Variation of Effective Atomic Numbers of some Thermoluminescence and Phantom Materials with Photon Energies

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Abstract

Effective atomic numbers (Z_{eff}) of 15 materials ($CaSO_4$, nylon, methyl but-3-enoate, mylar, C_2F_4, Al_2O_3, SiO_2, stearate, CH_4, $CaF2$, water, Iron sulphate, polystyrene, polyvinyl, and potassium calcium sulphate) used in dosimetry and substitute materials were calculated using standard formula based on their mass attenuation coefficients (μ_m). The μ_m of the materials were obtained for photon energies of 0.01 KeV to 20 MeV using WinXCOM. Generally, Z_{eff} for each of the substances considered is not a constant but varies with photon energy. Z_{eff} varies from11-17 for $CaSO_4$, 3-6 for nylon, 6-7 for methyl but-3-enoate, 4-7 for mylar, 8-9 for C_2F_4, 10-12 for Al_2O_3, 10-12 for SiO_2, 3-6 for stearate, 2-5 for CH_4, 13-18 for $CaF2$, 3-8 for water, 12-23 for Iron sulphate, 4-6 for polystyrene, 5-16 for polyvinyl, and 12-17 for potassium calcium sulphate. The variations of Z_{eff} with photon energy for all the 15 substances follow similar pattern. The variations were dictated by photon interaction processes. The highest value of Z_{eff} for all the materials was obtained at the lowest energy, while the lowest value was obtained between 0.1 and 1.5 MeV. The mean atomic number of each compound was also found to be equal to the Z_{eff} obtained at intermediate energies of the energy spectrum considered (0.1 MeV -1.5 MeV). The upper and lower limit of Z_{eff} for each of the considered materials was found to be dictated by the atomic numbers of the constituent elements of the materials.

Keywords: Dosimetry, substitute material, atomic number, photon interaction

Introduction

The understanding of interaction of photon with matter is an important discuss in various fields of radiation application and radiation protection such as radiation, nuclear and medical physics, space physics etc. the principal modes by which photon interact with matter to be attenuated and to deposit energy are by the photoelectric effect, Compton Effect, and pair production. Although photons also undergo Rayleigh scattering, Braggs scattering, photo-disintegration, and nuclear resonance scattering, however these result in negligible attenuation or energy deposition and are generally ignored in many application of radiation and radiation protection[1]. The photoelectric absorption coefficient τ, Compton interaction coefficient σ, and the pair production interaction coefficient κ of a material are all related to the atomic number Z of the material according to the approximation equations 1, 2 and 3[1]

$$\tau = c\frac{Z^5}{E^3} \quad (1)$$

$$\sigma = d\frac{Z}{E} \quad (2)$$

$$\kappa = eZ^2(E - 1.022) \quad (3)$$

Where c, d, and e are constants and E is energy (in MeV). The atomic number of a material is thus a basic quantity required in determining the penetration of photon in matter[2]. In composite materials the atomic number is represented by the

effective atomic number Z_{eff}. The affective atomic numbers are useful in medical radiation dosimetry for the calculation of dose in radiation therapy [3] and medical imaging. Precise knowledge of Z_{eff} of thermoluminiscence phosphors and substitute materials are very important for the evaluation of their energy dependence [4].

Some formulas have been presented[1,5,6] for evaluating Z_{eff}, all of which suggested that Z_{eff} is a constant. According to Hine[7] Z_{eff} for photon interactions for multi- element materials cannot be expressed as a single number (constant) for all photon energies. For each of the different processes by which photon interact with matter, the various atomic numbers in the material have to be weighted differently. Subsequent studies[8,9] concluded that Hine's predictions were correct. Consequently, for photon interactions Z_{eff} is not a constant for a composite material but a parameter varying with photon energy depending on the interaction processes involved.

Earlier evaluations of Z_{eff} were based on parameterization of the photon interaction cross section by fitting data over limited ranges of energy and atomic number[3]. Since accurate data on photonelectric cross sections as well as scattering cross section of individual elements are available[10]. This method yielded effective atomic numbers to an accuracy of about 1% in the low and high energy region[11].

