Effective atomic number of composite materials by Compton scattering - nondestructive evaluation method

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Abstract

Nondestructive evaluation (NDE) technique is a method to evaluate the properties of a material without damaging it. Gamma backscattering is one of the nondestructive evaluation methods that have an advantage of one side access of the material under study. The ability of gamma rays to penetrate deep in material makes its attractive for using it in NDE applications. The multiple scattering of gamma photons acting as a background in the study of Compton profiles can be used as an experimental technique to evaluate “effective atomic number” of composite materials. An intense collimated beam originating from ^{137}Cs (214 MBq) gamma source is made to irradiate copper, iron, aluminium, carbon, brass and polyvinyl chloride plates of dimensions 100 mm × 100 mm × 10mm. Backscattered photons are detected by a NaI(Tl) detector placed at a backscattered angle of 100°. Single scattered photons are obtained by analytical calculation to extract multiple scattered photons from the backscattered spectrum. It was observed the multiple backscattered photons increase with an increase of target thickness and then saturates. The best fit curve of saturation thicknesses versus atomic number of copper, iron, aluminium and carbon is used to assign effective atomic number of composite material. Experimental results are compared with Monte Carlo N Particle code and are in good agreement.

Keywords: Effective atomic number, saturation thickness, multiple scattering, MCNP simulation.

1. Introduction

A composite material is characterized by a number known as ‘effective atomic number’ (Z_{eff}) and this number provides conclusive information about the mixture when gamma radiation beam is incident on it. There exist a number of experimental techniques, which are used to determine effective atomic number, like chemical analysis, atomic absorption spectroscopy, X-ray fluorescence (XRF), particle-induced X-ray emission (PIXE) etc. Nuclear physics techniques are non-destructive and often have a great advantage over the traditional chemical techniques and is also very useful to visualize a number of characteristics of a material for technological, nuclear industry, space research programs, engineering and in many fields of scientific applications(Singh et al., 2007).

In Compton scattering experiments, involving a target of finite dimensions both in depth and lateral extension, the interaction of gamma photons with the target results in a significant fraction of multiply scattered photons in range as single scattering. Multiple Compton scattered photons make a significant contribution to the shape of the measured Compton profile on the low-energy side of the inelastic Compton peak. Multiple scattering is one of the principal difficulties for interpreting the spectra that are present in the same energy range as the single scattering.

The measurements (Dumond, 1930) (Halonen, V. Williams, 1979)(Pitkanen et al., 1986, 1987) (Singh et al., 2008) (Sabharwal et al., 2009)of multiple scattering of gamma rays have been performed to correct the Compton profile data from multiple scattering contaminations. (Paramesh et al., 1983) have measured z-dependence of the saturation depth of 662 keV multiply scattered gamma rays at 120° for aluminium, iron, copper and lead. (Barnea et al 1995) have measured the distribution of multiply scattered photons at 662keV energy for samples of aluminium, brass and tin at 90° and 120°, and compared the experimental results with the Monte Carlo simulations.

The present measurements the flux of backscattered photons obtained from the targets of various elements and brass at scattering angle of 100°. In order to determine the contribution of multiply scattered photons only, the spectrum of singly scattered photons is reconstructed analytically. Various parameters characterizing multiple scattering of gamma photons are reported. The best-fit curve of saturation thickness as a function of the atomic number of elemental targets is used to assign ‘effective atomic numbers’ to the binary alloy. A Monte Carlo simulation of the experiment supports the present measurements.

2. Experimental set-up for present measurements

The experimental setup to measure the backscattered radiation is shown in Fig. 1. The gamma ray spectrometer consists of 76 mm × 76 mm NaI (Tl) scintillation detector. The detector crystal is covered with an aluminium window of 0.8 mm thick and optically coupled to photo-multiplier tube. To avoid the contribution due to background radiations the detector is shielded by cylindrical lead shielding of length 200 mm, thickness of 35 mm and internal diameter of 90 mm. The distance of the scatterer from the detector is kept 175 mm so that the angular spread due to the detector collimator (60 mm) on the target is ±5.8°. The entire experimental setup was placed at a height of 340 mm on a sturdy wooden table. This table was placed in the center of the room to minimize scattering from the walls of the room. The source-detector assembly is arranged in such a way that the centers of source collimator and gamma ray detector pass through the center of scatterer.

