Research Journal of Physical Sciences _____ ISSN 2320–4796
Vol. **1(6),** 11-16, July **(2013)** *Res. J. Physical Sci.*

Mass Attenuation Coefficients, Effective atomic and Electron Numbers of Alkali Halides for Multi-Energetic Photons

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Available online at: www.isca.in
Received 4th June 2013, revised 22nd June 2013, accepted 1st July 2013

Abstract

Mass attenuation coefficients (μ_m) for alkali halides (RbCl, RbBr and RbI) were determined experimentally using narrow collimated beam transmission method. The samples were irradiated with radioactive point source of different γ-energies viz. Cs (0.662MeV), Am (0.0595MeV), Co (1.173MeV and 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 for all the alkali halides in the present work are compared with the calculated values and the values obtained from X-COM. Linear attenuation coefficient (μ_l), total atomic cross-section (σ_t), electronic cross-section (σ_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 all alkali halides 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.

Introduction

The interaction of high energy photons with matter is important in radiation, medicine and biology, nuclear engineering and space technology. The knowledge of parameters such as mass attenuation coefficient (μ_m), linear attenuation coefficient (μ_l), total atomic cross-section (σ_t), electronic cross-section (σ_e), effective atomic number (Z_{eff}), electron density (N_{eff}), mean free-path (λ) plays an important role in understanding the physical properties of composite materials. They are invaluable in many applied fields, such as nuclear diagnostics, radiation protection, nuclear medicine and radiation dosimetry. The quantities can be evaluated theoretically and experimentally. Mass attenuation coefficient is a measurement of how strongly a chemical specie or substance absorbs or scatters radiation at a given wavelength, per unit mass. Mass attenuation coefficient is an useful parameter to derive many other physical parameters. Linear attenuation coefficient (μ_l) describes the fraction of a beam of X-rays or γ- rays that is absorbed or scattered per unit thickness of the absorber. Researchers have focused on the studying of photon interaction parameters with matter.

There have been a great number of experimental and theoretical investigations to determine (μ_m) values in various elements and compounds/mixtures. Hubbel[1] reported (μ_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 (Z_{eff}) of Alkali Halides. 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.

Methodology

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 schematic arrangement of experimental setup in the present work is shown in Figure1. The gamma rays are well collimated using lead collimators. Each of the collimators has a cylindrical shape and a circular aperture.

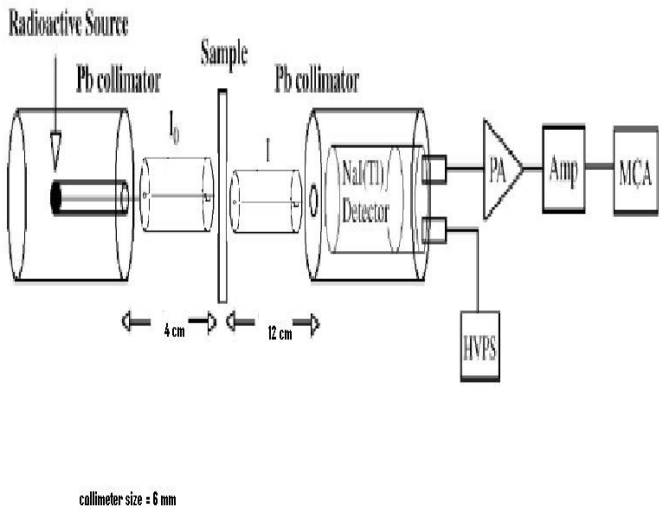

Figure-1
Schematic diagram of transmission experimental setup used in the present work

The present samples of alkali halides have high purities (99.5%–99.9%). The chemical composition of rubidium halides of the present study has been given in table-1.The sample materials each are shaped into pellets with a diameter of 20mm 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 2. 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 samples were irradiated by different radioactive point sources of γ – energies [Cs (0.66MeV), Am (0.0595MeV), Co (1.173MeV and 1.332MeV)]. 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 0.0762 m diameter and 0.0762 m thick crystal is integrally coupled to a 0.0762 m diameter photo multiplier tube (PMT). The PMT has a 14 pin base and can be mounted on two types of PMT preamplifier units. The one used in our study is a coaxial in-line pre-amplifier.

