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Research Article

Calculation of the effects of lead (Pb)-doped eyeglass lenses on radiation shielding efficiency Using Monte Carlo EGS4 code and WinXCOM

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Abstract – In this study, the effects of lead-doped eyeglass samples at different energies on the radiation shielding efficiency were investigated. Radiation shielding efficiency for samples were calculated using the EGS4 code and discussed theoretically by comparing with XCOM data. Mass attenuation coefficients (μ/ρ) for lead-doped eyeglass samples were investigated theoretically (WinXcom and EGS4) at gamma ray energies between 59.5 and 1332 keV. Then, using the mass attenuation coefficients, it was determined some shielding parameters such as mean free path (MFP), half value layer (HVL), one tenth layer thickness (TVL), radiation protection efficiency (RPE), effective atomic number (Zeff) and gamma–ray kerma coefficients (k_γ). It has been observed that lead (Pb) doping changes the parameters related to radiation protection efficiency in eyeglass samples.

Keywords – Lead-Doped Eyeglass Samples, Radiation Protection Efficiency, γ-Kerma Coefficient; EGS4

I. Introduction

The behavior of materials under gamma-ray radiation is of paramount importance across various scientific and applied disciplines. Gamma photons have applications in medical physics, radiotherapy, imaging, space technology, etc. Increasing widespread use in fields inspires radiation physicists and nuclear engineers to research more suitable designs for radiation shielding. Gamma-ray photons are extensively utilized in numerous fields due to their penetrating ability, making their interaction with matter a focal point for research and development. In high-energy particle physics experiments, understanding how materials respond to gamma-ray radiation is crucial for detector systems, shielding design, and minimizing background noise.

Research efforts focus on developing materials that not only effectively attenuate gamma-ray radiation but also meet criteria such as weight efficiency, durability, and cost-effectiveness for practical implementation in these varied applications. [1-2]. Adding heavy elements to the glass composition is known to significantly increase its radiation shielding properties. Average chemical composition of lead glassesas follows: $SiO2$: 53-68%, $Na2O$: 5-10%, PbO: 15-40%, $Al2O3$: 6-12%.

The Mass Attenuation Coefficient (MAC) serves as a critical parameter in understanding the interaction of materials with radiation. It quantifies the extent to which a material reduces the intensity of radiation as it traverses through it, playing a pivotal role in various scientific, industrial, and medical applications. In medical imaging, different tissues within the human body possess distinct attenuation coefficients for various types of radiation (such as X-rays or CT scans). Understanding these coefficients is essential as they directly impact the quality and clarity of diagnostic images. Optimizing imaging techniques based on these coefficients ensures precise and detailed representations of internal structures and abnormalities within the body. For radiation protection purposes, knowledge of the MAC for various shielding materials is crucial. This information guides the design and implementation of effective barriers to minimize radiation exposure in environments such as nuclear power plants, medical facilities, and industrial settings where radiation hazards are present. Engineers and safety professionals rely on these coefficients to select and design shielding materials that efficiently attenuate radiation. In industrial radiography, where materials are inspected using radiation for flaws or quality control, understanding the attenuation coefficients of different materials is vital. It allows technicians to select appropriate materials for shielding and ensures accurate interpretation of radiographic images for defect detection or material analysis. By studying how materials interact with radiation, scientists can deduce crucial information about the composition, structure, and properties of substances. Overall, the Mass Attenuation Coefficient serves as a fundamental parameter that facilitates numerous applications across multiple fields by providing insights into how materials interact with radiation, thereby enabling advancements in technology, medicine, safety measures, and scientific research.

Understanding the behavior of samples when exposed to gamma-ray radiation is crucial for developing materials that are more resistant to such radiation. Parameters like the mass attenuation coefficient (MAC), effective atomic number (Zeff), radiation protection efficiency (RPE), and gamma-ray kerma coefficient (kγ) are vital in designing materials that can withstand high-energy particle physics experiments [3].

The Tenth Value Layer (TVL), also known as Tenth Thickness or Tenth-Value Thickness, represents the thickness of a given material required to reduce the intensity of a specific type of radiation—such as gamma rays or X-rays—to one-tenth (10%) of its original value. The Zeff (Effective Atomic Number) parameter is important in characterizing the material's ability to interact with gamma rays depending on its elemental composition. Radiation Protection Efficiency (RPE) measures a material's ability to protect against radiation. Gamma-ray Kerma Coefficient (kγ) measures the energy that gamma-ray photons transfer to the material through interactions.

