fr

KEK Preprint 95-97
August 1995
R

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

Hideo Hirayama

*National Laboratory for High Energy Physics
1-1 Oho, Tsukuba-shi, Ibaraki 305 Japan*

SW9544

ABSTRACT

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. A particle-splitting technique is applied in order to obtain reasonable results 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.

Submitted to J. Nucl. Sci. Technol.

National Laboratory for High Energy Physics, 1995

KEK Reports are available from:

Technical Information & Library
National Laboratory for High Energy Physics
1-1 Oho, Tsukuba-shi
Ibaraki-ken, 305
JAPAN

Phone: 0298-64-5136
Telex: 3652-534 (Domestic)
(0)3652-534 (International)
Fax: 0298-64-4604
Cable: KEK OHO
E-mail: Library@kekvox.kek.jp (Internet Address)

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 applied to calculations of the gamma-ray exposure buildup factors by the EGS4 Monte Carlo code⁽²⁾ in order to overcome these difficulties.

The calculation results of EGS4 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.

II CALCULATION

II.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 Molière 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 can not 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. The number of splittings is 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 any 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

$$NSPLIT = NCASES/NPART + 1.$$

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 was set at each 5 mfp. In all calculations, 1,000,000 case histories were used.

II.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 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

III.1 Comparison with the standard data

Tables 1, 2 and 3 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.

For 0.1 and 1 MeV gamma-rays, the results of EGS4 agree very well within the statistical errors with the standard data calculated using the moments method or the PALLAS code, except for lead at 0.1 MeV. The slight overestimate tendency of the PALLAS code between 4 and 30 mfp is pointed out in reference 11 by comparing the results of ASFIT and EGS4.

In the case of 10 MeV, although the EGS4 results agree very well for water, 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 4). 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, and the emitted dominant direction of bremsstrahlung is chosen to be forward. These simplifications increase the photon flux, especially at deep penetrations. These tendencies are also discussed in reference 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 reference 11.

III.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 are 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, the results of an ordinary EGS4 calculation underestimate the energy flux. On the other hand, those of EGS4 calculations with a splitting agree well with those of PALLAS. Based on this comparison, an EGS4 calculation with a splitting can simulate gamma-ray transport at deep penetrations.

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.

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

References

- [1] Kitsos, S., Assad, A., Diop, C. M., Nimal, J. C.: *Nucl. Sci. Eng.*, **117**, 47(1994).
- [2] Nelson, W. R., Hirayama, H. and Rogers, D. W. O.: EGS4 code system, *SLAC-265*, (1985).
- [3] Chilton, A. B., Eisenhauer, C. M. and Simmons, G. L.: *Nucl. Sci. Eng.*, **73**, 97(1980).
- [4] Takeuchi, K., Tanaka, S.: PALLAS-1D(VII); A code for direct integration of transport equation in one dimensional plane and spherical geometries, *JAERI-M* 84-214, (1984).
- [5] Bielajew, A.F. and Rogers, D.W.O.: *Nucl. Instrum. and Methods*, **B 18**, 165(1987).
- [6] Trubey, D. K.: New gamma-ray buildup factor data for point kernel calculations; ANS-6.4.3 standard reference data, *NUREG/CR-5740*, U.S. Nuclear Regulation Commission (1991).
- [7] Hubbell, J. H.: Photon cross sections, attenuation coefficients and energy absorption coefficients from 10 keV to 100 GeV. *NSRDS-NBS-29*, (1969).
- [8] Radiation Shielding Information Center Data Package DLC-136/PHOTX, *Photon Interaction Cross Section Library*, contributed by National Institute of Standards and Technology.
- [9] Rogers, D. W. O, Duane, S., Bielajew, A. F. and Nelson, W. R.: Use of ICRU-37/NBS Radiative Stopping Power in the EGS4 system, NRCC, Ottawa, *Report PIRS-0177* (1989).
- [10] ICRU Radiation Quantities and Units, *Report 37*, (Bethesda, MD:ICRU Publications)(1984).
- [11] Hirayama, H., Tanaka, S., Sakamoto, Y., Subbaiah, K. V. and Harima, Y.: *J. Nucl. Sci. Technol.*, **27**, 524(1990).

Table 1 Gamma-Ray Exposure Buildup Factor
for Point Isotropic Source (0.1 MeV)

