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PHOTON INTERACTION PARAMETERS OF SOME TLD MATERIALS: MASS ATTENUATION COEFFICIENTS, EFFECTIVE ATOMIC NUMBERS, ELECTRON DENSITIES AND KERMA

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Abstract: Mass attenuation coefficients (μ/ρ), effective atomic numbers (Z_{eff}) and electron densities (N_{el}) of some TLD materials such as KBr, Al_2O_3, $SrSO_4$, LiF, $Li_2B_4O_7$ and $CaSO_4$ have been calculated for the total photon interactions in the wide energy range of 1 keV-100 GeV. The kerma values also have been calculated for the materials in the energy range 1 keV-20 MeV using WinXCom. The maximum values of μ/ρ, Z_{eff} and N_{el} are found in the low-energy range, where photoelectric absorption is the main interaction process. Compton scattering is the main interaction processes in intermediate energy region respectively. At high energies, pair production is the main dominating interaction process. It has been observed that Z_{eff} and N_{el} values are not true constants of the material, they vary as energy varies. The average values of Z_{eff} and N_{el} have been also calculated for total photon interaction processes. The Kerma values show sharp peak due to photoelectric absorption.

Key Words: Effective atomic numbers, electron density, Kerma, mass attenuation coefficients, TLD materials, WinXCom.

1. Introduction

The mass attenuation coefficient (μ/ρ) is a measure of the average number of interactions between incident photons and matter that occur in a given mass per unit area thickness of the substance under investigation [10]. The knowledge of mass attenuation coefficients of X-rays and gamma photons in biological and other important materials is of significant interest for industrial, biological, agricultural and medical applications [29]. The photon mass attenuation coefficients, effective atomic numbers and electron densities are the basic quantities required in determining the penetration of X-rays and gamma photons in matter [11, 16]. G J Hine [9] has pointed out that in composite materials for photon interactions, a single number cannot represent the atomic number uniquely across the entire energy region, as in the case of pure elements. This number for composite materials is known as "effective atomic number (Z_{eff}) and it varies with energy. The effective

electron density (N_{el}) is effective electron per unit mass of composite materials and can be calculated from Z_{eff} [3]. Kinetic energy released per unit mass, Kerma is defined as the initial kinetic energy of all secondary charged particles released per unit mass at a point of interest by uncharged radiation. In the Kerma approximation, the effects induced by photons on the chemical contents analysis are often scaled in terms of the absorbed dose (collision Kerma) [4].

As effective atomic numbers and electron densities are useful in many technological applications, several investigators have made extensive studies of effective atomic numbers in variety of composite materials like alloys, polymers compounds and mixtures, fluorescent compounds [26, 28, 17], thermo luminescent dosimetric compounds, semiconductors and superconductors. Shivalinge Gowda et al [27] have calculated Z_{eff} and N_{el} for some TLD compounds for the selected energies experimentally. This prompted us to study the mass attenuation coefficient (μ/ρ), effective atomic number Z_{eff} and electron density N_{el} of selected TLD materials such as KBr, Al_2O_3, $SrSO_4$, LiF, $Li_2B_4O_7$ and $CaSO_4$.The effective atomic number can be calculated using different method such as the Direct method, Interpolation method, Auto Zeff method and Single value XMuDat computer program [29].

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In the present work, the variations of mass attenuation coefficients, effective atomic numbers and electron densities with energy are shown graphically for total photon interaction (with coherent). The effective atomic number and electron densities have been calculated for TLD materials for all photon interaction such as coherent, incoherent, photoelectric absorption, pair production and total photon interaction (with coherent and incoherent). The kerma values have been calculated for the energies 1 keV-20 MeV and shown graphically for all the TLD materials.

2. Theoretical background

The total photon mass attenuation coefficient for a chemical compound or mixture was calculated using the WinXCom [5] and the following 'mixing rule.'[15]

$$\left(\frac{\mu}{\rho}\right)_{comp} = \sum_i \omega_i \left(\frac{\mu}{\rho}\right)_i \tag{1}$$

where and are the photon mass attenuation coefficient and the weight fraction of the ith constituent element in the compound, respectively.

