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Estimation of Minimum Counts for an Acceptable Pulse Shape Using Scintillation Detector from 200to 2000 keV Energy

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Abstract

This work was aimed for an investigation of minimum photon number recorded by NaI(Tl) crystal for the production of an acceptable, well resolved photo peaks from 200 to 2000 kev energy. The crystal used in our study is known as FJ374 model, which is of FH1902 and FH1909 gamma spectrum meter model. We estimated these counts by using certified standard sources of Cs-137 & Eu-152, and GEANT4 Monte Carlo simulation with real and modeled FJ374 NaI(Tl) crystal. The estimated values were 494 for Eu-344.4 kev, 760 for Cs-661.7 kev & 1102 for Eu-1112.6 kev. The plot of this result, (count vs energy), shows linear relation as a plot of energy vs channel number.

Keywords: *Gamma-ray spectrometer; GEANT4; Monte Carlo simulation; pulse shape; scintillation detector*

1. Introduction

Inorganic scintillators are widely used for detection of gamma rays, due to their high atomic number of iodine atom mixed with others like Na, Cs, Li and many others. Sodium iodide doped with thallium, NaI(Tl), is a widely used of this type for which (Tl) is used as an activator. It can be prepared in different geometries to achieve different detection efficiency. It is obvious that as surface area increases quality of measurements like resolution, efficiency and pulse shapes increases. The crystal used for this work is a model known by FJ374, which is a portion of model FH109 and FH1902 gamma spectrum-meters. It is a 4 cm x 4 cm with a resolution up to 11 % for 137Cs source according to factory specification. It works under a temperature of less than 400C and relative humidity less than 90 % [1]–[3].

In the measurement, the standard sources of EU-152 with activity 3.097 kBq and Cs-137 with activity 37 kBq were used which supplied by Canberra and PHYWE respectively. In addition, GEometry ANd Tracking (GEANT4) Monte Carlo code, version geant4.10.03.p02 were used. Eu-152 produces 10 photo peaks according to the specifications given by supplier and we used only two photo peaks of energy 344.4 keV and 1112.1 keV which were clearly shown by our crystal, where Cs-137 is a mono energetic gamma source of 661.7 kev. The effects of geometries of sources were not considered in our measurements, we roughly considered them as a point sources. GEANT4 Monte Carlo code (simulation) is one of the commonly used method in particle simulation for an increasing of accuracy of measurements and calibration of spectrum meters. We generated photo peaks of the two sources by using this Monte Carlo code in which we found a proper and well resolved pulse shape after modeling the crystal itself by Detector construction package of GEANT4 [3]–[6].

In this work, we used results of Monte Carlo simulation to estimate minimum count limits for an acceptable pulse shape, which were identified by calculating ratios of Full Width at Tenth Maximum (FWTM) to Full Width at Half Maximum (FWHM) and ratio of Full Width at Fiftieths Maximum (FWFM) to Full Width at Half Maximum for each photo peak we obtained. Using Ubuntu based SciDAVis software, graphs of ratios obtained by both methods versus count number were plotted on the same graphing sheet for each photo peak. The graphs are intersecting each other at points 494 for Eu-152 of 344.4 keV, 760 for Cs-137 of 661.7 keV and 1109 for Eu-152 of 1102 keV energy, where horizontal axis represents energy values. Finally, we used this points with energy from 200 kev to 2000 kev, to estimate the minimum counts required for an acceptable pulse shapes.

2. Methodology

GEANT4 code is a reliable toolkit for particle simulation, if geometrical parameters of a detector and gamma sources are known [3]. It is a Monte Carlo method that uses a composition method if a condition is true, and rejection if the condition is false [7]. In our work, we have not tried to check the quality performance of NaI(Tl) crystal. By using GEANT4 simulation and real experiment method, minimum photon number that produces an acceptable pulse shape were estimated in five steps.

- ✓ Counts were done at different count values starting from 150 to 4000 photon numbers after background had been subtracted.
- ✓ Resolution, FWHM, FWTM, and FWFM were calculated for each photo peaks of Cs-137 and Eu-152.
- ✓ Geometry of FJ374 scintillation crystal were modeled using GEANT4 Monte Carlo code.
- ✓ Spectrums had been simulated after the third step is completed and second step will be repeated.
- ✓ Results were analyzed using Ubuntu based SciDAVis plotting software.