The XCOM software was developed by Berger and Hubbell as a tool for calculating the mass attenuation coefficients and photon cross sections for elements, compounds, and mixtures over a wide range of energies, from 1 keV to 100 GeV [4]. To make the software more accessible and user-friendly, Gerward et al. developed a modified version of XCOM known as WinXCOM [5]. By simulating the behavior of gamma rays as they pass through materials, Monte Carlo methods were used to calculate mass attenuation coefficients and other parameters important to understanding gamma-ray interactions [6-10].

In this study, the mass attenuation coefficients of samples were theoretically Monte Carlo EGS4 and winXCOM calculated energies from59.5 to 1332 keV. The computed theoretical XCOM and EGS4 mass attenuation coefficient (MAC) values were used to determine some shielding parameters such as MFP, HVL, TVL, Zeff, RPE and gamma kerma coefficients (kγ).

II. MATERIALS AND METHOD

Monte Carlo Simulation

In the current study, in order to determine gamma attenuation parameters and kerma coefficients, EGS4 (Electron Gamma Showers) Nelson and Hirayama was used to perform the calculations [11]. Monte Carlo simulations with the EGS4 was used to simulate the HPGe detector response. Since random number generation is of importance in MC calculations, one must use a verified random number generator. A RANLUX random number generator was used with the EGS4 code, as it was shown to produce relatively better distribution and a longer sequence [12]. For the model executed with EGS4, the efficiency was divided into 10,010 energy bins, each one having a width of 0.3 keV.

The calculated area is divided into 241 cells and a cylindrical geometry is achieved when this shape is rotated 360° on the -axis given Fig. 1. It will be assumed that **Fig. 1** shows a series of cylindrical circular projectiles, each with a radius represented by R1, R2, …, R11 and planes represented by P1, P2, …., P20. A part of code was created for the point radioactive source in a manner where all photons were released over the z-axis, giving a beam of collimated photons [7,8,13].

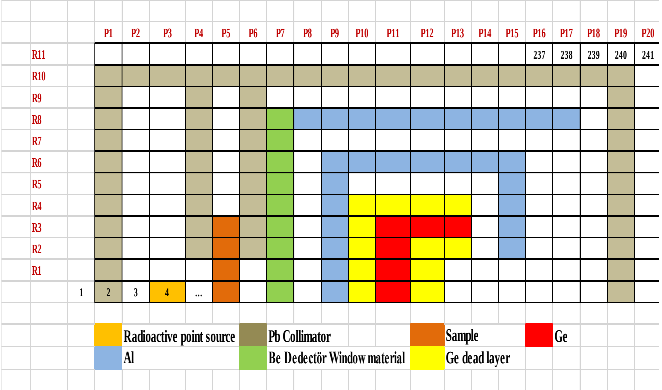

Fig. 1. Detector model for Monte Carlo (ESG4 code) calculations.

Gamma attenuation parameters

In this study, the mass attenuation coefficients (MAC) parameters of samples were determined as follows:

The attenuation of gamma rays in a material can be described using the Beer-Lambert law, which states:

$$I = I_0 e^{-\mu x} \quad (1)$$

where I is the intensity of the gamma-ray beam after it has passed through a thickness x of the material, I_0 is the initial intensity of the beam and μ (cm^{-1}) is the linear attenuation coefficient of the material for the specific energy of the gamma rays being considered.

While the linear attenuation coefficient (μ) is commonly used to describe how strongly a material absorbs gamma rays, it has the disadvantage of depending on the density of the material. Therefore, it is often more useful to use the density-independent mass attenuation coefficient (μ/ρ), which is expressed in units of cm^2/g.

The density-independent mass attenuation coefficient can be calculated using the following formula μ/ρ (cm^2/g):

$$I = I_0 e^{-(\mu/\rho)\rho x} = I_0 e^{-(\mu/\rho) d} \quad (2)$$

According to the Beer-Lambert law equation, the thickness "d" is expressed in unit area mass of the material (g/cm^2). When a sample contains more than one metal, the mass attenuation coefficient (μ/ρ) of the sample can be calculated using the mixture rule formula, which is given as:

$$\mu/\rho = \sum_i w_i \, (\mu/\rho)_i \quad (3)$$

where w_i is the weight fraction of the ith component in the sample and $(\mu/\rho)_i$ is the density-independent mass attenuation coefficient of the ith component [14].

The weight fraction (wi) of a chemical component i in a mixture can be calculated using the following relation:

$$w_i = \frac{a_i A_i}{\sum a_i A_i} \quad (4)$$

where a_i is the number of formula units, Ai is the atomic weight of the ith element, and the summation is taken over all components in the mixture.

