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Geant4 code for simulation attenuation of gamma rays through scintillation detectors

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ABSTRACT

Geant4-based Monte Carlo simulations have been carried out for studying mass attenuation for different types of scintillation detectors at different photon energies. The simulations showed that the calculated mass attenuation values are close to experimental values better than the other obtained theoretical data base for the same detector. The results indicate that Geant4 can be applied to estimate mass attenuation for various materials and energies.

1. Introduction

Scintillation detectors are widely used technique in detecting gamma rays through different fields in science and technology. They have much greater efficiency for interactions with gamma rays compared to gas and liquid filled detectors. This in turn provides a tool to measure the energy of a radiation interaction and identification of radionuclides based on their gamma ray energies. Scintillation detectors are usually coupled with photomultiplier tubes (PMTs) which generates electrical signals in response to light incident upon their faces (Knoll, 2000).

Most studies related to applications of scintillation detectors are concentrated in detecting X and γ rays without appropriate information and experience about mass attenuation of gamma rays through scintillation detector materials which represents the probability of a photon–atom interaction (scattered/absorbed) per unit path length. It is the fundamental parameter to derive many other parameters of dosimetric interest such as mass-energy absorption coefficient, molecular, atomic and electronic cross sections, effective atomic number and electron density. An extensive data is available in literature relevant to study attenuation for almost all elements, compounds as well as mixtures. Recently, there are significant number of publications in experimental and theoretical determination of mass attenuation coefficients of various elements, compounds and mixtures (Costa et al., 2013; Kucuk et al., 2013; Chanthima and Kaewkhao, 2013; Medhat, 2012a,b; Mavi, 2012; Kurudirek, 2011).

Most of the obtained experimental data are compared with the theoretical tabulations used by XCOM data base (Berger et al., 2010) and there are few attempts to apply Monte Carlo simulation for calculating attenuation coefficients in soils (Demir et al., 2013) and building materials (AkarTarim et al., 2013; Gurler and Akar Tarim, 2012).

Geant4 is a Monte Carlo simulation code based on the object-oriented programming (OOP) method. This way allows user to build C++ classes for describing geometry, particle interactions, and physics (CERN, 2007; Agostinelli et al., 2003). The main objectives of the present study were to use Geant4 simulations for calculating mass attenuation coefficients of some selected scintillation detectors and testing the validity of Geant4 by comparison with the experiment and theoretical values obtained by XCOM data base. Geant4 code was applied to estimate photon mass attenuation coefficients of different types of most common scintillation crystal detectors at energies 59.5, 80, 356, 661.6, 1173.2 and 1332.5 keV then compared with experimental measurements according to their relative deviation and the theoretical data obtained by XCOM program.

2. Experimental details

For narrow beam geometry with the various photon energies, the mass attenuation coefficients of investigated materials are determined by the transmission method according to Beere Lambert's law ($I = I_0 e^{-\mu_m x}$), where I_0 and I are the incident and attenuated photon intensity, respectively, μ_m ($cm^2\,g^{-1}$) is the mass attenuation coefficient and x is the thickness of the material. Mass

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attenuation coefficient μ_m is a density-independent and more accurately characterizing a given material with density (ρ) and is defined as $\mu_m = \mu/\rho$ (g^{-1} cm^2). The main properties of the investigated scintillation detectors are presented in Table 1. The obtained linear attenuation coefficient of the sample was divided by its respective density given as per manufacturer's specification.

The schematic arrangement of the experimental setup is shown in Fig. 1. The material sample, BGO (Φ: 3.0 × 6.0 cm^2), CsI (~2.0% Tl, Φ: 2.5 × 2.5 cm^2) and NaI (~2.0% Tl, Φ: 3.0 × 3.0 cm^2) were irradiated by 59.5, 81.0, 356.5, 661.6, 1173.2 and 1332.5 keV photons emitted by ^{241}Am (2.78 GBq), ^{133}Ba (2.92 GBq), ^{137}Cs (3.14 GBq), and ^{60}Co (3.7 GBq) radioactive point sources, respectively. Incident and transmitted photons for each detector material were measured for sufficiently large fixed preset time to reduce statistical uncertainty. The acquisition system consists of HPGe detector (Canberra model) coupled with a PC-based multichannel analyzer (MCA) along with Genie software installed in the PC. Genie 2000 software (Canberra Industries, Meriden, USA) was used to acquire and subsequently analyze the information provided by the gamma spectra. The measuring time is ranged from 5 to 10 min depending upon the photon energy and background noise. The background was counted in the same manner of measuring intensity of attenuated photons in the samples.

