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Utilization of Geant4 Monte Carlo Code for Simulations of Gamma Ray Attenuation Coefficients in Selected Materials

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استخدام مونتي كارلو كود *Geant4* لمحاكاة معاملات توهين أشعة جاما في مواد مختارة

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Abstract:
When gamma rays fall on a medium, part of it can penetrate it, while the other part is attenuated in the medium through three main interaction processes: the photoelectric effect, the Compton scattering and pair production. The attenuation of gamma radiation is dependent upon the energy of the incident gamma ray beam, the atomic number and the density of the absorbing medium. Monte Carlo simulation has become a powerful method for modelling and computation of the gamma ray attenuation coefficients in any type of material (pure element, compound and mixture). In this research, gamma ray attenuation coefficients for high atomic number materials such as lead and tungsten and low atomic number materials such as iron and aluminium were computed using Monte Carlo simulations. We utilized the GEANT4 Monte Carlo code to specifically determine the linear attenuation coefficients, mass attenuation coefficients and mean free paths in the materials under study at various photon energies including those emitted from 137Cs, 60Co and 152Eu sources. A simulation model was built consisting of a narrow photon beam, thin target and a detection region. The thickness of the target was optimized to avoid that all incident gamma rays were absorbed in the target or passed through the absorber without interacting. The Monte Carlo model assessed the contributions of photoelectric absorption, Compton scattering and pair production to the total mass attenuation coefficient for each type of materials under study. The simulated results of mass attenuation coefficients were compared with theoretical values obtained with XCOM database program. The theoretical calculations were in good agreement with their simulated results. The relative deviation between the results of simulation and theoretical data was less than 2%. In conclusion, an accurate Monte Carlo model was constructed and may be used to calculate the gamma rays attenuation coefficients in any given material. Furthermore, the model may be modified to estimate the radiation doses due to interactions of gamma rays with the shielding material.

Keywords: Monte Carlo, gamma radiation, attenuation coefficients, mean free path.

الملخص
عندما تسقط أشعة جاما على وسط، يمكن لجزء منها اختراقه ، بينما يتم إضعاف الجزء الآخر في الوسط من خلال ثلاث عمليات تفاعل رئيسية: التأثير الكهروضوئي، وتشتت كومبتون، وإنتاج الزوج. يعتمد توهين إشعاع جاما على طاقة حزمة أشعة جاما الساقطة، والعدد الذري وكثافة الوسط الماص. أصبحت محاكاة مونتي كارلو طريقة قوية لنمذجة وحساب معاملات التوهين لأشعة جاما في أي نوع من المواد (عنصر نقي, مركب, خليط). في هذا البحث تم حساب معاملات التوهين لأشعة جاما للمواد ذات العدد الذري العالي (الرصاص والتنجستن) والمواد ذات العدد الذري المنخفض (الحديد والألمنيوم) باستخدام

محاكاة مونتي كارلو. استخدمنا مونتي كارلو كود GEANT4 لتحديد معاملات التوهين الخطي ومعاملات التوهين الكتلي ومعدل المسارات الحر في المواد قيد الدراسة عند طاقات الفوتون المختلفة بما في ذلك تلك المنبعثة من مصادر Cs , 137 60Co و Eu152. تم بناء نموذج محاكاة يتكون من حزمة فوتونات ضيقة وهدف رفيع ومنطقة كشف. تم تحسين سماكة الهدف لتجنب امتصاص جميع أشعة جاما الساقطة في الهدف أو تمريرها عبر مادة الامتصاص (الهدف) دون تفاعل. ساهم نموذج مونتي كارلو بتقييم تفاعلات الامتصاص الكهروضوئي وتشتت كومبتون وإنتاج الأزواج في إجمالي معامل التوهين الكتلي لكل نوع من المواد قيد الدراسة. تمت مقارنة نتائج المحاكاة لمعاملات التوهين الكتلي بالقيم النظرية التي تم الحصول عليها باستخدام برنامج قاعدة بيانات XCOM. كانت الحسابات النظرية متوافقة جيدًا مع نتائج المحاكاة. كان الانحراف النسبي بين نتائج المحاكاة والبيانات النظرية أقل من 2٪. في الاستنتاج، تم بناء نموذج دقيق لمونتي كارلو يمكن استخدامه لحساب معاملات التوهين لأشعة جاما في أي مادة معينة. علاوة على ذلك، يمكن تعديل النموذج لتقدير جرعات الإشعاع بسبب تفاعلات أشعة جاما مع مادة التدريع.

الكلمات المفتاحية: مونتي كارلو، اشعة جاما، معامل التوهين، متوسط المسار الحر.

Introduction

The topic of the interaction of radiation with matter is an attractive research field, given the contribution of radiation in many areas. Nowadays, ionizing radiation (gamma rays, photons) is increasingly used in medical imaging, radiotherapy, industry, food irradiation and nuclear research centers. However, the disadvantage of radiation technology comes from its health hazardous on workers and public near its vicinity. Therefore, it is important to provide comprehensive knowledge and reliable data of radiation interactions from the prospective of safety procedures aiming to reduce exposure to workers and public in the area of ionizing radiation [1].

Different types of absorbers (pure elements, compounds, mixtures) are used as shields against gamma radiation. Gamma rays interact with matter through three main processes: the Photoelectric effect, Compton scattering, and pair/triplet production [2, 3]. These interactions cause attenuations of the incident gamma ray beam. The linear attenuation coefficient, the mass attenuation coefficient and the mean free path are important parameters which describe the penetration of gamma rays in matter. Thus, it is essential to compute these coefficients accurately for understanding the interaction of gamma ray with matter.

There are recent studies in literature that report the attenuation coefficients of gamma rays in a number of materials such as, concretes [4-7], different marble samples [8], aluminium [9], polyboron [10], lead and bismuth salts [11], soil and oil-soil samples [12], biological samples found in human body [13],soft tissues and water [14], and building materials [15].

Monte Carlo method has for long been accepted as a reliable method for the simulation of the passage of radiation through matter and provides information about attenuation of it in matter [16-18]. As a large number of incident particles are simulated, results can be obtained about the average values of quantities of interest such as the attenuation coefficients in a material of interest [19, 20]. However, the statistical uncertainties of the calculations using simulation outputs depend on the number of simulated particle histories [16].

In this paper, the Geant4 Monte Carlo code is utilized to simulate the gamma ray attenuation coefficients for different pure materials (lead, tungsten, iron and aluminium) at several photon energies emitted from point sources of Cs-137, Co-60 and Eu-152. A simulation model is constructed consisting of a narrow photon beam, thin target and a detection region. To validate the simulation, the computed results of mass attenuation coefficients were compared with theoretical values obtained with XCOM database program.