Mass attenuation coefficients (μ ρ/) of the samples under study are computed by Monte Carlo-EGS4 simulation code and compared to WinXCOM results in the energy range 0.0595–1.332 MeV. The theoretical mass attenuation coefficients (μ/ρ) of samples were determined using WinXCom software [5,7,15,16].

The Zeff of the samples under investigation have been computed using the formula [17]:

$$Z_{eff} = \frac{\sum f_i A_i \left(\frac{\mu}{\rho}\right)_i}{\sum \frac{f_i A_i}{Z_i} \left(\frac{\mu}{\rho}\right)_i} \quad (5)$$

where f_i fi is the weight fraction of the i-th element in the material, A_i is the atomic weight of the i-th element, is the atomic number of the i-th element [18].

Half value layer (HVL) of the materials is the thickness that reduced the half of the radiation entering it [17]: The HVL can be calculated using the following equation

$$HVL = \frac{0.693}{\mu} \quad (6)$$

The TVL can be calculated using the following equation

$$TVL = \frac{ln10}{\mu} \quad (7)$$

The mean free path (MFP) is a measure of the average distance a particle or photon can travel in a material before it interacts with the material in some way, such as absorption, scattering, or transmission. In general, the MFP is the inverse of the linear attenuation coefficient (μ) of a material, which describes how much radiation is absorbed or scattered per unit length of the material. The mean free path (MFP) were calculated using μ values as follows [19]:

$$MFP = \frac{1}{\mu} \quad (8)$$

where, μ is the linear attenuation coefficient, whose unit of measurement is cm^{-1}.
The radiation protection efficiency (RPE) parameter of sampless was investigated. The efficiency (RPE) in terms from incoming and transmitted photon densities is given equation below [20]:

$$RPE = \left(1 - \frac{I}{I_0}\right) * 100 \quad (9)$$

Kerma coefficient (Gy.cm^2/photon) for uncharged particles can be calculated using the mass attenuation coefficient and partial interaction probabilities. It is given by the equation:

$$K = k\phi\left[\frac{\mu_{tr}}{\rho}\right] \quad (10)$$

where K is uncharged radiation of energy E, $k\phi$ is the kerma coefficient and μ_{tr}/ρ is the mass energy-transfer coefficient of the substance [21]:
Methods for finding the photon kerma coefficients of samples have been given in previous studies [7,10,22,23]:

(11)

III. RESULTS AND DISCUSSION

Chemical composition of lead-doped eyeglass lenses (% weight percentage) is given Table 1. Calculated EGS4 and XCOM values of half value layer (HVL), one tenth layer thickness (TVL) and mean free path (MFP) of samples at different energies 59.5, 122,383,662 and 1332 keV have been given in Table 2. The values effective atomic number (Zeff), radiation protection efficiency (RPE) and theoretical (K_T) and simulation (K_{EGS4}) kerma coefficients for the samples have been given in Table 2. Lead-doped eyeglass lenses samples change graph of HVL and TVL values versus photon energy Variation of energy with half value layer (HVL) and one tenth layer thickness (TVL) for given samples was plotted in the 1 keV–100 MeV energy range and shown in Fig 2 and 3, respectively. From these figures, it is seen that both Half Value Layer (HVL) and one tenth layer thickness (TVL) values for the samples examined increase with increasing photon energy. In addition, when the HVL and TVL values of the examined samples were compared from the figures, it was seen that the Lead-doped eyeglass lense samples had lower HVL and TVL values as the lead contribution increased.

The variation of Zeff with photon energy in all samples is shown in Fig. 4. Lead-doped eyeglass lense samples differ in Zeff values depending on their chemical composition. Fig. 5 shows changes of RPE with photon energy for investigated samples. In figure 5, it is seen that the RPE values decrease as the photon energy increases. The graph of change of gamma kerma coefficients for samples is shown in Fig. 6.

The interactions of photons with matter are influenced by various factors, primarily the photon energy and the atomic number of the material it interacts with. When high-energy photons, like gamma rays, interact with matter, they undergo different processes such as the photoelectric effect, Compton scattering, and pair production. The likelihood of each process occurring depends on the photon's energy and the atomic number of the material.

Table 1. Chemical composition of lead-doped eyeglass lenses (% weight percentage).

