Simulation of Performance of LABR3:CE using GEANT4

Zarana Dave[1] Charmy Patel[2] Dipak Kumar Panda[3] Shiv Kumar Goyal[4]
[1,2]V.V.P. Engineering College Rajkot, Gujarat, India [3,4]Physical Research Laboratory (PRL) Ahmedabad, Gujarat, India

Abstract— Cerium-doped lanthanum bromide, $LaBr_3$ (Ce), scintillator shows attracting properties for spectroscopy that makes it a suitable solution for security, medical, geophysics and high energy physics applications. Here, the performance parameters of a cylindrical $LaBr_3$ (Ce) scintillator was investigated. The first aspect is the determination of the efficiency for γ - ray detection, measured with GEANT4 simulation toolkit from 10keV to 10MeV energy range. The second is the detailed study of background radiation of LaBr3 (Ce). It has relatively high intrinsic radiation background due to naturally occurring ^{138}La and ^{227}Ac radioisotopes.

Key words: $LaBr_3$ (Ce), GEANT4, Efficiency, Background radiation

I. INTRODUCTION

The development of cerium-doped lanthanum halide crystals have gained special interest due to their excellent scintillator properties compared other scintillation crystals. $LaBr_3$(Ce) is the most promising material with a high light output of about 63 photons/keV, a fast rise time of about 16 ns, a density of 5.08 gm/cm3, an emission wave length of 380 nm[1-4], due to the high Z of La and Ce atoms it is a good γ and β detector. In this work, the response function of the $LaBr_3$(Ce) detector was investigated to find efficiency and internal activities by Monte Carlo radiation transport code, GEANT4[9-11].

II. GAMMA RAY INTERACTIONS IN SCINTILLATORS

Photoelectric absorption, Compton scattering and Pair production are the three major interaction mechanisms that play vital roles in radiation measurements. In each of these processes partial or complete transfer of gamma ray photon energy to the electron, results in either disappearance entirely or scattering through a significant angle.

A. Photoelectric Absorption:

Here, a photoelectron is produced from the incident gamma ray photon. The kinetic energy of this photoelectron (Ee) is given by[8],

$$Ee = hv - Eb$$

Where, hv is the energy of gamma ray photon and Eb is binding energy of the photoelectron in its original shell.

B. Compton Scattering:

Compton scattering is an interaction process where the photon transfers a portion of its energy to the electron leading to the deflection of the photon through an angle θ with respect to its original direction and recoil of the target electron. The energy change during the process is given by[8],

$$Ee- = hv - hv' = hv\left(\frac{\left(\frac{hv}{m_0c^2}\right)(1-\cos\theta)}{1+\left(\frac{hv}{m_0c^2}\right)(1-\cos\theta)}\right),$$

Where, m_0c^2 is the rest mass energy of the electron, E_e is the recoil energy of the electron, v and v′ are the frequencies of the incident and deflected photon respectively.

C. Pair Production:

Pair production process is energetically possible only if gamma ray energy exceeds twice the rest mass energy of an electron. Here, gamma ray photon disappears and an electron positron pair is produced[8], i.e.

$$E_e + E_p = hv - 2m_0c^2$$

After production, the positron slows down and annihilate in the absorbing medium producing two annihilation photons as secondary products of interaction.

III. PROBLEM DEFINITION

Gamma ray detectors are used to find elemental composition on planetary bodies [5]. Currently used Gamma ray detectors for space science are HPGe (High Purity Germanium) and NaI(Tl) (Thallium based Sodium Iodide). But, from literature review we studied that resolution provided by NaI(Tl) is very poor while HPGe detector requires cooling system which increases the power and weight of the instrument[6]. So, $LaBr_3$ (Ce) is the best solution for mentioned problems. In this work, we will measure the performance parameters like efficiency and background radiation of designed $LaBr_3$ (Ce) Gamma ray detector with Geant4 simulation toolkit. One drawback with $LaBr_3$ (Ce) crystal is it's background radiation up to 2.8 MeV due to presence of metastable isotope ^{138}La and α particles from ^{227}Ac-chain.

IV. METHODOLOGY

A. Experimental Measurement:

Gamma-ray spectra were obtained with the cylindrical $LaBr_3$(Ce) detector (38.1 mm × 38.1 mm) was used to process the signals from it. Energy calibration was done by ^{22}Na (511keV, 1274keV), ^{137}Cs (662keV) and ^{60}Co (1173keV, 1332keV). Detector is surrounded by 0.5 mm thick Aluminium (Al) casing except its front surface. The sources are placed at 2 cm distance from the front surface of the detector. The detector was put inside a 10 cm lead shield box.

