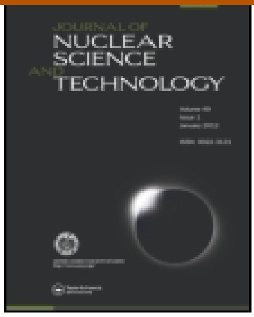

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Calculation of Gamma-ray Exposure Buildup Factors up to 40 mfp using the EGS4 Monte Carlo Code with a Particle Splitting

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Gamma-ray exposure buildup factors up to 40 mfp have been calculated using the Monte Carlo code EGS4 for water, iron and lead for point isotropic sources. The new algorithm which applies particle-splitting at each preset depth to simulate almost same number of particles from the preset depth is developed in order to obtain reasonable results with EGS4 at deep-penetrations. Comparisons of these results to the standard data calculated with the moments method or the discrete ordinates code PALLAS show good agreements if the same cross section data and energy absorption coefficients are used.

The EGS4 calculations with this new algorithm will be a useful tool for future studies of gamma-ray buildup factors including the review of the standard data.

KEYWORDS: ***Monte Carlo method, calculation method, EGS4 code, algorithms, mathematical logic, deep penetration, gamma-ray buildup factor, particle splitting, energy spectra***

I. INTRODUCTION

This report describes an attempt to apply a Monte Carlo method to a gamma-ray deep-penetration problem in calculating gamma-ray exposure buildup factors.

Experiments aimed at obtaining precise gamma-ray exposure buildup factors are generally not easy. Studies of gamma-ray buildup factors were therefore carried out using calculations. The Monte Carlo method is not suitable for deep-penetration calculations due to a statistical problem. Therefore, studies at deep penetrations were mainly performed by discrete ordinates methods.

It was recently reported by Kitsos *et al.*[1] that many energy groups, and an extremely fine space and angular mesh, were required to achieve reasonably accurate results in calculating gamma-ray exposure buildup factors. They showed that discrete ordinates methods are also difficult to apply at very deep penetrations, such as 40 mfp. This fact shows the necessity to compare the calculated buildup factors between the different calculation methods, especially at deep penetrations.

It has become possible to execute a Monte Carlo calculation of very large histories within a reasonable CPU time along with a recent drastic increase in computer power. It is still difficult to obtain reasonably accurate results at deep penetrations using the ordinary analog method.

The particle-splitting technique is one of the useful technique at the deep penetration problems. It is necessary to apply the particle-splitting at several depths to obtain reasonable results at very deep penetrations, such as 40 mfp and the number of splitting at each splitting point is not easy to determine. In the EGS4[2] calculations, moreover, this needs the very large stack number. The new algorithm was developed in order to overcome these difficulties.

The calculation results of EGS4 with this new algorithm were compared with those of the standard data calculated by the moments method[3] and the discrete ordinates code, PALLAS[4], in order to prove the validity of this algorithm.

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II. CALCULATION

1. Method of Calculation

The details concerning the EGS4 code have been described previously(2).

In photon transport, EGS4 considers Compton scattering (Klein-Nishina cross section applied to free electrons), pair production, and the photoelectric effect with K X-rays.

Electron-positron transport is simulated using the condensed-history technique with energy-loss fluctuations accounted for through the random nature of elastic scattering events. The PRESTA(5) algorithm was used to obtain accurate results without setting a very small step size. Bremsstrahlung production, positron annihilation in flight and at rest, elastic Møller and Bhabha scattering from electrons and Moilère multiple scattering from atomic nuclei were all taken into account.

The particle-splitting technique involves a kind of a variance reduction to obtain more information about such rare events at deep penetrations. In an ordinary way, a particle is split into many particles having less weight in order to compensate for an increase in number when it arrives at the position of interest.

This ordinary particle-splitting technique cannot be applied to the EGS4 code for calculating the exposure buildup factors up to 40 mfp due to the following reasons:

(1) It is necessary to apply particle splitting at several preset depths, for example at each 5 mfp, for deep-penetration calculations up to 40 mfp.

(2) The EGS4 code is an electron gamma shower code in which the number of particles increases at each interaction. The stack number (NP) is used to treat this phenomenon. A lower energy particle having a larger NP is traced first. If particle splitting is applied in the ordinary way, a large number of NP is necessary.