Lead-doped eyeglass lenses	O	Na	Al	Si	Pb
Sample-1	43.21	6.43	4.37	31.57	14.43
Sample-2	37,82	5.07	3.78	26.90	26.43
Sample-3	35.20	3.87	3.26	24.95	32.72

Table 2. Calculated (EGS4) and Theoretical (XCOM) values of HVL, TVL and MFP

	Density (g/cm^3)	**Sample-1** 3.190				**Sample-2** 3.546				**Sample-3** 3.742	
	Energy	59.54 keV		122 keV		383 keV		662 keV		1332 keV	
	Samples	XCOM	EGS4	XCOM	EGS4	XCOM	EGS4	XCOM	EGS4	XCOM	EGS4
Half value layer (HVL)	**Sample-1**	0.228	0.226	0.353	0.352	1.821	1.931	2.659	2.746	3.944	3.749
	Sample-2	0.126	0.130	0.195	0.198	1.416	1.470	2.280	2.221	3.540	3.567
	Sample-3	0.100	0.102	0.153	0.151	1.255	1.306	2.108	2.100	3.45	3.135
Tenth value layer (TVL)	**Sample-1**	0.757	0.749	1.171	1.167	6.043	6.407	8.825	9.114	13.090	12.441
	Sample-2	0.421	0.431	0.649	0.655	4.704	4.879	7.575	7.337	11.760	11.837
	Sample-3	0.333	0.339	0.511	0.502	4.170	4.333	7.005	6.970	11.114	10.405
Mean free path (MFP)	**Sample-1**	0.329	0.329	0.509	0.508	2.627	2.786	3.837	3.963	5.691	5.409
	Sample-2	0.183	0.188	0.282	0.285	2.043	2.121	3.290	3.190	5.108	5.147
	Sample-3	0.144	0.148	0.222	0.219	1.811	1.884	3.043	3.031	4.828	4.524

Table 3. Calculated (EGS4) and Theoretical (XCOM) values of effective atomic number (Z_{eff}) values, Radiation protection efficiency (%) and kerma coefficients *k* (in pGy.cm2/photon)

	Energy	59.54 keV		122 keV		383 keV		662 keV		1332 keV	
	Samples	XCOM	EGS4	XCOM	EGS4	XCOM	EGS4	XCOM	EGS4	XCOM	EGS4
Radiation protection efficiency (%)	**Sample-1**	88.07	88.34	74.69	74.81	23.38	22.23	16.67	16.19	11.57	12.14
	Sample-2	97.81	97.59	91.64	91.41	29.01	28.10	19.16	19.70	12.80	12.72
	Sample-3	99.20	99.12	95.72	95.94	32.04	31.03	20.54	20.62	13.49	14.34
Effective atomic number (Z_{eff})	**Sample-1**	32.86	31.24	32.78	31.05	13.60	13.42	12.02	12.14	11.45	11.35
	Sample-2	45.62	44.49	45.64	45.14	17.23	16.59	14.16	14.60	13.01	12.91
	Sample-3	50.96	49.94	50.99	51.51	19.42	18.67	15.50	15.56	13.99	14.74
Kerma coefficients *k* (in pGy.cm2/photon)	**Sample-1**	6.90	6.98	9.3	9.34	3.13	2.96	3.67	3.55	5.75	6.06
	Sample-2	12.01	11.73	16.59	16.39	4.25	4.10	4.14	4.27	5.89	5.84
	Sample-3	14.68	14.39	20.41	20.74	4.83	4.65	4.39	4.41	5.96	6.36

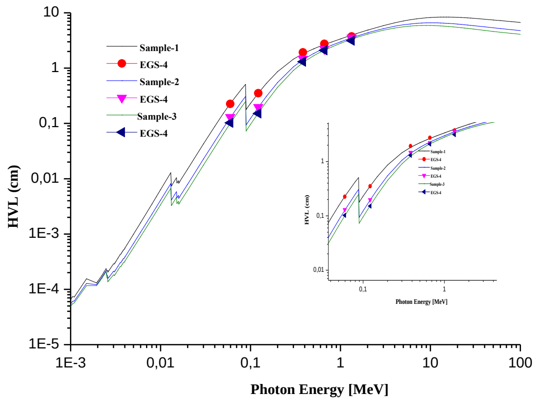

Fig. 2. The variation of the half value layer (HVL) with the energy for samples.

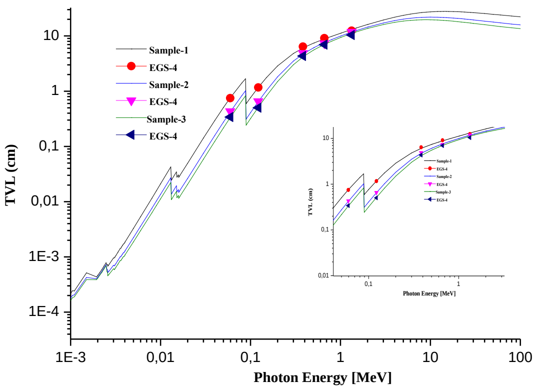

Fig. 3. The variation of the one tenth layer thickness (TVL) with the energy for samples.