Presently, accurate data bases of photon interaction cross sections and interpolation programs such as XMuDat[12], XCOM[13] and its windows successor; WinXCOM [14] have made it possible to calculate Z_{eff} with much improved accuracy and information content over a wide range of photon energy[15]. In 2008 Manohara et al.[15] presented comprehensive and consistent set of formulae for evaluating the Z_{eff} of all types of materials for photon energy greater than 1keV. In this work Z_{eff} for 15 materials ($CaSO_4$, nylon, methyl but-3-enoate, mylar, C_2F_4, Al_2O_3, SiO_2, stearate, CH_4, $CaF2$, water, Iron sulphate, polystyrene, polyvinyl, and potassium calcium sulphate) of interest in radiation Physics is presented based on these formulae. The variation of the Z_{eff} of the materials with energy for photon energies of 0.01- 20MeV is also presented.

Evaluation of Z_{eff}: The attenuation of a parallel beam of mono-energetic photons in matter is predicted by the Beer- Lambert's law:

$$I = I_o e^{-\mu_m t} \quad (1)$$

Where I and I_o are photon intensities with and without absorbing material, μ_m is the mass attenuation coefficient, and t the mass thickness (mass per unit area) of the absorbing material. For a composite material (compound and mixture),

$$\mu_{m=\sum_i w_i (\mu_m)_i} \quad (2)$$

Where w_i and $(\mu_m)_i$ are the weight fraction and the mass attenuation coefficient of the constituent elements. For all the 15 compounds considered in this work, $(\mu_m)_i$ was obtained theoretically from WinXCOM[16]. The program can calculate photon interaction cross section for any element compound or mixture in the energy spectrum of 1KeV-100GeV.

The values of the $(\mu_m)_i$ for each compound obtained from the program was then used to evaluate the total molecule cross section according to the equation:

$$\sigma = (\mu_m)_i \frac{M}{N_A} \quad (3)$$

Where M and N_A is the molecular weight of each compound and the Avogadro's number. Consequently the total atomic cross section was evaluated using the equation:

$$\sigma_t = \frac{\sigma}{\sum_i n_i} \quad (4)$$

The effective atomic number is then evaluated using the equation [15]:

$$Z_{eff} = \frac{\sigma_t}{\sigma_e} \quad (5)$$

where σ_e is the total electronic cross section, evaluated from:

$$\sigma_e = \frac{1}{N_A}\sum \frac{f_i A_i}{Z_i}\mu_i \qquad (6)$$

Results and Discursion

Generally, Z_{eff} for each of the substances considered is not a constant but varies with photon energy. The variation of obtained Z_{eff} with energy for all the 15 substances considered in this work is presented in figures 1, 2 and 3. Z_{eff} varies from11-17 for $CaSO_4$, 3-6 for nylon, 6-7 for methyl but-3-enoate, 4-7 for mylar, 8-9 for C_2F_4, 10-12 for Al_2O_3, 10-12 for SiO_2, 3-6 for stearate, 2-5 for CH_4, 13-18 for CaF2, 3-8 for water, 12-23 for Iron sulphate, 4-6 for polystyrene, 5-16 for polyvinyl, and 12-17 for potassium calcium sulphate. Generally, the behaviors of Z_{eff} with energy for all the substances considered in this work are similar- decreasing steadily as energy increases then becomes almost constant and latter increasing again (fig.1, 2, and 3). These variations can be attributed to the photon interaction dominating at the energies considered. For all the 15 substances considered in this work, their Z_{eff} was highest at the lower end of the energy spectrum considered (0.01-0.1 MeV) and their lowest Z_{eff} at intermediate energies (0.1-1.5 MeV). This behavior is attributed to the photoelectric effect and Compton scattering dominating at the low energy and intermediate energies respectively. At low energy the photoelectric absorption coefficient is dependent on the highest (5th) power of Z_{eff},(equation 1) this explains why the highest value of the effective atomic number of the substances was obtained at this energies. At intermediate energies (0.1-1.5 MeV) where Compton scattering dominates, according to equation 2, the interaction mode is dependent on a unit power of the atomic number. Thus the value of Z_{eff} for each substance is almost constant and equal to its mean atomic number <Z> (table 1). This is due to the fact that at the energy region wherein the Compton scattering is the dominant mode of photon interaction, the Z_{eff} can be represented by a mean atomic number[15]. Above 1.5 MeV, Z_{eff} begins to increase steadily as pair production becomes apparently the dominant interaction mode.

