

Experimental and Semi-Empirical Investigation of Photon Attenuation Parameters of $\text{Sb}_x\text{Bi}_{1-x}$ Alloys and Comparison with XCOM Database Values

Dr. Ch. Snehalatha Reddy¹; Dr. Narendar Kethireddy^{2*};
Dr. Boda Mahipal Reddy³

¹Department of Physics, Government Degree College Wardhannapet, Kakatiya University, Telangana, India.

²Department of Physics, Government Degree College Huzurabad, Satavahana University, Telangana, India.

³Department of Chemistry, Government Degree College Huzurabad, Satavahana University, Telangana, India.

Corresponding Author: Dr. Narendar Kethireddy^{2*}

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Abstract: This study investigates photon-interaction studies on binary antimony–bismuth (Sb–Bi) alloys at 661.6, 1173, and 1332 keV using experimental, semi-empirical (SE), and XCOM values for five alloy samples. The measured data set contains mass attenuation coefficient, linear attenuation coefficient, photon mean free path (reported as impact factor, λ), total atomic cross section, total electronic cross section, effective atomic number (Z_{eff}) and effective electron number (N_{eff}). The mass attenuation coefficient decreases with increasing photon energy for every sample, while the composition series shows systematic changes in all interaction parameters. At 661.6 keV, the experimental mass attenuation coefficient increases from 8.211×10^{-2} to $11.02 \times 10^{-2} \text{ cm}^2 \text{ g}^{-1}$ across Samples [1–5]. At 1173 and 1332 keV, the ranges are 5.62×10^{-2} – 6.301×10^{-2} and 5.20×10^{-2} – $5.80 \times 10^{-2} \text{ cm}^2 \text{ g}^{-1}$, respectively. Z_{eff} increases from 53.0451 to 78.0996, whereas N_{eff} decreases from 2.5144×10^{23} to $2.4121 \times 10^{23} \text{ electrons g}^{-1}$. Across all attenuation and cross-section points, the average absolute experimental deviations from XCOM are approximately 3.89% for the mass attenuation coefficient, 4.33% for the linear attenuation coefficient, 3.41% for the mean free path, 4.78% for the total atomic cross section, and 4.39% for the total electronic cross section. The supplied SE values are in comparable agreement. The results show that XCOM and the semi-empirical treatment reproduce the principal experimental trends within a few per cent.

Keywords: Sb–Bi Alloy, Gamma-Ray Attenuation, Photon Interaction Parameters, XCOM, Semi-Empirical Method.

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I. INTRODUCTION

Photon attenuation data are fundamental to radiation shielding, dosimetry, detector design, industrial radiography and nuclear instrumentation. Gamma-ray attenuation in matter is controlled by photoelectric absorption, coherent scattering, Compton scattering and pair production, with the relative contribution of each process depending strongly on photon energy and atomic composition [1–10]. The mass attenuation coefficient, μ/ρ , is particularly useful for comparing materials because it normalises attenuation to mass thickness [5,6].

For multicomponent materials, elemental attenuation coefficients can be combined using composition-weighted

mixture relations [5,12,15,16]. The NIST XCOM database and its WinXCom implementation are widely used for obtaining photon cross sections and attenuation coefficients over a broad energy range [1–4]. The database has become a standard reference for theoretical calculations of photon interaction in elements, compounds and mixtures [5–11].

Effective atomic number is a useful descriptor of a composite material, but it is not an intrinsic constant independent of photon energy and interaction mechanism [12–18].

Effective electron number and effective atomic and electronic cross sections offer complementary methods for understanding how photons interact with alloys and other composi

te materials. [12–18]. Experimental measurements of attenuation parameters have been reported for alloys, glasses, biological materials, dosimetric compounds and shielding materials [19–34].

Heavy-element alloys are attractive for gamma shielding because high atomic number and density can provide strong attenuation while alloying allows mechanical and processing properties to be tailored. Bismuth-containing materials are increasingly studied as lead-free shielding materials, while antimony is a useful heavy-element alloying constituent [32,38–40]. The present study therefore examines the submitted Sb–Bi data at the standard $^{137}\text{Cs}/^{60}\text{Co}$ gamma-ray energies and compares experiment with semi-empirical and XCOM values.

II. EXPERIMENTAL

Transmission experiments with the narrow beam (good-geometry) setup were used for measuring the incident and transmitted intensities to determine the attenuation coefficient. In the present work, the total attenuation coefficient was measured at 661.6, 1173, 1332keV photon energies using ^{137}Cs and ^{60}Co sources. The alloys studied in the present work were prepared by ingot metallurgy route. The alloys were melted in the air, in the induction furnace and cast-iron moulds were used to obtain ingots. These ingots were subsequently homogenized at about 813K and hot rolled to obtain 12mm - 15mm thick plates. These alloy plates were precipitation strengthened by heat treatment (aging).

In each case, the sample was shaped in to a cuboid for measuring the attenuation. The cuboid was stacked on the detector and the intensities of the transmitted photons were determined by choosing the counting time as 30 minutes. Counts were recorded under the photo peaks, as statistical uncertainty was to be kept as low as possible. The dimensions of the samples were measured with a screw gauge with tolerance of $\pm 0.01\text{mm}$.

