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MONTE CARLO CALCULATIONS OF INITIAL ENERGIES OF ELECTRONS IN WATER IRRADIATED BY PHOTONS WITH ENERGIES UP TO 1 GeV*

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Abstract—Previous calculations of the initial energies of electrons produced in water irradiated by photons are extended to 1 GeV by including pair and triplet production. Calculations were performed with the Monte Carlo computer code PHOEL-3, which replaces the earlier code, PHOEL-2. Tables of initial electron energies are presented for single interactions of monoenergetic photons at a number of energies from 10 keV to 1 GeV. These tables can be used to compute kerma in water irradiated by photons with arbitrary energy spectra to 1 GeV. In addition, separate tables of Compton-and pair–electron spectra are given over this energy range. The code PHOEL-3 is available from the Radiation Shielding Information Center, Oak Ridge National Laboratory, Oak Ridge, TN 37830.

1. INTRODUCTION

THIS paper extends previous calculations (Tu80) of initial electron energies in water irradiated by photons with energies up to 2 MeV. Pair and triplet production are now included and calculations are carried out up to 1 GeV. While the energy spectra of electron–positron pairs produced in the field of a nucleus are considered in detail, the energies of pairs produced in the field of an atomic electron ("triplets") are treated only in an approximate fashion, limiting the validity of the results to energies below about 1 GeV. In addition, the new work incorporates absolute values of photon cross sections, so that kerma in water can be estimated from the tables presented.

Computations were performed with the Monte Carlo computer code, PHOEL-3 (To81), which replaces the earlier code, PHOEL-2 (Tu80), that treated only the photoelectric effect and Compton scattering. PHOEL-3 was developed for microdosimetric studies of electrons slowing down in water (Ha78a; Ha78b). The reader is referred to (To81) for complete details about the basic input data and the code itself. PHOEL-3 can be obtained from the Radiation shielding Information Center, Oak Ridge National Laboratory; Oak Ridge, TN 37830.

2. TREATMENT OF PHOTON INTERACTIONS IN H_2O

The values of the cross sections used in PHOEL-3 at photon energies $\geq$1 MeV were taken directly from the tabulations of Hubbell, Gimm and Overbo (Hu80). Below 1 MeV, the cross sections from PHOEL-2 were retained (Ev 68).

The generation of photoelectrons and Compton electrons in PHOEL-3 is done in the same way as in the earlier work, including production of a 0.508 keV Auger electron from oxygen following the ejection of a photoelectron from the K shell. In the present

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calculations it is also assumed that a K vacancy is created one-fifth of the time following Compton scattering, since there are 2 K-shell electrons out of a total of 10 in the water molecule. When this occurs, a 0.508 keV Auger electron is also produced. The tables presented below thus give the electron energy spectra after all K vacancies have been filled.

When pair production occurs, the positron and electron energies are selected from the spectra presented graphically by Bethe and Ashkin (Be53). For photons of arbitrary energy, linear interpolation is used between the curves presented there for discrete photon energies. These curves are appropriate for positron–electron pairs produced in the field of a nucleus. When pair production occurs in the field of an atomic electron (triplet production), we assume that the energy spectra of the positron and electron are the same as they would be in the field of a nucleus. We also assume that the recoil momentum of the "target" electron is the same as it would be for the nucleus. Under these conditions, we select the recoil energy of the triplet "target" electron on the basis of the approximate momentum-distribution formula given by Bethe and Ashkin. With this approximation, we have limited the calculations to photon energies ≤ 1 GeV, where the triplet cross section is about 15% of the total photon cross section in water.

As a check on the present calculations, results obtained with PHOEL-3 were compared with the computations of Cormack and Johns (Co52), who considered photon energies up to 25 MeV. As seen from the comparison in Fig. 1, at 25 MeV good agreement was found. The two calculations are different in that Cormack and Johns neglect triplet production, which adds ~5% to the total photon interaction cross section at this energy. Our curve in Fig. 1 is generally higher than that of Cormack and Johns, attributable to the use of slightly different pair-production cross sections. Most of the triplet recoil electrons occur in the lowest energy intervals, greatly augmenting the relative number of electrons there, as seen in the figure.

