

Chapter One

X-ray and Gamma Ray

1.1 Introduction

Attenuation of X-ray or Gamma-rays means the decreasing in intensity that occurs when the radiation passes through mater. This attenuation is caused mainly by two effects: scattering and absorption.

Although absorption and attenuation are different physical phenomena, the transilluminated object is often referred to -inaccurately- as on absorber; this should more properly be termed an attenuator. However, this description will follow the traditional usage in some places and refer to absorbers instead of attenuators.

The scattering of X-ray or Gamma-rays quanta at the atoms of the attenuator material causes a part of the radiation to change direction. This reduces the intensity in the original direction. This scattering can either elastic or entail an energy loss or shift in wavelength, i.e. inelastic scattering.

In absorption, the entire energy of the X-ray or Gamma-rays quanta is transferred to the atoms or molecules of the irradiated material as excitation or ionizing energy.

If R_0 is the original counting rate in front of the attenuator and R is the counting rate behind it, we can quantify the transmission of the radiation to characterize the permeability of an attenuator.

The greater the so-called transmittance of an attenuator is, the lower is its attenuating capacity.

The transmittance depends on the thickness of the attenuator. If we assume that the properties of the incident radiation remain unchanged in spite of attenuation, an increase in the thickness X by the amount dX will cause a decrease in the transmittance T by the amount dT , the relative reduction in transmission is proportional to the absolute increase in thickness.

In this research different material such as Al, Ni, Fe, Cu, Plastic, and Glass were used in studding using two different source X-ray and Gamma ray.

1.2 The Problem

Two main approaches to reduce radiation damage are reducing the amount of energy deposited in the sensitive material or modification of the material to be less sensitive to radiation damage. In addition to the electronic device hardening mentioned above, some degree of protection may be obtained by shielding, usually with the interposition of high density materials between the radiation source and areas to be protected.

1.3 Literature review.

1.6.1 New basic empirical expression for computing tables of X-ray mass attenuation coefficients by Tran Pouch, Jean Leprous, *View Issue* Toc, volume 8, issue 2, April 1979, page 85-91.

This paper describes a new approach for deriving a simple relation between mass attenuation coefficient and X-ray energy or wavelength. Parameters of the latter have been adjusted to fit all up-to-date experimental, interpolated and extrapolated data thus providing means for computing a set of tables covering all values of coefficients usually encountered in applied X-ray spectroscopy. The accuracy is generally much better than $\pm 5\%$ with respect to the average of well-established data.

1.6.2 Gamma-ray attenuation coefficients in bismuth borate glasses by Kuwait Singh, Harvinder Singh, Vishal Sharma, Volume 194, Issue 1, July 2002, Pages 1-6

Mass attenuation coefficients of glasses in the system: $x\text{Bi}_2\text{O}_3(1-x)\text{B}_2\text{O}_3$ ($x=0.30, 0.35, 0.40, 0.45$ and 0.55) were determined at 356, 662, 1173 and 1332 keV photon energies using a narrow beam transmission method. Appreciable variations were observed in these coefficients due to changes in the chemical composition of glasses. These coefficients were then used to determine effective atomic numbers of glass samples, which were found to be constant with bismuth concentration and energy.

1.6.3 Specific γ -ray constant and exposure rate constant of ^{192}Ir by Glenn P. Glasgow, L. T. Dillman, *View Issue* TOC, Volume 6, Issue 1, January 1979, Pages 49-52.

Calculated values of the ^{192}Ir specific γ -ray constant Γ , range from the low value of $3.948 \text{ R cm}^2\text{h}^{-1}\text{mCi}^{-1}$ recommended in NCRP No. 41 to a high of 4.89

$\text{R cm}^2\text{h}^{-1}\text{mCi}^{-1}$. Measured values of Γ range only from 4.85 to 5.0

$\text{R cm}^2\text{h}^{-1}\text{mCi}^{-1}$. Discrepancies in reported calculated values exist because the isotope decay scheme and other nuclear spectroscopy data pertinent to these calculations were not well known. Using the 28 γ rays and relative intensities from the most recent Evaluated Nuclear Structure Data File (ENSDF), Γ is calculated to be 4.62 ± 0.0 $\text{R cm}^2\text{h}^{-1}\text{mCi}^{-1}$ and the exposure rate constant Γ_{δ} is 4.69 ± 0.05 $\text{R cm}^2\text{h}^{-1}\text{mCi}^{-1}$. These new calculations are presented and previously reported values of Γ and Γ_{δ} are reviewed.

1.4 The Aim of the Study

To investigate the attenuation of X-ray and Gamma-rays as a function of the absorber thickness and to verify Lambert's law of attenuation and to confirm the wavelength-dependency of attenuation.

1.5 The Methodology

Practical work would carry out using different samples and analysis the results.

1.6 Presentation

In thesis contain four chapter, Chapter one X-ray and Gamma ray, Chapter two radiation, Chapter three detectors. Chapter four practical

Chapter two

Radiation

2.1 Radiation

Is energy in the form of waves or streams of particles. There are many kinds of radiation all around us. When people hear the word radiation, they often think of atomic energy, nuclear power and radioactivity, but radiation has many other forms. Sound and visible light are familiar forms of radiation; other types include ultraviolet radiation (that produces a suntan), infrared radiation (a form of heat energy), and radio and television signals.

2.2 Types of Radiation

Radiation is energy in the form of waves of particles. There are two forms of radiation – non-ionizing and ionizing .

2.2.1 Non-ionizing radiation

Non-ionizing radiation has less energy than ionizing radiation; it does not possess enough energy to produce ions. Examples of non-ionizing radiation are visible light, infrared, radio waves, microwaves, and sunlight.

Global positioning systems, cellular telephones, television stations, FM and AM radio, baby monitors, cordless phones, garage-door openers, and ham radios use non-ionizing radiation. Other forms include the earth's magnetic field, as well as magnetic field exposure from proximity to transmission lines, household wiring and electric appliances. These are defined as extremely low-frequency (ELF) waves and are not considered to pose a health risk.[1]

2.2.2 Ionizing radiation

Ionizing radiation is radiation that carries enough energy to free electrons from atoms or molecules, thereby ionizing them. Ionizing radiation is made up of energetic subatomic particles, ions or atoms moving at high speeds (usually greater

than 1% of the speed of light), and electromagnetic waves on the high-energy end of the electromagnetic spectrum.

Gamma rays, X-rays, and the higher ultraviolet part of the electromagnetic spectrum are ionizing, whereas the lower ultraviolet part of the electromagnetic spectrum, and also the lower part of the spectrum below UV, including visible light (including nearly all types of laser light), infrared, microwaves, and radio waves are all considered non-ionizing radiation. The boundary between ionizing and non-ionizing electromagnetic radiation that occurs in the ultraviolet is not sharply defined, since different molecules and atoms ionize at different energies. Conventional definition places the boundary at a photon energy between 10 eV and 33 eV in the ultraviolet (see definition boundary section below).[1]

Spectral region	Approximate wavelength rang	Approximate range of photon energies
Radio wave	10000eV-1mm	$1.10^{-14} eV$ -0.001eV
Infrared rays	1mm-075 μ m	0.001eV-1.7eV
Visible light	0.75 μ m-0.4 μ	1.7eV-3.1eV
Ionizing electromagnetic radiation		
Ultraviolet light	0.4 μ m-10nm	3.1eV-100V
X-rays radiation	10nm-0.001nm	100eV-1MeV
Gamma radiation	<0.1nm	>10KeV

Table2.1. The scale of wavelengths of electromagnetic radiation

2.3 X-ray

X-rays a form of electromagnetic radiation, similar to light but of shorter wavelength and capable of penetrating solids and of ionizing gases.

Such radiation having wavelengths in the range of approximately 0.1–10 nm

2.3.1 Nature of X-rays

X-rays with energies ranging from about 100 eV to 10 MeV are classified as electromagnetic waves, which are only different from the radio waves, light, and gamma rays in wavelength and energy. X-rays show wave nature with wavelength ranging from about 10 to 10³ nm. According to the quantum theory, the electromagnetic wave can be treated as particles called photons or light quanta.

The essential characteristics of photons such as energy, momentum, etc., are summarized as follows.

The propagation velocity C of electromagnetic wave (velocity of photon) with frequency V and wavelength λ is given by the relation.

$$c = \lambda v \text{ (ms}^{-1}\text{)} \quad (2.1)$$

The velocity of light in the vacuum is a universal constant given as $C = 299792458$ m/s ($\approx 2.998 \cdot 10^8$ m/s). Each photon has an energy E , which is proportional to its frequency,

$$E = hv = \frac{hc}{\lambda} \quad (2.2)$$

where h is the Planck constant (6.625×10^{-34} Js). With E expressed in keV, and λ in nm, the following relation is obtained:

$$E(\text{KeV}) = \frac{1.240}{\lambda(\text{nm})} \quad (2.3)$$

The momentum p is given by mv , the product of the mass m , and its velocity v . The de Broglie relation for material wave relates wavelength to momentum.

$$\lambda = \frac{h}{P} = \frac{h}{mv} \quad (2.4)$$

The velocity of light can be reduced when traveling through a material medium, but it does not become zero. Therefore, a photon is never at rest and so has no rest mass m_e . However, it can be calculated using Einstein's mass-energy equivalence relation $E = mc^2$.

$$E = \frac{m_e}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} c^2 \quad (2.5)$$

It is worth noting that (2.5) is a relation derived from Lorentz transformation in the case where the photon velocity can be equally set either from a stationary coordinate or from a coordinate moving at velocity of v (Lorentz transformation is

given in detail in other books on electromagnetism: for example, P. Cornille, *Advanced Electromagnetism and Vacuum Physics*, World Scientific Publishing, Singapore, (2003)). The increase in mass of a photon with velocity may be estimated in the following equation using the rest mass m_e :

$$E = mc^2 - m_e c^2 = \frac{m_e}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} c^2 - m_e c^2 \quad (2.6)$$

$$v = c \cdot \sqrt{1 - \left(\frac{m_e c^2}{E + m_e c^2}\right)^2} \quad (2.7)$$

For example, an electron increases its mass when the accelerating voltage exceeds 100kV, so that the common formula of $\frac{1}{2}mv^2$ for kinetic energy cannot be used. In such case, the velocity of electron should be treated relativist ally as follows:

The value of m_e is obtained, in the past, by using the relationship of $m = h/(c\lambda)$ from precision scattering experiments, such as Compton scattering and $m_e = 9.109 \times 10^{-31}$ kg is usually employed as electron rest mass. This also means that an electron behaves as a particle with the mass of 9.109×10^{-31} kg ,and it corresponds to the energy of $E = mc^2 = 8.187 \times 10^{-14}$ J or 0.5109×10^6 eV in eV. There is also a relationship between mass, energy ,and momentum

$$\left(\frac{E}{c}\right)^2 - P^2 = (m_e c)^2 \quad (2.8)$$

It is useful to compare the properties of electrons and photons. On the one hand, the photon is an electromagnetic wave, which moves at the velocity of light sometimes called light quantum with momentum and energy and its energy depends upon the frequency ν . The photon can also be treated as particle. On the other hand, the electron has “mass” and “charge.” It is one of the elementary particles that is a constituent of all substances. The electron has both particle and wave nature such as photon. For example, when a metallic filament is heated, the electron inside it is supplied with energy to jump out of the filament atom. Because of the negative charge of the electron, ($e = 1.602 \times 10^{-19}$ C), it moves toward the

anode in an electric field and its direction of propagation can be changed by a magnetic field.[2]

2.3.2 Production of X-rays

When a high voltage with several tens of kV is applied between two electrodes, the high-speed electrons with sufficient kinetic energy, drawn out from the cathode, collide with the anode (metallic target). The electrons rapidly slow down and lose kinetic energy. Since the slowing down patterns (method of losing kinetic energy) vary with electrons, continuous X-rays with various wavelengths are generated. When an electron loses all its energy in a single collision, the generated X-ray has the maximum energy (or the shortest wavelength = λ_{SWL}). The value of the shortest wavelength limit can be estimated from the accelerating voltage V between electrodes.

$$eV \equiv hv_{max} \quad (2.9)$$

$$\lambda_{SWL} = \frac{c}{v_{max}} = \frac{hc}{eV} \quad (2.10)$$

The total X-ray intensity released in a fixed time interval is equivalent to the area under the curve in Fig.1.1. It is related to the atomic number of the anode target Z and the tube current I .

$$I_{cont} = A_i Z V^2 \quad (2.11)$$

where A is a constant. For obtaining high intensity of white X-rays, (2.11) suggests that it is better to use tungsten or gold with atomic number Z at the target, increase accelerating voltage V , and draw larger current i as it corresponds to the number of electrons that collide with the target in unit time. It may be noted that most of the kinetic energy of the electrons striking the anode (target metal) is converted into heat and less than 1% is transformed into X-rays. If the electron has sufficient kinetic energy to eject an inner-shell electron, for example, a K shell electron, the atom will become excited with a hole in the electron shell. When such hole is filled by an outer shell electron, the atom regains its stable state. This process also includes production of an X-ray photon with energy equal to the difference in the electron energy levels. As the energy released in this process is a value specific to the target metal and related electron shell, it is called characteristic X-ray. A linear relation between the square root of frequency of the characteristic X-ray and the atomic number Z of the target material is given by Moseley's law.

