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Comprehensive study of photon attenuation through different construction matters by Monte Carlo Simulation

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HIGHLIGHTS

- We measure mass attenuation of gamma rays through different materials.
- We model a design of a simple model using Geant-4 Monte Carlo Simulation for calculating mass attenuation of different composite materials.
- We compare the model with the theoretical calculation of NIST XCOM code.

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ABSTRACT

The main goal of this work is focused on testing the applicability of Geant4 electromagnetic models for studying mass attenuations for different types of composite materials at 59.5, 80, 356, 661.6, 1173.2 and 1332.5 keV photon energies. The simulated results of mass attenuation coefficients were compared with the experimental and theoretical data for the same samples and a good agreement has been observed. The results indicate that this process can be followed to determine the data on the attenuation of gamma-rays with the several energies in different materials.

1. Introuduction

Due to increasing use of radioactive sources in different areas of science such as radiation biophysics, nuclear industry, radiation shielding, space research applications and agriculture, etc., the study of photon interactions with matter has attained a significant importance. Useful information for designing experimental arrangements for handling the isotopes decaying by gamma emission can be obtained from studying attenuation of photons through materials. Recently, there are a significant number of publications in the experimental determination of photon attenuation coefficients of various elements, compounds and mixtures. The obtained experimental data are compared with the theoretical tabulations used by XCOM software (Berger et al., 2010) and there is also some attempts to apply Monte Carlo calculations (Medhat et al., 2014; Medhat and Wang, 2013; Shirmardi et al., 2013).

Modeling the photon attenuation through materials in computer environment gives flexibility and ease of use, instead of performing an experimental determination of mass attenuation of different composite materials. For this reason, the system model would be useful for further experiments where material and incident photon energy changed. Then, instead of performing photon attenuation for each sample, which may sometimes be impractical, the model can be used through macrofile to calculate mass attenuation coefficients of the sample at different energies.

GEANT4 code is widely used toolkit for carrying out Monte Carlo based particle transport calculations. It uses Monte Carlo methods and a number of theoretical models to fully simulate the passage of particles through matter. It is based on object-oriented programming and allows user to derive classes to describe the detector geometry which includes the materials used, detector sensitive components, etc., the primary particle generator which includes particle type, energy, position and direction distributions etc., along with the relevant particles, tracking, hits, and physics processes models along electromagnetic, hadronic, and decay physics (CERN, 2007; Agostinelli et al., 2003).

The main objective of this work is focused on the validation of Geant4 electromagnetic models to test the validity of GEANT4-based Monte Carlo simulations to demonstrate its success in radiation interactions. It was applied in calculating mass attenuation in different types of materials and compared with their experimental measurements and the theoretical data obtained by XCOM program.

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2. Monte Carlo model and simulations

The physics of GEANT4 simulation depends on narrow beam geometry with the various photon energies. The experimental set-up of the simulation, consisting of a mono-energetic photon beam impinging on a slab of one of the selected materials, the mass attenuation coefficients of investigated materials are determined by the transmission method according to Beer 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 slab. The thickness of the target is optimized according to the energy of the incident beam, to avoid that all the photons are absorbed in the target or traverse the slab without interacting. The primary photons emerging unperturbed from the slab are counted. The energy range of incident photons varied between 1 keV and 100 GeV. Attenuation of photons is calculated by simulating all relevant physical processes and interactions before and after inserting the investigated sample.

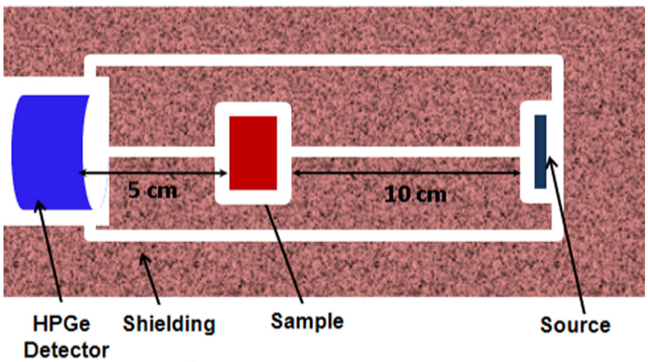

Fig. 1. Experimental setup for measuring mass attenuation coefficient.

