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Application of Penelope Code in The Investigation of The Major Types of Gamma Ray Interaction in Lead And Aluminum Slabs

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Abstract

PENELOPE as a Monte Carlo code has been applied by running its main program on the plat form of G77 FORTRAN compiler. Material slabs of lead and aluminum of the same thickness of 4.237cm and for an aluminum end-cap of detector housing, 0.127cm thick and photon sources of ^{60}Co (1332.502keV), ^{60}Co(1173.238keV), ^{137}Cs(661.66keV and ^{241}Am(59.537keV) have been used. The simulation of photons has revealed the cross section capabilities of the major gamma ray interaction mechanism with matter, namely, Rayleigh, Compton, photoelectric absorption and pair production cross sections. Simulated results reveal that pair production is possible only with photon sources which have threshold energy of 1.02MeV, in agreement with other works. Results show that both transmitted and backscattered particles are those that exhibit Rayleigh and Compton scattering. Most primary photons simulated by the high energy photon sources are transmitted through the aluminum end-cap. This is confirmed by the fractional transmission which is near unity. Thus the use of the Al (0.127cm) as a detector end-cap allows photon energies, which are not too small, to be transmitted. Due to the low scattering cross section of aluminum, the end-cap of a detector does not alter the photon count in an experiment, but provides a protective housing for the germanium crystal.

Keywords: PENELOPE, Monte Carlo, gamma ray or photon, lead slab, aluminum slab, HPGe pop top detector, FORTRAN G77, Rayleigh, Compton, photoelectric effect, pair production, transmitted backscattered, absorbed

1.0 Introduction

During an event of interaction a photon transfers some or all of its energy to a recoiling electron or atom or to an electron-positron pair. If it can be transferred to low energy electrons, then it will finally be dissipated as thermal energy in the material, but before that process is complete an event can occur that can have many branches. An incident energetic photon can create an electron-positron pair: each member of the pair can radiate photons which in turn can create further pairs or photoelectrons, which in their turn radiate photons. Thus the energy of one photon becomes the energy of many photons, electrons and positrons. Positrons can annihilate, moving or at rest, in an encounter with an electron, creating two or three photons. As the energy is spread among many particles, the photoelectric effect absorbs the photons, and low energy electrons lose energy which becomes thermal energy. The thickness in which the process is essentially complete is, for example, about 20 radiation lengths at 10GeV, increasing by 1 radiation length for every e-fold increase in energy [1].

Here we consider scattering models in the energy range: 100eV to 1GeV, where the dominant interaction processes are coherent (Rayleigh) scattering, incoherent (Compton) scattering, the photoelectric effect and electron-positron pair production. The effect of scattering models on results of Monte Carlo calculations is described by Reimer and Krefting [2]. Other gamma ray interactions such as photonuclear absorption occur with much smaller probability and can be disregarded for most practical purposes [3]. We further limit our consideration to the following energy range for the individual interactions of photons in both lead and aluminum slabs:

(i) Rayleigh scattering:- 100eV - 100keV
(ii) Photoelectric effect: - predominant in the energy range 100keV to 500keV
(iii) Compton effect: - important in the energy range ~ 100keV to 1.0MeV.
(iv) Pair-production: - possible only when energy is above 1.02MeV.

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In the foregoing theory we review the calculation of the analytical differential cross-sections for each of the major types of gamma ray interaction. Recommended values of fundamental physical constants can be obtained from Mohr and Taylor [4]. However, the scattering cross sections of most materials have been given in numerical form as data base in PENELOPE code [5].

THEORY: The major photon interaction mechanisms

(i) Coherent or Rayleigh scattering

Coherent or Rayleigh scattering is the process by which photons are scattered by bound atomic electrons without excitation of the target atom, that is, the energies of the incident and scattered photons are the same. The atomic differential cross section (DCS) per unit solid angle for coherent scattering is given approximately by [6]

$$\frac{d\sigma_{Ra}}{d\Omega} = \frac{d\sigma_T}{d\Omega}[F(q,Z)]^2 \tag{1a}$$

where

$$\frac{d\sigma_T}{d\Omega} = r_e^2\left(\frac{1+\cos^2\theta}{2}\right) \tag{1b}$$

is the classical Thompson DCS for scattering by a free electron at rest, θ is the polar scattering angle and $F(q, Z)$ is the atomic form factor. The quantity r_e is the classical electron radius and q is the magnitude of the momentum transfer given by

