Experimental measurement of Rayleigh to Compton cross-section ratio for 279 keV gamma photons

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Abstract

The present work involves measurement of Rayleigh to Compton scattering cross-section ratio of elements in the range $13 \le Z \le 79$ for 279 keV incident gamma photons. An HPGe gamma detector, placed at 50° to the incident beam, detects gamma photons scattered from the target under investigation. The intensities of Rayleigh and Compton scattered peaks observed in the recorded spectra, and corrected for photo-peak efficiency of gamma detector and absorption of photons in the target and air column present between the target and detector, along with the other required parameters provides differential cross-sections ratio for Rayleigh to Compton scattering. The measured values of cross-section ratio are found to agree with existing theories for low Z elements, but deviate for high Z elements.

1. Introduction

Rayleigh (coherent) scattering results in scattering of gamma photon without any change in energy, and is predominant at low incident photon energies, small scattering angles and high atomic number elements. The atomic Compton (incoherent) scattering results in degradation of gamma photon energy, and can be calculated with the incoherent scattering function modification to Klein-Nishina formula for Compton scattering. Rayleigh to Compton scattering ratio, *R*, has a power relation to Z in the region of elemental interest and this power dependence is based upon the ratio F^2/S, with $F(q,Z)$ being the form factor and $S(q,Z)$ is the incoherent scattering function. Hubbell *et al*. [1] have provided theoretical model for the calculation of Rayleigh to Compton cross-section ratio from the parameters $F(q, Z)$ and $S(q, Z)$.

Various theories have been developed to calculate atomic form factor based on non-relativistic form factor [1], relativistic form factor [2], modified relativistic form factor [3] and S-matrix theory [4]. According to these theories, the atomic form factor, $F(q, Z)$, is the Fourier transform of atomic charge distribution and can be evaluated by different wave functions. Icelli and Erzeneoglu [5] have measured the ratio of differential cross-sections for coherent and Compton scattering of 59.54 keV at scattering angles of 55° and 115° for Fe, Ni, Cu, Zn, Zr, Nb, Mo, Ag, Sn, Ta, Au and Pb targets using Ge(Li) detector. More recently, we [6] have determined coherent to incoherent scattering cross section ratio of elements for 145 keV gamma photons. An accurate determination of ratios of coherent to incoherent scattering for different elements is important because of their wide use in the fields of atomic and radiation physics, and non-destructive elemental analysis of materials. There have been various investigations on coherent (Rayleigh) to incoherent (Compton) scattering ratio method. This intensity ratio method has been quite successful in various fundamental and medical applications of gamma radiations. Our group has successfully used this ratio technique for non-destructive evaluation of scientific and biological samples, measurements of mandibular bone density and pulmonary edema etc. [7].

The knowledge of coherent to incoherent scattering cross-section ratio is useful in the calculations of radiation attenuation, reactor shielding, industrial applications and also in the field of medical sciences in a number of ways. In the present experiment, Rayleigh to Compton scattering cross-section ratio values are measured for elements in the range, $13 \le Z \le 79$, for 279 keV incident gamma photons. The measured results are compared with various existing theories available in literature (corresponding to 9.510 $\mathring{A}^{-1}$ photon momentum transfer).

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2. Experimental set-up and Method of Measurements

The principle of present measurements is to observe the intensities of Rayleigh and Compton scattered gamma photons at a particular scattering angle. The measurements are performed using ^{203}Hg (279 keV) radioactive source strength of activity 0.925 GBq, which is placed at the end of a cylindrical cavity of depth 20 mm and diameter 11 mm fabricated in a lead cube having each side 160 mm (Fig. 1). An aluminium hollow sleeve of internal diameter 12 mm, fitted in the centre of a rectangular block of lead having dimensions 80 mm × 80 mm × 15 mm, is placed coaxially adjacent to the cavity to obtain a narrow beam of photons. The distance of thin target under study from the source collimator (radius 3 mm) is kept as 100 mm. The source-target assembly is aligned in such a way that the

