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Determination of Photon Interaction Parameters of CaO and MgO for Multi-Energetic Photons using γ-Ray Attenuation Technique

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Abstract:*Mass attenuation coefficients(μ_m) ofCaO and MgOat different γ-energies were determined experimentally using narrow collimated beam transmission method. The samplewas 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 137Cs. 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 (μl), 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 CaO andMgO 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(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)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 usedto derive many other photon interaction 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.

There have been 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 dosimetricinterest [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 Win-Xcom.

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 CaOand MgO. 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 block diagram of the experimental setup is shown in Figure 1.

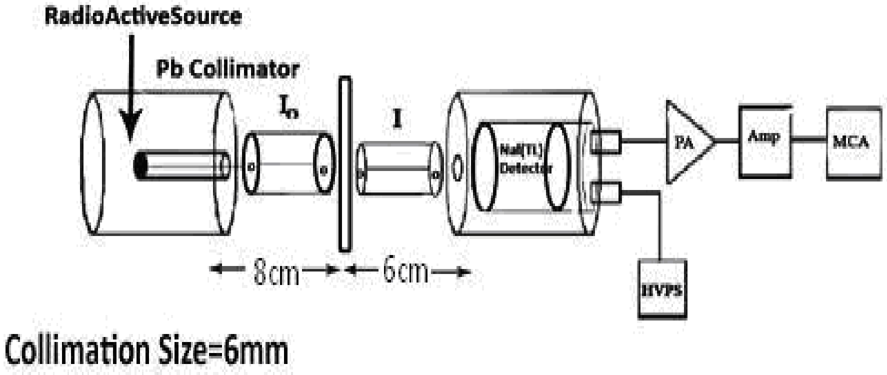

Fig. 1 Block diagram of the experimental setup

The CaOof the present study has high purities (99.5%–99.9%), consists 71.50% of Ca and 28.50% of Oxygen.The pellet is prepared by compressing the CaO powder at a pressure of 2000 psi. The weight of the powder is 20.0 gm and the thickness of pellet is 1.40 cm. The MgO of the present study has high purities (99.5%–99.9%), consists 60.30% of Mg and 39.70% of Oxygen. The pellet is prepared by compressing the MgO powder at a pressure of 2400 psi. The weight of the powder is 22.0 gm and the thickness of pellet is 1.40 cm. The sample materialhas 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. The sample holder along with the sampleis 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 pelletwas 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 respectivelyIntensities 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.

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. Every time the source of γ-radiation is replaced by the other in the source vault, the setup is recalibrated. The same procedure is followed for each sample pellet.

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:

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

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]:

$$\mu_m = \sum_i w_i (\mu_m)_i \tag{2}$$

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

$$w_i = \frac{n_i A_i}{\sum_i n_i A_i} \tag{3}$$

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

$$\sigma_t = \frac{\mu_m N}{N_A} \tag{4}$$

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

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

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 (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

$$Z_{eff} = \frac{\sigma_t}{\sigma_e} \tag{7}$$

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

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

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

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

Where (μ_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*) using the following relation

$$\Delta(\mu_m) = \frac{1}{\rho l}\left[\left(\frac{\Delta I_0}{I}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\ln\frac{I_o}{I}\right)^2 + \left(\frac{\Delta l}{l}\right)^2\right]^{\frac{1}{2}} \tag{10}$$

where$\Delta I_{0,}$, ΔI and Δl are the errors in the intensities I_0, I and thickness l respectively. In this experiment, the intensities I_0 and I have been recorded for the same time and under the same experimental conditions. Estimated error in these measurements was around 2%.

Theoretical values for the mass attenuation coefficients can also be obtained by WinX-Com 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 (μ_m)of CaO and MgOpellets 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 found to be in good agreement,as in the Tables1-2. It is clearly seen that mass attenuation coefficient depends on photon energy and chemical content. 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 for CaO and MgO studied in the present work tend to be slightly smaller than theoretical values. The total experimental uncertainty of mass attenuation coefficient values depend on the uncertainties of peak area evaluation, mass thickness measurements, experimental system, counting statistics, and efficiency errors and so on.The mass attenuation coefficient values decrease with increase in photon energy. The mass attenuation coefficient values for elements in the X-Com database pertain to isolated neutral atoms, and do not take into account molecular and solid-state effects which modify the μ_m values, especially in the vicinity of absorption edges. Also, database does not calculate energy absorption coefficients that represent the conversion of photon energy to kinetic energy of secondary Compton, photo and paired electrons. These factors seem to have little effect in the case of CaO and MgO.Linear attenuation coefficients (μ_l), total photon interaction cross-sections ($\sigma_t$and σ_e), effective atomic number (Z_{eff}), effective electron number (N_{eff}) and photon mean free path (λ) for CaO and MgO at different γ-energies are estimatedby 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 Tables1-2.Although the dependence of σ_τ and σ_e on the photon energy is dominant at low energies, it is negligible at high energiesTheZ_{eff} and the N_{eff} remains constant and are found to be independent of photon energy for a compound.The electron density is closely related to the effective atomic number and hence has the same qualitative energy dependence, as effective atomic numberAs seen from the Tables1-2 and from Figure 3 and Figure 4,total photon cross-section and electron cross-section ($\sigma_t$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 Tables 1-2 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 (μ_m) and related parameters (σ_t,σ_e, Z_{eff}, N_{eff} and λ) for CaO and MgOat 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_m) values CaO and MgOin the present study decreases with increase in photon energy. Also, the variation of ($\sigma_t$and σ_e) with energy is identical to mass attenuation coefficient. The data (μ_m, σ_t, σ_e, Z_{eff}, N_{eff} and λ) of Cao and MgO at different γ- energies in the present study has been reported for the first time.