mfp	Water				Iron		
	EGS4(NBS)		ANS-6.4.3	A/B	EGS4(NBS)	ANS-6.4.3	C/D
	A		B		C	D	
1.0	4.68	± 0.001	4.55	1.03	1.39±0.002	1.40	0.99
2.0	12.4	± 0.032	11.8	1.05	1.62±0.003	1.61	1.01
3.0	25.0	± 0.067	23.8	1.05	1.79±0.004	1.78	1.01
4.0	43.9	± 0.16	41.3	1.06	1.96±0.009	1.94	1.01
5.0	70.1	± 0.27	65.2	1.07	2.10±0.009	2.07	1.01
6.0	104.	± 0.43	96.7	1.08	2.23±0.008	2.20	1.01
7.0	148.	± 0.63	137.	1.08	2.34±0.011	2.31	1.01
8.0	203.	± 1.3	187.	1.09	2.46±0.013	2.41	1.02
10.0	354.	± 3.0	321.	1.10	2.66±0.019	2.61	1.02
15.0	1.05E+3 ^a	±13.	938.	1.12	3.07±0.029	3.01	1.02
20.0	2.35E+3	±35.	2.17E+3	1.08	3.43±0.035	3.33	1.03
25.0	4.82E+3	± 1.0E+2	4.36E+3	1.11	3.73±0.036	3.61	1.03
30.0	8.56E+3	± 2.4E+2	7.97E+3	1.07	4.02±0.058	3.86	1.04
35.0	1.44E+4	± 5.3E+2	1.35E+4	1.07	4.31±0.076	4.07	1.06
40.0	2.44E+4	± 1.6E+3	2.11E+4	1.16	4.51±0.088	4.23	1.07

mfp	Lead			
	EGS4(PHOTX)		ANS-6.4.3	E/F
	E		F	
1.0	2.17	± 0.003	2.04	1.06
2.0	3.53	± 0.005	3.39	1.04
3.0	5.57	± 0.010	5.60	0.99
4.0	8.99	± 0.020	9.59	0.94
5.0	14.8	± 0.023	17.0	0.87
6.0	25.0	± 0.036	30.6	0.82
7.0	43.2	± 0.067	54.9	0.79
8.0	75.9	± 0.11	94.7	0.80
10.0	243	± 0.42	320.	0.76
15.0	5.12E+3	± 11.	5.80E+3	0.88
20.0	1.23E+3	±300.	1.33E+5	0.93
25.0	3.17E+6	± 9.8E+3	3.34E+6	0.95
30.0	8.58E+7	± 3.0E+5	8.77E+7	0.98
35.0	2.38E+9	± 8.9E+6	2.36E+9	1.01
40.0	6.70E+10	± 2.7E+8	6.43E+10	1.04

^a Read as 1.05×10^3 .

Table 2 Gamma-Ray Exposure Buildup Factor
for Point Isotropic Source (1.0 MeV)

mfp	Water			Iron		
	EGS4(NBS)	ANS-6.4.3	A/B	EGS4(NBS)	ANS-6.4.3	C/D
	A	B		C	D	
1.0	2.10± 0.003	2.08	1.01	1.86±0.002	1.85	1.01
2.0	3.67± 0.006	3.62	1.01	2.88±0.004	2.85	1.01
3.0	5.60± 0.011	5.50	1.02	4.04±0.008	4.00	1.01
4.0	7.86± 0.021	7.68	1.02	5.35±0.015	5.30	1.01
5.0	10.3 ± 0.035	10.1	1.02	6.78±0.028	6.74	1.01
6.0	13.1 ± 0.045	12.8	1.02	8.39±0.022	8.31	1.01
7.0	15.9 ± 0.072	15.8	1.01	10.1 ±0.032	10.0	1.01
8.0	19.3 ± 0.11	19.0	1.02	12.0 ±0.064	11.8	1.02
10.0	26.4 ± 0.21	26.1	1.01	16.0 ±0.12	15.8	1.01
15.0	49.1 ± 0.74	47.7	1.03	28.1 ±0.34	27.5	1.02
20.0	74.3 ± 1.8	74.0	1.00	41.0 ±0.83	41.3	0.99
25.0	106. ± 3.0	104.	1.02	56.6 ±1.3	57.0	0.99
30.0	138. ± 4.1	139.	0.99	75.0 ±2.3	74.5	1.01
35.0	175. ± 7.3	177.	0.99	94.1 ±3.2	93.5	1.01
40.0	210. ±11.	218.	0.96	117. ±5.5	114.	1.03

Lead			
mfp	EGS4(PHOTX)	ANS-6.4.3	E/F
	E	F	
1.0	1.38±0.001	1.38	1.00
2.0	1.69±0.002	1.68	1.01
3.0	1.97±0.003	1.95	1.01
4.0	2.23±0.006	2.19	1.02
5.0	2.49±0.011	2.43	1.02
6.0	2.72±0.012	2.66	1.02
7.0	2.95±0.015	2.89	1.02
8.0	3.16±0.018	3.10	1.02
10.0	3.62±0.025	3.51	1.03
15.0	4.55±0.046	4.45	1.02
20.0	5.45±0.071	5.27	1.03
25.0	6.27±0.11	5.98	1.05
30.0	7.10±0.15	6.64	1.07
35.0	7.96±0.20	7.23	1.10
40.0	8.94±0.25	7.79	1.14

