. One of the desired features of modern nuclear experiments is an increased detection area for radioactive sources and the ability of the total spectrum to detect gamma rays with low emission probability without experiencing a pile-up effect. This system utilizes two NaI(Tl) detectors and can function as a coincidence setup through offline methods. Alternatively, it can be transformed into an online coincidence/anticoincidence experimental setup by adding a third non-NaI(Tl) detector, such as HPGe.

Conflicts of interest

There are no conflicts of interest in this work.

Acknowledge

We would like to thank Dr. Luciano Pandola for his valuable and useful comments and discussion.

References

[1] Bedir, M.E., Thomadsen, B., Bednarz, B., Development and Characterization of a Handheld Radiation Detector for Radio-Guided Surgery, *Radiat. Meas.*, 135 (2020) 106362.

[2] Borella, A., Camps, J., Paridaens, J., Vidmar, T., Characterization and Monte Carlo Simulations of a 4-Liter NaI Detection System for Use During Nuclear and Radiological Emergencies and for the Detection of Nuclear Materials, *AIP Conf. Proc.*, 1412 (2011) 335–342.

[3] Ghosh, C., Nanal, V., Pillay, R., Anoop, K., Dokania, N., Pal, S., et al., Characterization of Paris $LaBr_3(Ce)$-NaI(Tl) Phoswich Detectors up to $E_\gamma{\sim}22$ MeV, *J. Instrum.*, 11 (2016) P05023.

[4] Prieto, E., Casanovas, R., Salvado, M., Calibration and Performance of a Real-Time Gamma-Ray Spectrometry Water Monitor Using a $LaBr_3(Ce)$ Detector, *Radiat. Phys. Chem.*, 144 (2018) 444–450.

[5] Heranudin, S.M., van Wyngaardt, W., Guatelli, S., Li, E., Rosenfeld, A., Characterization of a Well-Type NaI(Tl) Detector by Means of a Monte Carlo Simulation for Radionuclide Metrology Application, *Appl. Radiat. Isot.*, 176 (2021) 109889.

[6] Yildirim, A., Solakci, S.O., Eke, C., Boztosun, I., Gamma Spectrometry Measurements of Natural and Artificial Radioactivity of Saklıkent-Antalya and Its Correlation to Quarries, *Arab. J. Geosci.*, 14 (2021) 1–11.

[7] Akkurt, İ., Arda, S., Gunoglu, K., Variation of Energy Resolution with Distance for a NaI(Tl) Detector, *Acta Phys. Pol. A*, 128 (2B) (2015a) B–422.

[8] Akkurt, İ., Gunoglu, K., Arda, S., Detection Efficiency of NaI(Tl) detector in 511–1332 keV Energy Range, *Sci. Technol. Nucl. Ins.*, 2014 (2014) 186798.

[9] Akkurt, İ., Tekin, H., Mesbahi, A., Calculation of Detection Efficiency for the Gamma Detector Using MCNPX, *Acta Phys. Pol. A*, 128 (2B) (2015b) 332–334.

[10] Mouhti, I., Elanique, A., Messous, M., Belhorma, B., Benahmed, A., Validation of a NaI(Tl) and $LaBr_3(Ce)$ Detector's Models via Measurements and Monte Carlo Simulations, *J. Radiat. Res. Appl. Sci.*, 11 (4) (2018) 335–339.

[11] Guss, P., Reed, M., Yuan, D., Beller, D., Cutler, M., Contreras, C., et al., Size Effect on Nuclear Gamma-Ray Energy Spectra Acquired by Different Sized $CeBr_3$, $LaBr_3{:}Ce$, and NaI:Tl Gamma-Ray Detectors, *Nucl. Technol.*, 185 (3) (2014) 309–321.

[12] Sariyal, R., Mazumdar, I., Sharma, Y., Patel, S., Chavan, P., Ranga, V., et al., Characterization of a Small Volume ($1' \times 1'$) $CeBr_3$ Crystal for γ-Ray Measurements up to 4.4 MeV, *J. Instrum.*, 16 (01) (2021) T01004.

[13] [Akkurt, İ., Waheed, F., Akyildirim, H., Gunoglu, K., Monte Carlo Simulation of a NaI(Tl) Detector Efficiency, *Radiat. Phys. Chem.*, 176 (2020) 109081.

[14] Yalcin, S., Gurler, O., Kaynak, G., Gundogdu, O., Calculation of Total Counting Efficiency of a NaI(Tl) Detector by Hybrid Monte-Carlo Method for Point and Disk sources, *Appl. Radiat. Isot.*, 65 (10) (2007) 1179–1186.

[15] Mitra, P., Tyagi, M., Thomas, R., Kumar, A.V., Gadkari, S., Optimization of Parameters for a CsI(Tl) Scintillator Detector Using Geant4-Based Monte Carlo Simulation Including Optical Photon Transport, *IEEE T. Nucl. Sci.*, 66 (7) (2019) 1870–1878.

[16] Tam, H.D., Yen, N.T.H., Chuong, H.D., Thanh, T.T., et al., Optimization of the Monte Carlo Simulation Model of NaI(Tl) Detector by Geant4 Code, *Appl. Radiat. Isot.*, 130 (2017) 75–79.

[17] Agostinelli, S., Allison, J., Amako, K.A., Apostolakis, J., Araujo, H., Arce, P., et al., Geant4—A simulation Toolkit, *Nucl. Instrum. Methods Phys. Res. A*, 506 (3) (2003) 250–303.

[18] Allison, J., Amako, K., Apostolakis, J., Araujo, H., Dubois, P.A., Asai, M., et al., Geant4 Developments and Applications, *IEEE T. Nucl. Sci.*, 53 (1) (2006) 270–278.

[19] Allison, J., Amako, K., Apostolakis, J., Arce, P., Asai, M., Aso, T., et al., Recent Developments in Geant4, *Nucl. Instrum. Methods Phys. Res. A*, 835 (2016) 186–225.

[20] Brun, R., Rademakers, F., Root — an Object Oriented Data Analysis Framework, *Nucl. Instrum. Methods Phys. Res. A*, 389 (1) (1997) 81-86.

[21] ROOT, Data Analysis Framework. Available at: https://root.cern/releases/release-62406/. Retrieved September 3, 2021.

[22] Knoll, G.F., Radiation detection and measurement. 4th Ed. John Wiley & Sons, (2010) 105-121.

[23] Freitas, E., Fernandes, L., Yahlali, N., Perez, J., Alvarez, V., Borges, F. et al., PMT Calibration of a Scintillation Detector Using Primary Scintillation, *J. Instrum.*, 10 (02) (2015) C02039.

[24] Demir, N., Kuluozturk, Z.N., Determination of energy resolution for a NaI(Tl) detector modeled with FLUKA code, *Nucl. Eng. Technol.*, 53 (2021) 3759-3763.

[25] Moszynski, M., Balcerzyk, M., Czarnacki, W., Kapusta, M., Klamra, et al., Study of Pure NaI at Room and Liquid Nitrogen Temperatures, *IEEE T. Nucl. Sci.*, 50 (4) (2003) 767-773.

[26] Oliveira, J.R.B., Moralles, M., Flechas, D., Carbone, D., Cavallaro, M., et al.,, First comparison of GEANT4 hadrontherapy physics model with experimental data for a NUMEN project reaction case, *Eur. Phys. J. A*, 56 (5) (2020) 153.

[27] Cappuzello, F., Agodi, C., Calabretta L., Calvo, D., Carbone, D., et al., The NUMEN Technical Design Report, *Int. J. Mod. Phys. A*, 36 (30) (2021) 2130018.