For each of the considered substances the lower and upper limit of their Z_{eff} is dictated by the range of atomic numbers of the constituent elements. Where the least value of Z_{eff} does not go below the least atomic number of the constituent element and the maximum value of Z_{eff} is also limited by the highest atomic number of the constituent element. Thus a substance with high spread of constituent atomic number also has high spread of Z_{eff} variation. Among the considered substances $FeSO_4$ has the highest spread of constituent element while C_2F_4 has the least. This explains why $FeSO_4$ has the highest spread of Z_{eff} and C_2F_4 has the least. Furthermore, $FeSO_4$ has the highest value of Z_{eff}, 23 and 12 at the least and highest energy respectively. This is also due to the presence of most dense element in its constituent among constituent element of the substances considered.

Conclusion

It is common to use the effective atomic number (Z_{eff}) as a means of characterizing the radiological properties of dosimeters, biological and substitute (phantom) materials, consequently the Z_{eff} of 15 radiological materials is evaluated and presented for 0.01-20 MeV photon energy. The results obtained shows that the variation of Z_{eff} with energy in the energy spectrum considered is similar for all the materials considered. Maximum value of Z_{eff} for all substances considered were obtained at the low energy end of the energy spectrum considered while the minimum values were obtained at the intermediate energy. At the energy range of 0.1-1.5 MeV (intermediate energy) where Compton scattering dominates the effective atomic number of each substance is almost equal to the mean atomic number of the substance. The results of the present investigation thus concur with the inference of the previous works[15,16] that in the energy region wherein the Compton scattering is a dominant mode of photon interaction, the Z_{eff} can be represented by a mean atomic number. For the use of dosimetric or substitute materials effective atomic number should

be evaluated for energy range of interest and not assumed to be a constant.

References

1. James E.M., Physics for Radiation Protection: A Handbook.Copyright WILEY- VCH Verlag GmbH and Co. KGaA, Weinheim, 822, **(2006)**

2. Cevik U., Damla N. andCelik A., Effective Atomic Numbers and Electron Densities For Cdse and Cdte Semiconductors, *Radiat. Meas.,* **43** 1437-1442 **(2008)**

3. Jackson D.F., Hawkes D.J., X-ray attenuation coefficients of elements and mixtures, *Phys. Rep*., **70**, 169–233 **(1981)**

4. Shivaramu V.R., Effective atomic numbers for photon energy absorption and energy dependence of some thermoluminescent dosimetric compounds, *Nuclear Instruments and Meth. Phys Research B*, **168,** 294-304 **(2000)**

5. Johns H.E. and Cunningham J.R., The Physics of Radiology, Charles C. Thomas, Springfield, IL, 796 **(1983)**

6. Khan F.M., The physics of radiation therapy. Lippincot Williams and Wilkins, Philadephia, 542 **(1984)**

7. Hine G.J., The effective atomic numbers of materials for various gammaray interactions, *Phys. Rev.,* **85**, 725 **(1952)**

8. Siddappa K., Khayyom A., Parthasaradhi K. and Rao J.R., Effective Atomic Numbers for Photoelectric and Incoherent Scattering Processes for Gamma Rays., *Nucl. Sci. Engng*., **45**, 96 **(1971)**

9. Kiran K.T., Venkerteratnam S. and Venkata R. K., Effective Number Studies in Clay Minerals for Total Photon Interaction in the Energy Region 10 Kev to 10 Mev., *Rad. Phys. Chem*., **48**, 70 **(1996)**

10. Hubbell J.H., Seltzer S., Tables of X-ray mass attenuation coefficients and mass energy-absorption coefficients 1 keV–20MeV for elements Z=1 to 92 and 48 additional substances of dosimetric interest, NISTIR 5632, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA, **(1995)**

11. Parthasaradhi K., Esposito A., Pelliccioni M., Photon attenuation coefficients in tissue equivalent compounds, *Int. J. Appl. Radiat. Isot*., **43**, 1481–1484 **(1992)**

12. Nowotny R., XMuDat: Photon attenuation data on PC. IAEA-NDS-195 International Atomic Energy Agency, Vienna, **(1998)**