The experimental setup in the present work is shown in Diagram. The gamma rays are well collimated using collimators of cylindrical shape and a circular aperture of 6mm diameter between the source and the detector. The signal is detected by NaI (Tl) scintillation detector of 3×3 inch crystal and a high bias voltage of 1000 volts. The detector was shielded by a lead screen to reduce the radiation coming directly from the source and scattered from the surroundings. The attenuation measurements were made with multichannel analyzer.

The samples were exposed to 661.6, 1173 and 1332keV photons emitted by 50 mCi ^{137}Cs and 100 mCi ^{60}Co radioactive point sources, respectively. I_0 and I the intensities before and after attenuation were measured by a high resolution NaI(Tl) detector. The sample was placed between the source and the detector, the distance between the radioactive point source with sample and the sample to detector was 12cm and 4cm, respectively. The measurements for the sample were carried out five times for each energy value. For each sample and energy I_0 (un attenuated) and I (attenuated) intensities were obtained. In every case the photo-peak had Gaussian distribution. The peak areas have been calculated from the spectrum obtained for each measurement. The each spectrum was recorded for 30 minutes to accumulate an adequate number of counts under the photo peak. I_0 and I intensity measurements and μ_m calculations were carried out for the photon energies 59.5, 661.6, 1173, 1332keV.

The uncertainty in the measurement of the mass attenuation coefficients has been estimated from errors in intensities I_0 , I and thickness (t) using the following relation.

$$\Delta(\mu_m) = (1/\rho t)[(\Delta I_0/I)^2 + (\Delta I/I)^2 + (\ln(I_0/I))^2 (\Delta t/t)^2]^{1/2} \quad \text{--- (1)}$$

Where ΔI_0 , ΔI and Δt are the errors in the intensities I_0 , I and thickness (t) respectively. In this experiment, the intensities I_0 and I were obtained for the same time and under the same experimental conditions. It is found that error in these measurements is in between 2.5% to 3.5%.

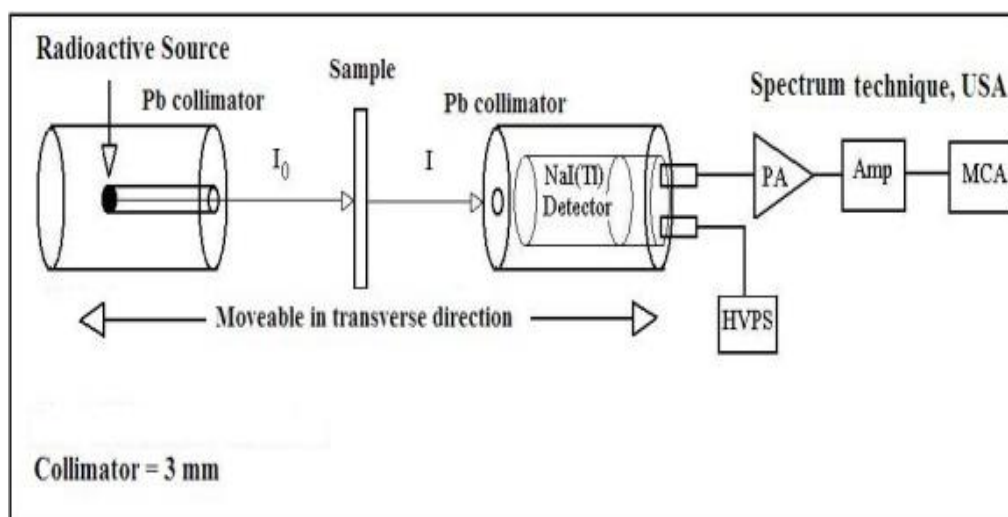


Fig 1 Block Diagram of Gamma Ray Absorption Setup

III. ANALYSIS OF DATA

The relations used in the present work are summarized in this section. The mass attenuation coefficients for Sb-Bi alloys at different energies were determined by performing transmission experiments and the experimental values were compared by values obtained from following semi empirical relations.

$$I = I_0 \exp(-\mu_m t) \quad (2)$$

Where I_0 and I are the un- attenuated and attenuated photon intensities

$\mu_m = \mu/\rho$ (cm²/g) is the mass attenuation coefficient

t (g/cm²) is sample mass thickness (the mass per unit area)

The total mass attenuation coefficient μ_m for any chemical compound or mixture of elements is given by mixture rule.

$$\mu_m = \sum_i w_i (\mu_m)_i \quad (3)$$

Where w_i is the weight fraction (the proportion by weight) $(\mu_m)_i$ is the mass attenuation coefficient of i th element

For a material composed of multi elements the fraction by weight is given by

$$w_i = \frac{n_i A_i}{\sum_i n_i A_i} \quad (4)$$

Where A_i is the atomic weight of the i th element and n_i is the number of formula units.

The total atomic cross-section σ_t for materials can be obtained from the measured values of μ_m using the following relation

$$\sigma_t = \frac{\mu_m N}{N_A} \quad (5)$$

Where $N_A = \sum_i n_i A_i$ is atomic mass of materials N_A is the Avogadro's number.