(3) It is desired to follow the almost same number of particles at each preset depth. The number of particles reaching to the splitting point depends on the medium, its depth and photon energy. The number of splitting is, therefore, not easy to determine for each problem.

The following algorithm is used to overcome these difficulties:

(1) When a particle reaches the position at which it is to be split (NCIR(ICRR), ICRR: the number of splitting points), write all information concerning the particle (positions, direction cosines, energy, weight and particle type) on the disk file and stop this history.

(2) When all of the histories (NCASES) are completed, calculate the splitting number (NSPLIT) based on the number of particles reaching the split position (NPART) and NCASES using

$$\mathrm{NSPLIT} = \mathrm{NCASES}/\mathrm{NPART} + 1.$$

(3) Continue calculating the NSPLIT times using the particle information written on the disk file using a particle weight of W(NP)/NSPLIT, where W(NP) is that before applying the splitting.

(4) When a particle reaches the next split position, carry out the same procedure as that mentioned above.

(5) If the calculations performed using the data at the deepest splitting point (NSIR($NSPP)) have been completed, discontinue the calculation and analyze the results.

It becomes possible to simulate almost the same number of particles at each splitting point by the above-mentioned method. A flow chart of this method is shown in **Fig.1**.

The data of 40 mfp in infinite water, iron and lead were estimated based on calculations in a sphere of 42-mfp thickness. The splitting point must be determined to have an enough number of particles reaching at each points. After testing for several depths, the splitting point was set at each 5 mfp. In all calculations, 1,000,000 case histories were used.

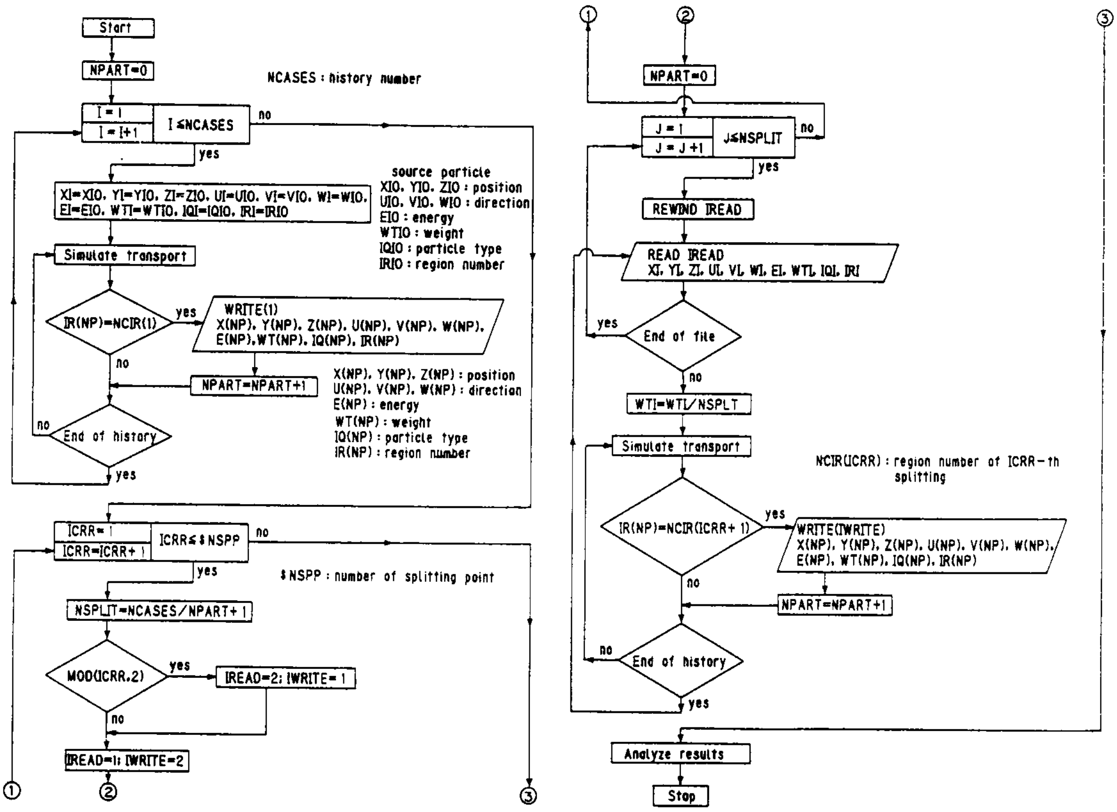

Fig.1 Flow chart of EGS4 calculation with splitting

Calculations were performed using the PURE (Pilot Unix R&D Environment) system at the Computing Center of National Laboratory for High Energy Physics (KEK).

