Chapter One

Introduction

1.1. Overview

Precise, accurate measurement of sheet thickness is critical in the controlled processing and quality assessment of flat rolled metal products. Through the years, many non destructive methods have been developed, each having specific, relevant applications, and certain characterizable advantages and disadvantages, [10-12]. These systems are provided in a variety of geometries and physical arrangements.

Probing is defined as the investigation of a particular location. Inspection provides an overall assessment that need not be location-specific. Monitoring is a passive process of probing or inspection. The probing process is particularly helpful in detecting discontinuities caused by abnormal thickness changes in the examined material. Unlike gauging and elemental analysis, probing and inspection do not necessarily provide quantified information. Therefore, probing and inspection can be seen as assessment tools for diagnosing the condition of an industrial object or a process.

1.2. Surface Condition

The surface condition of industrial components can be affected by deposition and erosion. For example, corrosion on the inside walls of pipelines and vessels can cause the condition of internal walls to deteriorate, creating safety and operational concerns.

While deposition causes the addition of undesirable material, erosion results in the loss of primary material. Therefore, both processes change the apparent thickness and density of affected walls, or in other words, the areal density (density ×thickness). This makes such measurements

particularly amenable to the radiation transmission method discussed in section.

1.3. Gamma Transmission

Gamma-ray beam transmission is useful for scanning for thickness defects in flat rolled products. With a narrow (well-collimated) beam, a rapid scan of a wall can be performed to detect changes in the transmission signal, which can be an indication of the occurrence of thickness defaults. Gamma-radiation is particularly useful for such applications due to its high penetrability, ease of collimation, portability (due to the small size of gamma-sources) and mobility (due to the self-powered nature of isotopic sources).

1.4. Previous studies

Radiation attenuation gauging involves the measurement of the thickness of a flat sheet of known (or calibrated) material composition, through the assessment of the degree of transmitted attenuation experienced by a beam of high energy ionizing radiation directed perpendicular to the planar surface of the material. Several contact and non-contact techniques including; Mechanical, Ultrasonic and laser gauges have been investigated, [1-9].

In Industrial radiography Gamma radiation is used to inspect metal parts and welds for defects. Gamma radiations are used for measuring viscosity, density and thickness in conditions where other methods would be difficult or impossible to apply. The study of absorption of gamma radiations in materials is important subject in the field of radiation physics [1].

The study of absorption of X- and Gamma radiations through different materials is of wide interest in industrial, medical and agricultural fields. The x-rays and gamma radiations can penetrate solid

materials. The extent of penetration depends upon several factors including density of the intervening material and the energy of the radiation. The x-rays and gamma radiations are used in industry to monitor the thickness of sheet metal, paper napkins, newspaper, plastics, and photographic film. X- and Gamma radiations are used in the automobile industry to test steel quality and in the aircraft industry to check flaws in jet engines. In radiography, Gamma rays are used to examine pipe, pressure vessels, and other assemblies in which access to the interior is difficult.

The study of X- and Gamma photon attenuation coefficients is an important parameter for characterizing the penetration and attenuation properties of x-ray and gamma rays in materials. Accurate data on photon attenuation coefficients are required in a verity of applications in nuclear science, technology and medicine [2].The thickness of metallic coatings can be determined by x-ray fluorescence spectrometry [3].

The transmission factors; linear and mass attenuation coefficients, effective atomic numbers, cross -sections and electron densities were studied for Al, Fe, Perspex, PVC and Brass by using gamma ray spectroscopy [4]. The gamma attenuation method has been used in the study of soil particle-size analysis [5, 6, 7]. Soil bulk density has been measured using gamma attenuation technique [8]. The Gamma transmission method was used to determine the moisture in soil by measuring the variation in density due to water addition [9].

1.5. Objective of the research

The objective of research is to develop a simple gamma transmission-based non destructive system and explore its practicality in providing a precise and accurate thickness measurement of flat rolled products such

as; ceramic, glass, aluminum and iron. The research is also oriented to explore the possibility of using such system to discriminate samples with respect to their density. The proposed system is composed of ^{241}Am photon source, NaI(Tl) scintillation detector, signal processing unit, shielding and a monitor.

