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An Experimental Study of Energy Dependence of Saturation Thickness of Multiply Scattered Gamma Rays

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

The possibility of a photon being scattered more than once may be significant for a rectangular sample having a finite depth and lateral dimensions. The current evaluation is carried out to study about the energy and intensity distributions of 279, 662 and 1120 keV gamma rays multiply scattered from rectangular samples of copper, iron and zinc having different thickness at a scattering angle of 90°. The scattered photons are detected by a 51 mmx51 mm NaI(Tl) scintillation detector whose detector response unraveling, transforming the pulse-height distribution to a photon energy spectrum, is attained with the help of 10x10 inverse response matrix. By applying the self-absorption correction in the sample, there is enhancement in the number of multiply scattered photons, while the saturation thickness remaining unchanged. When the same experiment is repeated with HPGe gamma detector, saturation thickness remains unaltered. We perceive that with increment in the incident gamma photon energy, the saturation thickness also increases. The signal-to-noise [1] ratio is found to be decreasing with increase in the sample thickness. Monte Carlo calculations based upon the package described by Bauer and Pattison [2] support the current experimental results.

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1. INTRODUCTION

In Compton scattering experiments, the multiply scattered radiation become one of the principle difficulties for interpreting data as these radiations may also reach the detector along with singly scattered ones, and get counted. In the multiple scattering, the unique relation between photon energy and electron momentum is lost, and this results in incorrect evaluation of Compton profiles (a means for determining the electron momentum distribution in an atom). Different approaches have been used to estimate the contribution arising from multiply Compton scattered radiation. The multiple scattering has been analyzed in both experimental and theoretical way by employing analytical and Monte Carlo approach. Measurements in [3] present a thorough analysis of analytical and Monte Carlo simulation approaches to study the multiple scattering with the accessible experimental data of these approaches. The measurements [3-5] have confirmed that the numbers of multiply scattered events, with identical energy as of singly scattered events, enhances with increase in sample thickness and saturate after a specific thickness of sample referred as saturation thickness. The saturation thickness [4,5] reduces with increase in atomic number of the sample. The current experiments are accomplished at 279, 320, 662 and 1120-keV incident photon energies to attain the stated objective.

2. EXPERIMENTAL SET-UP AND METHOD OF MEASUREMENTS

The current evaluation of multiple scattering of gamma rays in rectangular samples of copper are implemented with four distinct radioactive energy sources, ^{203}Hg (0.925 GBq, 279 keV), ^{51}Cr (2.04 GBq, 320 keV), ^{137}Cs (222 GBq, 662 keV) and ^{65}Zn (1.61 GBq, 1.12 MeV). The details of the source's assemblies and detector arrangement are given in our measurements [3]. In each of these experiments, the concept of measurements of multiply scattered gamma photons is on the basis of detection of all degraded scattered photons, arising from interactions within the primary gamma beam photons and rectangular samples of different thicknesses, by installing a properly lead shielded NaI(Tl) scintillation detector at 90° with respect to the incident beam of gamma photons. The resulted spectra are amalgamation of singly and multiply scattered events along with the events originating due to other gamma interaction processes. Analytical expression to determine the singly scattered gamma photon profile [3] is developed by using experimentally determined parameters like FWHM, counts at the peak etc. and is subtracted from the amalgamated spectra detected by the detector to acquire the intensity of only multiply scattered photons. When these numbers of multiply scattered events are rectified for photo-peak efficiency of gamma detector, iodine escape peak and absorptions in Al window of scintillator gamma detector.

3. RESULTS AND DISCUSSION

Measurements of the scattered photons are carried out as function of sample thickness, for the rectangular copper samples of thickness varying from 0.1 - 3.0 cm. A typical observed experimental spectrum, recorded by NaI(Tl) detector, is obtained by irradiating a typical sample of copper for 10 Ks (curve-a of Fig. 1). Also the background spectrum is recorded for the same period of time to permit registration of events unrelated to sample (curve-b of Fig. 1). The observed experimental spectrum obtained by subtracting the events under curve-b from those under curve-a, consists of both singly and multiply scattered events. The subtraction of reconstructed singly scattered spectrum (curve-d of Fig. 1) from this observed experimental spectrum (after subtracting background) in the range 210-330 keV results in multiply scattered photons only. The subtraction of reconstructed singly scattered process is then repeated for different rectangular copper sample at different incident photon energy. The plots of investigated number of multiply scattered photons, corresponding to different incident photon energies, as a function of sample thickness is shown in Fig. 2. The outcome of the experiment exhibits that the counts of multiply scattered gamma photons increments with the increment in sample thickness and saturates after a specific value of rectangular sample thickness, referred to as saturation depth. The increment in rectangular sample thickness results in more scattering centres for the interaction of incident gamma photons with sample material; whereas, the possibility of absorption within the rectangular sample is also enhanced with increment in sample thickness. Thus a limit is reached when the thickness of sample becomes sufficient to compensate the above increase and decrease of numbers of multiply scattered photons, and hence the number of multiply scattered photons emerging out of the rectangular sample becomes saturates. The optimum thickness for which the number of multiply scattered gamma photons saturates in Cu (copper) sample is 0.7, 0.1, 1.6 and 2.1 cm for 279, 320, 662 and 1120 keV incident photons respectively. The mean free path in copper is 0.946, 1.004, 1.537 and 2.007 cm for the corresponding incident photon energies. The saturation thickness, for which the numbers of multiply scattered gamma photons saturate, increments with increment in incident gamma photon energy and is nearly equal to one mean free path.