The pulse height distribution obtained during experimental study contains both single and multiple scattered photons. The methodology employed in the present measurements to determine multiple Compton scattered events, having same energy as in single Compton scattering, is based upon reconstruction of single scattered spectrum using experimentally

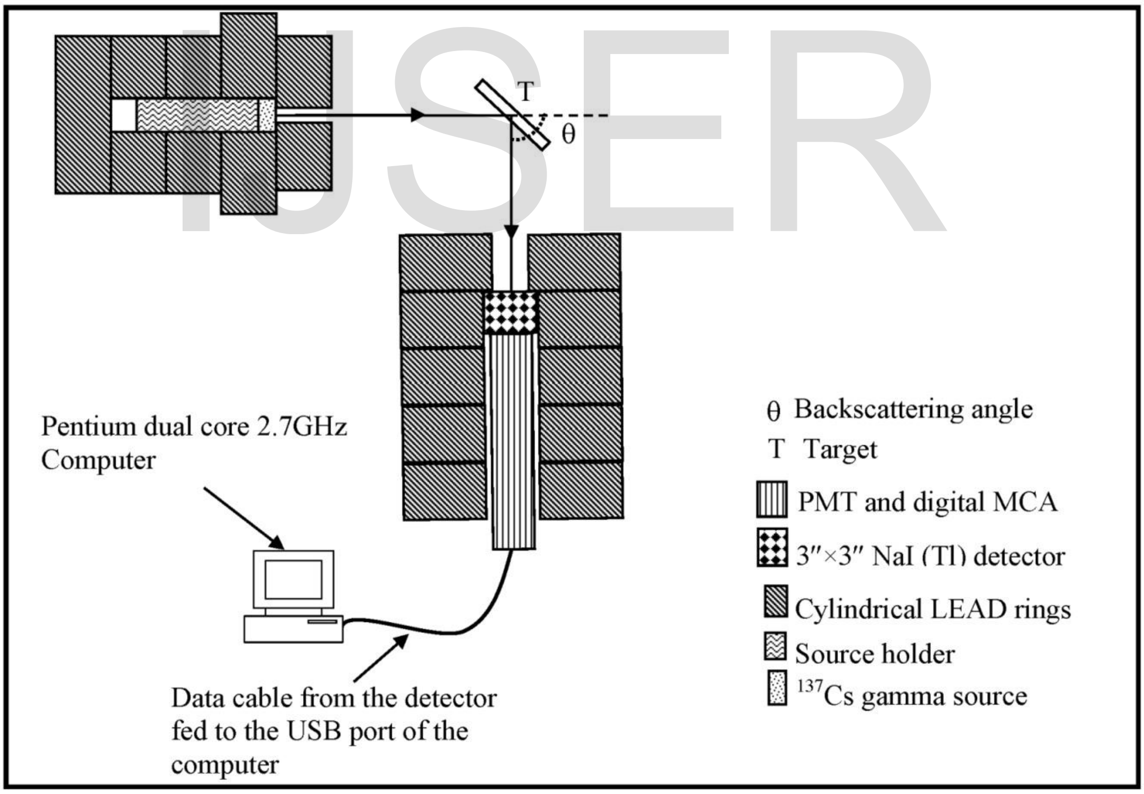

Fig. 1. Schematic diagram of the experimental setup.

determined parameters such as full width at half maximum (FWHM) and detector efficiency of gamma detector. The number of multiple scattered photons is obtained by subtracting counts

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due to analytically reconstructed distribution of single scatter events from measured experimental composite spectrum (Paramesh et al., 1983).

3. Results and discussion

In the present measurements, the experimental data are accumulated on a PC-based Thermoscientific digital Multi channel analyser (dMCA). A Windows-XP based spectroscopic application software winTMCA32 acts as user interface for system setup and display. A software program using winTMCA32 software package was written for the present experimental setup to evaluate parameters like multiple scattering events and single scattering events.

A target of known atomic number (Z) and thickness is placed in the primary incident beam. The following procedure is adopted for the present measurements:

(i) The backscattered scattered spectra are recorded for a period of 1000s by placing each of the targets, known Z and thickness, in the primary gamma beam.

(ii) The background is recorded after removing the target out of the primary beam to permit the registration of events due to cosmic rays and to any other process independent of the target.

