# PHOTON INTERACTION PARAMETERS OF ZNO FOR MULTI-ENERGETIC PHOTONS

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## ABSTRACT

*Mass attenuation coefficients ($\mu_m$) of ZnO at different γ-energies were determined experimentally using narrow collimated beam transmission method. The sample was irradiated with radioactive point source of different γ-energies viz. Am (0.0595MeV), Cs (0.66MeV), Co (1.173MeV & 1.332MeV). The transmitted γ- photons were detected and recorded by a NaI(TI) scintillation detector with resolution of 8.5% for 0.662MeV of $^{137}$Cs. Theoretical mass attenuation coefficients were estimated using mixture rule. The experimental values reported in the present work are compared with the calculated values and the values obtained from X-COM. Linear attenuation coefficient ($\mu_l$), total atomic cross-section ($\sigma_t$), electronic cross-section ($\sigma_e$), effective atomic number ($Z_{eff}$), electron density ($N_{eff}$) and photon mean free-path (λ) were determined with semi-empirical relations using mass attenuation coefficients obtained experimentally and theoretically. Experimental values of parameters reported for ZnO investigated in the present work using different γ-energies are compared with the estimated theoretical data.*

*Keywords: Mass Attenuation Coefficient, Linear Attenuation Coefficient, Effective Atomic Number, Effective Electron Density.*

## I INTRODUCTION

The interaction of high energy photons with matter is important in radiation medicine, biology, nuclear engineering and space technology. The study of parameters such as mass attenuation coefficient ($\mu_m$), linear attenuation coefficient ($\mu_l$), total atomic cross-section ($\sigma_t$), electronic cross-section ($\sigma_e$), effective atomic number ($Z_{eff}$), electron density ($N_{eff}$), mean free-path (λ) are important parameters in understanding the physical properties of composite materials. They are very important in many applied fields like nuclear diagnostics, radiation protection, nuclear medicine and radiation dosimetry. The quantities can be determined theoretically and experimentally. Mass attenuation coefficient is a measurement of how strongly a substance absorbs or scatters radiation at a given wavelength, per unit mass. Mass attenuation coefficient can be used to derive many other photon interaction parameters. Linear attenuation coefficient ($\mu_l$) describes the fraction of a beam of X-rays or γ- rays that is absorbed or scattered per unit thickness of the absorber.

There have been experimental and theoretical investigations to determine ($\mu_m$) values in various elements and compounds/mixtures. Hubbel [1] reported ($\mu_m$) values for 40 elements and 45 mixtures and compounds over the energy range from 1keV to 20MeV. These tables were replaced with Hubbel and Seltzer tabulation for all elements (Z=1-92) and 48 additional substances of dosimetric interest [2]. Berger and Hubbel developed the theoretical tables and computer program (XCOM) for calculating attenuation coefficients for elements, compounds and mixtures for photon energies from 1keV to 100GeV [3]. This program was transformed to the Windows platform by Gerward et al.[4] and the Windows version is being called WinXcom.

Scattering and absorption of X-ray and γ-radiation are related to the density and atomic numbers of an element. In composite materials, it is related to the effective atomic number ($Z_{eff}$) and the electron density ($N_{eff}$). In composite material, a single number cannot represent the atomic number uniquely across the entire energy range, as the partial interaction cross-section have different atomic number, Z, dependence [5]. This number is called the effective atomic number, ($Z_{eff}$), which is very useful parameter for many fields. Effective atomic number is a convenient parameter for representing the attenuation of X-rays and γ-rays in a composite medium and particularly for the calculation of dose in radiation therapy [6]. This number is very useful in choosing a substitute composite material in place of an element for a given energy depending on the requirement. Several investigators [7-19] have made extensive ($Z_{eff}$) studies in variety of composite materials such as biologically important materials, semiconductors, alloys, dosimetric compounds and glasses. In literature, there are almost no reports on the study of photon interaction parameters of ZnO. This prompted us to carry out this work.

The experimental values (of γ- interaction parameters with matter) obtained for different γ-energies are compared with the estimated theoretical data and the values of X-Com.