13. Berger M.J., Hubbell J.H., 1987/1999, XCOM: Photon cross sections database, web version 1.2, available at http://physics.nist.gov/xcom. National Institute of Standards and Technology, Gaithersburg, MD 20899, USA, Originally published as NBSIR 87-3597 XCOM: Photon cross sections on a personal computer **(1999)**

14. Gerward L., Guilbert N., Jensen K.B., Levring H., WinXCom-a program for calculating X-ray attenuation coefficients, *Radiat. Phys. Chem*., **71**, 653–654 **(2004)**

15. Manohara S.R., Hanagodimatha S.M., Thind K.S. and Gerward L., On the effective atomic number and electron density: a comprehensive set of formulas for all types of materials and energies above 1 keV., *Nucl. Instum. Meth. B,* **266**, 3906 **(2008)**

16. Manjunathaguru V., Umesh, T. K., Effective atomic numbers and electron densities of some biologically important compounds containing H,

C, N, and O in the energy range 145–1330 keV.,
J. Phys. B: At. Mol. Opt. Phys., **39**, 3969 **(2006)**

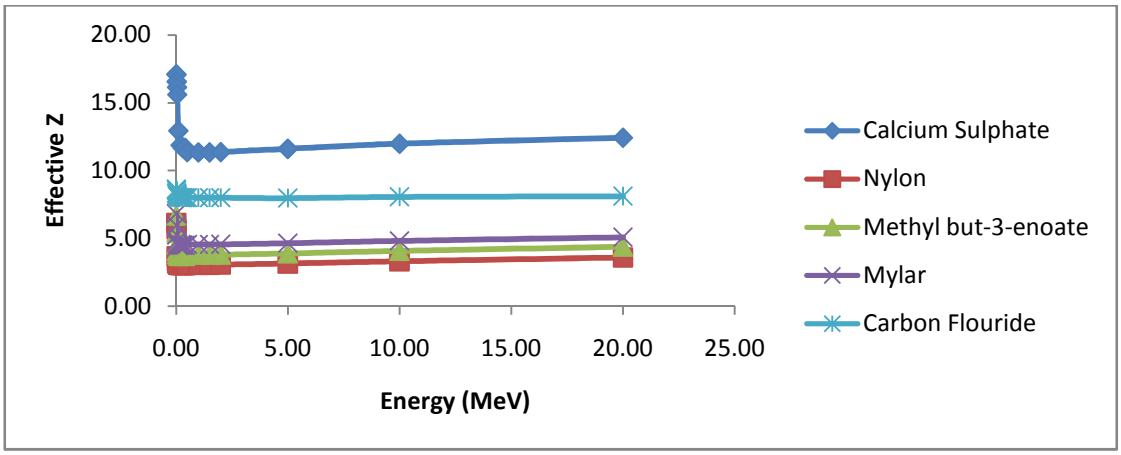

Figure-1: Variation of Z_{eff} with energy for $CaSO_4$, nylon, methyl but-3-enoate, mylar and C_2F_4

