Photon attenuation properties of some Thorium, Uranium and Plutonium compounds

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Abstract

Mass attenuation coefficients, effective atomic numbers, effective electron densities for nuclear materials; thorium, uranium and plutonium compounds have been studied. The photon attenuation properties for the compounds have been investigated for partial photon interaction processes by photoelectric effect, Compton scattering and pair production. The values of these parameters have been found to change with photon energy and interaction process. The variations of mass attenuation coefficients, effective atomic number and electron density with energy are shown graphically. Moreover, results have shown that these compounds are better shielding and suggesting smaller dimensions. The study would be useful for applications of these materials for gamma ray shielding requirement.

Keywords: Plutonium, Uranium, Attenuation coefficients, Shielding, Gamma ray.

1.- INTRODUCTION

Gamma radiation is associated with nuclear physics, radiation physics, medical physics, radiation dosimeter, radiation protection, radiation biology, nuclear technology and clinical applications. There is strong need for high efficient gamma shielding materials to improve the level of radiation protection by reducing radiation exposure for personnel involved in the work. The shielding materials required for gamma radiation are high atomic number elements, compounds or composite materials. Various types of radiation shielding materials have been invented and investigated for suitability.

The gamma ray shielding efficiency of a material is characterized by attenuation of photons in the material. The attenuation of gamma ray is described by linear attenuation coefficient or mass attenuation coefficient of material for particular photon energy. Higher the values of attenuation coefficients, better is shielding efficiency. In addition to mass attenuation coefficient, effective atomic number and effective electron density are parameters to define the shielding effectiveness. Various studies have been reported in literature for interaction of photon with materials [Singh and Badiger 2012a; Singh and Badiger 2012b].

Interaction of photon with a material is described by partial photon interaction process such as photoelectric effect, Compton scattering and pair production. These partial interaction processes are photon energy and atomic number dependent. For a compound or composite material, these partial photon interaction processes depend upon atomic number of all the elements.

Various types of shielding materials have been investigated and reported in literature. The nuclear materials used in reactors are source of radiations and emits various high range of gamma ray photons. As the nuclear materials are high atomic number elements, they should also be a very efficient gamma ray shielding materials. The photon interaction of these nuclear materials is important which could not found in literature.

The aim of present study is to evaluate the shielding efficiencies of nuclear materials; thorium, uranium and plutonium compounds using mass attenuation coefficients, effective atomic numbers and effective electron densities for photon energy 1 keV to 100 GeV. These photon interaction parameters were explained by partial photon interaction processes.

2.- MATERIALS AND METHODS

Nuclear materials such as thorium, uranium and plutonium compounds are vital materials in nuclear reactors. Generally, oxides of the nuclear materials are being used in nuclear reactors. Therefore, we have selected some compounds such as UO, UO_2, UO_3, UO_4, U2O5, U_3O_8, ThO_2, ThF_2, ThB_4, $ThAl_3$, PuC, PuO_2 and $PuPO_4$ for investigation of photon interaction.

The intensity of photon beam through a medium follows Lambert's Beer law as given below;

$$I = I_0 e^{-\mu t} \text{ .... (1)}$$

where I and I_0 are transmitted and initial photon densities, μ is linear attenuation coefficient and t is the thickness of medium.

2.1.- Mass attenuation coefficients

The mass attenuation coefficient for a compound or composite material is estimated using mixture rule [Jackson and Hawkes 1981] as given below;

$$\mu_m = (\mu/\rho) = \sum_i^n w_i(\mu/\rho)_i \text{...} (2)$$

where w_i is the proportion by weight and $(\mu/\rho)_i$ is mass attenuation coefficient of the ith element. The quantity proportion by weight, w_i is given by following relation;

$$w_i = n_i A_i / \sum_j^n n_j A_j \text{..} (3)$$

with the condition $\sum_i^n w_i = 1$, where A_i is the atomic weight of the ith element and n_i is the number of formula units in a compound or composite materials. The μ/ρ value of individual element can be referred from user-friendly Windows based WinXcom program [Gelward *et al*., 2004].