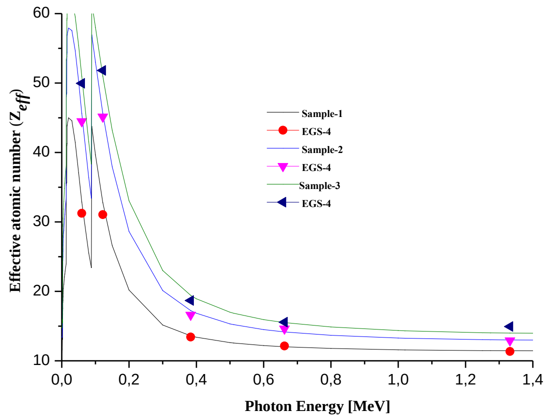

Fig. 4. The variation of effective atomic numbers Z_{eff} of samples versus the photon energy.

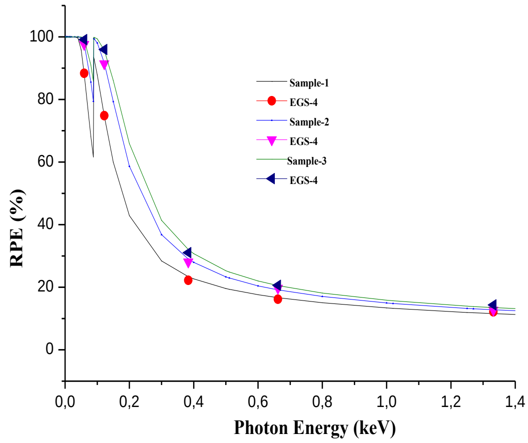

Fig. 5. The variation of radiation protection efficiency (RPE) of samples versus the photon energy.

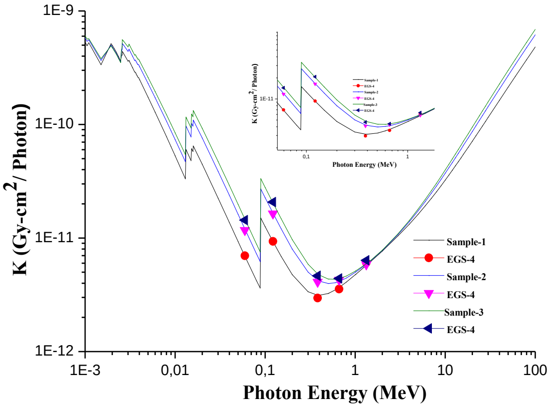

Fig. 6. The gamma kerma coefficients of samples as a function of photon energy.

IV. CONCLUSION

In this study, radiation protection parameters of lead-doped eyeglass samples were investigated at gamma energies 59.5, 122, 383, 661 and 1332 keV. Mass attenuation coefficients (μ/ρ) for samples were investigated theoretically (WinXcom and EGS4). Then, using the mass attenuation coefficients, it was determined some shielding parameters such as mean free path (MFP), one tenth layer thickness (TVL), half value layer (HVL), radiation protection efficiency (RPE), effective atomic number (Zeff) and gamma–ray kerma coefficients (kγ).

For lead-doped eyeglass samples, as the Lead (Pb) contribution increases, a significant decrease is observed in the for HVL, TVL and MFP the same energy values. As Lead (Pb) doping increases, the radiation protection efficiency (RPE) for samples decreases with increasing energy.

For the same energy values, it was observed that as the Lead (Pb) contribution increased, the Half value layer (HVL), mean free path (MFP), one tenth value layer (TVL) values of the samples decreased, while the effective atomic number (Zeff) and gamma-ray kerma coefficients (kγ) increased. The study of materials' interaction with radiation, particularly gamma rays and neutrons, holds immense significance in various fields. Effective shielding materials are indispensable in nuclear power plants, medical imaging, space exploration, and even in everyday applications where radiation exposure needs to be mitigated. By comprehending how materials respond to and attenuate radiation, researchers can engineer better shielding materials. This involves not only enhancing protective capabilities but also ensuring the efficient utilization of materials to create lighter, more durable, and cost-effective shielding solutions. The practical applications of such research are diverse. For instance, in medical imaging, advancements in shielding materials could lead to safer diagnostic procedures by minimizing patient and technician exposure to harmful radiation. In space exploration, developing robust shielding materials is crucial to safeguard astronauts from cosmic radiation.

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