RADIATION SHIELDING AND GAMMA RAY ATTENUATION PROPERTIES OF SOME POLYMERS

by

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In the present work we investigated the gamma radiation parameters as mass attenuation coefficients $\mu \rho$, the total atomic scattering cross-sections σ_t, the electronic scattering cross-sections σ_e, the effective atomic numbers Z_{eff}, and the effective electron densities N_{eff} for some polymers such as polyoxymethylene (CH_2O), poly acrylonitrile (C_3H_3N), natural rubber (C_5H_8), poly ethyl acrylate ($C_5H_8O_2$), polyphenyl methacrylate ($C_{10}H_{10}O_2$), and polyethylene tetraphthalate ($C_{10}H_8O_4$). The gamma ray photons were detected by NaI(Tl) detector with resolution of 8.2 % at 662 keV, using radioactive gamma ray sources ^{57}Co, ^{133}Ba, ^{137}Cs, ^{54}Mn, ^{60}Co, and ^{22}Na at energies 122, 356, 511, 662, 840, 1170, 1275, and 1330 keV. Values of μ/ρ for the chosen polymers decrease with increasing energy. The results of investigated data are useful in plastic industry, building materials, agriculture fields radiation shielding, accelerator centers, polymer industry, medical field, *etc*.

Key words: mass attenuation coefficient, total scattering cross-section, gamma-ray shielding, polymer

INTRODUCTION

As the use of radiation increased in many fields over the last few decades, it has been most important to study and investigate the gamma radiation parameters for the samples which found immense importance in the fields like nuclear physics, electronic industry, material modification, medical science, coating, paint industry, agriculture industry, *etc*. Polymers play very important role in protection against the gamma radiations [1]. Polymers are widely used in many fields because of its various good properties like softness, insulators, elasticity polymer materials are C-, H-, O-based and known as low-*Z* materials, that are not inflammable, having low weight, are less expensive, more stable on high temperature, and can be used at large scale [2] . They are also used in power plants and can be exposed to ionizing radiation for long time [3]. Polymer materials are used as tissue equivalent substances and phantoms as these materials are useful in biological fields [4].

Mass attenuation coefficient, effective atomic number, effective electron density, total atomic scattering cross-section, and electronic scattering cross-section are the basic parameters in the study of gamma ray interaction. The interaction of ionizing radiation with the materials involves different processes mainly depending upon the intensity and the type of absorbing material. The gamma rays have greater penetrating power and obey different absorption laws [5]. For the study of basic quantities; the values of effective atomic number, electron density and mass attenuation coefficient are required [6].The gamma radiations from the energy region 200 keV to 1500 keV interact with materials mainly due to the dominance of Compton scattering. The scattering and absorption are closely related to the density and atomic number of an element [7]. The photons of energy range 5-1500 keV have found to be of immense importance in the medical field for the measurement of dose rate [8]. The mass attenuation coefficient $\mu \rho$ is a measure of the probability of gamma ray or X-ray interaction with matter. The knowledge of mass attenuation coefficient of gamma rays and X-rays in biological, shielding, and other important materials is of significant interest for industrial, medical, biological, and agriculture fields [9, 10].

In future the protection from harmful radiation is a kind of issue because the high-*Z* materials are hard to design at large dimensions. Cost is another constraint; as compared to polymer materials the high-*Z* materials are expensive. To check the availability of the low-*Z* materials for radiation shielding an investigation was

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carried out. Few researchers studied and investigated the gamma ray attenuation, mechanical and thermal properties for polymers and polymer materials or elements doped with polymers [3, 4, 11]. Same work has been carried out for dosimetric materials, fatty acids, minerals, amino acids, low-Z materials, *etc*. [12-18]. Many researchers investigated the extensive data on total atomic scattering cross-section, electronic scattering cross-section, effective atomic number and effective electron density for different materials [19-22], and the comparison of investigated data with the theoretical values using Berger and Hubbell developed the computer program (XCOM) for absorption coefficient for elements, compounds and mixtures in the energy range 1 keV to 100 GeV [23, 24]. Further this program was modified for windows by Gerward *et al*. [25]