Table 3 Gamma-Ray Exposure Buildup Factor
for Point Isotropic Source (10.0 MeV)

mfp	Water			Iron		
	EGS4(NBS)	ANS-6.4.3	A/B	EGS4(NBS)	ANS-6.4.3	C/D
	A	B		C	D	
1.0	1.44±0.001	1.37	1.05	1.51±0.001	1.33	1.33
2.0	1.79±0.002	1.68	1.07	1.93±0.002	1.59	1.21
3.0	2.11±0.003	1.97	1.07	2.34±0.004	1.86	1.25
4.0	2.43±0.005	2.25	1.08	2.78±0.007	2.16	1.29
5.0	2.72±0.010	2.53	1.08	3.27±0.013	2.50	1.30
6.0	3.01±0.012	2.80	1.08	3.76±0.013	2.87	1.31
7.0	3.31±0.017	3.07	1.08	4.29±0.020	3.27	1.32
8.0	3.58±0.018	3.34	1.07	4.85±0.027	3.71	1.30
10.0	4.16±0.038	3.86	1.08	6.14±0.047	4.69	1.31
15.0	5.54±0.057	5.14	1.08	10.1 ±0.12	7.88	1.29
20.0	6.80±0.11	6.38	1.07	15.5 ±0.26	12.3	1.26
25.0	8.03±0.17	7.59	1.06	23.2 ±0.40	18.1	1.28
30.0	9.45±0.26	8.78	1.08	32.2 ±1.1	25.3	1.29
35.0	10.3 ±0.31	9.96	1.03	44.5 ±1.3	35.3	1.25
40.0	11.5 ±0.43	11.2	1.03	60.0 ±2.1	47.6	1.26

mfp	Lead			
	EGS4(PHOTX)		ANS-6.4.3	E/F
	E		F	
1.0	1.57	± 9.001	1.51	1.04
2.0	2.04	± 0.002	2.01	1.01
3.0	2.59	± 0.005	2.63	0.98
4.0	3.23	± 0.008	3.42	0.94
5.0	4.04	± 0.010	4.45	0.91
6.0	5.04	± 0.012	5.73	0.88
7.0	6.24	± 0.023	7.37	0.85
8.0	7.77	± 0.029	9.44	0.82
10.0	12.0	± 0.064	15.4	0.78
15.0	36.4	± 0.27	50.8	0.72
20.0	109.	± 1.0	161.	0.68
25.0	327.	± 4.9	495.	0.66
30.0	965.	± 15.	1.47E+3 ^a	0.66
35.0	2.80E+3± 55.		4.28E+3	0.65
40.0	7.65E+3±190.		1.22E+4	0.63

^a Read as 1.47×10^3 .

Table 4 Gamma-Ray Exposure Buildup Factor
for Point Isotropic Source (10.0 MeV)
Without Bremsstrahlung

mfp	Water			Iron		
	EGS4(NBS)	ANS-6.4.3	A/B	EGS4(NBS)	ANS-6.4.3	C/D
	A	B		C	D	
1.0	1.39±0.001	1.37	1.01	1.34±0.001	1.33	1.01
2.0	1.70±0.002	1.68	1.01	1.61±0.002	1.59	1.01
3.0	2.00±0.004	1.97	1.02	1.89±0.003	1.86	1.02
4.0	2.30±0.006	2.25	1.02	2.21±0.005	2.16	1.01
5.0	2.59±0.009	2.53	1.02	2.56±0.008	2.50	1.02
6.0	2.87±0.010	2.80	1.03	2.94±0.010	2.87	1.02
7.0	3.15±0.013	3.07	1.03	3.36±0.013	3.27	1.03
8.0	3.42±0.020	3.34	1.02	3.82±0.012	3.71	1.03
10.0	3.99±0.034	3.86	1.03	4.79±0.033	4.69	1.02
15.0	5.30±0.062	5.14	1.03	8.14±0.091	7.88	1.03
20.0	6.55±0.096	6.38	1.03	12.9 ±0.16	12.3	1.05
25.0	8.06±0.16	7.59	1.06	19.0 ±0.31	18.1	1.05
30.0	9.18±0.22	8.78	1.05	26.6 ±0.64	25.3	1.05
35.0	10.4 ±0.25	9.96	1.04	36.8 ±1.0	35.3	1.05
40.0	11.6 ±0.32	11.2	1.04	48.3 ±1.7	47.6	1.01

mfp	Lead			
	EGS4(PHOTX)		PALLAS (PHOTX)	E/F
	E		F	
1.0	1.20	± 9.001	1.19	1.01
2.0	1.33	± 0.001	1.31	1.02
3.0	1.50	± 0.002	1.47	1.03
4.0	1.71	± 0.004	1.68	1.02
5.0	1.98	± 0.005	1.96	1.01
6.0	2.32	± 0.006	2.31	1.00
7.0	2.74	± 0.008	2.77	0.99
8.0	3.28	± 0.012	3.34	0.98
10.0	4.83	± 0.025	4.99	0.97
15.0	13.8	± 0.11	15.2	0.91
20.0	41.8	± 0.46	48.5	0.86
25.0	129.	± 22.	116.	1.11
30.0	393.	± 64.	475.	0.83
35.0	1.18E+3 ^a	± 26.	1.43E+3	0.83
40.0	3.51E+3	±110.	4.19E+3	0.84

^a Read as 1.18×10^3 .

Fig. 1 Flow chart of the EGS4 calculation with splitting.

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