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Investigation on Gamma Ray Attenuation Parameters of Insulating Epoxy/Barite and Polyester/Barite Composites

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--***ABSTRACT***--
In the present work, the author investigated the linear attenuation coefficient, mass attenuation coefficient, effective atomic number and effective electronic number for electrically insulating epoxy/barite EP/Br (ρ=2.85 $gm\cdot cm^{-3}$) and polyester/barite CUP/Br (ρ=3.25 $gm\cdot cm^{-3}$) composites of radiation shielding potential. The linear attenuation coefficient μ was measured by using narrow beam transmission geometry experimental setup. The experiment was carried on for gamma ray photon energies (0.662, 1.173 and 1.332 MeV) obtained by Cs-137 and Co-60 radioactive sources with the NaI(Tl) scintillation detector.
The experimentally obtained linear attenuation coefficients were divided by the samples densities in order to achieve the mass attenuation coefficients (μ/ρ); as well, MCNP5 code and WinXCom program have been used as two different theoretical tools to evaluate the same parameters for confirmation. Both parameters, effective atomic number (Z_{eff}) and effective electronic number (N_{el}) have been experimentally and theoretically computed using the WinXCom program.
KEYWORDS: *Epoxy/barite, Polyester/barite, mass attenuation coefficient, effective atomic number, electronic density.*

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I. Introduction

In recent decades, gamma radioactive sources have a variety of uses in medicine, biophysics, petroleum plants, archeology, nuclear industry, agriculture and research work. Since these radiations are highly penetrating, we would expect degradation effect to electronic systems encapsulated in Ep/Br or Ps/Br composites attached to or nearby devices that acquire such technologies [1- 3].

The knowledge of the physical parameters related to gamma ray interaction such as the linear attenuation coefficient, total mass attenuation coefficient μ/ρ ($cm^2 \bullet gm^{-1}$), mean free path, half value layer, tenth value layer, effective atomic number Z_{eff} and effective electronic density N_{el} is very essential in radiation shield design [4].

This work is concerned with the experimental measurement of two barite composites using three gamma quanta emitted from Cs-137 and Co-60 radioactive sources.

The mass attenuation coefficient μ/ρ ($cm^2 \bullet gm^{-1}$) was experimentally evaluated depending on μ (cm^{-1}) values. In addition, two theoretical tools have been used to compute μ/ρ. Firstly, by running the Windows version WinXCom computer program for calculating cross-section and attenuation coefficient for elements, compounds and mixtures for photon energies from 1 KeV to 100 GeV. Secondly, by modeling the experiment and obtaining the linear attenuation μ (cm^{-1}) theoretically using MCNP5 code [5].

The code results were further divided by the sample densities to obtain $(\mu/\rho)_{MCNP5}$. A comparison was held between the experimentally evaluated and both theoretically calculated shielding parameters.

In multi-element materials, density and effective atomic number visualize the gamma rays scattering and absorption phenomena; Z_{eff} is defined as the ratio of total atomic cross-section to the total electronic cross-section. Both, Z_{eff} and N_{el}have been experimentally determined and theoretically calculated, and good agreement could be obtained [6,7].

In addition, the broad WinXCom energy range offered further theoretical knowledge of composites photon interaction parameters, mass attenuation coefficient (μ/ρ), the mean free path (λ), the effective atomic number (Z_{eff}) and effective electron density (N_{el}) which is useful for understanding their behavior towards ionizing radiation reactions [8,9].

As well, the effective atomic number (Z_{eff}) addresses the type of target being under radiation interaction. It gives information regarding target elemental composition; since composites of large Z_{eff} values corresponds to metallic or heavy elemental content, while low values predict light constituents.

The electron density N_{el}, which is considered as the number of electrons per unit mass of composite shows to have similar demeanor as that of Z_{eff} .

The experimentally determined and theoretically evaluated parameters are considered a valuable contribution to the investigated electrically insulating composites. Simulation of Z_{eff} and N_{el} could add information for energies wherever related experimental data are not obtained [10].

II. GAMMA RAY ABSORPTION MEASUREMENT

In order to perform the gamma-ray absorption measurements, the narrow beam (source – sample – detector) configuration was provided by the experimental setup as shown in figure(1).