2. Cross Section

The standard data of the gamma-ray exposure buildup factors[6] for water and iron have been calculated using the moments method[3] and Hubbell's data[7] (NSRDS-NBS-29). On the other hand, those for lead have been calculated using the discrete ordinates code, PALLAS[4], and PHOTX data[8].

The cross section data of each material and the energy absorption coefficients of air affect the exposure buildup factors. The same data base must be used to check the computational method by comparing the results between the different calculation methods. EGS4 calculations were therefore performed using the same data base as that mentioned above. The photoelectric cross sections, pair production cross sections and total cross sections used in the calculations are given in **Table 1**. The Compton-scattering cross section for free electrons was used in the standard data and the EGS4 calculations.

The material data used in EGS4 are calculated with PEGS4 (Preprocessor for EGS4). The IAPRIM option[9] is used to produce a radiative stopping power identical to that presented in ICRU37[10].

Ⅲ. Results and Discussion

1. Comparison with the Standard Data

Tables 2, 3 and **4** give comparisons of EGS4 calculations with the standard data of the exposure buildup factors for water, iron and lead for 0.1, 1.0 and 10 MeV, respectively.

Table 1 Photoelectric cross sections, pair production cross sections and total cross sections used in the calculation

Photon Energy (MeV)	Photoelectric Cross Section: Water[a] (Ref. 7) (cm²/g)	Iron[a] (Ref. 7) (cm²/g)	Lead[b] (Ref. 8) (cm²/g)	Total Cross Sectoon: Water (Ref. 7) (cm²/g)	Iron (Ref. 7) (cm²/g)	Lead (Ref. 8) (cm²/g)
1.00E−2[c]	4.78E+0	1.71E+2	1.256E+2	4.99E+0	1.72E+2	1.256E+2
1.50E−2	1.27E+0	5.55E+1	1.082E+2	1.48E+0	5.57E+1	1.083E+2
2.00E−2	5.05E−1	2.49E+1	8.398E+1	7.11E−1	2.51E+1	8.411E+1
3.00E−2	1.38E−1	7.71E+0	2.886E+1	3.38E−1	7.88E+0	2.900E+1
4.00E−2	5.48E−2	3.30E+0	1.335E+1	2.48E−1	3.46E+0	1.349E+1
5.00E−2	2.67E−2	1.68E+0	7.294E+0	2.14E−1	1.84E+0	7.426E+0
6.00E−2	1.50E−2	9.75E−1	4.433E+0	1.97E−1	1.13E+0	4.562E+0
8.00E−2	5.95E−3	4.06E−1	2.013E+0	1.79E−1	5.50E−1	2.136E+0
8.73E−2[d]			1.581E+0			1.703E+0
8.80E−2			1.548E+0			1.668E+0
8.80E−2[e]			7.323E+0			7.442E+0
1.00E−1	2.85E−3	2.04E−1	2.858E+0	1.68E−1	3.42E−1	5.355E+0
1.50E−1	7.76E−4	5.95E−2	1.815E+0	1.49E−1	1.84E−1	1.921E+0
2.00E−1	3.11E−4	2.51E−2	8.465E−1	1.36E−1	1.39E−1	9.432E−1
3.00E−1	8.86E−5	7.52E−3	2.930E−1	1.18E−1	1.07E−1	3.772E−1
4.00E−1	3.78E−5	3.33E−3	1.417E−1	1.06E−1	9.21E−2	2.172E−1
5.00E−1	2.04E−5	1.82E−3	8.180E−2	9.67E−2	8.29E−2	1.515E−1
6.00E−1	1.28E−5	1.15E−3	5.407E−2	8.95E−2	7.62E−2	1.179E−1
8.00E−1	6.42E−6	5.86E−4	2.901E−2	7.86E−2	6.65E−2	8.474E−2
1.00E+0	3.98E−6	3.64E−4	1.810E−2	7.07E−2	5.96E−2	6.848E−2
Photon Energy (MeV)	**Pair Production Cross Section: Water (Ref. 7) (cm²/g)**	**Iron (Ref. 7) (cm²/g)**	**Lead (Ref. 8) (cm²/g)**	**Total Cross Sectoon: Water (Ref. 7) (cm²/g)**	**Iron (Ref. 7) (cm²/g)**	**Lead (Ref. 8) (cm²/g)**
2.00E+0	3.93E−4	1.36E−3	5.451E−3	4.94E−2	4.25E−2	4.536E−2
3.00E+0	1.13E−3	3.78E−3	1.193E−2	3.97E−2	3.62E−2	4.199E−2
4.00E+0	1.89E−3	6.09E−3	1.716E−2	3.40E−2	3.31E−2	4.175E−2
5.00E+0	2.56E−3	8.13E−3	2.256E−2	3.03E−2	3.14E−2	4.257E−2
6.00E+0	3.17E−3	9.93E−3	2.535E−2	2.77E−2	3.05E−2	4.379E−2
8.00E+0	4.22E−3	1.30E−2	3.171E−2	2.43E−2	2.98E−2	4.667E−2
1.00E+1	5.08E−3	1.54E−2	3.699E−2	2.22E−2	2.98E−2	4.965E−2