1.6. Problem of Research

The research involved in this work explores the possibility of developing a simple gamma transmission-based non destructive system for scanning for thickness defects in flat rolled products and discriminate samples with respect to their density. Based on radiation attenuation, the study involves the measurement of the thickness of a flat sheets; of material composition; ceramic, glass, aluminum and iron, through the assessment of the degree of transmitted attenuation experienced by a beam of high energy ionizing radiation, such as ^{241}Am directed perpendicular to the planar surface of the material.

1.7. Significance of the research

The present study is directed to develop and method for gauging the thickness of a moving sheet of industrial products such as; ceramic, glass, aluminum and iron. This is accomplished by measuring the spectral energy of the radiation which has been transmitted by the material at different energies.

A source of penetrative radiation is positioned in such a manner as to provide the radiation beam perpendicularly through the sheet material. A radiation detector is positioned on the opposite side of the sheet material from the radiation source to measure the beam attenuation. The radiation detector is coupled with a signal processing unit which feeds the electrical outputs to a monitor. A processor then determines the thickness

of the material based on the values of these outputs. This result is then used to control the rolling mill to provide real-time, on-line feedback.

It is an advantage of the present invention to require only a single source and a single detector, thereby making the proposed system more cost effective than the conventional solutions. It is a further advantage of the proposed system that only the attenuation of the radiation is required to be measured. This increases the speed and accuracy of the device and reduces the need to have the source and detector in close proximity to the material being measured.

1.8. Limitations

Further experimental measurements are needed to verify the feasibility of utilizing other different gamma sources such as ^{60}Co and ^{137}Cs. Further studies on the applicability of the proposed system for different flat rolled industrial products are needed.

1.9. Organization of the research

This thesis consists of six chapters. The introduction is presented in chapter one. Chapter two cover Radioactivity. And Chapter three covered the working principles of the proposed gamma transmission-based sensor. Chapter four discussed the sensor geometry and experimental measurements. Chapter five covered the results and discussion. The conclusions and recommendations will be presented in chapter six.

Chapter Two
Radioactivity

2.1 Radioactivity

Radioactivity is a part of nature, everything is made of atoms. Radioactive atoms are unstable, that is they have too much energy. When radioactive atoms spontaneously release their extra energy, they are said to decay. All radioactive atoms decay eventually, though they do not all decay at the same rate. After releasing all their excess energy, the atoms become stable and are no longer radioactive. The time required for decay depends upon the type of atom [25-34].

2.2 Radioactivity In Nature

Our world is radioactive and has been since it was created. Over 60 radionuclides (radioactive elements) can be found in nature, and they can be placed in three general categories:

i. Primordial - from before the creation of the Earth (Natural Decay Series).

ii. Cosmogenic - formed as a result of cosmic ray interactions.

iii. Human produced - enhanced or formed due to human actions (minor amounts compared to natural).

Radionuclides are found naturally in air, water and soil. They are even found in us, being that we are products of our environment. Every day, we ingest and inhale radionuclides in our air and food and the

water. Natural radioactivity is common in the rocks and soil that make up our planet, in water and oceans, and in our building materials and homes, nowhere on Earth is free from natural radioactivity.

Naturally occurring raw building materials and processed products have radionuclides of the three most commonly known radioactive series such as: Uranium-radium series, thorium series and ^{40}K isotopes. High concentrations of natural radionuclides in building materials can result in high-dose rates indoors.

Gamma-irradiation from naturally occurring radioactive material (NORM) contributes to the whole body dose and in some cases β-irradiation contributes to the skin dose. As β particles have higher specific ionization than γ-particles, they lose their energy while they are still in the skin and cannot penetrate further into the body. Apart from β and γ radiations, there are other harmful effects of NORM, [25-29].

2.3 Types of Radioactive Decay

Types of radioactivity involve a number of basic decay mechanisms individually. They are: alpha decay; beta decay (β^-,β^+ and electron capture), gamma decay, internal conversion and spontaneous fission.