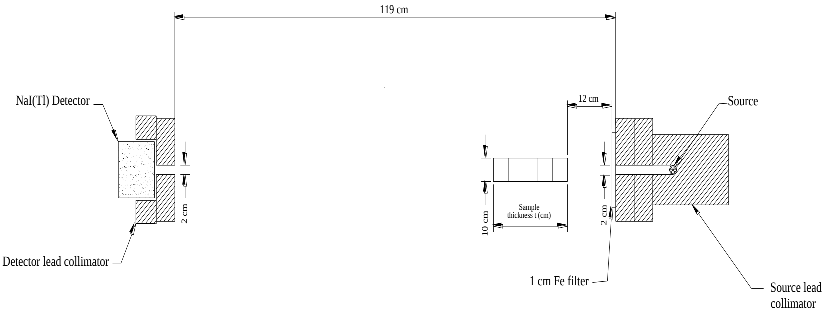


Fig.1. The experimental setup for transmission method

The radioactive sources (Cs-137 and Co-60 of strengths 1138.808 MBq, 318.618 MBq at the time of experiment) were positioned in the lead collimator, and samples were stacked on the samples shoulder close to the beam exit. The detector was a NaI(Tl) crystal of the dimensions (Ø = 5" × thickness = 2") with an energy resolution of 8% at 662 KeV in conjunction with multi-channel-analyzer (MCA) plug-in-card (1024 channel) running with related electronics. The data were monitored using Maistro-32 software package.

In order to perform an application for the simple Lambert-Beer law; the three gamma lines 0.662, 1.173 and 1.332 MeV emitted from both sources were collected by the detector before and after different sample thicknesses. The transmitted intensity I_o is for measured flux with no samples and I's represent the transmitted intensities for different thicknesses. For each counting process, the net area under a fixed symmetrical region pertains each photo-peak centroid gives the intensity of transmitted gamma rays. The recording time was sufficient in order to limit the statistical error by less than 0.3%.

III. CALCULATIONS

Gamma total mass attenuation coefficients μ/ρ

When Gamma rays encounter material, some beam is transmitted and other are absorbed. The decrease in intensity (I) as it passes through substance is given by:

$$I = I_o e^{-\mu x} \quad (1)$$

Where: (I_o) is the incident intensity, (I) transmitted intensity after traversing a thickness x (cm) in the material and (μ) is the linear attenuation coefficient. Since (μ) is dependant on target material we would rather use mass attenuation coefficient μ/ρ (cm^2•gm^{-1}) to avoid density dependence [11,12].

The theoretically calculated mass attenuation coefficients were obtained by two methods; with the classic tool, WinXCom program [13], and by using MCNP5 code [5] to get first the linear attenuation coefficient theoretically, which will be divided by the composites related densities.

MCNP5 is to design and model the experiment, the proper SDEF card for Cs-137 and Co-60 sources were used, and variance reduction technique DXTRAN sphere was used at the detection term to increase the results accuracy.

Computation of Z_{eff} and N_{el}

Both concerned parameters, Z_{eff} and N_{el} will be computed theoretically and evaluated experimentally. They allow the physical characterization of the investigated samples. Firstly, Z_{eff} will be calculated using the WinXCom program, complying with the mixture and compound rule

$$\mu_i = \Sigma_i w_i (\mu_m)_i \quad (2)$$

Where w_i = weight fraction of i_{th} element in sample, $(\mu_m)_i$ the mass attenuation coefficient of the i_{th} element in sample.

The Total electronic cross- section ($\sigma_{t,el}$) for individual elements is determined by the following relation [6,7,14]

$$\sigma_{t,el} = \frac{1}{N_A} \Sigma_i \frac{f_i A_i}{Z_i} \left(\frac{\mu}{\rho}\right)_i \quad (3)$$

Where f_i : is the fractional abundance of element i with respect total number of atoms; A_i the atomic weight and Z_i the charge of i_{th}element in composite. N_A is Avogadro's number.

As well, we can obtain the total atomic cross-section $\sigma_{t,a}$ from the following relation, [14]

$$\sigma_{t,a} = \frac{1}{N_A} \Sigma_i f_i A_i \, (\mu/\rho)_i \qquad (4)$$

From (3) and (4) we can determine the Z_{eff} as follows: [6]

$$Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}} \qquad (5)$$

In addition, the effective electron density could be expressed as follows: [7]

$$N_{eff} = \frac{N_A}{A} Z_{eff} \, \Sigma_i n_i = \frac{\mu_m}{\sigma_{el}} \qquad (6)$$

Where n_i is the number of formula units.

Secondly, the same Z_{eff} and N_{el} parameters were obtained experimentally. The experimental compositesμ/ρ values were obtained from the current study, and for individual elements, the values were taken from previous experimental measurements [15].

IV. RESULTS AND DISCUSSION

The radiation attenuation samples pertaining concerned formulationsEp, Ps, Ep/Br and Ps/Br were carefully positioned on the samples shoulder with different thicknesses. Figures 2(a-d) displays transmitted gamma rays of energies 0.662, 1.173 and 1.332 MeV through the concerned formulations. All attenuation relations show that transmitted gamma rays decrease as samples thickness increase.