The uniformity of the measurements was checked by exposing different parts of samples to the incident beam. Stability and reproducibility of the procedure was tested before and after each run. HPGe detector and samples were arranged in such a manner that the maximum angle of acceptance of scattered photons at the detector was <2°. Therefore for this acceptance angle, scattered radiations reaching the detector can produce a ray sum error of (0.5–1.0)%, which is within tolerable limit. The errors are attributed to the evaluation of the area under peaks, in the determination of the thickness of sample, the weighing of the sample, geometric factor, the intensity of the source, the systematic errors and the counting statistics. The statistical error has been determined by combining errors for the product of linear attenuation coefficient and thickness, density and thickness measurements in quadrature (Medhat, 2012a, and b).

Table 1
Properties of the investigated scintillator detectors.

	BaF_2	BGO	$CdWO_4$	CsI(Tl)	GSO	NaI(Tl)	YAP
Density (g/cm^3)	4.88	7.13	8	4.51	6.71	3.67	5.37
Effective decay time (ns)	630	300	14,000	900	70	230	27
Emission peak (nm)	310	480	475	550	440	415	370
Hardness (Mho)	3	5	4.5	2	5.7	2	8.6
Melting point (K)	1627	1323	1598	894	2446	924	2148
Refractive index	1.5	2.15	2.3	1.78	1.82	1.85	1.95
Photoelectron yield (% NaI(Tl))	16	8	30	47	15	100	40
Chemical structure	BaF_2	$Bi_4Ce_3O_{12}$	$CdWO_4$	CsI(Tl)	Gd_2SiO_5	NaI(Tl)	$YAlO_3$

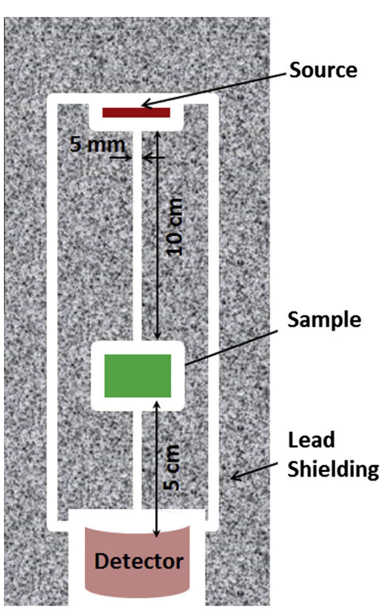

Fig. 1. Experimental setup for measuring mass attenuation coefficient.

3. Results and discussion

Calculations of the mass attenuation coefficients of all investigated scintillation crystals were carried out by the XCOM and Geant4 Monte Carlo simulation code. XCOM program can generate cross-sections and attenuation coefficients for elements, compounds or mixtures in the energy range between 1 keV and 100 GeV, in the form of total cross-sections and attenuation coefficients as well as partial cross-sections of the following processes: incoherent scattering, coherent scattering, photoelectric absorption and pair production in the field of the atomic nucleus and in the field of the atomic electrons. The program possesses a comprehensive database for all elements over a wide range of energies, constructed through the combination of photoelectric absorption, incoherent, coherent scattering, and pair production (nuclear and electric field) cross-sections. The partial and total mass interaction coefficients are also tabulated in the database.

Calculation of mass attenuation by Geant4 was done by writing C++ classes depending on object oriented programming (OOP) concept. The key class for all Geant4 applications is the G4RunManager which controls the initializations of geometry, physics list and primary particle generation. The user has full freedom to develop an own simulation program. The proposed model was written using three user mandatory classes, two initialization classes and one action class and some user action classes. The geometry of the model was coded in the mandatory class (Detector Construction). For this study, physics process defined in the mandatory class (Physics List). For gamma rays, Compton scattering, photo electric absorption, pair production and Rayleigh (coherent) scattering processes are defined with valid energy range from 250 eV up to 1 GeV. Attenuation of photons is calculated by simulating all relevant physical processes and interactions before and after inserting the investigated sample. The other run action mandatory class is (Primary Generator Action) which used to control the generation of primaries photons and describe the initial state of the primary events. Registration of interesting processes is made in Stepping Action class. Algorithm for generating computing efficiency was implemented in (Run Action) class.

The results of the present calculations were compared with the theoretical values obtained by XCOM database with coherent scattering and the experimental results. The results are shown in Fig. 2. It is clear that values of mass attenuation coefficient decrease sharply in the low energy region then become constant in the medium region. Table 2 shows the mass attenuation coefficients calculated by Geant4 versus photon energy together with theoretical values, calculated by XCOM database and experimental results of BGO, CsI(Tl) and NaI(Tl) detectors. It is clear that there is satisfactory agreement between experiment and theory, although the experimental values tend to be lower than the theory. Discrepancy in the calculated values and experiment could be due to deviations from narrow beam geometry in the source-detector arrangements. This may attribute to lower counting rates and the error in