The measurements for different elements are performed in the above sequence to minimize the effect of any possible drift in the system. Moreover, the calibration and stability of the system are checked before and after the recording of each of the scattered spectra and adjustments are made if required. The subtraction of events recorded under condition (ii), from those under condition (i) results in events originating from the interaction of primary gamma rays in the given target.

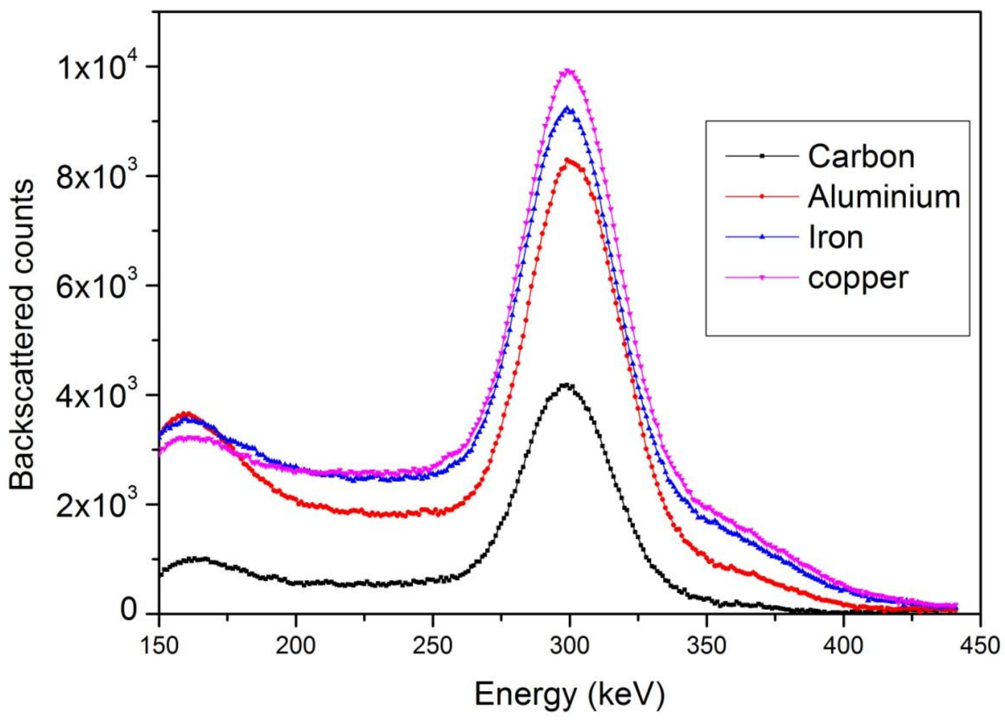

Fig. 2. Backscattered photons for elements.