B. Simulation:

The simulation has been carried out using the GEANT4 simulation toolkit to estimate the response function of $LaBr_3$(Ce) detector. In the present work, the GEANT4 toolkit version 4.9.4.p01 has been implemented as the Monte Carlo simulation method[7]. All aspects of the simulation process have been included in the toolkit.

The main classes in our code are: the first class is Detector Construction; which contains the geometrical information of experimental setup and the detector as provided by the manufacturer, describing the $LaBr_3$ (Ce) cylindrical detector (38.1 mm in diameter × 76.2 mm in length) casing by 0.5 mm Aluminium. The second class is the Physics List[4]; which contains G4DecayPhysics, and

G4RadioactiveDecayPhysics. The third class is Primary Generator Action; the general particle source (GPS) module[4] has been used as particle generator to create many shapes with specific position, angle and energy distribution, etc.

Fig 1 presents the GEANT4 simulated three - dimensional view with the exact specifications provided by the manufacturer as shown in Fig. 1(a) and tracking of γ - rays as isotropic source outside the detector in Fig. 1(b). The simulations were carried out for a large number of events (of the order of 10^6) to reduce the statistical uncertainty, taking all possible physics processes into account.

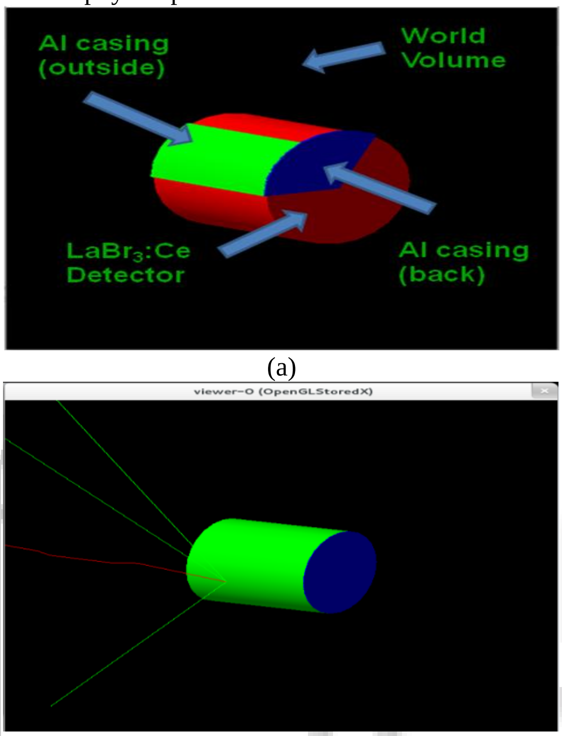

Fig. 1: Geant4 simulated 3D view of the detector (a) with specifications provided by manufacturer (b) isotropic source in front of the detector

V. Results and Discussion

To measure the efficiency of the designed detector using Geant4 simulation toolkit first gamma rays should be imparted on the detector. The amount of gamma particles which gets absorbed by the gamma ray detector defines its efficiency. To find the background radiation present in $LaBr_3$(Ce) the frequency response of each radioactive source and energy distribution based on it is mandatory to find[8].

A. *Response Function For Standard Source:*

In many applications of radiation detectors, object is to measure energy distribution of incident radiation. The energy spectrum of a chemical element is the spectrum of electromagnetic radiation emitted due to an atom making a transition from a high energy state to a low energy state. Each element's emission spectrum is unique.

We have produced energy spectrum of point sources ^{22}Na, ^{60}Co and ^{137}Cs. Fig 2 shows the measured energy spectrum for ^{22}Na. Consequently, we can successfully reproduce the energy spectrum of any isotope spectrum by using GEANT4 simulation toolkit.

