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Mass Attenuation Coefficient and Effective Atomic Number for Cu, Zn and Ag Alloys by Attenuation of Compton Scattered 662 keV Gamma Rays

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ABSTRACT: The mass attenuation coefficients (μ/ρ) and effective atomic numbers (Z_{eff}) of Cu–Ag, Cu–Zn and Ag–Zn alloys were experimentally studied with Compton-scattered gamma photons from a 662 keV ^{137}Cs source. By changing the angle of scattering from 45° to 0° , we had scattered photon energies in the range of (479–662) keV. Spectra were accumulated as an attenuated spectra with a resolution exceeding 256 channels using the NaI (Tl) scintillation detector coupled to the multichannel analyser (8K). FLUKA simulation and maximum-likelihood expectation-maximization (MLEM) deconvolution were used for photopeak reconstruction and peak discrimination enhancement. Mass attenuation coefficients were determined both experimentally by the Beer–Lambert law, and theoretically through the mixture rule and reference attenuation values. Then, atomic and electronic cross-sections were calculated in order to estimate Z_{eff} for each alloy composition. The measured attenuation coefficients exhibited a decreasing trend with increasing photon energy and were in good agreement with theoretical values. Results validate the utility of MLEM-complemented Compton-scattering measurements in describing photon attenuation in metallic alloy and suggest applicability to radiation-interaction, shielding and nondestructive-evaluation studies.

1. INTRODUCTION:

The wide spread utilization of gamma radiation in medical dosimetry, industries and basic sciences is becoming key aspects in handling radioactive sources. Therefore, needs accurate measurement of attenuation parameters such as μ/ρ and Z_{eff} . These parameters have immense importance for highly penetrating gamma radiations. The scattering of attenuated photons correlated with density and effective atomic mass number of absorbers. The electron density is important in radiography, imaging and in metrological science.

Hubbell and Seltzer (NIST, 1995) compiled theoretical mass attenuation coefficients (μ/ρ) for elements and selected biological materials over the 10 keV–100 MeV photon energy range. Shivalinge Gowda et.al (2004) measured photon attenuation coefficient with effective atomic number of thermo luminescent dosimetric compounds using range wise interpolation (best fit) method. The P. Limkitjaroenporn et.al (2012) measured mass attenuation coefficients and hence effective atomic numbers for Ag, Cu and Zn alloys at various composition by using Compton Scattering geometries. Singh et.al. (2008) measured attenuation shielding parameters for barium-borate fly ash glasses in the gamma ray energies (356 keV to 1332 keV) using

scattering method. I. Han (2009) determined μ/ρ and Z_{eff} electron numbers for several alloys at gamma energies sources Am^{221} and Cd^{109} . V.P Singh (2012) calculated Z_{eff} electron densities of some gases and biological sample from 10 keV to MeV photons for dosimetry interest. The spectral quality of Compton scattered gamma rays has wide FWHM which degrades resolution of scattered peak. Therefore Sangam et.al. (2019), Deshpande et. al. (2026) used deconvolution of attenuated spectra to improve resolution of attenuation parameters which mostly depends on geometrical factors.

In this study the μ/ρ and Z_{eff} of 3d and 4d metal alloy of AR grade Cu, Zn and Ag have measured at gamma ray photon in the range of 479-662 keV generated by Compton scattered photon of energy 662 keV radioactive source. The photo-peak generated after and before attenuation of spectra were analyzed by employing FLUKA and MLEM deconvolution software on counts respective channel energy of spectrum. The result obtained were compared with theoretical values given by Hubbell.

2. METHODOLOGY:

The effective atomic numbers were calculated from total photon attenuation coefficients μ/ρ for metal alloys were computed by Bear-Lambert exponential law in terms of mass thickness (ρt) of alloys with I_0 and I incident and transmitted counts without and with alloy foil absorber is

$$\left(\frac{\mu}{\rho}\right) = \frac{1}{\rho t} \ln \left(\frac{I_0}{I}\right), \text{ cm}^2/\text{gm} \quad (1)$$

where I_0 and I are the intensities of attenuated counts before and after attenuation of absorber and thickness of absorber $t = \rho \cdot x$ (gm/cm^2). The mass thickness of alloys is kept homogeneous during chemical process to prepare alloy foils.

The total mass attenuation coefficient of alloy has calculated theoretically by using mixture rule to elemental (μ/ρ) alloy values given in (NIST 1995).

$$\left[\frac{\mu}{\rho}\right] = \sum_i^n W_i \left(\frac{\mu}{\rho}\right)_i \quad (2)$$

where W_i is the fraction by weight for i^{th} element of homogeneous mixture.

The fraction by weight W_i by considering impurities present in pure metal is

$$W_i = \frac{n_i A_i}{\sum_j n_j A_j} \quad (3)$$

Where $W_1 + W_2 + W_3 + \dots + W_n = 1$, n_i is the number units in alloy w.r.t. i^{th} atomic weight (A_i).

Total atomic cross section (σ_a) of metal alloys in terms of mass attenuation coefficient is

$$\sigma_a = \frac{\left(\frac{\mu}{\rho}\right)}{n_i \sum_{i=1}^n \left(\frac{W_i}{A_i}\right)} \quad (4)$$

and electronic cross-section is

$$\sigma_e = \frac{1}{N_A} \sum_{i=1}^n \frac{f_i A_i}{Z_i} \left(\frac{\mu}{\rho}\right)_i \quad (5)$$

where Z_i is the atomic weight of i^{th} element in alloy f_i is the number of i^{th} atoms w.r.t. Z_i and N_A is Avogadro's number.

