CHAPTER 2

INTERACTION OF RADIATION WITH MATTER

2.1 Introduction

When gamma radiation interacts with material, some of the radiation will be absorbed by the material. There are five mechanisms involve in the interaction namely coherent scattering, incoherent scattering or Compton scattering, photoelectric absorption, pair production and photodisintegration. The interaction that occurs depends on the energy of the source used. Overall effect of these processes is described by the total attenuation coefficient μ .

The measurement of attenuation coefficient, μ is involved in many different applications. An example is the measurement of attenuation coefficients for building material. Medhat [7] has measured the gamma ray attenuation coefficients for some building materials in Egypt. Akkurt [8] meanwhile measured the photon attenuation coefficients for materials such as barite and concrete barite using Caesium-197 and Cobalt-60 gamma sources. Another work was done on the measurement of gamma ray attenuation coefficient in bismuth borate glasses that is used in shielding materials [9]. Singh et al [10] studied the mass attenuation coefficient of some compounds in the photon energy range of $10^{-2} – 10^{5}$ MeV.

In this chapter, we will describe briefly the interactions of each mechanism. However, focus will be on the Compton scattering because Compton process is dominant at energy range between 200 keV to 2 MeV which coincides with the energy spectrum from Iridium-192. In calculating the Compton scattering, one has to know the cross section. The cross section is sometimes called as the atomic absorption coefficient which is the

microscopic cross section [11]. Thus, this chapter will give a review on the calculation of cross section for Compton scattering.

2.2 Types of Radioisotopes

There are various radioisotopes that produce gamma radiations. However, the radioisotopes that are used in the industrial radiography applications namely are Iridium-192, Cobalt-60, Caesium-137 and Selenium-75. These radioisotopes have more than one spectrum lines and they are polychromatic radiation sources unlike X-ray that produces only single energy and it is called as monochromatic radiation. Hence, the calculation for attenuation coefficients will depend on more than one energy.

Iridium-192 is one of the commonly used gamma sources in the industrial radiography. Iridium-192 has a complex spectrum lines. According to Halmshaw [12], the energy range is from 0.13 MeV to 0.89 MeV. The spectrum can be considered as consisting of three major groups of energies which are 0.31 MeV, 0.47 MeV and 0.61 MeV. According to Rockley [13], the main energies for Iridium-192 are 0.61 MeV, 0.6 MeV, 0.59 MeV, 0.48 MeV, 0.46 MeV, 0,32 MeV, 0.31 MeV and 0.29 MeV. In this work, the range of energies proposed by Rockley are used to calculate the attenuation coefficient for Iridium-192. The energy and the relative intensity are shown in Table 2.1.

Table 2.1 Iridium-192 gamma radiation spectrum with its relative intensity [12].

Energy (MeV)	Relative Intensity
0.13	0.4
0.28	1.0
0.296	38.0
0.31	37.0
0.32	100.0
0.47	30.0
0.485	1.1
0.59	1.1
0.61	1.9
0.89	0.4

The decay of Iridium-192 produces two modes; continuous β decay spectrum with branching ratio 95% and electron capture with branching ratio 5%. The γ intensity from γ decay scheme is shown in Table 2.2. In Table 2.2, the attenuation coefficients of every energy in the Iridium-192 spectrum is calculated using XCOM [14]. The calculation of attenuation coefficients is based on the composition of the sample in the experiments that will be done (refer to Chapter 4). Figure 2.1 shows the intensity spectrum from the beta decay of Iridium-192 [15].

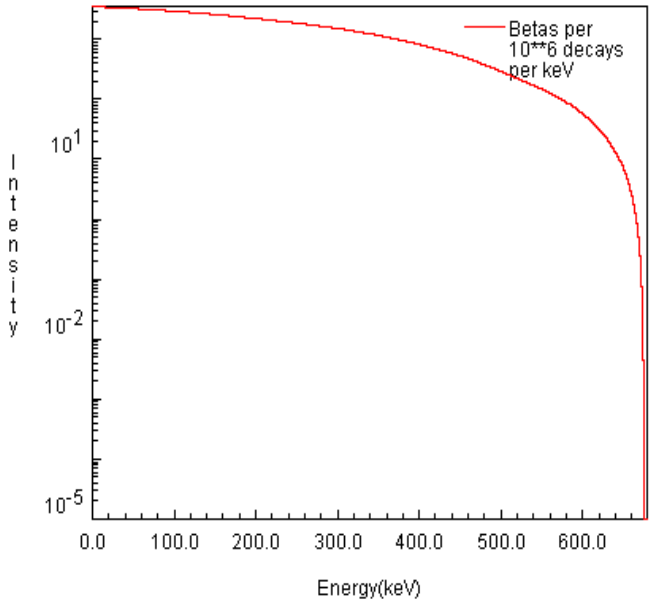

Figure 2.1 The intensity of beta decay of Iridium-192. Taken from [15].