[a] NSRDS-NBS-29, [b] PHOTX, [c] Read as 1.00×10^{-1}.
[d] K_{β_2} X-ray energy, [e] K edge energy

The standard data for water and iron have been calculated using the moments method[(3)] and those for lead have been calculated using the discrete ordinates code, PALLAS[(4)].

For 0.1 and 1 MeV gamma-rays, the results of EGS4 agree very well within the statistical errors with the standard data except for lead at 0.1 MeV. The slight overestimate tendency of the PALLAS code for lead at 0.1 MeV between 4 and 30 mfp is pointed out in Ref.(11) by comparing the results of the discrete ordinates code, ASFIT[(12)] and those of EGS4.

In the case of 10 MeV, although the EGS4 results agree very well for water and iron, they are slightly larger for iron and smaller for lead than the standard data.

In the moments calculations, bremsstrahlung events are neglected. This treatment decreases the photon flux inside the materials. To check this effect, EGS4 calculations without bremsstrahlung were compared with the standard data (**Table 5**). The EGS4 results agree very well with the standard data for iron. Therefore, the differences between EGS4 and the moments method can be explained as being bremsstrahlung contributions. The results of the PALLAS code for lead include the contribution of bremsstrahlung. The treatment in PALLAS, however, includes some simplifications. That is, PALLAS neglects the transport of charged particles,

Table 2 Gamma-ray exposure buildup factor for point isotropic source (0.1 MeV)