In present study, we have calculated mass attenuation coefficients $\mu\ \rho$, effective atomic numbers Z_{eff}, and effective electron densities N_{eff} for some polymer materials using NaI(Tl) detector. The results were compared with the theoretical values calculated from XCOM program and concluded that both of the results are agreed to within 4 % with each-other. Those data are useful in many fields like plastic industry, building materials, agriculture fields radiation shielding, accelerator centers, polymer industry, medical field *etc*.

THEORY

In present work, following formulae were used to determine the mass attenuation coefficients, total atomic scattering cross-sections σ_{t}, electronic scattering cross-sections σ_{e}, effective atomic numbers Z_{eff} and effective electron densities N_{eff} for polymer materials. When a beam of monochromatic gamma photons is attenuated on matter according to Lambert-Beer law

$$I \quad I_0 \mathrm{e}^{\quad \mu t} \tag{1}$$

where I_0 and I are the incident and transmitted photon intensities, respectively, μ [cm^{-1}] represents the linear attenuation coefficient of the material and t [cm] is the thickness of the target material or sample. Rearrangement of eq. (1) yields the following equation for the linear attenuation coefficient

$$\mu \quad \frac{1}{t} \ln \frac{I_0}{I} \tag{2}$$

The mass attenuation coefficients of the samples were calculated using the equation

$$\frac{\mu}{\rho} \quad _{i} \quad w_i (\mu_{\mathrm{m}})_i \tag{3}$$

where w_i is the weight fraction. The w_i can be defined as

$$w_i \quad \frac{n_i A_i}{_{i} \ n_i A_i} \tag{4}$$

where A_i is the atomic weight of the sample, and n_i is a number of formula units.

The values of mass attenuation coefficients obtained from eq. (3) were then used to determine the total atomic scattering cross-section σ_{t} by the relation

$$\sigma_{\mathrm{t}} \quad \frac{N}{N_{\mathrm{A}}} \frac{\mu}{\rho} \tag{5}$$

where $N = \ _{i} n_i A_i$ is the atomic mass of the sample and N_{A} – the Avogadro's number. Similarly, electronic scattering cross-section σ_{e} for the individual element is given by

$$\sigma_{\mathrm{e}} \quad \frac{1}{N} \quad _{i} \ \frac{f_i A_i}{Z_i} (\mu_{\mathrm{m}})_i \quad \frac{\sigma_{\mathrm{t,a}}}{Z_{\mathrm{eff}}} \tag{6}$$

where f_i is the fractional abundance of the sample and Z_i – the atomic number of the sample.

The total atomic scattering cross-section and electronic scattering cross-section are related with the effective atomic number Z_{eff} as

$$Z_{\mathrm{eff}} \quad \frac{\sigma_{\mathrm{t}}}{\sigma_{\mathrm{e}}} \tag{7}$$

The equation for N_{eff} is

$$N_{\mathrm{eff}} \quad \frac{N_{\mathrm{A}}}{N} Z_{\mathrm{eff}} \quad _{i} \ n_i \quad \frac{\mu/\rho}{\sigma_{\mathrm{e}}} \tag{8}$$