Materials and methods

Geant4 is software that uses Monte Carlo method for the simulation of the interactions of radiation with matter. It is a complex code and available free for research studies. It requires a deep knowledge of physics understandings to be able to use it efficiently. The software can be reached through the internet at https://geant4.web.cern.ch. In this study, we utilized the Geant4 Monte Carlo simulation code to compute the gamma-rays attenuation coefficients of lead, tungsten, iron and aluminium at several photon energies including those emitted from point sources of ^{137}Cs, ^{60}Co and ^{152}Eu.

A Monte Carlo model was built which consisted of a narrow beam of photons with varying energies incident on various thicknesses of the selected materials. The thickness of the target was optimized to avoid that all incident gamma rays were absorbed in the target or passed through the absorber without interacting. The energy cut was set to 0.01 mm for lead, tungsten and 0.1 mm for iron and aluminium these values corresponded to an energy threshold to less 10 keV for the selected materials. We run 1000,000 particles for each simulation to reduce the statistical error to an acceptable value.

At the end of each simulation run, an output file was created which included the relevant information of the attenuation coefficients including the contributions of photoelectric absorption, Compton scattering and pair production to the total mass attenuation coefficient for each type of materials under study. The obtained data were then tabulated and represented graphically for discussions.

For validation purpose, the simulation results of the gamma rays attenuation coefficients were compared with the theoretical values obtained using the XCOM database program. The XCOM is a database computer program that calculates the photon attenuation coefficients for elements, compounds and mixtures in a wide energy range [21-23]. It runs under windows operating system and can be reached through the internet at http://physics.nist.gov. In recent years, many researchers have used the XCOM program to study the photon attenuation coefficients of various materials [24].

Results and discussion

The linear attenuation coefficient is important parameter, it provides information about the amount of the reduction in the intensity of an energetic radiation beam as it traverses through a material. It is useful quantity in the determination of the mass attenuation coefficient and the mean free path of a given material for specific gamma ray energy.

The values of the linear and mass attenuation coefficients obtained from Monte Carlo simulations for the materials under study are listed in tables 1-4. Figures 1-4 show a graphical representation of the mass attenuation coefficients data listed in tables 1-4. The results indicated that the attenuation of gamma ray is related to attenuation coefficient and the density of the absorbing material. The material with large linear attenuation coefficient and higher density attenuate gamma ray photons more than the material with a low attenuation coefficient and small density. Figure 5 is a comparison of mass attenuation coefficient plotted against photon energy for lead (Z =82), tungsten (Z = 72), iron (Z = 26) and aluminium (Z = 13).

Note, in figure 1, there is a discontinuity at about 88 KeV, at this discontinuity the incident photon has just enough energy to eject the K-electron (called the k-shell electron binding energy) in lead. This discontinuity is called the k-absorption edge. As seen in figure 1, there is a sharp increase in the mass attenuation coefficient in lead at this edge (for photons of incident energy slightly higher than the binding energy of k-electrons) [3] and after that the attenuation coefficient decreases with increasing energy.

To validate our Monte Carlo model, the theoretical values of the mass attenuation coefficients for the materials under study were obtained using the XCOM database program. It can be seen from tables 1-4 and figures 6-9 that the simulated results of the mass attenuation coefficients for lead, tungsten, iron and aluminium were comparable to those calculated using XCOM database program. The differences in percentage between the simulated and calculated mass attenuation coefficients for the materials under study were found to be small. This indicated the consistency of the values for the mass attenuation coefficients shown in tables 1-4.

The attenuation coefficients for the photoelectric effect, the Compton Effect, and the pair production are highly dependent on the energy of the gamma radiation as illustrated in tables 1- 4. In general, when the energy of gamma rays is low, the photoelectric effect is very high, while the effect of Compton scattering is negligible. That is, the photoelectric effect then constitutes the main means of attenuation of gamma rays of lower energies where the attenuation coefficient of the Compton Effect is less than the attenuation coefficient of the photoelectric effect. As the energy of the gamma radiation increases, the attenuation coefficient of the photoelectric effect decreases rapidly, while the Compton Effect decreases with increasing energy slowly. Therefore, the Compton Effect becomes more important at energies in the range of 1 MeV. As for the effect of producing pairs, it does not occur at all if the gamma rays are less than 1.022 MeV.

The three interactions (photoelectric, Compton and pair production) compete with each other, but there are ranges of energy in which one of the interactions is often over the other two. The photoelectric effect is the most likely in the range of low energies and the probability of the Compton reaction is large in the field of medium energies, but for the production of a pair, its probability increases in the field of very high energies. The total cross section (σ_T) of the interaction of gamma rays with matter is defined as the sum of the cross sections of the three interactions [3].

$$\sigma_{T=}\sigma_{PE} + \sigma_{CS} + \sigma_{PP}$$

Whereσ_{PE}, σ_{CS} and σ_{PP} represent the contributions of mass attenuation coefficients (cross sections) due to the photoelectric effect, the Compton scattering and the Pair Production respectively. These contributions to the total mass attenuation coefficients are shown in tables 1-4 for the materials under investigations.

Figure 10 represents the photoelectric effect, Compton scattering and pair production branching ratios of lead (Pb) and tungsten (W) absorbers (obtained from tables one and two) as a function of photon energy. While figure 11 illustrates the photoelectric absorption, Compton scattering and pair production branching ratios of iron (Fe) and aluminium (Al) (obtained from tales three and four) absorbers as a function of photon energy. As can be seen from these two figures, most of the attenuation of photons is dominated by the photoelectric effect and Compton scattering. Photoelectric effect is more important for high atomic number absorbers such as lead (z = 82) and tungsten (z = 74) as displayed in figure 10. Whereas, Compton scattering is more important for low atomic number shields such as iron (z =26) and aluminum (z = 13) as illustrated in figure 11.

Table 1. The gamma ray attenuation coefficients in lead at different photon energies.