2.2.- Effective atomic numbers

The total atomic cross-section (σ_t) for a compound or mixture is obtained from the total mass attenuation coefficients by the following relation;

$$\sigma_t = \frac{\mu_m M}{N_A} \qquad (4)$$

where $M = \sum_i^n n_i A_i$ is the molecular weight of a compound or composite material and N_A is the Avogadro's number. The effective atomic cross section (σ_a) is calculated by the following equation:

$$\sigma_a = \frac{1}{N_A} \sum f_i A_i \left(\frac{\mu}{\rho}\right)_i \qquad (5)$$

The effective electronic cross-section (σ_e) is calculated by the following equation;

$$\sigma_e = \frac{1}{N_A} \sum \frac{f_i A_i}{Z_i} \left(\frac{\mu}{\rho}\right)_i = \frac{\sigma_a}{Z_{eff}} \qquad (6)$$

that $\sum_i^n f_i = 1$, Z_i is the atomic number of *i*th element.

The effective atomic number, Z_{eff} of a compound or composite material is given as by the following relation;

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \qquad (7)$$

2.3.- Effective electron density

The effective electron density of a compound or composite material is defined by the following relation;

$$N_{eff} = \frac{N_A}{M} Z_{eff} \sum n_i = \frac{\mu_m}{\sigma_e} \quad \text{.......(8)}$$

Recently, a program direct Z_{eff} has been developed by Adem and Tanfer [2014] for calculation of mass attenuation coefficients, effective atomic numbers and effective electron densities for a compound or composite material for photon energy 1 keV to 100 GeV. The program requires elemental composition or molar concentration of elements in a compound or composite material. In the present investigation, direct-Z_{eff} program was used to analyze photon attenuation properties.

3.- RESULTS AND DISCUSSION

The variation of mass attenuation coefficients, effective atomic numbers and effective electron densities for the selected nuclear materials is shown in Fig.1, Fig.2 and Fig.3, respectively. The variations of these photon interaction parameters are explained in next sections.

3.1.- Mass attenuation coefficients

The variation of mass attenuation coefficients (μ/ρ) for the nuclear materials in photon energy range 1 keV-100 GeV is shown in Fig.1.

In Fig.1, it is found that the μ/ρ values for the materials decreases very sharply in low-energy, reduction rate becomes slow in intermediate-energy and finally again increases in high-energy photon. Therefore, the variation of μ/ρ is divided into three energy regions low-, intermediate- and high-energy photon.

The μ/ρ values reduce sharply in low-energy because photoelectric effect is dominant in low-energy region, where interaction cross section is directly proportional to $Z^{4-5}/E^{7/2}$. Therefore μ/ρ values for the materials are found to be higher for those materials which contain high atomic numbers elements and it reduces as photon energy increase (up to 100 keV). Above 100 keV and below 1.022 MeV energy of photon, reduction rate of μ/ρ values diminishes because Compton scattering interaction dominant, where interaction cross section is directly proportion to Z.

Finally μ/ρ values initiate increasing and become stable due to dominance of pair production process, where interaction cross section is directly proportional to Z^2. There are various sharp peaks at particular energy in μ/ρ values due to K-, L- and M- absorption edges. It is observed that the μ/ρ values of PuC compound are the largest among selected nuclear materials.

Large values of μ/ρ signify that the removal capacity of photon from it is high or efficient shielding.

By comparing μ/ρ values for the nuclear materials with lead, it is found that μ/ρ values for the selected nuclear materials are very high except K-, L- and M- absorption edges. Therefore, these nuclear materials are found to high efficient gamma-ray shielding materials.