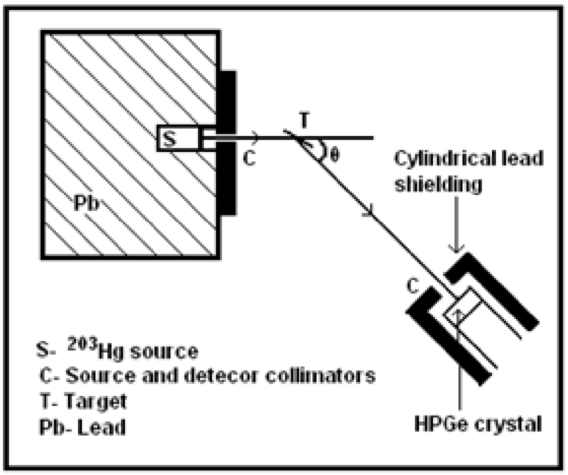

Fig.1: Experimental set-up

incident photon beam is confined to the target element. The intense collimated beam of gamma photons from the radioactive source is made to impinge on a given target, which is placed symmetrically with respect to incident and finally scattered directions. An HPGe solid-state gamma detector of dimensions 56.4 mm diameter and 29.5 mm length placed at scattering angle of 50° detects radiations scattered from the target. The field of view of the HPGe detector is confined to target only. The axes of source collimator, gamma detector and detector collimator pass through centre of the target. The distance between target under study and detector collimator (radius 4 mm) is kept 100 mm, so the angular spread about median ray in direction of gamma detector is ±2.9°. The HPGe detector is properly shielded by a cylindrical lead shielding having inner side covered with 2mm thick iron and 1mm thick aluminium, with iron facing lead to absorb K X-rays emitted by lead shielding. It has been checked that radiations scattered from source collimator opening do not reach directly to the active volume of HPGe detector. In the present measurements, Canberra HPGe detector and electronic modules (power supply and amplifier) are used. The experimental data are accumulated on a PC based ORTEC Mastreo-32 Multi channel analyser.

The formula used for the measurement of ratio of Rayleigh to Compton scattering cross-sections [6] is given as:

$$\frac{d\sigma_R(\theta)}{d\sigma_C(\theta)} = \frac{N_R}{N_C}\,\frac{N_E}{N_A}\,\frac{\beta_C}{\beta_R}\,\frac{\gamma_C}{\gamma_R}\,\frac{\varepsilon_C}{\varepsilon_R} \qquad (1)$$

where N_R/N_C is the ratio of the number of counts under Rayleigh and Compton scattered peaks, respectively; N_E/N_A is the ratio of number of electrons and atoms per unit volume in the target; β_C/β_R is the ratio of self-absorption correction factor in the target for Compton and Rayleigh scattered energies; γ_c/γ_R is the ratio of absorption of Compton scattered and Rayleigh scattered gamma rays in air, and $\varepsilon_c/\varepsilon_R$ is the ratio of the photo-peak efficiency of the HPGe detector for Compton and Rayleigh scattered energies.

3. Results and Discussion

In the present experiment, the intensity ratio of Rayleigh to Compton scattered peaks originating from interactions of primary gamma flux with the element, for a fixed geometrical source-target-detector arrangement (Fig.1) and incident gamma photon energy, have been measured. In the first step, the properly shielded HPGe gamma ray detector is placed at the desired angular position (θ = 50°) relative to the primary incident gamma beam. The spectrometer is calibrated using standard calibration gamma-sources of known energy. Measurements are then carried out by placing thin targets of known atomic number ($13 \leq Z \leq 79$) and thickness (40-500 mg-cm^{-2}) in the primary incident gamma beam. The following procedure is adopted for the present measurements.

(i). The target-in scattered spectra are recorded for a period of 10 ks by placing each of the targets (elements) in the primary gamma beam.

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

The present measurements for different elements are performed in the above stated sequence to minimize the effect of any possible drift in the system. The subtraction of events recorded under condition (ii), from those under condition (i) results in events originating from interaction of primary gamma rays in the given target. A typical scattered spectra, corrected for background events, originating from gold and brass targets is shown in Fig. 2. The spread in observed Compton peak is caused by finite angular aperture of the source and the detector collimators and the Doppler

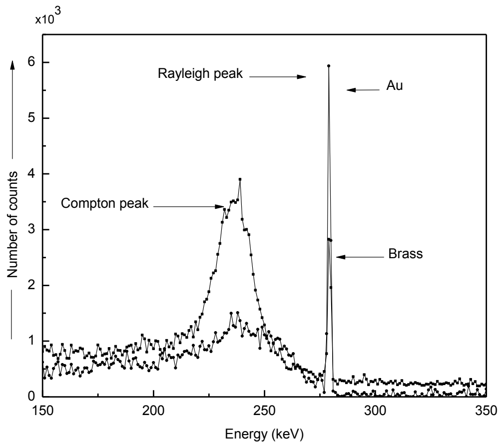

Fig. 2: Typical observed spectra at 50° from gold and brass targets for 279 keV incident photons

broadening of Compton peak in addition to inherent energy resolution of the HPGe detector. It has also been observed that Compton peak dominants the Rayleigh peak for low Z targets, but for higher atomic number element like Au (Fig. 2) the Rayleigh peak is dominant than Compton peak in the observed spectra.

The intensities under Rayleigh and Compton scattered peaks (Fig. 2) are deduced from the recorded scattered

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spectra. These observed intensities are corrected for photo-peak efficiency of the HPGe detector, absorption in air column present between target (element) and the detector, and self-absorption in elements and the detector, and self-absorption in the target, as per relation [6]:

$$N_{actual} = \frac{N_{obs}}{\varepsilon_\gamma \beta_{\gamma a} \beta_{\gamma t}} \qquad (2)$$

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

The measured values of differential cross-section ratio for Rayleigh to Compton scattering, are given in column 2 of Table 1. The statistical error involved in the cross-section measurements ranges from 8 -12%. The columns 2 to 5 of Table 1 provide the cross-section ratio values deduced from non-relativistic form factor [1], relativistic form factor [2], modified relativistic form factor [3], and S-matrix theory [4] respectively.

