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Research Article

Simulation of Pulse Height Distribution and Full Energy Peak Efficiency of 2″x2″ Scintillation Detectors

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Abstract

In this study, the variation of photon pulse height distributions and full energy peak efficiencies of 2x2 inch NaI(Tl) and $LaBr_3$(Ce) detectors depending on the distance between the detector and source were investigated. Calculations for 2 cm and 5 cm detector source distances and 30.973, 59.54, 80.998, 302.85, 356.01, 661.65, 1173.24, 1332.5 and 1408.01 keV gamma energies were obtained with FLUKA, one of the radiation transport simulation codes. The Compton edge in simulated photon pulse height distributions is compatible with the theoretically calculated results. In addition, when the full energy peak efficiency values are compared with the different methods in the literature, the FLUKA simulation results are observed are satisfactory.

Keywords: 2"x2" NaI(Tl) detector, 2"x2" $LaBr_3$(Ce) detector, Puls height distribution, Full energy peak efficiency, FLUKA.

2″x2″ Sintilasyon Dedektörlerinin Puls Yüksekliği Dağılımının ve Tam Enerji Tepe Verimliliğinin Simülasyonu

Öz

Bu çalışmada, 2x2 inç NaI(Tl) ve $LaBr_3$(Ce) dedektörlerinin foton puls yüksekliği dağılımlarının ve tam enerji tepe verimliliklerinin dedektör ve kaynak arasındaki mesafeye bağlı değişimleri araştırılmıştır. 2 cm ve 5 cm dedektör kaynak mesafeleri ve 30.973, 59.54, 80.998, 302.85, 356.01, 661.65, 1173.24, 1332.5 ve 1408.01 keV gama enerjileri için yapılan hesaplamalar radyasyon taşıma simülasyon kodlarından biri olan FLUKA ile elde edilmiştir. Simüle edilen foton puls yüksekliği dağılımlarındaki Compton sınır değerleri teorik olarak hesaplanan sonuçlarla uyumludur. Ek olarak, tam enerji tepe verimlilik değerleri literatürdeki farklı yöntemlerle karşılaştırıldığında FLUKA simülasyon sonuçlarının tatmin edici olduğu gözlenmiştir.

Anahtar Kelimeler: 2"x2" NaI(Tl) dedektör, 2"x2" $LaBr_3$(Ce) dedektör, Puls yüksekliği dağılımı, Tam enerji tepe verimliliği, FLUKA.

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1. Introduction

Scintillation detectors of different crystal types and sizes are often preferred due to their successful quantitative evaluation in gamma-ray analysis studies. NaI(Tl) detectors with thallium doped sodium crystal have been used as gamma spectroscopy system with engaging performances for many years. $LaBr_3$(Ce) detectors have been used as an alternative to the NaI(Tl) detector system in recent years due to its impressive properties such as energy resolution, high gamma detection efficiency, and room temperature operation. Calibration is one of the most essential criteria for the accuracy of radiation detection in these two scintillation detectors. The calibration procedure can be classified as resolution calibration, energy calibration, and efficiency calibration (Mouhti et al., 2018). Efficiency calibration is the relationship between the count under the peak of the relevant energy and the number of particles emitted from the radioactive source. Although efficiency calibration depends on the energy of the radiation source such as resolution and energy calibration, also parameters such as the distance between the source-detector; and the geometry of the source are additional factors that affect efficiency calibration (Casanovas et al., 2012).

Monte Carlo simulations, which can simulate the interaction of radiation with detector material, have become a useful method for characterizing detector parameters. There are many studies in which successful results are reported in the calculation of detector response function with Monte Carlo based codes (Baccouche et al., 2012; Casanovas et al., 2012; Salgado et al., 2012; Akkurt et al., 2015; Hajheidari et al., 2016; Tekin, 2016; Mouhti et al., 2018; Tarım & Gurler, 2018). This study is concerned with the FLUKA simulations of the efficiency of similar size 2″x2″ NaI(Tl) and 2″x2″ $LaBr_3$(Ce) detectors. The efficiency of 2″x2″ NaI(T1) and 2″x2″ $LaBr_3$(Ce) detectors were calculated for nine different sources in the 30.973 keV – 1408.01 keV energy range. The effect of source energy and detector-source distance on the efficiency of detectors was determined. The results obtained with FLUKA code were compared with different methods in the literature.