## II EXPERIMENTAL METHOD

Transmission experiment with the narrow beam (good-geometry) setup has been used for measuring the incident and transmitted intensities, and hence calculating the attenuation coefficient. The gamma rays are well collimated using lead collimators. Each of the collimators has a cylindrical shape and a circular aperture.

The ZnO of the present study has high purities (99.5%–99.9%), consists 80.34% of Zn and 19.66% of Oxygen. The pellet is prepared by compressing the ZnO powder at a pressure of 2700 psi. The weight of the powder is 25.0 gm and the thickness of pellet is 1.40 cm. The sample material has been shaped into pellet with a die set by using hydraulic press, for measuring the attenuation. The sample was then firmly mounted on the sample holder as shown in Figure 1.



**Fig.1. Sample Holder with Sample**

The sample holder along with the sample is fixed between the source and the detector at appropriate position ensuring a proper alignment of sample with collimation 6mm on either side. The distance between γ- source and sample was 8cm and the distance between sample and detector was 6cm. The sample pellet was irradiated by different γ–energies [(0.0595 MeV), (0.662 MeV), (1.173 MeV & 1.332 MeV)] emitted by 10 mCi [241]Am, 30 mci ^{137}Cs and 11.73 µCi ^{60}Co radioactive point sources respectively  Intensities of the transmitted photons were recorded, by choosing the counting time as 20 minutes, under the photo peaks.

The γ - ray counts of different energies with sample (I) and without sample ($I_o$) were detected and recorded using a NaI (Tl) scintillation detector of (3×3inch) crystal coupled with a multichannel analyzer. The gamma radiation detector used in our study is a sodium iodide – thallium activated detector. The detector has a resolution of 8.5% for 0.662MeV of [137]Cs.  The energy and the efficiency of the system were calibrated using a certified standard source from the International Atomic Energy Agency.

Measurement of γ-ray attenuation counts at every energy repeated a minimum of nine times before and after the sample was introduced and the average value was considered in all our calculations.  Every time the source of γ-radiation is replaced by the other in the source vault, the setup is recalibrated.

## III THEORY

The relations used in the present work are summarized in this section. Mass attenuation coefficients for the different materials and energies are determined by performing transmission experiments. This process is described by the following equation:

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

(1)

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

$\mu_m = \mu/\rho$ (cm$^2$/g) is the mass attenuation coefficient

t (g/cm$^2$)   is sample mass thickness (the mass per unit area)

The total mass attenuation coefficient $\mu_m$ for any chemical compound or mixture of elements   is given by mixture rule [6]:

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

(2)

Where     $w_i$     is the weight fraction

$(\mu_m)_i$   is the mass attenuation coefficient of ith element

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

$$w_i = \frac{n_i A_i}{\sum_i n_i A_i}$$

(3)

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 ($\sigma_t$) for materials can be obtained from the measured values of $\mu_m$ using the following relation

$$\sigma_t = \frac{\mu_m N}{N_A}$$

(4)

Where    $N = \sum_i n_i A_i$   is atomic mass of materials          (5)

        $N_A$   is the Avagadro's number.

Total electronic cross-section ($\sigma_e$) for the element is expressed by the following equation

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

(6)

Where  $f_i$  denotes  the  fractional  abundance  of  the  element  i  with  respect  to  the  number  of atoms such that   $f_1 + f_2 + f_3 + f_4 + \ldots \ldots f_i = 1$

$Z_i$   is the atomic number of $i^{th}$ element

The total atomic cross-section ($\sigma_t$) and total electronic cross-section ($\sigma_e$) are related to the effective atomic number ($Z_{eff}$) of the material through the following relation

$$Z_{eff} = \frac{\sigma_t}{\sigma_e}$$

(7)

Effective electron number or electron density ($N_{eff}$) (number of electrons per unit mass) can be calculated  using the following relation:

$$N_{eff} = \frac{N_A}{N} Z_{eff} \sum n_i = \frac{\mu_m}{\sigma_e}$$

(8)

The average distance between two successive interactions, called the photon mean free path ($\lambda$), is given by

$$\lambda = \frac{\int_0^\infty x \exp(-\mu x)\,dz}{\int_0^\infty \exp(-\mu x)\,dx} = \frac{1}{\mu_l}$$

(9)

Where ($\mu_l$) is linear attenuation coefficient and x is the absorber thickness.