Energy (MeV)	μ (cm^{-1})	μ/ρ (cm^2/g), CS	μ/ρ (cm^2/g), PE	μ/ρ (cm^2/g), PP	μ/ρ (cm^2/g)-MC	μ/ρ (cm^2/g)-NIST	% Diff
0.0150	1227.967	0.0371	108.2700	0	108.3071	108.3000	0.01
0.0395	154.953	0.0903	13.5830	0	13.6733	13.9000	1.63
0.0412	138.640	0.0916	12.1380	0	12.2296	12.4100	1.45
0.0453	107.405	0.0937	9.3819	0	9.4756	9.6220	1.52
0.0457	104.803	0.0939	9.1489	0	9.2428	9.3970	1.64
0.0466	99.467	0.0943	8.6755	0	8.7698	8.9190	1.67
0.0468	98.328	0.0944	8.5749	0	8.6693	8.8170	1.68
0.0880	18.469	0.0994	1.5286	0	1.6280	1.6470	1.15
0.1220	36.630	0.0972	3.1292	0	3.2264	3.2150	0.36
0.2447	6.904	0.0855	0.4994	0	0.5849	0.5825	0.41
0.3440	3.295	0.0776	0.2068	0	0.2844	0.2836	0.28
0.4110	2.341	0.0733	0.1327	0	0.2060	0.2050	0.50
0.4430	2.066	0.0714	0.1105	0	0.1819	0.1808	0.59
0.4440	2.058	0.0714	0.1099	0	0.1812	0.1802	0.56
0.5000	1.714	0.0668	0.0826	0	0.1494	0.1499	0.32
0.6620	1.184	0.0611	0.0432	0	0.1044	0.1035	0.85
0.7790	0.991	0.0570	0.0302	0	0.0872	0.0864	0.93
0.8670	0.890	0.0543	0.0241	0	0.0784	0.0776	0.98
0.9640	0.806	0.0517	0.0193	0	0.0710	0.0703	0.98
1.0000	0.780	0.0508	0.0179	0	0.0687	0.0680	0.93
1.0850	0.725	0.0488	0.0152	3.02E-05	0.0640	0.0634	0.88
1.0897	0.723	0.0487	0.0151	3.48E-05	0.0638	0.0632	0.87
1.1120	0.711	0.0482	0.0145	6.16E-05	0.0627	0.0622	0.89
1.1730	0.682	0.0469	0.0130	7.31E-04	0.0607	0.0596	1.83
1.2130	0.665	0.0461	0.0122	2.77E-04	0.0586	0.0581	0.90
1.2500	0.651	0.0454	0.0115	3.95E-04	0.0573	0.0568	0.88
1.2990	0.634	0.0445	0.0107	5.83E-04	0.0558	0.0554	0.80
1.3320	0.623	0.0439	0.0102	7.31E-04	0.0549	0.0545	0.76
1.4080	0.601	0.0427	0.0092	1.13E-03	0.0530	0.0527	0.62

CS = Compton Scattering, PE = Photoelectric Effect, PP = Pair Production

Table 2 The gamma ray attenuation coefficients in tungsten at different photon energies.

Energy (MeV)	μ (cm^{-1})	μ/ρ (cm^2 /g), CS	μ/ρ (cm^2 /g), PE	μ/ρ (cm^2 /g), PP	μ/ρ (cm^2 /g)-MC	μ/ρ (cm^2 /g)-NIST	% Diff
0.0150	2591.1000	0.0598	134.2700	0	134.3298	136.0000	1.23
0.0395	193.8200	0.0942	9.9524	0	10.0466	10.2200	1.70
0.0412	173.2833	0.0952	8.8871	0	8.9823	9.1110	1.41
0.0453	134.0900	0.0973	6.8567	0	6.9540	7.0400	1.22
0.0457	130.8700	0.0975	6.6852	0	6.7827	6.8740	1.33
0.0466	124.0500	0.0979	6.3368	0	6.4347	6.5200	1.31
0.0468	122.6400	0.0979	6.2627	0	6.3606	6.4450	1.31
0.0880	114.2000	0.1025	5.8144	0	5.9169	5.9030	0.24
0.1220	49.0083	0.0998	2.4386	0	2.5384	2.5430	0.18
0.2447	9.2418	0.0873	0.3724	0	0.4597	0.4590	0.15
0.3440	4.5525	0.0792	0.1519	0	0.2311	0.2302	0.39
0.4110	3.3045	0.0747	0.0965	0	0.1712	0.1703	0.51
0.4430	2.9476	0.0727	0.0801	0	0.1528	0.1520	0.51
0.4440	2.9376	0.0727	0.0796	0	0.1523	0.1515	0.50
0.5000	2.4898	0.0696	0.0595	0	0.1291	0.1283	0.62
0.6620	1.7933	0.0622	0.0309	0	0.0931	0.0922	0.91
0.7790	1.5335	0.0580	0.0215	0	0.0795	0.0787	0.96
0.8670	1.3958	0.0552	0.0171	0	0.0723	0.0716	0.91
0.9640	1.2793	0.0525	0.0137	0	0.0662	0.0656	0.90
1.0000	1.2416	0.0516	0.0127	0	0.0643	0.0637	0.94
1.0850	1.1623	0.0496	0.0108	2.60E-05	0.0604	0.0598	1.05
1.0897	1.1585	0.0495	0.0107	3.01E-05	0.0602	0.0596	1.06
1.1120	1.1406	0.0490	0.01025	5.31E-05	0.0593	0.0587	1.05
1.1730	1.0983	0.0477	9.23E-03	1.50E-04	0.0571	0.0565	1.01
1.2130	1.0739	0.0469	8.65E-03	2.39E-04	0.0558	0.0552	0.97
1.2500	1.0535	0.0462	8.16E-03	3.41E-04	0.0547	0.0542	0.90
1.2990	1.0288	0.0452	7.58E-03	5.03E-04	0.0533	0.0529	0.83
1.3320	1.0133	0.0447	7.23E-03	6.30E-04	0.0525	0.0521	0.78
1.4080	0.9804	0.0434	6.52E-03	9.77E-04	0.0509	0.0505	0.69

CS = Compton Scattering, PE = Photoelectric Effect, PP = Pair Production

Table 3 The gamma ray attenuation coefficients in iron at different photon energies.