$$q = 2\left(\frac{E}{c}\right)\sin\left(\frac{\theta}{2}\right) = \left(\frac{E}{c}\right)[2(1-\cos\theta)]^{\frac{1}{2}} \tag{2}$$

and the form factor is given by

$$F(q,Z) = \begin{cases} f(x,Z) \equiv Z\dfrac{1+a_1x^2+a_2x^3+a_3x^4}{(1+a_4x^2+a_5x^4)^2}, \\ \max\{f(x,Z), F_K(q,Z)\} \quad if \;\; Z > 10 \; and \;\; f(x,Z) < 2, \end{cases} \tag{3a}$$

where $$x = 20.6074\frac{q}{m_e c} \tag{3b}$$

and $$F_K(q,Z) \equiv \frac{\sin(2b\arctan Q)}{bQ(1+Q^2)^b}, \tag{3c}$$

with $$Q = \frac{q}{2m_e ca}, \quad b = \sqrt{1-a^2}, \quad a \equiv \alpha\left(Z - \frac{5}{16}\right), \tag{3d}$$

where α is the fine structure constant. The function $F_K(q,Z)$ is the contribution to the atomic form factor due to the two K-shell electrons [7]. The parameters of expression $f(x,Z)$ for Z = 1 to 92 have been determined by numerically fitting the atomic form factors [15]. The total coherent scattering cross-section per atom is

$$\sigma_{Ra} = \int \frac{d\sigma_{Ra}}{d\Omega}d\Omega = \pi r_e^2 \int_{-1}^{1}(1+\cos^2\theta)[F(q,Z)]^2 d(\cos\theta) \tag{4}$$

With this integral evaluated, it can be seen that the total cross-section has an asymptotic behaviour for small and large photon energies. For low photon energies, the form factor does not depart appreciably from the value $F(0,Z) = Z$, that is, coherent scattering reduces to pure Thompson scattering. Thus we have

$$\sigma_{Ra} \approx \frac{8}{3}\pi r_e^2 Z^2 \tag{5}$$

For high energy values (energies of the order of $Z/2$MeV),

$$\sigma_{Ra} \propto E^{-2} \tag{6}$$

(i) Photoelectric effect

In the photoelectric effect, a photon of energy E is absorbed by the target atom, which makes a transition to an excited state. With photons of above 100keV, the atomic binding of the electrons makes the photoelectric effect strongly dependent on the atomic number; in addition, it is the ejection of an electron from the K-shell which gives the largest part of the total atomic cross-section. For each K-shell electron the contribution to the cross-section is given by [8]

$$\sigma_{PE} \approx Z^5 b^4 (\frac{m_e c^2}{E})^n \tag{7}$$

where the subscript PE means photoelectric effect; E is the photon energy; Z is the atomic number of target element; e is the charge of the electron; b is a dimensionless quantity given by,

$$b = \frac{\alpha}{4\pi\varepsilon}, \text{ where } \alpha = \frac{e^2}{_o\hbar c} \tag{8}$$

α is the fine structure constant. The value of n is $\frac{7}{2}$ at $E < m_e c^2$ and changes to 1 at $E << m_e c^2$.
The DCS (per electron) [9] is given by

$$\frac{d\sigma_{PE}}{d\Omega_e} = \alpha^4 r_e^2 (\frac{Z}{K})^5 \frac{\beta^3}{\gamma} \frac{\sin^2\theta_e}{(1-\beta\cos\theta_e)^4}[1+\frac{1}{2}\gamma(\gamma-1)(\gamma-2)(1-\beta\cos\theta_e)] \tag{9a}$$

where r_e is the classical electron radius,

$$\gamma = 1 + \frac{E_e}{m_e c^2}, \quad \beta = \frac{\{E_e(E_e + 2m_e c^2)\}^{\frac{1}{2}}}{E_e + m_e c^2} \tag{9b}$$

The direction of emission of the photoelectron, relative to that of the absorbed photon, is defined by the polar and azimuthal angles θ_e and φ_e. The Sauter DCS, equation (9a), is applicable in most practical simulations, not only for ionization of the K-shell by high energy photons, but also for any photo-ionization event, irrespective of the atomic shell and the photon energy. The main reason being that the emitted photo-electron immediately starts to interact with the medium and its direction of movement is strongly altered after traveling a path length much shorter than the photon mean free path.