2.3.1 Characteristics of alpha decay

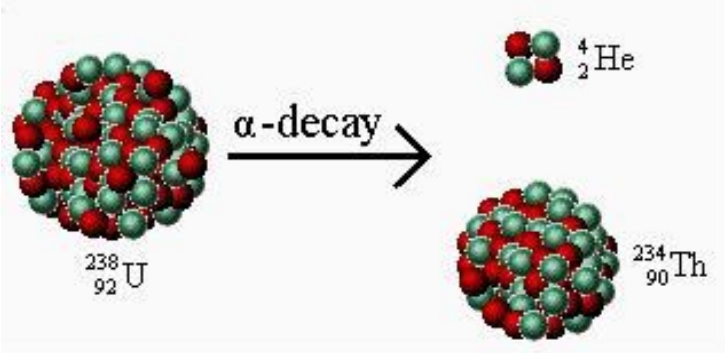


Fig. 2.1 : Emission of the alpha reduces the mass of the nucleus

The parent nucleus X emits an α particle. The daughter product is 4 mass units lighter and with 2 fewer units of electric charge. If it is energetically favorable for a nucleus to lose mass, the α particle (charge +2e and mass 4.0026 u ≡ 3.7 GeV) is most commonly emitted because it is a tightly bound system. Alpha decay occurs almost exclusively in heavy nuclei because *B/A* decreases with *A* when *A* is large and so the daughter product of α decay is more stable than the parent. Mass numbers of nearly all α emitters > 209 and typical α particle kinetic energies E_α = 4 to 6 MeV. Alpha particle energies are well defined as pass through matter, they lose energy rapidly. Alpha particles of a few MeV are easily stopped by paper or skin.

2.3.2 Mechanism of alpha decay

Alpha particles are tightly bound systems that exist within the potential well created by the daughter nucleus. The *Q* value must be positive for the decay to take place at all. Otherwise it is not possible for the α particle to tunnel through the barrier and escape. Prior to emission,

the α particle is considered to be confined within the potential well. It is assumed to be pre-formed inside the nucleus (not true in general). The pre-formation factor *F* is difficult to calculate and, normally, it is taken to be 1.

The confined alpha particle has kinetic energy and oscillates to and fro many times per second (frequency $f \sim 10^{22}$ s^{-1}). Each time it reaches the surface, there is a small but finite probability *P* that the α particle can tunnel through the barrier and be emitted. This is a quantum-mechanical process related to the wave nature of the α particle. Once it has penetrated the barrier, the α particle is repelled away from the daughter nucleus and escapes, [34-38].

2.3.3 Beta Decay

Nuclei with either too many protons or too many neutrons will undergo β decay via the weak nuclear force.

i. A neutron-rich nucleus will undergo β^- emission.

ii. A proton-rich nucleus will either emit a β^+ particle or be transformed by capturing an atomic electron in a process called electron capture.

i. B^- Emission

In β^- decay, the charge on the nucleus increases by one unit. The β^- particle is an electron (mass 0.0005486 u ≡ 511 keV and charge -*e*). It is considered to be created at the moment of decay. A second light particle, antineutrino (ν^-) is also created and emitted. It has no charge and very small mass, which generally is assumed to be zero and interacts extremely weakly with matter.

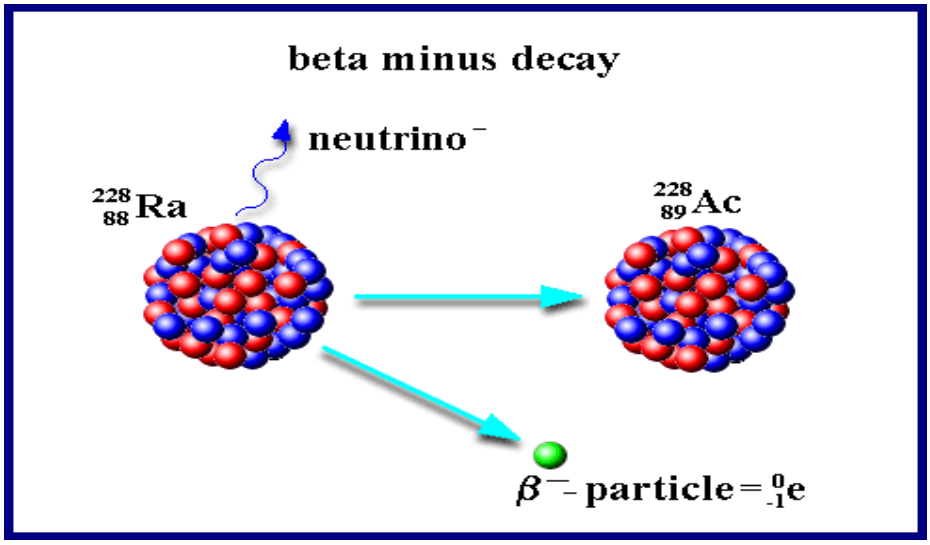


Fig 2.2 : B^- Emission

β^- decay involves the transformation of a neutron into a proton inside the nucleus:

$$n \rightarrow p + \beta^- + \nu^- \qquad (2.1)$$

Energy must be conserved and so the transformation given in Eq. (2-1) can occur only if the daughter nucleus is lighter (more stable) than the parent. This means that the Q value must be > 0:

$$Q_{\beta^-} = (m_P - m_D)\, c^2 \qquad (2.2)$$

Note that the masses m_P and m_D, for the parent and daughter, respectively, are atomic not nuclear masses and include the masses of the atomic electrons. A beta particle is much lighter than an α particle. Its speed, therefore, for a given energy is much greater and it is much more penetrating. A few mm of material will stop a 1 MeV β particle, [31-34].

ii. β^+ Emission

β^+ decay changes a proton rich nucleus into a more stable isobar. The nuclear charge is decreased by one unit.

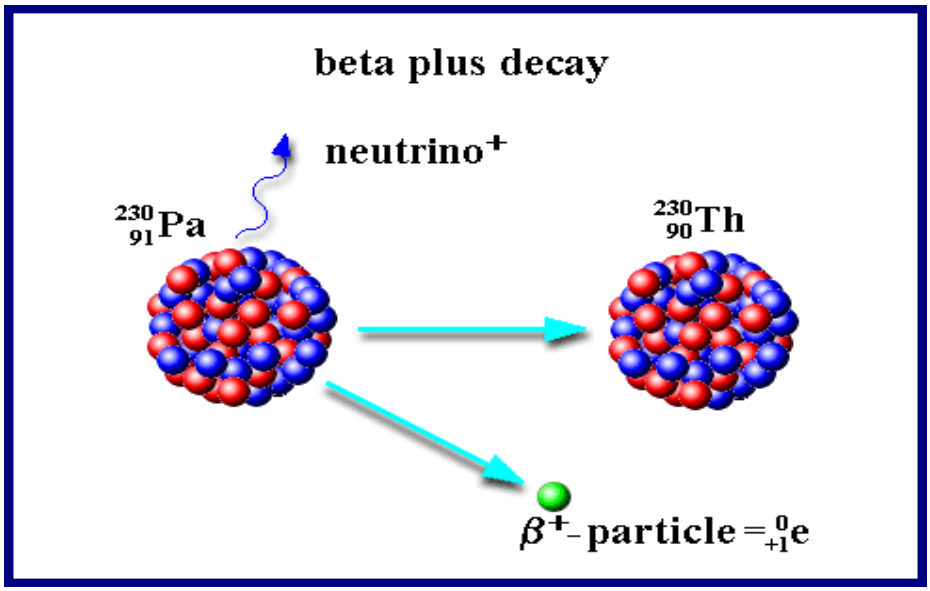


Fig 2.3 : B^+ Emission

β^+ particle is an ant electron, called a positron. It is identical to an ordinary electron except that it is positively charged. Effectively, β^+ decay converts (via the weak nuclear force) a proton into a neutron and a positron. A neutrino is also created in the process. Note that this is an ordinary neutrino not an antineutrino.

$$p \rightarrow n + \beta^+ + \nu \qquad (2.3)$$

There are 3 bodies in the final state and the positrons are emitted with a continuous range of energies, as are electrons in β^- decay. Using energy conservation, the β^+ decay Q value, using atomic masses, is given by:

$$Q_{\beta^+} = (m_P - m_D - 2m)\, c^2 \qquad (2.4)$$

This must be greater than zero for the process to be able to occur.