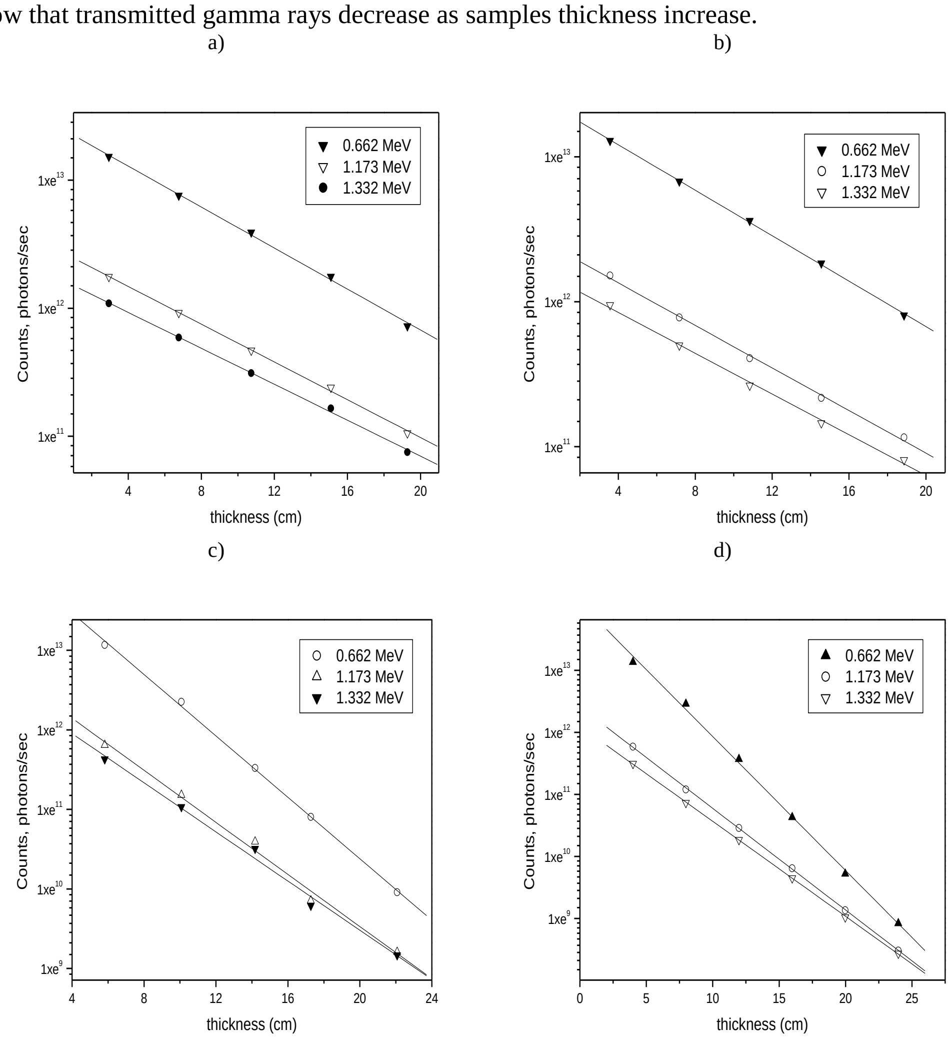


Figure2 a-d. Measured gamma ray counts behind different thicknesses of formulations.

From these attenuation relations linear attenuation coefficient μ (cm^{-1}) could be evaluated. The results were used to evaluate; mean free path λ (cm), Half Value Layer (H.V.L.) and Tenth Value Layer (T.V.L.). The results are presented in table (1).

It is shown that for each composite the shielding capability decreases as gamma energy increases.

Table 1. Evaluated and calculated attenuation parameters for blank formulas and loaded composites.

	Energy (MeV)	μ (cm^{-1})	λ (cm)	H.V.L. (cm)	T.V.L. (cm)
Ep	0.662	0.07999	12.50156	8.665423	28.78591
	1.173	0.07376	13.55748	9.397332	31.21726
	1.332	0.07017	14.2511	9.878113	32.81438
Ps	0.662	0.07838	12.75836	8.843419	29.3772
	1.173	0.07338	13.62769	9.445996	31.37892
	1.332	0.07023	14.23893	9.869674	32.78635
Ep/Br	0.662	0.19303	5.180542	3.590878	11.92864
	1.173	0.16373	6.107616	4.233477	14.06331
	1.332	0.15455	6.470398	4.484938	14.89864
Ps/Br	0.662	0.21594	4.630916	3.209906	10.66308
	1.173	0.16391	6.100909	4.228828	14.04786
	1.332	0.15329	6.523583	4.521803	15.0211

Table 2 shows mass attenuation coefficient of samples by one experimental and two theoretical tools. Reasonable agreement could be realized between experimental and theoretical results which confirm the precision of MCNP5 model.