EXPERIMENTAL DETAILS

Gamma ray transmission NaI(Tl) detector have been used to perform the present study and radioactive sources ^{57}Co, ^{133}Ba, ^{22}Na, ^{137}Cs, ^{54}Mn, and ^{60}Co emitting energies 122, 356, 511, 662, 840, 1170, 1275, and 1330 keV were used for irradiation in narrow beam good geometry set-up, using a gamma camera for the chosen polymer samples. The gamma ray photons were detected using NaI(Tl) detector with resolution of 8.2 % at 662 keV. Signals from the detector were enlarged and analyzed with 8K multichannel analyzer. The effectiveness of NaI(Tl) detector is higher at low source energy [26]. The uncertainty in determined experiment is found to be 1-4 % [27]. To make polyethylene ($C_{10}H_8O_4$), natural rubber (C_5H_8), polyphenyl methacrylate ($C_{10}H_{10}O_2$), poly-oxymethylene (CH_2O) poly acrylonitrile (C_3H_3N), and poly ethyl acrylate ($C_5H_8O_2$) as radiation target, we used KBr press machine to prepare pellets shaving of same thickness (0.13 gcm^{-2}) and then filled in a cylindrical plastic container having the same diameter as that of sample pellets. To determine the diameters of these samples, we used a travelling microscope. We did some experiment with the empty sample container and found that attenuation of photons with the empty containers were negligible (fig. 1).

To get accuracy in experiment, we prepared pellets and weighted it using sensitive digital balance having an accuracy of 0.001 mg for each sample. Samples were weighed several times and the mean of these samples weight was taken as mass of the sample. To satisfy the ideal condition the sample thickness is se-

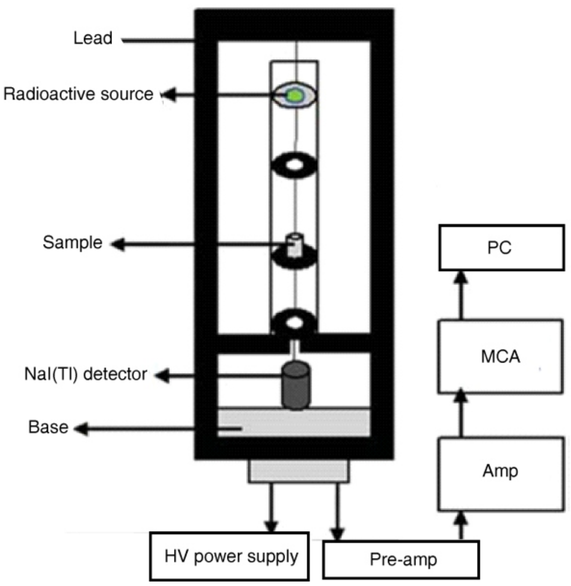

Figure 1. Schematic view of the experimental set-up

lected in the order $2 < \ln(I_0/I) < 4$ [28].Mass attenuation coefficients μ/ρ for all the samples of polymer materials were calculated using eq. (3).The values of mass attenuation coefficients were also obtained using the XCOM program by Berger and Hubbell [29] *et al.* photon energies of current interest. To optimize minor errors we have taken care of some errors that are counting statistics; impurities added in the sample: the error due to the sample impurities can be high only when large percentage of high Z impurities is present in the sample; uniformity of the sample: the non-uniformity of the sample material introduces a fraction of error of about half the root mean square deviation in mass per unit area; dead time; proper adjustment of the distance between the detector and source (30 cm < d < < 50 cm) [13] the maximum angle of scattering was below 30 min of the NaI(Tl) detector, *etc*. The photon built-up effect was kept to minimum by choosing optimum count rate and the counting time. The photon built-up depends on the atomic number and the sample thickness, and also on the incident photon energy. It is also a consequence of the multiple scattering inside the sample. In the multichannel analyzer used in the present study, there was a built-in provision for dead time correction. The pulse piles effects were kept at minimum by selecting an optimum count rate and counting time.