2. Material and Method

2.1. Description of Monte Carlo simulations

The efficiency simulations of 2″x2″ NaI(Tl) and $LaBr_3$(Ce) detectors were calculated using FLUKA Package 2020.0.3 version. More detailed information about this simulation code that describes radiation interaction and transport in detector materials is available in (Ferrari et al., 2005; Böhlen et al., 2014). The input file was prepared with FLAIR (version flair-2.3-0) (Vlachoudis, 2009) which an advanced interface for editing FLUKA input files and visualizing output files. The photons with an isotropic distribution of 30.973 keV – 1408.01 keV energy range were generated in the BEAM card. The sources were positioned with the BEAMPOS card at a distance of 2 cm and 5 cm from the detector. The NaI(Tl) and $LaBr_3$(Ce) detectors have a cylindrical geometry of 5.08 cm x 5.08 cm dimensions and are covered with 0.05 cm thick Al (Fig. 1). The next layer is MgO and air for NaI(Tl) and $LaBr_3$(Ce) detectors, respectively. The SiO_2 layer is present at the end of the crystal. The densities of the NaI, $LaBr_3$ MgO, Al and SiO_2 materials used in the simulation were defined 3.67 g/cm^3, 5.29 g/cm^3, 2.0 g/cm^3, 2.70 g/cm^3, and 0.94 g/cm^3, respectively. The properties (such as atomic number, atomic weight, density) of layers of the NaI(Tl) and $LaBr_3$(Ce) detectors used in the simulations were defined by MATERIAL card and COMPOUND cards. Detector geometry on the FLAIR geometry editor is shown in Figure 2, which allows visual editing of the bodies and regions with debugging information. The geometry was taken as one more than one right circular cylinder (RCC) and delimited by planes perpendicular to the z-axis (XYP) to form different layers in the dimensions given in Figure 1.

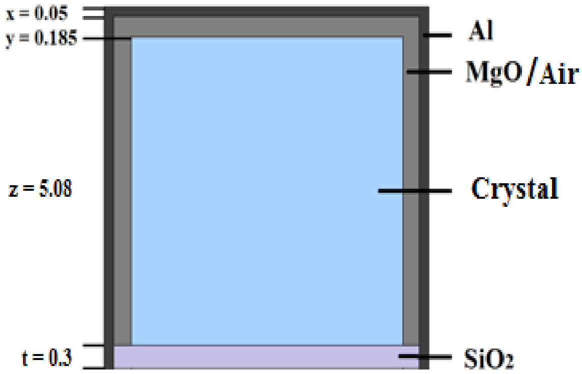

Figure 1. Geometry of 2"x2" scintillation detector

PRECISIOn was used as the DEFAULTS card allowing the most detailed FLUKA simulation, and the production and transport threshold energy values for the photons were taken as 10 keV. The statistical error in FLUKA depends on the number of particles to be simulated. To obtain an excellent statistical result, the input file was run with five million primaries as 5 parallel programs.

The full energy peak efficiency of the detectors was calculated as the ratio of the number of the photons emitted with the count in the full energy peak corresponding to the measured energy, for the quantitative evaluation of the simulation model (Tam et al., 2017). For this purpose, the DETECT card was used to calculate the amount of deposited energy per event in the detector crystal.

