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Attenuation studies near K-absorption edges using Compton scattered ^{241}Am gamma rays

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Abstract. We have carried out photon attenuation measurements at several energies in the range from 49.38 keV to 57.96 keV around the K-absorption edges of the rare earth elements Sm, Eu, Gd, Tb, Dy and Er using 59.54 keV gamma rays from ^{241}Am source after Compton scattering from an aluminium target. Pellets of oxides of the rare earth elements were chosen as mixture absorbers in these investigations. A narrow beam good geometry set-up was used for the attenuation measurements. The scattered gamma rays were detected by an HPGe detector. The results are consistent with theoretical values derived from the XCOM package.

Keywords. Photon interaction; ^{241}Am; gamma ray attenuation; Compton scattering; absorption edge; rare earth elements.

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1. Introduction

Photon interaction studies at energies around the absorption edge have attracted the attention of researchers in the field for quite some time now. Such studies [1–4] require a source of continuously variable energy photons to probe the energy region around the absorption edge. Compton scattering offers a convenient and excellent technique for this purpose. Here the primary gamma rays from a radioactive source are Compton scattered from a secondary exciter target of aluminium. The energy of the Compton scattered gamma rays at an angle θ is given by

$$E = \frac{E_0}{\{1 + \alpha(1 - \cos\theta)\}}, \tag{1}$$

where E_0 is the incident gamma energy and α is the ratio of E_0 to the rest mass energy of the electron. Thus the energy can be continuously varied from a lower

value to a maximum value depending on the practically allowed limits on the scattering angle θ. The only drawback of this technique is that the Compton scattered radiation will not be completely monochromatic. There is bound to be a certain spread in the scattering angles arising out of the finite dimensions of the source, target and detector, which will be reflected as a spread in the energy of the scattered radiation. It was Polat *et al* [5] who first reported using this technique for measuring the gamma ray attenuation coefficients for the elements Gd, Dy, Ho and Er at several energies around their K-edges. Good agreement was obtained between theory and experiment. ^{241}Am presents a very suitable gamma ray source for measurements around the K-edge absorption threshold region of the rare earth elements. Its gamma energy, 59.54 keV, lies in between the K-edges of the rare earth elements thulium (59.39 keV) and ytterbium (61.332 keV). Keeping this fact in mind, we had earlier carried out gamma ray interaction studies [6] at 59.54 keV using oxides of rare earth elements. Continuing this work, we have now carried out attenuation measurements at several energies near the K-absorption edges of the rare earth elements Sm, Eu, Gd, Tb, Dy and Er. The gamma rays of appropriate energies have been obtained by the process of Compton scattering from an aluminium target at various angles. The range of energies available by this technique is seen to be from 48.287 keV to 59.54 keV corresponding to angles of scattering between 180° and 0° respectively.

2. Experimental details

The experimental arrangement employed in the present investigations is shown in figure 1. The ^{241}Am source (S), procured from Amersham, England, had a strength of 300 mCi and was kept shielded with a 0.8 cm collimator in the front. The source, along with the shielding, was fixed to a rotating arm mounted on a rigid aluminium circular table at a distance of 33 cm from the centre of rotation. The round table had angular graduations all around its cirumference in order to facilitate accurate setting of the angle of scattering. The secondary exciter target (T) was an aluminium disc of thickness 1 cm placed in a reflection geometry, at the centre of the rotating table with its plane making an angle equal to $(\pi - \theta)/2$, θ being the scattering angle.