The total electronic cross-section σ_e for the element is expressed by the following equation

$$\sigma_e = \frac{1}{N_A} \sum_i \frac{f_i N_i}{Z_i} (\mu_m)_i = \frac{\sigma_t}{Z_{eff}} \quad (6)$$

Where f_i denotes the fractional abundance of the element i with respect to the number of atoms such that $f_1 + f_2 + f_3 + f_4 + \dots + f_i = 1$, Z_i is the atomic number of i th element

The total atomic cross-section σ_t and total electronic cross-section σ_e are related to the effective atomic number (Z_{eff}) of the material through the following relation.

$$Z_{eff} = \frac{\sigma_t}{\sigma_e} \quad (6)$$

The effective electron number or electron density N_e (number of electrons per unit mass) can be derived by using the following relation

$$N_e = \frac{N_A}{N} Z_{eff} \sum_i n_i = \frac{\mu_m}{\sigma_e} \quad (7)$$

Finally, the average distance between two successive interactions, called the photon mean free path (λ), is given by

$$\lambda = \frac{\int_0^\infty x \exp(-\mu x) dx}{\int_0^\infty \exp(-\mu x) dx} = \frac{1}{\mu} \quad (8)$$

Where (μ) is the linear attenuation coefficient and x is the absorber thickness

IV. RESULTS AND DISCUSSIONS

The combined results show that photon attenuation is controlled by photon energy, alloy composition and density. The reduction in μ/ρ from 661.6 to 1332 keV is systematic for every sample. The larger spread in μ demonstrates the additional role of density. For practical shielding design, linear attenuation coefficient and mean free path are therefore more directly related to required physical thickness, whereas μ/ρ is more convenient for composition-based comparisons [5,38–40].

The close agreement of SE and XCOM with experiment indicates that mixture-rule and semi-empirical approaches are suitable for estimating the photon-interaction behaviour of the investigated alloys. Similar agreement has been reported for metallic alloys, glasses, dosimetric compounds and other composite materials [15–18,32,35,37]. Deviations can arise from sample inhomogeneity, density and thickness uncertainty, counting statistics, background correction and the difference between an idealized mixture and a real metallurgical alloy.

Bismuth-containing materials have been widely investigated as lead-free gamma-shielding materials, and

recent studies of Bi-based alloys demonstrate the continuing interest in combining radiation attenuation with useful mechanical properties [38,40]. The present results indicate that Sb–Bi alloy composition can significantly change Z_{eff} , μ/ρ , μ and λ . Nevertheless, shielding suitability should be judged using attenuation coefficient, density, mechanical behaviour, corrosion, processing, cost and environmental considerations rather than Z_{eff} alone [38–40].

➤ Mass Attenuation Coefficient

Table 1 lists the measured values of the mass attenuation coefficient from the experimental, semi-empirical formula, and XCOM values. Figure 1 shows that it peaks at 661.6 keV and falls at 1173 and 1332 keV for all

samples. At 661.6 keV the experimental values rise from 8.211×10^{-2} to $11.02 \times 10^{-2} \text{ cm}^2 \text{ g}^{-1}$ across Samples 1–5. At 1173 keV the range is 5.62×10^{-2} – $6.301 \times 10^{-2} \text{ cm}^2 \text{ g}^{-1}$ and at 1332 keV it is 5.20×10^{-2} to $5.80 \times 10^{-2} \text{ cm}^2 \text{ g}^{-1}$. This energy dependence is consistent with established photon-interaction behaviour in the MeV region [5,6,12,18].

Across all 15 points, the mean absolute experimental deviation from XCOM is about 3.89%, while the corresponding deviation from SE is about 3.64%. The maximum EXP–XCOM difference is about 8.33%. Similar few-per cent differences between measured and mixture-rule/XCOM results are reported in alloy and composite studies [15,16,32,35,37,38].

Table 1 Mass Attenuation Coefficient, μ/ρ .

Composition	661.6/X COM	661.6/S E	661.6/EX P	1173/X COM	1173/S E	1173/EX P	1332/XCOM	1332/S E	1332/EX P
Sb _{0.9} Bi _{0.1}	7.950	7.953	8.211	5.370	5.369	5.62	4.990	4.991	5.200
Sb _{0.7} Bi _{0.3}	8.690	8.691	8.902	5.570	5.567	5.956	5.150	5.317	5.579
Sb _{0.5} Bi _{0.5}	9.420	9.425	9.987	5.723	5.765	5.986	5.300	5.301	5.504
Sb _{0.3} Bi _{0.7}	10.20	10.159	10.423	5.960	5.962	6.104	5.460	5.455	5.603
Sb _{0.1} Bi _{0.9}	10.90	10.893	11.020	6.160	6.160	6.301	5.610	5.611	5.800

Units: $10^{-2} \text{ cm}^2 \text{ g}^{-1}$. Values reproduced from the submitted dataset.

➤ Linear Attenuation Coefficient

Table 2 lists the measured values of the linear attenuation coefficient from the experimental, semi-empirical formula, and XCOM values. Figure 2 shows that it peaks at 661.6 keV and falls at 1173 and 1332 keV for all samples

The linear attenuation coefficient combines mass attenuation with density. Experimental values at 661.6 keV range from 58.64×10^{-2} to $104.6426 \times 10^{-2} \text{ cm}^{-1}$; at 1173 keV they range from 39.37×10^{-2} to $59.8324 \times 10^{-2} \text{ cm}^{-1}$; and at

1332 keV from 36.428×10^{-2} to $55.077 \times 10^{-2} \text{ cm}^{-1}$. The stronger spread in μ than in μ/ρ highlights the importance of density in practical shielding design [5,38–40].