The effective atomic numbers for gamma photons is given by ratio of equation (4) and (5)

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} = \frac{\frac{\left(\frac{\mu}{\rho}\right)}{n_i \sum_{i=1}^n \left(\frac{W_i}{A_i}\right)}}{\frac{1}{N_A} \sum_{i=1}^n \frac{f_i A_i}{Z_i} \left(\frac{\mu}{\rho}\right)_i} \quad (6)$$

The effective electron number (N_{eff}) is given by

$$N_{eff} = \frac{N_A}{N} Z_{eff} \sum n_i = \frac{\left(\frac{\mu}{\rho}\right)_{Alloy}}{\sigma_e} \quad (7)$$

3. MEASUREMENTS

A] Experimental Arrangement

The radioactive source (Cs^{137}) castle, aluminum scattering foil with table and 2" x 2" planar NaI (Tl) detector with lead shield are mounted on goniometer setup shown in figure 1. The radioactive source of energy 662 keV having activity 10 mCi is encapsulated in lead shield container. The scintillation head and source castle are mounted in opposite manner such that they can move angularly. The goniometer arms designed to rotate detector head by keeping position of source and aluminum absorber constant on angular scale.

The Compton scattering of 662 keV gamma rays by aluminum absorber at various angles is shown in Fig 1.

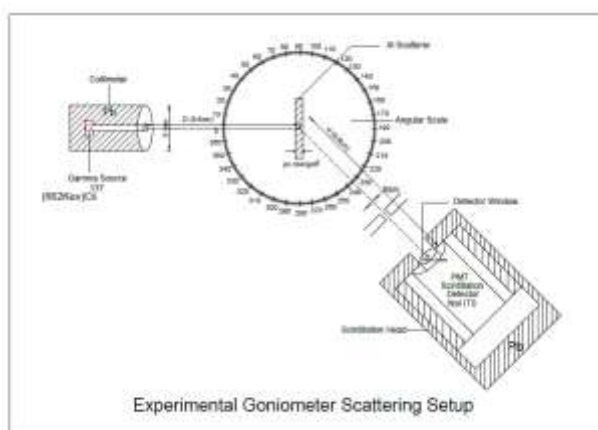


Fig. 1. Experimental setup

The output of detector is coupled to amplifier scalars, converters (ADC) and 8K multichannel analyzer. The distance between source to aluminum foil absorber is 8.3 cm and absorber to NaI (Tl) window surface is 9.6 cm. The collimator C_1 and C_2 has 0.8 cm entrance diameter so as to get fine narrow beam of photons. The aluminum absorber foils positioned in line with beam and is held in the place with the movable support stand in the circular angular scale. The geometry is shielded by 3mm thick lead foil to prevent background radiation from cosmic rays. The NaI (Tl) detector bin consisting of preamplifier, scalars, scintillation head, high voltage power supply, ADC converter and 8K Multi channel analyzer (MCA) are arranged so that the whole scattering histogram along with 662 keV energy photo peak is visible on computer screen. The goniometer scattering angle is selected between 0° to 45° to get inelastic photons.

Initially the MCA setting was calibrated with known gamma energy sources Co^{57} , Cs^{137} and Na^{23} . The accumulation time is selected 600 seconds. The accumulated scattering spectra has Photomultiplier tube (PMT) thermal noise, background spectra and Compton scattered peaks needs unfolding by means of MLEM deconvolution to get resolute peak described in earlier work¹⁵.

The Compton scattered spectrum comprising number of interaction peaks such as back scattered peak, blast current noise and interested Compton peak. The poor resolution of detector could not discriminate the nearby counts because of limitations assigned by the multichannel analyzer (MCA) software. The incoherent differential scattering cross sections as a function of scattering angle have been measured with a NaI (Tl) scintillation detector coupled to a goniometer. FLUKA simulation software was used to model the exact experimental setup and generate the Compton scattering peak for accurate determination of attenuation counts and MLEM simulator to have correct peak position and pulse height ratio analysis.

The multiple detector spectrum has scattering effect which is minimized by adjusting the distance between source to target and scatterer to detector face with minimum scattering angle. The differential cross-sectional counts have elastic and inelastic scattering peak. In this experiment inelastic scattering region counts were used for our investigation. The small correction angle was applied to attenuated spectra.

The non-uniformity of the alloy absorber contributes to a fractional uncertainty of about half the root mean square deviation in mass per unit area. The deviation in mass attenuation coefficient (μ/ρ) because of non-uniformity is given by relation (R.W. Carter 1967) as

$$\Delta\left(\frac{\mu}{\rho}\right) = \frac{1-BQQ\left(\frac{1}{\alpha}\left(\frac{\rho}{\mu}\right)\sinh\left(\alpha\frac{\rho}{\mu}\right)\right)}{\ln(R)} \quad (8)$$

where R is the mean transmission ratio for obtaining the value of (μ/ρ) , α is the maximum deviation in absorber thickness and ρ is the density of the absorber. The maximum uncertainty in the measured mass per unit area is 2 to 3 %. The experimental values of mass attenuation coefficient, σ_a , σ_{el} and Z_{eff} for various alloys combinations at different gamma energies are shown in Table 3 to 6.