The results based upon Monte Carlo calculations for multiply scattered intensity, at scattering angle of 90° for the four different incident photon energies in our experimental geometrical conditions, are also given in Fig. 2. The solid curves are the best-fit curves to simulated data (hollow symbols) and experimental data (solid symbols) points. The simulated data of multiply scattered intensity also increments with increment in sample thickness and then saturates for different incident photon energies which is different for different incident photon energy and the saturation value is found to be increasing with increment in incident gamma photon energy. The trend of the curves of simulated data points is in good agreement with the present experimental results. The experimental measured value of saturation thickness increases with increase in incident photon energy. Fig. 3 provides a plot of measured values of saturation thickness

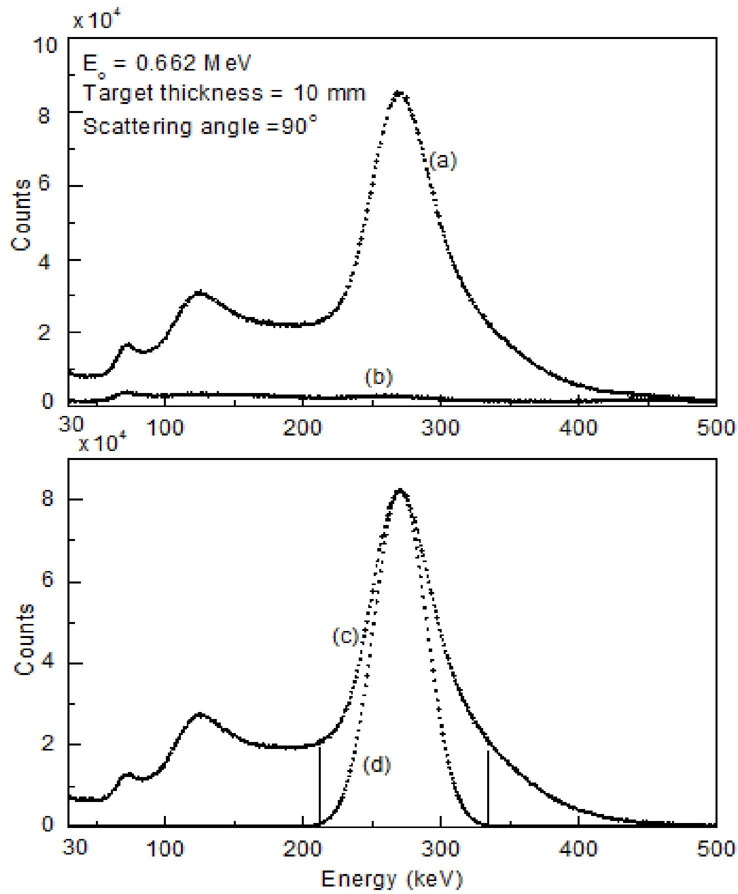

Fig. 1. A typical experimentally observed spectrum (curve-a) of 0.662 MeV incident photons with copper target of10 mm thickness at scattering angle of 90° for 10 ks irradiation time. Observed background spectrum for 10 ks without copper target in the primary beam (curve-b). Experimentally observed pulse-height distribution, (curve-c) obtained after subtracting background events. Normalised analytically reconstructed singly scattered full energy peak (curve-d) and pulse-height distribution to a photon spectrum

(solid symbol) as a function of incident photon energy. The increment in experimental measured value of saturation thickness with incident photon energy is caused by increasing penetration of gamma photons in matter with increasing incident energy. The Monte Carlo simulations of present experiments show good agreement between the experimentally evaluated and simulated intensities of multiply scattered photons. The inconsistency of some of the experimental and simulated data points is due to non-inclusion of scattering contributions from moving electrons and polarization effects [6,1] of scattered photons, which are not included in the present package. It is further required to carry out measurements at different scattering angles in other elemental and binary materials for gamma photon energies available in the nuclear domain for better understanding of multiple scattering processes.