In the measurement, we obtained more counts for each photo peak by decreasing the distance between sources and detector, which means shorter distance will give more counts. We can explain this by using equation of geometrical efficiency for a detector which is used in the calculation of Full-Energy Peak Efficiency (FEPE). This geometrical efficiency depend on a solid angle covered by radiation towards an effective area of a detector, which is calculated as;

$$\varepsilon_G = \frac{\Omega}{4\pi} \qquad (1)$$

The solid angle Ω is calculated by using relation;

$$\Omega = 2\pi\left(1 - \frac{d}{\sqrt{d^2 + r^2}}\right) \qquad (2)$$

where d distance and r is radius of detector (FJ374) which is 20mm [3], [4]. In our measurement, we used only the upper

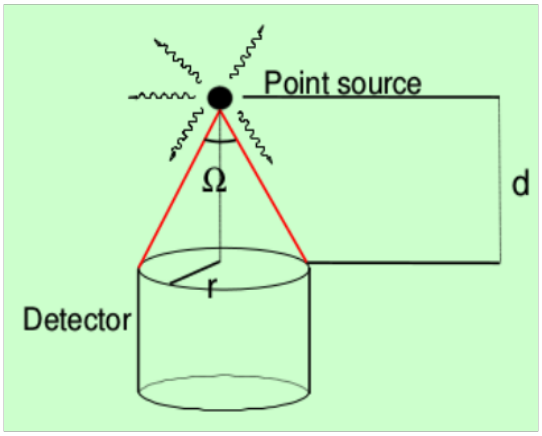

Fig. 1: Schematic diagram of symmetric source placement

part of a crystal due to the limited size of shielding materials from the side as seen in the fig: 1.

Full-Energy Peak-Efficiency [ε_P (E)] is a ratio of number of counts in FEPE [N_P (E)] to a number of photons emitted by the source with energy F(E) or directly we can calculate using eq: 1 as;

$$\varepsilon_p(E) = \varepsilon_G * \varepsilon_I \qquad (3)$$

where ε_I is intrinsic efficiency which depends on detectors materials and energy of incident photon.

Peak shape is determined by calculating ratio of Full Width at Tenth Maximum (FWTM) to Full Width at Half Maximum (FWHM) and ratio of Full Width at Fiftieth Maximum (FWFM) to FWHM. This is used to check if there is broadening of peak over time. The ideal and acceptable ratio for FWTM/FWHM is

1.82 for Gaussian peak and should be less than 1.9 in practice. While for FWFM/FWHM is 2.38 for Gaussian peak and should be less than 2.5 in practice [8].

Peak resolution is a difference in wave number, wavelength or frequency of two waves.[IUPAC]. When centroids of two peaks of good shape are 3 ∗ F W HM apart, they are clearly separated from each other [8]. Based on this we calculated energy resolution as a ratio of FWHM to the energy of that peak (E_0) using GEANT4.

$$E_R = \frac{FWHM}{E_0} \quad (4)$$

Experimentally, it is the ratio of F W HM to the centroid of that peak, Cp.

$$E_R = \frac{FWHM}{Cp} \quad (5)$$

If channel number to energy ratio is 1 : 1, both eq: 4 and 5 are the same. As "I depends on detector materials and photon energy, FWHM also depends on a detector type and gamma energy carried by photons. Mathematically it is expressed as:

$$FWHM = a + b\sqrt{E_0 + cE_0^2} \quad (6)$$

Where constants a, b and c are equal to -0.0137257, 0.0739501, and -0.152982 respectively, which is obtained from experimental fitting of eq: 6 [2], [3], [8]. In gamma spectrometry, using Genie-2000 eq: 6 is calculated using a relation;

$$FWHM = 2\sigma\sqrt{2\ln 2} \quad (7)$$

where σ is standard deviation which is not a constant because it is a function of the photon energy. In the same way, same relation is used for the calculation of FWTM and FWFM by putting in place of ln2, ln10 and ln50 respectively [11].

2.1. ***Monte Carlo Simulation***

Monte Carlo simulation is a type of simulation that relies on repeated random sampling and statistical analysis. It is a methodological way of doing what if analysis is true. From the result we identify a statistical distribution that we can use as a source for each of input parameters and draw random samples from each distribution [10].

2.1.1. ***GEometry ANd Tracking4 (GEANT4)***

GEANT4 is used in most case for optimization of radiometric experiments and calibration purposes. In this work we used 'G4RadioactiveDecay5.1.1 data' of version 10.02.p03 to a full detector construction to obtain an energy spectra of gamma radiation deposited on FJ374 NaI(Tl) crystal. Simulation of decay product is performed step by step. A true step length for a next physics interaction is randomly sampled using mean free path of interaction which can be given in terms of total cross section. The smallest step limit defines the new true step length [3], [7], [11].