The photoelectric cross-section used in PENELOPE for this work are obtained by interpolation in a numerical table that was extracted from the Evaluated Photon Data Library (EPDL), [10]. This library contains photoelectric cross-sections for all shells of the elements, Z = 1 – 100 and photon energies from 1eV to 1000GeV, derived from Scofield's theoretical calculations of shell cross-sections [11] and Hubbell's total cross-sections [3, 12]. The PENELOPE database for photoelectric absorption consists of tables of the total atomic cross-section $\sigma_{PE}(E)$ and the cross-sections for the K- and L-shells, $\sigma_{PE,i}(E)$ (I = K, L1, L2 and L3) for the elements Z = 1 – 92, which span the energy range from 100eV to 1000GeV.

(ii) Compton cross-section

An incident photon of energy E is scattered by an electron. The scattered photon is emitted at angle of θ and an energy of E', and the electron recoils at an angle of θ_e. It can be shown that the scattering mechanism leads to the following expression for the differential collision cross-section in the case of plane-polarized incident radiation [13]:

$$\frac{d\sigma_c}{d\Omega} = \frac{r_e^2}{2}(\frac{E'}{E})^2(\frac{E}{E'} + \frac{E'}{E} - 2\sin^2\theta\cos^2\eta) \tag{10}$$

where r_e is the classical electron radius; σ_c is the Compton collision cross-section; η is the angle between plane of incident polarization and scattering plane.

The differential collision cross-section for un-polarized incident radiation can be shown, from equation (10), to be

$$\frac{d\sigma_c}{d\Omega} = \frac{r_e^2}{2}(\frac{E'}{E})^2(\frac{E}{E'} + \frac{E'}{E} - \sin^2\theta) \tag{11}$$

where $d\Omega = 2\pi\sin\theta d\theta$.

The total collision cross-section is the summation of the probabilities of all possible collisions between the incident photon and each free electron. This represents the integrated probability per electron that some scattering event will occur. Hence it is clearer to speak of this integral as the average collision cross-section which is the same for polarized or un-polarized incident photons.

By integrating equation (11) over all possible values of θ, where the substitution of the energy of the scattered photon,

$$\frac{E'}{E} = \frac{1}{1+\kappa(1-\cos\theta)} \quad \text{and} \quad d\Omega = 2\pi \sin\theta d\theta \tag{12}$$

are made, we obtain

$$\sigma_c = \int_0^{\pi} d\sigma_c = 2\pi r_e^2 \{(\frac{1+\kappa}{\kappa^2})[\frac{2(1+\kappa)}{1+2\kappa} - \frac{1}{\kappa} In(1+2\kappa)] + \frac{1}{2\kappa} In(1+2\kappa) - \frac{1+3\kappa}{(1+2\kappa)^2}\} \tag{13}$$

per square centimetere per electron, where $\kappa = \frac{E}{m_e c^2}$. PENELOPE has incorporated this cross section as data base.

(iii) Pair production cross-section

When a photon of energy equal to or greater than 1.02MeV strikes a material of high atomic number, the photon is completely absorbed and a pair of electron and positron is produced. The pair production involves a momentum transfer to the nucleus. This momentum transfer decreases as the incident energy becomes greater and the electron mass becomes less significant. As the momentum transfer decreases the electric field needed to take up momentum decreases and the photon-nucleus impact parameter increases resulting to an increasing cross-section. This increase would continue indefinitely but for the screening effect of the atomic electrons. A full development of the pair production cross-section, σ_{pp}, requires an understanding of the atomic effects. The σ_{pp} starts from zero at the threshold value of the photon energy, $W = 2m_ec^2$ *(=1.02MeV),* rises and then reaches a plateau by an amount 1000MeV. This plateau depends on the material and is only for $E_\gamma >> m_e c^2$ [8],

$$\sigma_{pp} = \frac{28}{9} \frac{Z^2 \alpha^3 (\hbar c)^2}{(m_e c^2)^2} \left[In(\frac{183}{Z^{\frac{1}{3}}}) - \frac{2}{7} \right] \tag{14}$$

MATERIALS AND METHODOLOGY

The input data sources for the PENELOPE main program are as listed below, where the initial energies are those of ^{60}Co (1332.502keV), ^{60}Co(1173.238keV), ^{137}Cs(661.66keV and ^{241}Am(59.537keV), which are kept the Centre for Energy Research and Training, ABU, Zaria. Materials are lead and aluminum slabs of thickness 4.237 cm, also obtained in Physics Laboratory, ABU, Zaria. The G77 as a FORTRAN 77 compiler has been used as the plat form for running the PENELOPE main program.