mfp	Water			Iron			Lead		
	EGS4(NBS)	ANS-6.4.3[a]		EGS4(NBS)	ANS-6.4.3[a]		EGS4(PHOTX)	ANS-6.4.3[b]	
	A	B	A/B	C	D	C/D	E	F	E/F
1.0	4.68 ± 0.001	4.55	1.03	1.39±0.002	1.40	0.99	2.17 ± 0.003	2.04	1.06
2.0	12.4 ± 0.032	11.8	1.05	1.62±0.003	1.61	1.01	3.53 ± 0.005	3.39	1.04
3.0	25.0 ± 0.067	23.8	1.05	1.79±0.004	1.78	1.01	5.57 ± 0.010	5.60	0.99
4.0	43.9 ± 0.16	41.3	1.06	1.96±0.009	1.94	1.01	8.99 ± 0.020	9.59	0.94
5.0	70.1 ± 0.27	65.2	1.07	2.10±0.009	2.07	1.01	14.8 ± 0.023	17.0	0.87
6.0	104. ± 0.43	96.7	1.08	2.23±0.008	2.20	1.01	25.0 ± 0.036	30.6	0.82
7.0	148. ± 0.63	137.	1.08	2.34±0.011	2.31	1.01	43.2 ± 0.067	54.9	0.79
8.0	203. ± 1.3	187.	1.09	2.46±0.013	2.41	1.02	75.9 ± 0.11	94.7	0.80
10.0	354. ± 3.0	321.	1.10	2.66±0.019	2.61	1.02	243. ± 0.42	320.	0.76
15.0	1.05E+3[c]±13.	938.	1.12	3.07±0.029	3.01	1.02	5.12E+03± 11.	5.80E+03	0.88
20.0	2.35E+3 ±35.	2.17E+3	1.08	3.43±0.035	3.33	1.03	1.23E+03±300.	1.33E+05	0.93
25.0	4.82E+3 ± 1.0E+2	4.36E+3	1.11	3.73±0.036	3.61	1.03	3.17E+06± 9.8E+03	3.34E+06	0.95
30.0	8.56E+3 ± 2.4E+2	7.97E+3	1.07	4.02±0.058	3.86	1.04	8.58E+07± 3.0E+5	8.77E+07	0.98
35.0	1.44E+4 ± 5.3E+2	1.35E+4	1.07	4.31±0.076	4.07	1.06	2.38E+09± 8.9E+6	2.36E+09	1.01
40.0	2.44E+4 ± 1.6E+3	2.11E+4	1.16	4.51±0.088	4.23	1.07	6.70E+10± 2.7E+8	6.43E+10	1.04

[a] Calculations by the moments methods with NSRDS-NBS-29.
[b] Calculations by PALLAS with PHOTX.
[c] Read as 1.05×10^3.

Table 3 Gamma-ray exposure buildup factor for point isotropic source (1.0 MeV)

mfp	Water			Iron			Lead		
	EGS4(NBS)	ANS-6.4.3[a]		EGS4(NBS)	ANS-6.4.3[a]		EGS4(PHOTX)	ANS-6.4.3[b]	
	A	B	A/B	C	D	C/D	E	F	E/F
1.0	2.10± 0.003	2.08	1.01	1.86±0.002	1.85	1.01	1.38±0.001	1.38	1.00
2.0	3.67± 0.006	3.62	1.01	2.88±0.004	2.85	1.01	1.97±0.003	1.95	1.01
3.0	5.60± 0.011	5.50	1.02	4.04±0.008	4.00	1.01	1.97±0.003	1.95	1.01
4.0	7.86± 0.021	7.68	1.02	5.35±0.015	5.30	1.01	2.23±0.006	2.19	1.02
5.0	10.3 ± 0.035	10.1	1.02	6.78±0.028	6.74	1.01	2.49±0.011	2.43	1.02
6.0	13.1 ± 0.045	12.8	1.02	8.39±0.022	8.31	1.01	2.72±0.012	2.66	1.02
7.0	15.9 ± 0.072	15.8	1.01	10.1 ±0.032	10.0	1.01	2.95±0.015	2.89	1.02
8.0	19.3 ± 0.11	19.0	1.02	12.0 ±0.064	11.8	1.02	3.16±0.018	3.10	1.02
10.0	26.4 ± 0.21	26.1	1.01	16.0 ±0.12	15.8	1.01	3.62±0.025	3.51	1.03
15.0	49.1 ± 0.74	47.7	1.03	28.1 ±0.34	27.5	1.02	4.55±0.046	4.45	1.02
20.0	74.3 ± 1.8	74.0	1.00	41.0 ±0.83	41.3	0.99	5.45±0.071	5.27	1.03
25.0	106. ± 3.0	104.	1.02	56.6 ±1.3	57.0	0.99	6.27±0.11	5.98	1.05
30.0	138. ± 4.1	139.	0.99	75.0 ±2.3	74.5	1.01	7.10±0.15	6.64	1.07
35.0	175. ± 7.3	177.	0.99	94.1 ±3.2	93.5	1.01	7.96±0.20	7.23	1.10
40.0	210. ±11.	218.	0.96	117. ±5.5	114.	1.03	8.94±0.25	7.79	1.14

[a] Calculations by the moments methods with NSRDS-NBS-29.
[b] Calculations by PALLAS with PHOTX.

and the emitted dominant direction of bremsstrahlung is chosen to be forward. These simplifications increase the photon flux, especially at deep penetration. These tendencies are also discussed in Ref.(11). In a comparison without bremsstrahlung (Table 4), the results of PALLAS[(11)] are slightly larger than those of EGS4. The same tendency is seen in comparisons with those of ASFIT in Ref.(11).

