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Coherent and Incoherent Scattering cross sections for elements with $13 \leq Z \leq 50$ using ^{241}Am gamma rays

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Abstract—Coherent and incoherent scattering cross section measurements have been carried out using a HPGe detector on elements in the range of Z = 13 - 50 using ^{241}Am gamma rays. The cross sections have been derived by comparing the net count rate obtained from the Compton peak of aluminium with the corresponding peak of the target. The measured cross sections for the coherent and incoherent processes are compared with theoretical values and earlier reported values. Our results are in agreement with the theoretical values.

Keywords—cross section, coherent scattering, incoherent scattering, ^{241}Am

I. INTRODUCTION

MEASUREMENT of differential scattering cross sections for X-rays 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 X-ray crystallography. Coherent (Rayleigh) scattering accounts for only a small fraction of the total cross section, contributing at the most to 10% in heavy elements, just below the K-edge energy. Incoherent (Compton) scattering accounts for the rest of the total cross section. For low Z materials this process dominates over most part of the energy range.

An extensive review of previous work on incoherent and coherent scattering has been reported by Kane [1] and Bradley *et al* [2]. ^{241}Am is a very convenient radiation source for studies of photon interactions in the X-ray region, especially because of the relatively long half life of 450 years and its photon energy (59.54 keV) being in the vicinity of the K-edges of many elements in medium-Z region. We have embarked on a series of photon interaction studies using this versatile souce. Ramachandran *et al* [3] measured attenuation coefficients for these gamma rays in the rare earth elements with $57 < Z < 72$ and derived photoelectric cross sections therefrom. Good agreement with theoretical values based on the XCOM [4] have been reported by them. Subsequently, Abdullah *et al* [5] carried out attenuation studies near the K absorption edges in rare earth elements using ^{241}Am gamma rays, Compton scattered at various angles by an aluminium scatterer. More recently, Abdullah *et al* [6] made similar studies with the elements Zr, Nb, Mo and Pd. In both measurements, reasonable agreement has been observed between the experimental values and earlier results on one hand as well as with the XCOM values on the other hand.

Similar investigations have been reported by several groups in this direction. Casnati *et al* [7] measured total elastic cross section for 59.54 keV gamma rays for Al, V, Mo, Cd and Pb and compared with theoretical values of Kissel and co-workers [8], confirming the validity of their procedure within the atomic range $13 \leq Z \leq 82$ explored. Shahi *et al* [9] reported the measured elastic scattering cross sections for the 59.54 keV gamma rays for elements with atomic number between 12 and 92 at a backward scattering angle 121^0. Measured cross sections were compared with those based on: (1) relativistic modified form factors (RMFF) (2) a combination of RMFF's and angle independent anomalous scattering factors (RMFF + ASF) and (3) the relativistic second order S-matrix calculations. The modified form factor cross sections were found to be higher for the elements with K-shell binding energies close to the incident photon energy. The S matrix cross sections showed agreement with the measured data over the whole atomic region under investigation. In a later work, Shahi *et al*[10] have determined inealstic scattering cross sections at the same energy and angles for several elements with $12 < Z < 82$. The measured cross sections agree with calculations based on Klein-Nishina cross sections for Compton scattering by staionary free electrons and the non-ralativistic Hartee-Fock incoherent scattering function S(x,Z).

Elyaseery *et al* [11] using standard back scattering geometry measured the coherent and incoherent scattering cross sections at three angles 145^0, 154^0 and 165^0 for 59.54 keV gamma rays in the elements Cu, Zn, Zr, Nb, Mo, Ag, Cd, In, Sn, Ta and W. Comparison with values tabulated by Hubbel *et al.* [12] showed good agreement except at 165^0, where discrepancies of over 20% were observed in many cases. These discrepancies have been attributed to lower counting rates and the error in fixing the scattering angle. Simsek [13] in his meausrement has adopted a new method for determination of the incoherent scattering cross sections by comparing with the K-shell cross sections for the elements Ag, In and Sn at 59.54 keV in the angular range 40^0 - 135^0. Reasonable agreement with the non-relativistic Hartree-Fock values of Hubbel *et al* [12] were noted. In a subsequent study, Simsek and Mehmet [14] have measured differential coherent scattering cross sections for the same elements, angles and

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energy. The results have also been compared with available S-matrix calculations and also with relativistic modified form factor(RMFF) results. The authors conculde that the RMFF results are more appropriate for predicting the theoretical values in the momentum transfer range considered. Govinda Nayak $et\ al$ [22] using a reflection geometry set up and a graded shielding arrangement measured incoherent scattering cross sections for a number of elements in the region $29 \leq Z \leq 82$ at scattering angles 90^0, 60^0, 45^0 and 30^0 using 59.54 keV gamma rays.