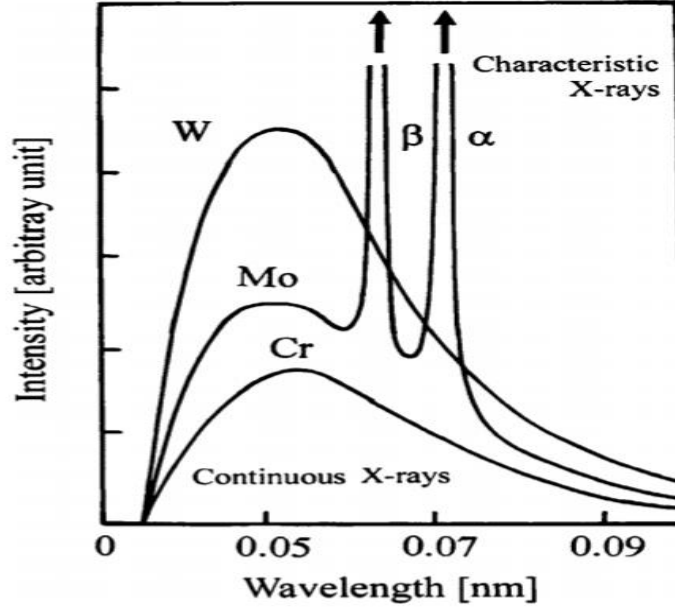


Figure (2.1) Schematic representation of the X-ray spectrum

$$\sqrt{\nu} = B_M (Z - \sigma_M) \quad (2.12)$$

Here, B_M and σ_M are constants. This Moseley's law can also be given in terms of wavelength λ of emitted characteristic X-ray:

$$\frac{1}{\lambda} = R(Z - S_M)^2 \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right) \quad (2.13)$$

Here, R is the Rydberg constant ($1.0973 \times 10^7 \text{ m}^{-1}$), S_M is a screening constant, and usually zero for K_α line and one for K_β line. Furthermore, n_1 and n_2 represent the principal quantum number of the inner shell and outer shell, respectively, involved in the generation of characteristic X-rays. For example, $n_1 = 1$ for K shell, $n_2 = 2$ for L shell, and $n_3 = 3$ for M shell. As characteristic X-rays are generated when the applied voltage exceeds the so-called excitation voltage, corresponding to the potential required to eject an electron from the K shell (e.g., Cu: 8.86keV, Mo: 20.0keV), the following approximate relation is available between the intensity of K_α radiation, I_K , and the tube current, i , the applied voltage V , and the excitation voltage V_K :

$$I_k = B_S i (V - V_k)^{1.67} \quad (2.14)$$

Here, B_S is a constant and the value of $B_S = 4.25 \times 10^8$ is usually employed. As it is clear from (1.14), larger the intensity of characteristic X-rays, the larger the applied voltage and current. It can be seen from (1.13), characteristic radiation is emitted as a photoelectron when the electron of a specific shell (the innermost shell of electrons, the K shell) is released from the atom, when the electrons are pictured as orbiting

the nucleus in specific shells. Therefore, this phenomenon occurs with a specific energy (wavelength) and is called “photoelectric absorption.” The energy, E_{ej} , of the photoelectron emitted may be described in the following form as a difference of the binding energy (E_B) for electrons of the corresponding shell with which the photoelectron belongs and the energy of incidence X-rays ($h\nu$):

$$E_{ej} = h\nu - E_B \quad (2.15)$$

The recoil of atom is necessarily produced in the photoelectric absorption process, but its energy variation is known to be negligibly small (Equation (1.15)) is based on such condition. Moreover, the value of binding energy (E_B) is also called absorption edge of the related shell.[2]

2.3.3 Absorption of X-rays

X-rays which enter a sample are scattered by electrons around the nucleus of atoms in the sample. The scattering usually occurs in various different directions other than the direction of the incident X-rays, even if photoelectric absorption does not occur. As a result, the reduction in intensity of X-rays which penetrate the substance is necessarily detected. When X-rays with intensity I_0 penetrate a uniform substance, the intensity I after transmission through distance x is given by.

$$I = I_0 e^{-\mu x} \quad (2.16)$$

Here, the proportional factor μ is called linear absorption coefficient, which is dependent on the wavelength of X-rays, the physical state (gas, liquid, and solid) or density of the substance, and its unit is usually inverse of distance. However, since the linear absorption coefficient μ is proportional to density ρ , (μ/ρ) becomes unique value of the substance, independent upon the state of the substance. The quantity of (μ/ρ). is called the mass absorption coefficient and the

specific values for characteristic X-rays frequently-used are compiled Equation (2.16) can be re-written as (2.17) in terms of the mass absorption coefficient.

$$I = I_0 e^{-\left(\frac{\mu}{\rho}\right)\rho x} \quad (2.17)$$

Mass absorption coefficient of the sample of interest containing two or more elements can be estimated from (1.17) using the bulk density, ρ , and weight ratio of w_j for each element j .

$$\left(\frac{\mu}{\rho}\right) = w_1 \left(\frac{\mu}{\rho}\right)_1 + w_2 \left(\frac{\mu}{\rho}\right)_2 + \dots + \sum_{j=1} w_j \left(\frac{\mu}{\rho}\right)_j \quad (2.18)$$

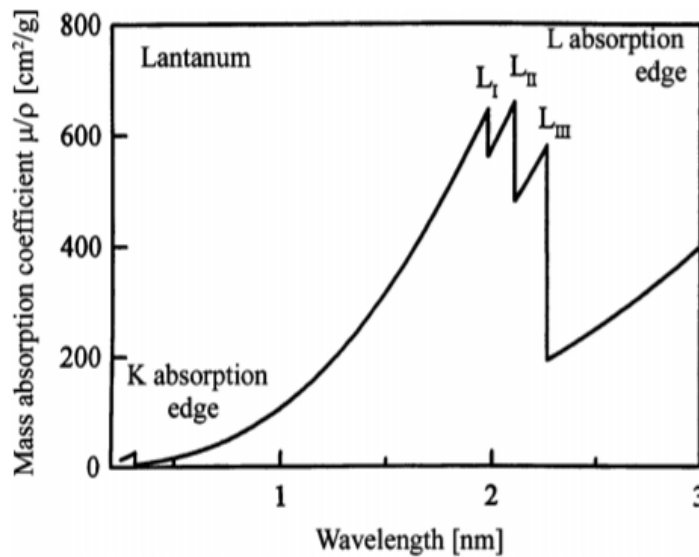


Fig. 2.2 Wavelength dependences of mass absorption coefficient of X-ray using the La as an example

Absorption of X-rays becomes small as transitivity increases with increasing energy(wavelength becomes shorter). However, if the incident X-ray energy comes close to a specific value (or wavelength) as shown in Fig2.3.3, the photoelectric absorption takes place by ejecting an electron in K-shell and then discontinuous variation in absorption is found. Such specific energy (wavelength) is called absorption edge. It may be added that monotonic variation in energy (wavelength)

dependence is again detected when the incident X-ray energy is away from the absorption edge.[2]

2.3.4 Half Value Layer

A useful way to characterize the penetrating quality of an x-ray beam by its half-value layer (HVL). The HVL is the thickness of an absorber, such as aluminum, required to reduce by one half the number of x-ray photons passing through it. As the average energy of an x-ray beam increases, so does its HVL. The term quality refers to the mean energy of an x-ray beam.[3]

2.3.5 Inverse Square Law

The intensity of an x-ray beam at a given point (number of photons per cross-sectional area per unit exposure time) depends on the distance of the measuring device from the focal spot. For a given beam the intensity is inversely proportional to the square of the distance from the source. The reason for this decrease in intensity is that the x-ray beam spreads out as it moves from the source. The relationship is as follows:

$$\frac{I_1}{I_2} = \frac{(D_2)^2}{(D_1)^2} \quad (2.19)$$

Where I is intensity and D is distance.[3]

2.3.6 Interaction of X-Rays with Matter

X-rays possess intrinsic energy that may be imparted to the matter they interact with. That interaction takes place as either absorption (transfer of energy from the X-ray photon to the absorbing material) or scattering (in which the X-ray photon is “redirected” by interaction with the scattering material). The process of scattering is the primary process responsible for diffraction, but both processes (that are, in many ways, interdependent) result in the production of potentially damaging secondary radiation. That radiation is capable of producing significant short- and long-term health effects in the event of exposure to human tissue. The X-rays produced for diffraction analysis by an X-ray source consist of the characteristic radiation (dependent on the anode target) plus the continuous spectrum.

The energy of X-rays and their wavelength are inversely proportional (higher energy = lower wavelength), and the continuous spectrum minimum wavelength decreases as the accelerating voltage (kV) of the X-ray source increases. It is important to understand that an increase in filament current (ma) and kV (beyond the minimum value required to produce characteristic radiation for the target) will result in an increase in the intensity of the generated X-rays, but will not change their energy.[3]

2.3.7 Energy Transfer

There are two basic types of energy transfer that may occur when X-rays interact with matter:

- Ionization, in which the incoming radiation causes the removal of an electron from an atom or molecule leaving the material with a net positive charge.
- Excitation, in which some of the X-ray's energy is transferred to the target material leaving it in an excited (or more energetic) state.

Theoretically there are twelve processes that can occur when X-rays interact with matter, but only three of these processes are important. These processes are:

- The photoelectric effect
- The Compton effect and
- Pair Production

Which process dominates is dependent on the mass absorption characteristics of the target (directly related to the atomic weight, Z) and the energy of the X-rays, shown schematically in the graph below. [3]

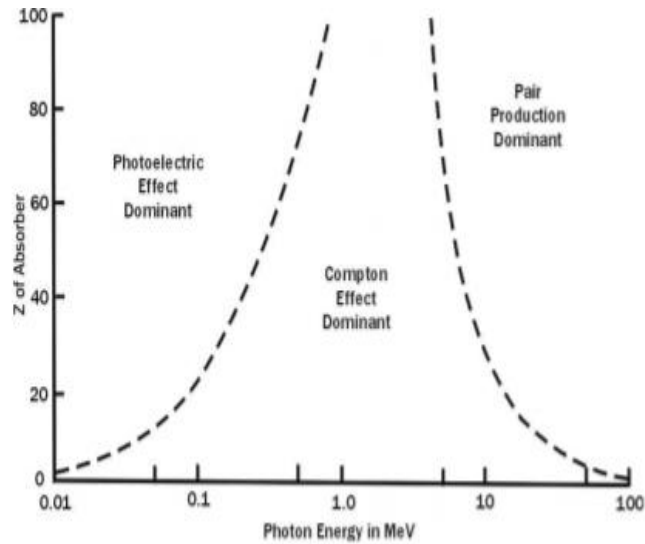


Figure (2.3)

2.3.8 The Photoelectric Effect

The photoelectric effect occurs when photons interact with matter with resulting ejection of electrons from the matter. Photoelectric (PE) absorption of x-rays occurs when the x-ray photon is absorbed resulting in the ejection of electrons from the atom. This leaves the atom in an ionized (i.e., charged) state. The ionized atom then returns to the neutral state with the emission of an x-ray characteristic of the atom. PE absorption is the dominant process for x-ray absorption up to energies of about 500 KeV. PE absorption is also dominant for atoms of high atomic numbers.

The photoelectric effect is responsible for the production of characteristic x-rays in the x-ray tube, but the process is also important as a secondary process that occurs when x-rays interact with matter. An x-ray photon transfers its energy to an orbital electron, which is then dislodged and exits the atom at high speed with a kinetic energy equal to:

$$KE = E_x - P \quad (2.20)$$

Where

KE is the kinetic energy of the photoelectron

E_x is the energy of the incident X-ray photon

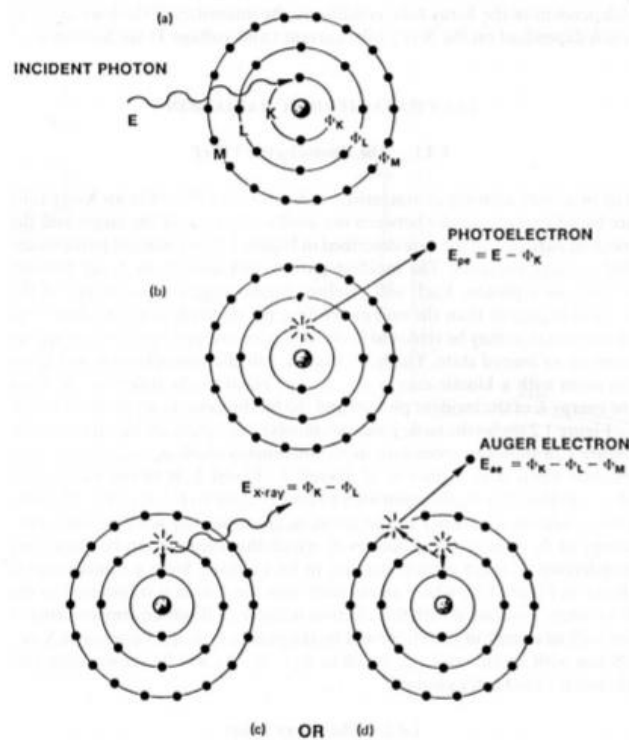
P is the energy required to remove the electron. This is equivalent to its binding energy in the atom.

The energy equivalent of the rest mass of an electron is m_0c^2 , and is equal to about 0.51 MeV (m_0 is the rest mass of an electron and c is the speed of light). When E_x is much lower than this value, the electron will exit at a high angle to the incident beam; when E_x is closer to this value, the electron will exit at close to parallel with the beam.

When the photoelectron is ejected, it has the capability, depending on its energy, to interact with subsequent electrons in other molecules or atoms in a chain reaction until all its energy is lost. If that interaction results in the ejection of an outer orbital electron, this is known as the Auger (au-jay) effect, and the electron called an Auger electron. The probability of producing a secondary photoelectron vs. an Auger electron is directly proportional to the KE of the photoelectron.

The production of photoelectric and Auger electrons is shown diagrammatically in the following figure from Jenkins and Snyder (1996). In the diagram (a) shows the incident X-ray photon, (b) shows the production of a high-energy primary photoelectron. In (c) a lower energy electron moves into the vacated K-shell resulting in the production of an X-ray photon that leaves the atom, and in (d) the X-ray photon is absorbed by an outer shell electron resulting in the emission of a Auger electron.

It is easy to see how the photoelectric (and Auger) effect can significantly damage the molecular structure of soft tissues encountered by an X-ray beam.[3]



Figure(2.4) photoelectric effect

2.3.9 The Compton Effect

The Compton effect or Compton scattering (C), also known as incoherent scattering, occurs when the incident x-ray photon ejects an electron from an atom and an x-ray photon of lower energy is scattered from the atom. Relativistic energy and momentum are conserved in this process¹ and the scattered x-ray photon has less energy and therefore greater wavelength than the incident photon. Compton Scattering is important for low atomic number specimens. At energies of 100 keV -- 10 MeV the absorption of radiation is mainly due to the Compton effect.

The Compton effect will occur with very low atomic weight targets even at relatively low X-ray energies. The effect may be thought of as a scattering of the photons by atomic electrons. In the process, also called Compton scattering, the incident X-ray changes direction and loses energy, imparting that energy to the electron (now called a Compton electron). The Compton electron will typically

interact with other atoms producing secondary ionizations. Since they possess relatively low energy, the x-rays produced will generally be low energy also.

The maximum possible energy, E , of a Compton electron (the “Compton edge”) is equal to:

$$E = \frac{E_x}{1 + 4E_x} \quad (2.21)$$

Where E_x is the energy of the incident photon. Qualitatively, it is easy to see that the Compton electrons will be significantly less energetic than photoelectrons for an equal value of E_x .