2. Comparison of the Spectrum in Lead for 0.1-MeV Gamma-Rays

The energy spectrum inside lead at 40 mfp for 0.1-MeV gamma-rays was compared between the PALLAS and EGS4 results in order to check on the usefulness of the EGS4 calculations with the splitting and is shown in **Fig.2**.

The differences at the K X-rays result from differences in the energy mesh between the two codes. At the other part, which is due to the scattering of primary gamma-rays and produced K X-rays, an ordinary EGS4 calculation underestimates the energy flux. On the other hand, EGS4 calculations with a splitting agree well with PALLAS. Based on this comparison, an EGS4 calculation with a splitting can simulate gamma-ray transport at deep penetrations.

Table 4 Gamma-ray exposure buildup factor for point isotropic source (10.0 MeV)

mfp	Water			Iron			Lead		
	EGS4(NBS)	ANS-6.4.3[a]		EGS4(NBS)	ANS-6.4.3[a]		EGS4(PHOTX)	ANS-6.4.3[b]	
	A	B	A/B	C	D	C/D	E	F	E/F
1.0	1.44±0.001	1.37	1.05	1.51±0.001	1.33	1.33	1.57 ± 9.001	1.51	1.04
2.0	1.79±0.002	1.68	1.07	1.93±0.002	1.59	1.21	2.04 ± 0.002	2.01	1.01
3.0	2.11±0.003	1.97	1.07	2.34±0.004	1.86	1.25	2.59 ± 0.005	2.63	0.98
4.0	2.43±0.005	2.25	1.08	2.78±0.007	2.16	1.29	3.23 ± 0.008	3.42	0.94
5.0	2.72±0.010	2.53	1.08	3.27±0.013	2.50	1.30	4.04 ± 0.010	4.45	0.91
6.0	3.01±0.012	2.80	1.08	3.76±0.013	2.87	1.31	5.04 ± 0.012	5.73	0.88
7.0	3.31±0.017	3.07	1.08	4.29±0.020	3.27	1.32	6.24 ± 0.023	7.37	0.85
8.0	3.58±0.018	3.34	1.07	4.85±0.027	3.71	1.30	7.77 ± 0.029	9.44	0.82
10.0	4.16±0.038	3.86	1.08	6.14±0.047	4.69	1.31	12.0 ± 0.064	15.4	0.78
15.0	5.54±0.057	5.14	1.08	10.1 ±0.12	7.88	1.29	36.4 ± 0.27	50.8	0.72
20.0	6.80±0.11	6.38	1.07	15.5 ±0.26	12.3	1.26	109. ± 1.0	161.	0.68
25.0	8.03±0.17	7.59	1.06	23.2 ±0.40	18.1	1.28	327. ± 4.9	495.	0.66
30.0	9.45±0.26	8.78	1.08	32.2 ±1.1	25.3	1.29	965. ± 15.	1.47E+3[c]	0.66
35.0	10.3 ±0.31	9.96	1.03	44.5 ±1.3	35.3	1.25	2.80E+3± 55.	4.28E+3	0.65
40.0	11.5 ±0.43	11.2	1.03	60.0 ±2.1	47.6	1.26	7.65E+3±190.	1.22E+4	0.63

[a] Calculations by the moments methods with NSRDS-NBS-29.
[b] Calculations by PALLAS with PHOTX.
[c] Read as 1.47×10^3.

Table 5 Gamma-ray exposure buildup factor for point isotropic source (10.0 MeV) without bremsstrahlung