The absorbers (A) for the present measurements were prepared using oxides of rare earth elements Sm, Eu, Gd, Tb, Dy and Er. The purity of the materials was better than 99.5%. The absorbers were in the form of pellets of diameter 1.2 cm prepared using a pelletizer at a pressure of 10–12 tonnes. In preparing the pellets, KBr was added as a binding agent. The absorber was positioned in between the aluminium target and the detector so that the gamma rays transmitted through the target were detected in a narrow beam good geometry. The scattered gamma rays from the aluminium target were detected by means of a well-shielded HPGe GammaX detector (D) procured from ORTEC, USA. It had a resolution of 1.14 keV at 60 keV. The amplifier output pulses were then fed to a CAMAC-based data acquisition and analysis system, consisting of a Kinetic CAMAC crate, crate controller, a 4 k Quad ADC, supplied by the Electronics Division, BARC and connected to a personal computer through a suitable interface card. A Linux-based package,

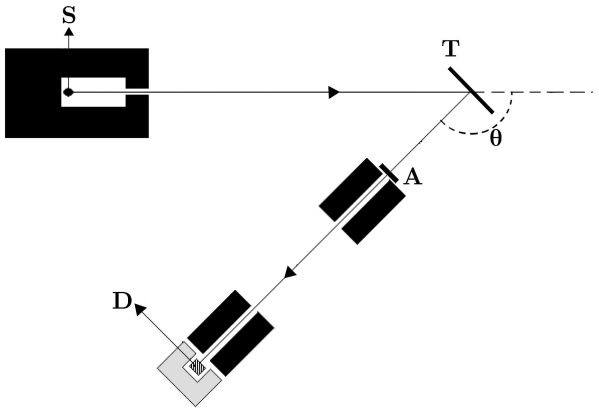

Figure 1. Schematic diagram of the experimental set-up for narrow beam geometry gamma attenuation measurements.

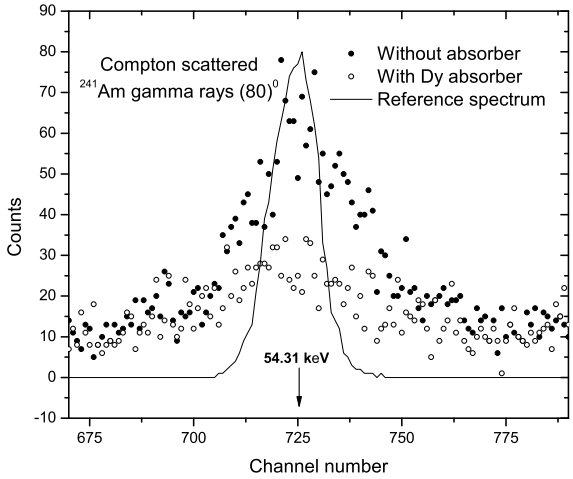

Figure 2. Comparison of spectra of Compton scattered radiations from a ^{241}Am source at 80° with and without the pellet absorber (Dy) with that of monoenergetic gammas of energy 54.31 keV.

FREEDOM [7], developed at the Inter University Accelerator Centre (IUAC), New Delhi was used for data collection and analysis.

The measurements first comprised of setting the angle of scattering for a specified scattered energy as given by eq. (1). The direct spectrum of the scattered radiation and the spectrum transmitted through the absorber were stored successively at intervals of 30 min each. Background spectra were also stored for the same time after removing the secondary exciter first and then the absorber. The background counts within the peak region of the scattered radiation were found to be the same, within statistical errors, in both the cases.

The spectra of the ^{241}Am gamma rays Compton scattered at 80° from the aluminium target, with and without a Dy pellet absorber are shown in figure 2. The

mean energy of the scattered radiation, as calculated from eq. (1) is 54.31 keV. For reference, the expected spectrum in the photopeak region of monoenergetic radiations of the same energy is also shown superimposed in the same figure. The effect of the finite spread in the scattering angles is clearly seen. The effective spread in the scattering angles can be calculated by comparing the widths of the scattered spectrum and the photopeak of the monoenergetic radiations of the same mean energy and is seen to be about 0.36°. The net counts under the peak region of the scattered radiation from the aluminium target were extracted after subtraction of the background, with and without the absorber. Knowing the absorber thickness, the attenuation coefficient was calculated from the equation