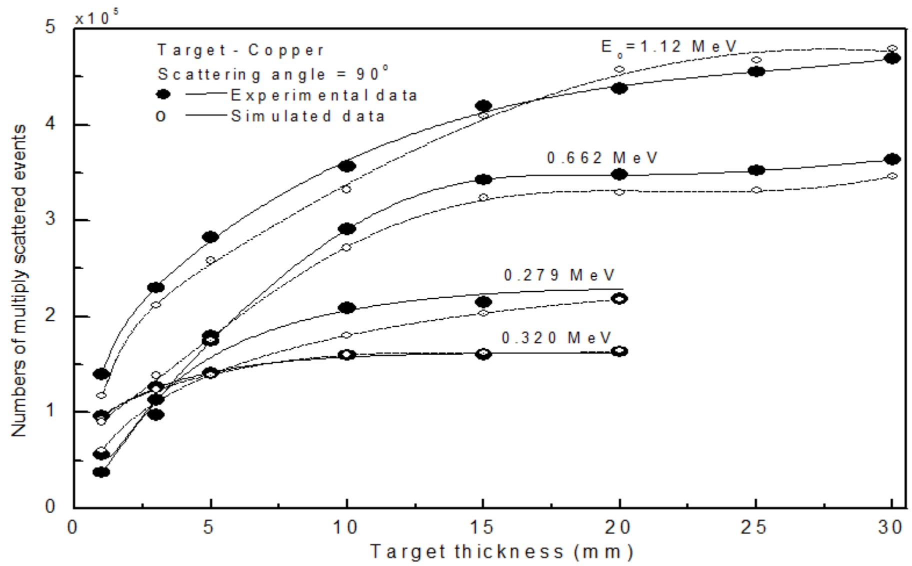

Fig. 2. Variation of experimentally observed and simulated numbers of multiply scattered events as function of thickness of the copper target for different incident photon energies

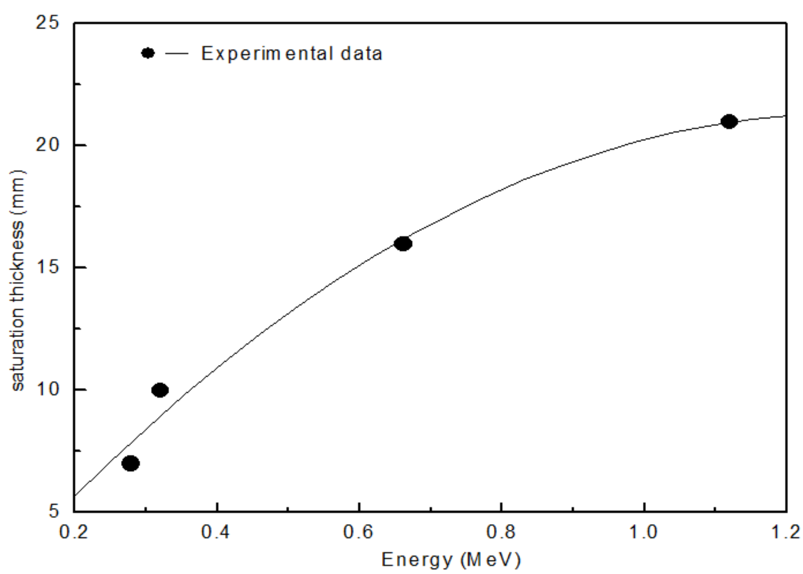

Fig. 3. Experimental observation of saturation depth in copper as function of incident gamma photon energy

4. CONCLUSIONS

The current experimental results confirm that for thick samples, there is significant contribution of degraded photon radiations emanating from the samples, having energy identical to that of singly scattered gamma photon. With the increment in sample thickness, intensity of multiply scattered photons increments, and saturates beyond a specific value, referred as saturation thickness. This trend supports the experimental results of Paramesh et al. [5]. We observe that the saturation thickness increases with increasing incident gamma photon energy. The saturation thickness is found to be decrease non-linearly with increase in atomic number [7] of the sample material. The Monte Carlo calculations carried out using the package developed by Bauer and Pattison [2] supports the present measurements. It is further required to perform the experiment at different incident photon energies for better understanding of the energy distribution of multiply scattered photons as a function of incident energy. There is also a need to simulate the experimental data with the Monte Carlo codes which include the polarization effects and the contribution of moving electrons like EGS4, GEANT4 and MCSHAPE, for better understanding of the multiple scattering processes.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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