In x-ray diffraction, Compton scatter will contribute to the overall background in the x-ray data produced, but because of the relatively low energies of the incident x-rays and the higher mass of the specimens and specimen holders, the contribution will usually be very small.[3]

2.3.10 Pair Production

Pair Production (PP) can occur when the x-ray photon energy is greater than 1.02 MeV, when an electron and positron are created with the annihilation of the x-ray photon. Positrons are very short lived and disappear (positron annihilation) with the formation of two photons of 0.51 MeV energy. Pair production is of particular importance when high energy photons pass through materials of a high atomic number.

Pair production is a rare process and only occurs at high X-ray photon energies with high atomic weight targets. It is virtually nonexistent at the low-energies involved in X-ray diffraction work. Pair production is impossible unless the incident X-rays exceed 1.02 MeV and does not become important until this exceeds about 2 MeV.

Pair production is not a significant process at the X-ray energies involved in X-ray diffraction.[3]

2.4 Gamma ray

2.4.1 Introduction

Gamma rays are high-energy electromagnetic radiation emitted in the deexcitation of the atomic nucleus. Electromagnetic radiation includes such diverse phenomena as radio, television, microwaves, infrared radiation, light, ultraviolet radiation, x rays, and gamma rays. These radiations all propagate thorough vacuum with the speed of light. They can be described as wave phenomena involving electric and magnetic field oscillations analogous to mechanical oscillations such as water waves or sound. They differ from each other only in the frequency of oscillation. Although given different names, electromagnetic radiation actually forms a continuous spectrum, from low frequency radio' waves at a few cycles per second to gamma rays at 10^{18} Hz and above (see Figure 1.1). The parameters used to describe an electromagnetic wave frequency, wavelength, and energy are related and maybe used interchangeably. It is common practice to use frequency or wavelength for radio waves, color or wavelength for light waves (including infrared and ultraviolet), and energy for x rays and gamma rays.[6]

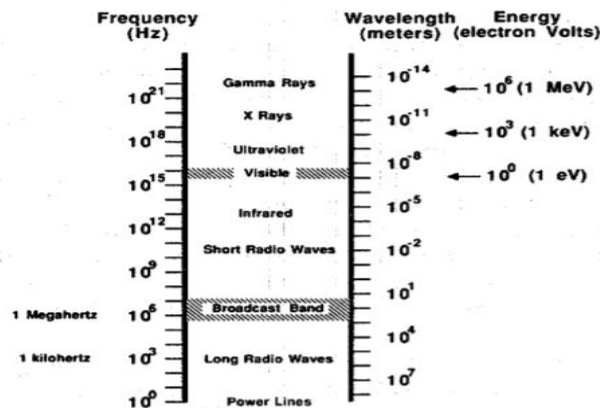


Figure (2.5)The electromagnetic spectrum showing the relationship between gamma rays, x rays, light waves, and radio waves.

2.4.2 Gamma-Ray Interactions with Matter

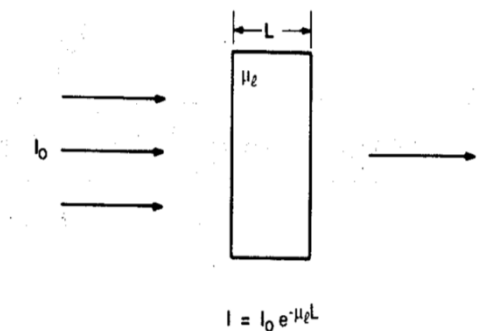
2.4.2.1 Introduction

A knowledge of gamma-ray interactions is important to the nondestructive assayist in order to understand gamma-ray detection and attenuation. A gamma ray must interact with a detector in order to be “seen.” Although the major isotopes of uranium and plutonium emit gamma rays at fixed energies and rates, the gamma-ray intensity measured outside a sample is always attenuated because of gamma-ray interactions with the sample. This attenuation must be carefully considered when using gamma-ray NDA instruments. This chapter discusses the exponential attenuation of gamma rays in bulk materials and describes the major gamma-ray interactions, gamma-ray shielding, filtering, and collimation. The treatment given here is necessarily brief.[5]

2.4.2.2 The Fundamental Law of Gamma-Ray Attenuation

When gamma radiation of intensity I_0 is incident on an absorber of thickness L . The emerging intensity (I) transmitted by the absorber is given by the exponential expression

$$I = I_0 e^{-\mu_\ell L} \quad (2.22)$$



Figure(2.6) The fundamental law of gamma-ray attenuation. The transmitted gamma-ray intensity I is a function of gamma-ray energy, absorber composition, and absorber thickness.

where μ_ℓ is the attenuation coefficient (expressed in cm^{-1}). The ratio I/I_0 is called the gamma-ray transmission. Figure (2.6) illustrates exponential attenuation for

three different gamma-ray energies and shows that the transmission increases with increasing gamma-ray energy and decreases with increasing absorber thickness. Measurements with different sources and absorbers show that the attenuation coefficient μ_ℓ depends on the gamma-ray energy and the atomic number (Z) and density (ρ) of the absorber. For example, lead has a high density and atomic number and transmits

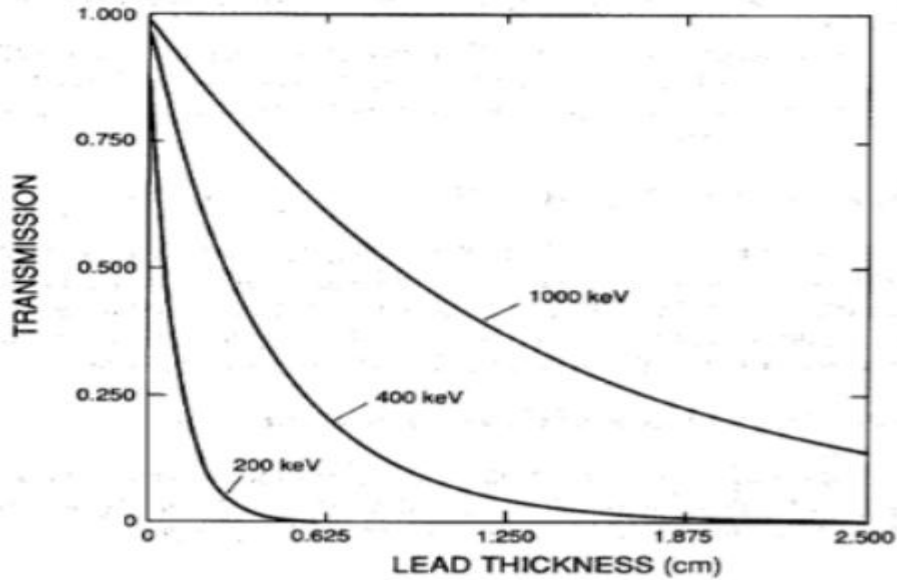


Figure (2.7) Transmission of gamma rays through lead absorbers.

a much lower fraction of incident gamma radiation than does a similar thickness of aluminum or steel. The attenuation coefficient in Equation (2.22) is called the linear attenuation coefficient.[5]

2.4.2.3 Mass Attenuation Coefficient

The linear attenuation coefficient is the simplest absorption coefficient to measure experimentally, but it is not usually tabulated because of its dependence on the density of the absorbing material. For example, at a given energy, the linear attenuation coefficients of water, ice, and steam are all different, even though the same material is involved. Gamma rays interact primarily with atomic electrons; therefore, the attenuation coefficient must be proportional to the electron density P , which is proportional to the bulk density of the absorbing material. However, for a given material the ratio of the electron density to the bulk density is a constant,

Z/A , independent of bulk density. The ratio Z/A is nearly constant for all except the heaviest elements and hydrogen.

$$P = Z\rho/A \quad (2.23)$$

Where: P = electron density

Z = atomic number

ρ = mass density

A = atomic mass.

The ratio of the linear attenuation coefficient to the density (μ_l/ρ) is called the mass attenuation coefficient μ and has the dimensions of area per unit mass (cm^2/g). The units of this coefficient hint that one may think of it as the effective cross-sectional area of electrons per unit mass of absorber. The mass attenuation coefficient can be written in terms of a reaction cross section, $\sigma(\text{cm}^2)$:

$$\mu = \frac{N_0\sigma}{A} \quad (2.24)$$

Where N_0 is Avagadro's number (6.02×10^{23}) and A is the atomic weight of the absorber. The cross section is the probability of a gamma ray interacting with a single atom. Using the mass attenuation coefficient, Equation (2.24) can be rewritten as

$$I = I_0 e^{-\mu\rho L} = I_0 e^{-\mu x} \quad (2.25)$$

where $x = \rho L$.

The mass attenuation coefficient is independent of density for the example mentioned above, water, ice, and steam all have the same value of μ . This coefficient is more commonly tabulated than the linear attenuation coefficient because it quantifies the gamma-ray interaction probability of an individual element. Equation (2.25)

is used to calculate the mass attenuation coefficient for compound materials:

$$\mu = \sum \mu_i W_i \quad (2.2)$$

where μ_i = mass attenuation coefficient of i^{th} element. .

W_i = weight fraction of i^{th} element.[5]

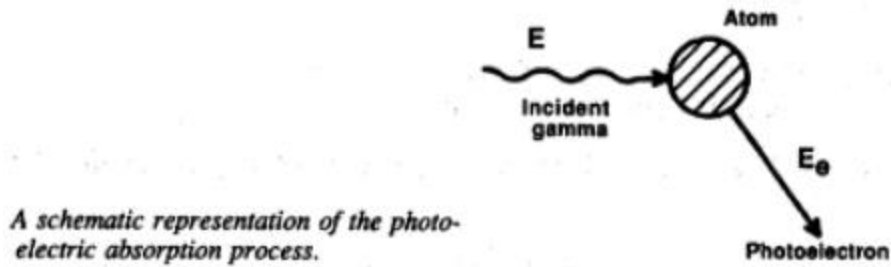
2.4.2.4 Interaction Processes

The gamma rays of interest to NDA applications fall in the range 10 to 2000 keV and interact with detectors and absorbers by three major processes: photoelectric absorption, Compton scattering, and pair production. In the photoelectric absorption process, the gamma ray loses all of its energy in one interaction. The probability for this process depends very strongly on gamma-ray energy E_γ and atomic number Z . In Compton scattering, the gamma ray loses only part of its energy in one interaction. The probability for this process is weakly dependent on E and Z . The gamma ray can lose all of its energy in one pair-production interaction. However, this process is relatively unimportant for fissile material assay since it has a threshold above 1 MeV.[5]

2.4.2.5 Photoelectric Absorption

A gamma ray may interact with a bound atomic, electron in such a way that it loses all of its energy and ceases to exist as a gamma ray (see Figure (2.8)). Some of the gamma-ray energy is used to overcome the electron binding energy, and most of the remainder is transferred to the freed electron as kinetic energy. A very small amount of recoil energy remains with the atom to conserve momentum. This is called photoelectric absorption because it is the gamma-ray analog of the process discovered by Hertz in 1887 whereby photons of visible light liberate electrons

from a metal surface. Photoelectric absorption is important for gamma-ray detection because the gamma ray gives up all its energy, and the resulting pulse falls in the full-energy peak.



Figure(2.8)

The probability of photoelectric absorption depends on the gamma-ray energy, the electron binding energy, and the atomic number of the atom. The probability is greater the more tightly bound the electron therefore, K electrons are most affected (over 80% of the interactions involve K electrons), provided the gamma-ray energy exceeds the K-electron binding energy. The probability is given approximately by Equation(2.4.2.1.1) which shows that the interaction is more important for heavy atoms like lead and uranium and low-energy gamma rays:

$$\tau \propto Z^4 / E^3 \quad (2.27)$$

where τ = photoelectric, mass attenuation coefficient.

This proportionality is only approximate because the exponent of Z varies in the range 4.0 to 4.8. As the gamma-ray energy decreases, the probability of photoelectric absorption increases rapidly. Photoelectric absorption is the predominant interaction for low-energy gamma rays, x rays, and bremsstrahlung. The energy of the photoelectron E_e released by the interaction is the difference between the gamma-ray energy E_γ and the electron binding energy E_b :

$$E_e = E_\gamma - E_b. \quad (2.28)$$

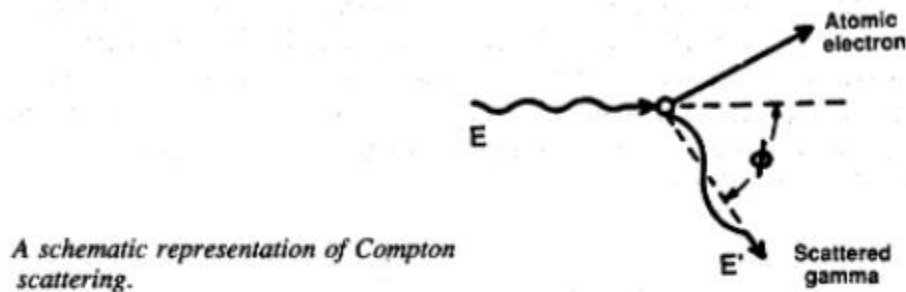
In most detectors, the photoelectron is stopped quickly in the active volume of the detector, which emits a small output pulse whose amplitude is proportional to the energy deposited by the photoelectron. The electron binding energy is not lost but appears as characteristic x-rays emitted in coincidence with the photoelectron. In most cases, these x rays are absorbed in the detector in coincidence with the

photoelectron and the resulting output pulse is proportional to the total energy of the incident gamma ray. For low-energy gamma rays in very small detectors, a sufficient number of K x-rays can escape from the detector to cause escape peaks in the observed spectrum; the peaks appear below the full-energy peak by an amount equal to the energy of the x-ray.[5]

2.4.2.6 Compton Scattering

Compton scattering is the process whereby a gamma ray interacts with a free or weakly bound electron ($E_\gamma \gg E_b$) and transfers part of its energy to the electron see Figure (2.9)

Conservation of energy and momentum allows only a partial energy transfer when the electron is not bound tightly enough for the atom to absorb recoil energy. This interaction involves the outer, least tightly bound electrons in the scattering atom. The electron becomes a free electron with kinetic energy equal to the difference of the energy lost by the gamma ray and the electron binding energy. Because the electron



Figure(2.9)

binding energy is very small compared to the gamma-ray energy, the kinetic energy of the electron is very nearly equal to the energy lost by the gamma ray:

$$E_e = E_\gamma - E' \quad (2.29)$$

Where E_e = energy of scattered electron

E_γ = energy of incident gamma ray

E' = energy of scattered gamma ray.

