EXTENSIVE THEORETICAL STUDY OF GAMMA-RAY SHIELDING PARAMETERS USING EPOXY RESIN-METAL CHLORIDE MIXTURES

by

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Gamma-ray detection and studying its interactions with matter is very important and serves in many fields of research. Besides, investigation of new shielding materials against gamma-ray will provide a lot of solutions for several problems accompanied by the presence of radiation sources in wide areas of applications, such as industry, medicine, agriculture, research laboratories, and nuclear power plants. In the present work, different gamma-ray attenuation parameters will be calculated theoretically using different metal chlorides mixed with epoxy resin polymers at different weight ratios. These attenuation parameters were calculated in a wide energy range started from 0.05 up to 3 MeV. This wide energy range covers almost the most known radionuclide gamma-ray energies. The obtained results were compared with pure epoxy resin polymer to show how well the modification of polymer properties was when mixed with other materials. Also, all mixture's attenuation parameters results were compared with lead metal results to check its validity as a gamma-ray shielding material. The obtained results found to be promising and the presented materials can be used instead of lead metal as an effective material in radiation protection

Key words: epoxy resin polymer, metal chlorides, gamma-ray detection, mass attenuation coefficient, radiation protection

INTRODUCTION

Gamma-rays are used in many wide fields like nuclear power plants, industry, medical applications, and agriculture. The need to study the effect of gamma-ray interactions with the matter has increased. The interaction process mainly depends upon the energy, the intensity of incident radiation, and the type of absorbing material. The study of the absorption of gamma-rays in shielding materials is particularly important for various radiation fields. The correct values of photon absorption coefficients in radiation shielding materials provide useful data in radiation protection, medicine, and radiation dosimetry fields. The mass attenuation coefficient, μ_m, is considered to be the basic quantity of measuring the probability of interaction in the photons and material [1].

Berger and Hubbell [2, 3] developed a computer program (XCOM) for calculating mass attenuation coefficients for elements, compounds, and mixtures for photon energies from 1 keV to 100 GeV. From the mass attenuation coefficient, several related parameters and coefficients can be derived, such as the total atomic cross-section, effective molecular cross-section, electronic cross-section, effective atomic number, effective electron density, relaxation length, half-value thickness, and the tenth-value layer. Several authors [4-14] studied these parameters and the coefficients for different elements, materials, compounds, and mixtures. The protection from the gamma-ray radiation and its hazards is a necessary issue. Unavailability, hazards, and cost are the main constraints for finding a suitable gamma shield material. To overcome these drawbacks, one needs to test different shielding materials, that can be used at large energy scale, which can be available at low-cost and nonpoisonous in nature. Therefore, the attempts were made to test the efficiency of some polymer materials [7]. The studying of the attenuation parameters of polymers as a gamma-ray shielding material has been raised.

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In the present work, the mass attenuation coefficients of four metal chlorides ($BiCl_3$, $CdCl_2$, CsCl, and $PbCl_2$) mixed with epoxy resin polymer $C_{21}H_{25}ClO_5$ at three different weight fraction ratios (5 %, 25 %, and 45 %). Basaed on the mass attenuation coefficients, all the following parameters total atomic cross-section, effective molecular cross-section, electronic cross-section, effective atomic number, effective electron density, relaxation length, half-value thickness, and the tenth-value layer will be calculated at different photon energy from 0.05 up to 3 MeV. Also, all these attenuation parameters were calculated for lead metal in the same energy range. The mixtures' attenuation parameters results were compared with lead metal results to check how well the epoxy resin polymer shielding properties modified and can be useful.

THEORETICAL BACKGROUND

Linear attenuation coefficient

The linear attenuation coefficient, μ is the probability of gamma-ray interaction with a material per unit path length [15]. According to Lambert-Beer law when a beam of gamma photons incident on the matter, it will attenuate as the following equation

$$I = I_0 e^{-\mu t} \qquad (1)$$

where I and I_0 are the transmitted and incident photon intensities, respectively, μ [cm^{-1}] – the linear attenuation coefficient of the material, while t [cm] – the thickness of the absorber.

Mass attenuation coefficient

The mass attenuation coefficient, μ_m, is a basic quantity that measures the average number of interactions between incident photons and matter that are used in calculations of the penetration and the energy deposition by photons (*X*-ray, gamma-ray, and bremsstrahlung) [16] and those of the chosen samples have been measured [11] using the following equation

$$\mu_m = \frac{\mu}{\rho} = \sum_i w_i (\mu_m) \qquad (2)$$

where ρ is the density of the material and w_i – the weight fraction of the constituent i given [11] as follows

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

where A_i is the atomic weight of element i in the sample and n_i – the number of formula units in the compounds.

Total atomic cross-section

The total photon interaction cross-section, σ, can be written as the sum over contributions from the principal photon interactions as the following [17]

$$\sigma = \sigma_{pho} + \sigma_{incoh} + \sigma_{coh} + \sigma_{pair} + \sigma_{tri} + \sigma_{ph.n} \qquad (4)$$

where σ_{pho} is the atomic photoelectric absorption cross-section which observed in the energy region below 0.01 MeV. At the intermediate energy region, 0.05 MeV $< E <$ 5 MeV, σ_{incoh} compton scattering (incoherent) is dominant. The σ_{pair} and σ_{tri} are pair production that occurred in the high-energy region, above 1.02 MeV. The $\sigma_{ph.n}$ is the photonuclear scattering cross-section. In this expression, coherent scattering has been omitted because of the negligible energy transfer associated with it.

The total atomic cross-section, σ_{atom}, can be obtained by dividing the mass attenuation coefficient of the compound by the total number of atoms present in one gram of that compound [4] as the following

$$\sigma_{atom} = \frac{\mu_m}{N_A \sum_i \frac{w_i}{A_i}} \qquad (5)$$

where N_A is the Avogadro constan, w_i – the fraction by weight of the element i, and A_i – the atomic weight of the i^{th} element.

Effective molecular cross-section

The effective molecular cross-section, σ_{mol}, is determined from the following equation using the values of the mass attenuation coefficient [17] of μ_m

$$\sigma_{mol} = \frac{\mu_m}{N_A} \sum_i n_i A_i \qquad (6)$$

Electronic cross-section

Similarly, the electronic cross-section, σ_{elec} [17] is given by

$$\sigma_{elec} = \frac{1}{N_A} \sum_i \frac{n_i A_i}{Z_i} (\mu_m)_i \qquad (7)$$

where f_i is the fractional abundance of i^{th} constituent element and it can be given as the following

$$f_i = \frac{n_i}{\sum_i n_i} \qquad (8)$$

Effective atomic number

Effective atomic number, Z_{eff}, is important for the determination of a substitute material for an element associated with the required energy. The effective atomic number [17, 18] is equal to the ratio of the atomic and electronic cross-sections

$$Z_{\text{eff}} \quad \frac{\sigma_{\text{atom}}}{\sigma_{\text{elec}}} \tag{9}$$

Effective electron density

Effective electron density, N_{eff}, is related to the effective atomic number and is given in the number of electrons per unit mass [4] by the next equation

$$N_{\text{eff}} \quad \frac{N_A}{\langle A \rangle} Z_{\text{eff}} \tag{10}$$

where $\langle A \rangle$ is the average atomic mass of the material.

