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The mass attenuation coefficients, effective atomic numbers and effective electron densities for GAGG:Ce and $CaMoO_4$ scintillators

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ABSTRACT

In this study, the mass attenuation coefficient (μ_m), the effective atomic number (Z_{eff}) and the effective electron density (N_{eff}) of $Gd_3Al_2Ga_3O_{12}$:Ce (GAGG) and $CaMoO_4$ scintillators were measured at different gamma ray energies. The samples were irradiated with eight different photon energies using Compton scattering technique. The scattered photons from ^{137}Cs source were detected by NaI(Tl) scintillation detector in an ordinary counting system. The experimental results were compared with the theoretical (WinXcom) values. The results show that the experimental values ofμ_m, Z_{eff} and N_{eff} of GAGG are higher than those of $CaMoO_4$ and all values are in good agreement with the theoretical ones. The values ofμ_m, Z_{eff} and N_{eff} increased toward the decrease of gamma ray energies. The partial interactions of the crystals were also investigated.

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1. Introduction

Inorganic scintilltors have an important role available for the detection of ionizing radiation of which a handful are suitable for use in nuclear engineering, space technology, agricultural and particularly in nuclear medicine, i.e., Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT) (Yeom et al., 2013). The experiment for determination of the mass attenuation coefficient (μ_m), is important for scintillator because of the experimental data of the μ_m shows probability of interaction and this data can be used for development and characterizations of new scintillation materials. Moreover, the total atomic cross-section ($\sigma_{t,a}$), the electronic cross-section ($\sigma_{t,el}$), the effective atomic number (Z_{eff}) and the effective electron density (N_{eff}) are the basic quantities required in determining the penetration of X-rays and gamma ray when they interact with matters. All mentioned parameters can be calculated using μ_m value. Theμ_m is a measure of probability of interaction that occurs between incident photons and matter per unit mass per unit area thickness of the material encountered (Gupta and Sidhu, 2014). Accurate values of μ_m are required to provide essential data in diverse fields such as nuclear diagnostics (computerized tomography), radiation protection, radiation dosimetry, gamma ray fluorescence studies, radiation physics, shielding, security screening and etc. (Gounhalli et al., 2012). Many literature reported the experimental and theoretical investigations on photon interaction in different materials such as glasses (Kaewkhao and Limsuwan, 2010; Singh et al., 2006; Sharma et al., 2006; Kaewkhao et al., 2010; Limkitjaroenporn et al., 2011; Yasaka et al., 2014), amino acids (Turşucu et al., 2013; Chaitali et al., 2016; Prashant and Pravina, 2014; Pravina and Govind, 2013), alloys (Narender et al., 2013; Han and Demir, 2009a,b,c, Han et al., 2012), natural minerals (Han et al., 2009), polymers (Kucuk et al., 2013), gemstones (Medhat, 2012; Korkut et al., 2011; Kaewkhao et al., 2012), semiconductors (Erzeneoğlu et al., 2006) and superconductors (Cevik and Baltas, 2007).

Hine, 1952 pointed out that, for photon interactions in composite materials, a single number cannot uniquely represent the atomic number across the entire energy region, as in the case of pure elements. This number, for composite materials, is known as “effective atomic number” (Z_{eff}) and it varies with energy. The effective electron density (N_{eff}) is effective electron per unit mass of composite materials and can be calculated from Z_{eff}.

In this work, the calcium molybdate ($CaMoO_4$) and cerium doped gadolinium aluminum gallium garnet ($Gd_3Al_2Ga_3O_{12}$:Ce or GAGG:Ce) were chosen for the study because they are very

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important scintillator and can be used in specific important applications. $CaMoO_4$ is one of the inorganic scintillator intensively studied for application in the very important experiment of neutrinoless ^{100}Mo double beta decay experiments in AMoRE (Advanced Mo Based Rare Experiment). ^{100}Mo is a good double beta decay candidate due to high transition energy (3034 keV) (Belogurov et al., 2005). The main properties of $CaMoO_4$ scintillators were also presented (Annenkov et al., 2008).

An ideal scintillation material for positron emission tomography (PET) would have high light yield, high density and effective atomic number, fast decay time, emission wavelength that matches well with the spectral sensitivity of the photodetector and low non-proportionality (Yeom et al., 2013). Cerium doped gadolinium aluminum gallium garnet ($Gd_3Al_2Ga_3O_{12}$:Ce or GAGG:Ce) is an attractive candidate for many applications such as PET and gamma spectroscopy due to very good properties of GAGG crystal such as high density, good energy resolution, high light yield, low non-proportionality and inexpensive to manufacture (Yeom et al., 2013). Moreover, GAGG:Ce does not contain natural radioactivity, since it does not uses Lu, which produce simultaneously beta-gamma emissions of natural Lu-176 that affect the minimum detectable activity limits of a system (David et al., 2015).