Table 1. The mean atomic numbers calculated from the chemical formula for polymer materials

Polymer material	Molar mass [gmol^{-1}]	Chemical formula	Mean atomic number Z
POM	30.02	CH_2O	4.000
PAN	53.06	C_3H_3N	41.000
NR	68.12	C_5H_8	2.923
PEA	100.11	$C_5H_8O_2$	3.600
PPM	100.12	$C_{10}H_{10}O_2$	3900
PET	192.20	$C_{10}H_8O_4$	4.545

POM – polyoxymethylene, PAN – polyacrylonitrile, NR – natural rubber, PEA – polyethylacrylate, PPM – polyphenyl methacrylate, PET – polyethylene tetraphthalate

RESULTS AND DISCUSSION

The values of mean atomic numbers calculated from chemical formulae for polymers are shown in tab. 1. It can be concluded that, the values of mean atomic number and molar mass of these samples change with the change in chemical composition of the samples.

The μ ρ values for selected materials were investigated using NaI(Tl) detector and calculated from XCOM program for the photon energy range 122 keV to 1330 keV were shown in tab. 2 and is depicted in fig. 2 that concludes that μ ρ values are a function of photon energy. It is clearly seen that the values of μ ρ decrease with increasing energy of gamma photons for all the samples. Also it can be seen from fig. 2, that the μ ρ values for natural rubber (NR) are more and considerably less for polyethylene tetraphthalate.

Similarly, experimental and theoretical values of total atomic scattering cross-sections and electronic scattering cross-sections are shown in tabs. 3 and 4 respectively. Figures 3 and 4 depict variation in t and e with energy. It is observed that the polyphenyl methacrylate and polyethylene tetraphthalate have highest values of photon scattering cross-section as shown in figs. 3 and 4, respectively. Experimental values of effective atomic numbers Z_{eff} along with XCOM results are tabulated in tab. 5. Figure 5 shows that the values of Z_{eff} for chosen polymers tend to be almost constant as a function of energy. This behavior of Z_{eff} with energy is due to the dominance of Compton scattering in the present energy range. Experimental values of N_{eff} are tabulated in tab. 6 along with theoret-

Table 2. Mass attenuation coefficient μ ρ [cm^{2}g^{-1}] of polymer materials

Polymer material	Energy [keV]															
	122		356		511		662		840		1170		1275		1330	
	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The
POM	0.152	0.147	0.105	0.980	0.090	0.086	0.079	0.075	0.078	0.073	0.052	0.048	0.052	0.043	0.052	0.043
PAN	0.150	0.145	0.104	0.970	0.088	0.085	0.078	0.074	0.075	0.070	0.053	0.049	0.052	0.042	0.052	0.042
NR	0.158	0.160	0.110	0.112	0.094	0.096	0.084	0.086	0.073	0.075	0.063	0.065	0.063	0.065	0.063	0.065
PEA	0.155	0.150	0.107	0.101	0.091	0.084	0.080	0.074	0.063	0.058	0.053	0.048	0.052	0.043	0.052	0.043
PPM	0.152	0.155	0.113	0.115	0.089	0.091	0.082	0.084	0.062	0.064	0.060	0.062	0.065	0.061	0.058	0.061
PET	0.150	0.152	0.103	0.105	0.080	0.084	0.078	0.081	0.053	0.055	0.051	0.053	0.051	0.053	0.050	0.052