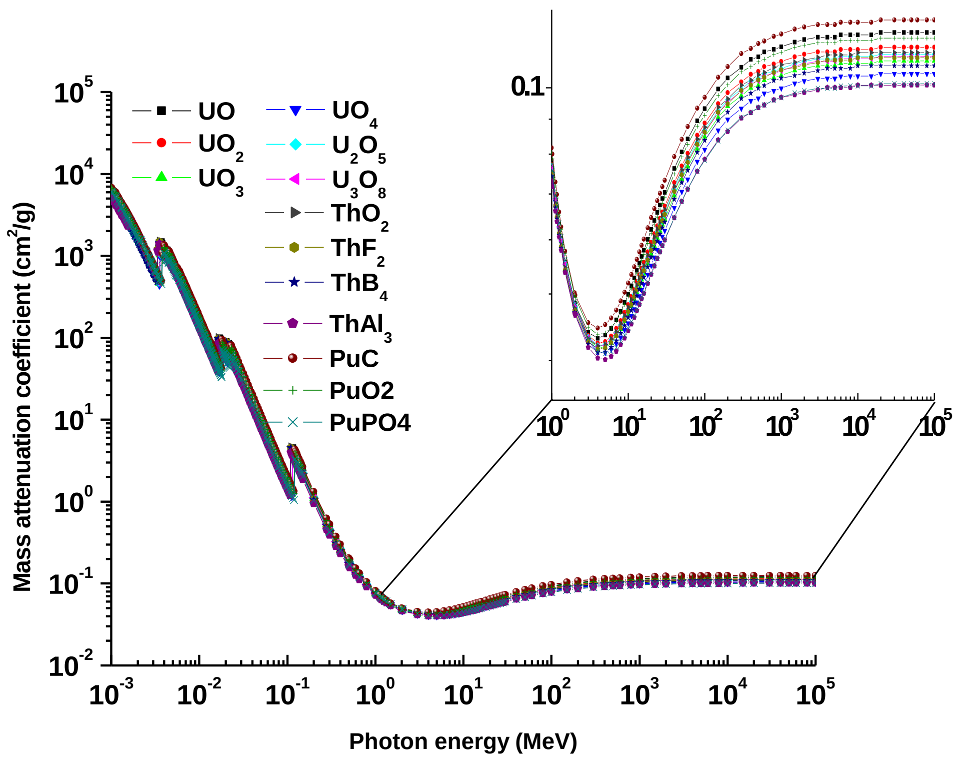

Figure 1.- Mass attenuation coefficients of Uranium, Thorium and Plutonium compounds

3.2.- Effective atomic numbers

The variation of effective atomic number (Z_{eff}) for the selected materials in energy range 1 keV to 100 GeV is shown in Fig. 2. Similar to the μ/ρ values, the Z_{eff} values also show various peaks in photoelectric effect region (low-energy photon region). Similarly intermediate- and high-energy photon regions of Z_{eff} values show analogous variation with μ/ρ values. Therefore, the variation of Z_{eff} with photon energy can be explained using partial photon interaction processes (photoelectric effect, Compton scattering and pair production).