3. Results and Discussion

In this study, the performance of the FLUKA code was tested for the efficiency of 2″x2″ NaI(Tl) and 2″x2″ $LaBr_3$(Ce) detectors. The full energy peak efficiency was calculated for 30.973, 59.54, 80.998, 302.85, 356.01, 661.65, 1173.24, 1332.5, and 1408.01 keV isotropic distribution at a distance of 2 cm and 5 cm from the detector surface. For the efficiency of 2″x2″ NaI(T1) and 2″x2″ $LaBr_3$(Ce) detectors, Casanovas et al. obtained experimental results and compared these results with the EGS code (Casanovas et al., 2012). For the efficiency of the 2″x2″ NaI(T1) detector, Mouthi et al. obtained experimental results and compared these results with the MCNP code (Mouhti et al., 2018). Similarly, for the 2″x2″ $LaBr_3$(Ce) detectors, Mouthi et al. compared the results obtained with MCNP code to the study of Casanovas et al..

Table 1 and Table 2 show the full energy peak efficiency values obtained by the FLUKA code for NaI(T1) and $LaBr_3$(Ce) detectors, respectively. These results are compared with the studies of Casanovas et al. and Mouthi et al.. Table 3 shows the relative differences (RD(%)) between the efficiency results calculated by the FLUKA code and the results of other methods previously reported in the literature. As seen from the results, the maximum RD(%) was observed for the NaI(Tl) detector at 59.54

keV energy. As it is understood from the tables, as the energy of the gamma source increases, the probability of the gamma interacting with the detector crystal to be absorbed will decrease and the detector efficiency will decrease. The results obtained by FLUKA code are in good agreement with experimental studies and other Monte Carlo codes.

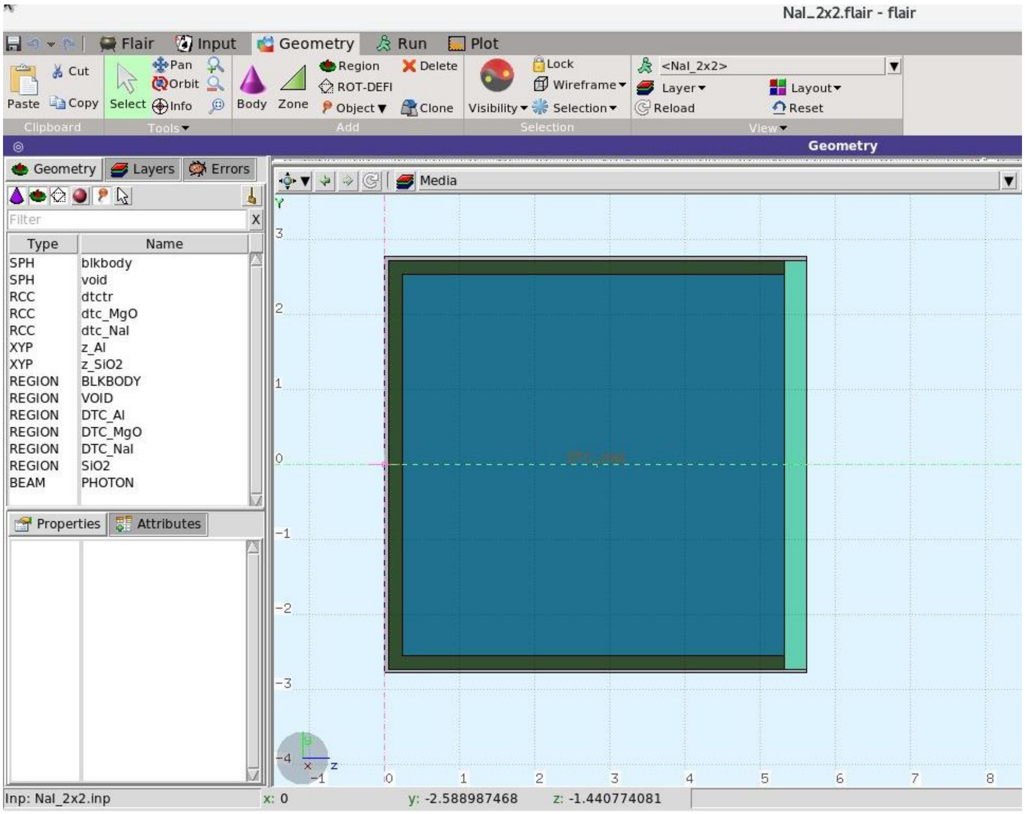

Figure 2. Detector geometry by FLAIR geometry editor

Table 1. Comparison of the full energy peak efficiency of 2"x2" NaI(T1) detector calculated by the FLUKA with experimental and MC codes

