Comparison of the simulated gamma-ray attenuation coefficients with the real measurements (Postprint)

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Date: 2023-06-18T00:00:00+00:00

Abstract

The gamma-ray linear and the mass attenuation coefficients of Pb, Al, Cu, and plexiglass materials were calculated from both experimental and theoretical (simulation) methods. For the experimental results, a spectrometer, which was consisted of a NaI(Tl) inorganic scintillation detector, was used. The theoretical attenuation values were calculated by means of the FLUKA Monte Carlo (MC) and XCOM programs. Obtained attenuation coefficients from the experiment and the theoretical methods were compared with each other and literature values.

Full Text

Preamble

Comparison of the Simulated Gamma-Ray Attenuation Coefficients with the Real Measurements

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(Received December 1, 2014; accepted in revised form February 5, 2015; published online October 20, 2015)

The gamma-ray linear and mass attenuation coefficients of Pb, Al, Cu, and plexiglass materials were calculated using both experimental and theoretical (simulation) methods. For the experimental measurements, a spectrometer consisting of a NaI(Tl) inorganic scintillation detector was employed. Theoretical attenuation values were calculated using the FLUKA Monte Carlo (MC) and

XCOM programs. The attenuation coefficients obtained from experimental and theoretical methods were compared with each other and with literature values.

Keywords: Gamma attenuation coefficients, NaI(Tl) scintillation detector, FLUKA, XCOM
DOI: 10.13538/j.1001-8042/nst.26.050401

Introduction

When gamma rays interact with matter, they undergo absorption, scattering, transmission, and other processes collectively known as attenuation. The attenuation of photons is characterized by coefficients that define both linear and mass attenuation [1].

The Monte Carlo (MC) method simulates the interaction of radiation with matter and can be conceptualized as a black box requiring specific input data, including details of the radiation source geometry, target and medium configuration, radiation type, energy, and flight direction [2]. FLUKA is one such MC program —a general-purpose tool for calculating particle transport and interactions with matter, with applications ranging from proton and electron accelerator shielding to target design, dosimetry, and detector design. FLUKA can simulate the interaction and propagation of any particle in matter [3, 4].

Data on photon scattering and absorption (X-rays, gamma-rays, bremsstrahlung) are essential for numerous scientific, engineering, and medical applications. A convenient alternative approach involves generating cross sections and attenuation coefficients for compounds and mixtures as needed using a personal computer. XCOM is a computer program that performs these calculations for energies ranging from 1 keV to 100 GeV [5].

Previous studies have investigated attenuation coefficients using various methods. Ermis and Celiktas [6] calculated gamma-ray linear attenuation coefficients of different materials using the pulse shape discrimination timing method, and later applied the same technique to beta attenuation coefficients [7]. Medhat and Wang [8] examined mass attenuation coefficients of various inorganic scintillation materials through experimental and GEANT4 MC methods. Demir et al. [9] investigated mass attenuation coefficients of water, bakelite, and concrete using the FLUKA MC method. Tarim et al. [10] used MC code to determine gamma-ray mass attenuation coefficients of soil samples.

In the present work, we determined the gamma-ray linear and mass attenuation coefficients of Pb, Al, Cu, and plexiglass materials using experimental and theoretical (simulation) methods. The FLUKA MC program was employed to calculate gamma-ray attenuation coefficients for various absorbers to validate its effectiveness for such calculations. Literature review revealed limited studies using FLUKA for attenuation coefficient calculations, which motivated this investigation. Experimental measurements were performed using a spectrometer with a NaI(Tl) inorganic scintillation detector. Theoretical attenuation coefficients were also calculated using the XCOM program to compare with FLUKA results. Additionally, we investigated the effect of incident gamma photon numbers on the calculated linear and mass attenuation coefficients in FLUKA. The results demonstrate that FLUKA can accurately calculate the linear and mass attenuation coefficients of materials.

Methods

Experimental Setup

The experimental spectrometer, shown in Fig. 1 [Figure 1: see original paper], utilized a NaI(Tl) scintillation detector (REXON Inc., Beachwood, OH, USA) with a 3-inch diameter and 3-inch thickness to determine the gamma-ray attenuation coefficients of Pb, Al, Cu, and plexiglass ($C_5O_2H_8$) materials. A standard radioactive ^{137}Cs solid point source served as the gamma emitter, with an activity of 5 µCi and half-life of 30.07 years [11].

The detector output was processed through a preamplifier (PA, ORTEC 113), then split to a main amplifier (MA, ORTEC 485) and a delay amplifier (DA, ORTEC 427A). The MA output was directed to a linear gate (LG, ORTEC 426), while a parallel output from the MA was sent to the LG through a timing single channel analyzer (TSCA, ORTEC 553) to select only 661.6 keV photons. The LG output was connected to a counter (C, ORTEC 775) and timer (T, ORTEC 719) to record photons passing through absorber materials.