According to Halmshaw [12], to reach stability, Iridium-192 will decay via beta emission to Platinum-192 and proceed to the second decay process by electron capture to Osmium-192. Both products Platinum-192 and Osmium-192 are stable elements. The decay scheme is shown in Figure 2.2.

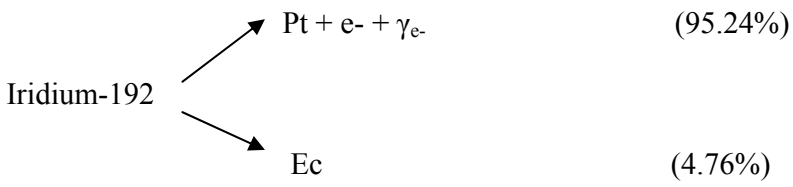

Figure 2.2 Iridium-192 decay scheme.

Table 2.2 Gamma decay of Iridium-192 where I_g is the intensity.

Energy (keV)	I_g (%) [15]	μ for iron (cm^2/g) [14]
110.093	0.0126	0.2794
136.34348	0.183	0.2011
176.98	0.0043	0.1505
201.3112	0.472	0.1350
205.79549	3.300	0.1328
214.7	<0.0026	0.1287
280.04	0.023	0.1091
283.2668	0.262	0.1084
295.95827	28.67	0.1059
308.45692	30.00	0.1036
314.8	<0.07	0.1026
316.50791	82.81	0.1023
329.312	0.0185	0.1003
374.4852	0.721	0.09419
415.4	<0.009	0.08973
416.4714	0.6647	0.08962
420.532	0.0737	0.08922
468.07152	47.83	0.08494
484.5780	3.184	0.08360
485.30	0.0022	0.08355
489.039	0.443	0.08326
588.5845	4.515	0.07651
593.37	0.0426	0.07622
599.35	0.0039	0.07558
604.41464	8.23	0.07512
612.46564	5.309	0.07043
703.98	0.0053	0.07043
739	<0.00050	0.06885
765.8	0.00149	0.06770
884.5418	0.00124	0.06321
1061.48	0.2923	0.05777
1089.7	0.0528	0.05701
1378.3	0.00108	0.05070

Cobalt-60 also has more than one energy but is not as complicated as Iridum-192. Cobalt-60 has two gamma photons; 1.17 MeV and 1.33 MeV. Cobalt-60 is usually used in inspection for larger thickness such as more than 100mm with shorter exposure time.

Caesium-137 is sometimes used for the NDT inspection. It is normally used for inspection of steel thicknesses between 40-100mm. However, this radioisotope only emits gamma ray with energy 0.662 MeV.

Another radioisotope that emits gamma radiation which is commonly used is Selenium-75. Selenium-75 is used to inspect discontinuity or defects for material with lower density as compared to steel such as aluminium, copper etc. This is because Selenium-75 has low energy gamma line spectrum. Selenium-75 has several energy lines in the spectrum. They are 0.08 MeV, 0.14 MeV, 0.27 MeV and 0.4 MeV [12].

2.3 Attenuation Processes

In industrial radiography, there are five mechanisms operative when γ-rays interact with material [16]. The five mechanisms involved are:

(a) Rayleigh scattering (coherent scattering)

(b) Compton scattering (incoherent scattering)

(c) Photoelectric absorption

(d) Pair production

(e) Photodisintegration

When these mechanisms occur in a material, the initial photon radiation I_0 emitted from the ionizing radiation source will be attenuated. Hence, the photon radiation received by the detector, I, placed on the other side of the material will be much lesser from the initial photon intensity. This observation is described by the Beer Lambert's attenuation law:

$$I = I_0 \, e^{-\mu t} \tag{2.1}$$

where μ is the (total) attenuation coefficient and t is the thickness of the material. It is worth noting that the relative probability of each type of interaction is proportional to the cross section for that process. The probability of the interaction is then proportional to the sum of the cross section. This issue will be discussed in Chapter 3. Hence, the total attenuation coefficient is the sum of the five interactions [17]:

$$\mu = \mu_{coh} + \mu_{incoh} + \mu_{photo} + \mu_{pair} + \mu_{dis} \tag{2.2}$$

where μ_{coh} is the attenuation coefficient from coherent scattering, μ_{incoh} the attenuation coefficient from incoherent scattering, μ_{photo} the attenuation coefficient from photoelectric absorption, μ_{pair} the attenuation coefficient from pair production and lastly, μ_{dis} the photodisintegration attenuation coefficient. Table 2.3 shows an example of the processes in the absorption of radiation that are dominant in soft tissue [17].