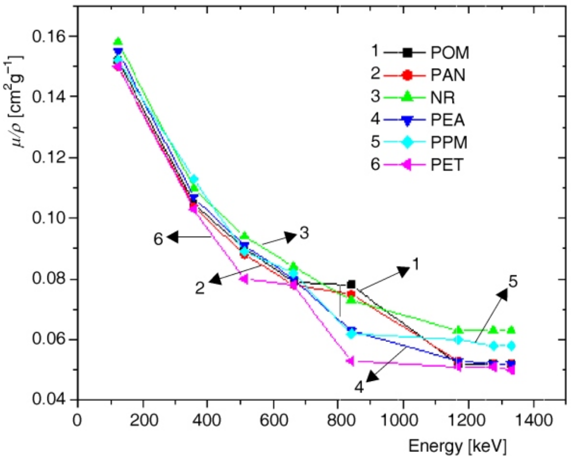

Figure 2. A typical plot of μ_m *vs.* energy selected polymers

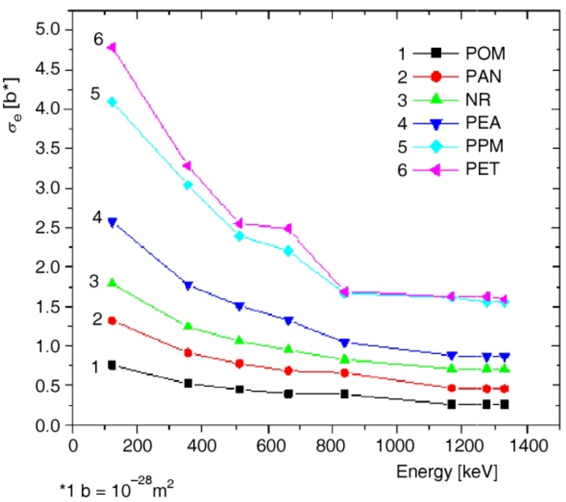

Figure 3. A typical plot of σ_t *vs.* energy selected polymers

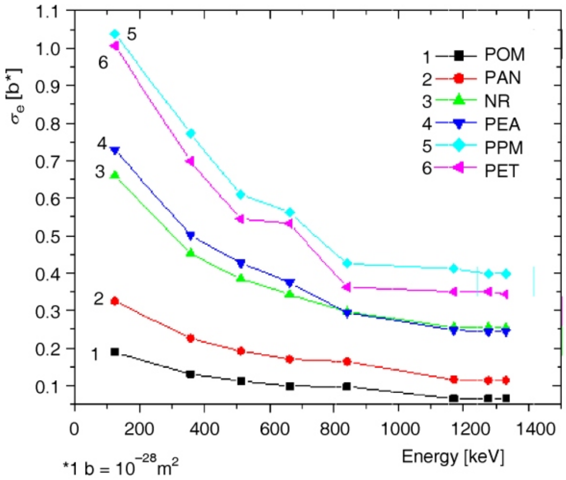

Figure 4. A typical plot of σ_e *vs.* energy selected polymers

ical values. Figure 6 shows N_{eff} as a function of energy. It has been observed form the graph, the variation in the values of N_{eff} is due to the change in the chemical composition of the polymer samples. The theoretical values calculated from XCOM program and investigated from the experiment show a good agreement.

CONCLUSION

In the present paper, we report mass attenuation coefficient μ/ρ, effective atomic number Z_{eff}, and effective electron density N_{eff} for some polymers. The energy dependence parameters Z_{eff} and N_{eff} that are useful to calculate the dose rate have been measured with sufficient accuracy. The obtained results should be suitable in medical application as polymers are composed of C-, H-, N-, and O-constituent elements and can be used as tissue

Table 3. Atomic cross-section σ_t (barn per molecule) od some polymer materials

Polymer material	Energy [keV]															
	122		356		511		662		840		1170		1275		1330	
	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The
POM	0.757	0.753	0.523	0.518	0.448	0.442	0.393	0.390	0.388	0.384	0.259	0.255	0.259	0.256	0.259	0.255
PAN	1.321	1.315	0.915	0.910	0.775	0.770	0.686	0.680	0.660	0.655	0.466	0.462	0.457	0.450	0.457	0.450
NR	1.787	1.790	1.2443	1.250	1.063	1.069	0.950	0.954	0.825	0.830	0.712	0.716	0.712	0.716	0.712	0.716
PEA	2.575	2.570	1.777	1.770	1.512	1.509	1.329	1.325	1.046	1.042	0.880	0.875	0.864	0.860	0.864	0.860
PPM	4.095	4.098	3.042	3.048	3.396	3.399	2.208	2.212	1.669	1.672	1.615	1.621	1.561	1.568	1.561	1.568
PET	4.783	4.785	3.284	3.287	2.551	2.554	2.487	2.490	1.690	1.694	1.626	1.630	1.626	1.630	1.594	1.598