Two particles leave the interaction site: the freed electron and the scattered gamma ray. The directions of the electron and the scattered gamma ray depend on the amount of energy transferred to the electron during the interaction. Equation (2.29) gives the energy of the scattered gamma ray, and Figure (2.9) shows the energy of the scattered electron as a function of scattering angle and incident gamma-ray energy.

$$E' = m_0c^2 / (1 - \cos \emptyset + m_0c^2/E) \quad (2.30)$$

where m_0c^2 = rest energy of electron = 511 keV

\emptyset = angle between incident and scattered gamma rays (see Figure (2.9))

This energy is minimum for a head-on collision where the gamma ray is scattered 180° and the electron moves forward in the direction of the incident gamma ray. For this case the energy of the scattered gamma ray is given by Equation (2.29) and the energy of the scattered electron is given by Equation (2.30)[5]

$$\begin{aligned} E'(min) &= m_0c^2 / (2 + m_0c^2/E) \\ &\cong m_0c^2 / 2 = 256 \text{ KeV}; \text{ if } E \gg m_0c^2 / 2 \\ E_e(max) &= E / [1 + m_0c^2 / (2E)] \\ &\cong E - m_0c^2 / 2 = E - 256 \text{ KeV}; \text{ if } E \gg m_0c^2 / 2 \end{aligned} \quad (2.31)$$

2.4.2.7 Pair Production

A gamma ray with an energy of at least 1.022 MeV can create an electron-positron pair when it is under the influence of the strong electromagnetic field in the vicinity of a nucleus (see Figure 2.10). In this interaction the nucleus receives a very small amount of recoil energy to conserve momentum, but the nucleus is otherwise unchanged and the gamma ray disappears. This interaction has a threshold of 1.022 MeV because that is the minimum energy required to create the electron and positron. If the gamma ray energy exceeds 1.022 MeV, the excess energy is shared between the electron and positron as kinetic energy. This

interaction process is relatively unimportant for nuclear material assay because most important gamma-ray signatures are below 1.022 MeV.

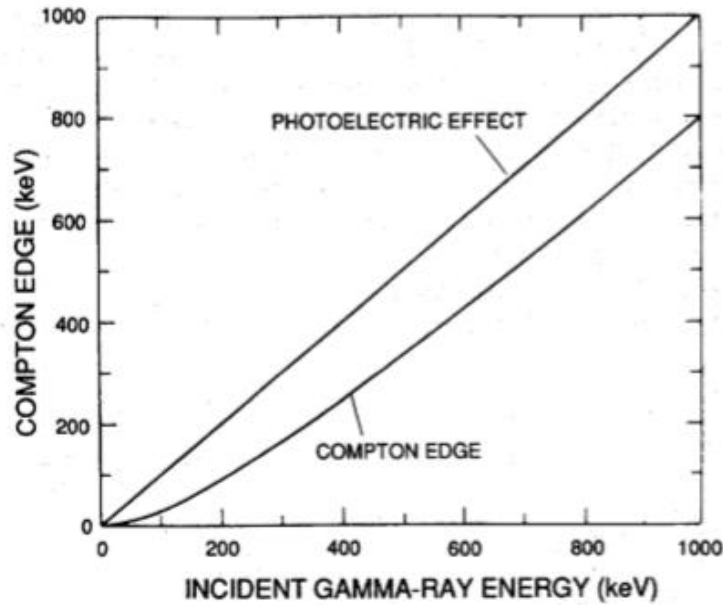
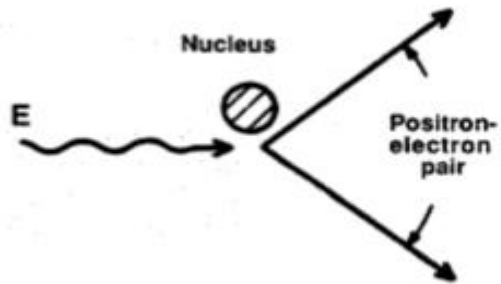


Figure (2.10)



A schematic representation of pair production.

Figure (2.11)

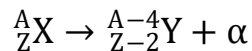
The electron and positron from pair production are rapidly slowed down in the absorber. After losing its kinetic energy, the positron combines with an electron in an annihilation process, which releases two gamma rays with energies of 0.511

MeV. The lower energy gamma rays may interact further with the absorbing material or may escape. In a gamma-ray detector, this interaction often gives three peaks for a high-energy gamma ray. The kinetic energy of the electron and positron is absorbed in the detector. One or both of the annihilation gamma rays may escape from the detector or they may both be absorbed. If both annihilation gamma rays are absorbed in the detector, the interaction contributes to the full-energy peak in the measured spectrum; if one of the annihilation gamma rays escapes from the detector, the interaction contributes to the single-escape peak located 0.511 MeV below the full-energy peak; if both gamma rays escape, the interaction contributes to the double-escape peak located 1.022 MeV below the full-energy peak. The relative heights of the three peaks, depend on the energy of the incident gamma ray and the size of the detector.

Pair production is impossible for gamma rays with energy less than 1.022 MeV. Above this threshold, the probability of the interaction increases rapidly with energy (see Figure 2.11). The probability of pair production varies approximately as the square of the atomic number Z and is significant in high- Z elements such as lead or uranium. In lead, approximately 20% of the interactions of 1.5 MeV gamma rays are through the pair-production process, and the fraction increases to 50% at 2.0 MeV. For carbon, the corresponding interaction fractions are 2% and 4%. [5]

2.4.2.8 Alpha decay

Alpha decay is the spontaneous emission of an α -particle, namely the ${}^4_2\text{He}$ nucleus. The process can be described by the following formula:



and appears in very few light nuclides and mostly in heavy nuclides. The energy release in an α -emission can be calculated using the above equation:

$$Q = [m_N({}^A_Z\text{X}) - m_N({}^{A-4}_{Z-2}\text{Y}) - m_\alpha]c^2$$

where m represents the mass of the nucleus. Since it's more convenient to deal with atomic masses, we can rewrite the above equation as:

$$Q = [m_N({}^A_Z\text{X}) - m_N({}^{A-4}_{Z-2}\text{Y}) - m({}^4_2\text{He})]c^2$$

where the electron masses are properly accounted for and the electronic binding energy has been ignored. This also assumes that the transitions are “between nuclear ground states.”

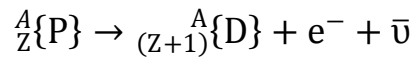
If $Q < 0$ the process is endothermic and cannot occur spontaneously .

If $Q > 0$ the process is exothermic and can occur spontaneously.

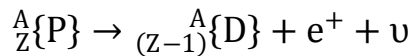
In the latter case the energy is given up to the α -particle and the daughter nucleus in the form of kinetic energy.

2.4.2.9 Beta Decay

β -decay is the radioactive decay of a nuclide in which an electron or a positron is emitted.

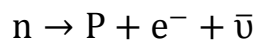


or



The atomic mass number is unchanged so that these reactions occur between “isobars”.

The electron (or positron) does not exist inside the nucleus but is created in the reaction



In fact the neutron has a mass that exceeds the sum of the masses of the proton plus the electron so that a free neutron can undergo this decay with a lifetime of about 11 minutes.

Inside a nucleus such a decay is not always energetically allowed because of the difference in the binding energies of the parent and daughter nuclei. When a neutron is converted into a proton the Coulomb repulsion between the nucleons increases - thereby decreasing the binding energy. Moreover there is a pairing term in the semi-empirical mass formula that favours even numbers of protons and neutrons and a symmetry term that tells us that the number of protons and neutrons should be roughly equal.

β -decay is energetically permitted provided the mass of the parent exceeds the mass of the daughter plus the mass of an electron.

$$M(A, Z) > M((Z + 1), A) + m_e$$

for electron emission, and

$$M(A, Z) > M((Z - 1), A) + m_e$$

for positron emission. In the latter case a proton is converted into a more massive neutron, but the binding energy of the daughter may be such that the total nuclear mass of the daughter is less than that of the parent by more than the electron mass m_e .

Chapter three

Detectors

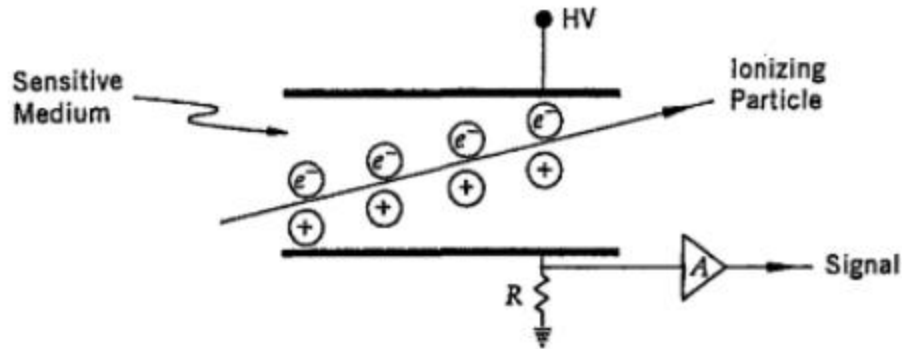
3.1 Introduction

The investigation of nuclear and particle collisions or disintegrations relies upon detectors for measuring the products of such interactions. Although subatomic particles are certainly too small to be observed through purely visual means, we can use the mechanisms for energy deposition to detect such particles. Although we will describe only the very simplest prototype detectors, the principles underlying their performance are similar to those used in even the most sophisticated devices.[7]

3.2 Ionization Detectors

Ionization detectors are devices designed to measure the ionization produced when an incident particle traverses some medium. If the number of detected electrons and positive ions is to reflect the energy deposited in the material, then any produced electron-ion pairs must be kept from immediately recombining into atoms. This can be done by applying a sufficiently high electric field across the medium. This field will separate the charges, start their drift towards their respective electrodes, and thereby keep them from recombining.

The basic ionization detector consists of a chamber that is filled with a suitable medium that can be easily ionized. The chamber has a cathode and an anode that are held at some large relative voltage, and the device is characterized by a capacitance (C) that is determined by the geometry of the electrodes. The operating medium should be chemically stable (or inert) so that the moving ionization electrons are not easily captured by the molecules of that medium. The medium should not be very sensitive to radiation damage so that its response to incident particles does not change markedly with use. In addition, the medium should have a low value of ionization potential (\bar{I}) in order to maximize the amount of ionization produced per energy deposited by any incident particle.



Figure(3.1) Basic elements of an ionization detector

When a charged particle traverses a sensitive region of a detector, it ionizes the medium and produces electron-ion pairs. These start drifting immediately along the electric field lines: electrons to the anode and the positive ions to the cathode. As the charges drift, they induce signals on the electrodes, which provide small currents that flow through some resistor R (see Fig.(3.1)). This, in turn, produces a voltage drop that can be sensed with an amplifier A . The amplifier signal can be analyzed to obtain a pulse height that can be related to the amount of produced ionization. The amount of produced ionization depends primarily on the density and atomic structure of the ionizable medium and, of course, on the charge of and energy deposited by the incident particle. However, the amount of ionization that is detected is determined by many technical factors, foremost among which is the nature and size of the applied electric field, or the applied voltage (see Fig.(3.2))

When the voltage difference between electrodes is small, the electrons and ions can recombine soon after they are produced, and only a small fraction of the produced electrons and ions reach their respective electrodes. This provides an output signal that corresponds to fewer electron-ion pairs than are produced in the medium. The range of operating voltage where this occurs is referred to as the recombination region. As the voltage difference is increased beyond the point where dissociated electron-ion pairs can recombine, we obtain a signal that reflects the total amount of produced ionization. This operating range is called the ionization region.

Increasing the voltage further, provides the initially freed electrons with sufficient acceleration and energy so that they can ionize additional atoms of the medium. This increased ionization is often referred to as signal amplification or

multiplication. The output signal in this operating region of voltages is larger than, but proportional to, the initially produced ionization, and, for this reason, this operating range is referred to as the proportional range. (It should be noted that proportional does not necessarily imply that the signal increases linearly with voltage.) Increasing the voltage even further, yields an avalanche of electron-ion pairs. In this mode, referred to as the Geiger-operating region, the energy of the original ionization electrons increases sufficiently rapidly so that they can excite or ionize more atoms, thereby providing more freed electrons or photons from de-excitation of atoms. This, in turn, produces more electron-ion pairs, and eventually leads to a discharge, that is, to a highly amplified output signal whose size is independent of the amount of original ionization. Finally, increasing the voltage beyond the Geiger range, leads to a breakdown that generates a continuous discharge of the medium, with the chamber no longer being sensitive to any incident ionization. Depending on the circumstances, most detectors are operated as ionization, proportional, or Geiger counters, depending on the circumstances, and most detectors use gas as the operating medium.[7]

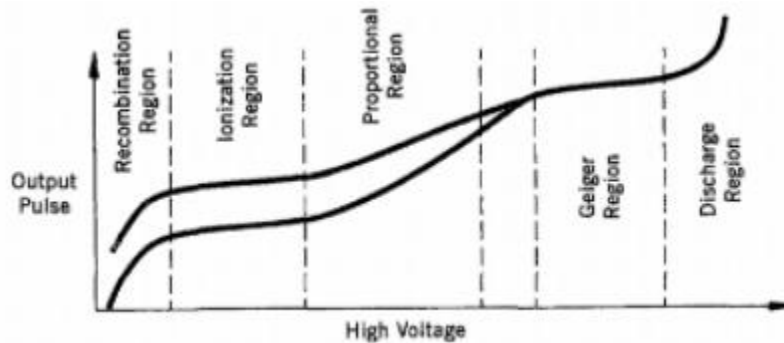


Figure (3.2) Signal response to ionization loss as a function of imposed voltage for heavily ionizing (top curve) and minimum ionizing particles (lower curve). In the Geiger region, the output does not depend on the voltage, nor on the amount of deposited energy or initial ionization.

