Development of a Monte Carlo Simulation to Study Linear Radiation Position Sensitive Detectors

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Abstract

This work describes a special Monte Carlo program proposed to study the extension of light generation in a bar of plastic scintillator used as a linear radiation position sensitive detector. The configuration uses two photomultipliers (or sensors) in both extremities of the scintillator detectors. This program is able to estimate the following parameters: (i) the distance length between the primary photon interaction and secondaries scatterings inside the detector. This parameter enables the research to know how many parts the detector can be divided virtually, making it capable of working as a multidetector system, (ii) the capability to absorb the incident energy (intrinsic efficiency) , (iii) the distribution of the different interactions (photoelectric, Compton, Rayleigh and pair productions) and finally (iv) the program can be useful as a guide to choose the optimized size of the detector.

1. INTRODUCTION

The mainly interactions of gamma and X-rays passing through matter, involve basically four interaction mechanisms: photoelectric effect, Rayleigh scattering (elastic interaction type), Compton scattering (inelastic interaction type) and pair production. In the photoelectric and Compton effects, the gamma (or X-rays) photon dissipates its energy by knocking out an electron from an atom. In the photoelectric effect, the gamma (or X) photon transfers its entire energy to the electron, on the other hand, in the Compton scattering, the photon transfers only part of its energy to the electron and survives with a lower energy and changes its original direction. In the pair production, the gamma (or X) photon is absorbed to create an electron-positron pair. For pair production occurs, the incident photon must have an energy equal to or greater than the rest mass of an electron-positron pair. This energy is 1.02 MeV, since the rest mass of each is 0.511 MeV. Finally, the Rayleigh scattering is a process by which photons are scattered by bound atomic electrons and in which the atom is neither ionized nor excited. This process occurs mostly at low energies and for high Z materials, practically in the same energy regions of occurrence of photoeletric and Compton effects. Although the photon in the Rayleigh scattering practically does not dissipate its energy, it should be considered in the detector design since the Rayleigh process is one of the most responsible factors for the photon scattering and consequently, it has an important role in the resolution of the tomography system [1,2,3].

The probability of each of these interaction mechanisms varies with the atomic number and the photon energy. The photoelectric and Rayleigh effects are more predominant at low photon energy and high atomic number. Compton scattering is predominant at energies around 1 MeV, especially for materials with a low atomic number. Pair production becomes dominant around 5 MeV for materials with a high atomic number (and at a somewhat higher energy for lighter elements) [1,4].

Scanners for transmission tomography employ radiation sources, such as an encapsulated gamma ray source, positioned on one side of the object to be scanned, and a set of collimated detectors arranged on the other side. Scanners of the second generation (parallel beam), an array of detectors, facing a single source, move around the object and provide a number of projections equal to the number of detectors. Generally, the objects analyzed in industrial tomography field have high density and large dimensions, such as the case of the diameters of the oil refining columns. Consequently, high energy radiation source is required in order to be capable to cross the material. A dense detector material or a large detector is necessary to absorb the photons from the source [5,6]. Commonly, detectors made with NaI(Tl) (3.8 g/cm3), CsI(Tl) (4.3 g/cm3) and BGO Bismuth-Germanium-Oxyde (Bi4Ge3O12, 7.13 g/cm3) are used in a multidetectors array. This system requires a complex hardware because each scintillator needs independent electronics, e.g., phototube, high voltage, preamplifier, amplifier and counter. On the other hand, for large objects several detectors are required to fit the object surface, making the system very expensive. An alternative is to use a unique bar of detector since it can be used as a position sensitive detector. Barouch and Marriete [3] developed a system using a CsI(Tl) bar.

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This kind of detector can be useful mainly in the case of industrial CT applications for large objects because it uses only two photomultiplier, thus requiring more simplified electronics, compared with those used in multiple detectors version. Besides, its cost is significantly cheaper.

Industrial computed tomography (CT) can be build using scintillator cylinder (or bar) as a detector sensitive to the radiation interaction position [7]. This system is designed with two photomultiplier-tubes set up in coincidence as shown in Fig. 1.

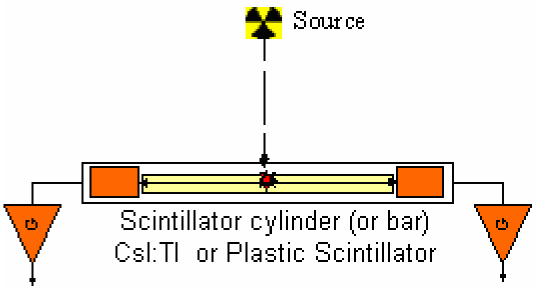


Fig. 1- A cylinder (or bar) of scintillator used as a detector sensitive to the radiation interaction position.