Relaxation length

Relaxation length or mean free path, λ, is the average distance between two successive interactions of photons in which the intensity of the incident photon beam [9, 19] is reduced by the factor 1/e

$$\lambda \quad \frac{1}{\mu} \tag{11}$$

Half-value thickness and tenth-value layer

Half-value thickness (HVT) and tenth-value layer (TVL) are defined as the thickness or layer of a shield or absorber that lessens the intensity of radiation by a factor of one-half and one-tenth of the initial intensity respectively [19]. For doing rapid, approxi-

Table 1. The details of four metal chloride with epoxy resin as mixtures

Mixture details			Weight ratio		
			5 %	25 %	45 %
$BiCl_3$	Constituent weight fraction	H	0.06093	0.04810	0.03528
		C	0.60991	0.48150	0.35310
		O	0.19344	0.15271	0.11199
		Bi	0.03314	0.16568	0.29822
		Cl	0.10259	0.15200	0.20141
	Molar mass [gmol^{-1}]		388.107	370.126	353.737
	<*A*>		11.942	28.471	43.537
	Z-average		5.475	11.375	17.275
	Density [gcm^{-3}]		1.241	1.470	1.802
$CdCl_2$	Constituent weight fraction	H	0.06093	0.04810	0.03528
		C	0.60991	0.48150	0.35310
		O	0.19344	0.15271	0.11199
		Cd	0.03066	0.15330	0.27594
		Cl	0.10507	0.16438	0.22369
	Molar mass [gmol^{-1}]		371.637	305.554	259.424
	<*A*>		12.983	29.870	41.658
	Z-average		5.167	9.833	14.500
	Density [gcm^{-3}]		1.239	1.451	1.750
CsCl	Constituent weight fraction	H	0.06093	0.04810	0.03528
		C	0.60991	0.48150	0.35310
		O	0.19344	0.15271	0.11199
		Cs	0.03947	0.19736	0.35524
		Cl	0.09623	0.12032	0.14439
	Molar mass [gmol^{-1}]		368.320	294.645	245.532
	<*A*>		15.9370	41.080	57.842
	Z-average		5.6	12	18.4
	Density [gcm^{-3}]		1.238	1.449	1.745
$PbCl_2$	Constituent weight fraction	H	0.06093	0.04810	0.03528
		C	0.60991	0.48150	0.35310
		O	0.19344	0.15271	0.11199
		Pb	0.03725	0.18626	0.33527
		Cl	0.09847	0.13142	0.16436
	Molar mass [gmol^{-1}]		384.936	356.135	331.344
	<*A*>		13.448	34.814	53.206
	Z-average		5.733	12.667	19.600
	Density [gcm^{-3}]		1.245	1.492	1.862

mate shielding calculations HVL and TVL are important parameters [20] and they are given as

$$\text{HVT} \quad \frac{\ln 2}{\mu} \tag{12}$$

$$\text{TVL} \quad \frac{\ln 10}{\mu} \tag{13}$$

MATERIALS AND METHOD

Four metal chlorides were used in the present work; these metal chlorides are $BiCl_3$, $CdCl_2$, CsCl, and $PbCl_2$. Each metal chloride was mixed with epoxy resin polymer ($C_{21}H_{25}ClO_5$) in three different weight ratios (5 %, 25 %, and 45 %). The NIST-XCOM photon cross-section database has been used to calculate the mass attenuation coefficients μ_m [cm^2g^{-1}] for all mixtures under study. Besides, the weight fraction for each constituent in each mixture was calculated using the XCOM database. The mass attenuation coefficient was calculated in a wide energy range started from 0.05 to 3 MeV. This wide energy range covers all known radionuclide gamma-ray energies. Moreover, the linear and mass attenuation coefficients μ [cm^{-1}] were determined. In addition to the total attenuation cross-section, atomic cross-section, electronic cross-section, effective atomic number, effective electron densities, HVL, TVL, and the relaxation length, λ, have been determined based on eqs. (5)-(13). All attenuation parameters were calculated for Pb metal and pure epoxy resin polymer.

RESULTS AND DISCUSSION

The weight fraction for each constituent in the mixture was obtained from the XCOM database and tabulated in tab. 1. Each mixture molar mass, average molar mass, the average atomic number, and the mixture density were calculated and were presented in tab. 1. The pure epoxy resin polymer, and lead metal properties and details are listed in tab. 2. The linear attenuation coefficient, μ, of pure epoxy resin, and lead metal at the energy range under study are tabulated in tab. 3. It is clearly noticeable that as the energy increases the linear attenuation coefficient value will be decreased. In addition, the linear attenuation coefficient for the four mixtures $BiCl_3$, CdCl2, CsCl, and $PbCl_2$ at the three different weight ratios under the energy range of the study are tabulated in tab. 4.

The total atomic cross-section for each metal chloride mixture was calculated and plotted in fig. 1. It was then compared with pure epoxy resin polymer and lead metal. The total atomic cross-section values decreased as the photon energy increased. It was also found that as the concentration of metal chloride increases the total atomic cross-section values will increase. Tables 5 and 6 were represented the calculated values of the effective molecular cross-section, σ_{mol}, and the electronic cross-section, σ_{elec}, for the four metal chloride mixtures at the three different weight ratios. In addition, the electron density, N_{el}, electrons/g for all mixtures are tabulated in tab. 7.

The variation of the effective atomic, Z_{eff}, with energy for all the mixtures understudy, was calculated and presented as shown in fig. 2, and it was compared with, Z_{eff}, values for pure epoxy resin polymer and lead metal. From fig. 2, it is clear to notice that, as the concentration of metal chloride increase the Z_{eff}, values will be increased and will be shifted toward the lead metal values.

The values of HVT, TVL, and the relaxation length, λ, were calculated for all the mixtures and plotted as presented in figs. 3-5. Also, it was compared with pure epoxy resin polymer and the lead metal. It was found that the three parameters HVT, TVL, and λ were decreased as the metal chloride-mixing ratio in the mixture increased. Also, it was noticed that as the energy was decreased as the values of these parameters would be decreased. The equivalent thickness, x_{eq}, of pure epoxy resin polymer to 0.1 cm lead metal shielding layer was calculated at different energies depending on eq. (14) and tabulated in tab. 8. The epoxy resin equivalent thickness found to be at low energies more than 31 cm and around 1 cm in the high energy region

$$x_{eq(sample)} \quad \frac{(\mu x)_{Pb}}{\mu_{sample}} \tag{14}$$

Table 2. Pure epoxy resin and lead metal details

Material			Value
Epoxy resin ($C_{21}H_{25}ClO_5$)	Constituent weight fraction	H	0.06414
		C	0.64201
		O	0.20362
		Cl	0.09024
	Molar mass [$gmol^{-1}$]		392.879
	<*A*>		7.555
	Z-average		4
	Density [gcm^{-3}]		1.195
Lead (Pb)	Molar mass [$gmol^{-1}$]		207.2
	Atomic number, Z		82
	Density [gcm^{-3}]		11.34

Table 3. Pure epoxy resin, lead metal linear attenuation coefficient, μ, total electronic cross-section, σ_{elec}, and total molecular cross-section, σ_{mol}

Energy [MeV]	Linear attenuation coefficient, μ		Total electronic cross-section, σ_{elec}		Total molecular cross-section, σ_{mol}	
	Epoxy resin	Pb	Epoxy resin	Pb	Epoxy resin	Pb
0.05	$2.677\cdot10^{-1}$	$8.377\cdot10^{+1}$	$6.016\cdot10^{-25}$	$3.234\cdot10^{-23}$	$1.462\cdot10^{-22}$	$2.542\cdot10^{-21}$
0.10	$1.920\cdot10^{-1}$	$6.051\cdot10^{+1}$	$4.948\cdot10^{-25}$	$2.316\cdot10^{-23}$	$1.048\cdot10^{-22}$	$1.836\cdot10^{-21}$
0.15	$1.698\cdot100^{-1}$	$2.166\cdot10^{+1}$	$4.436\cdot10^{-25}$	$8.287\cdot10^{-24}$	$9.268\cdot10^{-23}$	$6.572\cdot10^{-22}$
0.20	$1.550\cdot10^{-1}$	$1.061\cdot10^{+1}$	$4.062\cdot10^{-25}$	$4.066\cdot10^{-24}$	$8.461\cdot10^{-23}$	$3.220\cdot10^{-22}$
0.40	$1.206\cdot10^{-1}$	$2.436\cdot10^{+0}$	$3.167\cdot10^{-25}$	$9.281\cdot10^{-25}$	$6.586\cdot10^{-23}$	$7.390\cdot10^{-23}$
0.60	$1.019\cdot10^{-1}$	$1.323\cdot10^{+0}$	$2.676\cdot10^{-25}$	$5.010\cdot10^{-25}$	$5.565\cdot10^{-23}$	$4.015\cdot10^{-23}$
0.80	$8.955\cdot10^{-2}$	$9.535\cdot10^{-1}$	$2.351\cdot10^{-25}$	$3.592\cdot10^{-25}$	$4.889\cdot10^{-23}$	$2.893\cdot10^{-23}$
1.00	$8.053\cdot10^{-2}$	$7.715\cdot10^{-1}$	$2.114\cdot10^{-25}$	$2.898\cdot10^{-25}$	$4.396\cdot10^{-23}$	$2.341\cdot10^{-23}$
1.50	$6.558\cdot10^{-2}$	$5.770\cdot10^{-1}$	$1.720\cdot10^{-25}$	$2.159\cdot10^{-25}$	$3.580\cdot10^{-23}$	$1.751\cdot10^{-23}$
2.00	$5.631\cdot10^{-2}$	$5.137\cdot10^{-1}$	$1.473\cdot10^{-25}$	$1.922\cdot10^{-25}$	$3.074\cdot10^{-23}$	$1.559\cdot10^{-23}$
2.50	$4.993\cdot10^{-2}$	$4.882\cdot10^{-1}$	$1.301\cdot10^{-25}$	$1.823\cdot10^{-25}$	$2.726\cdot10^{-23}$	$1.481\cdot10^{-23}$
3.00	$4.525\cdot10^{-2}$	$4.763\cdot10^{-1}$	$1.174\cdot10^{-25}$	$1.781\cdot10^{-25}$	$2.470\cdot10^{-23}$	$1.445\cdot10^{-23}$