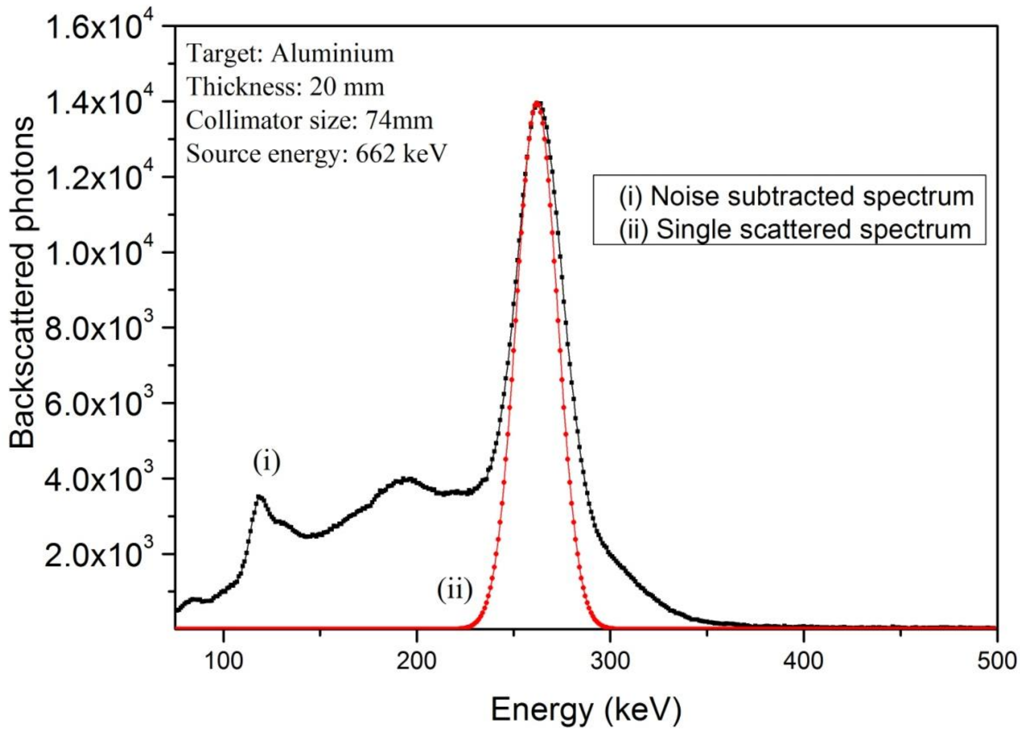

Fig. 3. Curve-i is a typical experimentally observed noise subtracted spectrum for 662 keV source with 20 mm thick aluminium target at a scattering angle of 100°. Curve-ii is the normalized analytically reconstructed single scattered full energy peak spectrum.

A typical observed pulse-height distribution from the elements - copper, iron, aluminium, carbon (thickness 40 mm) exposed to 0.662 MeV gamma photons is given in Fig. 2. The observed pulse-height distributions are a composite of singly and multiply backscattered photons along with background events. The spectrum (curve-i of Fig. 3), consists of intensity distribution of singly as well as multiply backscattered photons. The singly scattered events under the backscattered peak are obtained by reconstructing analytically the singly backscattered peak using the experimental parameters, such as FWHM and efficiency of the gamma ray detector corresponding to the back- scattered energy, counts at the photo-peak and Gaussian distribution of backscattered peak. The analytically reconstructed singly scattered peak is shown by curve-ii of Fig. 3

The plots of observed number of multiply backscattered events, having energy equal to singly scattered ones, for different atomic numbers as a function of target thickness is shown in Fig. 4. The present experimental results show that for each of the elemental target, the numbers of multiply backscattered events increases with increase in target thickness and then saturate after a particular value of target thickness, called saturation thickness. The saturation of multiply backscattered photons is due to the fact that an increase in target thickness results in higher number of scattering centres for the interaction of primary gamma rays with target material;

however, the probability for absorption within the target sample is also enhanced with increasing target thickness. Thus a stage is reached when the thickness of target becomes sufficient to compensate the above increase and decrease of the number of multiply backscattered photons, and hence the number of multiply backscattered photons coming out of the target saturates. The smallest value of target thickness beyond which the number of multiply backscattered events, having energy same as in singly scattered Compton distribution, emerging from the target remains constant is known as saturation thickness . Saturation thicknesses of Carbon, Aluminium, Iron and Copper are found to be 86 mm, 61 mm, 23 mm and 19 mm respectively.