B] Deconvolution of Compton scattered photo-peak

The Compton Scattered interest photo-peak counts respective to energy channels (E) is given in terms of intensity of scattered spectra $S(E)$ and detector response function $R(n, E)$ in integral form as

$$M_{(n)} = \int_{E_L}^{E_U} S(E) \cdot R(n, E) \cdot dE \quad (9)$$

Where E_L and E_U are lower and upper energy of selected limits photo peak.

If the alloy foil of having mass thickness X ($\rho \cdot t$) is placed between aluminum scatterer and detector, then the mass attenuation coefficient w.r.t. channel counts $A(E, X)$ is written as

$$A(E, X) = -e^{\left[-\left(\frac{\mu}{\rho}\right) \cdot X\right]} \quad (10)$$

Equation (8) in terms of channel intensities becomes

$$M_{(n, x)} = \int_{E_L}^{E_U} S(E) \cdot R(n, E) \cdot A(E, X) \cdot dE \quad (11)$$

The equation (11) in terms of summation given by

$$M_i(E) = \sum_{j=1}^n R_{ij} S_j \quad (12)$$

The interested photo-peak has small range of energy channels. The Compton scattering photo-peaks response matrix for linear counts energy for small linear portion of energy range the equations (11) can be written as matrix form as

$$\begin{bmatrix} M_1 \\ \vdots \\ M_i \\ \vdots \\ M_n \end{bmatrix} = \begin{bmatrix} R_1 & \cdots & R_{ij} \\ \vdots & \cdots & \vdots \\ R_i & \cdots & R_{ij} \end{bmatrix} \begin{bmatrix} S_1 \\ \vdots \\ S_2 \end{bmatrix} \quad (13)$$

The matrix M_i are the MCA counts, R_{ij} is the response function of the detector and S_j is the continuous distribution of incoming photons. The matrix R_{ij} is constructed such that i th rows represents counts corresponding to respective channels and j th columns are incident photon energies. The true counts per energy channel can be obtained by multiplying equation (13) by inverse matrix $(R_{ij})^{-1}$ gets

$$S = R^{-1} M \quad (14)$$

The bins of spectrum is adjusted such that rows and columns are equal number to have square matrix. The true counts bins will be affected by quantization error generated by ADC converters.

To retrieve true nearby energy peaks needs unfolding peak counts by applying *MLEM* deconvolution procedure given by L.B. Lucy (1974) is applied to equation (12). The *MLEM* maximizes the likelihood for each bin or intervals of equal width for appropriate counting statistics given by spectra. The iterative algorithm is applied for spectrum to obtain best fit.

The *MLEM* algorithm¹⁵, at every iteration, a new value of $X_e^{(n+1)}$ computed and this process continues until the tolerance value is attained. The tolerance value (T_n) in algorithm is calculated

$$T_{ol} = \frac{\sum_{j=1}^N (x_{(j+1)}^{(n)} - x_j^{(n)})^2}{\sum_{j=1}^N (x_j^{(n)})^2} \quad (15)$$

The iterative unfolds the spectral peaks with better resolution. The resolution of the photo-peak and the corresponding mass attenuation coefficient of the Al absorber at different scattering angles, before and after MLEM deconvolution, are summarized in Table 1.

C] Graphical estimation of Z_{eff} :

Elemental cross section exhibits nonlinear dependence on both gamma photon energy E and atomic number Z , therefore relation of this type expressed by

$$\sigma_a = AE^{-B} \quad (16)$$

where A and B are constants of energy variation in equation (16) and may be described as

$$\ln(\sigma) = \ln(A) - B \cdot \ln(E) \quad (17)$$

If $B > 0$ the graph decreases with energy then B should come negative. If the graph slopes downward $B < 0$. Equation (17) has straight line nature slope B and $\ln A$ as intercept. The obtained values of A and B are given in Table 2.

Further $\ln A$ is a function of atomic numbers then it can be written as,

$$A = A_1 Z^{B_1} \quad (18)$$

Plotting graph of $\ln(A)$ versus $\ln(Z)$ has a nature of straight line with best fit. The coefficient A_1 and B_1 were obtained graphically from equation (18) for various compositions of Cu-Ag and Cu-Zn alloys.

Therefore, it can be written as,

$$\sigma_a = A_1 \cdot Z^{B_1} \cdot E^{-B} \quad (19)$$

The effective atomic number $Z_{(eff)}$ obtained from equation (16)

$$Z_{(eff)} = \left[\frac{\sigma_a \cdot E^B}{A_1} \right]^{1/B_1} \quad (20)$$

Table 1.: Resolution of photo-peak and mass attenuation coefficient of Al absorber after MLEM deconvolution at various scattering angle. (Thickness of Al=324 mg/cm^2)

Scattering angle	Scattering Energy in KeV	Klein-Nishina Differential Cross-section ($\times 10^{-29}$)Barn/Sr	Intensities of Photopeak (MCA)				Intensities of Photopeak (After MLEM)	
			Counts without Al	Counts with Al	FWHM in keV	Resolution	Counts	Resolution
0	662.0000	1.59048	9800	8500	8.69	1.54	9800	6.23
5	658.7525	1.59227	9450	8100	10.45	1.59	9450	8.26
10	649.2223	1.59764	9100	7700	12.06	1.6	9100	10.60
15	634.0127	1.60662	8700	7300	13.06	1.62	8700	10.72
20	614.0272	1.61930	8200	6800	14.71	1.64	8200	10.85
25	590.3450	1.63597	7700	6300	17.78	1.66	7700	11.00
30	564.0937	1.65717	7200	5800	19.27	1.69	7200	11.20
35	536.3414	1.68384	6700	5300	21.96	1.73	6700	11.45

40	508.0236	1.71743	6200	4800	22.15	1.77	6200	11.75
45	479.9039	1.75998	5800	4400	24.04	1.83	5800	12.10

Table 2: Best fit coefficients for various Cu-Ag and Cu-Zn alloy at gamma energy range 479-662 keV.