Table 4. Linear attenuation coefficient, μ, for the four metal chloride mixtures at the three different weight ratios

Energy [MeV]	Linear attenuation coefficient, μ					
	$BiCl_3$			$CdCl_2$		
	5 %	25 %	45 %	5 %	25 %	45 %
0.05	$5.935\cdot10^{-1}$	$2.196\cdot10^{+0}$	$4.522\cdot10^{+0}$	$6.373\cdot10^{-1}$	$2.432\cdot10^{+0}$	$4.967\cdot10^{+0}$
0.10	$4.205\cdot10^{-1}$	$1.545\cdot10^{+0}$	$3.176\cdot10^{+0}$	$2.478\cdot10^{-1}$	$5.188\cdot10^{-1}$	$9.017\cdot1^{0-1}$
0.15	$2.517\cdot10^{-1}$	$6.548\cdot10^{-1}$	$1.240\cdot10^{+0}$	$1.900\cdot10^{-1}$	$2.883\cdot10^{-1}$	$4.272\cdot10^{-1}$
0.20	$1.954\cdot10^{-1}$	$3.941\cdot10^{-1}$	$6.824\cdot10^{-1}$	$1.660\cdot10^{-1}$	$2.197\cdot10^{-1}$	$2.956\cdot10^{-1}$
0.40	$1.301\cdot10^{-1}$	$1.766\cdot10^{-1}$	$2.440\cdot10^{-1}$	$1.250\cdot10^{-1}$	$1.462\cdot10^{-1}$	$1.762\cdot10^{-1}$
0.60	$1.071\cdot10^{-1}$	$1.327\cdot10^{-1}$	$1.698\cdot10^{-1}$	$1.052\cdot10^{-1}$	$1.209\cdot10^{-1}$	$1.430\cdot10^{-1}$
0.80	$9.333\cdot10^{-2}$	$1.119\cdot10^{-1}$	$1.388\cdot10^{-1}$	$9.227\cdot10^{-2}$	$1.055\cdot10^{-1}$	$1.242\cdot10^{-1}$
1.00	$8.360\cdot10^{-2}$	$9.869\cdot10^{-2}$	$1.206\cdot10^{-1}$	$8.293\cdot10^{-2}$	$9.457\cdot10^{-2}$	$1.110\cdot10^{-1}$
1.50	$6.788\cdot10^{-2}$	$7.921\cdot10^{-2}$	$9.566\cdot10^{-2}$	$6.752\cdot10^{-2}$	$7.697\cdot10^{-2}$	$9.032\cdot10^{-2}$
2.00	$5.836\cdot10^{-2}$	$6.846\cdot10^{-2}$	$8.313\cdot10^{-2}$	$5.804\cdot10^{-2}$	$6.647\cdot10^{-2}$	$7.837\cdot10^{-2}$
2.50	$5.188\cdot10^{-2}$	$6.147\cdot10^{-2}$	$7.539\cdot10^{-2}$	$5.155\cdot10^{-2}$	$5.945\cdot10^{-2}$	$7.061\cdot10^{-2}$
3.00	$4.715\cdot10^{-2}$	$5.652\cdot10^{-2}$	$7.013\cdot10^{-2}$	$4.681\cdot10^{-2}$	$5.442\cdot10^{-2}$	$6.516\cdot10^{-2}$
Energy [MeV]	Linear attenuation coefficient, μ					
	CsCl			$PbCl_2$		
	5 %	25 %	45 %	5 %	25 %	45 %
0.05	$9.085\cdot10^{-1}$	$4.016\cdot10^{+0}$	$8.394\cdot10^{+0}$	$6.165\cdot10^{-1}$	$2.358\cdot10^{+0}$	$4.964\cdot10^{+0}$
0.10	$2.898\cdot10^{-1}$	$7.639\cdot10^{-1}$	$1.432\cdot10^{+0}$	$4.403\cdot10^{-1}$	$1.680\cdot10^{+0}$	$3.534\cdot10^{+0}$
0.15	$2.034\cdot10^{-1}$	$3.662\cdot10^{-1}$	$5.957\cdot10^{-1}$	$2.587\cdot10^{-1}$	$7.028\cdot10^{-1}$	$1.367\cdot10^{+0}$
0.20	$1.718\cdot10^{-1}$	$2.535\cdot10^{-1}$	$3.687\cdot10^{-1}$	$1.987\cdot10^{-1}$	$4.167\cdot10^{-1}$	$7.429\cdot10^{-1}$
0.40	$1.257\cdot10^{-1}$	$1.501\cdot10^{-1}$	$1.846\cdot10^{-1}$	$1.308\cdot10^{-1}$	$1.814\cdot10^{-1}$	$2.570\cdot10^{-1}$
0.60	$1.053\cdot10^{-1}$	$1.215\cdot10^{-1}$	$1.444\cdot10^{-1}$	$1.075\cdot10^{-1}$	$1.352\cdot10^{-1}$	$1.767\cdot10^{-1}$
0.80	$9.226\cdot10^{-2}$	$1.054\cdot10^{-1}$	$1.238\cdot10^{-1}$	$9.358\cdot10^{-2}$	$1.137\cdot10^{-1}$	$1.437\cdot10^{-1}$
1.00	$8.287\cdot10^{-2}$	$9.419\cdot10^{-2}$	$1.102\cdot10^{-1}$	$8.380\cdot10^{-2}$	$1.001\cdot10^{-1}$	$1.245\cdot10^{-1}$
1.50	$6.744\cdot10^{-2}$	$7.650\cdot10^{-2}$	$8.927\cdot10^{-2}$	$6.803\cdot10^{-2}$	$8.027\cdot10^{-2}$	$9.859\cdot10^{-2}$
2.00	$5.799\cdot10^{-2}$	$6.617\cdot10^{-2}$	$7.768\cdot10^{-2}$	$5.849\cdot10^{-2}$	$6.941\cdot10^{-2}$	$8.575\cdot10^{-2}$
2.50	$5.153\cdot10^{-2}$	$5.933\cdot10^{-2}$	$7.032\cdot10^{-2}$	$5.201\cdot10^{-2}$	$6.240\cdot10^{-2}$	$7.796\cdot10^{-2}$
3.00	$4.682\cdot10^{-2}$	$5.447\cdot10$–2	$6.525\cdot10^{-2}$	$4.728\cdot10^{-2}$	$5.744\cdot10^{-2}$	$7.263\cdot10^{-2}$

