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Research paper

Determination of effective atomic number of composite materials using backscattered gamma photons – A novel method

M.M. Hosamani, N.M. Badiger *

Department of Studies in Physics, Karnatak University, Dharwad 580003, India

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ABSTRACT

The effective atomic number (Z$_{eff}$) of composite materials has been determined by measuring the backscattered gamma photons at 180°. A 661.6 keV gamma photons from ^{137}Cs radioactive source are allowed to scatter at an angle of 180° from the sample. The backscattered photons at 180° from the sample are detected with "2 × 2″ NaI(Tl) scintillation gamma ray spectrometer coupled to 16 K Multi Channel Analyzer (MCA). It is observed experimentally that the intensity of backscattered photons increases initially with increasing the thickness of the target and then it becomes saturated above a certain thickness. By knowing the saturated thickness values for known atomic number of the elemental targets, the Z$_{eff}$ of composite materials has been determined. The experimentally measured Z$_{eff}$ values have been compared with theoretical values predicted by direct method, power law method and AutoZ$_{eff}$ code.

1. Introduction

It is well known that the mechanism of interaction of gamma photon with matter depends on energy of the gamma photon as well as atomic number of the target. The gamma photon losses its energy in matter by the photo absorption process, the Compton scattering and the pair production process. The photo absorption cross section for given atomic number (Z) of target is proportional to Z^{3-4}, the Compton scattering cross section is proportional to Z and the pair production is proportional to Z^2 [1] For composite materials wherein the number of elements are in varying proportions, the effective atomic number is used. Therefore the effective atomic number is the ratio of the total atomic cross section to the total electronic cross section. In other words, it is the fraction of total number of electrons in composite material participates in photon - atom interaction number. Hine [2] has pointed that the effective atomic number for materials composed of various elements cannot be expressed in a single number. As Z$_{eff}$ characterizes the composite materials, it has wide applications in various fields such as radiation shielding in space technology and in nuclear reactor, radiation dosimeter, etc [3,4]. Therefore, determination of accurate values of effective atomic number of composite materials has been of experimental and theoretical interest in recent years [5,6]. Several methods have been adopted for measuring the Z$_{eff}$ of composite materials. The non destructive methods are gamma ray attenuation method and Compton back scattering method [7,8]. In gamma ray attenuation method, the mass attenuation coefficient (μ/ρ) of the sample is measured by adopting good geometry arrangement; the good geometry is used to prevent the scattered photons from entering into the detector [7]. Several investigators have adopted gamma ray attenuation method and measured Z$_{eff}$ of composite materials as well as biological system [9–11]. However, in Compton back scattering method, the incident gamma photon interact with the electron of the atom and scatters at an angle from 0° to 180°. The gamma photon which scatters at 180° is known as backscattered photon. Some investigators have also measured the Compton scattered photons by keeping the detector in between 0° and 180°, treating it as a backscattered photon [12]. It is interesting to note that the intensity of the backscattered photons for a given atomic number of the target increases with increasing the thickness of the target up to certain a thickness and after this thickness the backscattered photon intensity is saturated. The saturated thickness depends on the atomic number of the target as well as energy of incident gamma photon. In view of these dependence, several investigators have used Compton backscattered photon to determine the Z$_{eff}$ of several composite materials [13]. The Z$_{eff}$ of the composite material can also be determined by measuring the intensity ratio of Rayleigh to Compton peaks. Several investigators including our group [14] have measured Z$_{eff}$ of the composite material. Singh et al., [15] have measured the Z$_{eff}$ composite materials using Rayleigh to Compton scattering cross section ratio. Kurudirek et al., [16] have also estimated the Z$_{eff}$ of some composite materials by fitting method to the measured Rayleigh to Compton scattering ratios.

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* Corresponding author.
E-mail address: nbadiger@gmail.com (N.M. Badiger).

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The Z_{eff} values of the composite materials have been estimated theoretically by several investigators using direct method [17], Power law method [18] and Logarithmic interpolation method [19] and also using AutoZ_{eff} [20] code. The details of these theoretical calculation, computational program and comparative studies have been explained by Singh and Badiger [17]. It is interesting to note that the measured Z_{eff} values using gamma ray attenuation method, the Compton scattering method and Rayleigh to Compton scattering ratio method closely agree with the theoretical values predicted by AutoZ_{eff}, direct method, Power law method and Logarithmic interpolation method.

In the present investigations, we have determined the Z_{eff} of composite materials by measuring the intensity of backscattered photons at 180°, The backscattered photons are detected with 2“ × 2″ NaI(Tl) detector spectrometer. Using the intensity of backscattered photons and saturated thickness, the Z_{eff} has been measured. The measured values have been compared with AutoZ_{eff}, direct method, Power law method and Logarithmic interpolation method. In the present investigations, the effective atomic numbers of composite materials have been determined using a weak gamma source of strength about 10 μCi by adopting the Compton backscattering method. We have already shown in our earlier papers that using weak radioactive sources the K shell X-ray fluorescence parameters, K edge of high Z elements and the rest mass energy of electron can also be determined [21–23]. Therefore, the present experimental technique uses novel method to determine the effective atomic number of composite materials using a weak gamma source unlike strong source used by other investigators.