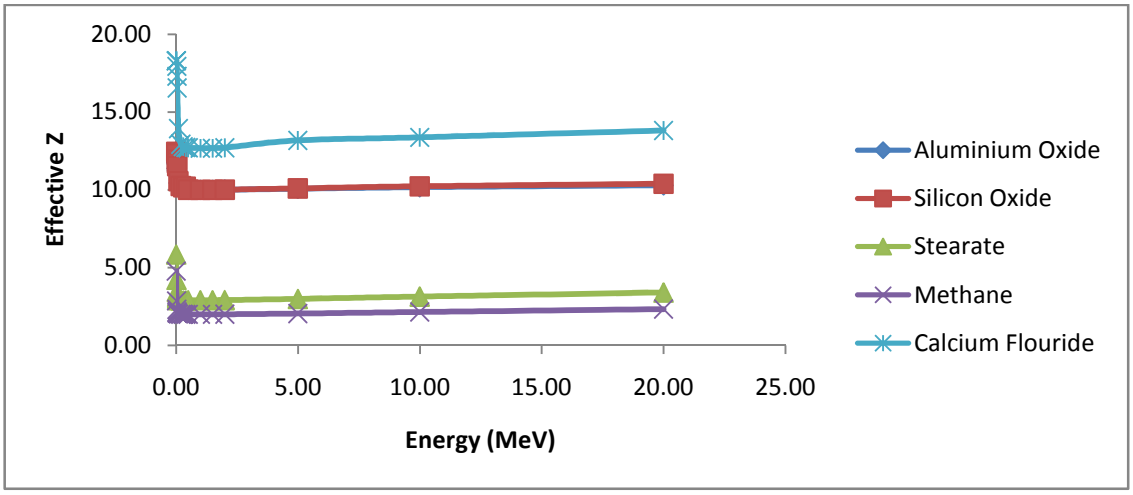

Figure-2: Variation of Z_{eff} with energy for Al_2O_3, SiO_2, stearate,CH_4,CaF_2

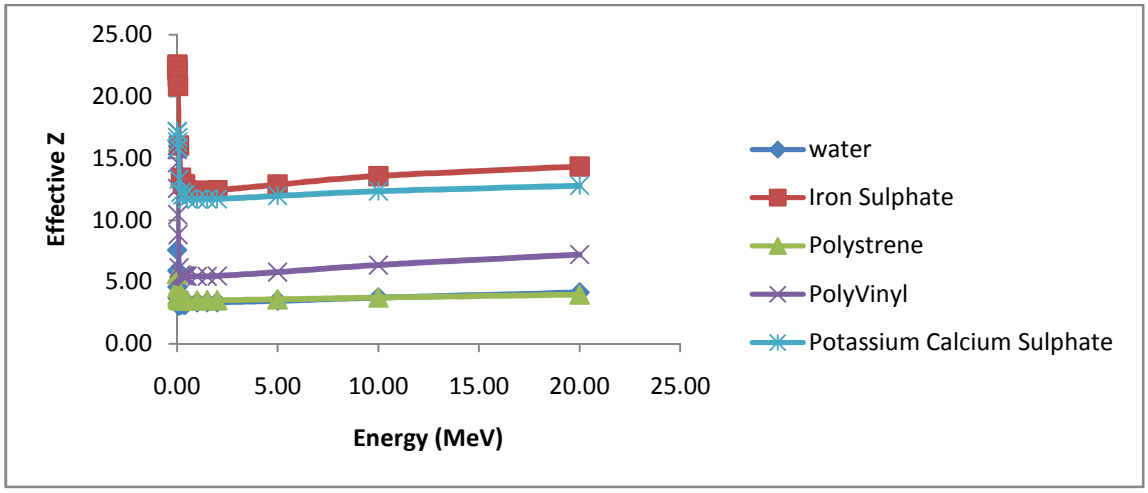

Fig.3. Variation of Z_{eff} with energy for water, Iron sulphate, polystyrene, polyvinyl, and potassium calcium sulphate.

Table-1: Mean atomic number (<Z>) and Z_{eff} at 0.5, 1.0, and 1.5 MeV photon energy

Compound	Formula	<Z>	Z_{eff} Energy(MeV)		
			0.5	1	1.5
Calcium Sulphate	$CaSO_4$	11.33	11.35	11.33	11.34
Hexanamide (Nylon)	$C_6H_{13}NO$	3.05	3.06	3.06	3.06
Methyl but-3-enoate	$C_5H_7O_2$	3.79	3.80	3.80	3.80
Mylar	$C_{10}H_8O_4$	4.55	4.56	4.56	4.56
Carbon Flouride	C_2F_4	8.00	8.00	8.00	8.00
Aluminium Oxide	Al_2O_3	10.00	10.01	10.00	10.00
Silicon Oxide	SiO_2	10.00	10.00	10.00	10.00
Stearate	$C_{18}H_{36}O_2$	2.86	2.90	2.90	2.90
Methane	CH_4	2.00	2.01	2.01	2.01
Calcium Flouride	CaF_2	12.67	12.70	12.67	12.68
Water	H_2O	3.33	3.35	3.35	3.35
Iron Sulphate	$FeSO_4$	12.33	12.42	12.36	12.37
Polystrene	C_8H_8	3.50	3.51	3.51	3.51
PolyVinyl	C_3H_3Cl	5.43	5.47	5.45	5.46
Potassium Calcium Sulphate	$K_2Ca_2(SO_4)_3$	11.68	11.71	11.69	11.69