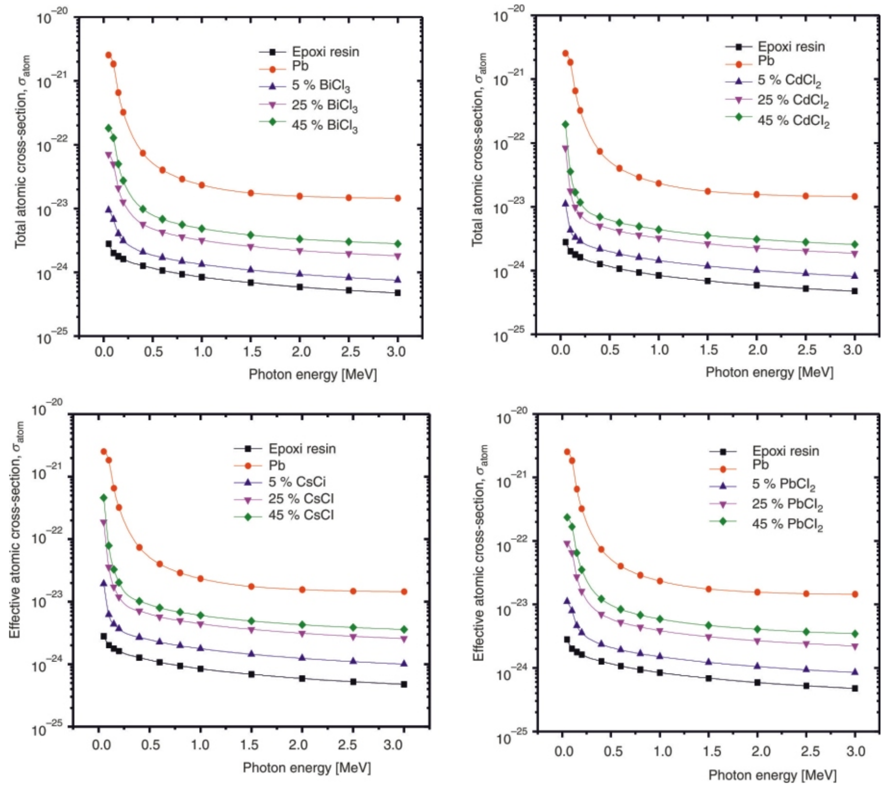

Figure 1. Variation of the total atomic cross-section for the four metal chloride mixtures, pure epoxy resin polymer and lead metal with photon energy

Table 5. Effective molecular cross-section $_{\text{mol}}$, for the four metal chloride mixtures at the three different weight ratios

Energy [MeV]	Effective molecular cross-section, σ_{mol}					
	$BiCl_3$			$CdCl_2$		
	5 %	25 %	45 %	5 %	25 %	45 %
0.05	$3.081\cdot10^{-22}$	$9.182\cdot10^{-22}$	$1.474\cdot10$–^{21}	$3.175\cdot10^{-22}$	$8.505\cdot10^{-22}$	$1.223\cdot10^{-21}$
0.10	$2.183\cdot10^{-22}$	$6.458\cdot10^{-22}$	$1.035\cdot10^{-21}$	$1.235\cdot10^{-22}$	$1.815\cdot10^{-22}$	$2.219\cdot10^{-22}$
0.15	$1.307\cdot10^{-22}$	$2.738\cdot10^{-22}$	$4.042\cdot10^{-22}$	$9.466\cdot10^{-23}$	$1.008\cdot10^{-22}$	$1.051\cdot10^{-22}$
0.20	$1.014\cdot10^{-22}$	$1.647\cdot10^{-22}$	$2.225\cdot10^{-22}$	$8.273\cdot10^{-23}$	$7.685\cdot10^{-23}$	$7.276\cdot10^{-23}$
0.40	$6.753\cdot10^{-23}$	$7.381\cdot10^{-23}$	$7.954\cdot10^{-23}$	$6.228\cdot10^{-23}$	$5.114\cdot10^{-23}$	$4.336\cdot10^{-23}$
0.60	$5.561\cdot10^{-23}$	$5.548\cdot10^{-23}$	$5.537\cdot10^{-23}$	$5.239\cdot10^{-23}$	$4.227\cdot10^{-23}$	$3.521\cdot10^{-23}$
0.80	$4.845\cdot10^{-23}$	$4.678\cdot10^{-23}$	$4.526\cdot10^{-23}$	$4.597\cdot10^{-23}$	$3.689\cdot10^{-23}$	$3.056\cdot10^{-23}$
1.00	$4.340\cdot10^{-23}$	$4.126\cdot10^{-23}$	$3.931\cdot10^{-23}$	$4.132\cdot10^{-23}$	$3.308\cdot10^{-23}$	$2.733\cdot10^{-23}$
1.50	$3.524\cdot10^{-23}$	$3.312\cdot10^{-23}$	$3.119\cdot10^{-23}$	$3.364\cdot10^{-23}$	$2.692\cdot10^{-23}$	$2.223\cdot10^{-23}$
2.00	$3.030\cdot10^{-23}$	$2.862\cdot10^{-23}$	$2.710\cdot10^{-23}$	$2.892\cdot10^{-23}$	$2.325\cdot10^{-23}$	$1.929\cdot10^{-23}$
2.50	$2.693\cdot10^{-23}$	$2.570\cdot10^{-23}$	$2.458\cdot10^{-23}$	$2.568\cdot10^{-23}$	$2.079\cdot10^{-23}$	$1.738\cdot10^{-23}$
3.00	$2.448\cdot10^{-23}$	$2.363\cdot10^{-23}$	$2.286\cdot10^{-23}$	$2.332\cdot10^{-23}$	$1.903\cdot10^{-23}$	$1.604\cdot10^{-23}$
Energy [MeV]	Effective molecular cross-section, σ_{mol}					
	CsCl			$PbCl_2$		
	5 %	25 %	45 %	5 %	25 %	45 %
0.05	$4.487\cdot10^{-22}$	$1.356\cdot10^{-21}$	$1.961\cdot10^{-21}$	$3.167\cdot10^{-22}$	$9.349\cdot10^{-22}$	$1.467\cdot10^{-21}$
0.10	$1.431\cdot10^{-22}$	$2.580\cdot10^{-22}$	$3.346\cdot10^{-22}$	$2.261\cdot10^{-22}$	$6.660\cdot10^{-22}$	$1.045\cdot10^{-21}$
0.15	$1.004\cdot10^{-22}$	$1.237\cdot10^{-22}$	$1.392\cdot10^{-22}$	$1.329\cdot10^{-22}$	$2.786\cdot10^{-22}$	$4.041\cdot10^{-22}$
0.20	$8.487\cdot10^{-23}$	$8.563\cdot10^{-23}$	$8.614\cdot10^{-23}$	$1.020\cdot10^{-22}$	$1.652\cdot10^{-22}$	$2.196\cdot10^{-22}$
0.40	$6.207\cdot10^{-23}$	$5.071\cdot10^{-23}$	$4.313\cdot10^{-23}$	$6.717\cdot10^{-23}$	$7.190\cdot10^{-23}$	$7.597\cdot10^{-23}$
0.60	$5.200\cdot10^{-23}$	$4.105\cdot10^{-23}$	$3.375\cdot10^{-23}$	$5.521\cdot10^{-23}$	$5.360\cdot10^{-23}$	$5.222\cdot10^{-23}$
0.80	$4.556\cdot10^{-23}$	$3.559\cdot10^{-23}$	$2.893\cdot10^{-23}$	$4.806\cdot10^{-23}$	$4.506\cdot10^{-23}$	$4.247\cdot10^{-23}$
1.00	$4.093\cdot10^{-23}$	$3.181\cdot10^{-23}$	$2.574\cdot10^{-23}$	$4.304\cdot10^{-23}$	$3.968\cdot10^{-23}$	$3.680\cdot10^{-23}$
1.50	$3.331\cdot10^{-23}$	$2.584\cdot10^{-23}$	$2.086\cdot10^{-23}$	$3.494\cdot10^{-23}$	$3.182\cdot10^{-23}$	$2.914\cdot10^{-23}$
2.00	$2.864\cdot10^{-23}$	$2.235\cdot10^{-23}$	$1.815\cdot10^{-23}$	$3.004\cdot10^{-23}$	$2.752\cdot10^{-23}$	$2.534\cdot10^{-23}$
2.50	$2.545\cdot10^{-23}$	$2.004\cdot10^{-23}$	$1.643\cdot10^{-23}$	$2.671\cdot10^{-23}$	$2.474\cdot10^{-23}$	$2.304\cdot10^{-23}$
3.00	$2.313\cdot10^{-23}$	$1.840\cdot10^{-23}$	$1.525\cdot10^{-23}$	$2.428\cdot10^{-23}$	$2.277\cdot10^{-23}$	$2.147\cdot10^{-23}$

Table 6. Electronic cross-section σ_{elec}, for the four metal chloride mixtures at the three different weight ratios