Table 2. Measured and calculated values of mass attenuation coefficient for the concerned formulations.

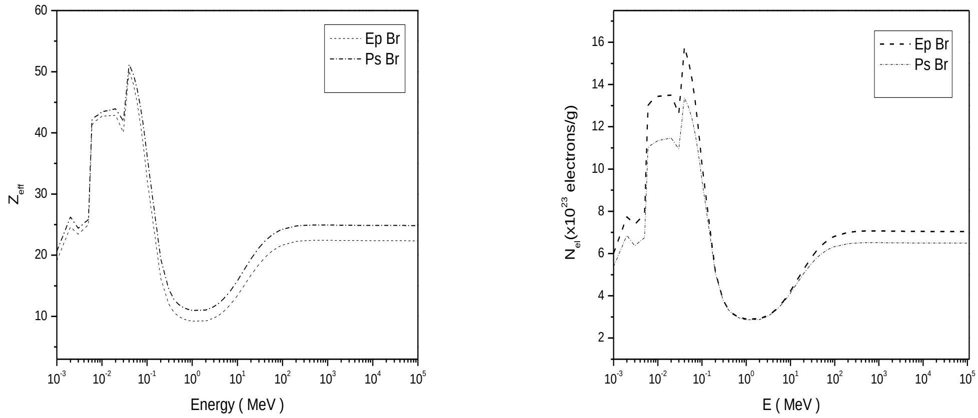
	Energy (MeV)	Experimentally evaluated μ/ρ (cm^{-1})	WinXCom	MCNP5
Ep	0.662	0.071676	0.082195	0.073324
	1.173	0.066093	0.062622	0.060501
	1.332	0.062876	0.058664	0.05748
Ps	0.662	0.072574	0.082212	0.084
	1.173	0.067944	0.062636	0.061564
	1.332	0.065028	0.058677	0.057037
Ep/Br	0.662	0.067730	0.078469	0.058091
	1.173	0.057449	0.056818	0.054210
	1.332	0.054228	0.053098	0.044157
Ps/Br	0.662	0.066443	0.078017	0.082523
	1.173	0.050434	0.056209	0.050858
	1.332	0.047166	0.052516	0.043043

The parameters effective atomic number (Z_{eff}) and effective electronic density (N_{el}) were determined using eq. 5 and eq. 6 respectively and are presented in table (3). As well, good agreement between experimentally estimated and theoretically calculated values could be recognized.

Table 3. Measured and calculated values of Z_{eff} and N_{el} for investigated samples.

	Energy (MeV)	Z_{eff}		N_{el}	
		Exp.	Theo.	Exp.	Theo.
Ep	0.662	3.35023196	3.853014	2.78638E+23	3.19E+23
	1.173	4.07792074	3.853192	3.3916E+23	3.19E+23
	1.332	4.12837095	3.852975	3.43356E+23	3.19E+23
Ps	0.662	3.36246313	3.816661	2.82384E+23	3.19E+23
	1.173	4.1532736	3.816828	3.48798E+23	3.19E+23
	1.332	4.2283898	3.816613	3.55106E+23	3.19E+23
Ep/Br	0.662	7.00538888	8.074584	2.21262E+23	2.54E+23
	1.173	8.66802825	8.523701	2.73776E+23	2.68E+23
	1.332	8.71879466	8.549945	2.7538E+23	2.69E+23
Ps/Br	0.662	8.26445372	9.65317	2.1657E+23	2.52E+23
	1.173	9.16247437	10.15256	2.40102E+23	2.65E+23
	1.332	9.13111445	10.18209	2.39281E+23	2.66E+23

Both parameters Z_{eff} and $N_{el}$for filled composites were presented over the energy range (10^{-3} to 10^{5}) MeV in figures (3 a, b).



a) b)

Figures3 (a,b). Variation of $Z_{eff}$and $N_{el}$with photon energy for total interaction (with coherent).
From the figures we can observe the trend of both parameters to be the same; both composites are heavy and at low energy range (E < 0.01 MeV) the parameters increase and give maximum value, where the dependence on photoelectric effect gives high values for barite constituent. At the intermediate region (0.05 < E < 5 MeV) and for compton reaction domination both parameters decline with energy. For high energies and by dominance of pair production reaction, the parameters go high again but with much smaller rate than the low energy range.

V. CONCLUSION

The filled composites EpBr and PsBr proved to have more efficient gamma ray attenuation parameters with respect to their plank formulations. The theoretically calculated values using WinXCom program and MCNP5 computer code are very close which validates the MCNP5 modeling process. In addition Z_{eff} and N_{el} experimentally evaluated and theoretically calculated values are almost the same. From all this we can conclude that both filled composites have the potential for practical applications as electrical insulators in addition to inherent shielding capability.

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