3.2.1 Ionization Counters

Ionization chambers, or ionization counters, operate at relatively low voltages, and therefore provide no amplification of the original signal. Consequently, the output pulses for single minimum-ionizing particles tend to be quite small and usually require special low-noise amplifiers for attaining efficient operating performance. For heavily ionizing nuclear fragments, however, or for a flux of many particles, the fully integrated signals can be substantial and easy to detect. Ionization chambers are not very sensitive to voltage variations, and provide very linear output response for a wide range of input signals. Because there is no inherent amplification of signal, or discharge in the operating medium, these types of counters do not require much time to recover from large currents, and can therefore be used in environments with high interaction rates. In addition, because there is no amplification, they provide excellent energy resolution, which is limited primarily by electronic noise and by the inherent fluctuations in the production of the initial ionization. Liquid-argon ionization chambers have been used with great success as "sampling" detectors in high-energy calorimetric measurements of energy deposition (to be discussed later). Solid-state devices, pioneered in nuclear physics, are now used commonly as ionization counters in high energy experiments. Gaseous ionization chambers are useful for monitoring high levels of radiation; they were also used in the past to measure, for example, ranges of α -particles from radioactive decays of nuclei.

Let us illustrate how an ionization counter can be employed to determine the range of 5.25 MeV α -particles emitted in $^{210}_{84}\text{Po}$ decay. The chamber can be chosen to be a precisely manufactured round-bottom flask with a radius of about 6 cm. The inside wall can be silver coated to serve as one of the two electrodes. A small sample of Po (about 10 μCi) can be suspended from a grounded insulated wire at the center of the flask. An operating gas can be admitted, under pressure if need be, and the flask sealed. (Alternatively, the chamber can be simply a parallel-plate device that has the α -particle source embedded on one of the surfaces.) A potential can be applied to the silvered surface, and the current monitored through an amplifier, as sketched in Fig(3.2) .If the ionizing medium is air, then we expect to produce a small but detectable current. The value of \bar{I} for air is about 30 eV; thus,

the number of electron-ion pairs that will be produced by one α -particle will be about

$$n = \frac{5.25 \times 10^6 eV}{30 eV} = 1.75 \times 10^5 \quad (3.1)$$

The activity of the source is

$$\begin{aligned} A &= 10 \mu\text{Ci} = 10 \times (10^{-6} \times 3.7 \times 10^{10}) \alpha\text{-particle/sec} \\ &= 3.7 \times 10^5 \alpha\text{-particle/sec.} \end{aligned}$$

Hence, the number of charged pairs produced per second is

$$N = nA = (1.75 \times 10^5) \times (3.7 \times 10^5 / \text{sec}) \approx 6.5 \times 10^{10} / \text{sec.}$$

Consequently, if both the positive and negative charges are collected, this will provide a current

$$\begin{aligned} J &= Ne = 6.5 \times 10^{10} / \text{sec} \times 1.6 \times 10^{-19} \text{C} \\ &= 1.04 \times 10^{-8} \text{C/sec} = 1.04 \times 10^{-8} \text{A.} \end{aligned}$$

Currents of this size can be measured in a straightforward manner. (For the parallel-plate geometry, the current would be only ≈ 5 nA, because only half of the α -particles would be emitted into the sensitive region.)

The measurement of range proceeds as follows. The current is monitored as a function of decreasing gas (air) pressure. As long as the density of the air is high enough to stop the α -particles, the observed current, reflecting the total ionization produced by the α -particles, remains constant. When the pressure drops below that critical value, the α -particles do not lose all their kinetic energy within the gas volume, and therefore produce fewer electron-ion pairs in the sensitive region. As a result, the current drops, and keeps decreasing as the pressure is decreased further. For an α -particle range of 6 cm in air, at a temperature of 25°C, the critical pressure P_{crit} is found to be 51 cm of Hg. Thus, at any other temperature and pressure, the range R can be calculated assuming the scaling of the simple gas law. In particular, for standard conditions of $T = 288$ K and $P = 76$ cm of Hg, we obtain

$$R = R_{\text{crit}} \times \frac{P_{\text{crit}}}{P} \frac{T}{T_{\text{crit}}} = 6\text{cm} \times \frac{51 \text{ cm Hg}}{76 \text{ cm Hg}} \frac{288 \text{ K}}{298 \text{ K}} = 3.9 \text{ cm}.$$

Although, in principle, the observed current provides an absolute measure of the total energy deposited in the form of ionization, it is always wise to calibrate ionization chambers with sources or signals of known energy. This is particularly important when counting rates are very high and individual pulses must be counted in rapid succession. Under such conditions, small concentrations of impurities in the detector medium (often at less than a part per million level) can cause loss of electron signal through attachment. That is, some of the electrons drifting towards the anode can be attracted to the contaminant (electronegative) molecules that can form negative ions, which drift far slower than electrons, and therefore do not contribute to the fast output pulse that is produced by the electrons.[7]

3.2.2 Geiger-Müller Counters

A Geiger-Müller counter, or simply a Geiger counter, is an ionization detector that operates in the Geiger range of voltages, namely at a voltage high enough so that any produced ionization causes a gaseous discharge, independent of the initial energy deposited in the medium. To appreciate the advantage of a Geiger counter, let us consider the example of an electron, with a kinetic energy of 0.5 MeV, that loses all its energy within the counter. Suppose that the gaseous medium is helium, with an average ionization energy of 42 eV. The number of electron-ion pairs produced in the gas will be:

$$n = \frac{0.5 \times 10^6 \text{ eV}}{42 \text{ eV}} \approx 12,000$$

If the detector operates as an ionization chamber, and has a capacitance of $\approx 10^9 \text{ F} = 1 \text{ nF}$, then the resulting voltage signal would correspond to

$$V = \frac{Q}{C} = \frac{ne}{C} = \frac{(12 \times 10^3)(1.6 \times 10^{-19} \text{ C})}{10^{-9} \text{ F}} \approx 2 \times 10^{-6} \text{ V}$$

which is very small, indeed. On the other hand, if the detector operates in the Geiger mode, because of multiplication, the expected number of ion pairs would be $\approx 10^{10}$, independent of electron energy. Consequently, the voltage pulse in this case would be a large and easily detectable signal.

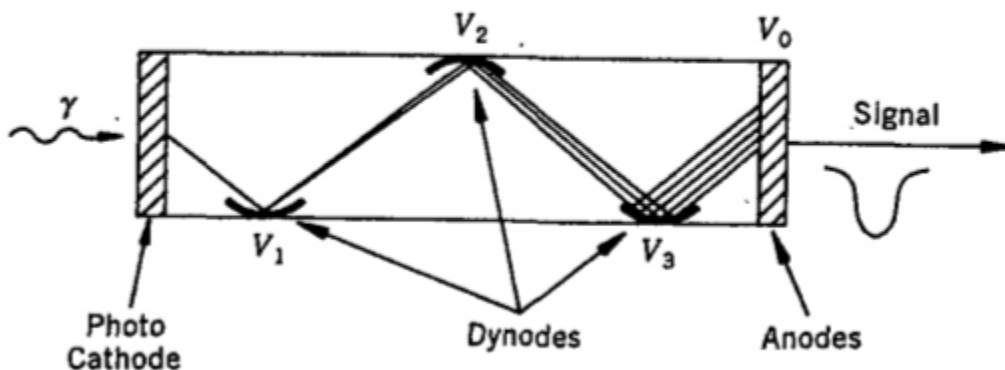
The technical advantage of a Geiger counter is its simplicity of construction and its insensitivity to small voltage fluctuations. It is very useful for general measurement of nuclear radiation, but it has two important disadvantages. First, there is no information whatsoever on the nature of the ionization that caused the pulse. Second, because of the large avalanche induced by any ionization, a Geiger counter takes a long time (about 1 ms) to recover between successive pulses, and so it has a substantial dead-time, which means that it cannot be used for high counting rates.[7]

3.2.3 Scintillation Detectors

The ionization produced by charged particles can excite atoms and molecules in the medium to higher energy levels. When these atoms and molecules de-excite, they emit light that, in principle, can be detected and provide evidence for the traversal of the charged particle. Scintillators are kinds of materials that provide detectable photons in the visible part of the light spectrum, following the passage of a charged particle. There are primarily two types of scintillators in common use in nuclear and particle physics: organic or plastic scintillators and inorganic or crystalline scintillators. Although the physics of light emission is different in the two kinds of scintillators, and somewhat complicated, it is nevertheless well understood, but we will not discuss it here in any detail. Organic scintillators, such as anthracene or naphthalene, tend to emit ultraviolet light in their molecular de-excitation. Unfortunately, light of such frequency is rapidly attenuated, and consequently "wavelength shifter" material has to be admixed with the scintillator to permit detection of photons. That is, the initially produced light interacts with the wave-shifter material, which shifts the light to the visible part of the spectrum. Inorganic crystals, such as NaI or CsI, are usually doped with activators that can be excited by electron-hole pairs produced by charged particles in the crystal lattice; these dopants can then de-excite through photon emission.

Organic scintillators have fast decay times (typically $\approx 10^{-8}$ sec), while inorganic crystals are usually far slower ($\approx 10^{-6}$ sec) although some also have fast components in their response. Plastic scintillators are therefore more appropriate for use in high-flux environments. It takes substantially more energy to produce a detectable photon in a scintillator than an electron-ion pair through ionization (typically by a factor of 10), and because inorganic scintillators produce more light than organic scintillators, they are consequently better for applications at low energies.

In the pioneering days of nuclear studies, different phosphors were used routinely in experiments, and viewed by eye. The light produced in scintillators is usually very weak and normally cannot be seen in this manner. For scintillation light to be detected, the scintillator material must be transparent to its own radiation, that is, it cannot have a short attenuation length at the frequencies of interest. In addition, because of the low intensity of the emitted light, the photon signal must somehow be amplified in order to be counted. Signal amplification is achieved most commonly by using photomultiplier tubes (PMT) that view the scintillator either directly or through light guides. A photomultiplier tube converts a weak photon signal to a detectable electric pulse. The device consists of several components (see Fig 3.2.3.1)) .First, right after a thin entry window, is a photocathode, which is made



Figure(3.3)Sketch of the main elements of a photomultiplier tube. The most common tubes have ≈ 5 cm diameters and are about ≈ 20 cm long.

of material in which the valence electrons are weakly bound and have a high cross section for converting photons to electrons via the photoelectric effect. As a result, any photon striking the photocathode will have a high probability for releasing an electron. (Cathode diameters are typically 212 cm, but far larger PMTs are also available.) Next, within the tube, there is a series ("stages") of dynodes made of material of relatively low work function. These electrodes are operated at ever increasing potential $\Delta V \approx 100 - 200 \text{ V}$ (between dynodes), which can be provided, for example, through a regulated DC power supply and a resistor-divider chain. The dynodes accelerate the initial electrons to the next stage, and multiply them through secondary emission at each dynode. There are typically 6-14 dynode stages in PMTs, with a total gain, or electron amplification factor, in the range of $\approx 10^4 - 10^7$ (usually the multiplication factor is $\approx 3-5$ per dynode). The voltage is applied to the electrodes through pins embedded at the back end of the glass PMT; these pins are connected directly to the dynodes that are located within the vacuum region of the tube.

The quantum conversion efficiency of the photocathodes is typically ≈ 0.25 in the usual range of operating wavelengths ($\approx 400 \text{ nm}$). The output signal is usually taken from the anode or last dynode of the PMT. Except for statistical fluctuation, this signal is linearly proportional to the amount of light incident on the photocathode. Although there is some spread in the time of arrival of the signal due to different electron transit times (different paths and different velocities), this is typically only several nanoseconds. The output signals are therefore quite narrow, and, in conjunction with fast plastic scintillators, can be used very effectively for triggering any detector system on interesting events, and for timing intervals between successive signals.

A scintillator used in conjunction with a photomultiplier is consequently an excellent detector of charged particles, and of any photons or neutrons that interact within the scintillator material. As an example, let us consider the β -decay of ${}^{60}_{27}\text{Co}$



The $^{60}_{28}\text{Ni}$ nucleus in this decay is, in fact, left in an excited state and decays to the ground level through two successive photon emissions: one of 1.17 MeV to the first excited level, which is followed by a 1.33 MeV photon to the ground level. Let us suppose that the $^{60}_{27}\text{Co}$ sample is mounted on the front face of a NaI(Tl) crystal (thallium activated NaI scintillator), and a PMT is attached to the opposite side of the crystal. Because the anticipated signals are small, the crystal and PMT must be properly wrapped to prevent external light from leaking into the detector. Also, because crystals such as NaI are often hygroscopic, they must be well sealed to prevent deterioration through absorption of moisture. (Plastic scintillators do not have this disadvantage).

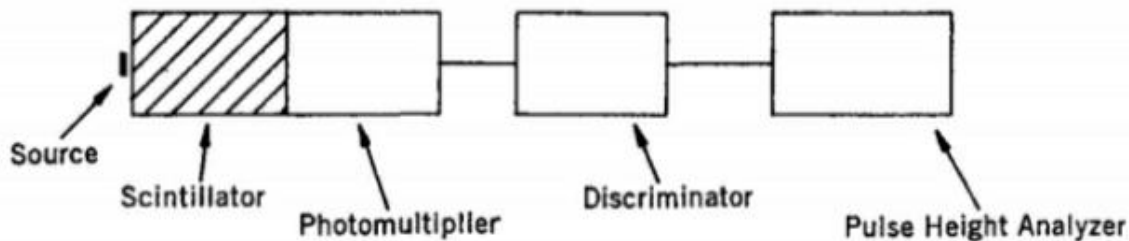


Figure (3.4) Block diagram of apparatus needed for measuring the decay products in the decay of $^{60}_{27}\text{Co}$

When photons from the de-excitation of $^{60}_{28}\text{Ni}$ enter the scintillator, they can interact through the photoelectric effect, through Compton scattering or through e^+e^- pair production. Any photon that is converted to a photoelectron through the photoelectric effect generally deposits all of its energy within the scintillator in the form of ionization produced by the emitted electron. The intensity of the subsequently produced scintillation light is therefore proportional to the energy of the original photon. On the other hand, photons that undergo Compton scattering usually do not deposit all their energy within the scintillator, unless that scintillator block is exceedingly large. That is, although the scattered electrons often deposit their entire energy, the scattered photons tend to escape from the scintillator. (The radiation length of NaI is about 2.6 cm, while that of plastic scintillator is about 40 cm. It is therefore not surprising that, for detectors several cm on a side, only a

fraction of the energy of the incident photon is converted into ionization, and some leaves the detector.) Pair production is exceedingly unlikely for low-energy photons, but, when it occurs, the produced electron and positron deposit their kinetic energy in the scintillator, and eventually the positron annihilates with an atomic electron, yielding two 0.511 MeV photons.