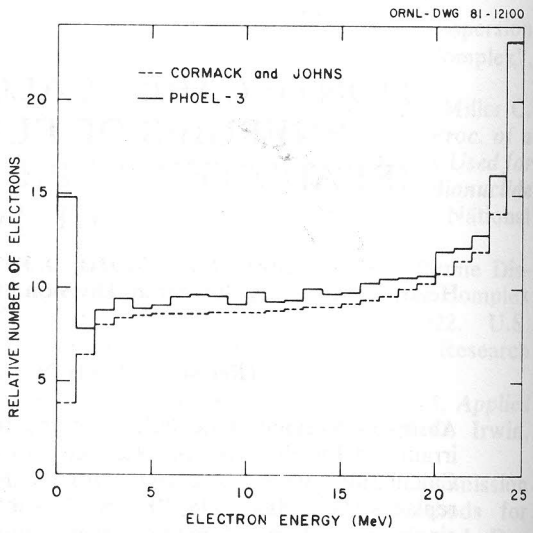

FIG. 1. Initial energy distribution of the total number of electrons and positrons produced by 25 MeV photons in water as computed with PHOEL-3 (solid histogram) and by Cormack and Johns (Co52, dashed histogram). The difference in the two computations is consistent with the inclusion of triplet production in PHOEL-3.

3. NUMERICAL RESULTS

In this section we present tables of the initial energies of electrons produced in water irradiated by monoenergetic photons with energies to 1 GeV. Only single interactions of the incident photons are treated; multiple Compton scattering and bremsstrahlung are neglected. Absolute values of the data are given, so one can use the tables to calculate kerma from photons with arbitrary energy spectra up to 1 GeV. For completeness, single-collision tables for energies up to 2 MeV, which were not presented in the earlier work (Tu80), are included here. The output of PHOEL-3 lists separately the contributions of photoelectrons (including Auger electrons), Compton electrons (including Auger), pair electrons, pair positrons and the triplet recoil "target" electrons. These particle spectra are combined for Tables 1–4. The Compton spectra alone are given in Tables 5 and 6, and the separate positron spectra in Tables 7 and 8. The program output also lists the calculated standard deviations for all quantities (To81), which will only be summarized here.

Table 1. Initial electron-energy distribution in water (first-collision spectrum). Number of electrons/cm^3 · keV per photon/cm^2

Electron Energy Interval (keV)	Photon Energy (keV)															
	10	20	30	40	50	60	70	80	90	100	120	140	160	180	200	220
0-5	201	108	64.2	47.1	31.7	24.7	20.5	17.4	15.2	13.6	11.3	9.58	8.44	7.63	7.03	6.61
5-10	188	0	0	3.79	13.8	12.2	8.60	6.97	6.13	5.22	4.27	3.37	2.69	2.18	1.80	1.47
10-15		0	0	0	0	5.40	11.5	6.73	5.06	4.48	3.53	2.84	2.44	2.08	1.75	1.51
15-20		70.2	0	0	0	0	0.202	8.02	5.85	4.11	3.08	2.58	2.13	1.78	1.57	1.37
20-25			0	0	0	0	0	0	5.91	5.16	2.90	2.34	1.97	1.72	1.42	1.28
25-30			21.8	0	0	0	0	0	0	4.51	3.11	2.16	1.79	1.61	1.41	1.20
30-35				0	0	0	0	0	0	0	3.87	2.19	1.67	1.46	1.32	1.17
35-40				8.82	0	0	0	0	0	0	3.52	2.40	1.67	1.36	1.21	1.11
40-45					0	0	0	0	0	0	0	2.97	1.77	1.29	1.13	1.03
45-50					4.17	0	0	0	0	0	0	3.55	1.91	1.32	1.08	1.00
50-55						0	0	0	0	0	0	0	2.29	1.39	1.08	0.935
55-60						2.38	0	0	0	0	0	0	2.79	1.56	1.10	0.913
60-65							0	0	0	0	0	0	1.10	1.80	1.14	0.912
65-70							1.40	0	0	0	0	0	0	2.15	1.27	0.914
70-75								0	0	0	0	0	0	2.28	1.41	0.974
75-80								0.919	0	0	0	0	0	0	1.63	1.04
80-85									0	0	0	0	0	0	1.94	1.17
85-90									0.601	0	0	0	0	0	1.27	1.24
90-95	MULTIPLY TABLE VALUES BY 10^{-3}									0	0	0	0	0	0	1.51
95-100										0.341	0	0	0	0	0	1.72
100-110											0	0	0	0	0	0.360
110-250											0.00899	0.00583	0.00253	0	0	0
Average Number of Electrons/cm^3 per Photon/cm^2	1.94	0.891	0.430	0.298	0.248	0.224	0.211	0.200	0.194	0.187	0.179	0.171	0.164	0.158	0.153	0.149