Absorber materials (Pb, Cu, Al, and plexiglass) with dimensions of 10 cm × 10 cm were placed between the detector and gamma-ray source at a distance of 2 cm from the detector surface. Material thicknesses were 0.1 cm for Pb and Al, 0.11 cm for Cu, and 0.2 cm for plexiglass. Counting periods were 100 s per thickness, with background correction performed to obtain net counts. These net counts (N) were plotted against absorber thickness on semi-logarithmic attenuation graphs, and linear attenuation coefficients were calculated from the slopes. Mass attenuation coefficients were determined by dividing linear attenuation coefficients by absorber densities.

Theoretical Simulation

The theoretical section employed the FLUKA MC simulation program (ver. 2011.2.15) installed on an Ubuntu (ver. 11.04) operating system to determine the number of gamma photons transmitted through absorber materials. The number of absorbed photons was then used to evaluate linear and mass attenuation coefficients. For each material and gamma energy, ten simulation cycles were run, with output files analyzed using a ROOT (ver. 5.34.13) macro. Results are presented as the mean of ten cycles with standard deviations calculated by the program. A schematic representation of the source and detector geometry in FLUKA is shown in Fig. 2 [Figure 2: see original paper].

To parallel the experimental procedure, 661.6 keV monoenergetic gamma photons were used in FLUKA calculations. The effect of photon statistics was investigated by sending 500, 1000, 5000, and 10,000 photons to each absorber material. The theoretical gamma energy spectrum obtained from FLUKA is shown in Fig. 3 [Figure 3: see original paper].

XCOM Calculations

For comparison, gamma-ray mass attenuation coefficients were also calculated using the XCOM program (version 3.1) developed by Berger and Hubbell [5]. The procedure involved selecting the absorber material from the database, specifying the gamma-ray energy, and calculating the mass attenuation coefficient. These results were compared with experimental, FLUKA, and literature values to validate the simulation.

Results and Discussion

The semi-logarithmic experimental attenuation graphs (recorded counts vs. absorber thickness) for Pb, Cu, Al, and plexiglass are shown in Fig. 4 [Figure 4: see original paper]. Theoretical attenuation graphs from FLUKA at various photon numbers are presented in Fig. 5 [Figure 5: see original paper], revealing the effect of incident photon statistics on the calculations.

The experimental and theoretical gamma-ray mass attenuation coefficients are summarized in Tables 1–3 . Figure 6 [Figure 6: see original paper] illustrates the relationship between gamma-ray linear and mass attenuation coefficients versus absorber densities.

The gamma-ray linear and mass attenuation coefficients for Pb, Al, Cu, and plexiglass were successfully determined using three methods: experiment, FLUKA MC simulation, and XCOM program. In the experimental section, a NaI(Tl) scintillation detector spectrometer was used, while XCOM and FLUKA provided theoretical values.

The ^{137}Cs gamma energy spectrum was obtained from both experimental measurement and FLUKA simulation. Dead time is a critical parameter in experimental data acquisition, as it can cause pulse pile-up and spectrum distortion [1]. In this work, dead time values remained below the 30–40% threshold, preventing these effects [15]. This contributed to the compatibility between experimental and theoretical results. The energy resolution values were 10.88% from experimental spectra and 10.84% from theoretical spectra—remarkably close agreement.

To enhance reliability, monoenergetic 661.6 keV gamma photons were used in both experimental and theoretical sections. Previous studies have achieved theoretical gamma energy spectra for various radioisotopes using MC programs such as MARTHA, EGS4, MCNP, and GEANT4 [16-19]. This work extends such investigations by calculating gamma-ray linear and mass attenuation coefficients via FLUKA and comparing them directly with experimental and literature values.

The results indicate that calculations using more than 1000 photons generally agree better with literature values. This suggests that due to the small number of transmitted gamma photons through absorbers, using >1000 photons is recommended for more reliable results with reduced systematic error when calculating attenuation coefficients with FLUKA.

Comparison with literature values shows that all attenuation coefficients obtained through experimental and theoretical methods are in good agreement with published data (Tables 1-3). The compatibility of FLUKA results with experiment, XCOM calculations, and literature demonstrates that FLUKA can serve as an alternative method for determining material attenuation coefficients.

Conclusion

This study demonstrates that the FLUKA Monte Carlo program can accurately calculate gamma-ray linear and mass attenuation coefficients for various materials. The excellent agreement between FLUKA simulations, experimental measurements, XCOM calculations, and literature values validates FLUKA as a reliable alternative method for attenuation coefficient determination. The investigation of photon statistics reveals that using more than 1000 incident photons yields more accurate results, providing guidance for future simulation studies.

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Note: Figure translations are in progress. See original paper for figures.