Consequently, ignoring the low-energy electron in, the energy deposited in the NaI will, in general, have two kinds of contributions: First, the full energies of any of the photons that convert into photoelectrons, and, second, a continuous spectrum of energies deposited by the Compton-scattered recoil electrons. The scintillation light and the output from the PMT will therefore have signals equivalent to the deposition of 1.17 MeV, 1.33 MeV, and a continuum of energies below these peak values. (If enough 0.511 MeV photons are produced from the annihilation of e^+e^- pairs, they can provide photoelectrons and therefore a very useful calibration signal at 0.511 MeV.) The PMT output signals can be passed through a discriminator to eliminate any small signals from pulses produced through thermal electron emission from the cathode and dynode surfaces ("random noise"). After discrimination, the pulses can be digitized and displayed on a pulse-height analyzer (see Fig. (3.4). Because of fluctuations in ionization loss, differences in the efficiency of light collection, and fluctuations from electron multiplication, the 1.17 MeV and the 1.33 MeV energy signals will not be sharp, but will have a shape that reflects the experimental resolution of the detector system. The energy resolution for NaI(Tl) crystals in this range is about 10%.) We should point out that our simplified discussion has ignored the possibility of the simultaneous observation of the summed signals from the two emitted photons.[7]

Chapter four

Practical

4.1 Introduction

This chapter contains the practical results of the experiment and the discussion of these results.

4.2 Instruments

X-ray apparatus –different material –GM counter -



(a) X-ray apparatus



(b) GM counter

Figure (4.1) Instruments of X-ray and Gamma ray

4.3 The Method

In this experiment the attenuation coefficient of X and gamma ray is studied by exposed six samples from different material (Al, Fe, Ni, Cu, Glass and Plastic) with different thickness for X and gamma ray.

The results were written on tables below and the relationship between the thickness (d(mm)) and the rate of radiation(R/s) was draw for each element in gamma ray experiment. The relationship between the thickness (d (mm)) and Ln T(T is transmission of the radiation) was draw for reach element in gamma ray experiment.

The attention coefficient of X and gamma ray was calculated from the curve of each element.

4.4 Results

Table (4.1) the relationship between the thickness of aluminum plates and the rate of gamma ray radiation

Al	
d(mm)	R/sec
0	5864
1	5853
2	5557
3	5455
4	5336
5	5291

Table (4.2) the relationship between the thickness of iron and the rate of gamma ray radiation

Fe	
d(mm)	R/sec
0.00	5864
0.28	5616
0.56	5481
0.84	5395
1.12	5199
1.40	5103

Table (4.3) the relationship between the thickness of nickel and the rate of gamma ray radiation

Ni	
d(mm)	R/sec
0	5864
0.53	5485
1.06	5446
1.59	5381
2.12	5344
2.65	5121

Table (4.4) the relationship between the thickness of copper and the rate of gamma ray radiation

Cu	
d(mm)	R/sec
0	5864
0.2	5672
0.4	5470
0.6	5420
0.8	5387
1.00	5213

Table (4.5) the relationship between the thickness of glass and the rate of gamma ray radiation

Glass	
d(mm)	R/sec
0	5864
4.68	5459
9.36	5062
14.04	4828
18.72	4564
23.4	4374

Table (4.6) the relationship between the thickness plastic and the rate of gamma ray radiation

Plastic	
d(mm)	R/sec
0	5864
0.61	5853
1.22	5557
1.83	5455
2.44	5336
3.05	5103

Table (4.7) the relationship between the thickness of aluminum and transimition of gamma ray.

Al			
d(mm)	R/sec	$T = R_0/R$	$\ln T$
0	5864	1	0
1	5853	0.998	0.002
2	555	0.948	0.053
3	5455	0.930	0.072
4	5336	0.910	0.094
5	5291	0.900	0.11

Table (4.8) the relationship between the thickness of iron and transimition of gamma ray.

Fe			
d(mm)	R/sec	$T = R/R_0$	$\ln T$
0	5864	1	0
0.28	5616	0.957	0.044
0.56	5481	0.934	0.068
0.84	5395	0.920	0.083
1.12	5199	0.887	0.119
1.40	5103	0.870	0.139

Table (4.9) the relationship between the thickness of nickel and transimition of gamma ray.

Ni			
d(mm)	R/sec	$T = R/R_0$	$\ln T$
0	5864	1	0.0
0.53	5485	0.935	0.067
1.06	5446	0.928	0.075
1.59	5381	0.918	0.085
2.12	5344	0.911	0.093
2.65	5121	0.873	0.136

Table (4.10) the relationship between the thickness of copper and transimition of gamma ray.

Cu			
d(mm)	R/sec	$T = R/R_0$	$\ln T$
0	5864	1.0	0
0.2	5672	0.967	0.034
0.4	5470	0.933	0.069
0.6	5420	0.924	0.079
0.8	5387	0.918	0.085
1.0	5213	0.889	0.118

Table (4.11) the relationship between the thickness glass and transimition of gamma ray.

Glass			
d(mm)	R/sec	$T = R/R_0$	$\ln T$
0	5864	1	0
4.68	5459	0.936	0.073
9.36	5062	0.863	0.157
14.04	4828	0.825	0.195
18.72	4564	0.778	0.251
23.4	4374	0.746	0.293

Table (4.12) the relationship between the thickness of plastic and transimition of gamma ray.

Plastic			
d(mm)	R/sec	$T = R/R_0$	$\ln T$
0	5864	1	0
0.61	5853	0.998	0.003
1.22	5557	0.947	0.054
1.83	5455	0.930	0.073
2.44	5336	0.910	0.094
3.05	5103	0.870	0.139

Table (4.13) the relationship between the thickness aluminum and the rate of X- ray.

Al X-ray	
d(mm)	R/sec
0	509.87
0.5	189.89
1	84.99
1.5	39.61
2	19.42
2.5	11.11
3	5.01

Table (4.14) the relationship between the thickness aluminum and transmission of X- ray.

Al X-ray			
d(mm)	R/sec	$T = R/R_0$	$\ln T$
0	509.87	1	0
0.5	189.89	0.372	0.988
1	84.99	0.167	1.790
1.5	39.61	0.078	2.551
2	19.42	0.038	3.270
2.5	11.11	0.022	3.816
3	5.01	0.010	4.605

Table (4.15) the relationship between the thicknesses of different material and the attenuation coefficient of X-ray.

	R/sec	$T = R/R_0$	$\ln T$	$\mu = \ln T/d$
None	1300.83	1	0	0
C	1269.23	0.976	0.0242	0.0484
Al	708.17	0.544	0.609	1.218
Fe	42.860	0.033	3.411	6.822
Cu	3.733	0.003	5.809	11.618
Zr	54.263	0.042	3.170	6.34
Ag	13.55	0.010	4.605	9.21

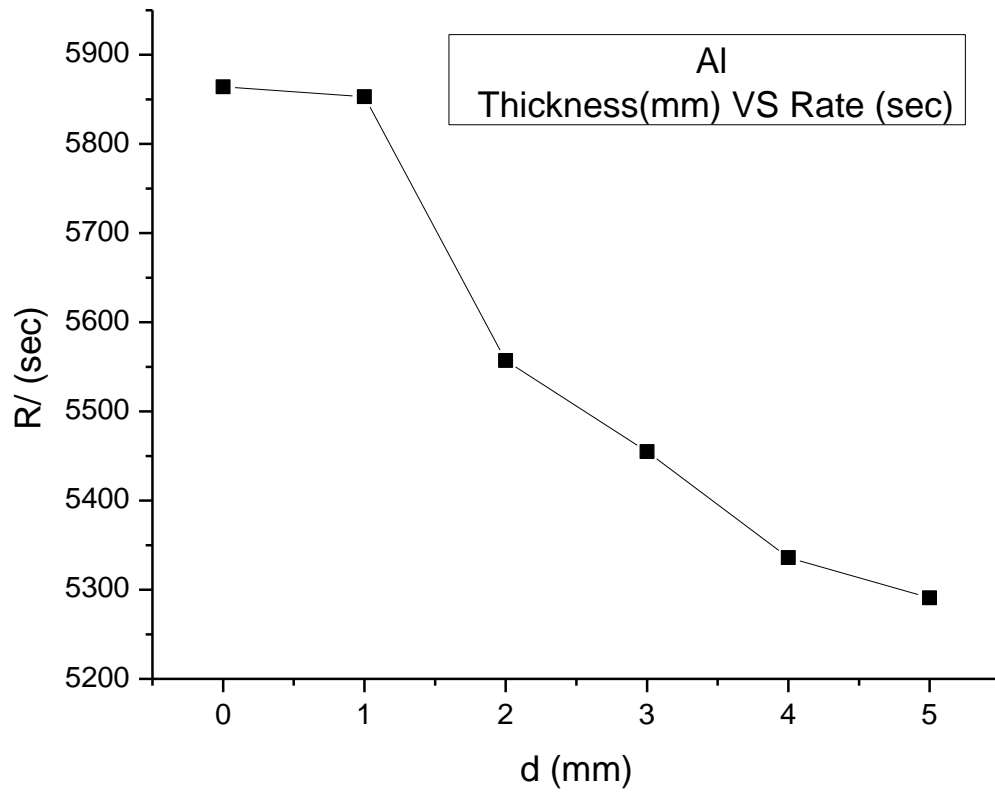


Figure (4.2) the relationship between the thickness of aluminum and the rate of gamma ray.

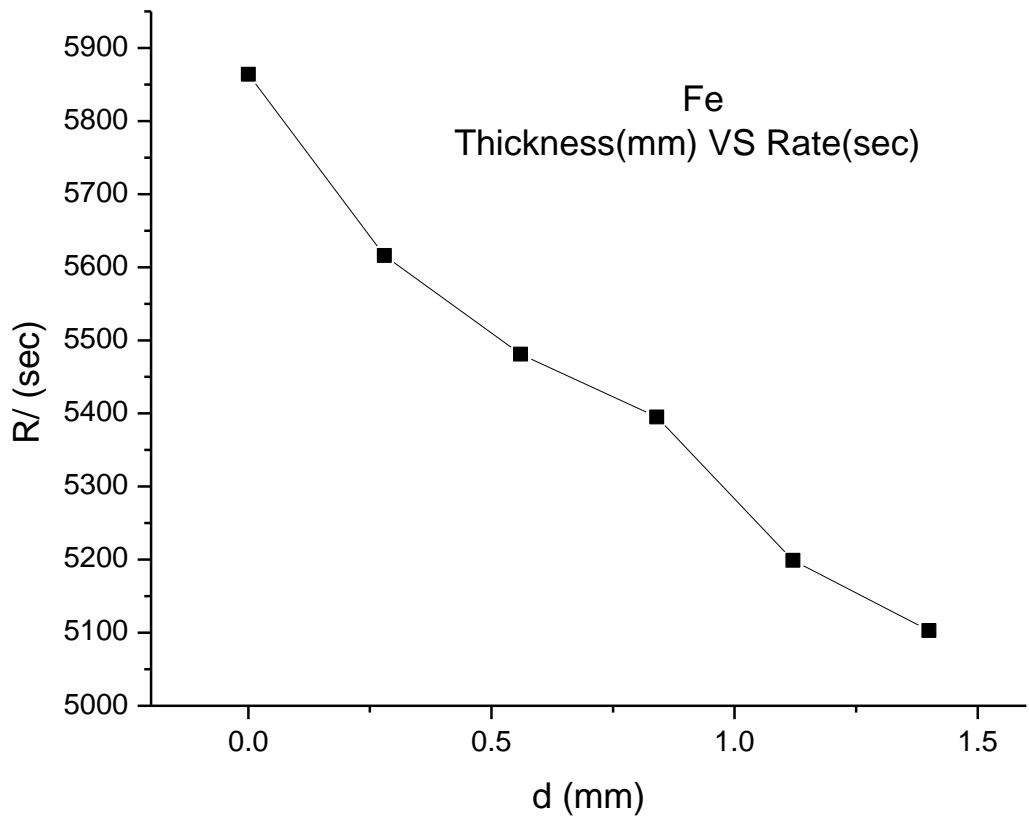


Figure (4.3) the relationship between the thickness of iron and the rate of gamma ray.

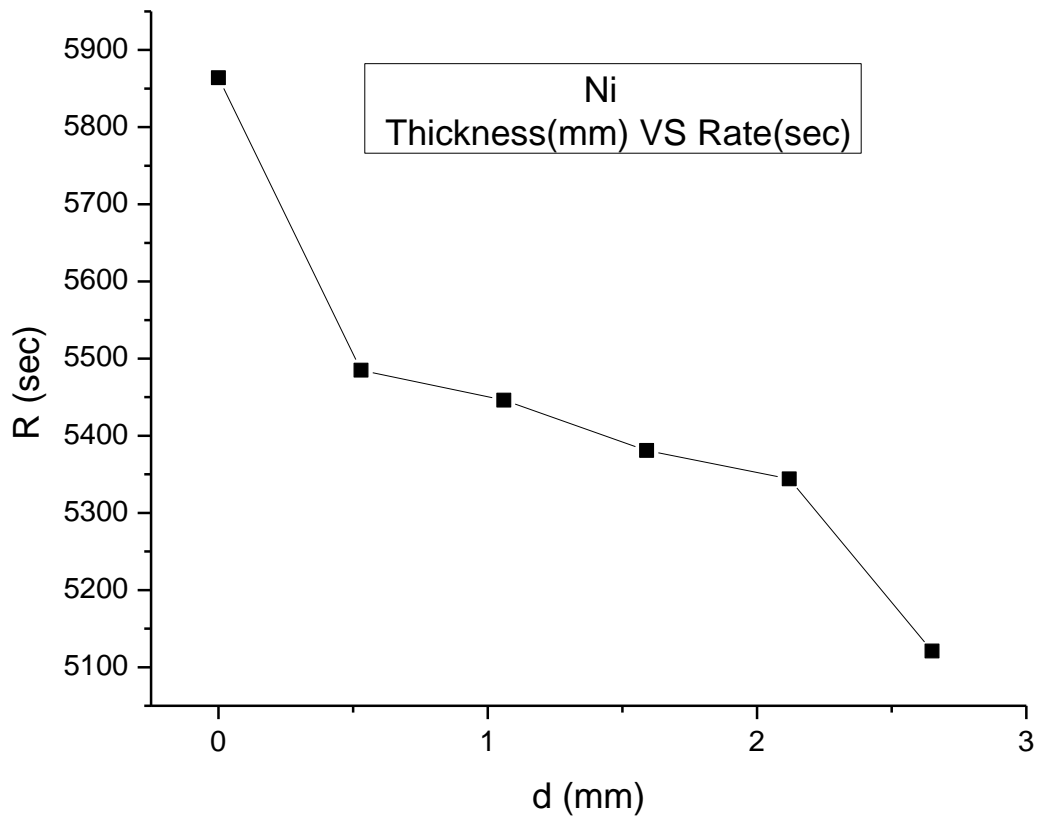


Figure (4.4) the relationship between the thickness of nickel and the rate of gamma ray.