Gamma Energy (keV)	**Source-detector distance** (cm)	**2″x2″ NaI(Tl)**				
		FLUKA (Present work)	**EGS** (Casanovas et al.)	**EXP** (Casanovas et al.)	**MCNP** (Mouhti et al.)	**EXP** (Mouhti et al.)
30.973	2	5.15	-	-	-	-
	5	2.40	-	-	-	-
59.54	*2*	12.80	-	-	13.04	11.30
	5	3.25	2.570	2.5	-	-
80.998	*2*	6.89	-	-	-	-
	5	3.00	3.141	3.2	-	-
302.85	*2*	4.55	-	-	-	-
	5	1.99	-	-	-	-
356.01	*2*	3.86	-	-	-	-
	5	1.69	1.506	1.5	-	-
661.65	*2*	3.03	-	-	3.05	2.98
	5	1.05	1.045	1.0	-	-
1173.24	*2*	1.60	1.302	1.3	1.44	1.27
	5	0.56	-	-	-	-
1332.5	*2*	1.40	1.141	1.2	1.27	1.21
	5	0.49	-	-	-	-
1408.01	*2*	1.31	-	-	-	-
	5	0.46	-	-	-	-

Table 2. Comparison of the full energy peak efficiency of 2"x2" $LaBr_3(Ce)$ detector calculated by the FLUKA with experimental and MC codes

Gamma Energy (keV)	Source-detector distance (cm)	2″x2″ $LaBr_3(Ce)$			
		FLUKA (Present work)	EGS (Casanovas et al.)	EXP (Casanovas et al.)	MCNP (Mouhti et al.)
30.973	*2*	7.00			
	5	3.07			
59.54	*2*	10.28	-	-	-
	5	3.76	3.09	3.00	3.95
80.998	*2*	7.94	-	-	-
	5	3.38	3.576	3.80	-
302.85	*2*	5.19	-	-	-
	5	2.24	2.01	2.00	2.34
356.01	*2*	4.53	-	-	-
	5	1.96	2.01	1.80	2.05
661.65	*2*	4.08	-	-	-
	5	1.39	1.31	1.30	1.45
1173.24	*2*	2.38	2.15	2.10	2.48
	5	0.83	-	-	-
1332.5	*2*	2.13	1.90	2.00	2.20
	5	0.74	-	-	-
1408.01	*2*	2.02	-	-	-
	5	0.70	-	-	-

Table 3. Relative differences ($RD(\%) = A - B/A\,x100$) between the FLUKA code and other methods for the efficiency of NaI(T1) and $LaBr_3(Ce)$ detectors

	2″x2″ NaI(Tl) RD(%)		2″x2″ $LaBr_3(Ce)$ RD(%)	
	max	min	max	min
FLUKA - EGS [Casanovas et. al., 2012]	-26.46	-0.48	-21.68	2.49
FLUKA - MCNP [Mouhti et. al., 2018]	-11.11	0.65	4.81	3.18
FLUKA - EXP [Casanovas et. al., 2012]	-23.07	-0.23	-25.33	-6.5
FLUKA - EXP [Mouhti et. al., 2018]	-25.98	-1.68	-	-