2.1.2. ***Modeling the FJ374 NaI(Tl) detector***

In this work, detector modeling was done according to the physical FJ374 NaI (Tl) crystal, which is a cylindrical type provided by Beijing Nuclear Instrument Factory. Some of the geometrical parameters are provided by manufacturer, where as, some of the others are from literature (3,17) which are given as NaI(Tl) crystal density, 3.667 $g{:}cm^{-3}$, Al_2O_3 reflector density, 3.970 $g{:}cm^{-3}$ and aluminum density, 2.7 $g{:}cm^{-3}$. To account for back scattering, window of Photo Multiplier Tube (PMT) was modeled as being composed from glass (SiO2) layer, having an effective density of 0.94 $g{:}cm^{-3}$. In real crystal, we do not have any information about this layer. The PMT for these model is named as GDB-44 (D.F) which is very difficult because of its complex structures of dynodes using GEANT4 [2], [3].

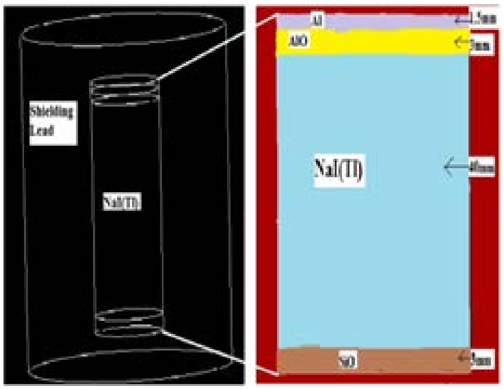

Fig. 2: Cross sectional view of modeled FJ374 NaI(Tl) crystal and lead shield

2.2. *Experimental procedure*

Experimental set up for FJ374 NaI(Tl) crystal was allowed to stand 900 upward and point source has been placed at several distance on symmetric axis of crystal starting from far distance for the achievement of less count. For the simplicity of calculation of geometrical efficiency and limited size of shielding materials (Pb), side surface of FJ374 NaI(Tl) crystal was not used.

Fig. 3: Experimental set up for FJ374 NaI(Tl) scintillation detector

2. Results and Discussion

Measurements of counts versus channel number using FJ374 NaI(Tl) were done using standard sources of Cs-137 and Eu-152 at several distance from end cap of crystal keeping symmetry axis. Shielding materials used for reduction of background

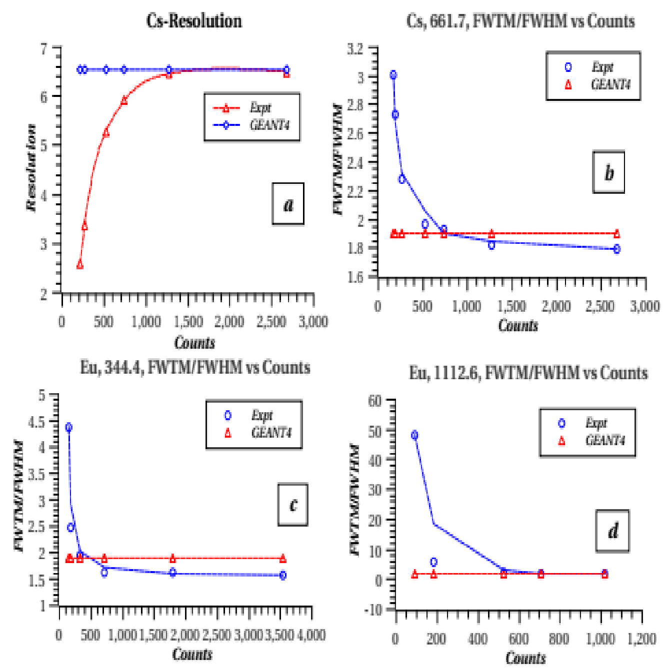

Fig. 4: Cs-137 Photo peaks at different distance from end cap of crystal

radiations were thin aluminum layer and heavy lead from outer part, which is very thick and massive.

In the same way, the simulation result were found from a plot of intensity versus energy of photons using a modeled crystal in figure 2:

At shorter distance from end cap, we confirmed large value of efficiency and as we increase the separation it decreases exponentially. This is also true for the number of photons recorded by crystal. Using GEANT4 Monte Carlo simulation

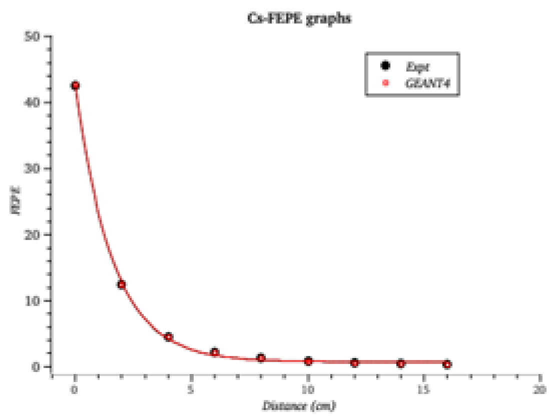

Fig. 5: Full-Energy Peak-Efficiency vs end cap to source distances (d)

with other mathematical calculations, we found that the ratios FWTM/FWH and FWFM/FWHM of photo peaks as 1.82 and 2.38 respectively. We considered these values to estimate a boundary limit with an experimental error of 10% which is 1.9 and 2.5 respectively. Experimentally these ratios are more than the above values for less counts and become less than the above values as count increases. For any more values of the ratios given above, there is a peak broadening that affects the qualities of measurements and less than this value of ratio will give good quality of measurement which is also described as good resolution.