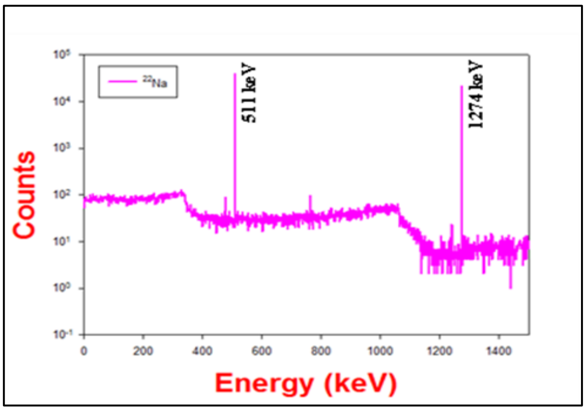

Fig. 2: Simulated Energy Spectrum of 22Na Placed At 2 Cm Distance From The Front Surface Of Labr3 (Ce) Detector

B. *Efficiency Calculation:*

Uncharged Gamma rays first undergo a significant interaction in detector before detection is possible. This radiation can travel large distances between interactions and thus detectors are often less than 100% efficient. The detector efficiency is not only dependent on detector properties but also on the details of the counting geometry (primarily the distance from source to detector) [8].

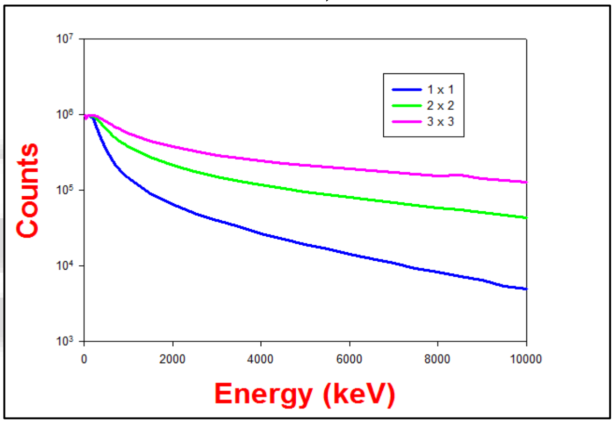

Fig. 3: Simulated efficiency of a 3”× 3” LaBr3:Ce detector

Here, the experiment to calculate the efficiency of designed Gamma Ray detector is performed for 10^6 counts having energy range from 10keV to 10MeV. For detector size 1”x1”, 2”x2” and 3”x3” Geant4 result shows that as detector size increases, efficiency also gets increased. If counts for which the experiment is performed gets increased Geant4 result becomes more accurate. We can see from the results that as energy gets increased efficiency of the detector is getting reduced. This is because efficiency of detector is defined as the amount of energy which detector can absorb from the energy imparted on it. Detector will absorb less energy as source emits more energy on it. The reason for why 3”x3” sized detector has high efficiency compared to 1”x1” sized detector is same.

$$\varepsilon_{abs} = \frac{\text{total no. of gammas detected}}{\text{no. of gammas emitted by source}}$$

$$\varepsilon_{peak} = \frac{\text{no. of gammas detected under the photopeak}}{\text{no. of gammas emitted by source}}$$

The following table shows the output counts that were absorbed by 1”x1”, 2”x2”and 3”x3”sized $LaBr_3$(Ce) when 10^6 counts of gamma rays of different energies were imparted on it.

Energy	Counts		
	1x1	2x2	3x3
10keV	967254	974441	981516
50keV	918549	918903	919016
100keV	972621	972813	973065
500keV	341760	646019	809444
1000keV	146054	375534	570727
5000keV	19437	95868	214787
10000keV	4911	43595	127169

Table 1: Output counts for 1"x1", 2"x2" and 3"x3" sized LaBr3(Ce) for different input energies

C. *Background Radiation:*

$LaBr_3$:Ce Detector has its own background, where decayed products of radioisotope 138La are present up to 1.6 MeV with contributions from X - rays, γ - rays and β - particles. Between 1.8 and 2.8 MeV peaks due to α - emitters of ^{227}Ac decay chain are present.