The total cross section (σ) and different partial cross-sections are related by the relation

$$\sigma = \sigma_{coh} + \sigma_{incoh} + \tau + \kappa + \sigma_{ph,n} \tag{2}$$

where σ_{coh} and σ_{incoh} the scattering cross-sections of coherent and incoherent processes, respectively. τ is the atomic photoelectric cross-section, $\sigma_{ph,n}$ is the photonuclear cross-

section, and κ is the positron electron pair production cross-section. The following equation connects the effective atomic cross-section (σ_a) and the effective molecular cross-section (σ_m) [13],

The effective molecular cross section (σ_m) is estimated using the values of mass attenuation coefficients $(\mu/\rho)_{comp}$ by the following relation

$$\sigma_m = \left(\frac{\mu}{\rho}\right)_{comp} \frac{\sum_i n_i A_i}{N} \tag{3}$$

where N is the Avogadro's number, n_i and are the total number of atoms and atomic weight of the i^{th} element in a molecule respectively.

$$\sigma_a = \frac{\sigma_m}{\sum_i n_i} \tag{4}$$

Similarly, electronic cross-section (σ_e) is given by the following equation,

$$\sigma_e = \frac{1}{N}\sum_i \left(\frac{f_i A_i}{Z_i}\right)\left(\frac{\mu}{\rho}\right)_i \tag{5}$$

where and are the atomic number and fractional abundance of the constituent element. Effective atomic number (Z_{eff}) is the ratio of the atomic and electronic cross-sections and it is given by

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \tag{6}$$

Using the above equations Manohara et. al [19] have shown that Z_{eff} is given by

$$Z_{eff} = \frac{\sum_i n_i A_i \left(\frac{\mu}{\rho}\right)_i}{\sum_i n_i \frac{A_i}{Z_i}\left(\frac{\mu}{\rho}\right)_i} \tag{7}$$

where is the atomic number of the ith element present in a molecule.

The effective electron density (N_{el}) which is another parameter related to Z_{eff}, which represents the number of electrons per unit mass of interacting materials and may be computed using the following relationship[12],

$$N_{el} = \frac{(\mu/\rho)_{comp} Z_{eff}}{\sigma_a} \tag{8}$$

The Kerma is the product of the mass energy absorption coefficient and the energy fluency. The Kerma of compounds with respect to air can be calculated as [20]

$$K_a = \frac{K_{comp}}{K_{air}} = \frac{(\mu_{en}/\rho)_{comp}}{(\mu_{en}/\rho)_{air}} \tag{9}$$

3. Results and Discussions

In the present work, the variations of μ/ρ, Z_{eff} and N_{el} with photon energy for TLD materials such as KBr, Al_2O_3, $SrSO_4$, LiF, $Li_2B_4O_7$ and $CaSO_4$ composed of different elements were studied.

Table 1. The chemical composition

Sample No	Name of Compound	Molecular Formula
1	Potassium Bromide	KBr
2	Aluminium Oxide	Al_2O_3
3	Strontium Sulfate	$SrSO_4$
4	Lithium fluoride	LiF
5	Calcium sulphoxide	$CaSO_4$
6	Lithium boronoxide	$Li_2B_4O_7$

3.1 Mass attenuation coefficients

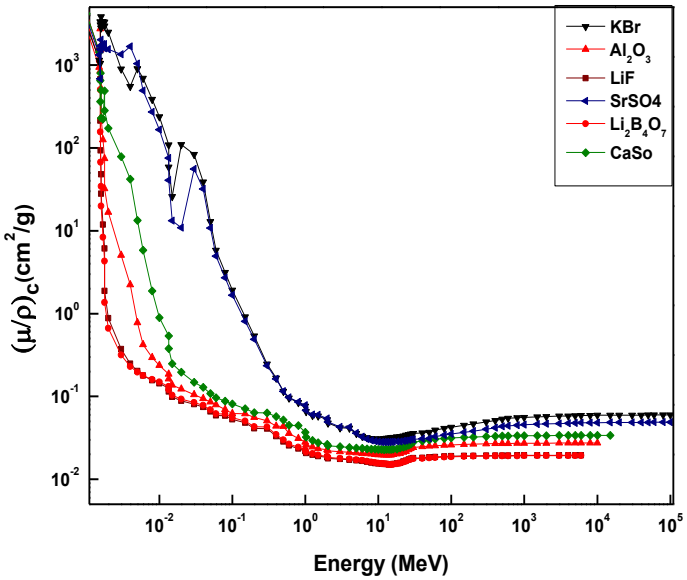

Fig 1. Variation of mass attenuation coefficients as function of energy of TLD Materials.