2.3.4 Electron capture

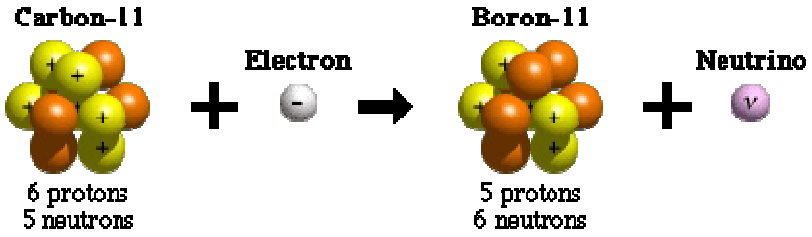


Fig 2.4 : Electron capture

Electron capture EC is an alternative process to β^+ decay in that a proton is converted into a neutron. The parent absorbs an atomic electron, usually from the innermost orbit.

$$e^- + p \rightarrow n + \nu \qquad (2.5)$$

Energy conservation gives the *Q* value as:

$$Q_{EC} = (m_P - m_D)\, c^2 \qquad (2.6)$$

Note that Q_{EC} is greater than $Q_{\beta+}$ by $2mc^2$. In electron capture, the mass of an atomic electron is converted into energy, whereas, in β^+ decay, energy is required to create a positron.

This means that EC can occur when β^+ decay cannot. No β particle is emitted in electron capture and so, except for a very small amount of

recoil energy of the daughter nucleus, the energy released escapes undetected,

[31-34].

2.3.5 Gamma Emission and Internal Conversion

i. Gamma Emission

A nucleus in an excited state generally decays rapidly to the ground state by emitting rays. A schematic diagram for gamma emission is showing bellow:

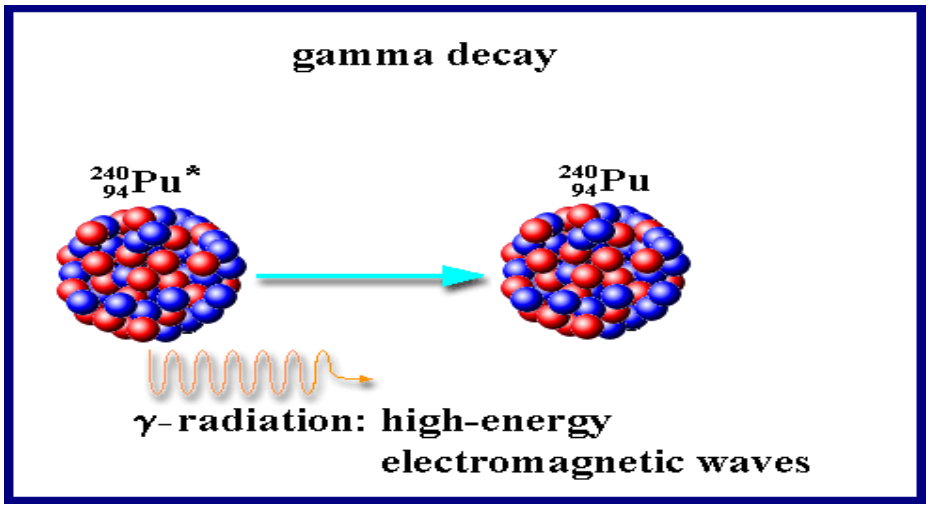


Fig 2.5 : gamma emission

Gamma-ray energies *E* typically, are in the range 0.1 to 10 MeV and can be determined very accurately with a modern detector. *E* is characteristic of the emitting nucleus and are widely used to identify radioactive nuclei. Gamma rays of about an MeV do not interact strongly in matter and will penetrate many cm of moderate-density material.

ii. Internal conversion

This is an alternative to γ emission whereby an excited nucleus de-excites by ejecting an electron from an atomic orbit. Both γ emission and internal conversion are due to the action of the electromagnetic force.

