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Investigation of shielding parameters for smart polymers

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ABSTRACT

In this work, the gamma and neutron shielding properties of 8 different types of smart polymers have been investigated. We have calculated the mass attenuation coefficient (μ/ρ), effective atomic number (Z_{eff}) and electron density (N_e) for total photon interaction in the wide energy range of 1 keV–100 GeV using WinXCom program. Furthermore, the macroscopic effective removal cross-sections ($\sum_R$) for fast neutron were calculated. The dependence of different parameters on incident photon energy and chemical content has been discussed. Among the selected smart polymers DMSO and PEI showed superior shielding properties for γ-ray and neutron, respectively. This work was carried out to explore the advantages of the smart polymers in γ-ray and neutron shielding applications.

1. Introduction

Nowadays nuclear technology is used in different fields such as, medicine, industry, agriculture, military, scientific research and other scientific and technological fields. In fact, this technology produced many types of dangerous radiations to human health and environment, such as gamma rays and neutrons [1]. Hence, it became important to assess the risks and quantify the level of exposure to such radiations and develop technologies for protecting against these radiations. The most important factor for reducing the effect of these, is determining the most adequate material for shielding.

Radiation shielding involves placing a mass of material between the ionizing radiations source and the worker or the environment to reduce the exposure of these radiations. Generally, the radiations which have to be considered are: gamma rays and neutrons, every kind of these radiations interacts in various ways with shielding material.

While, it is necessary to evaluate the effective shielding materials for gamma rays and neutrons, so it is extremely important to study the attenuation of these radiations in the shielding materials. The mass attenuation coefficient (μ/ρ), effective atomic number (Z_{eff}) and effective electron density (N_e), are the basic parameters which describe the interaction of gamma rays with shielding materials. The mass attenuation coefficient is a measure of the probability of interactions of photon with matter and it is measured in (cm^2/g) [2]. It is the basic tool used to derive other photon interaction parameters like effective atomic number and electron density. Effective atomic number (Z_{eff}) is parameter similar to the atomic number of elements, which describes the properties of the composite materials (compounds or mixtures) in terms of equivalent elements, and it varies with energy [3]. The effective atomic number is related to another parameter called effective electron density (N_e) which is defined as the number of electrons per unit mass of the interacting materials and measured in electrons/g.

On the other hand neutron attenuation in shielding materials is described by different parameters such as the macroscopic thermal neutron cross-sections and the macroscopic effective removal cross-sections for fast neutrons ($\sum_R$). The macroscopic

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effective removal cross-sections for fast neutrons, or for simplicity the removal cross-section is the probability of one neutron undergoing a specific reaction per unit path length of travel through the shielding material [4].

In previous extensive reports, many researchers determined γ-ray and neutron shielding parameters for different materials such as alloys, semiconductors, organic and inorganic compounds, glasses, building materials and soils. For example, Akman et al. [3] determined the total mass attenuation coefficient of some samarium compounds experimentally in the X-ray energy range from 36.847 up to 57.142 keV, using the measured mass attenuation coefficient the authors calculated the effective atomic numbers and electron densities of these compounds. They found that measured values were in good agreement with the theoretically calculated ones.

In addition, Gowda et al. [5] determined the effective atomic numbers and electron densities of some amino acids and sugars using the measured total attenuation cross sections at different energies. El-Sayed and Bourham [6] concluded that concretes with added materials in the aggregate can provide more efficient gamma ray shielding when compared to ordinary concrete. They have calculated linear and mass attenuation coefficients, the mean free path and half value layer for different concrete composition. Sidhu et al. [7] measured the total mass attenuation coefficient, total photon interaction cross-section, effective atomic number (Z_{eff}) and electron density (N_e) for some organic compounds at photon energy 59.54 keV. The obtained results were then compared with theoretically calculated values of XCOM, and excellent agreement was obtained between experimental and theoretical values within experimental uncertainties.

Tellili et al. [8] calculated the macroscopic fast neutron removal cross-sections ($\sum_R$) for different lunar soils. They found that the macroscopic effective removal cross section of lunar soil varies from one region to another region and this is due to the variation of density. Oto et al. [4] determined the removal macroscopic cross section values for concrete samples with and without limonite ore experimentally and theoretically. As reported by the authors, the limonite concrete is effective neutron shielding material comparing to the normal concrete sample. El-Khayatt and El-Sayed Abdo [9] developed a computer program [MERCSF-N] to calculate ($\sum_R$) for fast neutrons transmitted through homogeneous mixtures, composites, concretes and compounds. Comparison between the results of MERCSF-N program and previously published results were made in order to test the validity of this program yielding a good agreement. Yılmaz et al. [10] evaluated the effective fast neutron removal cross-sections ($\sum_R$) for different concrete samples with and without mineral additives using NXcom program. They concluded that the elemental composition, hydrogen content and the concrete density contribute an important rule for neutrons attenuation.

In this work mass attenuation coefficient (μ/ρ), effective atomic number (Z_{eff}), and electron density (N_e) have been calculated for eight smart polymers. Furthermore, the macroscopic effective removal cross-section of fast neutrons was calculated in order to determine their effectiveness as gamma ray and neutron shielding material. The eight smart polymers selected for this study are dimethyl sulfoxide, N-Vinylcaprolactam, Polyacrylic acid, Polyethylenimine, Polymethyl methacrylate, PolyN-isopropylacrylamide, Polyacrylonitrile and Polydimethylsiloxane.

Smart polymers are high-performance polymers that may overcome dramatic property changes responding to small changes in the environment. These polymers are also called as intelligent polymers because small changes occurs in response to an external trigger until a critical point is reached, and they are capable of returning to its initial state as soon as the trigger is removed [11,12]. These materials can be sensitive to a number of factors, such as pH, temperature, the intensity of light, mechanical stress, magnetic and electric field and biological molecules [13,14].

Smart polymers become one important class of polymers because of their vast applications in medicine [13,15], chemical and pharmaceutical industries [16,17], textile applications [18,19], active aircraft equipment [20] and interactive electronic apparatuses [21].

Smart polymers contain hydrogen which is the most effective 'moderator' because the mass of hydrogen is nearly the same as that of the neutron. We chose these materials in this investigation since they are newly developed recently and used in various applications.

2. Calculation method

2.1. Mass attenuation coefficient

In case of mixture of elements, the mass attenuation coefficient can be calculated using the mixture rule given by the following equation [22].

$$\mu/\rho = \sum_i w_i(\mu/\rho)_i \tag{1}$$

where w_i is the weight fraction of element i and $(\mu/\rho)_i$ is the mass attenuation coefficient of the ith element. The mass attenuation coefficients for the selected smart polymers have been calculated by the WinXCom program [23]. This program is able to generate total cross sections, attenuation coefficients as well as partial cross sections for various interaction processes, such as incoherent and coherent scattering, photoelectric absorption and pair production, for elements, compounds and mixtures as needed at energies from 1 keV to 100 GeV.