Alloys of elements	Alloy ID	Z_{eff}	A	B	$\ln(Z)$	$\ln(A)$	Constants
Cu-Ag	Alloy ₁ (Pure Cu ₁₀₀)	47.00000	848.09961	0.63986	3.85015	6.74300	$A_1 = 4.1349 \times 10^5$
	Alloy ₂ (Cu ₇₅ -Ag ₂₅)	43.01088	452.98755	0.56660	3.76145	6.11586	
	Alloy ₃ (Cu ₅₀ -Ag ₅₀)	38.70797	355.52891	0.53892	3.65605	5.87361	$B_1 = -4.134977$
	Alloy ₄ (Cu ₂₅ -Ag ₇₅)	34.05272	192.34986	0.47881	3.52791	5.25932	
Cu-Zn	Alloy ₅ (Pure Cu ₁₀₀)	30.0000	184.08978	0.49594	3.40120	5.21542	$A_1 = 0.66837$
	Alloy ₆ (Cu ₇₅ -Zn ₂₅)	29.7051	195.08978	0.49514	3.39132	5.27346	
	Alloy ₇ (Cu ₅₀ -Zn ₅₀)	29.4435	212.1359	0.50903	3.38247	5.35723	$B_1 = -1.6872$
	Alloy ₈ (Cu ₂₅ -Zn ₇₅)	29.2099	163.71583	0.46946	3.37451	5.09813	

Table 3 : Mass Attenuation Coefficient for various alloy compared with theoretical values.

Scattering Energy (keV)	Mass Attenuation coefficient (μ/p) of Cu-Ag alloys in (cm^2/gm)								Mass Attenuation coefficient (μ/p) of Cu-Zn alloys in (cm^2/gm)							
	Alloy ₁		Alloy ₂		Alloy ₃		Alloy ₄		Alloy ₅		Alloy ₆		Alloy ₇		Alloy ₈	
	$(\mu/p)_{Expt}$	$(\mu/p)_{Th}$	$(\mu/p)_{Expt}$	$(\mu/p)_{Th}$	$(\mu/p)_{Expt}$	$(\mu/p)_{Th}$	$(\mu/p)_{Expt}$	$(\mu/p)_{Th}$	$(\mu/p)_{Expt}$	$(\mu/p)_{Th}$	$(\mu/p)_{Expt}$	$(\mu/p)_{Th}$	$(\mu/p)_{Expt}$	$(\mu/p)_{Th}$	$(\mu/p)_{Expt}$	$(\mu/p)_{Th}$
662.0000	0.0748	0.0763	0.0740	0.0754	0.0730	0.0744	0.0722	0.0735	0.0725	0.0732	0.0722	0.0731	0.0718	0.0729	0.0715	0.0728
658.7525	0.0749	0.0766	0.0741	0.0756	0.0731	0.0747	0.0722	0.0737	0.0727	0.0734	0.0724	0.0732	0.0720	0.0731	0.0717	0.0729
649.2223	0.0755	0.0773	0.0745	0.0763	0.0732	0.0753	0.0727	0.0743	0.0730	0.0739	0.0725	0.0738	0.0723	0.0736	0.0721	0.0735
634.0127	0.0759	0.0785	0.0755	0.0774	0.0736	0.0763	0.0732	0.0753	0.0738	0.0748	0.0737	0.0747	0.0731	0.0743	0.0730	0.0743
614.0272	0.0777	0.0802	0.0766	0.0790	0.0745	0.0778	0.0741	0.0766	0.0748	0.0761	0.0746	0.0759	0.0743	0.0757	0.0742	0.0756
590.3450	0.0786	0.0825	0.0781	0.0811	0.0767	0.0797	0.0753	0.0783	0.0766	0.0776	0.0764	0.0774	0.0757	0.0772	0.0753	0.0771
564.0937	0.0819	0.0852	0.0810	0.0835	0.0788	0.0819	0.0780	0.0803	0.0784	0.0794	0.0783	0.0792	0.0778	0.0790	0.0770	0.0789
536.3414	0.0849	0.0884	0.0821	0.0864	0.0817	0.0845	0.0791	0.0826	0.0799	0.0815	0.0798	0.0813	0.0797	0.0819	0.0785	0.0809
508.0236	0.0875	0.0921	0.0862	0.0898	0.0835	0.0875	0.0810	0.0852	0.0825	0.0838	0.0823	0.0836	0.0815	0.0834	0.0810	0.0832
479.9039	0.0920	0.0963	0.0885	0.0936	0.0861	0.0909	0.0845	0.0881	0.0846	0.0864	0.0845	0.0861	0.0848	0.0859	0.0834	0.0857

Table 4: Effective atomic cross-section for various alloy compared with theoretical values.