The uncertainty in the measured physical parameters depends on uncertainty in the furnace temperature and measurement of the mass attenuation coefficient, which has been estimated from errors in intensities $I_0$, $I$ and thickness ($l$). Estimated error in these measurements was around 2%.

Theoretical values for the mass attenuation coefficients can also be obtained by Win Xcom program [20]. This program is based on mixture rule to calculate the partial and total mass attenuation coefficients for all elements and mixtures at standard as well as selected energies.

## IV RESULTS AND DISCUSSION

Mass attenuation coefficients ($\mu_m$) of ZnO studied in the present work have been obtained experimentally for different photon energies. The values obtained experimentally are compared with theoretical values calculated by using semi-empirical relations (1, 2 and 3) of section-3 and with the values of X-Com and are in good agreement, as seen in the Table 1. The mass attenuation coefficient values decrease with increase in photon energy as seen from Figure.2. The mass attenuation coefficient of a material decreases because probability of absorption reduces with increasing incident photon energies which results in the increase in the transmission of photons through it. The experimental values of ZnO studied in the present work are smaller than their theoretical values. The difference might be from experimental setup, counting and efficiency errors. Linear attenuation coefficients ($\mu_l$), total photon interaction cross-sections ($\sigma_t$ and $\sigma_e$), effective atomic number ($Z_{eff}$), effective electron number ($N_{eff}$) and photon mean free path ($\lambda$) for ZnO at different $\gamma$-energies are estimated by using mass attenuation coefficients (experimental, theoretical and X-Com values) obtained, with the help of semi-empirical relations (4-9) of section-3 as seen from Table 1. The $Z_{eff}$ and the $N_{eff}$ remains constant and are found to be independent of photon energy for a compound. As seen from the Table 1 and from Figure 3 and Figure 4, total photon cross-section and electron cross-section ($\sigma_t$ and $\sigma_e$) decreases with the increase in photon energy. Lastly, the photon mean free path ($\lambda$) for a compound found to be increasing with the photon energy as seen from the Table 1 and Figure 5. This is due to the decrease in the probability of interaction of photons in the material with the increase in energy

## V CONCLUSIONS

Present experimental study has been undertaken to get information on the ($\mu_m$) and related parameters ($\sigma_t$, $\sigma_e$, $Z_{eff}$, $N_{eff}$ and $\lambda$) for ZnO at different $\gamma$-energies. We can understand that the ($\mu_m$) is useful and sensitive physical quantity to determine the ($Z_{eff}$) and ($N_{eff}$) of a compound. The ($\mu_m$) values ZnO in the present study decreases with increase in photon energy. Also, the variation of ($\sigma_t$ and $\sigma_e$) with energy is identical to mass attenuation coefficient. The data ($\mu_m$, $\sigma_t$, $\sigma_e$, $Z_{eff}$, $N_{eff}$ and $\lambda$) of ZnO at different $\gamma$- energies in the present study has been reported for the first time.

## VI ACKNOWLEDGEMENTS

**Table-1**

**$\mu$, $\mu_l$, $\sigma_t$ , $\sigma_e$, $Z_{eff}$ , $N_{eff}$. and $\lambda$ values (comparison between experimental, theoretical and X-com ) of ZnO at different $\gamma$-energies**