Energy [MeV]	Electronic cross-section, σ_{elec}					
	$BiCl_3$			$CdCl_2$		
	5 %	25 %	45 %	5 %	25 %	45 %
0.05	$1.153\cdot10^{-24}$	$3.231\cdot10^{-24}$	$5.124\cdot10^{-24}$	$1.921\cdot10^{-24}$	$6.025\cdot10^{-24}$	$8.890\cdot10^{-24}$
0.10	$8.490\cdot10^{-25}$	$2.184\cdot10^{-24}$	$3.400\cdot10^{-24}$	$6.758\cdot10^{-25}$	$1.239\cdot10^{-24}$	$1.632\cdot10^{-24}$
0.1	$5.655\cdot10^{-25}$	$1.025\cdot10^{-24}$	$1.444\cdot10^{-24}$	$4.986\cdot10^{-25}$	$6.698\cdot10^{-25}$	$7.893\cdot10^{-25}$
0.20	$4.629\cdot10^{-25}$	$6.766\cdot10^{-25}$	$8.714\cdot10^{-25}$	$4.298\cdot10^{-25}$	$5.032\cdot10^{-25}$	$5.545\cdot10^{-25}$
0.40	$3.261\cdot10^{-25}$	$3.615\cdot10^{-25}$	$3.938\cdot10^{-25}$	$3.200\cdot10^{-25}$	$3.301\cdot10^{-25}$	$3.371\cdot10^{-25}$
0.60	$2.711\cdot10^{-25}$	$2.846\cdot10^{-25}$	$2.969\cdot10^{-25}$	$2.687\cdot10^{-25}$	$2.723\cdot10^{-25}$	$2.748\cdot10^{-25}$
0.80	$2.370\cdot10^{-25}$	$2.441\cdot10^{-25}$	$2.506\cdot10^{-25}$	$2.357\cdot10^{-25}$	$2.375\cdot10^{-25}$	$2.388\cdot10^{-25}$
1.00	$2.126\cdot10^{-25}$	$2.171\cdot10^{-25}$	$2.212\cdot10^{-25}$	$2.117\cdot10^{-25}$	$2.129\cdot10^{-25}$	$2.136\cdot10^{-25}$
1.50	$1.727\cdot10^{-25}$	$1.753\cdot10^{-25}$	$1.777\cdot10^{-25}$	$1.723\cdot10^{-25}$	$1.732\cdot10^{-25}$	$1.739\cdot10^{-25}$
2.00	$1.481\cdot10^{-25}$	$1.511\cdot10^{-25}$	$1.538\cdot10^{-25}$	$1.479\cdot10^{-25}$	$1.497\cdot10^{-25}$	$1.510\cdot10^{-25}$
2.50	$1.311\cdot10^{-25}$	$1.349\cdot10^{-25}$	$1.384\cdot10^{-25}$	$1.311\cdot10^{-25}$	$1.341\cdot10^{-25}$	$1.362\cdot10^{-25}$
3.00	$1.186\cdot10^{-25}$	$1.233\cdot10^{-25}$	$1.275\cdot10^{-25}$	$1.187\cdot10^{-25}$	$1.228\cdot10^{-25}$	$1.257\cdot10^{-25}$
Energy [MeV]	Electronic cross-section, σ_{elec}					
	CsCl			$PbCl_2$		
	5 %	25 %	45 %	5 %	25 %	45 %
0.05	$3.507\cdot10^{-24}$	$1.222\cdot10^{-23}$	$1.803\cdot10^{-23}$	$1.368\cdot10^{-24}$	$4.145\cdot10^{-24}$	$6.535\cdot10^{-24}$
0.10	$9.172\cdot10^{-25}$	$2.185\cdot10^{-24}$	$3.029\cdot10^{-24}$	$1.007\cdot10^{-24}$	$2.862\cdot10^{-24}$	$4.460\cdot10^{-24}$
0.15	$5.759\cdot10^{-25}$	$9.727\cdot10^{-25}$	$1.237\cdot10^{-24}$	$6.200\cdot10^{-25}$	$1.259\cdot10^{-24}$	$1.810\cdot10^{-24}$
0.20	$4.641\cdot10^{-25}$	$6.377\cdot10^{-25}$	$7.535\cdot10^{-25}$	$4.881\cdot10^{-25}$	$7.849\cdot10^{-25}$	$1.040\cdot10^{-24}$
0.40	$3.251\cdot10^{-25}$	$3.503\cdot10^{-25}$	$3.671\cdot10^{-25}$	$3.302\cdot10^{-25}$	$3.793\cdot10^{-25}$	$4.215\cdot10^{-25}$
0.60	$2.706\cdot10^{-25}$	$2.796\cdot10^{-25}$	$2.856\cdot10^{-25}$	$2.727\cdot10^{-25}$	$2.913\cdot10^{-25}$	$3.073\cdot10^{-25}$
0.80	$2.366\cdot10^{-25}$	$2.413\cdot10^{-25}$	$2.444\cdot10^{-25}$	$2.378\cdot10^{-25}$	$2.477\cdot10^{-25}$	$2.562\cdot10^{-25}$
1.00	$2.123\cdot10^{-25}$	$2.153\cdot10^{-25}$	$2.172\cdot10^{-25}$	$2.131\cdot10^{-25}$	$2.193\cdot10^{-25}$	$2.246\cdot10^{-25}$
1.50	$1.727\cdot10^{-25}$	$1.747\cdot10^{-25}$	$1.760\cdot10^{-25}$	$1.730\cdot10^{-25}$	$1.766\cdot10^{-25}$	$1.796\cdot10^{-25}$
2.00	$1.483\cdot10^{-25}$	$1.515\cdot10^{-25}$	$1.535\cdot10^{-25}$	$1.484\cdot10^{-25}$	$1.524\cdot10^{-25}$	$1.558\cdot10^{-25}$
2.50	$1.317\cdot10^{-25}$	$1.364\cdot10^{-25}$	$1.395\cdot10^{-25}$	$1.315\cdot10^{-25}$	$1.365\cdot10^{-25}$	$1.408\cdot10^{-25}$
3.00	$1.195\cdot10^{-25}$	$1.257\cdot10^{-25}$	$1.299\cdot10^{-25}$	$1.190\cdot10^{-25}$	$1.251\cdot10^{-25}$	$1.303\cdot10^{-25}$

Table 7. The effective electron number or electron density, N_{el}, electron per gram for the four metal chloride mixtures at the three different weight ratios