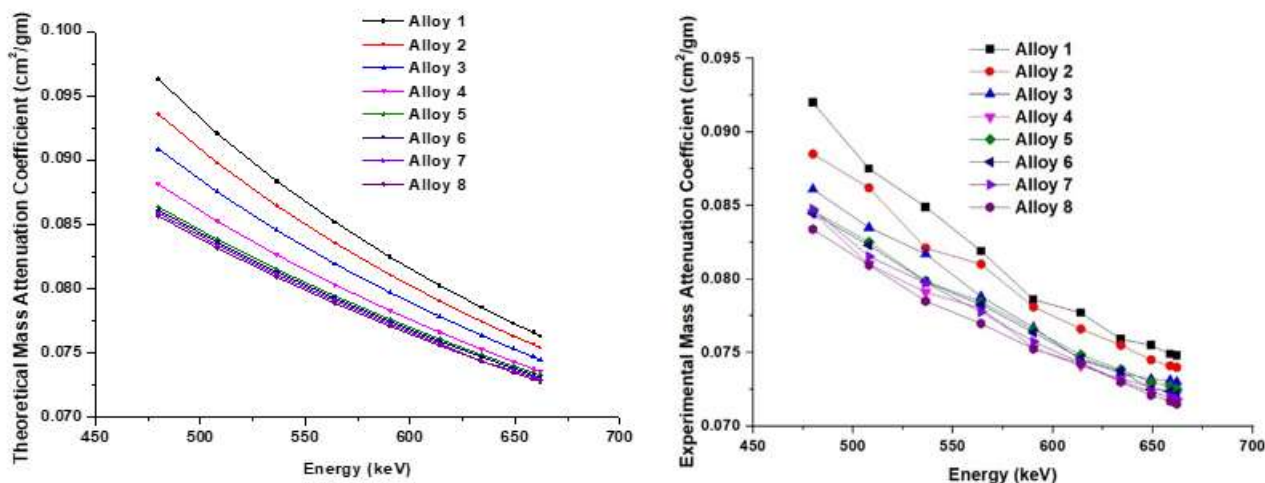
Scattering Energy (keV)	Atomic cross section (σ_a) of Cu-Ag alloys in (barn/atom)								Atomic cross section (σ_a) of Cu-Zn alloys in (barn/atom)							
	Alloy ₁		Alloy ₂		Alloy ₃		Alloy ₄		Alloy ₅		Alloy ₆		Alloy ₇		Alloy ₈	
	$(\sigma_a)_{Expt}$	$(\sigma_a)_{Th}$	$(\sigma_a)_{Expt}$	$(\sigma_a)_{Th}$	$(\sigma_a)_{Expt}$	$(\sigma_a)_{Th}$	$(\sigma_a)_{Expt}$	$(\sigma_a)_{Th}$	$(\sigma_a)_{Expt}$	$(\sigma_a)_{Th}$	$(\sigma_a)_{Expt}$	$(\sigma_a)_{Th}$	$(\sigma_a)_{Expt}$	$(\sigma_a)_{Th}$	$(\sigma_a)_{Expt}$	$(\sigma_a)_{Th}$
662.0000	13.4020	13.6635	11.4728	11.6896	10.8235	11.0332	8.6243	8.7822	7.8734	7.9494	7.8343	7.9320	7.7996	7.9146	7.7627	7.8984
658.7525	13.4199	13.7190	11.4883	11.7327	10.8279	11.0695	8.6278	8.8076	7.8940	7.9689	7.8593	7.9516	7.8137	7.9353	7.7844	7.9179
649.2223	13.5238	13.8426	11.5535	11.8335	10.8561	11.1599	8.6816	8.8757	7.9244	8.0276	7.8712	8.0102	7.8495	7.9928	7.8278	7.9754
634.0127	13.6008	14.0630	11.7101	12.0107	10.9109	11.3163	8.7437	8.9913	8.0167	8.1242	8.0058	8.1068	7.9364	8.0666	7.9255	8.0710
614.0272	13.9197	14.3728	11.8808	12.2585	11.0473	11.5335	8.8548	9.1504	8.1253	8.2566	8.0992	8.2382	8.0656	8.2197	8.0590	8.2024
590.3450	14.0701	14.7705	12.1119	12.5750	11.3749	11.8092	8.9898	9.3511	8.3109	8.4238	8.2903	8.4043	8.2230	8.3848	8.1698	8.3663
564.0937	14.6774	15.2559	12.5571	12.9593	11.6728	12.1419	9.3160	9.5916	8.5161	8.6214	8.4955	8.6008	8.4412	8.5813	8.3565	8.5606
536.3414	15.2147	15.8273	12.7386	13.4092	12.1160	12.5288	9.4474	9.8687	8.6692	8.8473	8.6638	8.8255	8.6573	8.8918	8.5215	8.7821
508.0236	15.6733	16.4901	13.3653	13.9273	12.3813	12.9705	9.6708	10.1817	8.9591	9.0991	8.9352	9.0752	8.8516	9.0524	8.7886	9.0286
479.9039	16.472	17.2514	13.7221	14.5171	12.7578	13.4678	10.0949	10.5291	9.1882	9.3749	9.1697	9.3488	9.2012	9.3239	9.0524	9.2989

Table 5 : Effective electronic cross-section for various alloy compared with theoretical values.