Mass attenuation coefficient and attenuation cross-section data are available in photon energy range of 1 keV to 100 GeV in the XCOM program which has been transformed to windows operating system WinXCom [18]. Effective atomic numbers are derived by calculation of the mass attenuation coefficients and atomic cross-sections of the elements of compound/mixture. Fig. 1 shows the variation of mass attenuation coefficient against energy of the TLD materials KBr, Al_2O_3, $SrSO_4$, LiF, $Li_2B_4O_7$ and $CaSO_4$ obtained by WinXCom for total photon interaction process (with coherent). Photoelectric absorption is dominant attenuation mechanism for the energy range 1 keV to 8 keV, K- absorption edges were observed for KBr and $SrSO_4$ 1 keV- 30 keV. Compton scattering is the dominant interacting process at intermediate energies 8 keV-10 MeV. At high energies above 10 MeV pair production will become the dominating interaction process [23].

3.2 Effective atomic number and electron density of total photon interaction (with coherent and incoherent)

The Z_{eff} and N_{el} of TLD Materials were calculated using mass attenuation coefficients of chemical composition of the given molecule or compound. From Fig. 2 & 3 it can be seen that the Zeff and Nel are mainly dominated by different partial photon interaction processes [20]. The value of average effective atomic number $<Z_{eff}>$ and electron density $<N_{el}>$, have been given in the Table 2-7. The Z dependency of total atomic cross–sections explains all changes, leading to effective atomic numbers such as Z^{4-5} for photoelectric absorption, Z for Compton scattering and Z^2 for pair production [16, 21].

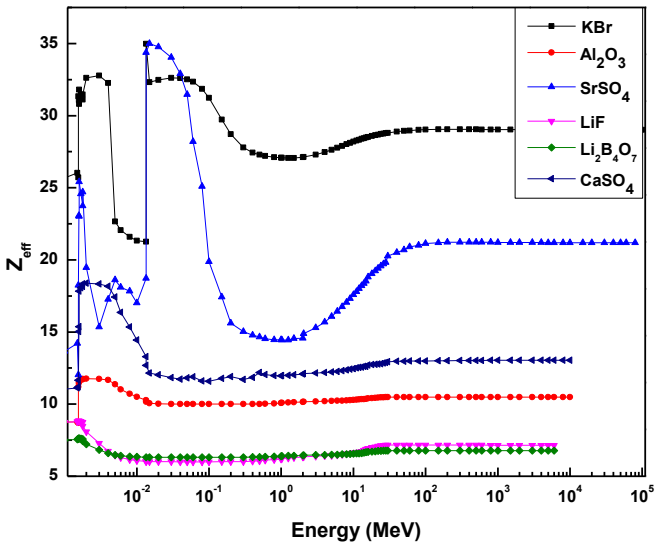

Fig 2. Variation of effective atomic number a function of energy of TLD Materials.

The Z_{eff} varies from a higher value at lower energies to a lower value at higher energies, with a peak due to photoelectric effect near the K-edge of the high Z element present in TLD Materials. The Maximum values of Z_{eff} were found for KBr and $SrSO_4$ comparing to Al_2O_3, LiF, $Li_2B_4O_7$ and $CaSO_4$ due to the presence of high Z elements. KBr, $SrSO_4$ and $CaSO_4$ show K-absorption edges energies below 20 keV energy.