Table 4. Electronic cross-sectons σ_e (barn per molecule) of some polymer materials

Polymer material	Energy [keV]															
	122		356		511		662		840		1170		1275		1330	
	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The
POM	0.188	0.182	0.130	0.125	0.111	0.107	0.098	0.095	0.097	0.093	0.064	0.060	0.064	0.059	0.064	0.059
PAN	0.324	0.320	0.225	0.220	0.191	0.186	0.169	0.165	0.163	0.159	0.115	0.110	0.113	0.108	0.113	0.108
NR	0.660	0.664	0.452	0.454	0.384	0.386	0.342	0.347	0.296	0.300	0.255	0.259	0.254	0.260	0.254	0.260
PEA	0.728	0.724	0.501	0.497	0.426	0.421	0.374	0.370	0.294	0.291	0.247	0.241	0.243	0.240	0.243	0.240
PPM	1.038	1.041	0.772	0.774	0.609	0.612	0.561	0.564	0.424	0.426	0.411	0.414	0.397	0.401	0.397	0.401
PET	1.006	1.009	0.698	0.700	0.544	0.548	0.532	0.536	0.632	0.366	0.350	0.354	0.350	0.354	0.343	0.345

Table 5. Effective atomic number Z_{eff} of polymer materials

Polymer material	Energy [keV]															
	122		356		511		662		840		1170		1275		1330	
	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The
POM	4.022	4.019	4.011	4.008	4.005	4.000	4.002	3.990	3.999	3.995	3.995	3.991	3.994	3.992	3.993	3.992
PAN	4.066	4.060	4.052	4.048	4.046	4.041	4.042	4.041	4.039	4.035	4.035	4.030	4.033	4.028	4.032	4.028
NR	2.706	2.708	2.748	2.747	2.761	2.763	2.771	2.773	2.780	2.782	2.793	2.795	2.796	2.797	2.794	2.795
PEA	3.533	3.529	3.544	3.540	3.546	3.541	3.549	3.545	3.551	3.549	3.554	3.550	3.554	3.550	3.554	3.550
PPM	3.943	3.945	3.936	3.934	3.931	3.933	3.929	3.930	3.927	3.925	3.925	3.924	3.924	3.922	3.923	3.921
PET	4.752	4.755	4.703	4.701	4.684	4.686	4.672	4.675	4.661	4.663	4.645	4.647	4.641	4.642	4.639	4.642

Table 6. Effective electron densities N_{eff} (10^{23}) for polymer materials

Polymer material	Energy [keV]															
	122		356		511		662		840		1170		1275		1330	
	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The	Exp.	The
POM	3.228	3.233	3.219	3.215	3.214	3.210	3.212	3.208	3.210	3.207	3.207	3.201	3.206	3.201	3.205	3.200
PAN	3.231	3.227	3.221	3.218	3.216	3.211	3.213	3.210	3.210	3.205	3.207	3.202	3.205	3.200	3.205	3.200
NR	3.111	3.113	3.159	3.158	3.174	3.172	3.186	3.185	3.196	3.194	3.211	3.210	3.215	3.217	3.215	3.217
PEA	3.189	3.185	3.199	3.195	3.201	3.194	3.203	3.193	3.205	3.192	3.208	3.200	3.209	3.201	3.209	3.201
PPM	3.222	3.220	3.216	3.215	3.212	3.214	3.211	3.213	3.209	3.211	3.207	3.208	3.206	3.205	3.206	3.205
PET	3.279	3.281	3.245	3.243	3.232	3.234	3.223	3.222	3.216	3.218	3.205	3.206	3.202	3.205	3.200	3.201