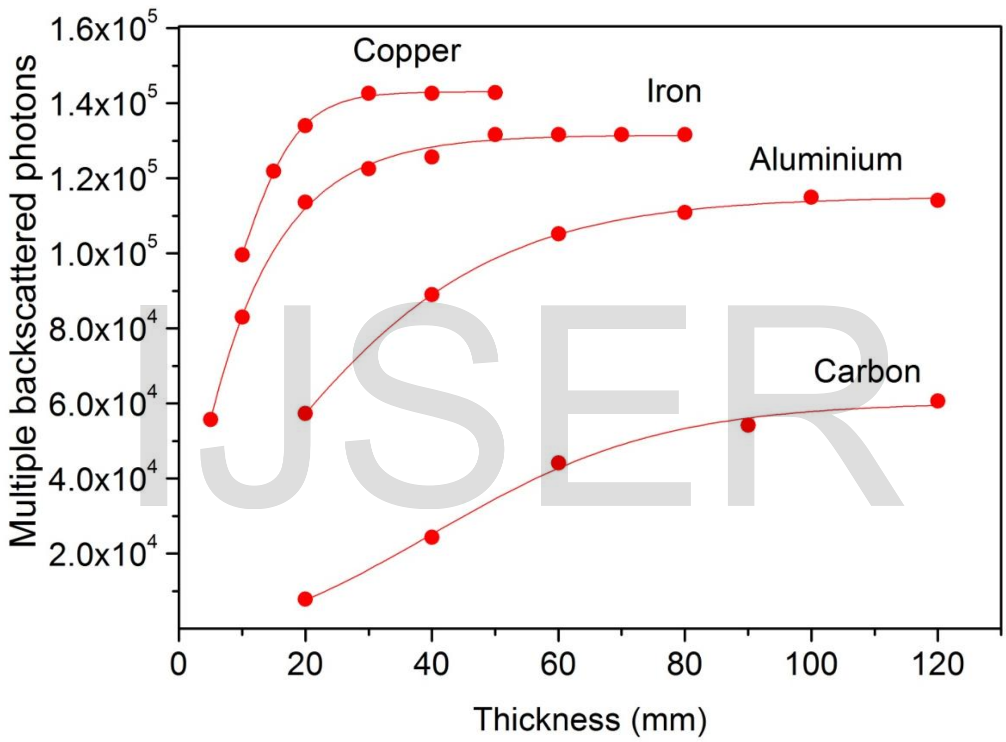

Fig. 4. Multiple scattered photons for various elements.

To validate the results obtained, the experimental setup has been simulated using Monte Carlo N-Particle (MCNP) code .The simulated data of multiple scattered intensity increases with increase in target thickness and attains saturation (Fig. 5). This behavior supports the present experimental data.

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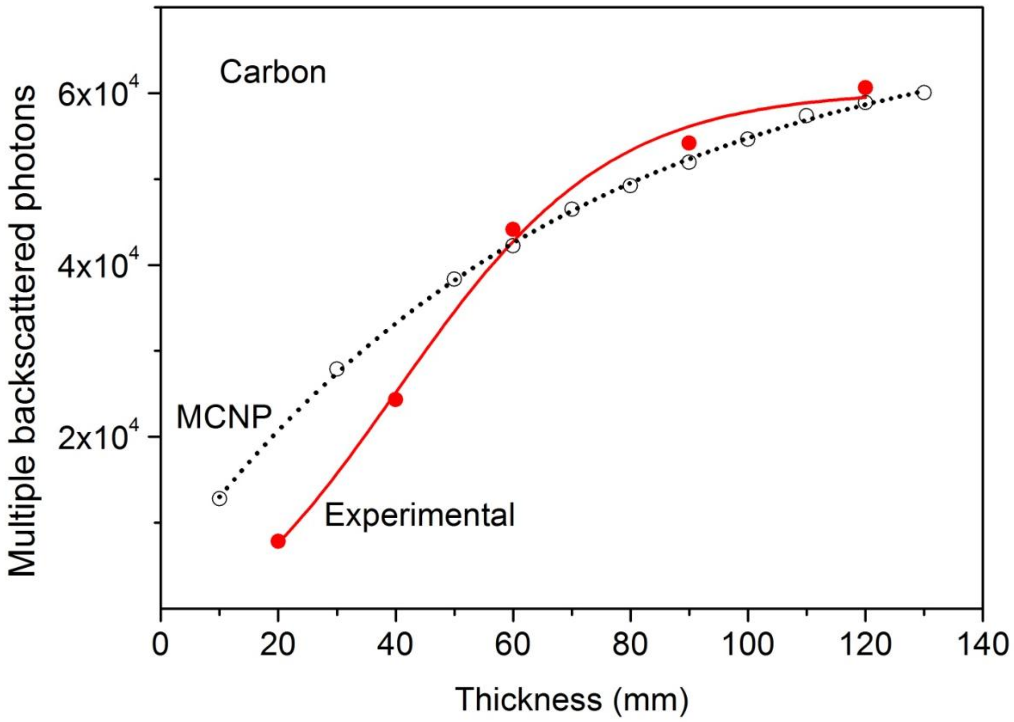

Fig. 5. A comparison of simulated and experimental data.