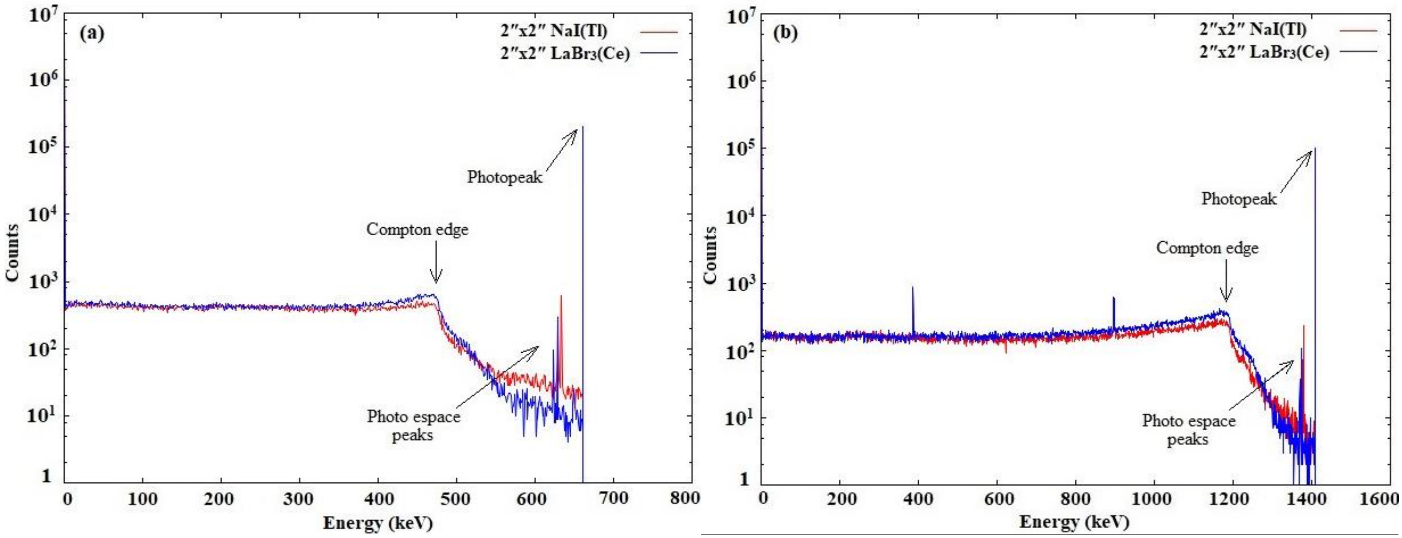

Figure 3. The pulse height distributions obtained by the FLUKA code for gamma sources of (a) 661.65 keV and (b) 1408.01 keV placed at 2 cm distance to the detector