mfp	Water			Iron			Lead		
	EGS4(NBS)	ANS-6.4.3[a]		EGS4(NBS)	ANS-6.4.3[a]		EGS4(PHOTX)	PALLS[b] (PHOTX)	
	A	B	A/B	C	D	C/D	E	F	E/F
1.0	1.39±0.001	1.37	1.01	1.34±0.001	1.33	1.01	1.20 ± 9.001	1.19	1.01
2.0	1.70±0.002	1.68	1.01	1.61±0.002	1.59	1.01	1.33 ± 0.001	1.31	1.02
3.0	2.00±0.004	1.97	1.02	1.89±0.003	1.86	1.02	1.50 ± 0.002	1.47	1.03
4.0	2.30±0.006	2.25	1.02	2.21±0.005	2.16	1.01	1.71 ± 0.004	1.68	1.02
5.0	2.59±0.009	2.53	1.02	2.56±0.008	2.50	1.02	1.98 ± 0.005	1.96	1.01
6.0	2.87±0.010	2.80	1.03	2.94±0.010	2.87	1.02	2.32 ± 0.006	2.31	1.00
7.0	3.15±0.013	3.07	1.03	3.36±0.013	3.27	1.03	2.74 ± 0.008	2.77	0.99
8.0	3.42±0.020	3.34	1.02	3.82±0.012	3.71	1.03	3.28 ± 0.012	3.34	0.98
10.0	3.99±0.034	3.86	1.03	4.79±0.033	4.69	1.02	4.83 ± 0.025	4.99	0.97
15.0	5.30±0.062	5.14	1.03	8.14±0.091	7.88	1.03	13.8 ± 0.11	15.2	0.91
20.0	6.55±0.096	6.38	1.03	12.9 ±0.16	12.3	1.05	41.8 ± 0.46	48.5	0.86
25.0	8.06±0.16	7.59	1.06	19.0 ±0.31	18.1	1.05	129. ± 22.	116.	1.11
30.0	9.18±0.22	8.78	1.05	26.6 ±0.64	25.3	1.05	393. ± 64.	475.	0.83
35.0	10.4 ±0.25	9.96	1.04	36.8 ±1.0	35.3	1.05	1.18E+3[c]± 26.	1.43E+3	0.83
40.0	11.6 ±0.32	11.2	1.04	48.3 ±1.7	47.6	1.01	3.51E+3 ±110.	4.19E+3	0.84

[a] Calculations by the moments methods with NSRDS-NBS-29.
[b] Ref.(11), [c] Read as 1.18×10^3.

IV. CONCLUSIONS

The purpose of the present study was to show the usefulness of EGS4 Monte Carlo calculations for deep-penetration problems.

The point isotropic exposure buildup factors calculated using EGS4 agree very well with the standard data calculated using the moments method for water and iron if the calculation conditions were the same. It was also found that the contribution of bremsstrahlung can be seen at 10 MeV, even for iron.

For lead, the results of EGS4 agree well with those of PALLAS at 1 MeV. There are differences, however, for 0.1 or 10 MeV. At these energies, energy groups, the space and angular mesh used affected the results. It is therefore necessary to study the reasons for the differences by comparing the spectrum at various depths.

It is concluded that EGS4 calculations with a splitting can give reasonable results up to 40 mfp, and can be a very useful tool for studying the buildup factors at deep penetrations.

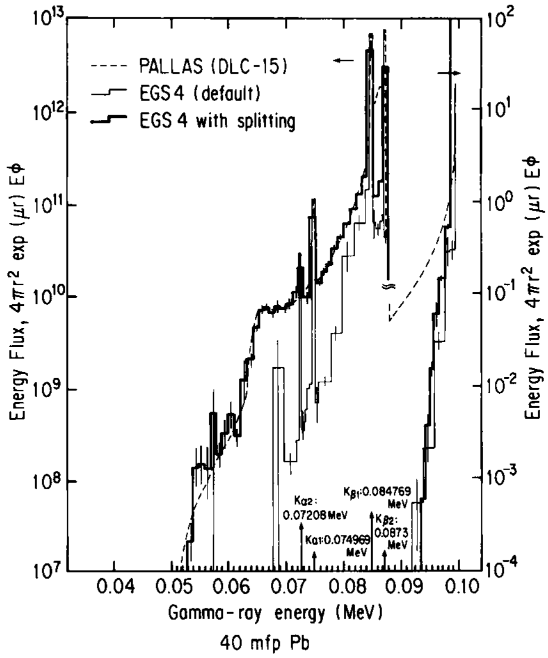

Fig.2 Comparison of calculations using PALLAS and EGS4 codes for a spectrum transmitted through 40 mfp lead for a 0.1-MeV point isotropic source

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