After those energies Compton scattering will become the dominant interaction process, between energies 20 keV-5 MeV. Z_{eff} and N_{el} becoming constant with a minimum value at intermediate energies; further, there is an increasing trend in Z_{eff} values due to the relative dominance of photon interaction processes in various energy regions. From 5-26 MeV pair production starts becoming dominating process. After 26 MeV Z_{eff} will become energy independent [14, 1, 25, 24, 7, 8]. The average values of effective atomic number and electron density of the molecules for total interaction processes in the energy range of 1 keV-100 GeV are given in Table 2.

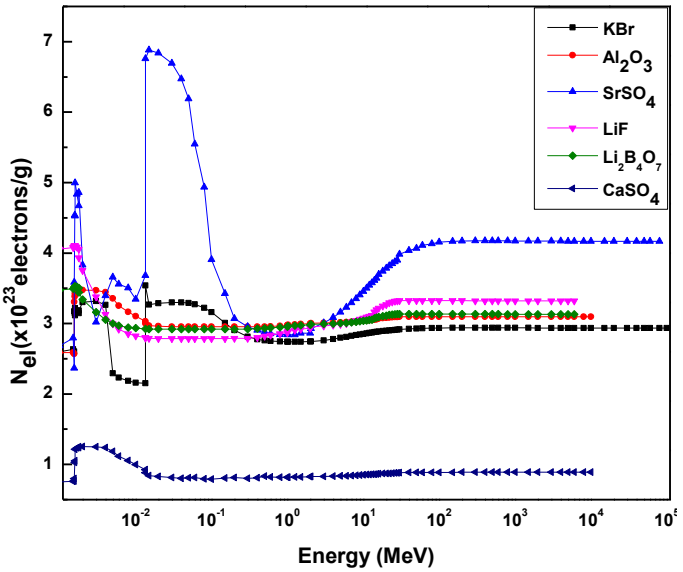

Fig 3. Variation of electron density as function of energy of TLD Materials.

Table 2 Average of Effective atomic number and Electron densities (10^{23} e/g) of TLD material (KBr).

Sample No	Name of the process	<Zeff>	<Nel>
1	Total noncoherent	29.14	2.95
2	Total coherent	28.77	2.91
3	Pair electron	29.60	2.99
4	Pair nuclear	31.56	3.19
5	Photo electric	33.23	3.36
6	Incoherent	27.04	2.74
7	Coherent	33.06	3.36e

Table 3 Average of Effective atomic number and Electron densities (10^{23} e/g) of TLD material (SrSO4).

Sample No	Name of the process	<Zeff>	<Nel>
1	Total noncoherent	19.78	3.89
2	Total coherent	20.06	3.94
3	Pair electron	23.25	4.57
4	Pair nuclear	31.61	6.22
5	Photo electric	35.55	6.99
6	Incoherent	23.41	4.60
7	Coherent	34.31	6.75

Table 4 Average of Effective atomic number and Electron densities (10^{23} e/g) of TLD material (Al_2O_3).

Sample No	Name of the process	<Zeff>	<Nel>
1	Total noncoherent	10.42	3.04
2	Total coherent	10.42	3.08
3	Pair electron	14.28	4.22
4	Pair nuclear	11.21	3.31
5	Photo electric	12.23	3.61
6	Incoherent	10.65	3.15
7	Coherent	11.58	3.42

Table 5 Average of Effective atomic number and Electron densities (10^{23} e/g) of TLD material (LiF).

Sample No	Name of the process	<Zeff>	<Nel>
1	Total noncoherent	6.9111	3.21
2	Total coherent	6.9170	3.21
3	Pair electron	7.3437	3.41

4	Pair nuclear	8.3301	3.87
5	Photo electric	8.9688	4.16
6	Incoherent	7.2859	3.38
7	Coherent	8.6166	4.00

Table 6 Average of Effective atomic number and Electron densities (10^{23} e/g) of TLD material ($CaSO_4$).

Sample No	Name of the process	<Zeff>	<Nel>
1	Total noncoherent	13.16	7.44
2	Total coherent	13.18	7.45
3	Pair electron	14.79	2.00
4	Pair nuclear	12.80	8.36
5	Photo electric	18.16	1.78
6	Incoherent	13.80	7.97
7	Coherent	17.22	1.30

Table 7 Average of Effective atomic number and Electron densities (10^{23} e/g) of TLD material ($Li_2B_4O_7$).