The Monte Carlo Method [8] can be used as a powerful tool to know some properties of this system, such as, the best scintillator dimension, the energy absorption capability, and the spatial resolution spread for each incident photon. In this work the Monte Carlo Method was specially developed to know these parameters.

In the Monte Carlo method is necessary to know in details the attenuation of electromagnetic radiation, e.g., gamma or X-rays passing through matter. Basically, these involve four mechanisms, already mentioned each accompanied by secondary processes.

2. METHODOLOGY

Main Monte Carlo Simulations Step

The program was developed in Visual Basic 6 capable to interactions with Windows Excel. The four types of gamma-ray scattering and absorption interactions described above lead to energy deposition in the linear detector. In order to obtain the energy loss spectra the following steps should be done:

1. Number of history (NH) ← 0 and Number of interaction (Ni) ← 0;
2. Define all variables linked with incident quantum including energy, initial coordinates (x, y, z) and direction cosines ($\cos\alpha`$, $\cos\beta`$, $\cos\gamma`$) for photon incidence on the lateral surface of the crystal;
3. Increase the number of histories NH ← NH+1;
4. Compute the mean free path of photons, l and the point (x’, y’, z’) of interaction. If point (x’, y’, z’) lies within the detector goes to step 5; otherwise, return to step 2;
5. Number of interaction Ni ← Ni + 1;
6. If Ni > number of desired histories then go to 12;
7. Select randomically the type of photon interaction: photoelectric or Compton or pair production or Rayleigh [9,10].
8. Define the energy imparted among the gamma radiation and/or electron, if it exists;
9. Compute the quantity of electron energy absorbed (E_{abs}) by the scintillator and spans and sums it in its correspondent energy channel;
10. Take all resulting gamma-ray information of step 8, return to step 7 and rebuilt its history until its total disappearance;
11. Return to step 2;
12. Compute the response function of detector by convoluting the energy loss spectrum with a Gaussian function that simulates the energy resolution effects;
13. Ends MC simulation.

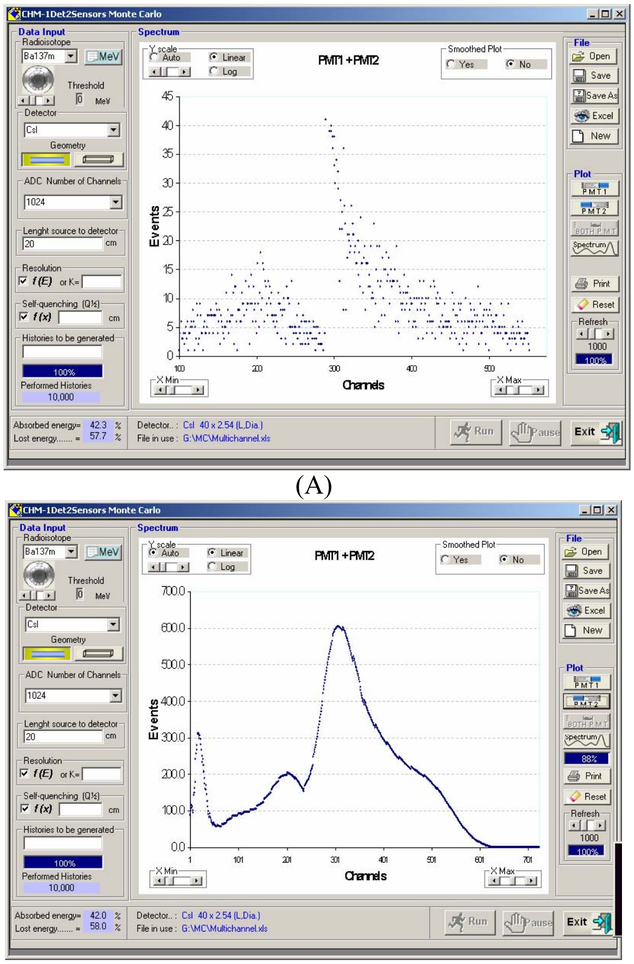
3. RESULTS AND DISCUSSION

Table 1 and Fig. 2 and 3 illustrate typical results for a device using the CsI(Tl) and plastic scintillator detectors assuming a ^{137}Cs source, 20 cm far from detector, considering an ADC with 1024 channel and ten thousand simulation histories.