The average absolute EXP–XCOM difference is about 4.33%. The largest isolated difference is approximately 12.94% at 1173 keV. This point should be evaluated against the original density and transmission-count uncertainty before being interpreted as a limitation of the theoretical model.

Table 2 Linear Attenuation Coefficient (μ)

Composition	661.6/X COM	661.6/S E	661.6/EX P	1173/X COM	1173/S E	1173/EX P	1332/XCOM	1332/S E	1332/EX P
Sb _{0.9} Bi _{0.1}	55.72	37.611	34.963	55.72	37.611	34.96	58.64	39.37	36.428
Sb _{0.7} Bi _{0.3}	66.279	42.465	39.253	66.294	42.462	40.556	67.904	45.429	42.555
Sb _{0.5} Bi _{0.5}	77.753	43.728	43.736	77.761	47.56	43.732	80.079	49.388	45.406
Sb _{0.3} Bi _{0.7}	90.151	52.91	48.412	90.142	52.904	48.407	89.015	54.161	49.72
Sb _{0.1} Bi _{0.9}	103.41	58.493	53.271	103.44	58.495	53.276	104.64	59.832	55.077

Units: 10^{-2} cm^{-1} . Values reproduced from the submitted dataset.

➤ Mean Free Path

Table 3 lists the measured values of the Mean free path from the experimental, semi-empirical formula, and XCOM values. Figure 3 shows that Mean free path is inversely related to the linear attenuation coefficient. For Sample 1 the experimental λ is 1.7385 cm at 661.6 keV, 2.54 cm at 1173 keV and 2.7452 cm at 1332 keV. Across Samples 1–5 at 661.6 keV, λ decreases from 1.7385 to 0.9556 cm,

indicating stronger attenuation per unit thickness toward the high- μ end of the series.

The average absolute EXP–XCOM difference in λ is approximately 3.41%. Because λ is derived from μ , its agreement also provides an independent check of the numerical consistency between the two tables.

Table 3 Photon Mean Free Path, λ (Impact Factor).

Composition	661.6/X COM	661.6/S E	661.6/EX P	1173/X COM	1173/S E	1173/EX P	1332/XCOM	1332/S E	1332/EX P
Sb _{0.9} Bi _{0.1}	1.7947	2.6588	2.8601	1.7948	2.6588	2.8604	1.7385	2.54	2.7452

Sb _{0.7} Bi _{0.3}	1.5088	2.3549	2.5476	1.5084	2.355	2.4657	1.4727	2.2013	2.3499
Sb _{0.5} Bi _{0.5}	1.2861	2.223	2.2865	1.286	2.2232	2.2867	1.3232	2.148	2.2024
Sb _{0.3} Bi _{0.7}	1.1093	1.89	2.0656	1.1094	1.8902	2.0658	1.1234	1.8463	2.0113
Sb _{0.1} Bi _{0.9}	0.967	1.7096	1.8772	0.9668	1.7096	1.877	0.9556	1.6713	1.8156

Units: cm; $\lambda = 1/\mu$.

➤ Total Atomic Cross Section

Table 4 lists the measured values of the Total atomic cross section from the experimental, semi-empirical formula, and XCOM values. Figure 4 shows that Experimental σ_t at 661.6 keV increases from $1.7322 \times 10^{-23} \text{ cm}^2$ to $3.568 \times 10^{-23} \text{ cm}^2$ across Sample 1- Sample 5. At 1173 keV the values are 1.1856 – $2.0401 \times 10^{-23} \text{ cm}^2$, and at 1332 keV they are 1.097 – $1.878 \times 10^{-23} \text{ cm}^2$. The trends follow

those of the attenuation coefficient because σ_t is derived from μ/ρ and the effective atomic mass [12,15,16].

The average absolute EXP–XCOM difference is about 4.78%. The larger deviations at selected points are inherited from the experimental attenuation data and should be interpreted together with the uncertainty of density, sample thickness and transmitted intensity.

Table 4 Total Atomic Cross Section, σ_t .

Composition	661.6/X CO M	661.6/S E	661.6/EX P	1173/X CO M	1173/S E	1173/EX P	1332/XCO M	1332/S E	1332/EX P
Sb _{0.9} Bi _{0.1}	1.678	1.1327	1.0529	1.6779	1.1326	1.0528	1.7322	1.1856	1.097
Sb _{0.7} Bi _{0.3}	2.008	1.2865	1.1892	2.0084	1.2864	1.2287	2.0572	1.3763	1.2892
Sb _{0.5} Bi _{0.5}	2.4078	1.354	1.3542	2.4078	1.4727	1.3541	2.6099	1.5292	1.406
Sb _{0.3} Bi _{0.7}	2.9017	1.703	1.5582	2.9014	1.7028	1.5581	2.8651	1.7433	1.6003
Sb _{0.1} Bi _{0.9}	3.4094	1.9945	1.8164	3.5269	1.9945	1.8166	3.568	2.0401	1.878

Units: 10^{-23} cm^2 .