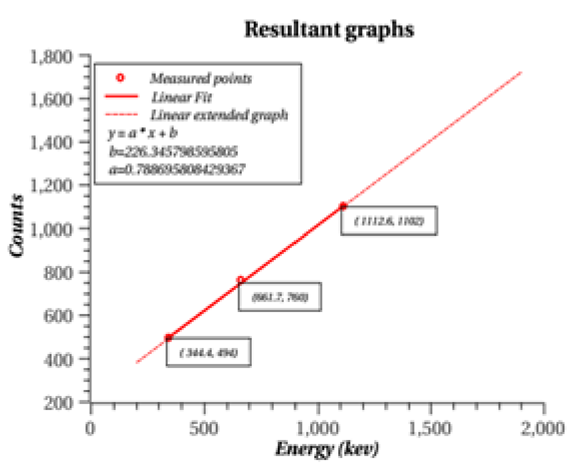

Fig. 6: Minimum count identifying graphs for three photo peaks b, c and d where a, shows achievement of good resolution by more counts.

As seen from figure 6:, measurements of counts was started from 150 photons to few thousands of counts. Comparing this results with that of the simulation,

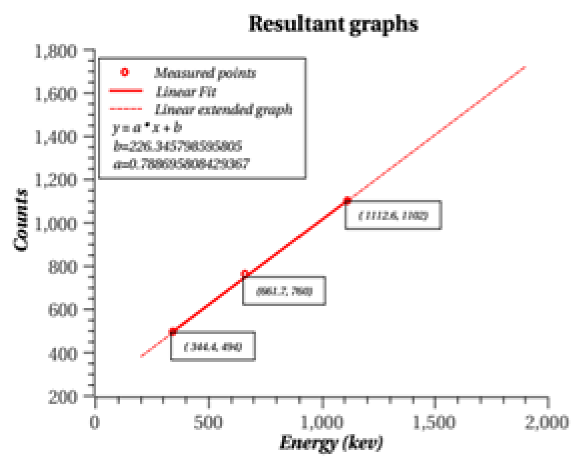

Figure 7: Lower boundary line for which the upper part gives good resolution and lower is not for energy 344.4 - 1112.6 kev

a point of intersection will give a minimum count (lower count limit) of an acceptable photo peak.

We found a linear relationship between the number of counts and energies of sources which indicates for more energy more counts are required. As we observed from figure 7:, the obtained graph and fitting graph is almost the same. So we extended the graph to 200 kev to the minimum energy side and 2000 kev to the maximum energy side. As we tasted, any value of a count in the above region of a graph will give an acceptable, well resolved pulse shape for the corresponding energy value. We confirmed also the fact, as energy increases resolution decreases in the crystal as seen in figure 8:.

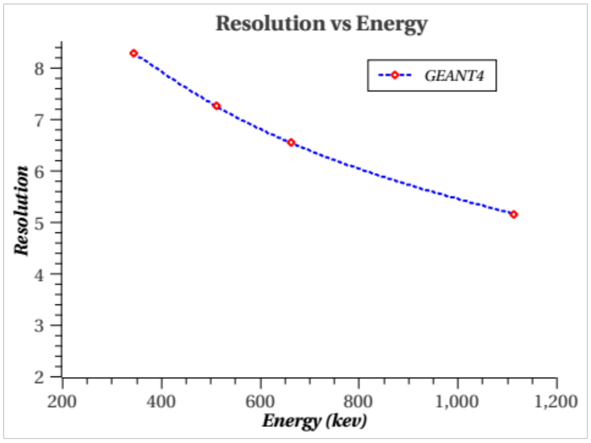

Fig. 8: Resolution-Energy relation in NaI(Tl) crystal

4. Conclusions

In this work, We took a 4cm x 4cm FJ374 model and investigated the minimum photon number that deposit its energy in a crystal for the formation of an acceptable pulse shape on a display. GEANT4 was used to make a well resolved photo peak from known sources and the peaks were used as a reference for experimentally obtained photo peaks, where standard sources were used to generate photons from 150 to 4000. So we identified that, for higher energy sources more counts are required and for lower energy sources less counts are required. The slope of plot obtained in figure 7: increases for smaller size crystals and decreases for larger size crystals because of a count number relation with the crystal size.

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