The photon interaction data are very important for both of crystals. Until now, there is no data on photon interactions of $CaMoO_4$ and GAGG:Ce crystals In this paper, the photon interaction properties of $CaMoO_4$ and GAGG scintillation crystals have been studied. Theμ_m, Z_{eff} and N_{eff} of both crystals were investigated for eight different photon energies in the range of 223–662 keV. The experimental values obtained by the Compton scattering technique were compared with the calculated theoretical data using WinXcom program.

2. Theory

2.1. Compton scattering

The Compton scattering process is the interaction the incident gamma ray and an electron in the absorbing material. It is most often the predominant interaction mechanism for gamma ray energies typical of radioisotope sources. The expression that relates the energy transfer and the scattering angle for any given interaction can be simply derived by writing simultaneous equations for the conservation of energy and momentum (Knoll, 2000). The Compton scattering requires that the light is viewed as a particle and not just a wave because it is the collision of the photon with the electron results in the exchange of energy, which accounts for the shift in energy. The energy imparted to the recoil electron is given by the following equation (Trousfanidis, 1983).

$$E'_\gamma = \frac{E_\gamma}{1 + (1 - \cos\theta)E_\gamma/m_0c^2} \tag{1}$$

where E'_γ is the scattered gamma ray energy, $E_\gamma$is the incident gamma ray energy, θ is the scattering angle and m_0c^2 is the rest-mass-energy of the electron (551 keV).

2.2. Computation of mass attenuation coefficient (μ_m)

If a material of thickness t is placed in the path of a beam of gamma radiation, the intensity of the beam is attenuated according to the Beer–Lambert's law:

$$I = I_0 \exp^{-\mu t} \tag{2}$$

where I_0 is the incident gamma ray intensity when measured without sample and I is transmitted gamma ray intensity when it pass through the sample, t is the sample thickness (cm). A more convenient parameter coefficient characterizing a given material is the density independent mass attenuation coefficient by the following relation (Gerward et al., 2004).

$$\begin{aligned}\mu_m &= \mu/\rho\ \left(\mathrm{cm}^2\ \mathrm{g}^{-1}\right)\\ &= \frac{\ln\frac{I_0}{I}}{\rho t}\end{aligned} \tag{3}$$

Theoretical values of the mass attenuation coefficient of mixture or compound have been calculated by WinXcom (Gerward et al., 2001, 2004), based on the rule of mixture

$$\mu_m = \sum_i w_i(\mu_m)_i \tag{4}$$

where w_i is the weight fraction of element in scintillation crystal, $(\mu_m)_i$ is µass attenuation coefficient for individual element in scintillation crystal. The value of mass attenuation coefficient can be used to determine the total atomic cross-section ($\sigma_{t,a}$) by the following relation (Limkitjaroenporn et al., 2011):

$$\sigma_{t,a} = \frac{(\mu_m)_{crystal}}{N_A \sum_i^n \left(\frac{w_i}{A_i}\right)} \tag{5}$$

where N_A is Avogadro's number, A_i is the atomic weight of constituent element of scintillation crystal. The total electronic cross-section ($\sigma_{t,el}$) for the element is also expressed by the following formula (Limkitjaroenporn et al., 2011):

$$\sigma_{t,el} = \frac{1}{N_A} \sum_i^n \frac{f_i A_i}{Z_i}(\mu_m)_i \tag{6}$$

where f_i is the number of atoms of element i relative to the total number of atoms of all elements in alloy, Z_i is the atomic number of each element in scintillation crystal. Total atomic cross-section and total electronic cross-section are related to the effective atomic number (Z_{eff}) of the compound through the formula (Limkitjaroenporn et al., 2011):

$$Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}} \tag{7}$$

The effective electron density (N_{eff}) can be defined as the number of electrons per unit mass, and it can be mathematically written as follows (Kaewkhao et al., 2008):

$$N_{eff} = \frac{\mu_m}{\sigma_{t,el}} \tag{8}$$

Calculation procedures and formula for mass attenuation coefficients and effective atomic number were explained in our previous papers (Chanthima et al., 2012; Kaewjang et al., 2014; Kaewkhao et al., 2010, 2011; Limkitjaroenporn and Kaewkhao, 2014).

3. Experimental setup

GAGG and $CaMoO_4$ scintillation crystals with the size of 10 × 10 × 8 mm^3, and 10 × 10 × 10 mm^3 respectively were obtained from Kyungpook National University (Korea). The density of GAGG and $CaMoO_4$ crystals are 6.63 g/cm^3 and 4.20 g/cm^3, respectively. The schematic arrangement of Compton scattering technique for

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