TITLE	Lead	[Aluminum, Lead]
KPAR	2	[Primary particles: 1 = electron, 2 = photon, 3 = positron]
E0	1332.502E3	[1173.238E3, 661.660E3, 59.537E3, Initial energy in eV]
Z0	-1.0	[Z - coordinate of the source in cm]
POLAR 0.0 0.0	[Polar angle interval limits, in deg]	
SIMPAR	1.0E4 1.0E4 1.0E4 0.10 0.10 1.0E3 -1.0E3 [EABSs, C1, C2, W_{CC}, W_{CR}]	
PFNAME	Lead.mat	[al.mat, lead.mat, air.mat material file name]
THICKN	4.237	[Slab thickness in cm]
DSMAX	0.004	[Maximum allowed step length in cm]
NSIMSH	2147483647	[Desired number of showers, max = 2147483647]
TIME	300	[Allocated simulation time, in sec.]
SEED	12345 54321	[Random seeds]

Discussion of Results

The mean number of events per primary track for the major types of gamma ray interaction with matter for lead and aluminum slabs of the same thickness, 4.237cm and for an aluminum end-cap of detector housing, 0.127cm thick are presented in Tables 1 to 3.

Lead slab: It can be seen from Table 1 that both transmitted and backscattered particles are those particles that experience coherent or Rayleigh scattering and Compton scattering, except in the case of low energy gamma rays of ^{241}Am where zero transmission has been registered. Since it requires 1.02MeV to produce a pair, the initial photon energies are too small to produce more electron-positron pairs. From the table it is clear that lead has high scattering cross section for photoelectric absorption while the threshold photon energies are not satisfied for pair production and low cross section for Rayleigh and Compton scattering. Hence no event is transmitted or backscattered but all simulated events are absorbed for all the energy sources. The threshold energy for pair production is not satisfied for cesium and americium. This is in agreement with theory; [8, 14].

Aluminum slab: Table 2 presents results obtained for the aluminum slab which shows the same relationship with Table 1 for the lead slab except that transmission has been registered for Rayleigh and Compton scattering by the ^{241}Am in aluminum slab. This confirms the lower scattering cross section of aluminum as compared to lead.

Aluminum end-cap (0.127cm): Table 3 indicates the mean number of events for the major types of gamma ray interaction with matter simulated using the Al end-cap of the HPGe Pop Top detector housing. The number of events simulated is generally very low for Rayleigh and low for Compton, for all the energy sources, while zero or few events are registered for photoelectric effect (PE) and pair production (PP). The few events that are simulated are absorbed. The end-cap therefore does not alter the count rate of the detector appreciably.

Table 1: Mean number of events per primary track for the major types of gamma ray interaction with matter for lead slab for a thickness of 4.237cm.

Photon interaction type	^{60}Co (1332.502keV)	^{60}Co (1173238keV)	^{137}Cs (661.66keV)	^{241}Am (59.537keV)
Transmitted				
Rayleigh	8.230453E-02 ± 5.3E-02	1.179775E-01 ± 8.0E-02	3.333333E-01 ± 3.7E-01	0
Compton	7.901235E-01 ± 1.7E-01	6.573034-01 ± 1.8E-01	5.238095E-01 ± 5.2E-01	0
Photoelectric Absorption	0	0	0	0
Pair production	0	0	0	0
Backscattered				
Rayleigh	8.000000E-02 ± 1.6E-01	6.250000E-02 ± 1.8E-01	8.333333E-02 ± 1.4E-01	7.105263E-01 ± 2.0E-01
Compton	1.160000E+00 ± 2.2E-01	1.187500E+00 ± 2.9E-01	1.194444E+00 ± 2.8E-01	4.473684E-01 ± 1.7E-01
Photoelectric Absorption	0	0	0	0
Pair production	0	0	0	0
Absorbed				
Rayleigh	9.139785E-02 ± 2.6E-02	8.698630E-02 ± 2.4E-02	1.012931E-01 ± 2.2E-02	1.022771E-01 ± 8.2E-03
Compton	1.357911E+00 ± 8.9E-02	1.233562E+00 ± 8.1E-02	7.896552E-01 ± 5.4E-02	1.921335E-02 ± 3.4E-03
Photoelectric Absorption	9.838710E-01 ± 1.0E-02	9.958904E-01 ± 5.0E-03	1.000000E+00 ± 2.3E-10	1.000000E+00 ± 2.0E-10
Pair production	1.612903E-021.0E-02	4.109589E-03 ± 5.0E-03	0	0

Table 2: Mean number of events per primary track for the major types of gamma ray interaction with matter for aluminum slab for a thickness of 4.237cm.