Table 2.3 The dominant attenuation process in soft tissue [17].

Photon Energy	Process
Up to 50 keV	Photoelectric absorption is important
60 keV to 90 keV	Photoelectric and Compton are equally important
200 keV to 2 MeV	Compton absorption is present
5 MeV to 10 MeV	Pair production begins to be important
50 MeV to 100 MeV	Pair production is the most important type of absorption

Another example is the attenuation process in iron as depicted in Figure 2.3 [18].

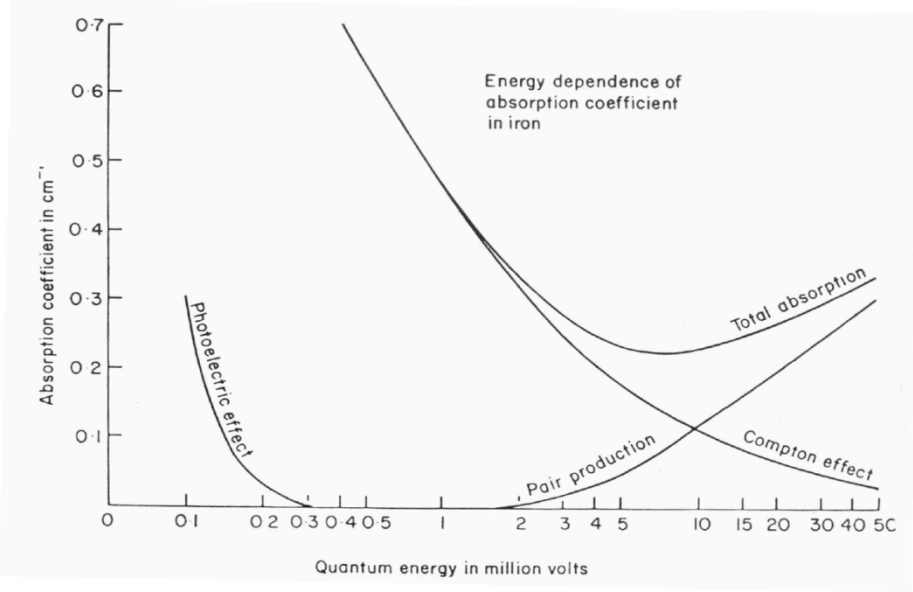

Figure 2.3 Attenuation in iron [18].

Generally, the attenuation mechanisms fall into two main categories; scattering or absorption [16]. However, the attenuation process taking place in a sample is in fact, a combination of both categories with one or two dominating mechanisms. To determine which process dominate will depend on the photon energy. There are two types of scattering; coherent and incoherent scatterings. Coherent scattering has well-defined relationship between the phase of the incident wave and the phase of the outgoing wave [3]. In scattering process, there are parameters involving direction, phase and intensity. For coherent scattering, there is no change in the direction between the incident wave and the outgoing wave, the phase between the incoming wave and the outgoing wave and the intensity before interaction and after interaction. For coherent scattering, the wave is directional, there is no phase difference and no intensity change. An example of coherent scattering is the Rayleigh scattering. The incoherent scattering is the opposite of coherent scattering that is scattering with no well-defined relationship of the incoming wave and the scattered wave. When incoherent scattering occurs, the direction, phase and intensity will

change after the interaction. For incoherent scattering, the wave is omni-directional, the angle of incident wave and the scattered wave are different and the intensity after interaction is less than the intensity before interaction. An example of incoherent scattering is the Compton scattering. In an absorption process, the incident photon energy is absorbed by the material. The absorbed energy may or may not produce secondary radiation [16]. In most radioactive sources, the energy range rarely relevant to the photodisintegration mechanism. The four main interactions will be Rayleigh scattering, Compton or incoherent scattering, photoelectric absorption and pair production. Hence, the total attenuation coefficient is the sum of the four interactions [17]:

$$\mu = \mu_{coh} + \mu_{incoh} + \mu_{photo} + \mu_{pair} . \tag{2.3}$$

The coherent scattering is often neglected due to the scattered radiation has the same wavelength as the incident photon and in this event there is no energy transfer to the material involved [17]. If we ignore the Rayleigh elastic coherent scattering, the total energy absorption coefficient involves only three processes that lose some fraction of the incident energy which are the Compton scattering, photoelectric absorption and pair production. Thus Equation (2.3) reduces to:

$$\mu = \mu_{incoh} + \mu_{photo} + \mu_{pair} . \tag{2.4}$$

(a) Rayleigh Scattering

Rayleigh scattering is also known as coherent or elastic scattering. For it to occur, the incident photon energy is < 0.1 MeV [19] in high atomic number materials [2]. It is an elastic collision where no energy is lost and the phase is unaltered. This process is not significant and seldom being the main contributor to total attenuation.

(b) Compton Scattering

Compton scattering is a process whereby gamma ray or photons interact with free or weakly bound electrons. The idea of Compton scattering was first introduced by Sir Arthur H. Compton [20]. The theory of Compton scattering came out when J.J. Thomson's classical theory fails to explain many recent experiments at that period of time. Thomson's classical theory explains that the energy scattered by an electron traversed by an X-ray beam of unit intensity is the same whatever may be the wavelength of the incident rays. In other words, it means that when X-ray traverses a thin layer of material, the intensity of the scattered radiation on both sides of the layer should be the same. His predictions were correct only when X-rays of moderate hardness are employed in experiments on the scattering of X-rays by light element. However, his theory is incapable to explain when very hard X-rays or γ-rays are employed. Instead of having the same intensity on both sides, the experiment showed that the scattered energy is found to be less than Thomson's predicted theoretical value and to be strongly concentrated on the emergent side of the scattering plate.

Compton in his paper [20] discussed thoroughly on the quantum hypothesis of scattering involving the change of wavelength due to scattering, energy distribution and the intensity of scattering from the recoiling electron. However, the assumption made by Compton was probably legitimate for very light elements and not for heavy elements. He proposed to investigate the conditions of scattering for heavy elements. He also mentioned that the explanation of certain phenomena, for example in the cases of excess scattering and X-ray reflection, is still not yet clear when the electron is bound in the atom that is too firmly to recoil.

Compton scattering is an inelastic relativistic scattering by a photon on a free electron and the interaction involves only within the atomic scale which means only with

the electrons and not the nucleus or the electric field around the nucleus. Inelastic collision happens when an incoming particle causes the electron it strikes to become excited. In this collision, some of the kinetic energy of the colliding bodies is converted into internal energy in one body so that the kinetic energy is not conserved. This phenomenon involves scattering of a photon with incoming momentum, $\hbar\vec{k}$ by a free and stationary electron that is treated relativistically. The photon will be scattered at an angle, θ with momentum, $\hbar\vec{k}'$ while the electron scattered at an angle, φ with momentum, $\vec{p}$ and kinetic energy, T .

Jauncey [21], however commented that Compton was able to explain the definite change in wavelength due to scattering whereby his prediction in the change of wavelength is in good accord with the experimental observations. But to calculate the intensity of the scattered beam Compton has not proven that the two scattering processes giving the same wavelength change will necessarily given the same distribution of scattered energy. However, Jauncey [21] developed a form of corpuscular quantum theory that does not involve Doppler effect. For long wave lengths, the momentum $\hbar/\lambda$ of the corpuscular ray is small, then the mass of the scattering electron is large compared with the effective mass of the quantum electron. His theory is in good accord with the experiments when the scattering is expressed using classical theory. However, for small wavelengths, the effective mass of the quantum $\hbar/\lambda c$ approaches that of the electron, the recoil of the scattering electron after impact with the corpuscular ray will affect the distribution and the energy of the scattered rays.

In Compton scattering on materials, the energy from the incident photons is partially transferred to the loosely held orbital electrons. This event takes place when the energy of the photons is about 0.1 to 3.0 MeV [1]. The Compton scattering is dominant and contributes to the unsharpness of the image formed in the film of industrial radiography

applications over most of the useful NDE energy and atomic number, *Z* range. The photons from Compton scattering process can cause blurring of the radiograph image. In Compton scattering, there are two types of detrimental forms. The first type of the detrimental form is that the scattered photons are uniformly distributed and this causes uniform background noise that will reduce the dynamic range of the detector. The second type of detrimental form is that the scattered photons that are correlated with the photons passing through the object in a straight line creates both noise and image blurring which means fuzzing or unsharpness of sharp features [16].