$$I = I_0 \exp[-(\mu/\rho)x \cdot \rho], \tag{2}$$

where μ is the linear attenuation coefficient (cm^{-1}), ρ is the density of the sample ($\mathrm{g\ cm}^{-3}$), x is the thickness of the absorber (cm), I_0 is the count value without the sample and I is the count value of the radiation penetrating through the sample. The procedure was repeated for several energies to cover the K-edge, by varying the angular position of the source, thereby changing the scattering angle also. In the case of Sm and Eu, measurements could be made only on one side of the K-edge energy because of the obvious practical limitations on the scattering angle θ. In our geometry, the angular range which could be scanned was from 40° to 140°. This corresponds to an energy range from 49.38 keV to 57.96 keV. The K-edge energies of Sm and Eu are 46.835 keV and 48.519 keV respectively, which obviously are outside the above range.

As already mentioned, at each setting of the angle of Compton scattering of the primary gamma rays, there is a certain spread in the scattering angles, decided by the finite dimensions of the absorber and the detector. Consequently, the attenuation coefficients derived from the observed spectra are really values averaged over the unavoidable energy spread and will not correspond to the attenuation coefficient values for the discrete energy corresponding to that scattering angle. In order to extract the attenuation coefficients at the mean energy, we have adopted the following iterative procedure.

First of all, we assume reasonable starting values for the attenuation coefficients at several equally spaced energy values covering the total spread in the scattered energies for the particular scattering angle chosen. Obviously, the best set of starting values would be the XCOM values themselves. These are treated as parameters in a least squares fitting programme. An effective attenuation coefficient for the non-monochromatic Compton scattered radiation is then evaluated as an average over the various possible scattering angles in the set-up used. These values are then compared with the experimental values. The assumed values of the attenuation coefficients are then varied and an optimum set is arrived at using the least squares method.

The mass attenuation coefficients measured as above correspond to the mixtures of the rare earth oxides with potassium bromide. In order to extract the mass attenuation coefficients of the rare earth elements, it is first necessary to know the coefficients of KBr. The values of the mass attenuation coefficients were separately measured for KBr using pure KBr pellets. Using these additional data, the mixture rule [8] was used to extract the mass attenuation coefficients of the rare earth

oxides. The rule gives the attenuation coefficient of any substance as the sum of the appropriately weighted contributions from the individual atoms. Thus the mass attenuation coefficient is given by

$$(\mu/\rho) = \sum_i w_i(\mu/\rho)_i, \tag{3}$$

where w_i is the proportion by weight, μ is the linear attenuation coefficient in cm^{-1}, ρ ($\mathrm{g/cm}^3$) is the density of the element and $(\mu/\rho)_i$ (cm^2/g) is the mass attenuation coefficient of the constituent element i of the compound. Theoretical values of the coefficients for oxygen required for extracting the values of the coefficients for the rare earth elements were obtained from the XCOM package [9,10]. This package is a computer programme and data base, developed by Berger and Hubbell, which can be used to calculate, using a personal computer, theoretical photon cross-sections for scattering, photoelectric absorbtion and pair production, as well as total attenuation coefficients, in any element, compound or mixture, at energies from 1 keV to 100 GeV. It utilises a vast database for all elements from hydrogen to fermium.

3. Results and discussion

As a representative of the results for the average attenuation coefficient values obtained in the present studies, we present in figure 3 the results for the mixture of dysprosium oxide and potassium bromide.

In figure 3, experimental values represented by solid circles, are the raw data obtained from the spectra with and without the mixture absorbers. The XCOM values averaged over the spread in scattering angles are represented by the solid line. The extracted values of the attenuation coefficient for the mixture at discrete energies corresponding to different scattering angles are indicated by open circles

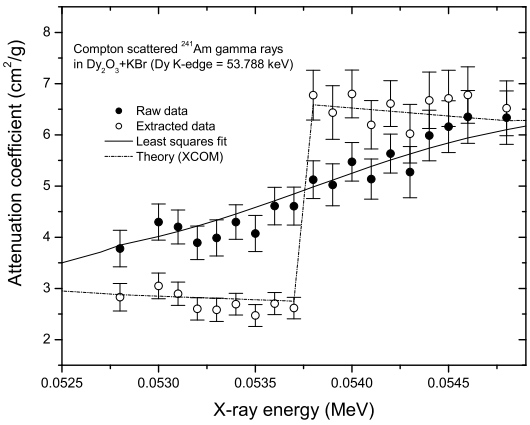

Figure 3. Variation of the attenuation coefficient with energy for a mixture of dysprosium oxide and potassium bromide.

