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Determination of total mass attenuation coefficients, effective atomic numbers and electron densities for different shielding materials

Y. Elmahroug [a,*], B. Tellili [a,b], C. Souga [c]

[a] Université de Tunis El Manar, Faculté des Sciences de Tunis, Unité de Recherche de Physique Nucléaire et des Hautes Energies, 2092 Tunis, Tunisia
[b] Université de Tunis El Manar, Institut Supérieur des Technologies Médicales de Tunis, 1006 Tunis, Tunisia
[c] Université de Carthage, École Polytechnique de Tunisie, B.P. 743-2078 La Marsa, Tunisia

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ABSTRACT

In this paper, the interaction of gamma rays with some shielding materials has been studied. The total mass attenuation coefficient (μ_t) for eight shielding materials has been calculated by using WinXCOM program in the energy range from 1 keV to 100 GeV. Also, the effective atomic number (Z_{eff}) and the effective electron density (N_{eff}) were calculated using the values of the total mass attenuation coefficient. The dependence of these parameters on the incident photon energy and the chemical composition has been examined.

1. Introduction

With the increasing use of gamma radiation in various applications such as industry, medicine, agriculture, nuclear reactors and particle accelerators, the exposure for longer duration of these radiations can cause very harmful effects on human health. Therefore, the use of shielding becomes a paramount thing to use these radiations without risk. A variety of materials can be used for protection against gamma rays radiations. To choose an appropriate type of shielding material, the energy of radiation must be taken in consideration. Indeed, the effectiveness of the shielding material is determined by the interactions between the incident radiation and the atoms of the absorbing medium. The interactions which occur depend essentially on the radiation energy, the chemical composition and the density of the material. Thus, the knowledge of the parameters of shielding such as the total mass attenuation coefficient, the effective atomic number, the electron density, is absolutely necessary.

For shielding from gamma rays, the best materials are those that are composed of heavy elements. In this work, the interaction of gamma rays with some shielding materials has been investigated. These materials are both absorbers of gamma rays and fast neutrons, in fact, they contain hydrogen which is the most effective 'moderator' because its mass is almost the same as that of the neutron and they contain boron which is a suitable absorber of thermal neutrons. Also, they are heavy elements such as Mn, Fe, Zn and Sr which are good absorbers of gamma radiation. These types of materials are useful in a large variety of applications. They are materials which are widely used as a neutron and gamma rays shielding in nuclear power plants, particle accelerators, research reactors, neutrons source and medical facilities. These materials are characterized by a good durability for neutron and gamma ray irradiation, a high heat resistance and a high mechanical strength. These materials were chosen for this study because they are used in several applications. The chemical compositions of the eight types of shielding materials were obtained from Bladewerx company and have been tabulated in Table 1. The aim of this study is to make a comparison between these materials in order to know the materials that are effective for gamma rays shielding.

The attenuation parameters of fast neutron for these materials are already calculated. In this study, the mass attenuation coefficients (μ_t) of eight materials which are: Flexi-boron, 7.5% Lithum Polythylene, 8.97% Borated Flexi Panel, Self Extinguishing Borated Polythylene, 5.45% Borated Polyethylene, High Temperature Boron Silicone, Polykast Dry Mix and Field castable Heat Resistant shielding, has been determined theoretically by using WinXCom code which is a Windows version of the XCOM database (Gerward et al., 2001, 2004). This code is used to calculate the cross sections of photons interactions with matter and it can also calculate the attenuation coefficient of gamma rays for the chemical elements ($Z = 1–100$), compound and mixtures at energies from 100 keV to 100 GeV (Gerward et al., 2001, 2004). The (Z_{eff}) and (N_{eff}) were determined by using the values of (μ_t).

* Corresponding author.
E-mail address: youssef_phy@hotmail.fr (Y. Elmahroug).

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Table 1
Chemical composition (%) of the eight shielding materials.

Element	Flexi-Boron	7.5% Lithium Polyethylene	8.97% Borated Polyethylene	Self Extinguishing Borated Polyethylene	5.45% Borated Polyethylene	High Temperature Boron Silicone	Polykast Dry Mix	Field castable Heat Resistant shielding
H	2.76	7.84	6.68	5.84	5.72	4.74	10.3	3.37
Li	–	7.5	–	–	–	–	–	–
B	25.3	–	8.97	1	5.45	1.08	0.9	1.56
C	20.1	57.76	27.2	18.02	25.96	11.01	46	–
N	–	–	5.28	–	–	–	–	–
O	24.2	26.13	51.9	47.83	39.69	46.56	32.5	58.7
Na	–	–	–	0.19	0.23	0.12	–	0.59
Mg	–	–	–	0.14	0.76	–	0.04	0.5
Al	–	–	–	24.94	11.92	18.75	0.03	23.9
Si	26.9	–	–	0.26	1.37	17.54	0.43	2.13
S	–	–	–	0.02	0.13	–	3.99	0.19
Ca	–	–	–	1.53	8.37	–	5.72	8.83
Fe	0.41	–	–	0.02	0.09	0.02	0.05	0.27
Zn	0.26	–	–	–	–	0.1	–	–
Sr	–	–	–	0.1	0.53	–	–	–