1) *In Case Of Low Energy Region (0 To 1600 Kev):*

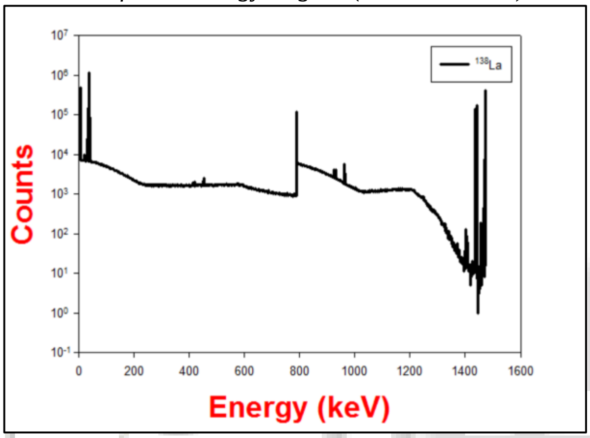

Fig. 4: Simulated Background spectrum of LaBr3 (Ce) in the low energy region

Decay Scheme of ^{138}La

$$^{138}_{57}La + e^{-} = {}^{138}_{56}Ba + \gamma(1436keV) + x(32keV)$$

$$^{138}_{57}La = {}^{138}_{58}Ce + \gamma(789keV) + \beta^{-}(255keV)$$

^{138}La has two decay modes,

- Decay by electron capture (EC) followed by γ - ray (1436 keV), and X - ray (32 keV - K_α and 38 keV - K_β) from ^{138}Ba. Coincidence between γ - ray (1436) and X - ray (32 - 37) generates peak at 1468 keV.
- Decay by β - (255 keV) followed by γ - ray (789 keV) from ^{138}Ce. Coincidence between γ - ray (789) and β - particle generates peak at 789 keV.

In the Physics List file we have included the processes like Compton Scattering, Gamma Conversion, Photo Electric Effect, Pair production, Bremsstrahlung, Ionization and Multiple Scattering. To generate stable daughter nuclei of ^{138}La and ^{227}Ac we have included Radioactive Decay Module which includes G4Decay and G4RadioactiveDecay files [7]. Here, we have considered gamma, e-, e+ and proton particles for interaction. The energy range is from 100eV to 100GeV.

2) *In Case of High Energy Region (1800 To 2800 Kev):*

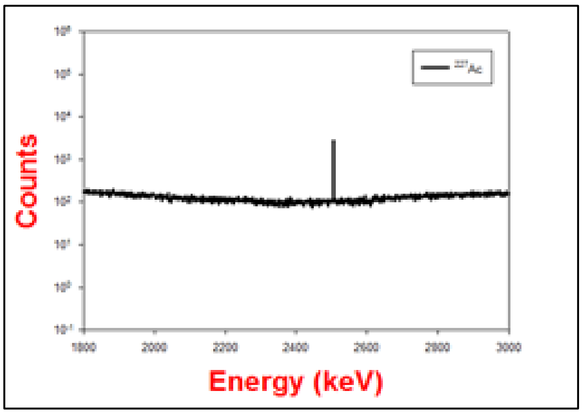

Fig. 5: Simulated background spectrum of LaBr3 (Ce) in high energy region

a) Decay Scheme of ^{227}Ac

The presence of naturally occurring alpha - contamination can be measured, as ^{227}Ac is in the same periodic group (group IIIB) as Lanthanum, which results in four broad peaks in the background spectra. Of these decays, long lived ^{227}Ac is the contributing element, which beta-decays to ^{227}Th, and subsequently alpha decays to ^{207}Tl, as given in decay scheme of ^{227}Ac. Here, we have imparted ^{138}La in the whole body of the designed detector and source ^{227}Ac, ^{238}U and ^{232}Th at 2.0 cm distance from the front surface of the detector. Peak in the background spectrum is originated from ^{227}Th, ^{223}Ra, ^{219}Rn, ^{215}Po and ^{211}Bi. The Geant4 simulated result of background radiation of $LaBr_3$:Ce is shown in figure 6.

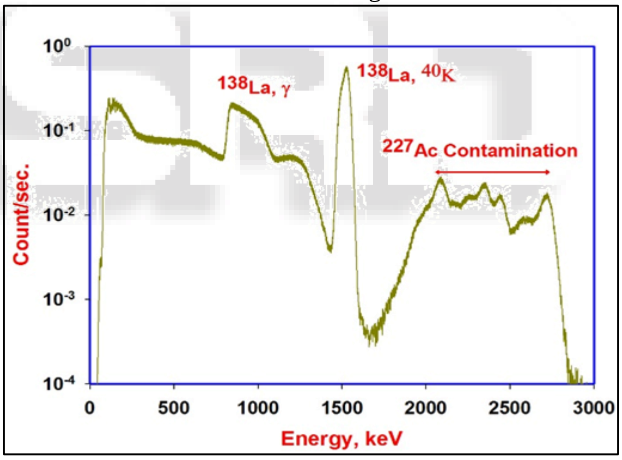

Fig. 6: Background radiation of LaBr3(Ce)

VI. Conclusion

The response function of $LaBr_3$ (Ce) has been calculated using GEANT4 simulation toolkit. We have measured the performance parameters of $LaBr_3$(Ce) like efficiency from 10keV to 10MeV for 10^6 counts and background radiation of present due to radioactive isotopes ^{138}La and ^{227}Ac.

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