Table 2. Initial energy distribution of total number of electrons and positrons in water (first-collision spectrum). Number of electrons/cm^3 · keV per photon/cm^2

Electron Energy Interval (keV)	Photon Energy (keV)					
	300	500	750	1000	2000	3000
0-10	3100	2170	1720	1460.	979.	769.
10-20	801	310	146	77.8	21.4	8.10
20-30	807	314	146	84.6	25.8	12.6
30-40	703	290	126	72.9	21.8	7.01
40-50	673	297	136	87.9	18.3	10.8
50-60	638	307	141	72.9	23.1	7.63
60-70	619	296	130	77.0	16.8	6.70
70-80	570	271	141	78.6	22.6	11.2
80-90	522	258	136	84.4	24.9	10.9
90-100	524	253	146	76.7	21.0	9.35
100-200	440	238	127	77.8	21.1	10.2
200-300		255	119	71.8	21.3	10.0
300-400		136	113	72.5	22.5	9.85
400-500			142	70.3	21.9	10.1
500-600			139	72.4	21.1	10.8
600-700				92.7	21.3	10.8
700-800				145.	20.5	10.3
800-900					21.2	11.5
900-1000					22.8	10.3
1000-1200					22.6	11.2
1200-1400	MULTIPLY TABLE VALUES BY 10^{-6}				25.5	11.0
1400-1600					34.4	11.4
1600-1800					53.7	12.1
1800-2000						12.4
2000-2400						15.7
2400-2800						29.5
Average Number of Electrons/cm^3 per Photon/cm^2	0.133	0.111	0.0936	0.0819	0.0583	0.0476

Table 3. Initial energy distribution of total number of electrons and positrons in water (first-collision spectrum). Number of electrons/cm^3 · MeV per photon/cm^2