| E [MeV] | Am(0.0595) | | | Cs(0.662) | | | Co(1.173) | | | Co(1.332) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Photon interaction parameter | X-Com value | Empirical value | Expt. Value | X-Com value | Empirical value | Expt. Value | X-Com value | Empirical value | Expt. Value | X-Com value | Empirical value | Expt. Value |
| $\mu_m$ [$10^{-3}$ m$^2$kg$^{-1}$] | 148 | 148.4 | 147.4 | 7.401 | 7.4014 | 7.39 | 5.52 | 5.5514 | 5.544 | 5.204 | 5.2039 | 5.191 |
| $\mu_l$ [m$^{-1}$] | 833 | 832.4 | 826.91 | 41.52 | 41.522 | 41.46 | 30.97 | 31.143 | 31.1 | 29.194 | 29.194 | 29.122 |
| $\sigma_t$ [$10^{-25}$ barn/atom] | 100 | 100.2 | 99.583 | 5.0001 | 5.0004 | 4.993 | 3.729 | 3.7505 | 3.746 | 3.5158 | 3.5157 | 3.507 |
| $\sigma_e$ [$10^{-26}$barn/atom] | 51.5 | 51.48 | 51.139 | 2.5677 | 2.5678 | 2.564 | 1.915 | 1.926 | 1.923 | 1.8055 | 1.8054 | 1.801 |
| $Z_{eff}$ | 19.5 | 19.47 | 19.473 | 19.473 | 19.473 | 19.47 | 19.47 | 19.473 | 19.47 | 19.473 | 19.473 | 19.473 |
| $N_{eff}$ [$10^{23}$ electron/g] | 2.88 | 2.882 | 2.8824 | 2.8824 | 2.8824 | 2.882 | 2.882 | 2.8824 | 2.882 | 2.8824 | 2.8824 | 2.8824 |
| $\lambda$ [$10^{-2}$ m] | 0.12 | 0.12 | 0.1209 | 2.4085 | 2.4084 | 2.412 | 3.229 | 3.211 | 3.215 | 3.4253 | 3.4254 | 3.4339 |
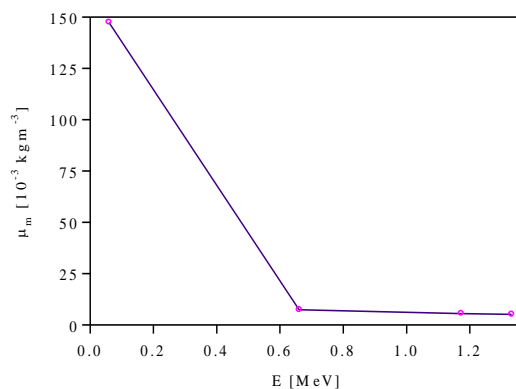
**Fig.2 μ$_m$ Versus Energy**
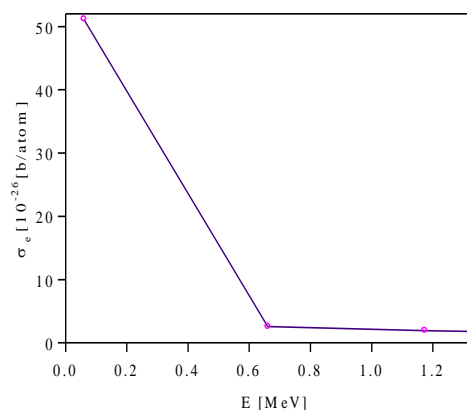


**Fig. 4 ($\sigma_e$) Verses Energy**
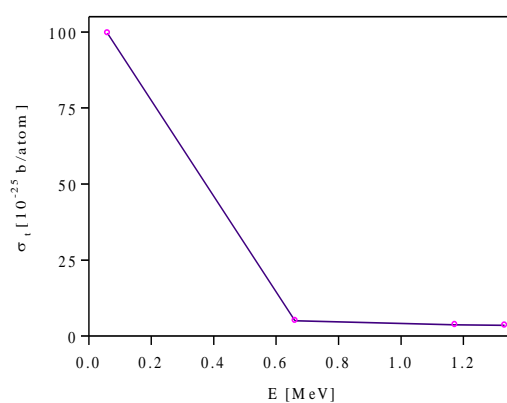


**Fig.3 $\sigma_\tau$ Versus Energy**
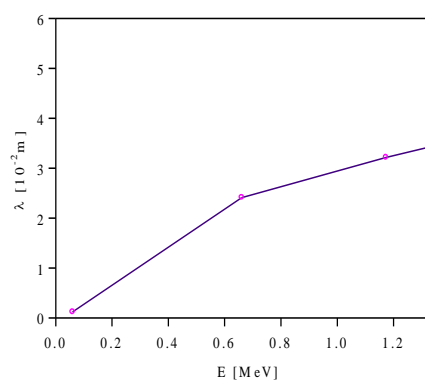


**Fig. 5 $\lambda$ Verses Energy**

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