Figure-2
Sample holder

The weak detector pulse enters the preamplifier (or preamp.) which has two main functions; pulse shaping and amplitude gain, The amplified pulse is then fed to the Multi-Channel Analyzer (MCA), which converts the analog signal into a digital number through an analog to digital converter (ADC), in this case the software is used to control the MCA functions and other settings, 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. This procedure was repeated for all the samples and for all γ- energies studied in the present work. Every time the source of γ-radiation is replaced by the other in the source vault, the setup is recalibrated.

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:

$$I = I_0 \exp(-\mu_m t) \quad (1)$$

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 μ_m for any chemical compound or mixture of elements is given by mixture rule [6]:

$$\mu_m = \sum_i w_i (\mu_m)_i \quad (2)$$

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

$$w_i = \frac{n_i A_i}{\sum_i n_i A_i} \quad (3)$$

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 (σ_t) for materials can be obtained from the measured values of μ_m using the following relation

$$\sigma_t = \frac{\mu_m N}{N_A} \quad (4)$$

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 (σ_e) for the element is expressed by the following equation

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

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

$$Z_{eff} = \frac{\sigma_t}{\sigma_e} \quad (7)$$

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

$$N_{eff} = \frac{N_A}{N} Z_{eff} \sum n_i = \frac{\mu_m}{\sigma_e} \quad (8)$$

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

$$\lambda = \frac{\int_0^\infty x \exp(-\mu x)\, dz}{\int_0^\infty \exp(-\mu x)\, dx} = \frac{1}{\mu_l} \quad (9)$$

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

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.

Results and Discussion

Mass attenuation coefficients (μ_m) for rubidium halides (RbCl, RbBr, RbI) 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-2. The mass attenuation coefficient values decrease with increase in photon energy as seen from figure-3. The experimental values for almost all the rubidium halides 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 (μ_l), total photon interaction cross-sections (σ_t and σ_e), effective atomic number (Z_{eff}), effective electron number (N_{eff}) and photon mean free path (λ) for the rubidium halides at different γ-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-2. As seen from the figure-4 and figure-5, 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-2 and from figure6 and figure-7, total photon cross-section and electron cross-section (σ_t and σ_e) decreases with the increase in photon energy. Lastly, the photon mean free path (λ) for a compound found to be increasing with the photon energy as seen from the table-2 and figure-8.

Conclusion

Present Experimental Study Has Been undertaken to get some information on the (μ_M) and related parameters (Σ_T, Σ_E, Z_{EFF}, N_{EFF} and Λ) for rubidium halides (RBCL, RBBR and RBI) at different γ-energies. We can understand that the (μ_M) is useful and sensitive physical quantity to determine the (Z_{EFF}) and (N_{EFF}) of a compound. The (μ) values of rubidium halides in the present study decreases with increase in photon energy. Also, the variation of (Σ_T and $_{\Sigma E}$) with energy is identical to mass attenuation coefficient. The data of (μ_M, ΣT, Σ_E, Z_{EFF}, N_{EFF} and Λ) at different γ- energies for rubidium halides in the present study has been reported for the first time.

Acknowledgements

Authors thank University Grants Commission (UGC), New Delhi for the financial assistance through Special Assistance Programme (SAP) No. F.530/8/DRS/2009 (SAP-1).

Table-1
Chemical compositions of elements in rubidium halides

RbCl		RbBr		RbI	
Rb %	**Cl %**	**Rb %**	**Br %**	**Rb %**	**I %**
70.68	29.32	51.68	48.32	40.14	59.76

Table-2
μ, μ_l, σ_t, σ_e, Z_{eff}, N_{eff}. And λ values (comparison between experimental, theoretical and X-com) of rubidium halides at different γ-energies

