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Measurement of effective atomic number of composite materials using scattering of γ-rays

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Abstract

In the present experiment, to determine the effective atomic number of composite materials, the scattering of 145 keV γ-rays is studied using a high-resolution HPGe semiconductor detector placed at 70° to the incident beam. The experiment is performed on various elements of different atomic number, $6 \leqslant Z \leqslant 64$, for 145 keV incident photons. The intensity ratio of Rayleigh to Compton scattered peaks, corrected for photo-peak efficiency of the γ-detector and absorption of photons in the target and air, is plotted as a function of atomic number and constituted a fit curve. From this fit curve, the respective effective atomic numbers of the composite materials are determined. The agreement of measured values of effective atomic number with the theory is found to be quite satisfactory.

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Keywords: Composite materials; Effective atomic number; Rayleigh and Compton scattering; Intensity ratio

1. Introduction

A composite material is characterized by a number known as "effective atomic number" and this number, Z_{eff}, provides conclusive information about the mixture when γ-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, particle-induced X-ray emission (PIXE), X-ray fluorescence (XRF), proton-induced γ-ray emission (PIGE), fast neutron activation analysis (FNAA), acoustic methods and electrical impedance method. Nuclear physics techniques are non-destructive and often have a great advantage over the traditional chemical techniques used for determination of effective atomic number of samples of environmental, biological, agricultural, industrial and medical interest.

The effective atomic number (Z_{eff}) of the composite material is defined as the ratio of total atomic cross-section to the total electronic cross-section. Duvauchelle et al. [1,2] have developed a method of calculating effective atomic numbers of mixture, compound and aqueous solution using coherent (Rayleigh) to incoherent (Compton) scattering ratio applicable for any material, scattering angle or photon energy. They concluded that Rayleigh to Compton scattering cross-section ratio depends only on the mixture under study and provides a non-destructive technique to measure the Z_{eff} of composite materials and Z-number of unknown elements. They also suggested that a given Z_{eff} must define a mixture on the basis of the intensity ratio of Rayleigh to Compton scattering, as a single atom is characterized by its atomic number.

İçelli and Erzeneoğlu [3] have successfully applied this technique to measure the atomic number of some of elements satisfying, $26 \leqslant Z \leqslant 82$, by measuring the Rayleigh to Compton scattering cross-section ratio of 59.54 keV incident photons at scattering angles of 55° and 115°. İçelli [4] has also provided in detail a theoretical procedure to compute effective atomic number of a composite material of known composition.

The present technique utilises the strong dependence of the Rayleigh to Compton scattering intensity ratio on the effective atomic number of the scattering medium. In the

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present experiment, we observe the scattering of 145 keV γ-photons by placing a high-resolution HPGe solid-state detector at 70° to the primary incident beam. The effective atomic number of different samples of composite materials are deduced from Rayleigh to Compton scattered intensity ratio values.

2. Experimental set-up for present measurements

In scattering experiments, for a γ-flux impinging on a target, there is significant probability for elastic (Rayleigh) scattering to occur in addition to well-known inelastic Compton process. The principle of present measurements is to observe the intensities of these Rayleigh and Compton scattered γ-photons at a particular scattering angle using a high-resolution semiconductor γ-detector.

While designing an experiment based on this technique, care must be taken to select properly the incident photon energy, scattering angle and material to be probed. The intensity of the elastically and inelastically scattered peaks should be sufficient and the two peaks must be well separated from each other, otherwise the analysis procedure becomes complicated. Because this method involves the ratio of intensity of Rayleigh and Compton scattered peaks, the cross section ratio depends on Z-number of the target only for a fixed geometrical source-sample-detector arrangement and incident photon energy.

The experimental set-up used in the present measurements is shown in Fig. 1. A well-collimated beam of 145 keV γ-rays from of ^{141}Ce source (strength 20 mCi) irradiates the sample. The distance of the thin target under study from the source collimator is kept 100 mm so that the angular spread due to the source collimator (radius 2 mm) on the target is limited to $\pm 1.45°$. The γ-photons scattered from the target are detected by an HPGe solid-state detector (56.4 mm diameter and 29.5 mm length) placed at scattering angle of 70°. The radioactive source and the detector are properly shielded and aligned in such a way that the axes of source and the detector collimators coincide with the centre of the target. The distance between the target under study and the detector collimator (radius 4 mm) is kept 100 mm, so the angular spread about the median ray in direction of the γ-detector is $\pm 2.9°$. It has been checked that radiation scattered from the source collimator opening do not reach directly the active volume of the HPGe detector. The field of view of the HPGe detector is confined to the target only.

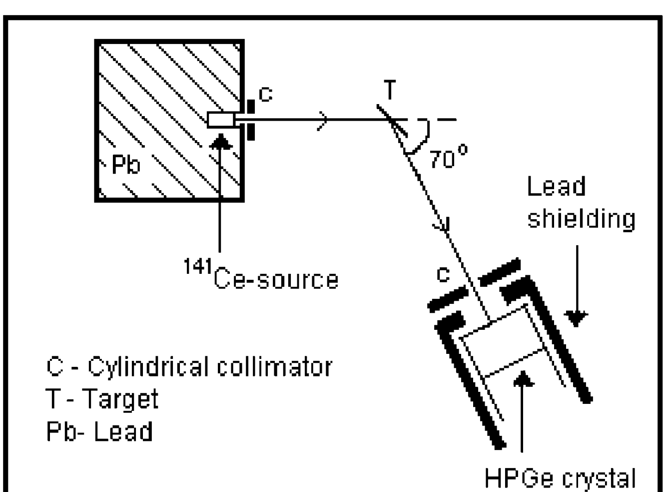

Fig. 1. Experimental set-up.

3. Results and discussions

In the present measurements, the experimental data are accumulated on a PC-based ORTEC Mastreo-32 Multi channel analyser (MCA). 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:

(1) The target-in scattered spectra are recorded for a period of 20 ks by placing each of the targets, known Z and thickness, in the primary γ-ray beam. The registered events correspond to true and background events.
(2) 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 minimise 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 γ-rays in the given target. The intensities under the Rayleigh and Compton scattered peaks are deduced from the recorded scattered spectra. These observed intensities are corrected for photo-peak efficiency [5] of the HPGe detector, absorption in air present between target and the detector, and self-absorption in the target [6], as per relation given below

$$N_{\mathrm{actual}} = \frac{N_{\mathrm{obs}}}{\varepsilon_\gamma \beta_{\gamma\mathrm{a}} \beta_{\gamma\mathrm{t}}}. \tag{1}$$

Here N_{obs} is the observed intensity under the Rayleigh (or Compton) peak; $\beta_{\gamma\mathrm{a}}$ is the correction factor for absorption of photons in the air present between the target and the detector; $\beta_{\gamma\mathrm{t}}$ is the self-absorption correction factor for the scattered photons in the target; and ε_γ is the photo-peak efficiency of the γ-detector for Rayleigh (or Compton) scattered photons.

The corrected values of ratio of Rayleigh to Compton scattered intensity, for different targets of known atomic number and thickness, are given in column 3, of the Table 1. The errors quoted in intensity ratio indicate