Photon interaction type	^{60}Co (1332.502keV)	^{60}Co (1173238keV)	^{137}Cs (661.66keV)	^{241}Am (59.537keV)
Transmitted:				
Rayleigh	8.870806E-3 ± 2.4E-03	1.121187E-02 ± 3.3E-03	1.641193E-02 ± 3.2E-03	3.763300E-01 ± 2.4E-02
Compton	6.296939E-01 ± 3.0E-02	6.939819E-01 ± 3.5E-02	8.754723E-01 ± 3.2E-02	6.179407E-01 ± 3.6E-02
Photoelectric absorption	0	0	0	0
Pair production	0	0	0	0
Backscattered:				
Rayleigh	5.889831E-02 ± 1.6E-02	5.638903E-02 ± 1.7E-02	7.231504E-02 ± 1.3E-02	2.214351E-01 ± 1.8E-02
Compton	2.705085E+00 ± 1.2E-01	2.657527E+00 ± 1.2E-01	2.649881E+00 ± 8.5E-02	1.385937E+00 ± 2.6E-02
Photoelectric absorption	0	0	0	0
Pair production	0	0	0	0
Absorbed:				
Rayleigh	2.886435E-01 ± 7.3E-02	2.739212E-01 ± 7.3E-02	2.738854E-01 ± 4.7E-02	2.371801E-01 ± 6.9E-03
Compton	6.157729E+00 ± 3.3E-01	6.041276E+00 ± 3.4E-01	5.727530E+00 ± 2.1E-01	9.498486E-01 ± 1.5E-02
Photoelectric absorption	9.889590E-01 ± 1.2E-02	9.962477E-01 ± 7.9E-03	0	0
Pair production	1.104101E-02 ± 1.2E-02	3.752345E-03 ± 7.9E-03	0	0

Table 3: Mean number of events per primary track for the major types of gamma ray interaction with matter for aluminum slab of a HPGe PopTop detector end cap absorbing layer of 0.127cm thick.

Photon interaction type	^{60}Co (1332.502keV)	^{60}Co (1173238keV)	^{137}Cs (661.66keV)	^{241}Am (59.537keV)
Transmitted				
Rayleigh	3.118902E-05 ± 5.8E-06	4.23636E-05 ± 5.8E-06	1.248592E-04 ± 9.9E-06	1.147906E-02 ± 8.6E-05
Compton	1.396018E-02 ± 1.3-04	1.47769E-02 ± 1.1E-04	1.86089E-02 ± 1.3E-04	2.770941E-02 ± 1.4E-04
Photoelectric Absorption	0	0	0	0
Pair production	0	0	0	0
Backscattered				
Rayleigh	1.899953E-03 ± 6.7E-04	1.27564E-03 ± 4.5E-04	1.58096E-03 ± 4.1E-04	4.800733E-02 ± 1.2E-03
Compton	1.098303E+00 ± 5.0E-03	1.09239E+0 ± 4.0E-03	1.09550E+0 ± 3.3E-03	1.062622E+0 ± 1.7E-03
Photoelectric Absorption	0	0	0	0
Pair production	0	0	0	0
Absorbed				
Rayleigh	0	0	2.69542E-03 ± 8.1E-03	1.183905E-02 ± 4.5E-04
Compton	2.196078E-01 ± 1.1E-01	4.33526E-01 ± 1.7E-01	4.5822E-01 ± 1.2E-01	1.17043E-01 ± 1.5E-03
Photoelectric Absorption	2.941176E-01 ± 8.6E-02	6.82081E-01 ± 1.1E-01	0	1.0 ± 2.7E-11
Pair production	7.058824E-01 ± 8.6E-02	3.17919E-01 ± 1.1E-01	0	0

CONCLUSION

PENELOPE code has been applied by running its main program on the plat form of G77 FORTRAN compiler. Material slabs of lead and aluminum of the same thickness of 4.237cm and for an aluminum end-cap of detector housing, 0.127cm thick and photon sources of ^{60}Co (1332.502keV), ^{60}Co(1173.238keV), ^{137}Cs(661.66keV and ^{241}Am(59.537keV) have been used. Results revealed the cross section capabilities of the major gamma ray interaction mechanisms with matter, namely, Rayleigh, Compton, photoelectric absorption and pair production cross sections. The mean number of events per primary track for the major types of photon interaction with matter shows that both transmitted and backscattered particles are those that exhibit Rayleigh and Compton scattering. The threshold energy for pair production is not satisfied for cesium and americium. The Monte Carlo simulated results reveal that pair production is possible only with photon sources which have threshold energy of 1.02MeV, in agreement with theory [1] and the works of Hubbell and others [3]. Results also show that both transmitted and backscattered particles are those that exhibit Rayleigh and Compton scattering.