Energy (MeV)	μ (cm^{-1})	μ/ρ (cm^2 /g), CS	μ/ρ (cm^2 /g), PE	μ/ρ (cm^2 /g), PP	μ/ρ (cm^2 /g)-MC	μ/ρ (cm^2 /g)-NIST	% Diff
0.0150	443.4467	0.1095	56.2020	0	56.3115	56.3400	0.05
0.0395	27.6393	0.1365	3.3775	0	3.5140	3.5760	1.73
0.0412	24.5753	0.1370	2.9861	0	3.1231	3.1700	1.48
0.0453	18.8130	0.1377	2.2511	0	2.3888	2.4200	1.29
0.0457	18.3257	0.1377	2.1898	0	2.3275	2.3600	1.38
0.0466	17.3493	0.1378	2.0657	0	2.2035	2.2330	1.32
0.0468	17.1390	0.1378	2.0394	0	2.1772	2.2070	1.35
0.0880	3.4105	0.1323	0.3012	0	0.4335	0.4348	0.30
0.1220	1.8489	0.1247	0.1102	0	0.2350	0.2361	0.49
0.2447	0.9292	0.1041	0.0132	0	0.1172	0.1180	0.66
0.3440	0.7717	0.0931	4.83E-03	0	0.0979	0.0981	0.18
0.4110	0.7104	0.0874	2.92E-03	0	0.0903	0.0902	0.13
0.4430	0.6876	0.0849	2.38E-03	0	0.0873	0.0871	0.26
0.4440	0.6868	0.0849	2.37E-03	0	0.0872	0.0870	0.26
0.5000	0.6515	0.0811	1.75E-03	0	0.0828	0.0824	0.48
0.6620	0.5746	0.0722	8.63E-04	0	0.0730	0.0725	0.77
0.7790	0.5326	0.0671	5.92E-04	0	0.0677	0.0672	0.83
0.8670	0.5065	0.0639	4.68E-04	0	0.0643	0.0638	0.83
0.9640	0.4807	0.0607	3.74E-04	0	0.0611	0.0606	0.81
1.0000	0.4715	0.0596	3.47E-04	0	0.0600	0.0595	0.80
1.0850	0.4520	0.0573	2.95E-04	6.58E-06	0.0576	0.0571	0.78
1.0897	0.4510	0.0572	2.92E-04	7.60E-06	0.0574	0.0570	0.79
1.1120	0.4462	0.0566	2.80E-04	1.34E-05	0.0569	0.0564	0.77
1.1730	0.4341	0.0551	2.53E-04	3.78E-05	0.0553	0.0549	0.74
1.2130	0.4269	0.0541	2.37E-04	6.04E-05	0.0544	0.0540	0.71
1.2500	0.4208	0.0533	2.24E-04	8.62E-05	0.0536	0.0532	0.69
1.2990	0.4132	0.0522	2.09E-04	1.27E-04	0.0526	0.0522	0.66
1.3320	0.4083	0.0515	1.99E-04	1.59E-04	0.0519	0.0516	0.64
1.4080	0.3973	0.0500	1.80E-04	2.47E-04	0.0505	0.0502	0.58

CS = Compton Scattering, PE = Photoelectric Effect, PP = Pair Production

Table 4 The gamma ray attenuation coefficients in aluminium at different photon energies.

Energy (MeV)	μ (cm^{-1})	μ/ρ (cm^2 /g), CS	μ/ρ (cm^2 /g), PE	μ/ρ (cm^2 /g), PP	μ/ρ (cm^2 /g)-MC	μ/ρ (cm^2 /g)-NIST	% Diff
0.0150	20.4520	0.1335	7.4323	0	7.5658	7.6410	0.98
0.0395	1.3957	0.1530	0.3642	0	0.5172	0.5141	0.61
0.0412	1.2738	0.1531	0.3193	0	0.4724	0.4685	0.82
0.0453	1.0510	0.1529	0.2360	0	0.3889	0.3853	0.93
0.0457	1.0319	0.1529	0.2291	0	0.3820	0.3788	0.84
0.0466	0.9928	0.1528	0.2152	0	0.3680	0.3650	0.83
0.0468	0.9849	0.1528	0.2123	0	0.3651	0.3620	0.85
0.0880	0.4537	0.1421	0.0271	0	0.1693	0.1697	0.25
0.1220	0.3821	0.1325	9.31E-03	0	0.1418	0.1429	0.77
0.2447	0.2963	0.1088	1.05E-03	0	0.1098	0.1106	0.69
0.3440	0.2626	0.0969	3.85E-04	0	0.0973	0.0975	0.15
0.4110	0.2455	0.0908	2.33E-04	0	0.0910	0.0909	0.15
0.4430	0.2384	0.0882	1.89E-04	0	0.0884	0.0882	0.27
0.4440	0.2382	0.0881	1.88E-04	0	0.0883	0.0881	0.27
0.5000	0.2274	0.0841	1.33E-04	0	0.0842	0.0839	0.43
0.6620	0.2019	0.0748	6.46E-05	0	0.0748	0.0743	0.67
0.7790	0.1878	0.0695	4.41E-05	0	0.0695	0.0690	0.74
0.8670	0.1788	0.0661	3.48E-05	0	0.0662	0.0657	0.75
0.9640	0.1697	0.0628	2.79E-05	0	0.0629	0.0624	0.70
1.0000	0.1665	0.0617	2.58E-05	0	0.0617	0.0613	0.68
1.0850	0.1593	0.0593	2.20E-05	2.89E-06	0.0593	0.0589	0.65
1.0897	0.1590	0.0591	2.18E-05	3.33E-06	0.0592	0.0588	0.63
1.1120	0.1574	0.0585	2.09E-05	5.89E-06	0.0586	0.0582	0.62
1.1730	0.1531	0.0570	1.89E-05	1.66E-05	0.0570	0.0567	0.60
1.2130	0.1505	0.0560	1.77E-05	2.65E-05	0.0560	0.0557	0.57
1.2500	0.1482	0.0551	1.68E-05	3.78E-05	0.0552	0.0549	0.55
1.2990	0.1454	0.0540	1.56E-05	5.58E-05	0.0541	0.0538	0.50
1.3320	0.1436	0.0533	1.49E-05	6.99E-05	0.0534	0.0531	0.47
1.4080	0.1398	0.0517	1.35E-05	1.08E-04	0.0519	0.0517	0.41