Energy	Am (0.0595 MeV)			Cs (0.662 MeV)			Co (1.173 MeV)			Co (1.332 MeV)		
Sample	Expt. Value	X-Com Value	Theor. Value	Expt. Value	X-Com Value	Theor. Value	Expt. Value	X-Com Value	Theor. Value	Expt. Value	X-Com Value	Theor. Value
$\mu_m (10^{-3})$ m^2 kg^{-1}												
RbCl	22.85	22.85	22.85	7.202	7.209	7.209	5.31	5.35	5.35	5.01	5.012	4.99
RbBr	28.47	28.51	28.51	7.111	7.116	7.116	5.239	5.242	5.243	4.903	4.911	4.91
RbI	58.52	58.57	58.57	7.458	7.467	7.467	5.263	5.266	5.266	4.915	4.918	4.92
μ_lm^{-1}												
RbCl	63.98	63.98	63.98	20.17	20.19	20.19	14.87	14.98	14.98	14.03	14.03	14.00
RbBr	95.37	95.51	95.52	23.82	23.84	23.84	17.55	17.56	17.56	16.43	16.45	16.40
RbI	182	182.2	182.1	23.19	23.22	23.22	16.37	16.38	16.38	15.29	15.29	15.3
$\sigma_t(10^{-5})$ b/atom												
RbCl	22.94	22.94	22.94	7.23	7.237	7.237	5.33	5.37	5.37	5.029	5.031	5.01
RbBr	39.08	39.14	39.14	9.762	9.769	9.769	7.192	7.196	7.198	6.731	6.742	6.74
RbI	103.2	103.3	103.3	13.16	13.16	13.15	9.279	9.284	9.284	8.665	8.67	8.67
$\sigma_e(10^{-6})$ b/atom												
RbCl	8.338	8.338	8.338	2.628	2.63	2.63	1.938	1.952	1.952	1.828	1.829	1.82
RbBr	10.86	10.87	10.87	2.711	2.713	2.713	1.998	1.999	1.999	1.869	1.872	1.87
RbI	22.85	22.87	22.87	2.913	2.916	2.916	2.055	2.057	2.057	1.919	1.921	1.92
Z_{effect}												
RbCl	27.51	27.51	27.51	27.51	27.51	27.51	27.51	27.51	27.51	27.51	27.51	27.5
RbBr	36.01	36.01	36.01	36.01	36.01	36.01	36.01	36.01	36.01	36.01	36.01	36.00
RbI	45.14	45.14	45.14	45.14	45.14	45.14	45.14	45.14	45.14	45.14	45.14	45.10
$N_{eff}(10^{23})$ electron/g												
RbCl	2.741	2.741	2.741	2.741	2.741	2.741	2.741	2.741	2.741	2.741	2.741	2.74
RbBr	2.623	2.623	2.623	2.623	2.623	2.623	2.623	2.623	2.623	2.623	2.623	2.62
RbI	2.561	2.561	2.561	2.561	2.561	2.561	2.561	2.561	2.561	2.561	2.561	2.56
$\lambda(10^{-2})$ m												
RbCl	1.563	1.563	1.563	4.959	4.954	4.954	6.726	6.676	6.675	7.129	7.126	7.16
RbBr	1.048	1.047	1.047	4.198	4.195	4.195	5.698	5.695	5.694	6.088	6.078	6.08
RbI	0.549	0.549	0.549	4.311	4.306	4.306	6.11	6.106	6.106	6.542	6.538	6.54