Table 1 – Typical results for a ^{137}Cs source 20 cm far from a CsI(Tl) detector and Plastic scintillator cylinders of 40cm length and ∅=2.54cm.

Parameter	CsI(Tl)	Plastic Scintillattor
Absorved Energy	42.3%	9.9%
Rayleigh scattering	5.6%	0.6%
Photoelectric	39.0%	1.7%
Compton scattering	57.0%	24.9%
Pair-Production	0.0%	0.0%
Secondaries Scattering distance*	0.23cm [0 to 4.1]cm	0.25cm [0 to 6.9]cm

*Length from the first gamma interaction point (3 standard deviation)



(A)

Radioisotope: Ba137m
Threshold: 0 MeV
Detector: CsI
ADC Number of Channels: 1024
Lenght source to detector: 20 cm
Resolution: ☑ f(E)
Self-quenching (QⅠ½): ☑ f(x)
Performed Histories: 10,000
Absorbed energy= 42.3 %
Lost energy....... = 57.7 %
Detector.. : CsI 40 x 2.54 (L,Dia.)
File in use : G:\MC\Multichannel.xls

(B)

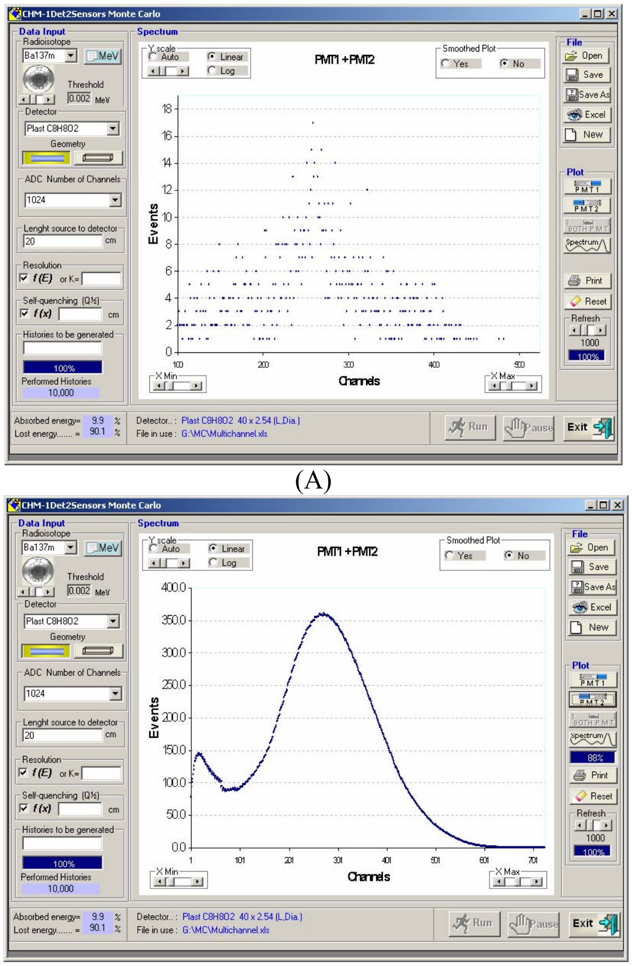
Radioisotope: Ba137m
Threshold: 0 MeV
Detector: CsI
ADC Number of Channels: 1024
Lenght source to detector: 20 cm
Resolution: ☑ f(E)
Self-quenching (QⅠ½): ☑ f(x)
Performed Histories: 10,000
Absorbed energy= 42.0 %
Lost energy....... = 58.0 %
Detector.. : CsI 40 x 2.54 (L,Dia.)
File in use : G:\MC\Multichannel.xls

Fig. 2 – (A) The interaction profile (channel vs no. of events) and (B) after convolution, for a ^{137}Cs source 20 cm far from a CsI:Tl cylinder of 40cm length and ∅=2.54cm.

Fig 4 shows a typical output in a data sheet of Microsoft Excel.

Fig 5 shows as the user can interact with the calculation using an easy file type RTF created with the Microsoft Word.

Concluding, the proposed program is useful as an auxiliary tool to optimize the detector material and its dimensions. Comparing the CsI(Tl) crystal and the plastic scintillator performances, the first is approximately four times more efficient to detect gamma photons from ^{137}Cs and presents better resolution, although both detectors shown similar secondaries scattering distance.