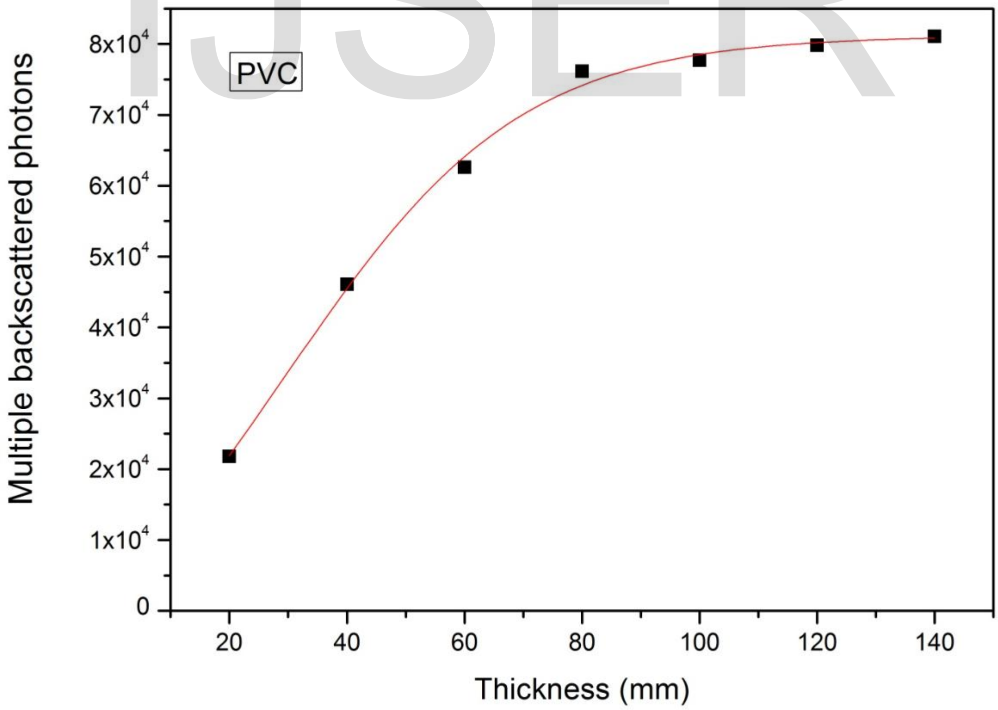

Fig. 6. Multiple scattered photons as a function of target thickness.

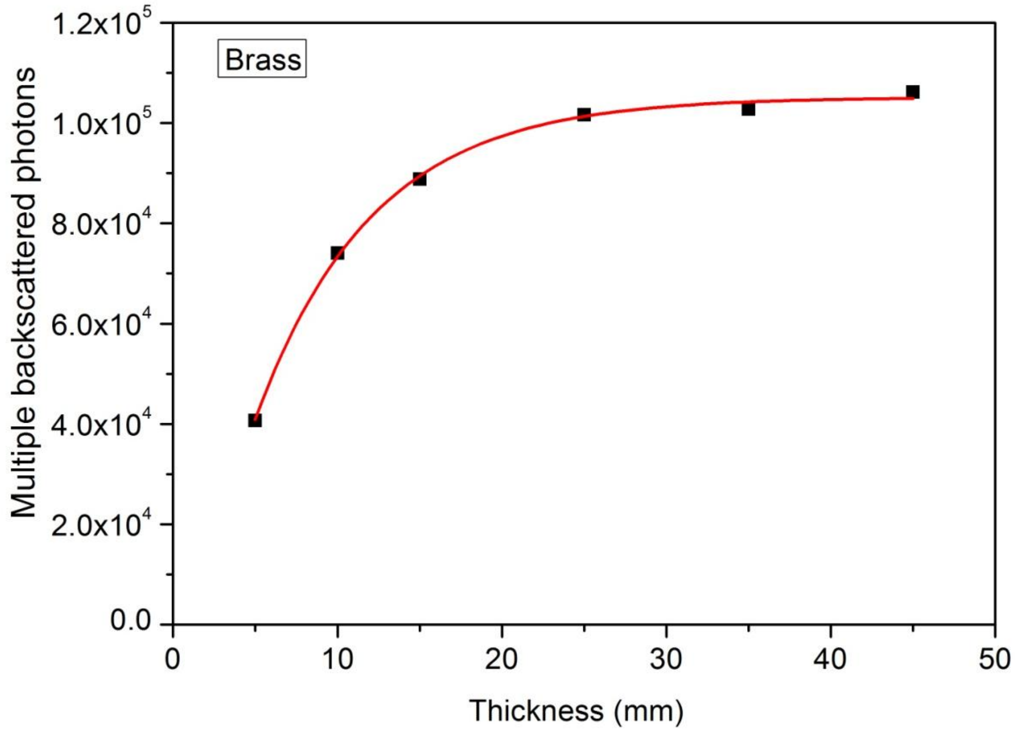

Fig. 7. Multiple scattered photons as a function of target thickness.