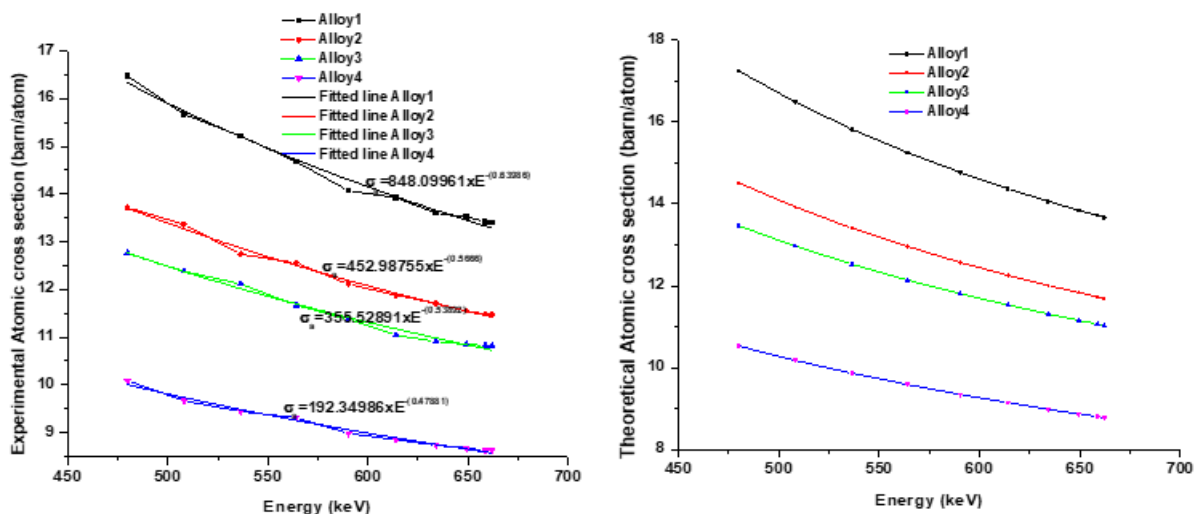
Scattering Energy (keV)	Electronic Cross-section (σ_e) of Cu-Ag alloys in ($\times 10^3$ barn/atom)								Electronic Cross-section (σ_e) of Cu-Zn alloys in ($\times 10^3$ barn/atom)							
	Alloy 1		Alloy 2		Alloy 3		Alloy 4		Alloy 5		Alloy 6		Alloy 7		Alloy 8	
	(σ_e) _{Expt}	(σ_e) _{Th}	(σ_e) _{Expt}	(σ_e) _{Th}	(σ_e) _{Expt}	(σ_e) _{Th}	(σ_e) _{Expt}	(σ_e) _{Th}	(σ_e) _{Expt}	(σ_e) _{Th}	(σ_e) _{Expt}	(σ_e) _{Th}	(σ_e) _{Expt}	(σ_e) _{Th}	(σ_e) _{Expt}	(σ_e) _{Th}
662.0000	2.8515	2.9071	2.7726	2.8250	2.7037	2.7561	2.6472	2.6957	2.6245	2.6498	2.6114	2.6440	2.5889	2.6382	2.6189	2.6328
658.7525	2.8553	2.9189	2.7764	2.8354	2.7048	2.7651	2.6483	2.7035	2.6313	2.6563	2.6198	2.6505	2.5829	2.6451	2.6174	2.6393
649.2223	2.8774	2.9452	2.7921	2.8598	2.7118	2.7877	2.6648	2.7244	2.6415	2.6759	2.6415	2.6701	2.6225	2.6643	2.6552	2.6585
634.0127	2.8938	2.9921	2.8300	2.9026	2.7255	2.8268	2.6839	2.7599	2.6722	2.7081	2.6686	2.7023	2.6676	2.6889	2.6882	2.6903
614.0272	2.9616	3.0581	2.8712	2.9625	2.7596	2.8810	2.7180	2.8087	2.7084	2.7522	2.7102	2.7461	2.6885	2.7399	2.7225	2.7341
590.3450	2.9936	3.1427	2.9271	3.0390	2.8414	2.9499	2.7594	2.8703	2.7703	2.8079	2.7634	2.8014	2.7773	2.7949	2.7594	2.7888
564.0937	3.1228	3.2459	3.0347	3.1319	2.9158	3.0330	2.8595	2.9441	2.8387	2.8738	2.8318	2.8669	2.8498	2.8604	2.7678	2.8535
536.3414	3.2372	3.3675	3.0785	3.2406	3.0265	3.1297	2.8999	3.0292	2.8897	2.9491	2.9136	2.9418	2.8859	2.9639	2.8535	2.9274
508.0236	3.3347	3.5085	3.2300	3.3658	3.0928	3.2400	2.9685	3.1253	2.9864	3.0330	2.9907	3.0251	2.9869	3.0175	2.8935	3.0095
479.9039	3.5047	3.6705	3.3162	3.5084	3.1869	3.3642	3.0986	3.2319	3.0627	3.1250	3.0566	3.1163	3.1032	3.1080	3.0176	3.0996