Results of the aluminum end-cap show that most primary photons simulated by the high energy photon sources are transmitted. This is confirmed by the fractional transmission which is near unity. Thus the use of the Al (0.127cm) as a detector end-cap allows photon energies, which are not too small, to be transmitted without being appreciably backscattered or absorbed so as to be registered by the detector. To the low scattering cross section of aluminum, the end-cap thickness of (0.127cm) a Pop Top detector does not alter the photon count in an experiment. Due to the low scattering cross section of aluminum, the end-cap thickness of (0.127cm) a Pop Top detector does not alter the photon count in an experiment, but provides a protective housing for the germanium crystal.

References

[1] Salvat, F.; Fernandez-Varea, J. M.; Acosta, E. and Sempau, J. (2001). PENELOPE – A code system for Monte Carlo simulation of electron and photon transport. *Nuclear Energy Agency, NEA, OECD, France.*

[2] Reimer, L. and Krefting, E. R. (1976), The effect of scattering models on the results of Monte Carlo calculations, *National Bureau of Standards Special Publication 460 (US Government Printing Office, Washington DC)* pp. 45 – 60.

[3] Hubbell J. H.; Gimm H. A. and Overbo I. (1980), Pair, triplet, and total atomic cross sections (and mass attenuation coefficients) for 1MeV – 100GeV photons in elements Z = 1 to 100, *J. Phys. Chem. Ref. Data* 9, 1023 – 1147.

[4] Mohr P. J. and Taylor B. N. (2000), CODATA recommended values of the fundamental physical constants 1998, *Rev. Mod. Phys*. 72, 351 – 495.

[5] Salvat, F.; Fernandez-Varea, J. M.; Acosta, E. and Sempau, J. (2003). PENELOPE (version 2003) – Subroutine package for Monte Carlo simulation of coupled electron-photon transport in homogeneous media. *Universitat de Barcelona.*

[6] Born M. (1969), Atomic Physics, *Blackie and Son, London*, pp.80 – 87.

[7] Baro J.; Roteta M.; Fernandez-Varea J. M. and Salvat F. (1994), Analytical cross-sections for Monte Carlo simulation of photon transport, *Radiat. Phys. Chem. 44, 531-552.*

[8] Williams, W. S. C. (1991), Nuclear and Particle physics, *Clarendon Press, Oxford,* Chaps. 9 and 11, p.252.

[9] Sauter, F. (1931), Uber den atomaren Photoeffekt in der K-Schale nach der relativistischen Wellenmechanik Diracs, *Ann. Phys. 11*, 454-488.

[10] Cullen D. E.; Hubbell J. H. and Kissel L. (1997), EPDL97 The evaluated data Library, 1997 version, *Report UCRL-50400 vol. 6, rev. 5 (Lawrence Livermore National Laboratory, Livermore, CA).*

[11] Saloman E. B.; Hubbell J. H. and Scofield J. H. (1988), X-ray attenuation cross sections for energies 100 eV to 100 keV and elements Z = 1 to Z = 92*, At. Data Nucl. Data Tables 38,* 1 – 197.

[12] Berger M. J. and Hubbell J. H. (1987), XCOM: Photon Cross Sections on a Personal Computer, Report NBSIR 87 – 3597 *National Bureau of Standards, Gaithersburg, MD0.*

[13] Nelms A. T. (1953). Graphs of the Compton Energy-Angle Relationship and the Klein-Nishina Formula from 10 keV to 500 MeV, *Natl. Bur. Standards (U.S.) Cir.* 542, Chap. 23, sec.2.

[14] Evans, R. D. (1955). The Atomic Nucleus. *Mcgraw-Hill Book Company, Inc., New York.* Pp. 712-717

[15] Hubbell J. H., Veigele Wm. J., Briggs E. A., Brown R. T., Cromer D. T., and Howerton R. J. (1975). Atomic form factors, incoherent scattering functions and photon scattering cross sections. J. Phys. Chem. Ref. Data Vol., 471 – 538; Erratum: ibid, Vol. 6 (1977) 615 – 616.