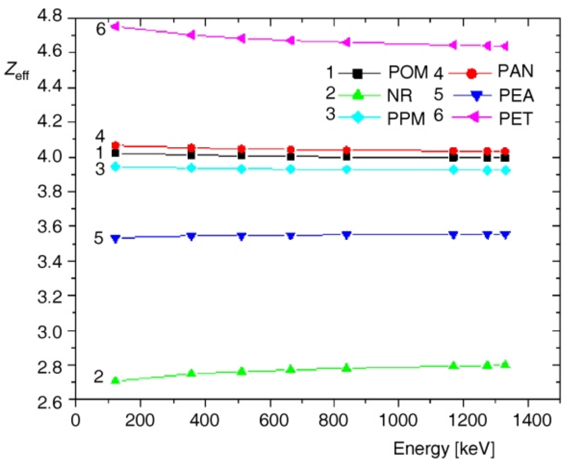

Figure 5. A typical plot of Z_{eff} *vs.* energy selected polymers

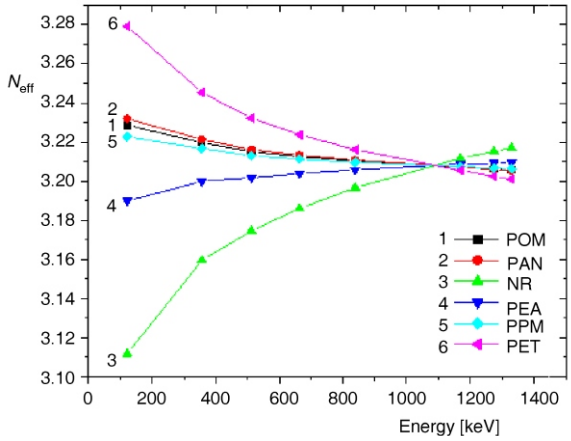

Figure 6. A typical plot of N_{eff} *vs.* energy selected polymers

substitute materials. From the present work it was concluded that poly-oxymethylene and natural rubber can be used as best shielding polymer material amongst the selected polymer materials as natural rubber and poly-oxymethylene have more μ ρ values.

AUTHORS' CONTRIBUTIONS

Theoretical and experimental results were obtained by R. R. Bhosale, C. V. More, and D. K. Gaikwad. All data were analyzed by P. P. Pawar and M. N. Rode. The whole manuscript was reviewed by all authors.

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ЗАШТИТНЕ ОСОБИНЕ И СПОСОБНОСТ СЛАБЉЕЊА ГАМА ЗРАЧЕЊА НЕКИХ ПОЛИМЕРА

У овом раду, применом NaI(Tl) детектора гама зрачања, извршено је испитивање следећих параметара гама зрачења: масеног атенуационог коефицијента μ/ρ, укупног атомског ефикасног пресека за расејање σ_t, електронског ефикасног пресека за расејање σ_e, ефективног атомског броја Z_{eff} и ефективне густине електрона N_{eff} неких полимера међу којима су поликсиметилен (CH_2O), поли акрилонитрил (C_3H_3N), природна гума (C_5H_8), поли етил акрилат ($C_5H_8O_2$), полифенил метакрилат ($C_{10}H_{10}O_2$), полиетилен терафталат ($C_{10}H_8O_4$). За детекцију гама фотона коришћен је NaI(Tl) детектор резолуције од 8.2 % на енергији од 662 keV применом радиоактивних извора ^{57}Co, ^{133}Ba, ^{137}Cs, ^{54}Mn, ^{60}Co и ^{22}Na на енергијама 122, 356, 511, 662, 840, 1170, 1275 и 1330 keV. Вредности μ/ρ за изабране полимере су опадале са порастом енергије. Добијени резултати имају примену у индустрији пластике, грађевинским материјалима, заштити од зрачења агрикултурних поља, у акцелераторским центрима, индустрији полимера, у области медицине, итд.

Кључне речи: масени атенуациони коефицијент, укупни ефикасни пресек за расејање, заштита од гама зрачења, полимер