Electron Energy Interval (MeV)	Photon Energy (MeV)													
	4	5	6	7	8	9	10	12	14	16	18	20	22	25
0-1	127.	99.2	83.4	71.7	63.1	57.1	52.2	48.1	42.6	38.8	36.3	33.5	33.9	32.0
1-2	70.5	49.6	37.6	31.1	26.2	22.6	19.6	16.3	13.7	11.7	10.0	8.73	9.01	7.91
2-3	82.8	54.4	40.8	33.6	27.4	24.3	21.3	17.4	15.1	13.4	11.5	10.4	9.98	8.75
3-4	137.	65.4	44.1	35.2	30.2	26.1	23.2	18.3	15.0	12.9	12.1	11.1	10.3	9.40
4-5		111.	56.5	39.3	30.9	26.9	24.7	18.5	16.3	14.2	12.2	10.9	10.0	8.91
5-6			92.3	48.3	33.7	28.7	24.3	18.8	16.2	14.3	13.3	12.1	10.4	9.09
6-7				80.1	43.0	30.7	25.3	19.5	16.1	14.6	12.7	12.3	10.8	9.52
7-8					69.0	38.3	27.7	20.5	16.9	14.4	13.4	11.5	10.3	9.65
8-9						61.7	34.2	21.9	17.0	14.9	13.0	12.4	10.2	9.56
9-10							55.6	24.4	17.8	14.6	13.7	12.3	10.3	9.14
10-11								30.5	19.2	16.0	13.2	12.7	10.4	9.77
11-12								47.9	21.7	15.7	14.4	12.2	10.6	9.28
12-13									26.1	17.5	14.3	12.8	10.7	9.36
13-14									40.7	19.0	14.8	13.3	10.7	10.0
14-15										22.0	15.6	12.7	11.5	9.70
15-16										36.5	16.9	13.7	11.9	9.82
16-17											19.5	14.5	11.7	10.3
17-18											32.5	14.3	13.1	10.5
18-19												17.5	13.9	10.6
19-20												28.9	14.4	10.7
20-21	MULTIPLY TABLE VALUES BY 10^{-4}												18.1	12.0
21-22													26.3	12.2
22-23														12.9
23-24														16.1
24-25														23.2
Average Number of Electrons/cm^3 per Photon/cm^2	0.0417	0.0379	0.0355	0.0339	0.0323	0.0316	0.0308	0.0302	0.0294	0.0291	0.0289	0.0288	0.0289	0.0290

distribution in water from single interactions with monoenergetic photons of energies from 10 to 220 keV. Photoelectric absorption, followed by emission of an Auger electron, is the principal process that occurs at the lowest energies. The energy of the photoelectron is equal to the photon energy minus the K-shell orbital binding energy in oxygen (532 eV). At

Table 4. Initial energy distribution of total number of electrons and positrons in water (first-collision spectrum). Number of electrons/cm^3 · MeV per photon/cm^2

Electron Energy Interval (MeV)	Photon Energy (MeV)							
	30	50	75	100	250	500	750	1000
0-1	29.8	27.1	25.3	25.3	27.1	28.0	29.1	30.0
1-5	7.35	4.86	3.12	2.21	1.43	0.680	0.489	0.370
5-10	8.04	5.43	3.76	2.74	1.44	0.631	0.356	0.369
10-20	8.34	5.27	4.00	3.13	1.53	0.717	0.407	0.233
20-30	10.9	5.17	3.88	3.14	1.55	0.809	0.456	0.292
30-40		5.56	3.82	3.16	1.56	0.797	0.498	0.340
40-50		7.27	3.89	3.10	1.45	0.803	0.507	0.322
50-60			4.13	3.14	1.44	0.857	0.559	0.381
60-70			4.38	3.20	1.37	0.826	0.563	0.393
70-80			2.71	3.23	1.41	0.824	0.558	0.387
80-90				3.35	1.25	0.801	0.516	0.441
90-100				3.60	1.28	0.755	0.562	0.401
100-200					1.31	0.740	0.543	0.424
200-300					0.819	0.688	0.513	0.407
300-400						0.743	0.492	0.402
400-500						0.830	0.493	0.389
500-600	MULTIPLY TABLE VALUES BY 10^{-4}						0.533	0.389
600-700							0.561	0.403
700-800							0.250	0.407
800-900								0.427
900-1000								0.365
Average Number of Electrons/cm^3 per Photon/cm^2	0.0292	0.0306	0.0325	0.0338	0.0381	0.0406	0.418	0.0422

Table 5. Initial Compton electron-energy distribution in water (first-collision spectrum). Number of electrons/cm^3 · MeV per photon/cm^2