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Table-1μ_m,μ_l,σ_t,σ_e, Z_{eff} , N_{eff}. & λ values (comparison between experimental, theoretical and X-com)of CaO at different γ-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**
μ_m [10^{-3} m^2kg^{-1}]	53.394	53.394	53.350	7.769	7.769	7.764	5.893	5.893	5.890	5.524	5.524	5.520
μ_l [m^{-1}]	172.98	173.980	172.850	25.172	25.173	25.155	19.093	19.094	19.084	17.898	17.898	17.885
σ_t [10^{-25} barn/atom]	24.8542	24.8559	24.836	3.6166	3.6169	3.6143	2.7433	2.7435	2.7419	2.5715	2.5715	2.5697
σ_e [10^{-26}barn/atom]	17.7450	17.7470	17.732	2.5822	2.5824	2.5806	1.9587	1.9588	1.9577	1.8360	1.8360	1.8347
Z_{eff}	14.006	14.006	14.006	14.006	14.006	14.006	14.006	14.006	14.006	14.006	14.006	14.006
N_{eff} [10^{23} electron/g]	3.0087	3.0087	3.0087	3.0087	3.0087	3.0087	3.0087	3.0087	3.0087	3.0087	3.0087	3.0087
λ [10^{-2} m]	0.5781	0.5781	0.5785	3.9727	3.9724	3.9753	5.2374	5.2372	5.2401	5.5873	5.5873	5.5913

Table-2 μ_m, μ_l, σ_t ,σ_e, Z_{eff} , N_{eff}. & λ values (comparison between experimental, theoretical and X-com) of MgO at different γ-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**
μ_m [10^{-3} m^2kg^{-1}]	23.3	23.26	23.15	7.677	7.67715	7.665	5.842	5.8412	5.835	5.476	5.4754	5.462
μ_l [m^{-1}]	83.3	83.27	82.88	27.484	27.4842	27.441	20.914	20.911	20.889	19.604	19.602	19.554
σ_t [10^{-25} barn/atom]	7.78	7.783	7.746	2.5686	2.56865	2.5646	1.9546	1.9544	1.9523	1.8322	1.832	1.8275
σ_e [10^{-26}barn/atom]	7.77	7.773	7.736	2.5653	2.5654	2.5613	1.9522	1.9519	1.9498	1.8299	1.8297	1.8252
Z_{eff}	10	10.01	10.01	10.013	10.0127	10.013	10.013	10.013	10.013	10.013	10.013	10.013
N_{eff} [10^{23} electron/g]	2.99	2.993	2.993	2.9926	2.99258	2.9926	2.9926	2.9926	2.9926	2.9926	2.9926	2.9926
λ [10^{-2} m]	1.2	1.201	1.207	3.6385	3.63845	3.6442	4.7814	4.7821	4.7871	5.101	5.1015	5.1141

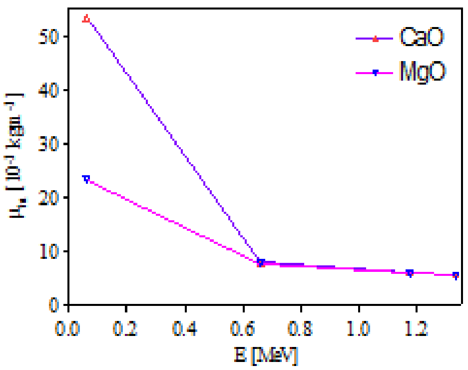

Fig.2 μ_m versus energy

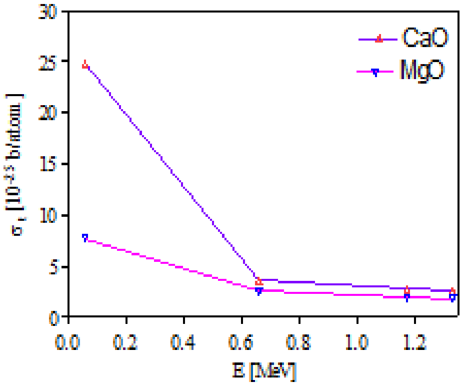

Fig.3 σ_t versus energy

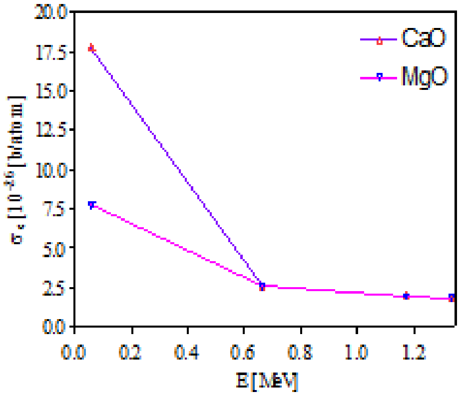

Fig. 4 (σ_e) verses energy

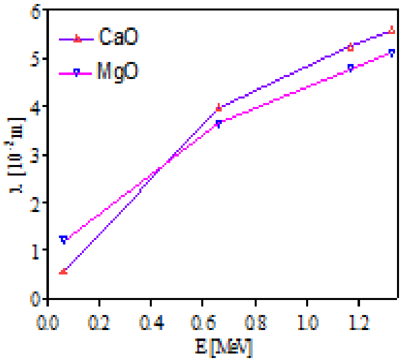

Fig. 5 λ verses energy

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