2.3.6 Spontaneous Fission and Neutron Emission

i. Spontaneous fission

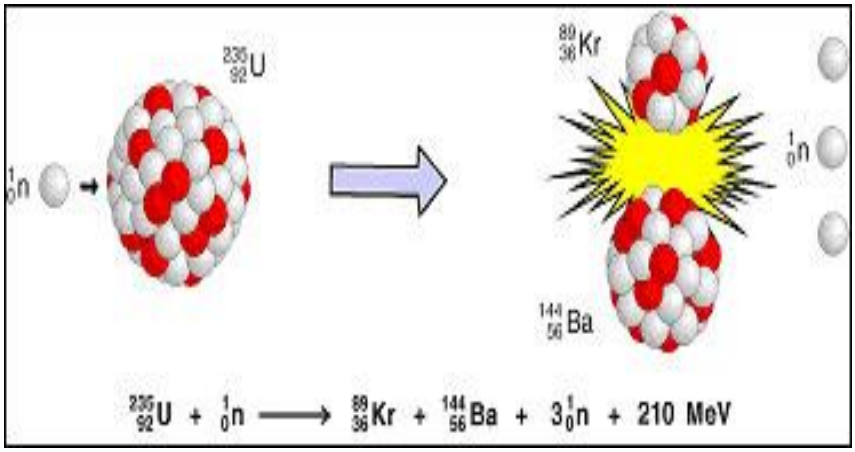


Fig 2.6 : Spontaneous fission

In spontaneous fission a nucleus breaks up into two roughly equal mass fragments. The process normally is restricted to heavy nuclei for which *BE/A* for the fragments > *BE/A* for the initial nucleus. Fission also can be induced by a nuclear reaction, e.g. neutron capture.

Spontaneous fission occurs only in very heavy nuclei, such as ^{252}Cf, when the *Q* value is large enough to overcome the energy needed to deform the parent into two separate pieces. Fission fragments are very neutron rich. Also, several neutrons are emitted during fission.

ii. Neutron Emission

Neutrons are uncharged and deposit their energy in matter via nuclear interactions. This means that their interaction probability generally is small and their range is not well defined. Neutrons of several MeV will penetrate many 10s of cm of moderately dense materials, such as concrete, [30].

Neutron-rich fission products decay by β^- emission. Often, they follow a chain of decays to stability. Occasionally (in 1 to 2% of cases), a

daughter is formed in an excited state that can decay by neutron emission. Compared with β^- decay, neutron decay is very rapid and if there is preceding β decay, the neutron emission is delayed hence, the term: delayed neutrons.

2.4 Natural Decay Series (Uranium, Radium, and Thorium)

Uranium, radium, and thorium occur in three natural decay series, headed by uranium-238, thorium-232, and uranium-235, respectively. In nature, the radionuclide's in these three series are approximately in a state of secular equilibrium, in which the activities of all radionuclide's within each series are nearly equal.

Two conditions are necessary for secular equilibrium. First, the parent radionuclide must have a half-life much longer than that of any other radionuclide in the series. Second, a sufficiently long period of time must have elapsed, for example ten half-lives of the decay product having the longest half-life, to allow for in growth of the decay products.

Under secular equilibrium, the activity of the parent radionuclide undergoes no appreciable changes during many half-lives of its decay products, [33-39].

Radioactive decay occurs when an unstable (radioactive) isotope transforms to a more stable isotope, generally by emitting a subatomic particle such as an alpha or beta particle. Radionuclide's that give rise to alpha and beta particles are shown in these figures, as are those that emit significant gamma radiation. Gamma radiation is not a mode of radioactive decay (such as alpha and beta decay). Rather, it is a mechanism by which excess energy is emitted from certain radionuclide's, i.e., as highly energetic electromagnetic radiation emitted

from the nucleus of the atom. For simplicity, only significant gamma emissions associated with the major decay modes that is, radionuclide's listed are those for which the radiation dose associated with gamma rays may pose a health concern. The gamma component is not shown for those radionuclide's whose gamma emissions do not generally represent a concern.

Of the two conditions noted above for secular equilibrium, the first is generally met for the uranium-238, thorium-232 and uranium-235 decay series in naturally occurring ores. While the second condition may not be met for all ores or other deposits of uranium and thorium (given the extremely long half-lives for the radionuclide's involved and the geological changes that occur over similar time scales), it is reasonable to assume secular equilibrium for naturally occurring ores to estimate the concentrations of the various daughter radionuclide's that accompany the parent. The state of secular equilibrium in natural uranium and thorium ores is significantly altered when they are processed to extract specific radionuclides.

After processing, radionuclides with half-lives less than one year will reestablish equilibrium conditions with their longer-lived parent radionuclides within several years, [20-29].

For this reason, at processing sites what was once a single, long decay series (for example the series for uranium-238) may be present as several smaller decay series headed by the longer-lived decay products of the original series (that is, headed by uranium-238, uranium-234, thorium-230, radium-226, and lead-210 in the case of uranium-238). Each of these sub-series can be considered to represent a new, separate

decay series. Understanding the physical and chemical processes associated with materials containing uranium, thorium, and radium is important when addressing associated radiological risks, [32].