Table1: Experimental and theoretical Rayleigh to Compton scattering cross section ratio as a function of atomic number at 279 keV at 50^o

Element (Atomic number)	Present results (Expt.)	Theory [1] (NRFF)	Theory [2] (RFF)	Theory [3] (MRFF)	Theory [4] (S-Matrix)
Al (13)	0.0415 ± 0.0053	2 x 10^{-5}	1.9 x 10^{-5}	1.7 x 10^{-5}	1.9 x 10^{-5}
Cu (29)	0.0560 ± 0.0064	0.0092	0.010	0.0087	0.0077
Ag (47)	0.114 ± 0.0093	0.026	0.029	0.023	0.024
Gd (64)	0.1723 ± 0.0345	0.039	0.048	0.034	0.038
Au (79)	0.5655 ± 0.0487	0.059	0.092	0.061	0.093

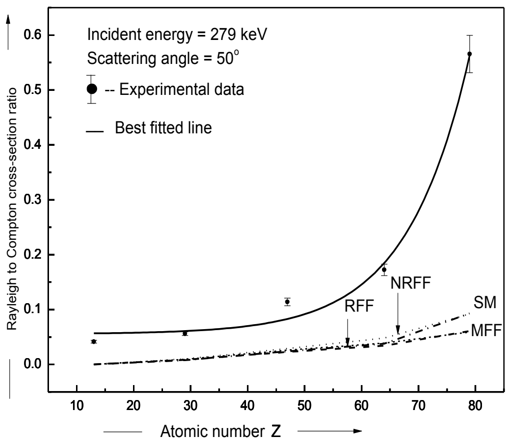

Fig 3: Variation of Rayleigh to Compton scattering cross-section ratio as a function of atomic number

Figure 3 shows the plot of Rayleigh to Compton cross-section ratio as a function of *Z*-number of the target. It is observed that as the atomic number increases, the value of Rayleigh to Compton scattering cross-section ratio increases non-linearly and the trend is similar to that predicted by various theoretical models [1-4]. The measured differential cross-section values for Rayleigh to Compton ratio are compared with theoretical values calculated by employing non-relativistic form factor, relativistic form factor, modified relativistic form factor and S-matrix theory. At incident energy of 279 keV and scattering angle of 50^o, our experimental results of differential Rayleigh to Compton scattering cross-section ratio increases non-linearly with the increase in atomic number in the range $13 \leq Z \leq 79$, but are higher than the theoretical data due to all the theories. The deviation of experimental results increases very sharply for high atomic number materials. This may be due to low probability of Rayleigh scattering process and high probability of Compton scattering process at high incident energy and also binding effects of the inner shell electrons. It also confirms that the binding effects of electrons are important in measurements of the Compton scattering differential cross-section especially at low scattering angles.

The photo-peak efficiency values are also measured experimentally using single energy sources of known source strength of ^{203}Hg (279 keV) and ^{137}Cs (662 keV). The experimental measured values of photo-peak efficiency using single energy sources of ^{203}Hg and ^{137}Cs of known source strengths come to be 2.5% and 1.12%, respectively and are nearly in agreement with Canberra Germanium detector user's manual values of 2.4% and 1.10% respectively. The targets used in the present experiments are thin, with $\mu t \ll 1$, here μ is the linear attenuation coefficient and t is the thickness of the target under study. The contribution of events resulting from Bremsstrahlung originating from slowing down of photoelectrons and Compton recoil electrons is estimated on the basis of an experimental technique suggested by Sandhu et al [8], and is found to be less than 1% under the present experimental conditions.

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These results constitute the first experimental report of ratios of coherent to incoherent scattering cross-sections, corresponding to 9.510 $\mathring{A}^{-1}$ photon momentum transfer for the elements studied, as there are no earlier reports in the literature. The measurements of these ratios are also important because by comparison with theoretical predictions based on atomic models, there is the possibility of testing the validity of these models. One of the major advantages of the method is that by taking the ratio of the coherent (Rayleigh) to incoherent (Compton) scattered photons, a number of parameters such as absolute source strength, solid angles subtended by source and the detector at the target, etc. are eliminated in the expression of R/C ratio, otherwise determination of these parameters introduce large amount of error in the measured results. As measurement of differential scattering cross sections is useful in the studies of radiation attenuation, transport and energy deposition and plays an important role in medical physics, reactor shielding, industrial radiography in addition to crystallography. So, there is need to explore this ratio method to provide plots for element cross-section ratio versus wide range of scattering angle to determine the optimum angular position while using this technique for 279 keV.

4. References

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