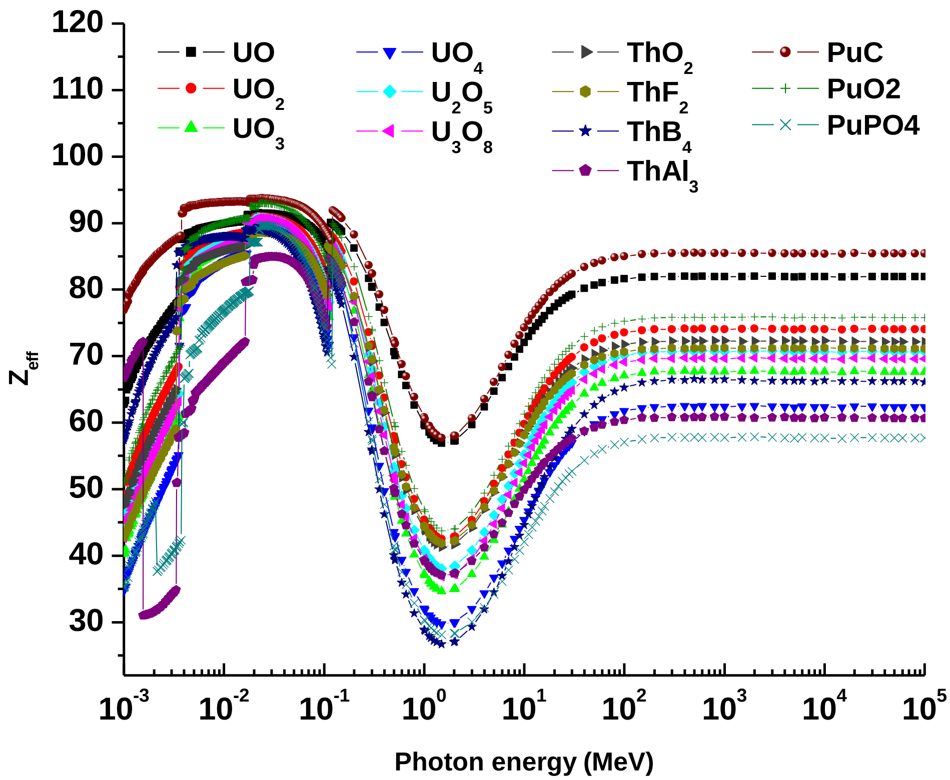

Figure 2.- Effective atomic numbers of Uranium, Thorium and Plutonium compounds.

The Z_{eff} values for PuC are found to be the highest among the selected nuclear materials. It is to be noted that the effective atomic numbers for selected materials are lesser than the element with higher atomic number. Similar to μ/ρ values, very large values of the Z_{eff} signifies that the nuclear materials are high efficient shielding materials.

3.3.- Effective electron density

The variation of effective electron density (N_{eff}) for the selected materials in energy range 1 keV to 100 GeV is shown in Fig.3. The variation of N_{eff} with photon energy can be explained similar to the Z_{eff} and μ/ρ values using partial interaction processes. It is to be noted the N_{eff} values coincide to a single value in Compton scattering region.

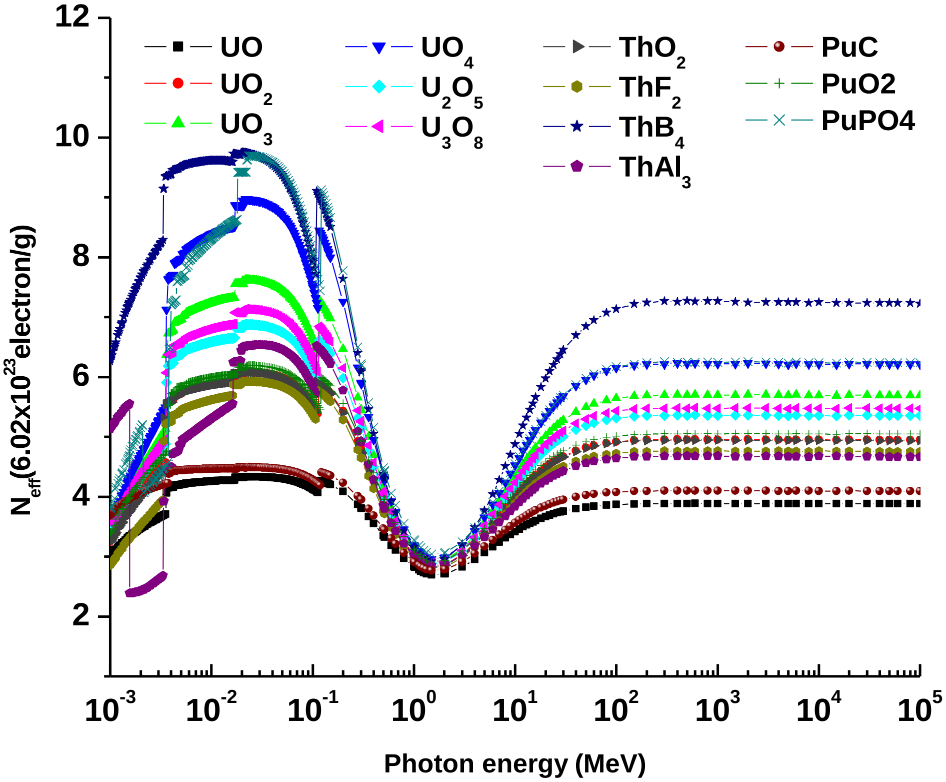

Figure 3.- Effective electron density of Uranium, Thorium and Plutonium compounds

4.- CONCLUSION

In the present investigation, mass attenuation coefficients, effective atomic numbers and effective electron densities for some nuclear materials have been studied for photon energy in the range 1 keV to 100 GeV.

The variations of these parameters were explained using partial photon interaction processes and found that major fluctuation was in low-energy photon region due to dominance of photoelectric effect. It is found that the nuclear materials are high shielding efficient for gamma-rays.

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