2.5 Radioactive Decay

Naturally occurring radioactive nuclei undergo a combination of α, β and γ emission. Artificially produced nuclei may also decay by spontaneous fission, neutron emission and even proton and heavy-ion emission. Any decay process is subject to the same basic law, [34-39].

2.6 Radioactive Decay Law

The rate of decay (number of disintegrations per unit time) is proportional to N, the number of radioactive nuclei in the sample:

$$\frac{dN}{dt} = -\lambda N \qquad 2.7$$

The negative sign signifies that N is decreasing with time. λ is called the decay constant "probability per unit time that a given radioactive nucleus will decay".

Equation (2-7) can be integrated to give:

$$N(t) = N_0 e^{-\lambda t} \qquad (2.8)$$

Where N_0 = number of radioactive nuclei at $t = 0$.

2.7 Activity and Half-Life

i. Activity

Number of disintegrations per unit time:

$$A(t) = N(t) = N_0 e^{-\lambda t} = A_0 e^{-\lambda t} \quad \textbf{(2.9)}$$

This has the same exponential fall off with time as $N(t)$.

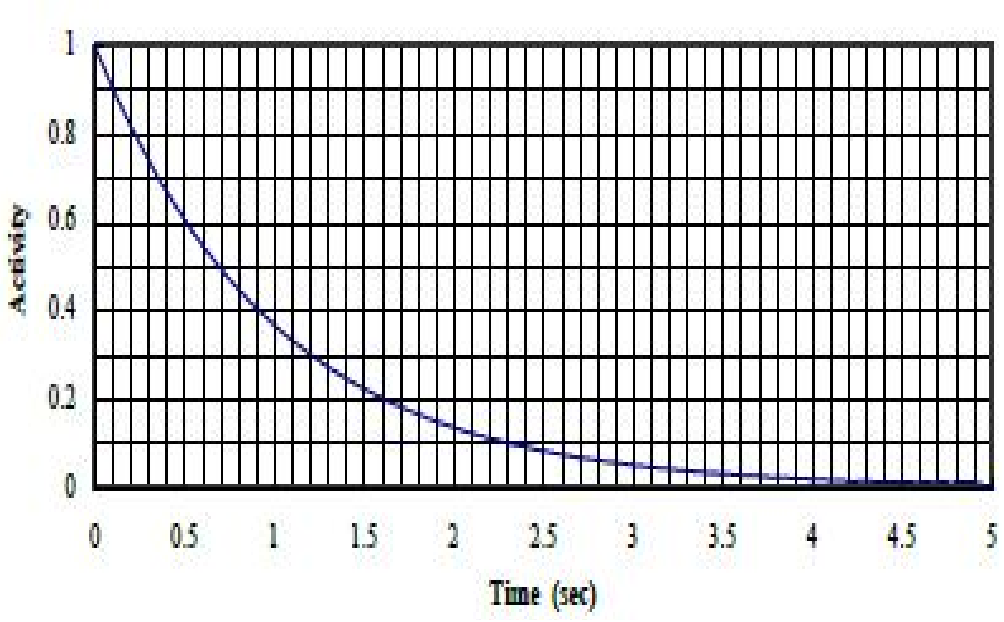


Fig (2.7): Activity and time is the exponential function

ii. Half-life

Time for half the radioactive nuclei in the sample to decay. Substituting $N_0 = N_0/2$ and $t = t_{1/2}$ into Eq. (2-2) gives:

$$t_{1/2} = \ln 2/\lambda \quad \textbf{(2.10)}$$

The figure above shows the activity of a sample decaying at a rate of exp (-*t*). The half-life of this sample = ln2 (≈ 0.7 s).

Chapter Three

Gamma transmission-Based Systems for Thickness Measurement

3.1 Introduction

The main advantages of radiation gauges are the non-contact measurement of the passing strip and the less susceptibility against external influence. Radiation gauges are useful not only for measuring strip with especially sensitive surface but also for any standard cold rolling application. Other applications are measurements on hot strip and plate slabs. Gauges of the Gamma or X-ray type use a high voltage X-ray tube to produce the radiation. Gamma type gauges have a radioactive isotope in a capsulated container to generate the measurement radiation. Both system types (isotope or X-ray gauges) use basically the same radiation because Gamma radiation and X-rays are identical in their characteristics except for the location where they are generated. X-rays are generated in the electron shell of an atom while Gamma -radiation is generated in the atomic nucleus (protons, neutrons). Both kinds of radiation are energy-rich light quantum's, [11-18]. In this work, we explored the possibility of developing a gamma transmission-based system for thickness measurements. This is due to the portability and self powered nature of radioisotopes.