(A)

Radioisotope: Ba137m
Threshold: 0.002 MeV
Detector: Plast C8H8O2
ADC Number of Channels: 1024
Lenght source to detector: 20 cm
Resolution: ☑ f(E)
Self-quenching (QⅠ½): ☑ f(x)
Performed Histories: 10,000
Absorbed energy= 9.9 %
Lost energy....... = 90.1 %
Detector.. : Plast C8H8O2 40 x 2.54 (L,Dia.)
File in use : G:\MC\Multichannel.xls

(B)

Radioisotope: Ba137m
Threshold: 0.002 MeV
Detector: Plast C8H8O2
ADC Number of Channels: 1024
Lenght source to detector: 20 cm
Resolution: ☑ f(E)
Self-quenching (QⅠ½): ☑ f(x)
Performed Histories: 10,000
Absorbed energy= 9.9 %
Lost energy....... = 90.1 %
Detector.. : Plast C8H8O2 40 x 2.54 (L,Dia.)
File in use : G:\MC\Multichannel.xls

Fig. 3 – (A) The interaction profile (channel vs no.of events) and (B) after convolution, for a ^{137}Cs source 20 cm far from a Plastic scintillator cylinder of 40cm length and ∅=2.54cm.

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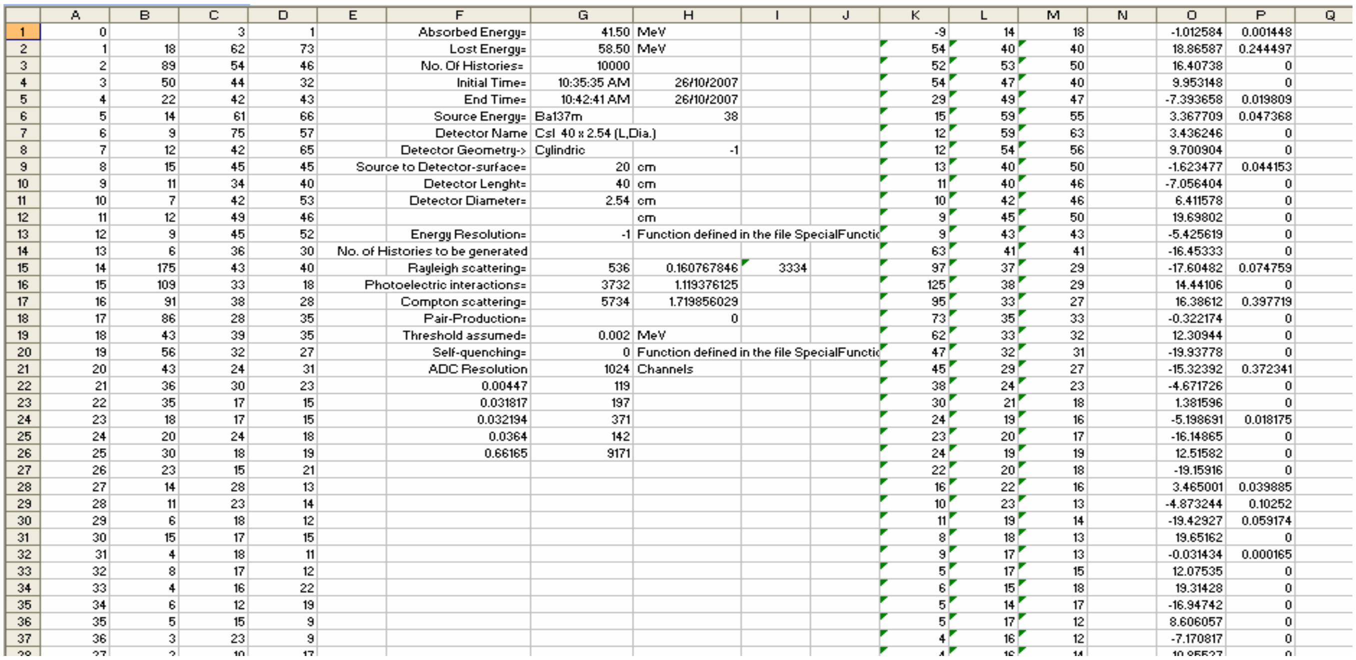

