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A method for determination mass absorption coefficient of gamma rays by Compton scattering

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HIGHLIGHTS

- Compton scattering of $\gamma-$rays was used for determining mass absorption coefficient.
- Scattered intensities were determined by the MCSHAPE software.
- Mass absorption coefficients were determined for some compounds, mixtures and alloys.
- Mass absorption coefficients were calculated by Winxcom software.
- Good agreements were found between determined and calculated results.

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ABSTRACT

A method was proposed for determination mass absorption coefficient of gamma rays for compounds, alloys and mixtures. It is based on simulating interaction processes of gamma rays with target elements having atomic numbers from $Z=1$ to $Z=92$ using the MCSHAPE software. Intensities of Compton scattered gamma rays at saturation thicknesses and at a scattering angle of 90° were calculated for incident gamma rays of different energies. The obtained results showed that the intensity of Compton scattered gamma rays at saturations and mass absorption coefficients can be described by mathematical formulas. These were used to determine mass absorption coefficients for compound, alloys and mixtures with the knowledge of their Compton scattered intensities. The method was tested by calculating mass absorption coefficients for some compounds, alloys and mixtures. There is a good agreement between obtained results and calculated ones using WinXom software. The advantages and limitations of the method were discussed.

1. Introduction

Gamma rays interact with matter with three interactions mechanisms. They are photoelectric absorption, Compton scattering and pair production (Knoll, 1980). Mass absorption coefficient (μ/ρ) measures the probability of these interactions; it depends on the incident γ-ray energy and the nature of the absorbing material. Accurate values of μ/ρ are needed in various fileds (industry, biology, agriculture, and medicine). In addition, they are required in solving some problems in radiation physics. Measurements, calculations and compilations for the mass absorption coefficients have been published by a number of authors (see for example Limkitjaroenporn et al., 2013; Önder et al., 2012; Kore and Pawar, 2014; Gerward et al., 2004).

Compton scattering is used in some studies related to non-destructive testing and imaging. For example, Boldo and Appoloni (2014) examined reinforced concrete samples by Compton back-scattering. Harding (1997) reviewed and discussed the principles and applications of a technique, known as Compton scatter imaging (CSI), which is based on direct registration of the Compton scatterred radiation. Ho and Hussein (2000) presented a method for quantifying information obtained from the indications of a Compton scattering nondestructive testing technique. Bull et al. (1997) reviewed inspection techniques based on the elastic and inelastic scattering of X-rays and their potential in the food and agricultural industry. Limkitjaroenporn et al. (2013) used Compton scattering to modify the 661.6 keV energy of the ^{137}Cs γ-ray source to determine mass attenuation coefficients and effective atomic numbers for Inconel 738 alloy for different energies. Priyada et al. (2012) used Compton scattering and transmission method to determine concentration of low-Z solutions. Sharma et al. (2012, 2010) used a non-destructive Compton

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scattering technique for investigation of pulmonary edema and pipelines. Singh et al. (2008) observed energy, intensity and angular distributions of multiple scattering of 661.6 keV γ-rays, emerging from targets of pure elements and binary alloys as a function of target thickness in reflection and transmission geometries. It was shown that the numbers of multiply scattered events increase with the increase of target thickness, and saturate for a particular thickness called saturation thickness. They used this phenomenon to determine the so-called effective atomic number for some binary alloys.

The mass absorption coefficient of elements, mixtures, compounds and alloys can be determined either experimentally or theoretically. Experimental methods depend on the exponential attenuation law (Gerward et al., 2004) of Beer–Lambert given by

$$I = I_0 \exp(-\mu x), \quad (1)$$

where x is the thickness of a material placed in the path of a fine beam of γ-rays, I_0 and I are the unattenuated and attenuated γ-ray intensities, respectively, and μ (cm^{-1}) is the linear attenuation coefficient of the material. A coefficient more accurately characterizing a given material is the density-independent mass attenuation coefficient μ/ρ ($cm^2\ g^{-1}$). Only direct transmitted γ-rays should be registered by a proper detector. Namely, the Compton scattered γ-rays is unwanted component and should not registered. The mass attenuation coefficient for a compound, mixture and alloy is given by the addition rule (Gerward et al., 2004):

$$\mu/\rho = \sum_i w_i (\mu/\rho)_i, \quad (2)$$

where w_i is the weight fraction of the constitute elements i. The mass absorption coefficient lambing the partial interactions coefficients of photoelectric, Compton and pair production, depends on the energy of the interacting γ-rays as well as atomic number of target materials. Theoretically, values for the mass attenuation coefficients or photon interaction cross-sections for any element, compound or mixture at energies from 1 keV to 100 GeV can be obtained by the available free software WinXCom (Gerward et al., 2004).