(c) Photoelectric Absorption

Photoelectric absorption occurs at photon energy ≤ 0.5 MeV [19]. When an incident photon interacts with matter, the photon will be absorbed and transfers all of its energy to the electron of an atom. The electron that receives the energy will be ejected from the shell and leave the atom with a vacancy in the shell. At that instance, the vacancy will be filled with an electron from other shells and when the event takes place the characteristic X-ray is produced. Photoelectric absorption is more dominant at low energy [16].

When photons with energy, $h\nu$ hit an atom where ν is the frequency, the energy is completely transferred to the electron at the *K*-shell or the *K*-electrons from the atom. The electron that receives the energy will be ejected from the atom. The interactions can also take place with electrons in the *K*, *L*, *M* or *N* shells [17]. In this process the photon energy, $h\nu$ must be larger than the binding energy, E of the electron shell from where it was ejected. Thus, the energy absorbed, E_{pe} is

$$E_{pe} = h\nu - E \,. \tag{2.5}$$

The photoelectric effect is almost negligible for materials with low atomic number and for photon energies greater than 100 keV.

(d) Pair Production

Pair production becomes possible when the energy of the incident photons is greater than 1.02 MeV [19]. This process is only significant at highest energy range of a source and highest Z [16]. In pair production, the photon produces an electron-positron pair. However, the positron will annihilate with an electron to produce another two photons with energy of 0.511 MeV each.

(e) Photodisintegration

This process is only possible if a photon has sufficiently high energy. Photodisintegration is a threshold reaction in which the quantum energy must exceed a certain minimum value that depends on the absorbing nucleus [11]. This reaction involves cases of very high energy photons from electron accelerators, for instance, betatrons and synchrotrons. The cross section for this reaction is also very much smaller than the total cross section for photoelectric absorption, Compton scattering and pair production. However, there is an exception case for ^{9}Be with the threshold energy of 1.666 MeV. Since the energy required for photodisintegration is high, hence it is not included in this work. According to [16], photodisintegration and Rayleigh scattering are never dominant.

2.4 Linear Attenuation Coefficient

Linear attenuation coefficient, μ of electromagnetic waves depends on the energy of the source and on the material of the target sample. However, if the source is polychromatic, one should consider the traversed sample thickness as well. The importance of the linear attenuation coefficient of gamma rays in Non Destructive Testing is to have good estimation of the depth of the defects due to corrosion and erosion. Dorobantu suggested using Iridium-192 that has the behaviour of a polychromatic source, one can estimate the defect dimension in a pipeline with a variable thickness [22].

Linear attenuation coefficient depends on two factors which are the atomic number, *Z* of the interacting material and the energy, *E* of the photons [17]. In this thesis, the source would be radioisotope Iridium-192 since it is widely used in the industrial radiography as the gamma radiation source. When the photons interact with matter, the interactions listed in the previous section except photodisintegration would occur.

There exist discrepancies between some experimental and theoretical values of linear attenuation coefficients. The actual process that is operative depends on the energy of the incident photons. The Beer Lambert's formula Equation (2.1) describes the attenuation law where the measurements are made under good beam geometry condition which is a well-collimated, narrow beam of radiation [11].

Hubbell [23] and Dorobantu [22] suggest two approaches in deriving the attenuation coefficient. In this research, the radioisotope used is Iridium-192 which for this radioisotope, the interaction processes involve are only photoelectric effect and Compton scattering.

Linear absorption coefficient, μ_l is used when the absorber thickness *t* is measured in centimetres while mass absorption coefficient, μ_m is used when *t* is measured in g/cm^2. The relation between linear attenuation coefficient and mass absorption coefficient is shown in Equation (2.6),

$$\mu_l \,\mathrm{cm}^{-1} = \mu_m \frac{\mathrm{cm}^2}{\mathrm{g}} \times \rho \frac{\mathrm{g}}{\mathrm{cm}^3} \tag{2.6}$$

where ρ is the density of the absorber.

There is also another term to express attenuation coefficient in the literature which is the atomic absorption coefficient, μ_a. The atomic absorption coefficient is defined as a fraction of an incident gamma ray beam that is absorbed by a single atom. In other words, it

is the probability that an absorber atom will interact with one of the photons in the beam [11].