CS = Compton Scattering, PE = Photoelectric Effect, PP = Pair Production

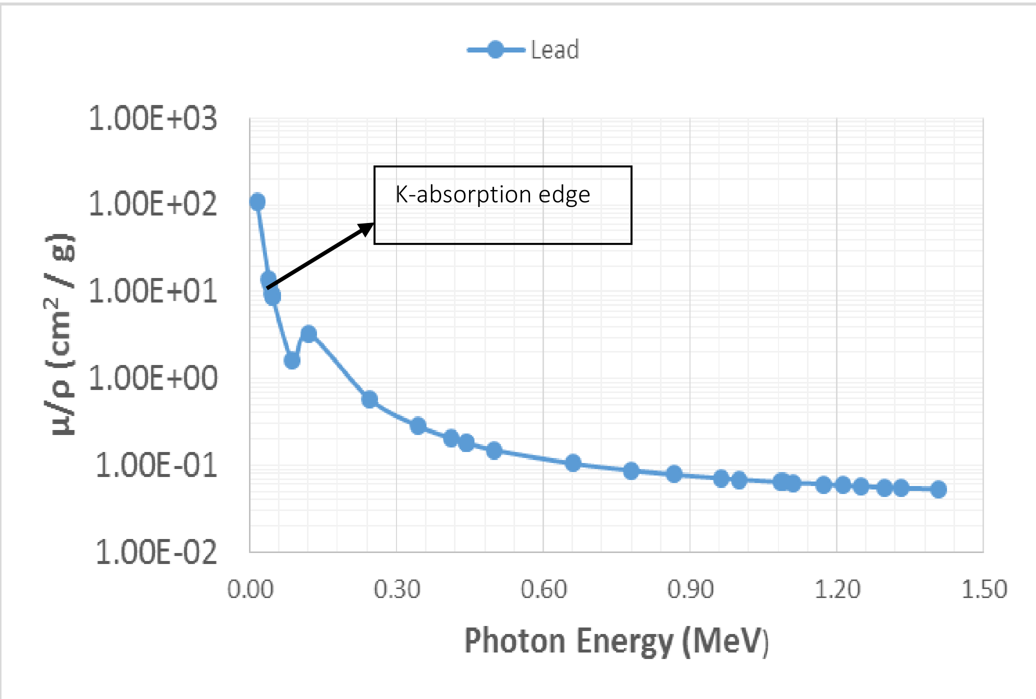

Figure 1. Mass attenuation coefficient plotted against photon energy for lead absorber.

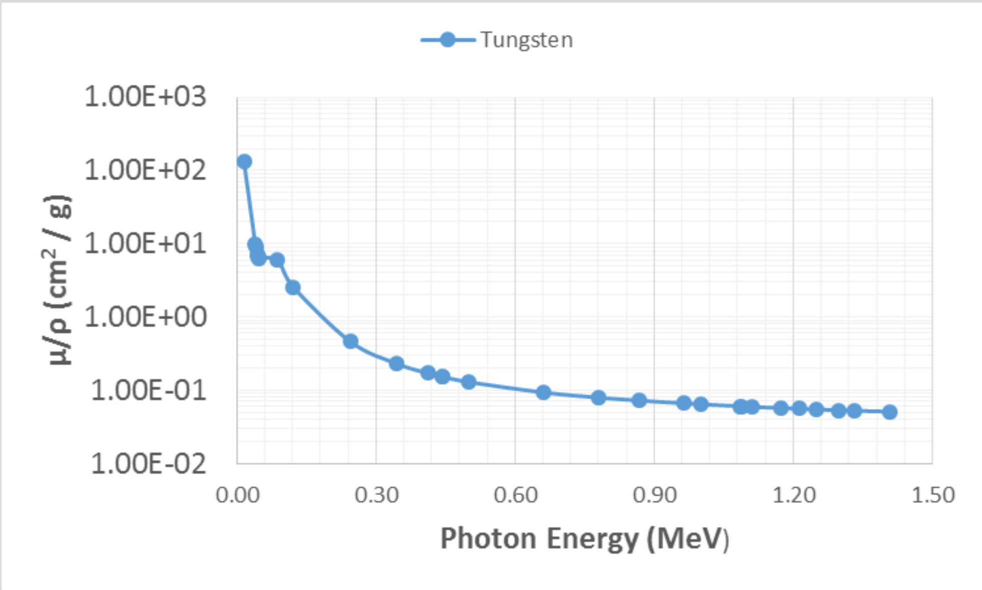

Figure 2. Mass attenuation coefficient plotted against photon energy for tungsten absorber.

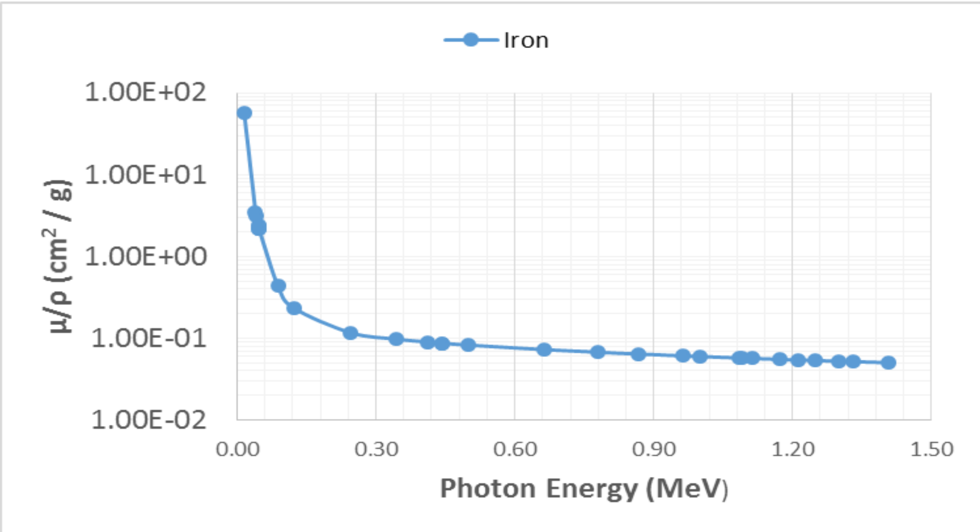

Figure 3. Mass attenuation coefficient plotted against photon energy for iron absorber.

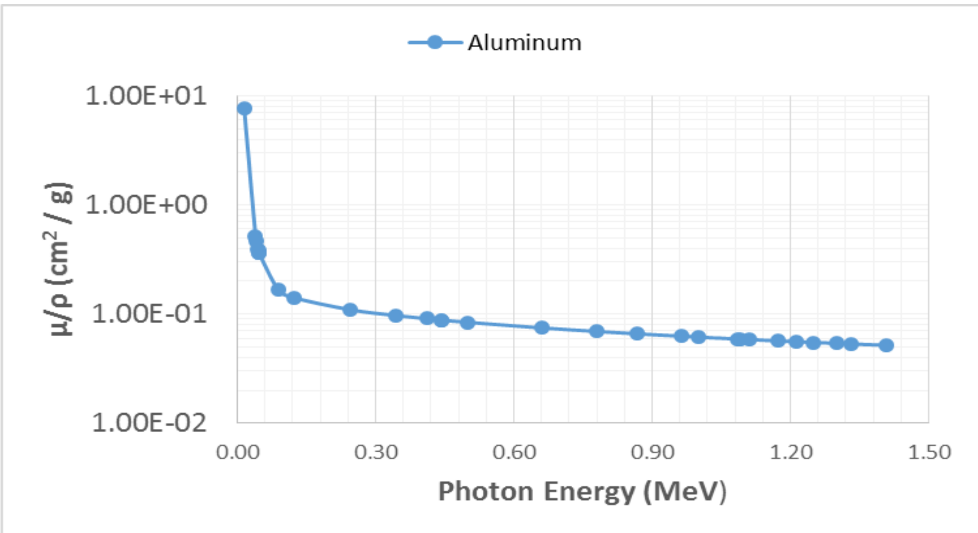

Figure 4. Mass attenuation coefficient plotted against photon energy for aluminium absorber.