According to the author knowledge, Compton scattering of γ-rays was not used before to determine mass absorption coefficient (μ/ρ). In this work, a method is proposed to determine mass absorption coefficient for mixtures, compounds and alloys. It relies on simulating γ-ray interactions with elements (from $Z=1$ to $Z=92$). Intensities of Compton scattered γ-rays from the investigated target elements at saturation thicknesses are related to their mass attenuation coefficients by mathematical formulas. With the knowledge of Compton scattered intensity at saturation thickness for any compound, mixture and alloys, the derived formulas are used to determine their mass absorption coefficients. The MCSHAPE software based on γ-rays transport equation (Fernández et al., 2004, 2003, 1998; Fernández, 1991; Fernández and Molinari, 1992; Fernández and Scot, 2007; Bastiano and Fernández, 1996; Scot et al., 2007) was used to simulate γ-rays interactions with elements, compounds, mixtures and alloys. Obtained results were compared with those calculated by WinXcom software (Gerward et al., 2004).

2. The MCSHAPE software

Diffusion of photons into matter can be formally described in the frame of the transport theory using Boltzmann equation. The MCSHAPE is a Monte Carlo (MC) code for simulating the diffusion of X- and γ-ray photons described by the Boltzmann equation (Fernández et al., 2004, 2003, 1998; Fernández, 1991; Fernández and Molinari, 1992; Fernández and Scot, 2004, 2007; Bastiano and Fernández, 1996; Scot et al., 2007). Boltzmann equation describes the balance between the number of photons of a given energy and direction entering and leaving an infinitesimal volume element. This balance may be formulated for conditions where the X or γ-ray source is a constant in time (steady-state problem) and, therefore, also the photon flows in the medium. The scalar model approximation of the Boltzmann equation considers a photon which does not modify its polarization state (Fernández et al., 2004, 2003, 1998; Fernández, 1991; Fernández and Molinari, 1992; Fernández and Scot, 2004, 2007; Bastiano and Fernández, 1996; Scot et al., 2007). The solution to the Boltzmann equation gives the possibility of analyzing different aspects of the emitted X or γ-ray spectra, from the spectral intensity distribution as a function of energy. A more general model is the vector form of the Boltzmann equation which takes into account the polarization state of γ-rays (Fernández et al., 2004, 2003, 1998; Fernández, 1991; Fernández and Molinari, 1992; Fernández and Scot, 2004, 2007; Bastiano and Fernández, 1996; Scot et al., 2007). Further details on the code are cited at http://shape.ing.unibo.it/index.htm and references (Fernández et al., 2004, 2003, 1998; Fernández, 1991; Fernández and Molinari, 1992; Fernández and Scot, 2004, 2007; Bastiano and Fernández, 1996; Scot et al., 2007). User of the code has the option to select either the scalar or vector type of simulations (polarization state). The code takes into account photoelectric effect, and Compton and Rayleigh scatterings.

Intensity of Compton scattered γ-rays can be extracted from MCSHAPE software for single collision or more. This can be carried out for γ-ray energies up to 1 MeV at any scattering angle. Elements which can be investigated are up to $Z=92$. In addition, compound, mixtures and alloys can be investigated.

3. Details of simulations

Three input files for target, γ-ray source and geometry are necessary to run the MCSHAPE software. The targets can be elements, mixtures, and /or compounds. They can be defined according to their atomic numbers (or chemical formulas, and/or symbol), thicknesses, concentrations and densities. Up to 10 elements can be defined for any mixture, alloy and/or compound. Gamma ray source can be of a single γ-ray line or more. The polarization of the incident γ-ray should be defined. The geometry of simulation can be carried out using either XRF usual reference system or transparent reference system. These input files were created for elements from $Z=1$ to $Z=92$ as well as for some mixture and compounds using single line γ-ray sources and using transparent reference system for geometry.

Before running the software, the transport modal either scalar or vector modals should be chosen. In addition, the number of collisions, histories, output energy resolution including maximum energy of incident γ-rays and channel width, and scattering angle should be defined. In the present simulation, the scalar modal, single, two, three, four and 100 collisions, and a scattering angle of 90 were chosen. Runs of the code were carried out for elements from $Z=1$ to $Z=92$, at the incident γ-rays of the energies 59.9 keV, 145 keV, 356 keV and 661.6 keV. Large thicknesses of the targets were chosen such that scattered intensities at saturation thickness are obtained. Some runs were performed for elements with different thicknesses. After finishing every run, an output folder containing files of γ-ray spectra of interaction components is created. Among these files, only Compton scattering spectrum file was used in the present work. It contains intensity of Compton scattered γ-rays versus energy. The sum of these intensities over energies of the scattered γ -rays was calculated for every run.