Energy [MeV]	Electron density N_{el} [g^{-1}]					
	$BiCl_3$			$CdCl_2$		
	5 %	25 %	45 %	5 %	25 %	45 %
0.05	$4.146\cdot10+23$	$4.624\cdot10+23$	$4.898\cdot10+23$	$2.678\cdot10+23$	$2.782\cdot10+23$	$3.192\cdot10+23$
0.10	$3.990\cdot10^{+23}$	$4.812\cdot10^{+23}$	$5.184\cdot10^{+23}$	$2.961\cdot10^{+23}$	$2.886\cdot10^{+23}$	$3.156\cdot10^{+23}$
0.15	$3.585\cdot10^{+23}$	$4.346\cdot10^{+23}$	$4.767\cdot10^{+23}$	$3.076\cdot10^{+23}$	$2.967\cdot10^{+23}$	$3.093\cdot10^{+23}$
0.20	$3.399\cdot10^{+23}$	$3.962\cdot10^{+23}$	$4.346\cdot10^{+23}$	$3.119\cdot10^{+23}$	$3.010\cdot10^{+23}$	$3.046\cdot10^{+23}$
0.40	$3.213\cdot10^{+23}$	$3.322\cdot10^{+23}$	$3.439\cdot10^{+23}$	$3.154\cdot10^{+23}$	$3.054\cdot10^{+23}$	$2.986\cdot10^{+23}$
0.60	$3.183\cdot10^{+23}$	$3.172\cdot10^{+23}$	$3.175\cdot10^{+23}$	$3.159\cdot10^{+23}$	$3.060\cdot10^{+23}$	$2.975\cdot10^{+23}$
0.80	$3.172\cdot10^{+23}$	$3.118\cdot10^{+23}$	$3.074\cdot10^{+23}$	$3.161\cdot10^{+23}$	$3.062\cdot10^{+23}$	$2.971\cdot10^{+23}$
1.00	$3.168\cdot10^{+23}$	$3.093\cdot10^{+23}$	$3.026\cdot10^{+23}$	$3.162\cdot10^{+23}$	$3.063\cdot10^{+23}$	$2.969\cdot10^{+23}$
1.50	$3.166\cdot10^{+23}$	$3.074\cdot10^{+23}$	$2.988\cdot10^{+23}$	$3.164\cdot10^{+23}$	$3.063\cdot10^{+23}$	$2.968\cdot10^{+23}$
2.00	$3.174\cdot10^{+23}$	$3.083\cdot10^{+23}$	$3.000\cdot10^{+23}$	$3.168\cdot10^{+23}$	$3.061\cdot10^{+23}$	$2.966\cdot10^{+23}$
2.50	$3.186\cdot10^{+23}$	$3.099\cdot10^{+23}$	$3.024\cdot10^{+23}$	$3.175\cdot10^{+23}$	$3.057\cdot10^{+23}$	$2.963\cdot10^{+23}$
3.00	$3.202\cdot10^{+23}$	$3.119\cdot10^{+23}$	$3.053\cdot10^{+23}$	$3.184\cdot10^{+23}$	$3.054\cdot10^{+23}$	$2.961\cdot10^{+23}$
Energy [MeV]	Electron density N_{el} [g^{-1}]					
	CsCl			$PbCl_2$		
	5 %	25 %	45 %	5 %	25 %	45 %
0.05	$2.092\cdot10^{+23}$	$2.268\cdot10^{+23}$	$2.667\cdot10^{+23}$	$3.623\cdot10^{+23}$	$3.814\cdot10^{+23}$	$4.080\cdot10^{+23}$
0.10	$2.551\cdot10^{+23}$	$2.414\cdot10^{+23}$	$2.709\cdot10^{+23}$	$3.515\cdot10^{+23}$	$3.934\cdot10^{+23}$	$4.257\cdot10^{+23}$
0.15	$2.851\cdot10^{+23}$	$2.599\cdot10^{+23}$	$2.760\cdot10^{+23}$	$3.353\cdot10^{+23}$	$3.741\cdot10^{+23}$	$4.058\cdot10^{+23}$
0.20	$2.990\cdot10^{+23}$	$2.744\cdot10^{+23}$	$2.804\cdot10^{+23}$	$3.270\cdot10^{+23}$	$3.559\cdot10^{+23}$	$3.836\cdot10^{+23}$
0.40	$3.122\cdot10^{+23}$	$2.958\cdot10^{+23}$	$2.881\cdot10^{+23}$	$3.182\cdot10^{+23}$	$3.205\cdot10^{+23}$	$3.275\cdot10^{+23}$
0.60	$3.142\cdot10^{+23}$	$3.001\cdot10^{+23}$	$2.898\cdot10^{+23}$	$3.167\cdot10^{+23}$	$3.111\cdot10^{+23}$	$3.088\cdot10^{+23}$
0.80	$3.148\cdot10^{+23}$	$3.014\cdot10^{+23}$	$2.904\cdot10^{+23}$	$3.162\cdot10^{+23}$	$3.076\cdot10^{+23}$	$3.014\cdot10^{+23}$
1.00	$3.151\cdot10^{+23}$	$3.021\cdot10^{+23}$	$2.907\cdot10^{+23}$	$3.160\cdot10^{+23}$	$3.060\cdot10^{+23}$	$2.977\cdot10^{+23}$
1.50	$3.154\cdot10^{+23}$	$3.023\cdot10^{+23}$	$2.907\cdot10^{+23}$	$3.152\cdot10^{+23}$	$3.048\cdot10^{+23}$	$2.948\cdot10^{+23}$
2.00	$3.157\cdot10^{+23}$	$3.016\cdot10^{+23}$	$2.900\cdot10^{+23}$	$3.162\cdot10^{+23}$	$3.054\cdot10^{+23}$	$2.957\cdot10^{+23}$
2.50	$3.160\cdot10^{+23}$	$3.004\cdot10^{+23}$	$2.889\cdot10^{+23}$	$3.178\cdot10^{+23}$	$3.065\cdot10^{+23}$	$2.974\cdot10^{+23}$
3.00	$3.165\cdot10^{+23}$	$2.991\cdot10^{+23}$	$2.879\cdot10^{+23}$	$3.197\cdot10^{+23}$	$3.078\cdot10^{+23}$	$2.995\cdot10^{+23}$

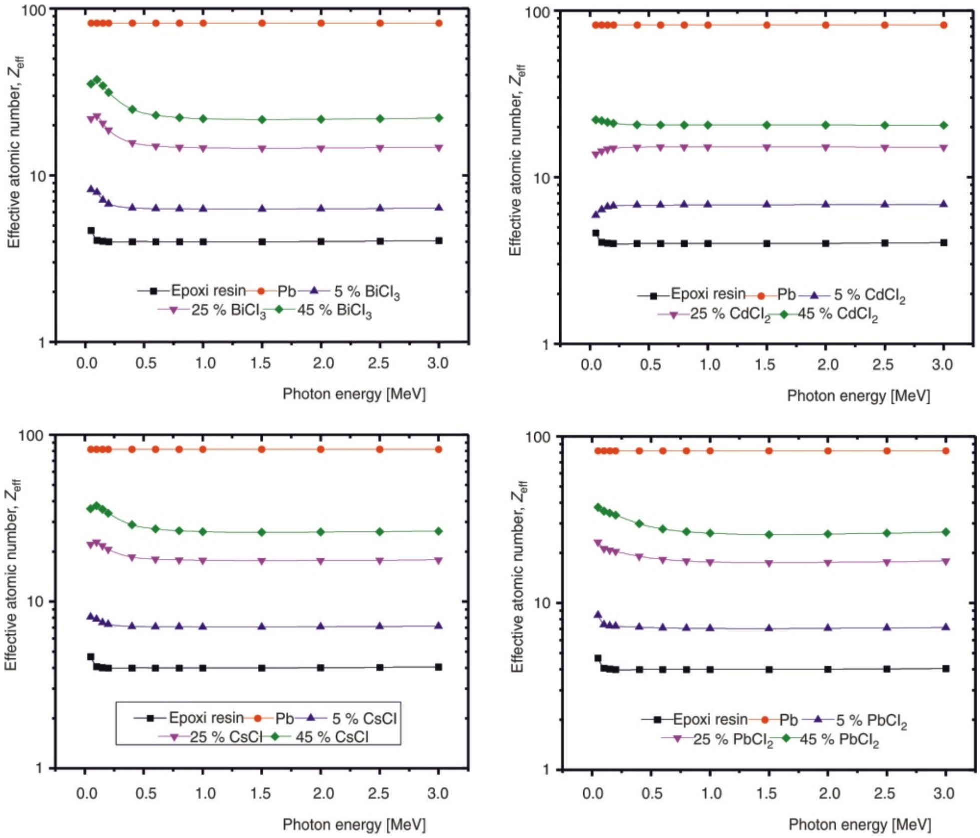

Figure 2. Variation of the effective atomic number, Z_{eff}, for the four metal chloride mixtures, pure epoxy resin polymer, and lead metal with photon energy

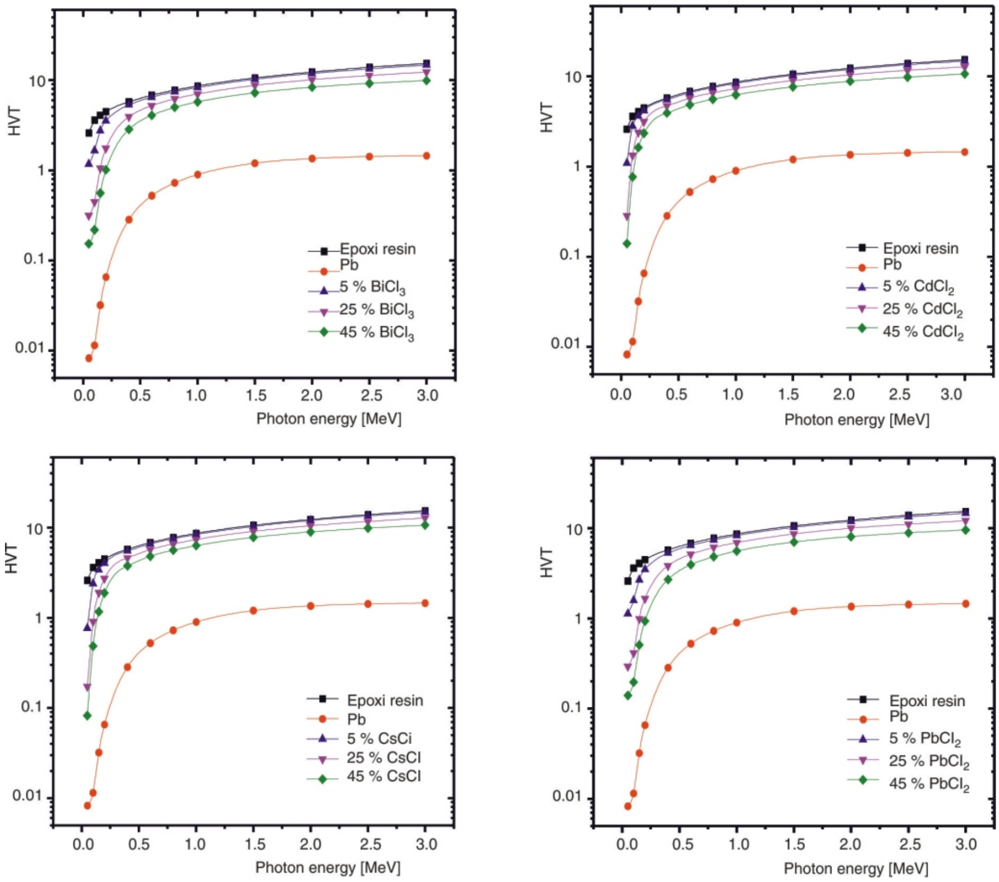

Figure 3. Variation of the HVT for the four metal chloride mixtures, pure epoxy resin polymer, and lead metal with photon energy