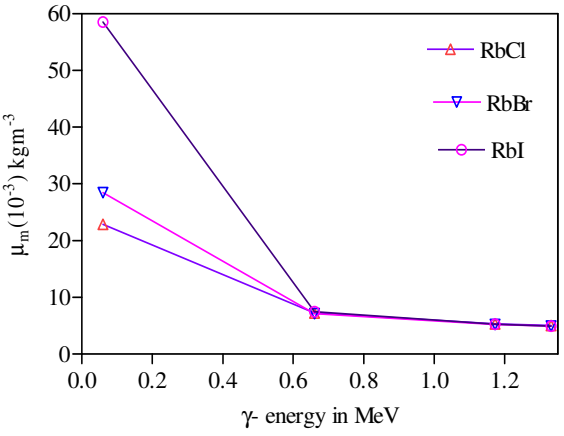

Figure-3
μ_m of rubidium halides versus energy

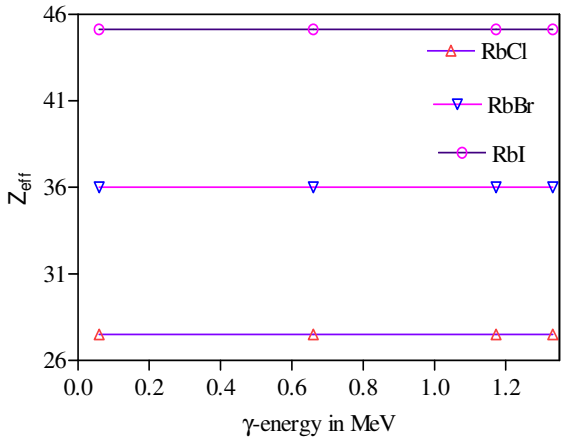

Figure-4
Z_{effec} of rubidium halides versus energy

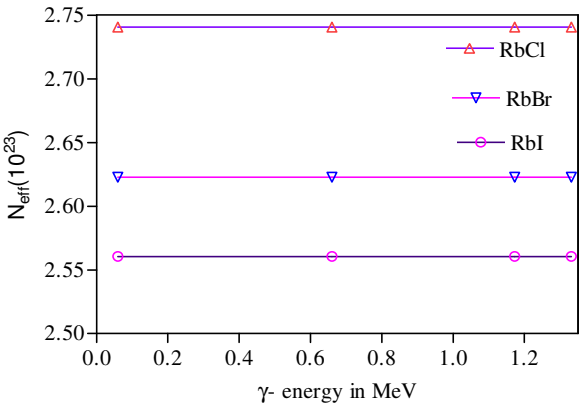

Figure-5
N_{effec} of rubidium halides versus energy

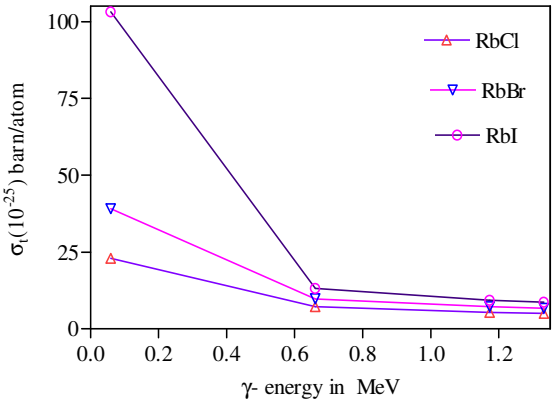

Figure-6
σ_t in rubidium halides versus energy

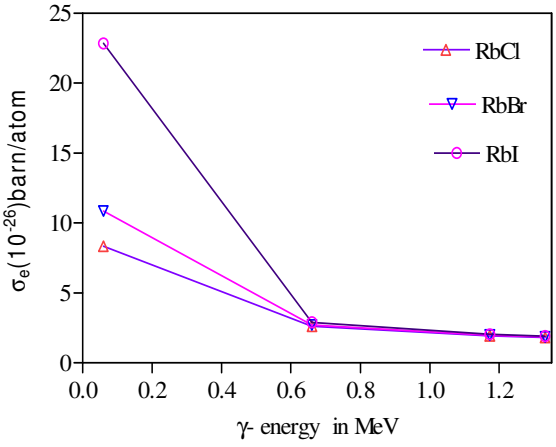

Figure-7
σ_e of rubidium halides versus energy

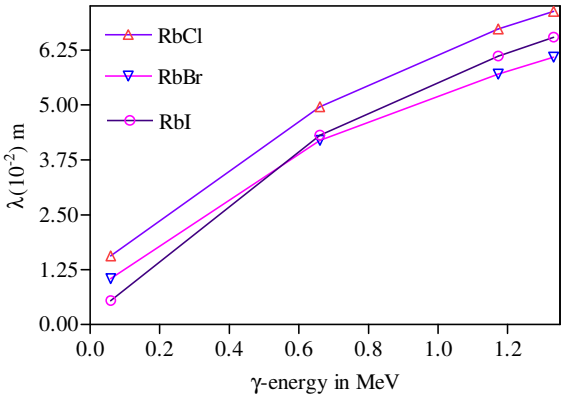

Figure-8
λ of rubidium halides versusenergy

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