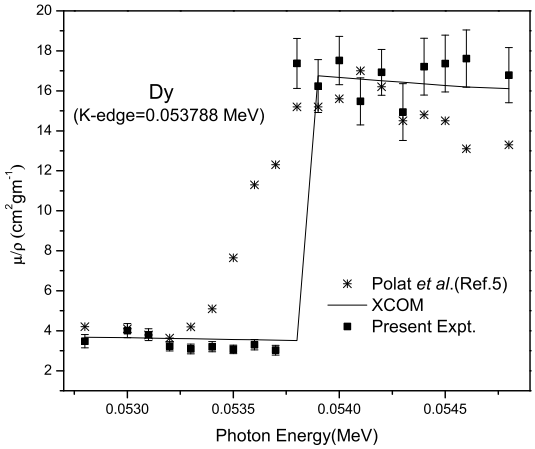

Figure 4. Comparison of the attenuation coefficients for Dy with XCOM values.

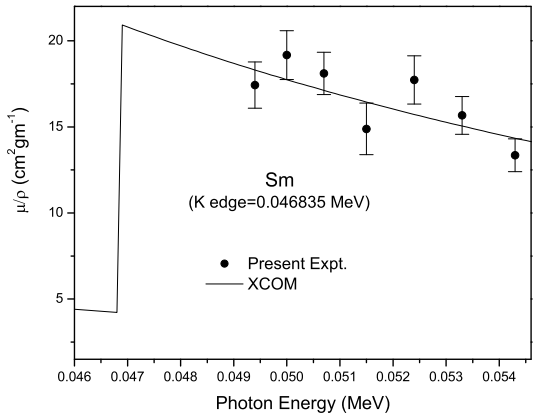

Figure 5. Comparison of the attenuation coefficients for Sm with XCOM values.

and the corresponding theoretical XCOM values by the dotted line. It is seen that there is reasonably good agreement between theory and experiment for the two sets of values. The errors on the experimental values are statistical errors. The K-edge energy for Dy is 53.788 keV. It may be noted that below the K-edge, the raw data are larger than the theoretical XCOM data represented by the dotted line, whereas above the K-edge, the raw data are smaller than the XCOM values. This is obviously due to the spread in scattering angles. The effect is dominant at the K-edge as is obvious from the plot. As the energy of the incident radiation moves away from the K-edge on either side, the raw data approach the dotted line as expected.

The results of our iterative procedure for extracting the attenuation coefficient values for the rare earth elements, as outlined earlier, are presented in figures 4–9.

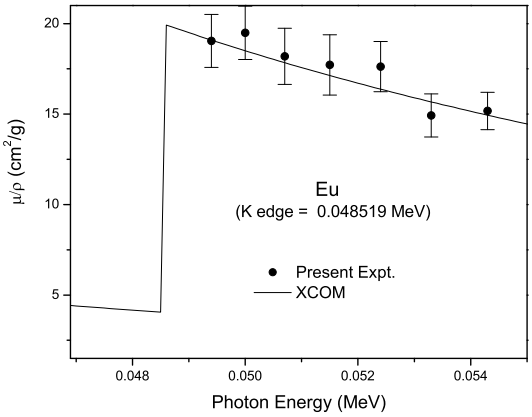

Figure 6. Comparison of the attenuation coefficients for Eu with XCOM values.