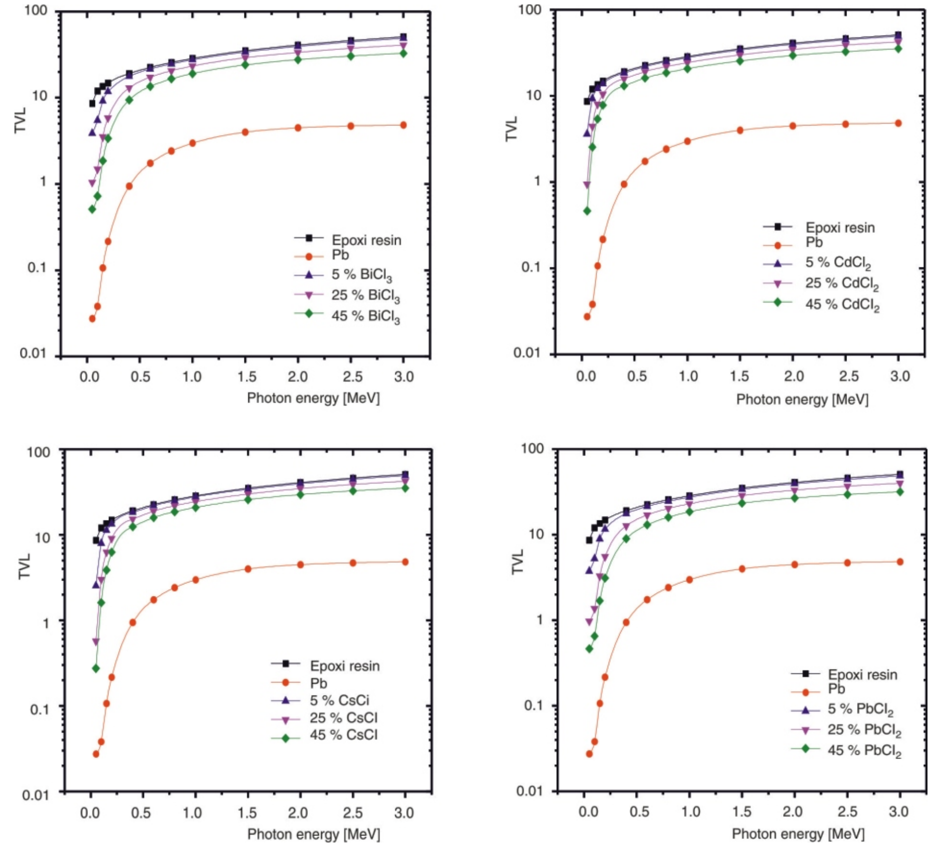

Figure 4. Variation of the TVL for the four metal chloride mixtures, pure epoxy resin polymer, and lead metal with photon energy

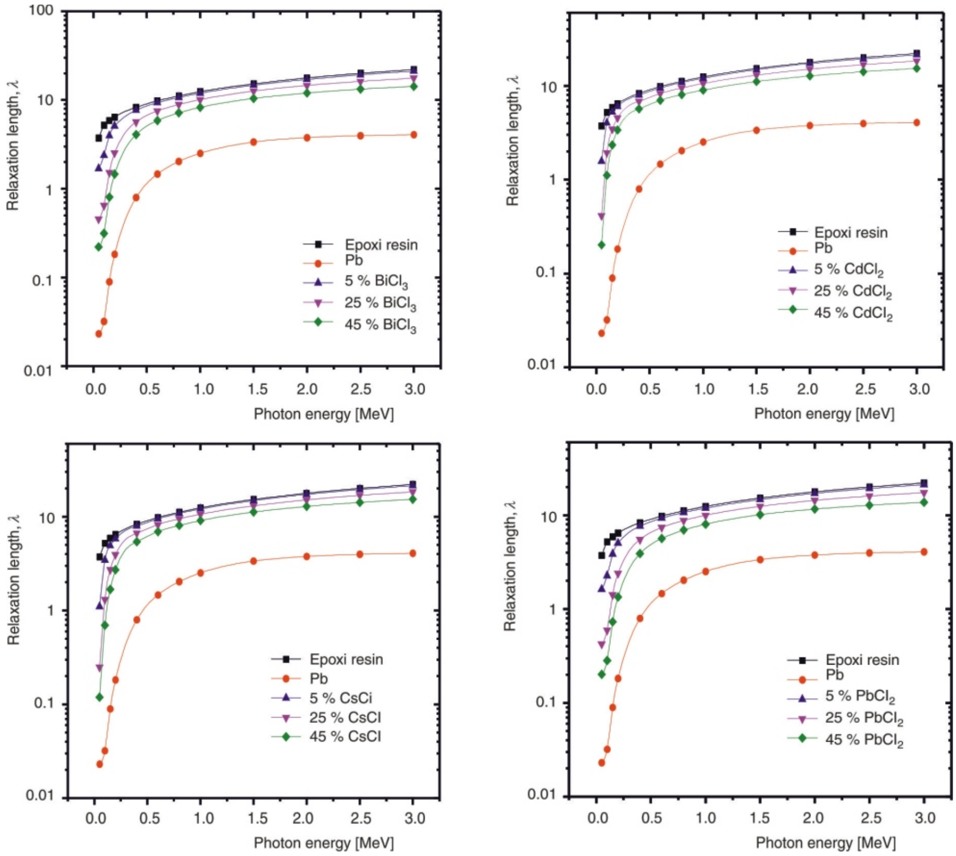

Figure 5. Variation of the relaxation length, λ, for the four metal chloride mixtures, pure epoxy resin polymer, and lead metal with photon energy

Table 8. The equivalent thickness of pure epoxy resin polymer to 0.1 cm lead metal at different photon energies

Energy [MeV]	Equivalent thickness [cm]
0.05	31.29
0.10	31.51
0.15	12.76
0.20	6.85
0.40	2.02
0.60	1.30
0.80	1.06
1.00	0.96
1.50	0.88
2.00	0.91
2.50	0.98
3.00	1.05

The effect of doping the epoxy resin polymer with the different metal chlorides at different amounts raises the shielding properties of epoxy resin polymer against gamma-ray radiation. Table 9 and 10 contain the equivalent thickness for $BiCl_3$, $CdCl_2$, CsCl, and $PbCl_2$ mixtures to 0.1 cm lead metal at different photon energies, in addition to the modification percentage for pure epoxy resin polymer as presented, and it was calculated depending on eq. (15). It is noticed that by adding 5 % of metal chlorides only to the epoxy resin polymer the equivalent thickness shielding properties raised to more than 54 % with respect to pure polymer. The efficiency of doping is raised as a metal chloride ratio increased the modification percentage of pure polymer raised to more than 94 % in the low energy region and around 30 % in the high energy region.

$$\text{Modification percentage}$$
$$\frac{x_{\text{eq(pure epoxy resin)}} \quad x_{\text{eq (mixture)}}}{x_{\text{eq (pure epoxy resin)}}} \, 100\,\% \qquad (15)$$

CONCLUSIONS

The results show that the epoxy resin polymers have a big chance to be used as radiation shielding materials, especially if it mixed with different metal chlorides. Epoxy resin polymers have many characteristics such as enhanced strength, well flexural control, excellent resistance to wear, peeling, cracking, corrosion, moisture, and to chemical and environmental dreadful conditions. The total atomic cross-section, the effective molecular cross-section, the electronic cross-section, the effective atomic number, the effective electron density, the relaxation length, half-value thickness and the tenth-value layer as a function of photon energy from 0.05 up to 3 MeV for four metal chlorides ($BiCl_3$, $CdCl_2$, CsCl, and $PbCl_2$) mixed with epoxy resin polymer $C_{21}H_{25}ClO_5$ at three different weight fraction ratios (5 %, 25 %, and 45 %) lie between pure epoxy resin polymer and lead metal. While the metal chloride ratio increased inside the epoxy resin polymers, these parameters going to be more closed to the lead metal. As a result of doping the epoxy resin polymer by different metal chlorides with different amounts, the shielding properties of epoxy resin polymer against γ-ray radiation were going higher. Especially, change the equivalent thickness for $BiCl_3$, $CdCl_2$, CsCl, and $PbCl_2$ mixtures to 0.1 cm lead metal at different photon energies.