The Physics processes defined in Physics List are low-energy electromagnetic processes with valid energy range down to 250 eV. This variant is based on the use of experimental data parameterizations using databases developed by Lawrence Livermore National Laboratory: Evaluated Photon Data Library (EPDL97), Evaluated Electron Data Library (EEDL) and Evaluated Atomic Data Library (EADL). Photon interactions include photoelectric effect, Compton scattering, pair production, Rayleigh scattering, and electrons interactions include Bremsstrahlung, multiple scattering and ionization. Atomic effects after photoelectric effect, as X-rays emission and Auger effect are included. So it is possible to have a vertex from photoelectric effect (Amako et al., 2005).

Table 1
Chemical compositions of the investigated materials.

Category	Material	Elemental concentrations (% weight)
Alloys	Dental fillings	Hg (0.50), Ag (0.32), Sn (0.09), Cu (0.08), Zn (0.01)
	Red brass	Cu (0.85), Sn (0.05), Pb (0.05), Zn (0.05)
	Steel	C (0.0021), Si (0.0215), Mn (0.012), Cr (0.191), Mo (0.028), Ni (0.121), Co (3×10^{-4}), Cu (4×10^{-4}), Fe (0.622)
Biology	Blood	H (0.102), C (0.11), N (0.033), O (0.745), Na (0.001), P(0.001), S (0.002), Cl (0.003), K (0.002), Fe (0.001)
	Bone	H (0.064), C (0.278), N (0.027), O (0.41), Mg (0.002), P(0.07), S (0.002), Ca (0.147)
	Muscle	H (0.102), C (0.123), N (0.035), O (0.729), Na (8×10^{-4}), Mg(2×10^{-4}), P (0.002), S (0.005), K (0.003), Ca (7×10^{-5})
Building Materials	Bricks	C (0.558), Na (0.023), Mg (0.001), Al (0.082), Si (0.082), Ca (0.246), Fe (0.008)
	Cement	O (0.37), Mg (0.004), Al (0.209), Si (0.021), Ca (0.279), Fe (0.117)
	Concrete	H (0.009), C (0.001), O (0.536), Na (0.005), Mg (0.001), Al (0.013), Si (0.367), S (0.001), K (0.003), Ca (0.056), Fe (0.006)
Precious stones	Beryl	Be (0.050), O (0.535), Al (0.100), Si (0.313)
	Pearl	C (0.120), O (0.480), Ca (0.400)
	Tourmaline	Li (0.015), Na (0.016), Mg (0.052), Al (0.175), K (0.028), Ca (0.029), V (0.220), Cr (0.224), Mn (0.118), Fe (0.120)
Glasses	Quartz	O (0.532), Si (0.467)
	Pyrex	B (0.041), O (0.54), Na (0.028), Al (0.012),Si (0.38), K (0.0033)
	Soda lime	O (0.468), Na (0.096), Mg (0.001), Al (0.007), Si (0.345), S (8×10^{-4}),K (0.003), Ca (0.075), Ti (6×10^{-4}), Fe (0.003)
Minerals	Amber	H (0.111), C (0.799), O (0.089)
	Mica	H (0.004), O (0.473), F (0.009), Al (0.203), Si (0.211), K (0.098)
	Olivine	O (0.417), Mg (0.253), Si (0.183), Fe (0.146)
Plastics	CR-39	H (0.066), C (0.525), O (0.408)
	LR-115	H (0.031), C (0.285), N (0.111), O (0.571)
	Makrofol	H(0.055), C (0.755), O (0.189)
Soil	Clay	O (0.451), Na (0.020), Mg (0.011), Al (0.107), Si (0.245), K (0.038), Ca (0.027), Ti (0.005), Fe (0.094)
	Sand	O (0.490), Na (0.015), Mg (0.011),Al (0.028),Si (0.353), K (0.0262), Ca (0.009),Ti (0.05291), Fe (0.01423)
	Silt	O (0.479),Na (0.016), Mg (0.014),Al (0.067), Si (0.314), K (0.004), Ca (0.032), Ti (0.0066), Fe (0.0665)
Solution	Solution (S_1)	H (0.102), N (0.010), O (0.844), Mn (0.008), Cu (0.0042), Pb (0.031)
	Solution (S_2)	H (0.105), N (0.009), O (0.864), Cu (0.017), Zn (0.004)
	Solution (S_3)	H (0.106), N (0.004), O (0.858), Pb (0.0312)