A composite material is characterized by a number known as "effective atomic number" (Z_{eff}) which provides conclusive information about the mixture when a gamma radiation beam is incident on it. Z_{eff} of composite materials is defined as the ratio of total atomic cross-section to the electronic cross-section. Effective atomic number of composite materials can be found using empirical relation given below:

$$Z_{eff} = \sqrt[2.94]{f_1 \times (Z_1)^{2.94} + f_2 \times (Z_2)^{2.94} + \cdots}$$

where f_n is fraction of total number of electrons associated with each element and Z_n is atomic number of each element.

From the graph, measured saturation thickness value of glass is used to find effective atomic number. The measured value of effective atomic number of brass, an alloy of copper and zinc is 29.4 ± 0.11, is in good agreement with theoretical value 29.31 (70% Cu, 30% Zn). The measured value of effective atomic number of PVC (poly vinyl chloride) is 14± 0.14, is in good agreement with theoretical value 13.86 (38% C, 9% H, 53% Cl).

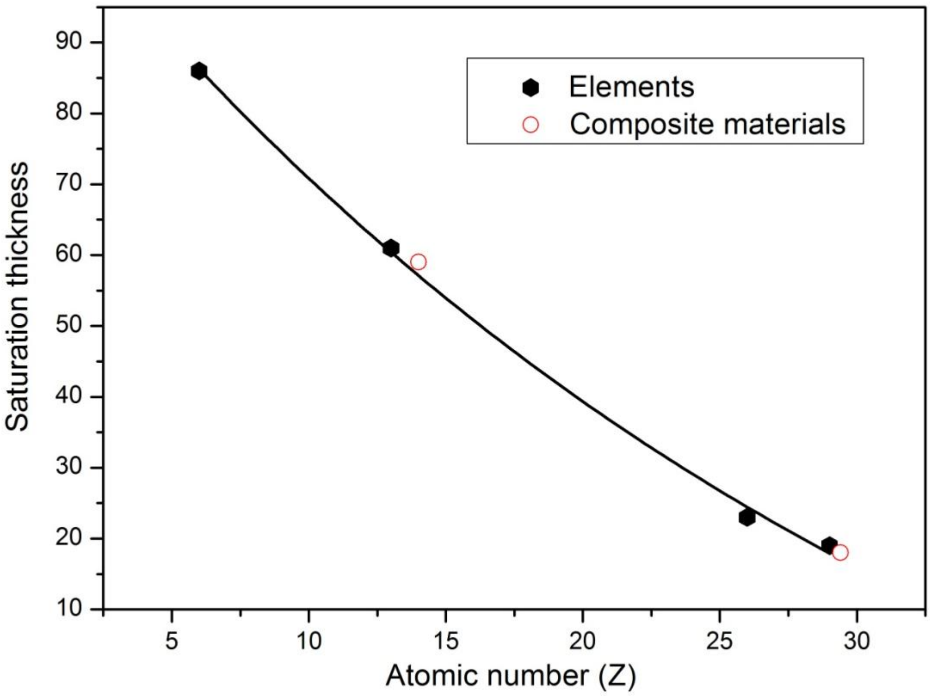

Fig. 8. A plot of saturation thickness (mm) versus atomic number Z.

The comparison between the experimental measured values and those deduced from theory indicate that agreement of present experimental results with theory appears to be satisfactory.

It also confirms that the usability of this experimental technique to measure the effective atomic number of homogeneous mixtures and compounds of known elemental composition.

4. Conclusions

The present experimental results confirm that for thick targets, there is significant contribution of multiply scattered radiations emerging from the targets, having energy equal to that of the singly scattered Compton process. The intensity of multiply scattered events increases with an increase in target thickness, and saturates beyond a particular value, called saturation thickness, The multiple scattering of gamma photons, acting as background in the study of Compton profiles and cross-section measurements, is successfully used as an experimental technique for evaluation of 'effective atomic number' of the composite materials .

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