AUTHORS CONTRIBUTIONS

A. A. Thabet and C. V. More calculated the shielding parameters presented in the paper and performed numerical testing. P.P. Pawar, M. S. Badawi, and A. A. Thabet conceived and wrote the paper. A. A. Thabet and C. V. More made valuable contributions in various phases of the work. All authors extensively interacted, exchanging ideas, especially during the preparation of the article.

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Table 9. The equivalent thickness for BiCl$_3$ and CdCl$_2$ mixtures to 0.1 cm lead metal at different photon energies and the modification percentage for pure epoxy resin polymer

Energy	Equivalent thickness [cm]	Modification percentage	Equivalent thickness [cm]	Modification percentage	Equivalent thickness [cm]	Modification percentage
	5 % BiCl$_3$		25 % BiCl$_3$		45 % BiCl$_3$	
0.05	14.12	54.88 %	3.81	87.81 %	1.85	94.08 %
0.10	14.39	54.33 %	3.92	87.57 %	1.91	93.95 %
0.15	8.61	32.55 %	3.31	74.08 %	1.75	86.31 %
0.20	5.43	20.67 %	2.69	60.67 %	1.56	77.29 %
0.40	1.87	7.26 %	1.38	31.67 %	1.00	50.56 %
0.60	1.24	4.85 %	1.00	23.19 %	0.78	39.98 %
0.80	1.02	4.04 %	0.85	19.97 %	0.69	35.50 %
1.00	0.92	3.67 %	0.78	18.40 %	0.64	33.22 %
1.50	0.85	3.39 %	0.73	17.22 %	0.60	31.45 %
2.00	0.88	3.52 %	0.75	17.75 %	0.62	32.26 %
2.50	0.94	3.76 %	0.79	18.78 %	0.65	33.78 %
3.00	1.01	4.04 %	0.84	19.95 %	0.68	35.48 %
Energy	Equivalent thickness [cm]	Modification percentage	Equivalent thickness [cm]	Modification percentage	Equivalent thickness [cm]	Modification percentage
	5 % CdCl$_2$		25 % CdCl$_2$		45 % CdCl$_2$	
0.05	13.14	57.99 %	3.44	88.99 %	1.69	94.61 %
0.10	24.42	22.52 %	11.66	62.99 %	6.71	78.70 %
0.15	11.40	10.65 %	7.51	41.12 %	5.07	60.26 %
0.20	6.39	6.66 %	4.83	29.47 %	3.59	47.57 %
0.40	1.95	3.49 %	1.67	17.49 %	1.38	31.52 %
0.60	1.26	3.07 %	1.09	15.66 %	0.93	28.74 %
0.80	1.03	2.95 %	0.90	15.10 %	0.77	27.87 %
1.00	0.93	2.89 %	0.82	14.85 %	0.69	27.47 %
1.50	0.85	2.88 %	0.75	14.80 %	0.64	27.40 %
2.00	0.89	2.99 %	0.77	15.28 %	0.66	28.15 %
2.50	0.95	3.16 %	0.82	16.02 %	0.69	29.29 %
3.00	1.02	3.35 %	0.88	16.85 %	0.73	30.56 %

Table 10. The equivalent thickness for CsCl and PbCl$_2$ mixtures to 0.1 cm lead metal at different photon energies and the modification percentage for pure epoxy resin polymer

Energy	Equivalent thickness [cm]	Modification percentage	Equivalent thickness [cm]	Modification percentage	Equivalent thickness [cm]	Modification percentage
	5 % CsCl		25 % CsCl		45 % CsCl	
0.05	9.22	70.53 %	2.09	93.33 %	1.00	96.81 %
0.10	20.88	33.74 %	7.92	74.86 %	4.23	86.59 %
0.15	10.65	16.52 %	5.91	53.64 %	3.64	71.50 %
0.20	6.18	9.81 %	4.19	38.87 %	2.88	57.96 %
0.40	1.94	4.01 %	1.62	19.64 %	1.32	34.64 %
0.60	1.26	3.18 %	1.09	16.13 %	0.92	29.43 %
0.80	1.03	2.93 %	0.90	15.01 %	0.77	27.68 %
1.00	0.93	2.82 %	0.82	14.50 %	0.70	26.89 %
1.50	0.86	2.77 %	0.75	14.28 %	0.65	26.54 %
2.00	0.89	2.91 %	0.78	14.90 %	0.66	27.52 %
2.50	0.95	3.12 %	0.82	15.85 %	0.69	29.00 %
3.00	1.02	3.37 %	0.87	16.94 %	0.73	30.66 %
Energy	Equivalent thickness [cm]	Modification percentage	Equivalent thickness [cm]	Modification percentage	Equivalent thickness [cm]	Modification percentage
	5 % PbCl$_2$		25 % PbCl$_2$		45 % PbCl$_2$	
0.05	13.59	56.57 %	3.55	88.65 %	1.69	94.61 %
0.10	13.74	56.39 %	3.60	88.57 %	1.71	94.57 %
0.15	8.37	34.38 %	3.08	75.85 %	1.58	87.58 %
0.20	5.34	21.98 %	2.55	62.81 %	1.43	79.14 %
0.40	1.86	7.75 %	1.34	33.48 %	0.95	53.06 %
0.60	1.23	5.17 %	0.98	24.61 %	0.75	42.31 %
0.80	1.02	4.30 %	0.84	21.21 %	0.66	37.69 %
1.00	0.92	3.90 %	0.77	19.55 %	0.62	35.32 %
1.50	0.85	3.60 %	0.72	18.31 %	0.59	33.48 %
2.00	0.88	3.74 %	0.74	18.88 %	0.60	34.33 %
2.50	0.94	4.00 %	0.78	20.00 %	0.63	35.96 %
3.00	1.01	4.30 %	0.83	21.23 %	0.66	37.71 %

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ОПСЕЖНА ТЕОРИЈСКА СТУДИЈА ПАРАМЕТАРА ЗАШТИТЕ ОД ГАМА ЗРАЧЕЊА ПРИМЕНОМ СМЕША ЕПОКСИДНЕ СМОЛЕ И ХЛОРИДА МЕТАЛА

Детекција гама зрачења и изучавање интеракције гама зрачења са материјалима има велику важност и примењује се у многим областима истраживања. Поред тога, истраживање нових материјала за заштиту од гама зрачења даје многа решења за више проблема који се јављају у примени радиоактивних извора у различитим областима као што су индустрија, медицина, пољопривреда, истраживачке лабораторије и нуклеарне електране. У овом раду, различити параметри слабљења гама зрачења биће израчунати теоретски користећи различите хлориде метала помешане са полимерима епоксидне смоле при различитим односима тежина. Ови параметри слабљења израчунати су за широки опсег енергија од 0.05 MeV до 3 MeV. Овај широки спектар енергија обухвата скоро све енергије гама зрачења најпознатијих радионуклида. Добијени резултати су упоређени са резултатима за чист полимер епоксидне смоле како би се показала ефикасност модификације полимера при додавању других материјала. Такође, параметри слабљења свих смеша упоређени су са параметрима слабљења олова како би се проверила валидност смеша као материјала за заштиту од гама зрачења. Резултати добијени у овом раду су обећавајући и приказани материјали могу се користити као ефективна замена за олово у заштити од зрачења.

Кључне речи: полимер епокси смоле, метал хлорид, детекција гама зрачења, масени коефицијент слабљења, заштита од зрачења