➤ Total Electronic Cross Section

Table 5 lists the measured values of the Total electronic cross section from the experimental, semi-empirical formula, and XCOM values. Figure 5 shows that Experimental σ_e ranges from 3.266×10^{-25} to $4.569 \times 10^{-25} \text{ cm}^2$ at 661.6 keV, from 2.235×10^{-25} to $2.612 \times 10^{-25} \text{ cm}^2$ at 1173 keV, and from 2.068×10^{-25} to $2.405 \times 10^{-25} \text{ cm}^2$ at 1332

keV. The average absolute EXP–XCOM difference is about 4.39%.

The relationship $Z_{\text{eff}} = \sigma_t/\sigma_e$ is reproduced by the supplied data. For Sample 1 at 661.6 keV, $1.678 \times 10^{-23}/(3.1633 \times 10^{-25}) = 53.05$, matching the tabulated Z_{eff} of 53.0451. Similar agreement occurs throughout the dataset.

Table 5 Total Electronic Cross Section, σ_e .

Composition	661.6/X CO M	661.6/S E	661.6/EX P	1173/X CO M	1173/S E	1173/EX P	1332/XCO M	1332/S E	1332/EX P
Sb _{0.9} Bi _{0.1}	3.1633	2.1353	1.9849	3.163	2.135	1.985	3.266	2.235	2.068
Sb _{0.7} Bi _{0.3}	3.4818	2.2308	2.0621	3.483	2.231	2.131	3.567	2.386	2.236
Sb _{0.5} Bi _{0.5}	3.8107	2.1431	2.1435	3.811	2.331	2.143	3.905	2.42	2.225
Sb _{0.3} Bi _{0.7}	4.154	2.438	2.2307	4.154	2.438	2.231	4.102	2.496	2.291
Sb _{0.1} Bi _{0.9}	4.3654	2.5537	2.3257	4.5159	2.554	2.326	4.569	2.612	2.405

Units: 10^{-25} cm^2 .

➤ Effective Atomic Number

Table 6 lists the measured values of the Effective atomic number from the experimental, semi-empirical formula, and XCOM values. Figure 6 shows that Z_{eff} increases from 53.0451 to 78.0996 across Samples 1–5. The same Z_{eff} values are reported for XCOM, SE and EXP,

indicating that this parameter was derived consistently from cross-section relationships rather than being independently measured as a primary transmission observable. Effective atomic number is a composition dependent but neither energy nor calculation method dependent it is a unique material constant [12–20].

Table 6 Effective Atomic Number, Z_{eff} .

No.	Composition	Z_{eff} at 661.6 keV	Z_{eff} at 1173 keV	Z_{eff} at 1332 keV
1	Sb _{0.9} Bi _{0.1}	53.0451	53.0451	53.0451
2	Sb _{0.7} Bi _{0.3}	57.6703	57.6703	57.6703
3	Sb _{0.5} Bi _{0.5}	63.1791	63.1791	63.1791
4	Sb _{0.3} Bi _{0.7}	69.8515	69.8515	69.8515
5	Sb _{0.1} Bi _{0.9}	78.0996	78.0996	78.0996

➤ Effective Electron Number

Table 7 lists the measured values of the Effective electron number from the experimental, semi-empirical formula, and XCOM values. Figure 7 shows that N_{eff} decreases from 2.5144×10^{23} to 2.4121×10^{23} electrons g^{-1} . It is nearly independent of photon energy and measurement

method in the supplied dataset because it is principally a composition-weighted Z/A quantity [12–18]. The simultaneous increase of Z_{eff} and decrease of N_{eff} illustrates that these parameters describe different aspects of photon interaction and should not be used interchangeably. It is noticed that N_{eff} decreases with increasing Bi composition.

Table 7 Effective Electron Number (N_{eff})

No.	Composition	Z_{eff} at 661.6 keV	Z_{eff} at 1173 keV	Z_{eff} at 1332 keV
1	$\text{Sb}_{0.9}\text{Bi}_{0.1}$	2.5144	2.5144	2.5144
2	$\text{Sb}_{0.7}\text{Bi}_{0.3}$	2.4955	2.4955	2.4955
3	$\text{Sb}_{0.5}\text{Bi}_{0.5}$	2.4731	2.4731	2.4731
4	$\text{Sb}_{0.3}\text{Bi}_{0.7}$	2.4458	2.4458	2.4458
5	$\text{Sb}_{0.1}\text{Bi}_{0.9}$	2.4121	2.4121	2.4121

➤ Quantitative Comparison

Table 8 Overall Absolute Percentage Deviations of Experimental Values.

Parameter	Mean EXP–XCOM	Maximum EXP–XCOM	Mean EXP–SE	Maximum EXP–SE
Mass attenuation coefficient	3.89%	8.33%	3.64%	6.99%
Linear attenuation coefficient	4.33%	12.94%	3.49%	6.99%
Mean free path	3.41%	7.76%	3.21%	6.53%
Total atomic cross section	4.78%	12.94%	3.71%	8.39%
Total electronic cross section	4.39%	12.92%	3.31%	6.95%

Overall, the SE and XCOM calculations reproduce the experimental attenuation behavior within a few per cent for most points. The semi-empirical values are slightly closer on average for several primary parameters. The larger isolated discrepancy at 1173 keV should be evaluated using the

original experimental uncertainty rather than being assigned automatically to the theory. Z_{eff} and N_{eff} are derived quantities and should be identified as such in the final manuscript [12,17,35].