Table 6: Z_{eff} values for various alloy combination

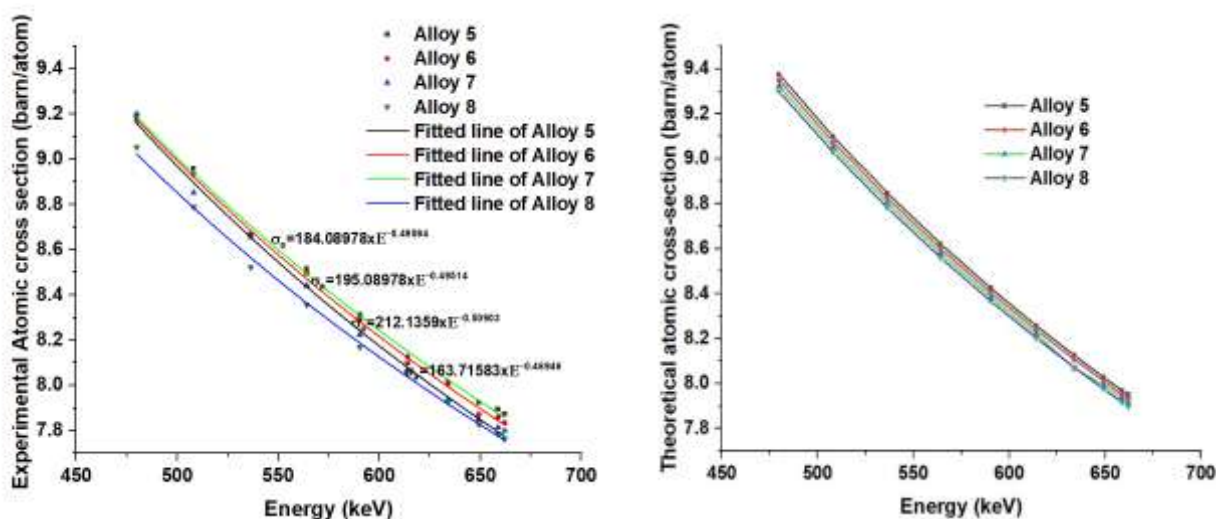
Scattering Angle (θ)	Scattering Energy (keV)	Z_{eff} of Cu-Ag and Cu-Zn alloys							
		Alloy 1	Alloy 2	Alloy 3	Alloy 4	Alloy 5	Alloy 6	Alloy 7	Alloy 8
0	662.0000	48.0673	41.5740	39.3599	34.1503	29.1096	28.9346	30.4436	26.0686
5	658.7525	48.0473	41.5603	39.3396	34.1350	29.1126	28.9474	30.4311	26.0761
10	649.2223	48.0295	41.5355	39.2922	34.1290	29.0543	28.8498	30.3798	26.0563
15	634.0127	47.9248	41.5358	39.2223	34.0959	29.0512	28.9392	30.3607	26.0760
20	614.0272	47.9543	41.5007	39.1787	34.0747	29.0094	28.8662	30.3579	26.1019
25	590.3450	47.7956	41.4719	39.2511	34.0457	29.0625	28.9320	30.3455	26.0275
30	564.0937	47.9404	41.5704	39.2631	34.1544	29.0940	28.9651	30.4002	26.0467
35	536.3414	47.9808	41.4346	39.3542	34.0748	28.9701	28.8731	30.3928	25.9830
40	508.0236	47.9256	41.5996	39.2858	34.0544	29.0731	28.9415	30.2955	26.0663
45	479.9039	48.0720	41.5431	39.2792	34.1772	29.0216	28.9023	30.4711	26.1103



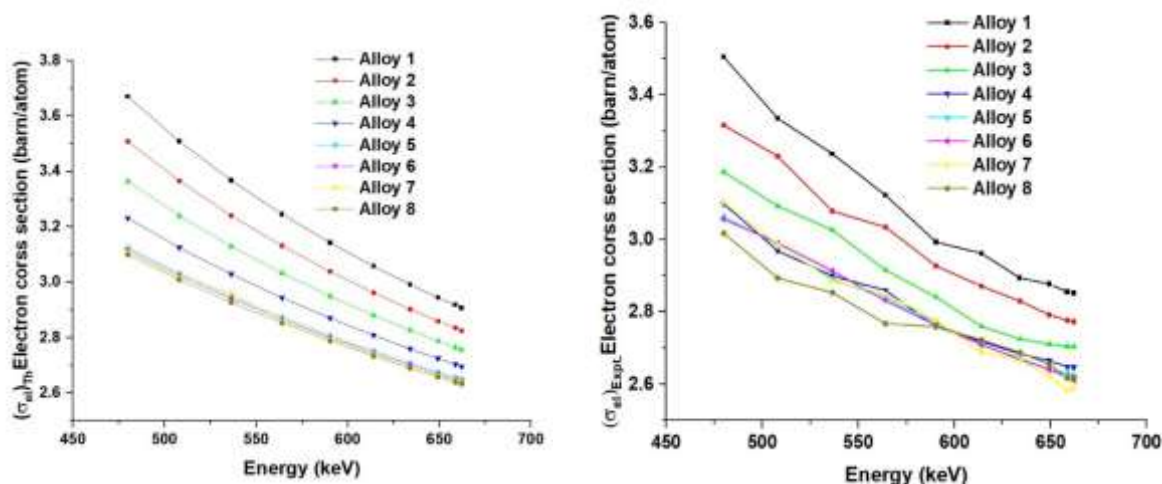
Graph 1 : Variation of mass attenuation coefficient of Cu-Ag and Cu-Zn alloys with Scattering energy.