Electron Energy Interval (MeV)	Photon Energy (MeV)													
	4	5	6	7	8	9	10	12	14	16	18	20	22	25
0-1	116.	88.0	72.3	61.0	52.6	46.8	42.2	36.3	31.5	27.5	24.8	22.2	20.7	18.5
1-2	55.2	35.0	23.4	17.7	13.5	10.5	8.44	5.70	4.10	3.27	2.60	2.16	1.84	1.43
2-3	72.0	39.7	26.2	18.9	13.5	10.6	8.61	5.95	4.53	3.33	2.63	2.18	1.77	1.34
3-4	137	55.9	30.2	20.5	15.2	11.5	9.07	6.42	4.37	3.36	2.78	2.05	1.80	1.43
4-5		111	47.7	26.1	17.0	12.4	10.1	6.70	5.20	3.44	2.59	2.26	1.86	1.29
5-6			92.3	40.0	21.4	15.1	10.3	6.93	4.79	3.96	2.85	2.22	1.82	1.40
6-7				80.1	35.7	18.9	12.7	7.66	5.22	3.75	2.95	2.37	1.96	1.35
7-8					69.0	31.6	17.0	8.50	5.59	4.11	2.95	2.46	1.97	1.57
8-9						61.7	28.3	10.6	5.86	4.13	3.33	2.25	2.04	1.64
9-10							55.6	14.1	7.28	4.25	3.31	2.62	1.88	1.59
10-11								23.9	8.79	5.33	3.41	2.63	2.32	1.53
11-12								47.9	12.4	6.05	3.96	3.11	2.23	1.60
12-13									20.7	7.56	4.63	2.81	2.56	1.65
13-14									40.7	10.9	5.56	3.52	2.32	1.86
14-15										17.4	6.84	4.04	2.79	2.00
15-16										36.5	9.78	4.72	3.33	1.92
16-17											15.6	6.42	3.55	2.23
17-18											32.5	8.11	4.52	2.45
18-19												14.1	5.78	2.80
19-20												28.9	7.57	3.13
20-21	MULTIPLY TABLE VALUES BY 10^{-4}												13.3	4.09
21-22													26.3	4.88
22-23														6.76
23-24														11.8
24-25														23.2
Average Number of Electrons/cm^3 per Photon/cm^2	3.79	3.29	2.92	2.64	2.38	2.19	2.02	1.81	1.61	1.45	1.33	1.21	1.14	1.03
	MULTIPLY VALUES BY 10^{-2}													

Table 6. Initial Compton electron–energy distribution in water (first-collision spectrum). Number of electrons/cm^3 · MeV per photon/cm^2

Electron Energy Interval (MeV)	Photon Energy (MeV)							
	30	50	75	100	250	500	750	1000
0-1	1544.	1019.	719.	559.	264.	169.	101.	77.1
1-5	88.4	27.7	10.8	8.97	1.56	0.539	0.216	0.112
5-10	95.8	33.7	13.6	8.60	1.43	0.452	0.173	0.0988
10-20	119	36.9	15.6	8.66	1.45	0.430	0.173	0.0972
20-30	520	44.5	17.2	8.59	1.49	0.448	0.153	0.102
30-40		64.2	19.7	9.03	1.44	0.431	0.161	0.0741
40-50		312	22.2	10.2	1.48	0.398	0.189	0.0787
50-60			31.9	12.1	1.42	0.438	0.149	0.103
60-70			66.2	13.7	1.31	0.394	0.127	0.106
70-80			169	17.6	1.57	0.452	0.183	0.0833
80-90				30.5	1.54	0.398	0.163	0.0849
90-100				155	1.50	0.401	0.175	0.0710
100-200					2.25	0.443	0.161	0.0890
200-300					9.37	0.523	0.167	0.0912
300-400						0.804	0.185	0.0958
400-500						6.23	0.242	0.102
500-600	MULTIPLY TABLE VALUES BY 10^{-6}						0.325	0.119
600-700							0.663	0.149
700-800							3.11	0.191
800-900								0.302
900-1000								2.62
Average Number of Electrons/cm^3 per Photon/cm^2	8.76	5.88	4.25	3.29	1.57	1.01	0.602	0.462
	MULTIPLY VALUES BY 10^{-3}							