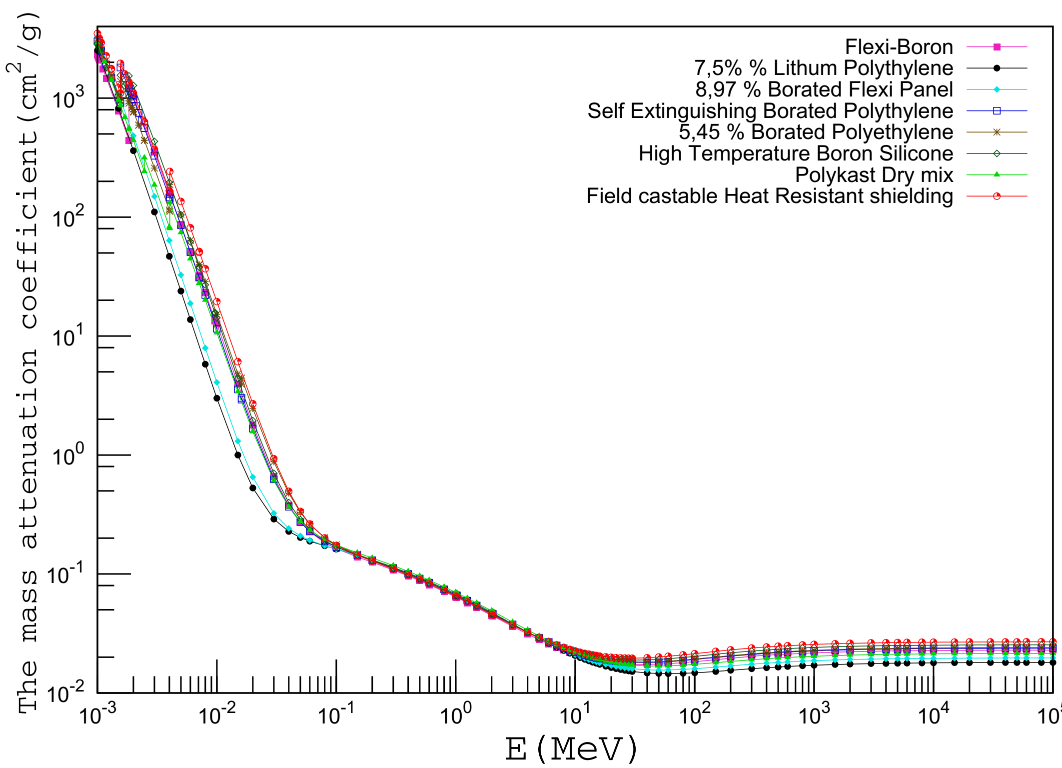

Fig. 1. Variation of total mass attenuation coefficients versus incident photon energy for some shielding materials.

The total mass attenuation coefficients (μ_t), the effective atomic numbers (Z_{eff}) and the effective electron densities (Z_{eff}), are the fundamental parameters which characterize the penetration of gamma rays in the shielding materials. The (μ_t) is a measure of the probability of interactions of photon with matter and it is measured in (cm^2/g) (Hubbell, 1999, 1982; Hubbell and Seltzer, 1995). This coefficient is not constant but depends on the incident photon energy, the material density and the atomic number of elements. But for compound and mixtures, it depends on the effective atomic number (Z_{eff}). The idea of this number is to assume that a compound or a mixture can be considered as a simple element characterized by the atomic number (Z_{eff}), but it is not constant, it varies with the incident photon energy. The notion and the theoretical expression of this parameter were suggested by Hine (1952). The effective atomic number is related to another important physical parameter called effective electron density (N_{eff}) which is defined as the electron per unit mass of the target material (Akkurt, 2009; Akkurt and El-Khayatt, 2013b; Gowda et al., 2005, 2004; Içelli et al., 2011; Manohara et al., 2008).

2. Theoretical method

During its passage through a material medium, a photon undergoes several interactions such as photoelectric absorption, coherent scattering, incoherent scattering and pair production. If a photon beam having an initial intensity I0 penetrates the matter, it will be attenuated and its intensity decreases exponentially according to the exponential law:

$$I = I_0 e^{-\left(\frac{\mu_{linear}}{\rho}\right)\rho x} = I_0 e^{-\mu_t d} \quad (1)$$