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	0		3	1		Absorbed Energy=	41.50	MeV			-9	14	18		-1.012584	0.001448	
2	1	18	62	73		Lost Energy=	58.50	MeV			54	40	40		18.86587	0.244497	
3	2	89	54	46		No. Of Histories=	10000				52	53	50		16.40738	0	
4	3	50	44	32		Initial Time=	10:35:35 AM	26/10/2007			54	47	40		9.953148	0	
5	4	22	42	43		End Time=	10:42:41 AM	26/10/2007			29	49	47		-7.393658	0.019809	
6	5	14	61	66		Source Energy=	Ba137m	38			15	59	55		3.367709	0.047368	
7	6	9	75	57		Detector Name	CsI 40 x 2.54 (L,Dia.)				12	59	63		3.436246	0	
8	7	12	42	65		Detector Geometry->	Cylindric	-1			12	54	56		9.700904	0	
9	8	15	45	45		Source to Detector-surface=	20	cm			13	40	50		-1.623477	0.044153	
10	9	11	34	40		Detector Lenght=	40	cm			11	40	46		-7.056404	0	
11	10	7	42	53		Detector Diameter=	2.54	cm			10	42	46		6.411578	0	
12	11	12	49	46				cm			9	45	50		19.69802	0	
13	12	9	45	52		Energy Resolution=	-1	Function defined in the file SpecialFunctic			9	43	43		-5.425619	0	
14	13	6	36	30		No. of Histories to be generated					63	41	41		-16.45333	0	
15	14	175	43	40		Rayleigh scattering=	536	0.160767846	3334		97	37	29		-17.60482	0.074759	
16	15	109	33	18		Photoelectric interactions=	3732	1.119376125			125	38	29		14.44106	0	
17	16	91	38	28		Compton scattering=	5734	1.719856029			95	33	27		16.38612	0.397719	
18	17	86	28	35		Pair-Production=		0			73	35	33		-0.322174	0	
19	18	43	39	35		Threshold assumed=	0.002	MeV			62	33	32		12.30944	0	
20	19	56	32	27		Self-quenching=	0	Function defined in the file SpecialFunctic			47	32	31		-19.93778	0	
21	20	43	24	31		ADC Resolution	1024	Channels			45	29	27		-15.32392	0.372341	
22	21	36	30	23		0.00447	119				38	24	23		-4.671726	0	
23	22	35	17	15		0.031817	197				30	21	18		1.381596	0	
24	23	18	17	15		0.032194	371				24	19	16		-5.198691	0.018175	
25	24	20	24	18		0.0364	142				23	20	17		-16.14865	0	
26	25	30	18	19		0.66165	9171				24	19	19		12.51582	0	
27	26	23	15	21							22	20	18		-19.15916	0	
28	27	14	28	13							16	22	16		3.465001	0.039885	
29	28	11	23	14							10	23	13		-4.873244	0.10252	
30	29	6	18	12							11	19	14		-19.42927	0.059174	
31	30	15	17	15							8	18	13		19.65162	0	
32	31	4	18	11							9	17	13		-0.031434	0.000165	
33	32	8	17	12							5	17	15		12.07535	0	
34	33	4	16	22							6	15	18		19.31428	0	
35	34	6	12	19							5	14	17		-16.94742	0	
36	35	5	15	9							5	17	12		8.606057	0	
37	36	3	23	9							4	16	12		-7.170817	0	

Fig. 4 – Projection of results in the Excel data sheet.

```
                'Attenuation Sinal in Function of Lenght
                                   'or
                         'Auto-Quenching Function

'You can use the space between Function SignalAttenuation(x) and End
Function
'below to write the signal attenuation in function of the distance X (in
'centimeters).

'You can use the space between Function Resolution(Energy) and
'End Function below to write the dependency of the resolution in
'function of the photon Energy (in MeV).

'You can use all the VBScript instructions in order to define the
'SignalAttenuation function.

'Please, substitute the example equations (exp(-x/19.32)) for your
appropriated
'self equation.

'Do not forget that SignalAttenuation=(your equation) or
'Resolution=(your 'equation) must be the last line of your function
'equation (just before End 'Function).

Function SignalAttenuation(x) 'x in centimeter

'SignalAttenuation=exp(-x/19.32)' For Plastic Scintillator
SignalAttenuation=exp(-x/15.78691)' For CsI(Tl) L=40 phi=2.54 cm bar

End Function


Function Resolution(Energy)  'Energy in MeV

Resolution = 0.138761/Sqr(Energy/0.511) ' For CsI(Tl)
'Resolution = 0.3128/Sqr(Energy/0.511) ' For Plastic Scintillator

End Function
```

Fig 5 – An example how the user can pass special informations to program. For this, the user edit their especial functions to Monte Carlo program in the file named “SpecialFunction.rtf”.