In the energy region in which Compton scattering is a major part of the total cross section, the differential incoherent scattering cross section is given by the Klein Nishina formula [15]. For low Z materials and high energies the free electron Klein-Nishina formula requires a correction term for including the small possibility of emission of an additional photon (double-Compton effect) [16], [17], [18] and radiative corrections [16], [19], [20]. Similarly we need to consider modifying this formula for the scattering of low energy photons from high Z elements to account for the electron binding effects. Since the present studies concern only with photons of energies much below 1 MeV, it is safe to ignore double Compton effect and radiative corrections. The angular distribution function for unpolarized photons scattered from a free electron under the above assumptions, and also neglecting radiative correction and double Compton effect is given by the Klein Nishina formula.

The differential incoherent cross section per atom $(\frac{d\sigma}{d\Omega})_{incoh}$ is given as the product of the $Klein-Nishina$ cross section $\frac{d\sigma_{KN}}{d\Omega}$ and the incoherent scattering function $S(x, Z)$.

$$(\frac{d\sigma}{d\Omega})_{incoh} = [\frac{d\sigma_{KN}}{d\Omega}]S(x, Z). \quad (1)$$

The differential Rayleigh (Coherent) Scattering cross section in the form factor approximation can be expressed as the product of Thomson Scattering cross section $(\frac{d\sigma}{d\Omega})_T$ and the square of the atomic form factor $f(x, Z)$.

Thus the coherent(Rayleigh) scattering cross section is given by

$$(\frac{d\sigma}{d\Omega})_{coh} = (\frac{d\sigma}{d\Omega})_T f(x, Z)^2 \quad (2)$$

where the distribution function for classical Thomson Scattering $(\frac{d\sigma}{d\Omega})_T$ by an electron is given by

$$(\frac{d\sigma}{d\Omega})_T = (1 + cos^2\theta)\frac{r_e^2}{2} \quad (3)$$

Here r_e is the classical electron radius.

In the present studies, we have carried out Coherent and incoherent scattering measurements on the elements in the range of $Z = 13 \leq Z \leq 50$ using ^{241}Am gamma rays. The details of the measurements and the results obtained therefrom are given in the following sections.

II. EXPERIMENTAL SET UP

The experimental set up employed in the present work is shown schematically in fig.1. A $1.1 \times 10^{10} Bq\ Am^{241}$ source (S) procured from Amersham England was used as the source for 59.54 keV gamma rays. The gamma rays were scattered by targets kept at an angle 45^0 with the incident ray. The targets used were of 99.9% purity and are in the form of thin square foils with 1.2 cm side. The mass per unit area of the targets were determined using a sensitive electronic balance. A HPGe Gamma-X detector(D) of active volume $85cm^3$ supplied by ORTEC, USA was used for detecting the scattered photon beams. The spectra of the scattered radiations from the targets were recorded typically for about 6 - 9 hours such that the statistical errors in the total scattered counts were of the order of 1% or less. The detector resolution is 1.14 keV at 60 keV. The detector is arranged at an angle of 90^0 with the incident gamma beam. The signals from the detector were processed by the standard ORTEC modules and are then fed to a CAMAC based data acquisition system. The data analysis software, PAW, developed by CERN laboratories [21] has been used for data analysis in the present studies. A representative spectrum recorded with 59.54 keV gamma rays scattered at 90^0 by a Ag scatterer is shown in fig.2.