Sample No	Name of the process	<Zeff>	<Nel>
1	Total noncoherent	6.694	3.10
2	Total coherent	6.695	3.10
3	Pair electron	6.801	3.15
4	Pair nuclear	7.246	3.35
5	Photo electric	7.806	3.61
6	Incoherent	6.777	3.14
7	Coherent	7.433	3.44

3.3 Kerma relative to air

In Fig. 4 the variation of Kerma relative to air (K_a) of KBr, Al_2O_3, $SrSO_4$, LiF, LiB_4O_7 and $CaSO_4$ with photon energy 1 keV to 20 MeV is shown. The K_a values were calculated

using equation (9) and values of the selected TLD materials. K_a values attain maximum value, where photoelectric absorption is the dominating interaction process [24, 25]. It is clearly seen that Kerma depends on the chemical content. Later, The reason for such variation in kerma is the photoelectric cross section proportional to Z^{4-5}. Above 30 keV photon energy, the compositional dependence of K_a is almost negligible. This is due to the dominance of the Compton scattering phenomenon, the interaction cross-section for which is essentially independent of atomic number Z. The absorption peaks were observed between the 40- 80 keV range. Maximum absorption peaks were observed for KBr and $SrSO_4$ comparing to Al_2O_3, LiF, LiBr and $CaSO_4$ [26-29].

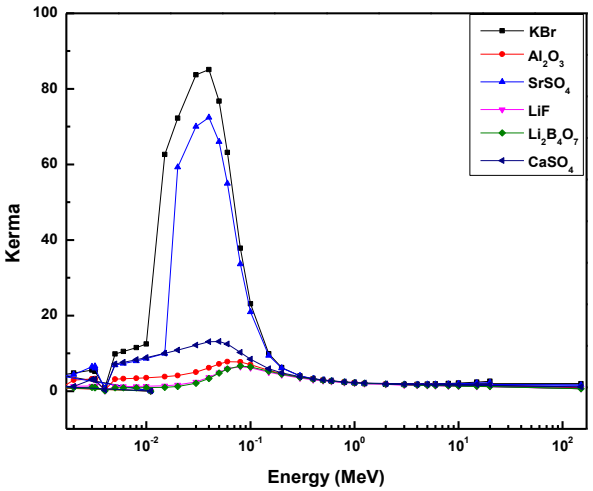

Figure 4. Variation of kerma relative to air as function of energy of TLD Materials.

4. Conclusions

Studies on mass attenuation coefficient, effective atomic number, electron densities and Kerma of TLD material are useful to understand the following processes:

1. Mass attenuation coefficient of TLD materials have the variation similar for Al_2O_3, LiF, $Li_2B_4O_7$ and $CaSO_4$, other than KBr and $SrSO_4$, it may be due to presence of high-Z elements in the compound.
2. The effective atomic number Zeff and the corresponding effective electron density N_{el} of TLD material KBr, Al_2O_3, $SrSO_4$, LiF, $Li_2B_4O_7$ and $CaSO_4$ has been calculated in the extended energy region from 1 keV-100 GeV using WinXCom program.
3. In total photon interaction with coherent and incoherent one can distinguish three energy regions. The main photon interaction processes in these regions are photoelectric absorption, incoherent (Compton) scattering and pair production.
4. The maximum values of Z_{eff} and N_{el} are found for KBr and SrSO4 in the low energy range E< 20 keV, where photoelectric absorption is the main interaction process. The minimum values of Z_{eff} and N_{el} are found at intermediate energies 5

MeV<E<26 MeV, where Compton scattering is dominant. At high energies Z_{eff} and N_{el} remains almost constant. This may be due to the dominance of pair production in the high energy region E>26 MeV.

5. Z_{eff} and N_{el} for different processes such as pair production in nuclear and electric field, photoelectric absorption, coherent and incoherent scattering has also been calculated. The variations depends on the elements in compound.

6. The Kerma values show maximum photoelectric absorption peaks for KBr and $SrSO_4$, than Al_2O_3, LiF, $Li_2B_4O_7$ and $CaSO_4$ in the energy range 1 keV- 20 MeV.

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