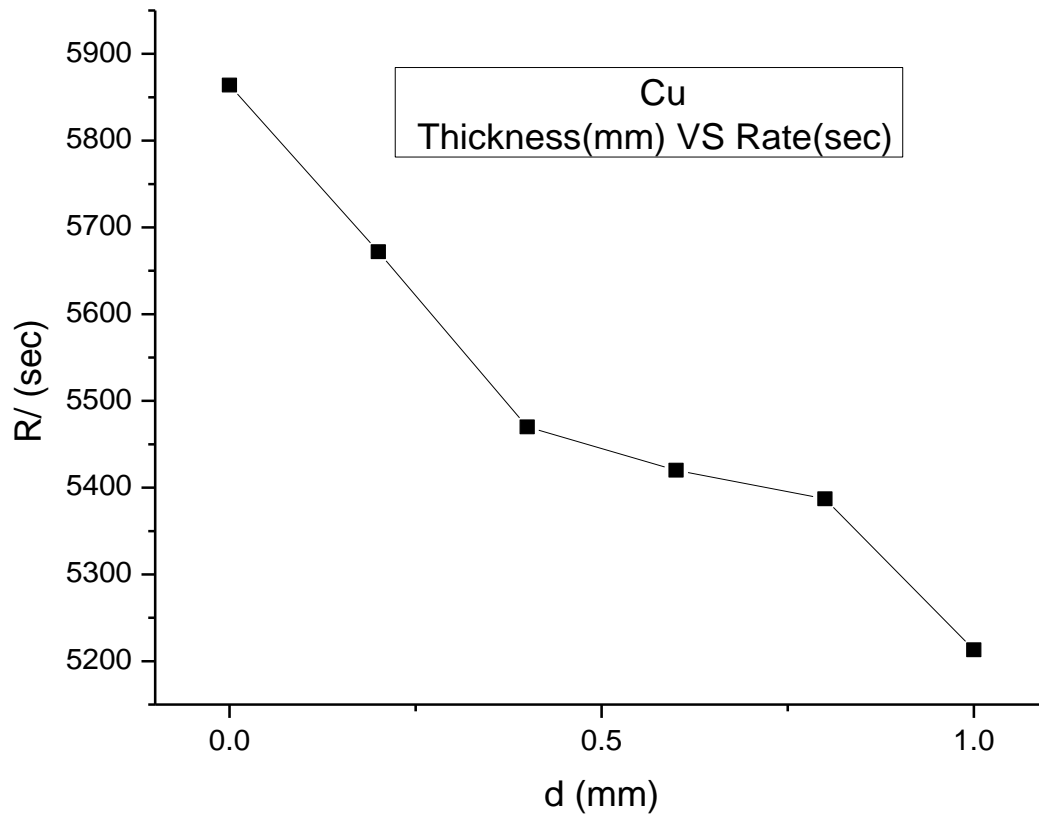


Figure (4.5) the relationship between the thickness of copper and the rate of gamma ray.

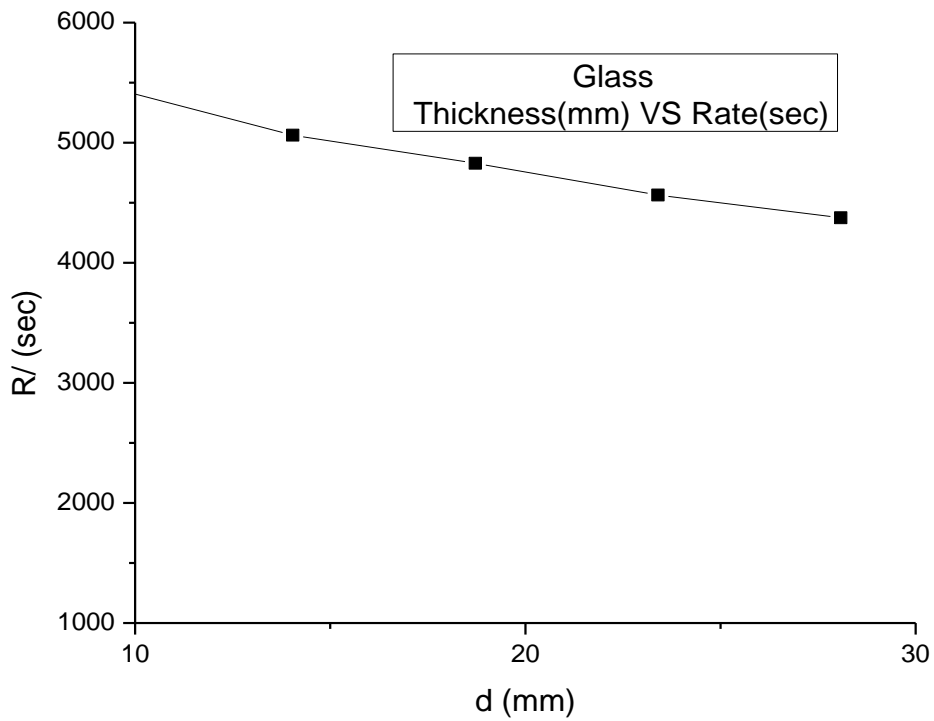


Figure (4.6) the relationship between the thickness of glass and the rate of gamma ray.

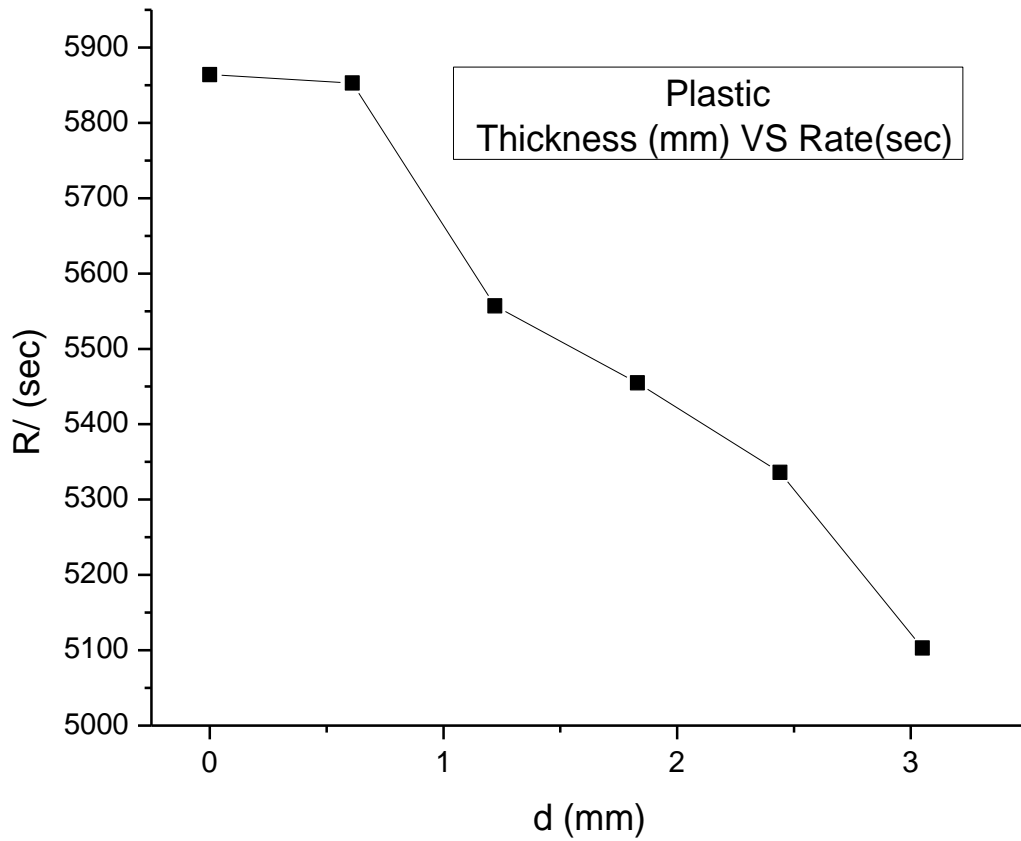


Figure (4.7) the relationship between the thickness of plastic and the rate of gamma ray.

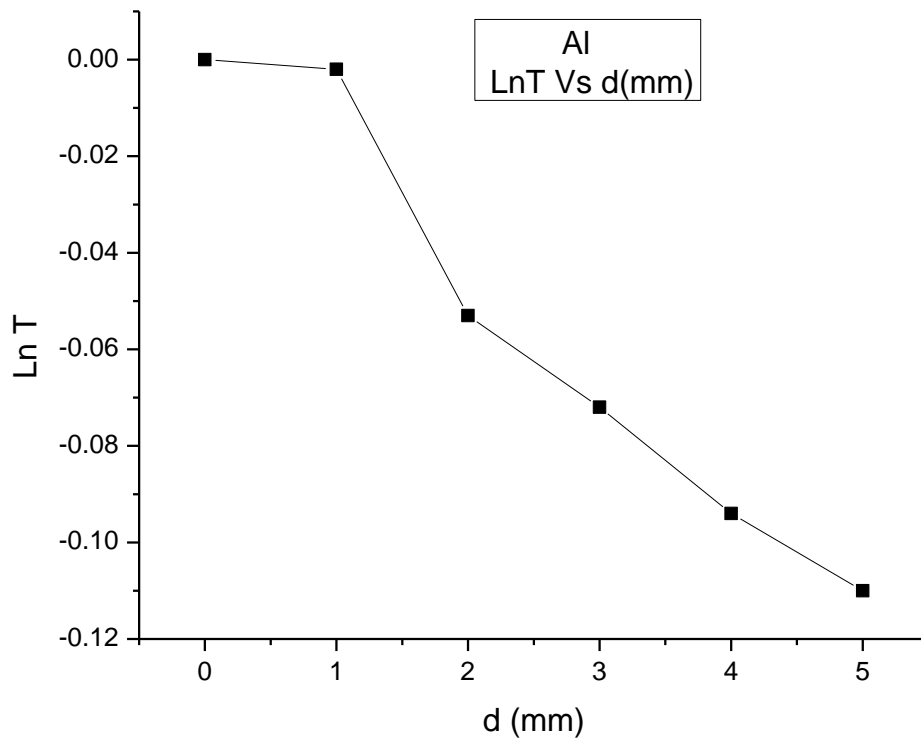


Figure (4.8) the relationship between the thickness of aluminum and the transmission of gamma ray.

$$\mu = \text{Slope} = \frac{\ln T}{d} = 0.0235 \text{ m}^{-1}$$

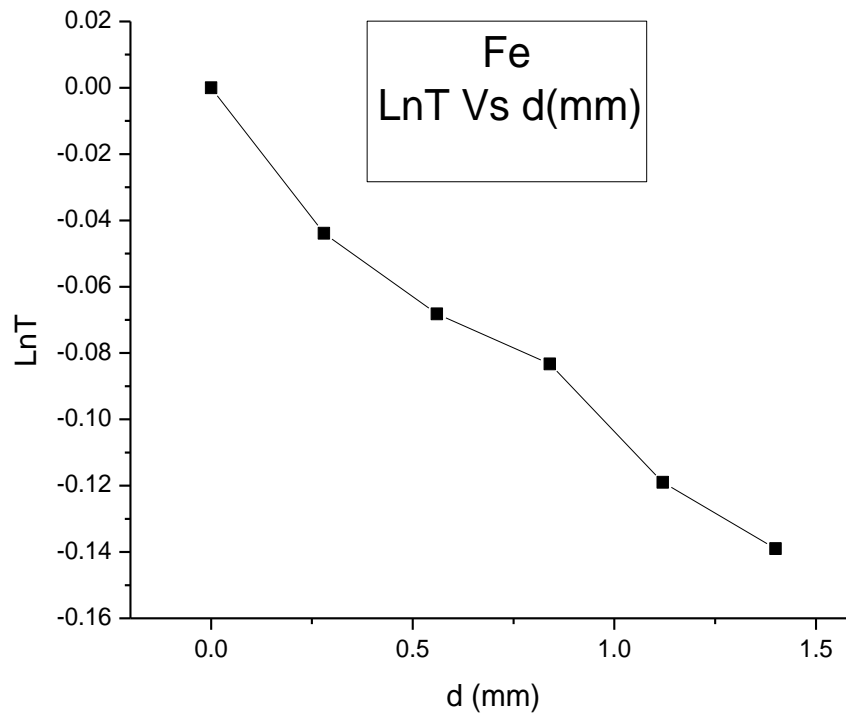


Figure (4.9) the relationship between the thickness of iron and the transmission of gamma ray.

$$\mu = \text{Slope} = \frac{\ln T}{d} = 0.085 \text{ m}^{-1}$$

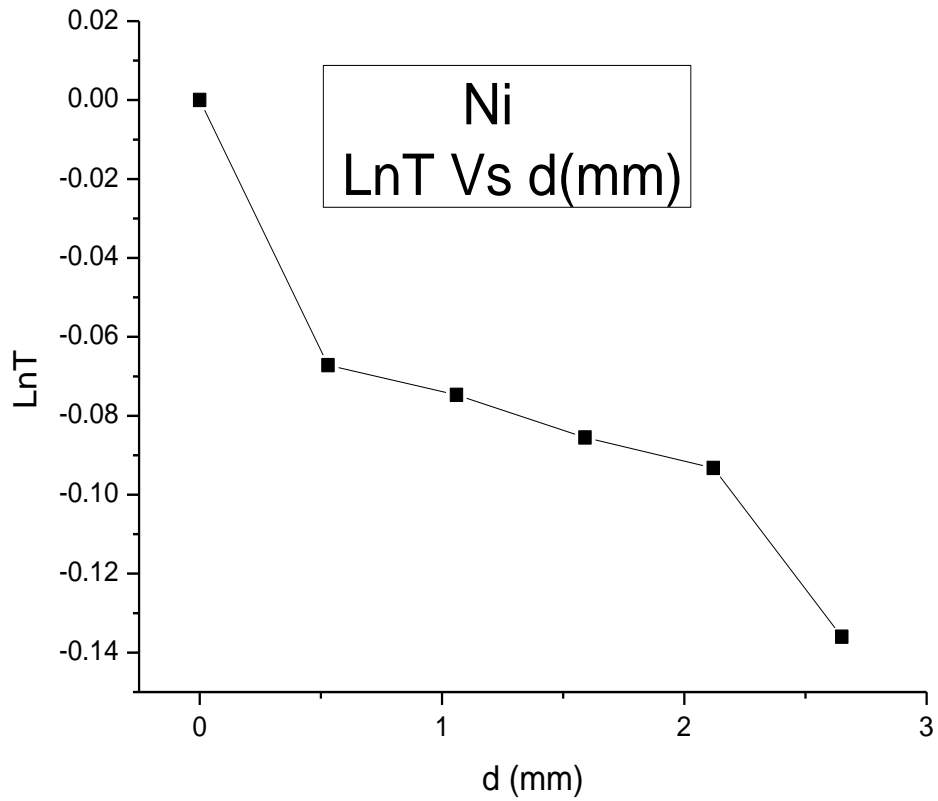


Figure (4.10) the relationship between the thickness of nickel and the transmission of gamma ray.