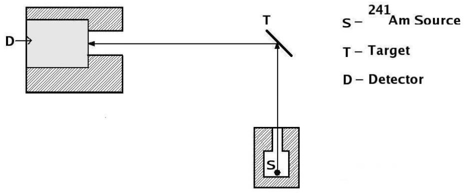

Fig. 1 Schematic diagram of the experimental set up

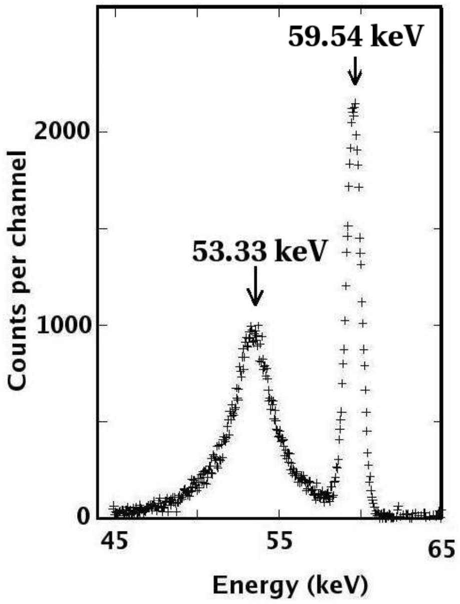

Fig. 2 Representative spectrum for Ag scatterer, showing the elastic and inelastic peaks

Incoherent scattering cross section is measured first with aluminium and is used as a reference value. Any cross section (coherent as well as incoherent) of interest was evaluated by comparing the net count rate obtained from the Compton peak of aluminium with respect to the corresponding peak of the target. This method was useful in eliminating the necessity to know the absolute source strength. Thus,

$$\frac{d\sigma}{d\Omega} = [\frac{d\sigma_{KN}}{d\Omega}]S(x, Z = 13)\frac{n_{Al}N_T}{n_T N_{Al}}\frac{\eta_c T_{Al}}{\eta T_T}\frac{(\Omega_T\Omega_D)_{Al}}{(\Omega_T\Omega_D)_T} \quad (4)$$

where,

N_{Al} is the count rates for aluminium under the Compton peak, N_T is the count rate for target under the corresponding (Coherent or Incoherent) peak, n_{Al} is the number of scattering centres of aluminium, n_T is the number of scattering centres of the target, $n = \frac{N_A \rho m}{A}$ [A is the mass number, N_A is the Avagadro Number, ρ the density of the target material and m is the mass per unit area of the target.], T_{Al} and T_T represent the transmission factors which account for the absorption of the incoming and scattered photon beams while traversing the targets, η is the efficiency for coherent or incoherent photon beam, Ω_T is the solid angle subtended by the target at the centre of the source, Ω_D is the solid angle subtended by the detector at the target centre.

Equation(6) holds good only for targets having dimensions negligible compared to the distances between the source, the target and the scatterer. A target of finite dimensions can be considered to be made up of a large number of infinitesimally small elements within this target. The solid angle factor and the transmission factor vary from element to element. A rectangular co-ordinate system is set up with the X-Y plane coinciding with the target plane. For reflection geometry, the effective transmission factor corresponding to the i^{th} element can be shown to be given by

$$T_i = \frac{1 - \exp\left[-m(\mu sec\gamma_i + \mu' sec\gamma_i^{'})\right]}{m(\mu sec\gamma_i + \mu' sec\gamma_i^{'})} \quad (5)$$

where μ and μ' are the mass attenuation coefficients of the target for the incident and scattered gamma rays respectively, m is the mass per unit area of the target, γ_i and $\gamma_i^{'}$ are the angles made by the incident and scattered gamma rays with the normal to the target plane at the position of the i^{th} element. The effective sum of the product $T_i \times \Omega_T \times \Omega_D \times \eta$ over all the elements was used in the expression for cross section. The mass attenuation values required for the transmission factor calculation were obtained from the XCOM [4].

III. RESULTS AND DISCUSSION

The differential coherent and incoherent scattering cross sections for the elements studied in this work are tabulated in tables 1 and 2 respectively along with the theoretical values and available other experimental data. Typical errors in the quoted cross sections have been estimated to be about 6%, with the major part arising from uncertainties in the target mass per unit area.