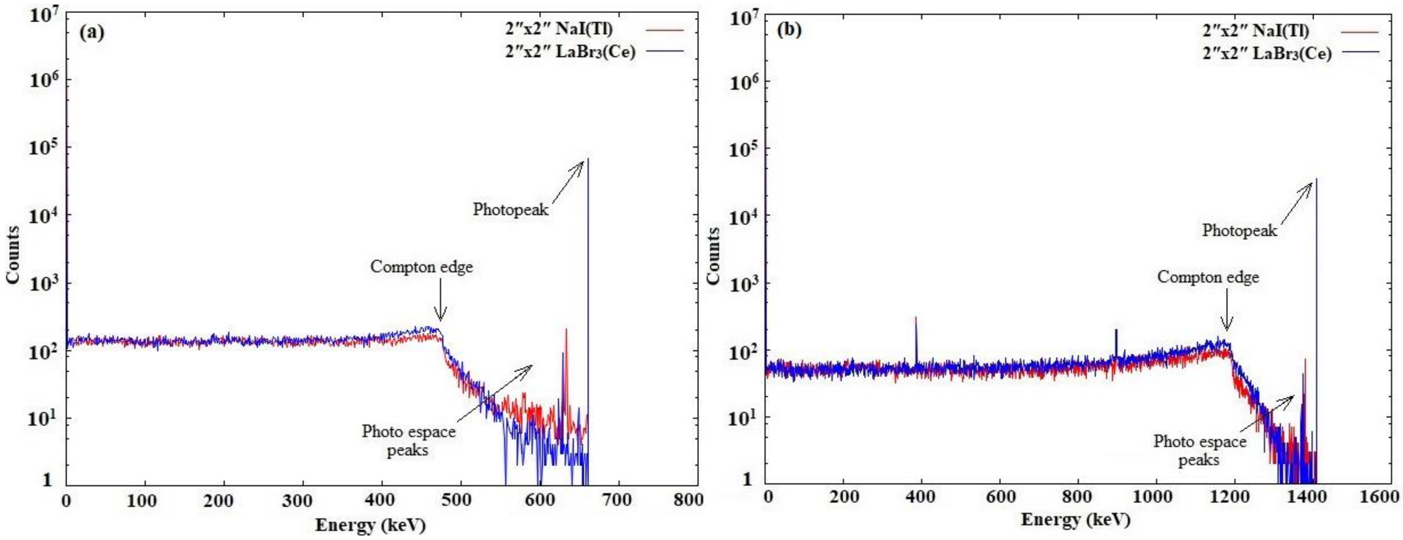

Figure 4. The pulse height distributions obtained by the FLUKA code for gamma sources of (a) 661.65 keV and (b) 1408.01 keV placed at 5 cm distance to the detector

The pulse height distributions obtained by the FLUKA code of 661.65 keV and 1408.01 keV energy sources in distances 2 cm and 5 cm from the detector surface for the detectors are presented in Figure 3(a) and 3(b) and Figure 4(a) and 4(b), respectively. These spectra were obtained without taking into account the effects of the detector electronics such as the energy resolution of the detector. As in Tables 3 and 4, the spectrums of Figures 3 and 4 show that the efficiency of the $LaBr_3$(Ce) detector is higher than the NaI(T1) detector. In addition, it is observed that the full energy peak efficiency decreases with increasing distance between the source-detector. As a result of the interaction of the photon and the detector crystal in the spectra, the photopeak is seen at 661.65 keV and 1408.01 keV, that is, where the photon deposited all its energy. The Compton edge energy was theoretically calculated using equations 1 and 2 (Physics Courses Lecture Notes, 2014) for the Compton effect that occurs with the interaction of photon and detector crystal in the spectra.

$$E_T = E - E^{'} \quad (1)$$

$$E_{Compton} = E_{T(max)} = \frac{2E^2}{m_e c^2 + 2E} \quad (2)$$

Where E, E' and E_T are respectively the energy of the incident photon, the outgoing photon and the Compton edge energy, and m_e is the mass of the electron and c is the speed of light. The Compton edge energies for 30.973 - 1408.01 keV energy range and for 2″x2″ NaI(Tl) and $LaBr_3$(Ce) detectors were read from the output files of the simulations. The theoretically calculated Compton edge values were compared with the Compton edge values obtained with FLUKA code. The minimum and maximum RD(%) of the Compton edge results obtained by the two methods were found as 0.0098 - 10.44 % and 0.125 - 10.44 % for the distance of the detector-source 2 cm and 5 cm, respectively.

4. Conclusions and Recommendations

Efficiency calibration, one of the three calibration procedures, was determined by the FLUKA code for two different scintillation detectors. Firstly, these two detectors were modeled in the FLUKA code with the detector details given in Figure 1 and 2. Different detector - source distance and different source energies were used as simulation parameters for these two different scintillation detectors. The slight inconsistencies between the FLUKA values with the other methods may be due to the location between the source and detector, the detector modeling, failure to transfer of all information of the detector to the simulation environment. An error of less than 1% was obtained with respect to the primaries in the FLUKA simulation. Increasing the particle number will also reduce the statistical error. In this way, the RD(%) values of the results obtained with FLUKA can be further reduced. When the results in Tables 1 and 2 were evaluated, the FLUKA code results showed good agreement with the previously reported experimental, EGS code, and MCNP code results for the efficiency of each detector. In addition, it was observed that the Compton edge results obtained by the FLUKA simulation are compatible with the theoretical results.

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