2. Theorical background

It is well known that the Compton scattering cross section depends on energy of incident photon and on the angle of scattered photons. The differential scattering cross section for Compton scattering in accordance with the Klein-Nishina formula [24] is given by

$$\frac{d\sigma_c}{d\Omega} = r_o^2\left[\frac{1}{1+\alpha(1-\cos\theta)}\right]^2\left[\frac{1+\cos^2\theta}{2}\right]\times\left[1+\frac{\alpha^2(1-\cos\theta)^2}{(1+\cos^2\theta)[1+\alpha(1-\cos\theta)]}\right] \quad (1)$$

Using this formula, we have calculated the differential scattering cross section per electron for scattering of 661.6 keV and 184.3 keV at different angle and they are shown in Fig. 1. From the figure, we notice that the differential cross section for scattering of 184.3 keV gamma photons at angle 180° has higher cross section than that for 661.6 keV. In other words the 184.3 keV gamma photons scattered at angle 180° gives more number of Compton scattered photons than that produced by 661.6 keV. Therefore in the present experiment we have measured energy as well as intensity of 184.3 keV back scattered photons from various elements and composite materials. The intensity of backscattered photons increases with increasing the thickness of the target and then it saturates. Using the saturated intensity and the thickness at which saturation occurs, we have determined the Z_{eff} of the composite samples and also compared our experimentally measured Z_{eff} values with the values predicted by AutoZ_{eff}, direct method and power law methods.

The AutoZ_{eff} software is user friendly program and it calculates the Z_{eff} computationally with error of 1% to 2% for photon energies 10 keV to 1000 MeV. This software is freely available and in the present work we have used the version 1.7. This version of software is executable on windows (Microsoft Corporation, USA) systems only. It is developed by Medical Radiation Research group RMIT University.

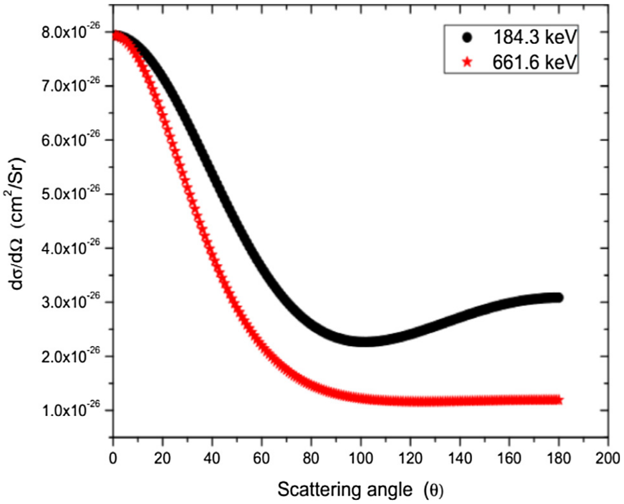

Fig. 1. Plot of Compton differential scattering cross section versus scattering angle for 184.3 keV and 661.6 keV; at 180°, cross section for 184.3 keV is higher than 661.6 keV. The differential scattering cross section as a function of angle predicted by the Klein-Nishina formula.

The Direct method uses the following expression to calculate the effective atomic number of given mixture materials:

$$Z_{eff} = \frac{\sum_i f_i A_i \left(\frac{\mu}{\rho}\right)_i}{\sum_i \frac{f_i A_i}{Z_i}\left(\frac{\mu}{\rho}\right)_i} \quad (2)$$

where f_i is the ith element fractional composition by weight in the mixture material, A_i is the atomic mass number of the ith element, $\frac{\mu}{\rho}$ is the mass attenuation coefficient of the ith element which is obtained from the WinXcom computer program.

The Power law method uses the following expression to calculate the effective atomic number of given mixture materials:

$$Z_{eff} = \sqrt[m]{\sum(f_i Z_i^m)} \quad (3)$$

where f_i is the elemental fractional composition by weight in the sample and Z_i is the atomic number of the element present in the composite material. We know that the photoelectric cross section per electron varies at Z^m, where 'm' is the empirical constant ranging from 2.94 to 3.5. In the present work for good approximations we have considered 'm' is 2.94. For a more detailed discussion regarding 'm', the interested readers may refer [16].

3. Experimental details

The experimental arrangement adopted in the present investigations for measuring the Z_{eff} is shown in Fig. 2. It consists of a weak radioactive ^{137}Cs gamma source, pure elemental and composite targets and 2“ × 2″ NaI(Tl) gamma ray scintillation spectrometers. We have used 661.6 keV gamma photons from ^{137}Cs weak radioactive source whose strength is about 10 μCi. We have used the elemental and composite targets with uniform thickness throughout the sample effective area. The targets are placed just over the gamma source so that the 661.6 keV gamma photons interact with electrons of target and scattered back at an angle 180°; the energy of backscattered photon is 184.3 keV. The advantage of this geometry is that it generates more number of backscattered photons of 184.3 keV at an angle 180°. Such back scattered photons are detected with NaI(Tl) scintillation detector spectrom-