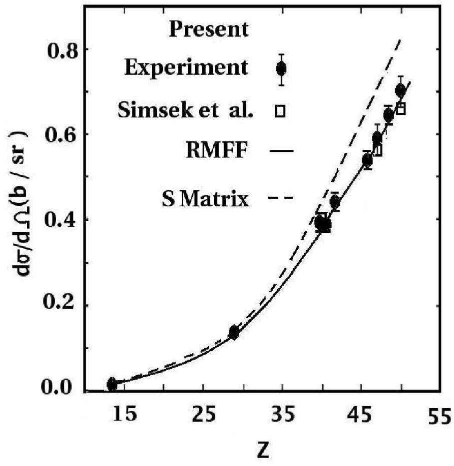

Fig. 3 Differential coherent Scattering cross sections at 59.54 keV

TABLE I
DIFFERENTIAL COHERENT SCATTERING CROSS SECTIONS (B/SR)

		$(\frac{d\sigma}{d\Omega})_{coh}$(barns/sr)		
Z	Element	Experimental	Theoretical	
			RMFF	S-matrix
13	Al	0.0170±0.001	0.0167	0.0164
29	Cu	0.118±0.006	0.106	0.119
40	Zr	0.386±0.020	0.358	0.424
41	Nb	0.385±0.020	0.391	0.461
42	Mo	0.435±0.023	0.425	0.499
46	Pd	0.555±0.028	0.558	0.665
47	Ag	0.580±0.029 0.571[14]	0.591	0.706
48	Cd	0.613±0.031	0.622	0.746
50	Sn	0.708±0.036 0.666[14]	0.682	0.824

The S-matrix values taken from the tabulations of Chatterjee *et al* [23] and the differential coherent scattering cross sections calculated using the relativistic modified form factor(RMFF) values [24] for all the elements under study corresponding to an angle 90^0 are listed in Table 1. It is observed that there is better overall agreement of the present experimental values with the values calculated on the basis of RMFF. It is also observed that the S-matrix values are always higher than the present experimental values. This discrepancy with respect to the S-matrix values may be attributed to the neglect of the electron correlation effects in the theoretical S-matrix calculations, as pointed out by Chatterjee *et al* [23]. Similar discrepancies had also been noticed by Shahi *et al* [9]. We are in the midst of further investigations in this direction at lower energies with X-rays produced by the Proton Induced X-ray Emission (PIXE) technique.

In Table 2, the differential incoherent scattering cross section is compared with the cross section calculated using non-relativistic Hartree Fock incoherent scattering function S(x,Z) obtained from the tables of Hubbell [12]. Our results agree with the theoretical values.

Figures 3 and 4 present the results of this work respectively

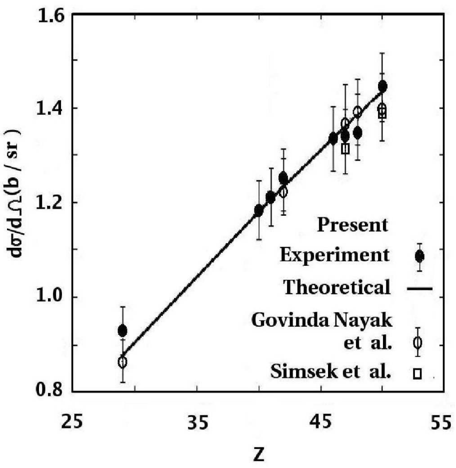

Fig. 4 Differential Incoherent Scattering cross sections at 59.54 keV

TABLE II
DIFFERENTIAL INCOHERENT SCATTERING CROSS SECTIONS (B/SR)

		$(\frac{d\sigma}{d\Omega})_{incoh}$(barns/sr)	
Z	Element	Eexperimental	Theoretical
29	Cu	0.92900±0.0501 0.865±0.044[22]	0.878
40	Zr	1.183±0.0615	1.180
41	Nb	1.211±0.0616	1.206
42	Mo	1.246±0.0650 1.232±0.060[22]	1.233
46	Pd	1.335±0.0676	1.335
47	Ag	1.328±0.0671 1.309[13] 1.378±0.069[22]	1.360
48	Cd	1.359±0.0685 1.390±0.069[22]	1.385
50	Sn	1.442±0.0729 1.394[13] 1.401±0.070[22]	1.434

for coherent and incoherent scattering. These figures show that our experimental results are, in general, close to the theoretical values represented by the solid curves. To the best of our knowledge sufficient experimental data is not available in literature for 59.54 keV at 90^0. It is clear that the present cross section results are in good agreement with the available experimental values reported in literature. It is also worth mentioning that the results show no systematic trend in departure from the theoretical values except for the S-matrix values mentioned earlier. Comparison indicates that for most cases agreement is obtained between present result and the theoretical predictions.

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