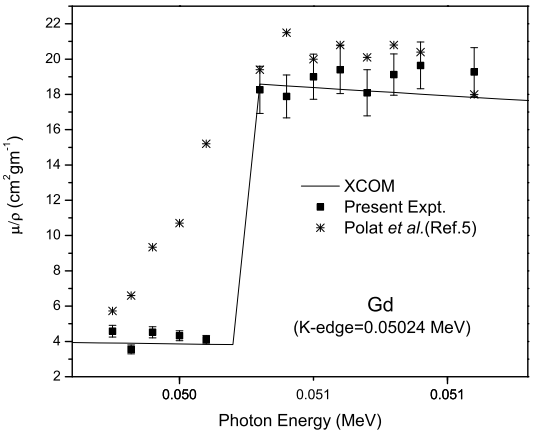

Figure 7. Comparison of the attenuation coefficients for Gd with XCOM values.

In figure 4, the attenuation coefficient values derived from the experimental results for the element Dy (as extracted by the procedure given in the previous section) are shown. Also given by means of the solid line are the corresponding XCOM values. We can see an overall agreement between theory and experiment.

In figures 4, 7, 8 and 9 we have shown by cross marks some representative experimental results of Polat *et al* [5] for the elements Dy, Gd, Tb and Er respectively in the energy range of our present measurements. It is obvious from the plots that our results are in closer agreement with theory than those of Polat *et al*. A comparison of the plots of their results with figure 3 suggests that probably the results of Polat *et al* are the averaged values over the relevant spread in scattering angles in their set-up. No mention of this effect has been made by these authors in their paper. Probably, if due account of the effect had been taken by the authors, their results would have been in closer agreement with the theoretical XCOM values as observed

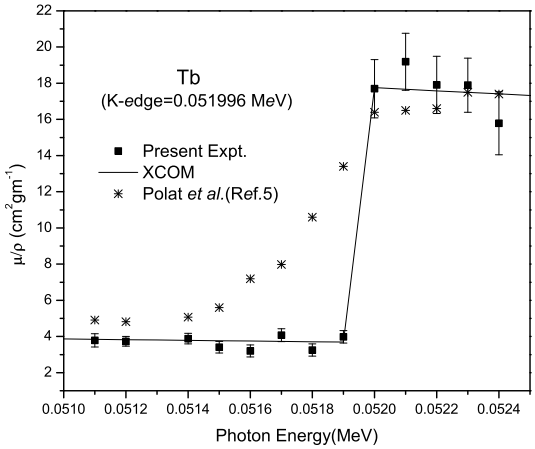

Figure 8. Comparison of the attenuation coefficients for Tb with XCOM values.

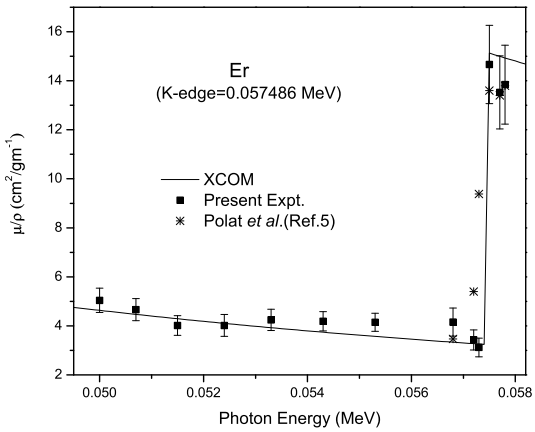

Figure 9. Comparison of the attenuation coefficients for Er with XCOM values.

in our case. In the rest of the figures, we present the attenuation coefficient values for the other rare earth elements investigated.

In all the cases extracted, experimental values for the attenuation coefficients are seen to be consistent with the theoretical XCOM values within the quoted uncertainties. At the near K-edge energies investigated, our results do not indicate any breakdown of the mixture rule. The agreement with theory proves the reliability of the present method of extraction of the attenuation coefficients for the pellets at the discrete energies from the raw values, averaged over the spread in the energies.

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