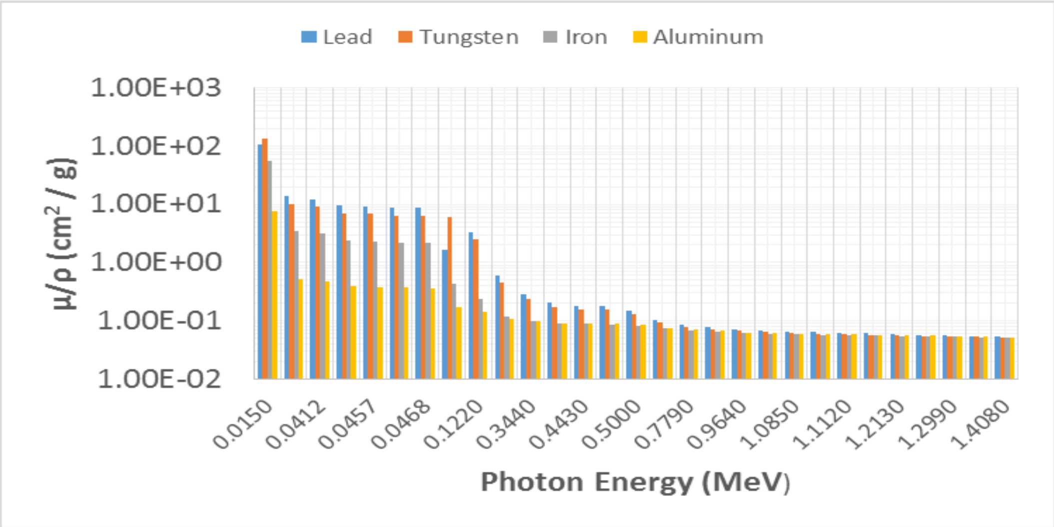

Figure 5. Comparison of mass attenuation coefficient plotted against photon energy for lead (Z =82), tungsten (Z = 72), iron (Z = 26) and aluminum (Z = 13).

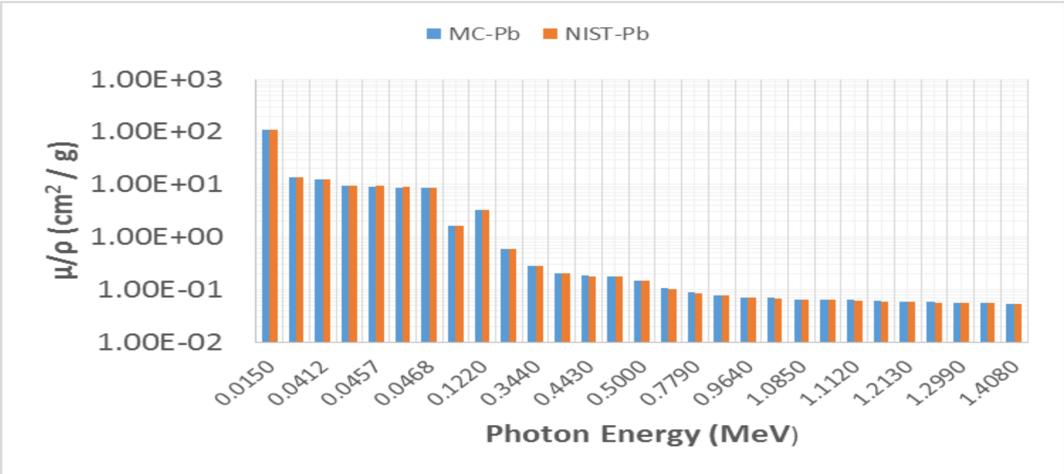

Figure 6. Comparison of mass attenuation coefficient plotted against photon energy for lead absorber obtained from simulations and XCOM database calculations.

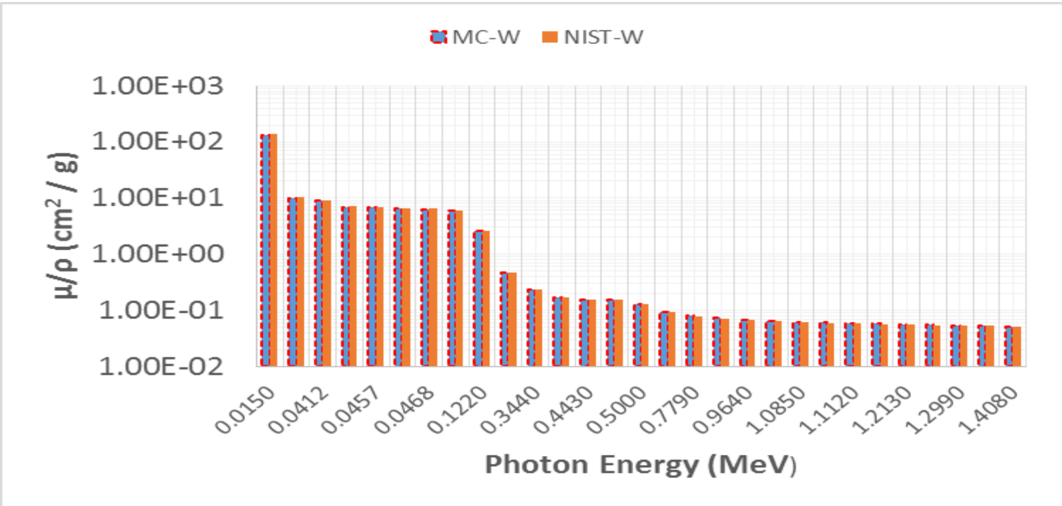

Figure 7. Comparison of mass attenuation coefficient plotted against photon energy for tungsten absorber obtained from simulations and XCOM database calculations.