There is a relation between the cross section and the attenuation coefficient. The atomic absorption coefficient is referred as the microscopic cross section, σ, with its unit in barns (1 barn = 10^{-28} m^2) while the linear attenuation coefficient denotes the macroscopic (bulk) cross section. The relation between the microscopic cross section and the macroscopic cross section is given as

$$\mu_l \,\mathrm{cm}^{-1} = \sigma \frac{\mathrm{cm}^2}{\mathrm{atom}} \times N \frac{\mathrm{atom}}{\mathrm{cm}^3}. \tag{2.7}$$

Inserting Equation (2.7) into Equation (2.1):

$$\frac{I}{I_0} = e^{-\sigma N t} \tag{2.8}$$

.

Dorobantu [24] had done his calculations on attenuation coefficient μ for steel using Iridium-192 as the radiation source. In his work, he has calculated that for uncollimated beam, the attenuation coefficient is shown in Equation (2.9),

$$\mu_{noncol} = 0.46868 + \frac{0.09}{\sqrt{t}} \tag{2.9}$$

where t is the thickness. For collimated beam and scattered radiation, the attenuation coefficients are shown in Equations (2.10) and (2.11) respectively,

$$\mu_{col} = 0.68379 + \frac{0.128998}{\sqrt{t}} \tag{2.10}$$

$$\mu_{sc} = 0.2015 + \frac{0.039}{\sqrt{t}}. \tag{2.11}$$

Behrok [25] in his paper give the details on the derivation of attenuation coefficient, μ. If I_j is the intensity of photons with the energy of E_j transmitted across distance *t*, then

$$I_j = I_{j_0} e^{-\mu_j t} \ , \ j=0,1.....n \ \text{(n=number of different energies).} \qquad (2.12)$$

where, I_{j_0} is the initial intensity of photons with the energy E_j, μ_j the corresponding linear attenuation coefficient related to the energy E_j and *t* the thickness of the sample. Summing over all energies in the radiation, the total transmitted intensity is given as

$$I = \sum_{j=1}^{n} I_j = \sum_{j=1}^{n} I_{j_0} e^{-\mu_j t} = I_{10} e^{-\mu_1 t} + I_{20} e^{-\mu_2 t} + I_{30} e^{-\mu_3 t} + ... + I_{n0} e^{-\mu_n t} . \qquad (2.13)$$

To obtain the equivalent linear attenuation coefficient, μ_l, the total transmitted intensity due to the bulk property of the sample is defined as,

$$I = \left(I_{10} + I_{20} + ... + I_{n0}\right) e^{-\mu_l t} \qquad (2.14)$$

Equating (2.13) with Equation (2.14):

$$\left(I_{10} + I_{20} + ... + I_n\right) e^{-\mu t} = I_{10} e^{-\mu_1 t} + I_{20} e^{-\mu_2 t} + ... + I_n e^{-\mu_n t}$$

$$e^{-\mu_l t} = \frac{I_{10} e^{-\mu_1 t} + I_{20} e^{-\mu_2 t} + ... + I_{n0} e^{-\mu_n t}}{I_{10} + I_{20} + ... + I_{n0}}$$

$$\mu_l = -\frac{1}{t}\left[ln \frac{\left(I_{10} e^{-\mu_1 t} + I_{20} e^{-\mu_2 t} + ... + I_{n0} e^{-\mu_7 t}\right)}{\left(I_{10} + I_{20} + ... + I_{n0}\right)} \right]. \qquad (2.15)$$

Since the denominator in the ln function is just the initial intensity, then the defining equation for the linear attenuation coefficient is

$$\mu_l = -\frac{1}{t} ln\left(\frac{I}{I_0}\right). \qquad (2.16)$$

When the interaction involves only primary radiation, the attenuation coefficient is shown in Equation (2.17):

$$\mu = -\frac{1}{t}\ln\left(\frac{I_{collided}}{I_0}\right) \tag{2.17}$$

where the total intensity, $I_{collided}$ refers to the photons that collided with the atoms in the sample.

However, if the interaction also involves primary radiation and scattered radiation, the effective attenuation coefficient is given by Equation (2.18):

$$\mu_{eff} = -\frac{1}{t} ln \frac{\left(I_{total}\right)}{I_0} \tag{2.18}$$

where the total intensity, I_{total} includes the primary radiation and scattered radiation.