V. GRAPHICAL REPRESENTATION

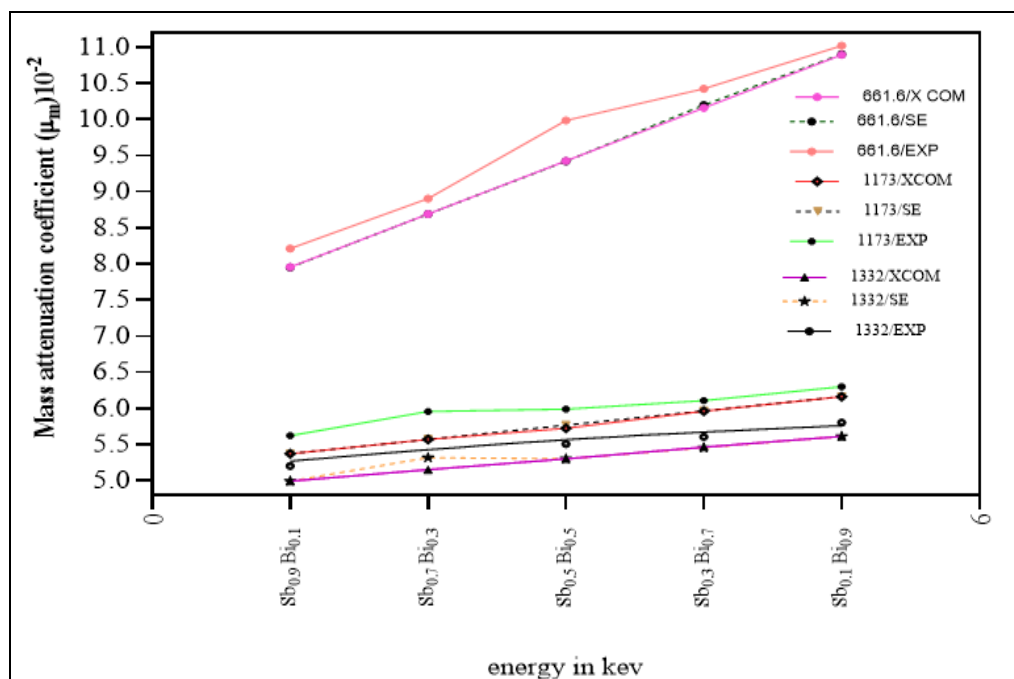


Fig 2 Variation of Values of Mass Attenuation Coefficient μ_m With Energy

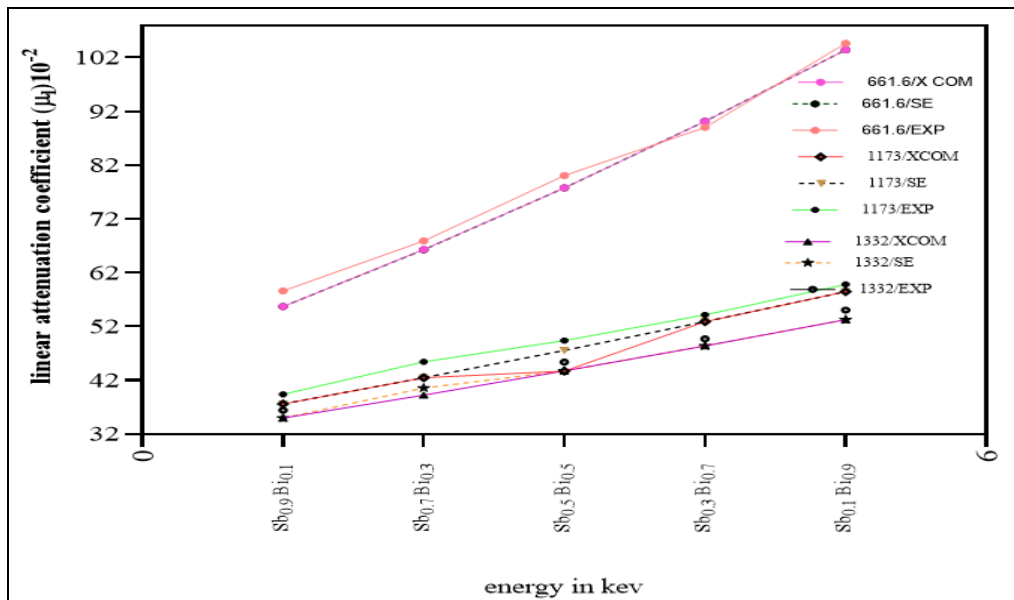


Fig 3 Variation of Values of Linear Attenuation Coefficient μ_l With Energy

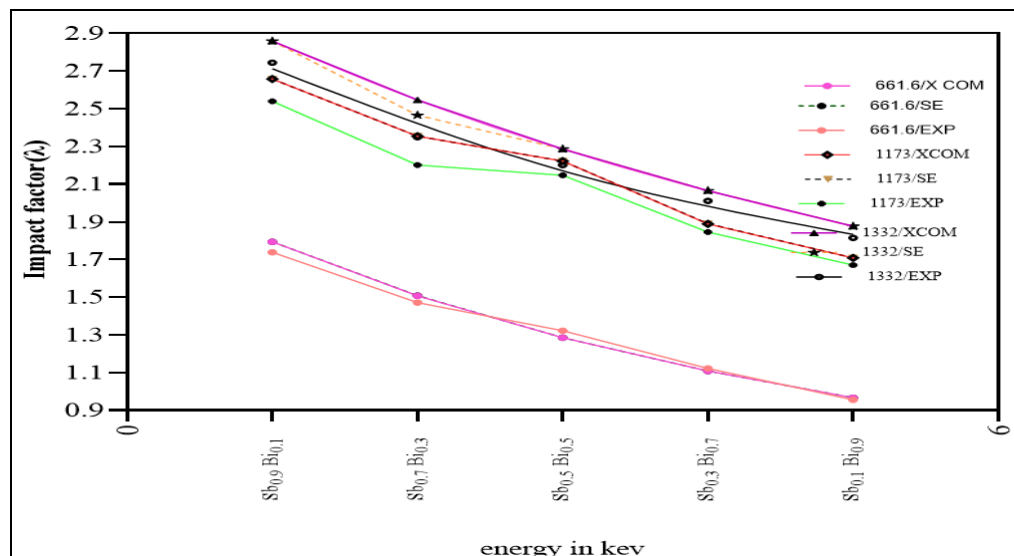


Fig 4 Variation of Values of Impact Factor (λ) with Energy

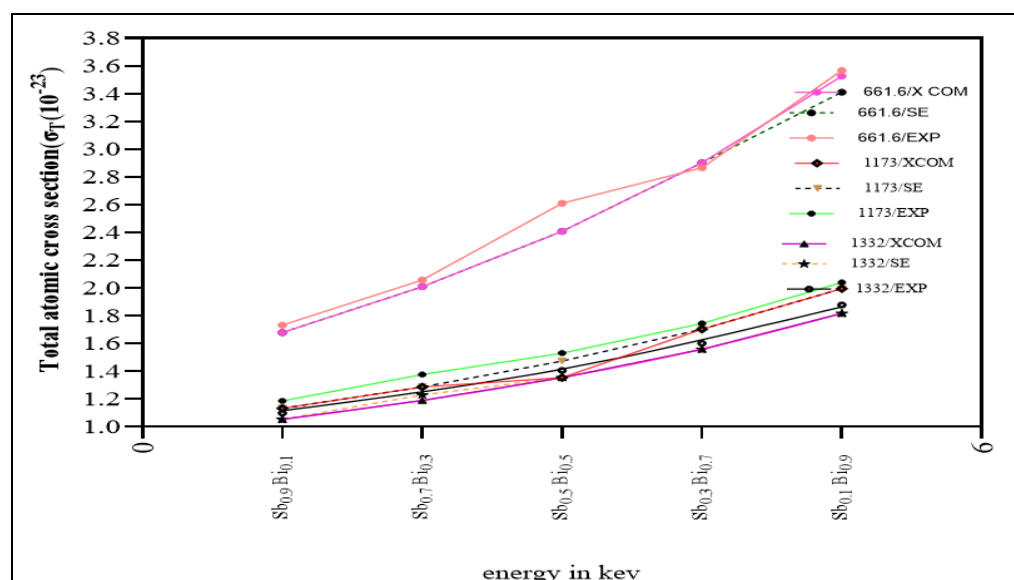


Fig 5 Variation of Total Atomic Cross Section ($\sigma_T(10^{-23})$) with Energy

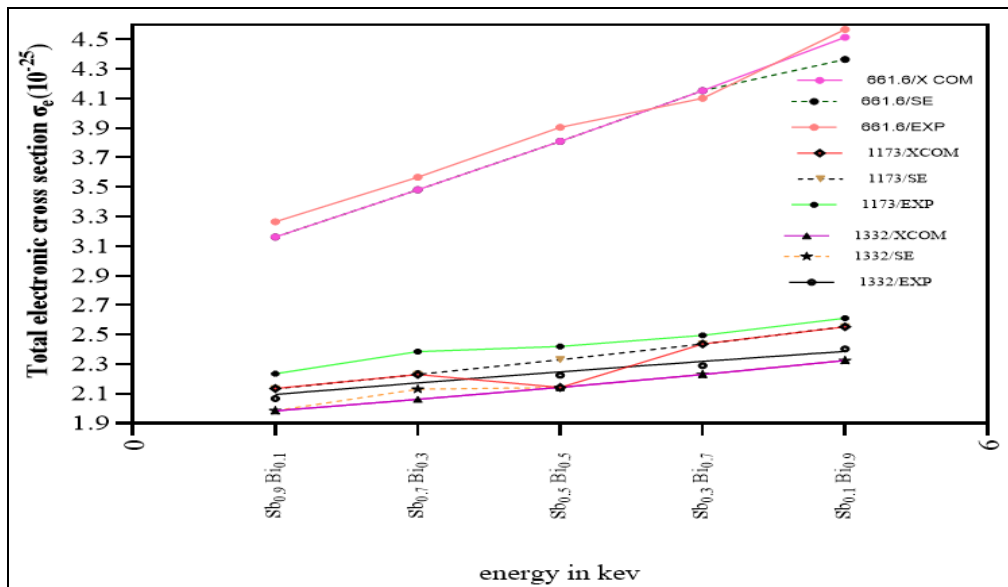


Fig 6 Variation of Total Electronic Cross Section σ_e (10^{-25}) with Energy

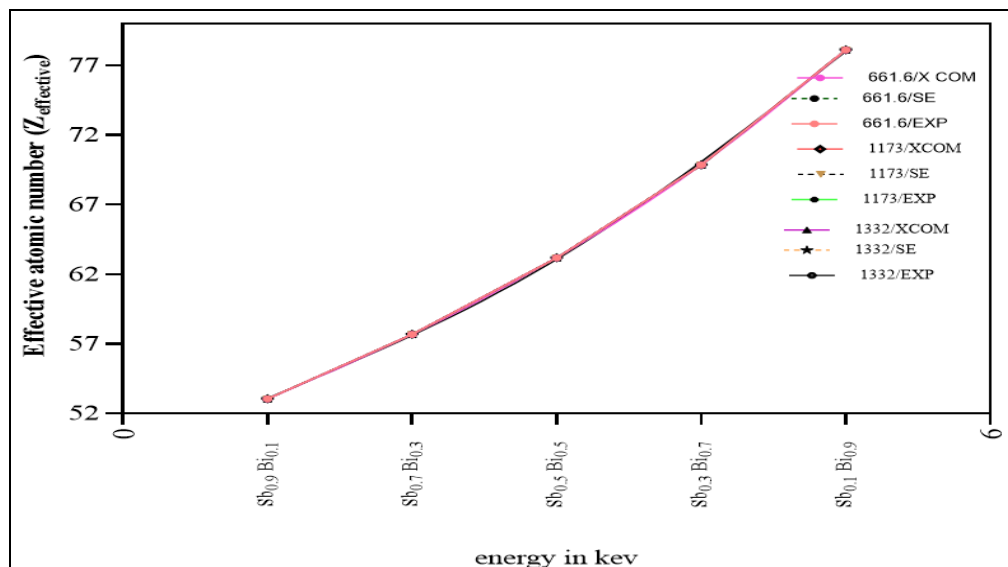