Table 7. Initial positron-energy distribution in water (first-collision spectrum). Number of positrons /cm^3 · MeV per photon/cm^2

Electron Energy Interval (MeV)	Photon Energy (MeV)													
	4	5	6	7	8	9	10	12	14	16	18	20	22	25
0-1	5.65	5.02	4.51	4.16	3.97	3.63	3.05	3.42	2.77	2.28	2.13	1.71	2.53	2.25
1-2	7.62	7.33	7.13	6.67	6.16	6.12	5.64	5.20	4.64	4.18	3.33	3.03	3.23	2.92
2-3	5.43	7.27	7.37	7.28	6.98	6.78	6.37	5.75	5.47	5.00	4.17	3.96	4.02	3.62
3-4		4.82	6.88	7.41	7.45	7.23	7.11	6.00	5.47	4.72	4.83	4.71	4.44	4.02
4-5			4.57	7.00	6.90	7.27	7.30	5.97	5.52	5.40	4.85	4.32	4.13	3.78
5-6				4.24	6.22	6.84	6.93	5.96	5.74	5.30	5.27	5.02	4.52	4.02
6-7					3.66	5.74	6.25	5.81	5.44	5.39	5.00	4.89	4.32	4.13
7-8						3.28	5.25	5.89	5.65	5.17	5.05	4.57	4.31	3.89
8-9							2.96	5.65	5.58	5.45	4.93	4.99	4.07	4.01
9-10								5.14	5.09	5.05	5.32	4.84	4.10	3.81
10-11								3.41	4.94	5.25	4.72	5.09	4.05	4.27
11-12									4.75	4.91	5.19	4.48	4.31	3.80
12-13									2.84	4.88	4.74	5.10	4.07	4.34
13-14										4.10	4.42	4.81	4.08	3.90
14-15										2.34	4.61	4.37	4.45	3.82
15-16											3.79	4.24	4.05	3.92
16-17											1.97	4.13	4.06	4.16
17-18												3.23	4.07	3.95
18-19												1.71	4.10	3.77
19-20													3.70	3.76
20-21	MULTIPLY TABLE VALUES BY 10^{-4}												2.38	3.92
21-22														3.71
22-23														3.28
23-24														2.08
24-25														
Average Number of Positrons/cm^3 per Photon/cm^2	1.87	2.44	3.05	3.65	4.13	4.69	5.09	5.82	6.39	6.94	7.43	7.92	8.30	8.87
	MULTIPLY VALUES BY 10^{-3}													

Table 8. Initial positron-energy distribution in water (first-collision spectrum). Number of positrons/cm^3 · MeV per photon/cm^2

Electron Energy Interval (MeV)	Photon Energy (MeV)							
	30	50	75	100	250	500	750	1000
0-1	1.88	1.60	1.21	1.03	0.817	0.394	0.244	0.184
1-5	3.15	2.24	1.46	1.07	0.701	0.317	0.183	0.124
5-10	3.57	2.54	1.80	1.34	0.739	0.332	0.180	0.146
10-20	3.59	2.41	1.95	1.51	0.741	0.373	0.206	0.122
20-30	2.83	2.36	1.81	1.52	0.767	0.393	0.244	0.146
30-40		2.50	1.82	1.53	0.774	0.373	0.254	0.175
40-50		2.08	1.86	1.51	0.702	0.417	0.244	0.169
50-60			1.92	1.50	0.716	0.414	0.265	0.193
60-70			1.85	1.53	0.674	0.410	0.291	0.196
70-80			0.492	1.53	0.695	0.425	0.268	0.180
80-90				1.53	0.629	0.365	0.281	0.209
90-100				0.972	0.627	0.380	0.284	0.215
100-200					0.646	0.365	0.269	0.209
200-300					0.362	0.341	0.254	0.203
300-400						0.370	0.246	0.199
400-500						0.385	0.245	0.195
500-600	MULTIPLY TABLE VALUES BY 10^{-4}						0.265	0.193
600-700							0.281	0.201
700-800							0.106	0.203
800-900								0.214
900-1000								0.167
Average Number of Positrons/cm^3 per Photon/cm^2	0.965	1.17	1.33	1.43	1.71	1.85	1.92	1.96
	MULTIPLY VALUES BY 10^{-2}							