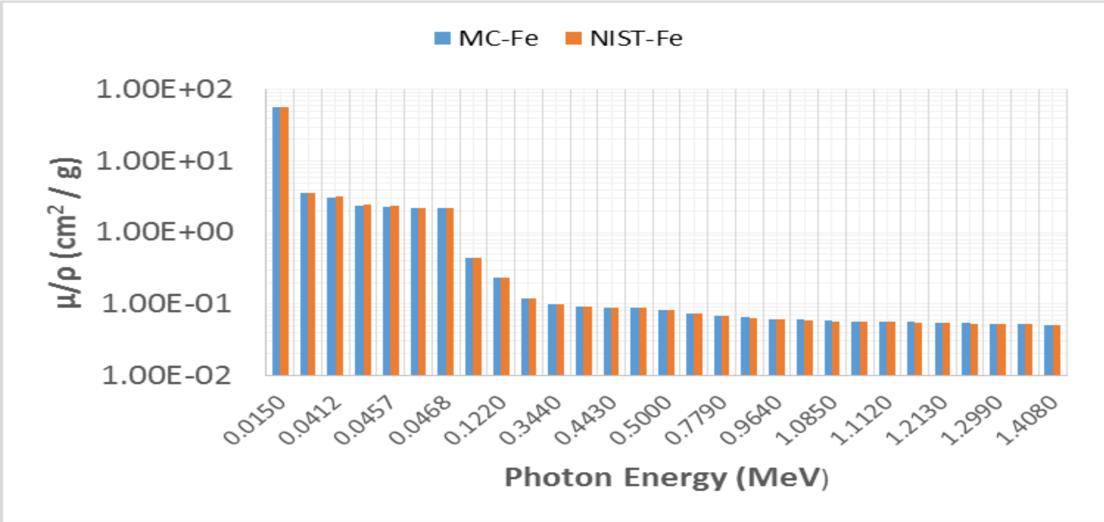

Figure 8. Comparison of mass attenuation coefficient plotted against photon energy for iron absorber obtained from simulations and XCOM database calculations.

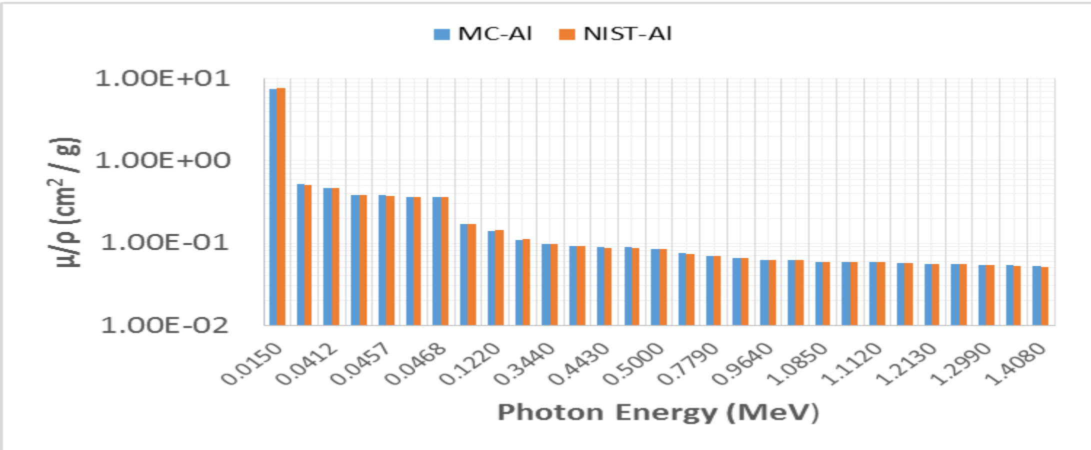

Figure 9. Comparison of mass attenuation coefficient plotted against photon energy for aluminum absorber obtained from simulations and XCOM database calculations.

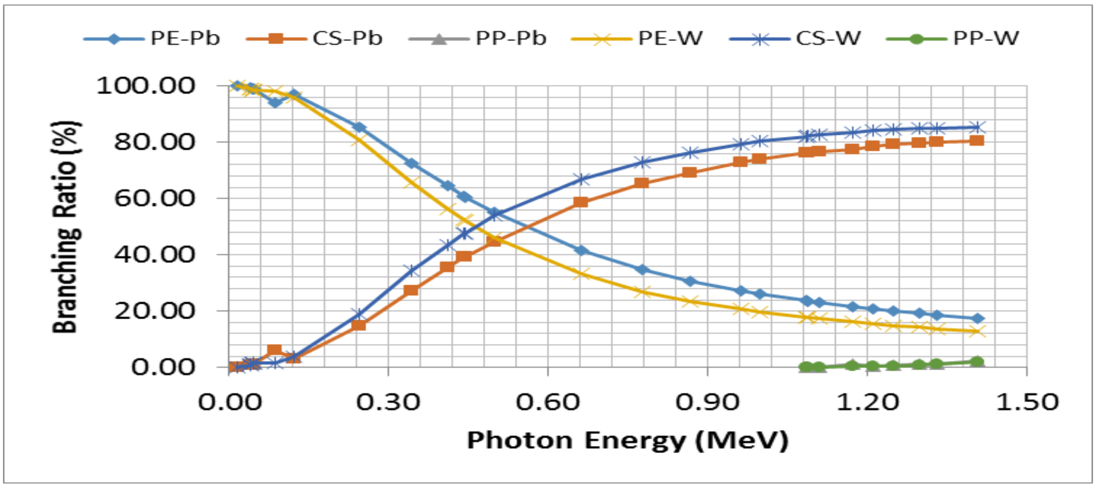

Figure 10. Photoelectric effect, Compton scattering and Pair production branching ratios of lead (Pb) and tungsten (W) absorbers as a function of photon energy.

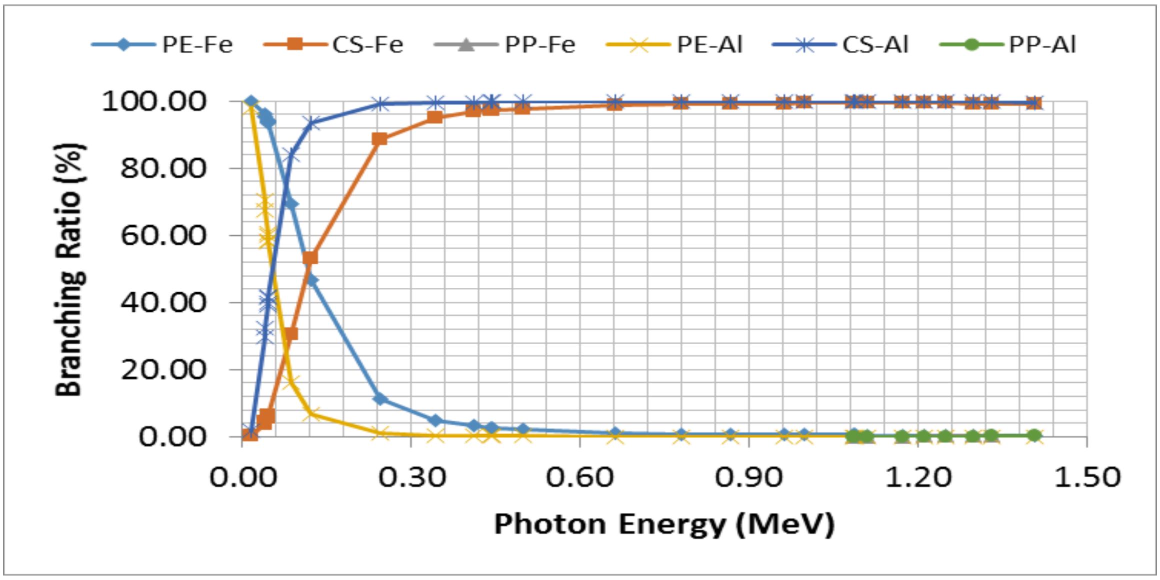

Figure 11. Photoelectric absorption, Compton scattering and pair production branching ratios of iron (Fe) and aluminum (Al) absorbers as a function of photon energy.