Fig 7 Variation of Effective Atomic Number ($Z_{\text{effective}}$) with Energy

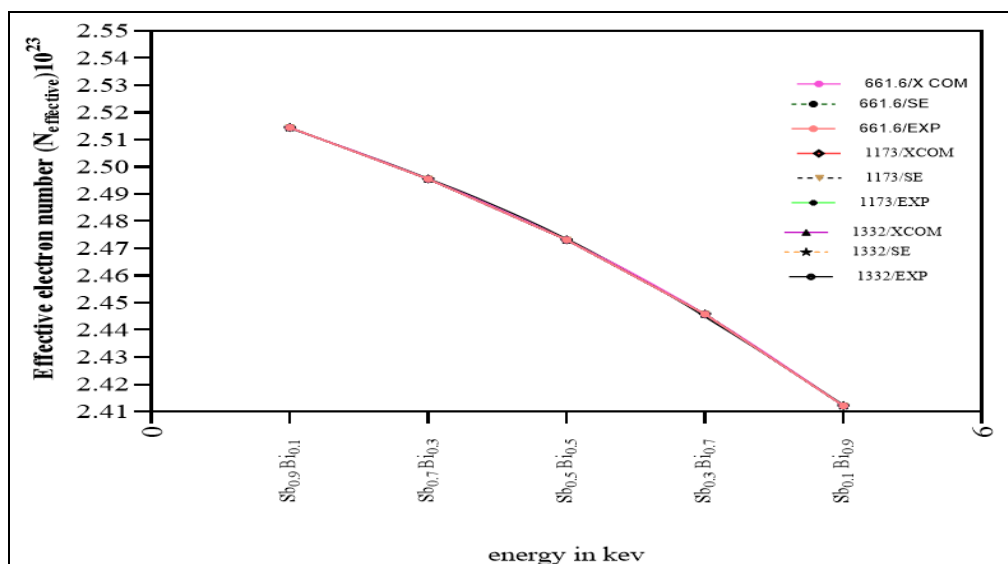


Fig 8 Variation of Effective Electron Number ($N_{\text{effective}}$) 10^{23} with Energy

VI. CONCLUSIONS

- The Sb–Bi dataset exhibits a systematic decrease of mass attenuation coefficient with increasing photon energy from 661.6 to 1332 keV.
- At 661.6 keV, experimental μ/ρ increases from 8.211×10^{-2} to $11.02 \times 10^{-2} \text{ cm}^2 \text{ g}^{-1}$ across Samples 1–5; corresponding ranges are 5.62×10^{-2} to 6.301×10^{-2} at 1173 keV and 5.20×10^{-2} to 5.80×10^{-2} at 1332 keV.
- Linear attenuation coefficient and mean free path obey the expected relationship $\mu = \rho \mu_m$ and $\lambda = 1/\mu$.
- Total atomic and electronic cross sections are mutually consistent and reproduce Z_{eff} through $Z_{\text{eff}} = \sigma_t/\sigma_e$.
- Z_{eff} rises from 53.0451 to 78.0996, while N_{eff} decreases from 2.5144×10^{23} to 2.4121×10^{23} electrons g^{-1} .
- The average absolute experimental deviations from XCOM are approximately 3.89% for μ/ρ , 4.33% for μ , 3.41% for λ , 4.78% for σ_t and 4.39% for σ_e .
- The data support XCOM and semi-empirical calculations as useful predictive tools for photon-interaction studies of Sb–Bi alloys.

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