$$\mu = \text{Slope} = \frac{\ln T}{d} = 0.052 \text{ m}^{-1}$$

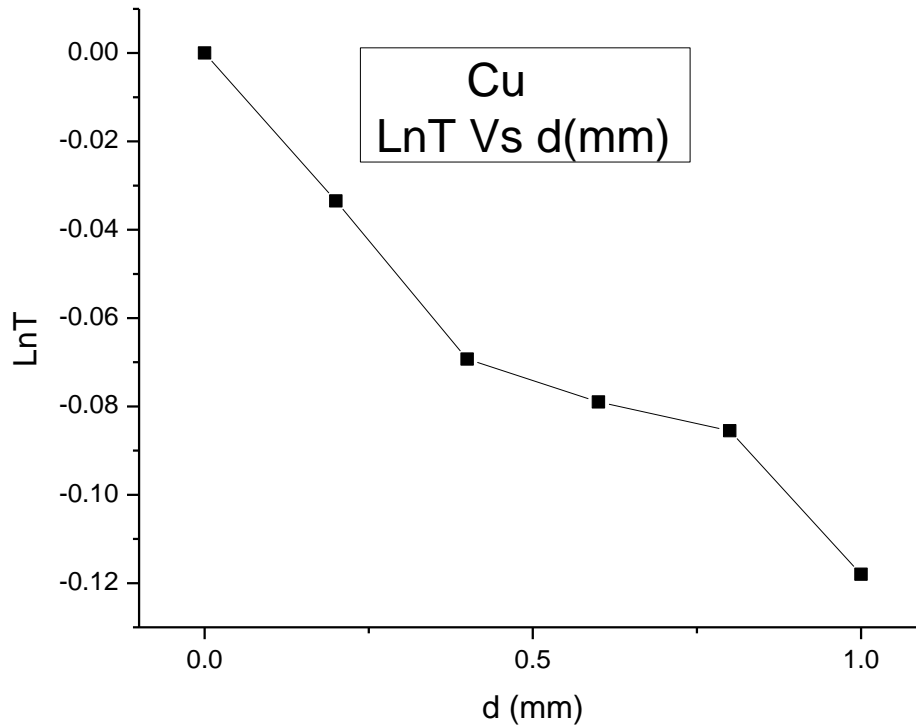


Figure (4.11) the relationship between the thickness of copper and the transmission of gamma ray.

$$\mu = \text{Slope} = \frac{\ln T}{d} = 0.103 \text{ m}^{-1}$$

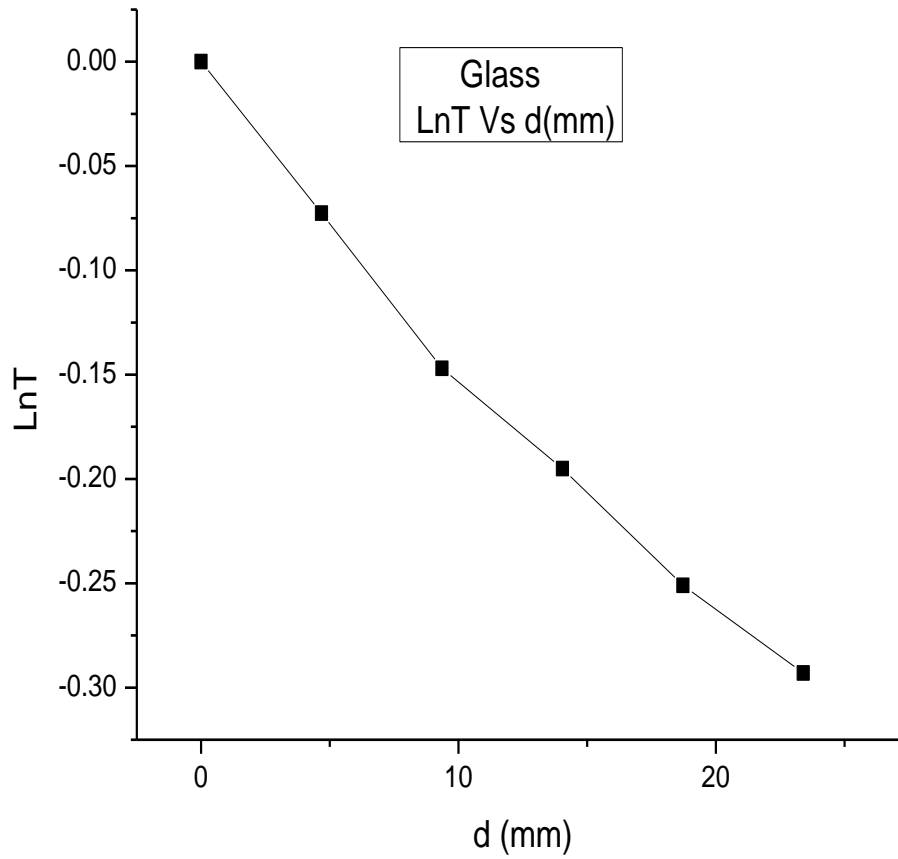


Figure (4.12) the relationship between the thickness of glass and the transmission of gamma ray.

$$\mu = \text{Slope} = \frac{\ln T}{d} = 0.012 \text{ m}^{-1}$$

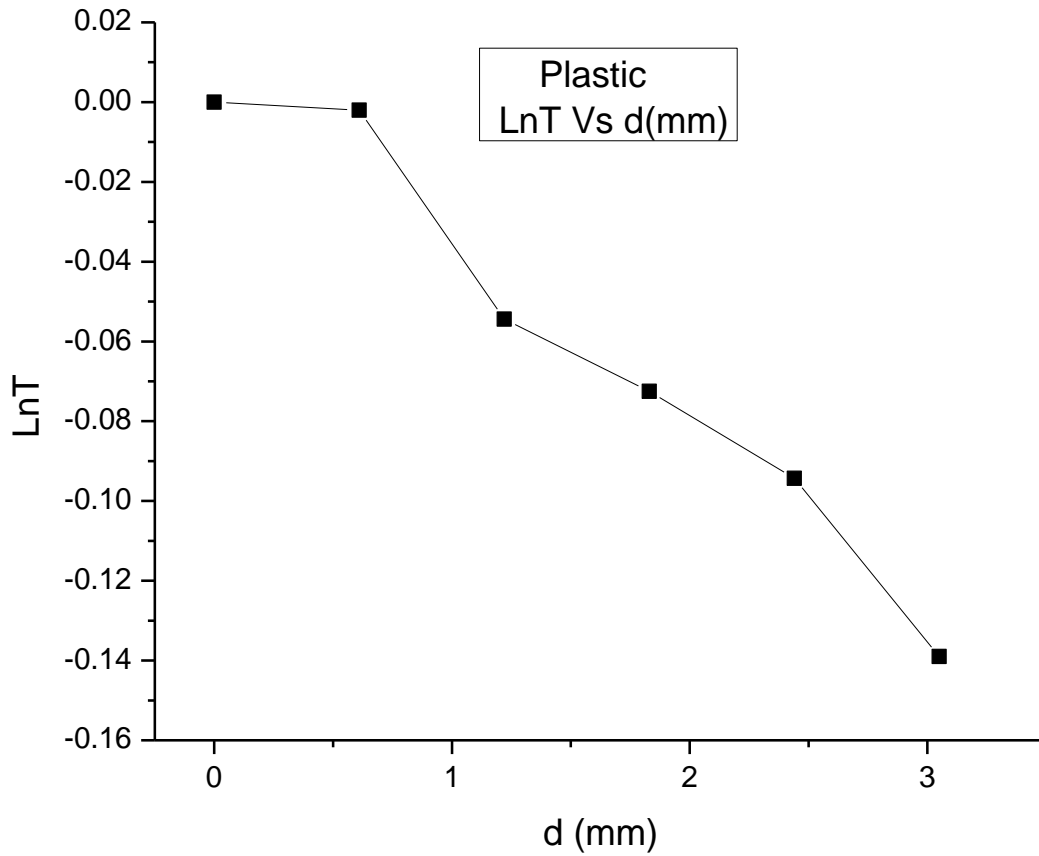


Figure (4.13) the relationship between the thickness of plastic and the transmission of gamma ray.

$$\mu = \text{Slope} = \frac{\ln T}{d} = 0.028 \text{ m}^{-1}$$

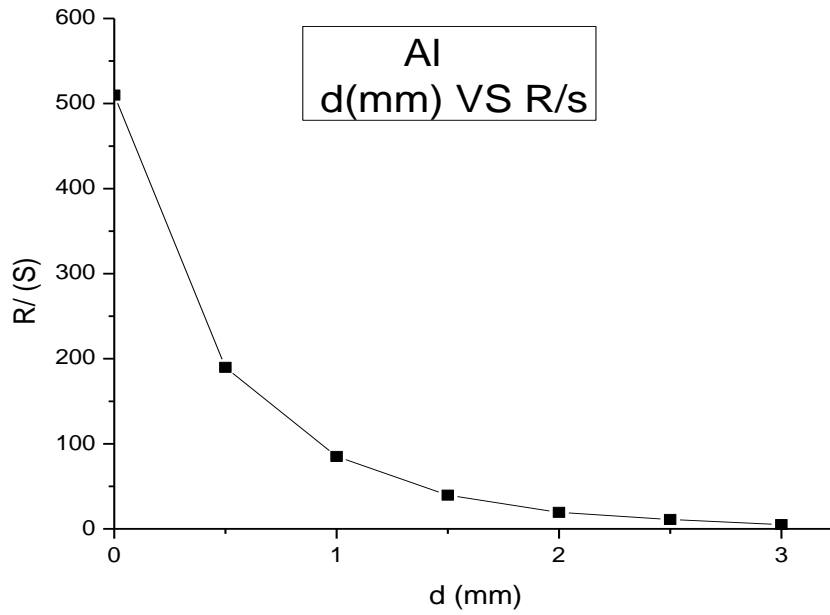


Figure (4.14) the relationship between the thickness of aluminum and the rate of X-ray.

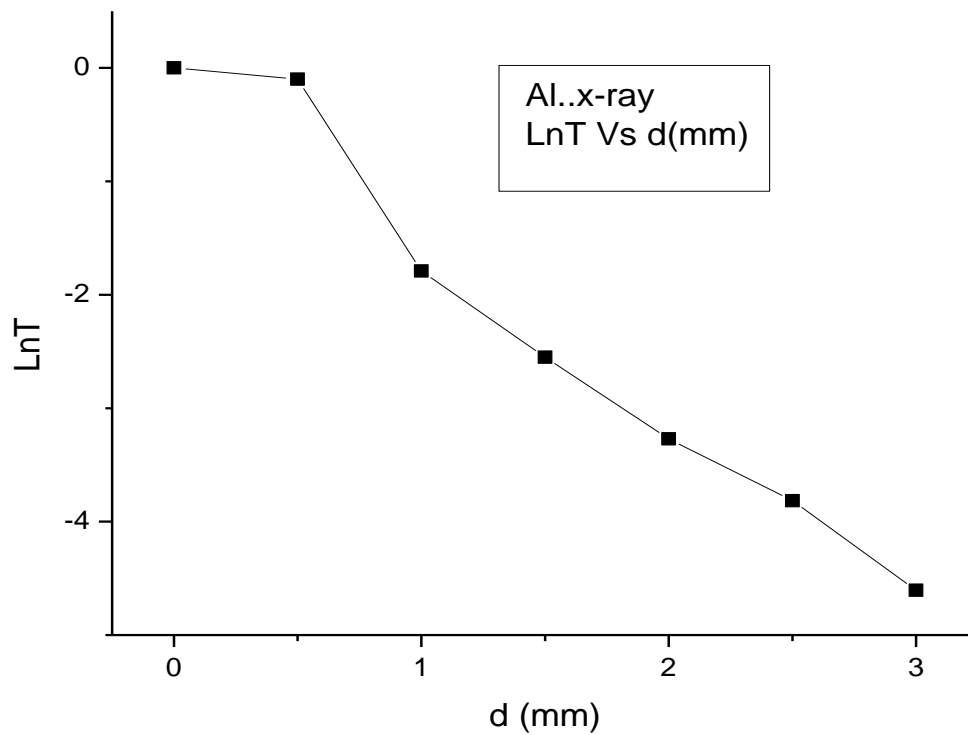


Figure (4.15) the relationship between the thickness of aluminum and the transmission of X-ray.

$$\mu = \text{Slope} = \frac{\ln T}{d} = 1.5 \text{ m}^{-1}$$

4.5 Discussion

From the figures [(4.7), (4.8) and(4.9)] and table (4.15) it clear that the relation between R/s and the thickness The rate decrease exponentially and attenuation coefficient for (Al) in X –ray is equals 1.2 while in gamma ray is equals 0.0235 and for (Fe) in X-ray is 6.82 while in gamma ray is 0.6875 and for Cu in X-ray is 11.7 while for gamma ray is 0.103.

It's clear that the attenuation coefficient when subjected to gamma radiation is small compared to X-ray.

The maximum value of attenuation obtained for Cu which will be the best shield in our study.

4.6 conclusion

Gamma is higher energetic radiation than X-ray in its reaction with mater and its attenuation coefficient depend on the type of material.

4.7 Recommendation

- Different sample must used to study the attenuation either with X-ray or Gamma ray
- Simulation must be hold and carried out in order to compare the result of different methods used

4.8 References

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