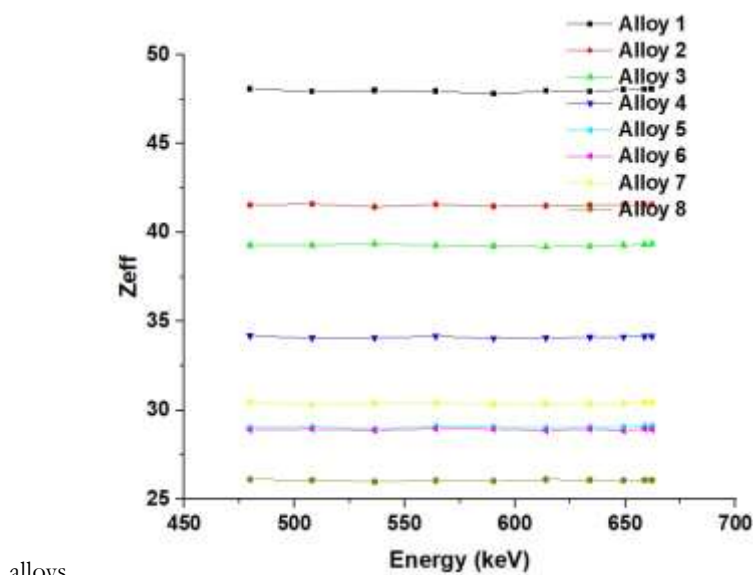
Graph 2 : Energy dependence of the atomic cross section for Cu–Ag alloys.



Graph 3 : Variation in atomic cross-section of Cu-Zn alloys with various energy.



Graph 4 : Effect of gamma-ray energy on the electron cross section of Cu–Ag and Cu-Zn.



Graph 5 : Effective atomic number of Cu-Ag and Cu-Zn alloys as a function of gamma-ray energy.

4. RESULT AND DISCUSSION

The energy absorption in a given medium can be calculated if certain constants are known. These necessary constants are Z_{eff} and electron density N_e of the medium. Therefore, the study of Z_{eff} numbers of the biological samples is so useful for many technological applications and calculation of medical dose in radiation therapy. The measured experimental μ/ρ and Z_{eff} values for Cu, Zn and Ag alloys samples for gamma ray energies 479 keV to 662 keV are shown in Table 3 and 6 respectively, compared with the theoretical values³ calculated by using mixture rule. The values of Z_{eff} are estimated graphically with best fit method are shown in Table 2, shows the nonlinear response due to small span of energy. The metrological process for preparation of alloy samples through number of processes may change basic chemical and morphological properties. Over the photon energy range of 479–662 keV, it was observed that the effective atomic number Z_{eff} values, which were computed from the ratio of the experimental atomic cross section (σ_a) to the electronic cross section (σ_{el}) remained almost constant. The values of Z_{eff} is best fit parameters obtained in plot of σ_a versus gamma ray energies are mentioned in Table 2. The variation in Z_{eff} values for Cu, Zn and Ag alloys are shown in Graph 5. The trend in graph is linear with small variation with respect to energy. The effective atomic number is generally useful for low Z material encountered in medical dosimetry. Z_{eff} is calculated in the Compton domain so that variation is observed in the Z_{eff} measurements. For Cu-Ag alloy, the variation of Z_{eff} in Alloy 2 and 3 is less as compared to alloy 1 and 4. Similarly the variation of Z_{eff} is less in alloy 5 and 6 as compared to alloy 7 and 8. From graph 1, it is observed that Cu–Ag and Cu–Zn alloys' experimental mass attenuation coefficients show a steady declining trend as the gamma-ray energy increases, the separation among alloy curves is greater at lower energies and the curves gradually converge near 662 keV. Alloy 2 and 3 trends of atomic cross section are closer as compared to alloy 1 and 4. The mass-energy absorption of energy during interaction is higher at lower energy and tends to decrease towards higher energy side.

5 CONCLUSION:

In the present work, the Z_{eff} values for the various combination of alloy samples are measured by using experimental (μ/ρ) values in gamma energy range 479 keV to 662 keV by employing Compton scattering geometry. In this energy region the Compton scattering effect is more dominant. The accuracy in measurement may depend on elemental composition of mixture of alloys, purity and homogeneity. The uncertainty in mass attenuation calculation is near about 2 to 3 %. The pure copper and silver element have partially filled d-orbitals in its neutral state. However, Zn has completely filled 3d¹⁰ shell into ground state. The electronic configuration of alloys slightly differs μ/ρ and Z_{eff} values from theoretical values³. The results are in accordance with the theoretical values³ also highlights the MLEM and FLUKA applications on accumulated PHA spectral analysis. An integrated framework for advanced radiation shielding studies and non-destructive evaluation of alloy systems has been established by the successful application of the MLEM algorithm for effective atomic number (Z_{eff}) determination, demonstrating its dependability as a useful tool for calculation of attenuation parameters.

Declarations:

- **Availability of data and materials:** The data will be made available on reasonable request.
- **Competing interests**

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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Author Contributions: A.H.D. designed the study and wrote the manuscript. S.N.N. performed experiments and data analysis. A.U. carried out FLUKA simulations and MLEM analysis. C.S.M. contributed to theoretical calculations and manuscript revision. All authors reviewed and approved the final manuscript.

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