Table 1 shows the initial electron energy each photon energy in Table 1 up to 180 keV, where the photoelectric effect becomes negligible, the highest-energy electron intervals are populated by the photoelectrons. The intermediate intervals, where zeroes appear, lie at electron energies above the kinematic maximum for Compton scattering. In all cases, the number of electrons was divided by the full width of the electron energy interval shown in the left-hand column of the Table. The lowest energy interval contains the Auger electrons, which are to be included in kerma (IC80).

Entries in the main body of Table 1 and the following tables are to be multiplied by the indicated factor. For example, for 40 keV photons the average number of electrons/cm^3/keV with energies between 0 and 5 keV is 47.1×10^{-3} per photon/cm^2. The number of electrons/cm^3 in this interval is $5 \times 47.1 \times 10^{-3} = 0.2355$ per photon/cm^2. This multiplicative factor does not apply to the average number of electrons/cm^3 per photon/cm^2 given in the bottom line of the tables—these entries are absolute in the units indicated, unless another multiplicative factor is shown. For example, at 40 keV an average of 0.298 electrons/cm^3 are produced per photon/cm^2. The average number of electrons/cm^3 produced per photon/cm^2 decreases to 0.124 at 220 keV, where photoelectric absorption is negligible. In this and the following tables 25,000 photon interactions were used to compile the electron spectra. The standard deviations (not shown) for the calculated values in Table 1 are ~3% at 200 keV and less at the lower energies.

Table 2 presents the single-collision electron spectra for photon energies from 300 to 3000 keV. Compton scattering predominates in this energy range, the threshold energy for pair production being 1022 keV. The standard deviations of the values in Table 2 vary from <5% at photon energies below 100 keV and at electron energies above 100 keV to 10–20% for electrons below 100 keV at the photon energy of 3000 keV. Table 3 gives the spectra for photon energies from 4 to 25 MeV, the standard deviations all being <4%. Table 4 covers photon energies from 30 to 1000 MeV. The standard deviations for this table are less than a few percent, except for electrons in the range 1–10 MeV for 500 MeV photons and 1–50 MeV for 1000 MeV photons. Standard deviations for these entries are ~5–8%.

In some applications it may be desirable to assess the separate contributions of Compton and pair electrons to the total spectrum of initial electron energies. Table 5 shows the spectra of initial energies of Compton electrons produced by photons with energies of 4–25 MeV. The standard deviations are <3% below 10 MeV and <8% everywhere. Table 6 extends the Compton electron spectra to photon energies of 1000 MeV; standard deviations here are <10%. The separate positron spectra are given in Tables 7 and 8. Standard deviations in both tables are ≲5% except for the positrons with initial energies below 100 MeV that are produced by 1000 MeV photons. The spectra of pair electrons are the same as the positron spectra, except for the addition of the relatively low-energy recoil electrons that occur from triplet production.

In conclusion, the spectra of initial energies of electrons and positrons have been presented for water irradiated by photons with energies from 10 keV to 1 GeV. By including the Auger electrons that are emitted following a K-shell vacancy in oxygen, all charged particles liberated initially by the action of the incident photons are represented. The spectra can thus be used directly to calculate kerma per incident photon/cm^2. In addition, the separate Compton-electron and positron spectra are presented for energies from 4 MeV to 1 GeV. No energy losses by secondary electrons are calculated here. Likewise, we have not considered the production of secondary photons from Compton scattering, bremsstrahlung, or electron–positron annihilation.

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