We also computed another important radiation parameter called the mean free path (MFP). The mean free path is the average distance at which an energetic photon travels through a material before undergoing an interaction within the material [3, 25]. The MFP is the reciprocal of the linear attenuation coefficient. The values of the mean free path for gamma rays in the materials under study are listed in table 5 and plotted in figure 12.

As can be seen from table 5, the MFP in tungsten is lower than that of lead and thus tungsten is more efficient in shielding of gamma rays. The mean free path in aluminum and iron are much higher than that of tungsten and lead. The MFP in the materials is influenced by the density of the material and increases with increases in energy of the photon. Higher density materials have lower mean free path. A material with lower MFP means it is a better shielding material [26]. According to the values of linear attenuation coefficient (tables 1-4) and figure 12, tungsten has the lowest MFP and hence a good shielding performance.

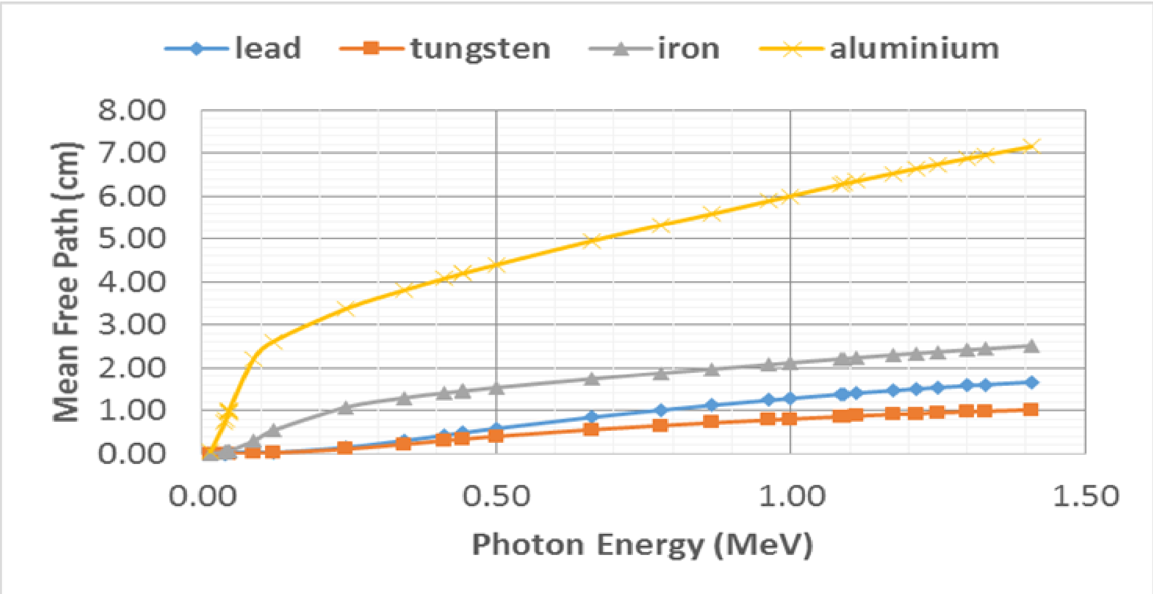

Figure 12. Variation of mean free path versus photon energy for the materials under study.

Table 5. The mean free path (MFP) of the materials under study at different photon energies.

Energy (MeV)	MFP (cm) lead	MFP (cm) tungsten	MFP (cm) iron	MFP (cm) aluminum
0.0150	0.0008	0.0004	0.0023	0.0489
0.0395	0.0065	0.0052	0.0362	0.7165
0.0412	0.0072	0.0058	0.0407	0.7851
0.0453	0.0093	0.0075	0.0532	0.9515
0.0457	0.0095	0.0076	0.0546	0.9691
0.0466	0.0101	0.0081	0.0576	1.0073
0.0468	0.0102	0.0082	0.0583	1.0154
0.0880	0.0541	0.0088	0.2932	2.2041
0.1220	0.0273	0.0204	0.5409	2.6169
0.2447	0.1448	0.1082	1.0761	3.3748
0.3440	0.3035	0.2197	1.2958	3.8084
0.4110	0.4271	0.3026	1.4077	4.0738
0.4430	0.4840	0.3393	1.4544	4.1950
0.4440	0.4859	0.3404	1.4560	4.1988
0.5000	0.5834	0.4016	1.5349	4.3979
0.6620	0.8446	0.5576	1.7402	4.9541
0.7790	1.0093	0.6521	1.8774	5.3256
0.8670	1.1241	0.7164	1.9745	5.5922
0.9640	1.2412	0.7817	2.0804	5.8942
1.0000	1.2826	0.8054	2.1207	6.0078
1.0850	1.3793	0.8603	2.2124	6.2763
1.0897	1.3840	0.8632	2.2171	6.2904
1.1120	1.4070	0.8767	2.2410	6.3546
1.1730	1.4672	0.9105	2.3036	6.5299
1.2130	1.5041	0.9312	2.3426	6.6431
1.2500	1.5370	0.9492	2.3763	6.7473
1.2990	1.5781	0.9720	2.4204	6.8768
1.3320	1.6044	0.9869	2.4492	6.9627
1.4080	1.6627	1.0200	2.5168	7.1553

Conclusion

In this study, the gamma rays attenuation coefficients and mean free path were computed for lead, tungsten, iron and aluminium in the range of 0.015-1.4 MeV using the Geant4 Monte Carlo method. The simulated results were validated with the aid of the XCOM database computer program. We observed that there was a good agreement between the simulations and theoretical results. Depending on the results and the discussions above, the following conclusions were listed;

- The mass attenuation coefficient is an energy depend, it decreases with increasing energy.
- Higher linear attenuation coefficient means better radiation attenuation in this case lead and tungsten are better attenuation materials than iron and aluminum
- Geant4 values are comparable to XCOM database values
- The results from Monte Carlo simulation with Geant4 may be used to design the radiation shielding for laboratories with radioactive sources.

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