3.2 Nature of gamma rays

Alpha and beta decay of a radioactivity nucleus usually leave the daughter nucleus in an excited state . if the excitation energy available with the daughter nucleus is not sufficient for further particle emission, it loss its excess energy by gamma decay .The gamma ray is a photon of electromagnetic radiation with a very short wavelength and high energy.

It is emitted from an unstable atomic nucleus and has high penetrating power .it's always travel with velocity of light irrespective the energy of gamma ray .they do not cause any appreciable ionization and are not deflected by electric or magnetic fields. [34-39]

3.3 Gamma Radiation Sources

Radiation sources are components that generate radiation for application to the measurement process. To limit and direct this discussion, we will focus only on sources that produce high energy photons (electromagnetic waves or γ-Rays). Although β-Ray sources are common, a vast majority of the industrial applications employ γ-Ray emissions. As noted previously, it is necessary to draw specific distinctions between the forms of electromagnetic radiation, under consideration, in terms of their origins.[31-39]

Sources Gamma rays originate from two main sources:

(1)excited atomic nuclei and

(2) annihilation reaction.

1-**Nuclear excitation**:- Whenever a radioactive nucleus decays byemission of an α or a β particle, the daughter nucleus has a different atomic number than the parent. In most instances the daughter nucleus is left in an excited state (surplus of energy called execution energy). Note that there are nuclear energy states analogous to orbital electronic energy states. Usually the excited daughter nucleus de-excites or decays or decays immediately (half-life less than 10^{-13} sec) by γ ray emission, to the lowest energy state, called the ground state. However, in some Cases the excited daughter lingers in this condition for a signification period of time; if it decays with a half-life greater than 10^{-6} sec, it is said to have been in the metastable state and its decay is designated a san isomeric transition. In either case,

the emission of γ photons is the means whereby excited nuclei may decay to ground state when they cannot get rid of their surplus energy by particle emission alone. It must be stressed that the energy of the γ photon is characteristic of the excited daughter nucleus, and not the parent. An example of isomeric transition is technetium 99m (m indicates meat stable state) to ground state technetium 99 by γ -ray emission with a half-life of six hours .Certain radioactive nuclei undergo particle decay to daughters which are immediately in the ground state. Under these circumstances no γ radiation occurs.

Nuclear excitation can also be induced by process called radioactive capture.

When atoms are irradiated with slow neutrons, any nucleus which happens to capture a neutron, any nucleus which happens to capture a neutron enters an excited state. In returning to ground state, the excited nucleus emits a γ ray as described above. Radioactive capture is also possible though less likely, with certain other types of bombarding particles.

Nuclear excitation can be caused by still another process electron capture. In neutron-poor nuclei in which the neutron proton (n/p) ratio is too small for maximum nuclear stability, an electron from the K shell or, more rarely, from the L shell, may fall into the nucleus and combine with a proton to form a neutron.

Because of the disappearance of one nuclear positive charge, the atomic number of the daughter is one less than that of the parent. The daughter is usually excited as the result of electron capture whereupon it decays to ground state by γ emission. Auger electrons are also ejected by interaction of characteristic X- ray with orbital electrons.

Finally, certain excited nuclei can dissipate their excitation energy not only by direct α-ray emission, but also by an alternate route internal conversion. Here an interaction occurs between the nucleus and an inner shell electron, usually a K electron. In the process, the energy that would otherwise be emitted as a γ ray is transferred to the electron, now an internal conversion electron. It is ejected from the atom with the following energy

$$E_{ie} = hf - E_K \qquad (3.1)$$

Where E_{ie} is the kinetic energy of the internal conversion electron, hf is the energy of the internally converted γ photon, and E_K is the binding energy of the K shell. The internal conversion coefficient for a particular shell, such as $\alpha._K$ for the K shell is defined as follows:

$$\alpha._K = \frac{\text{Number of k conversion electrons}}{\text{number of unconverted } \gamma \text{ rays}}$$

2-Annihilation reaction:

When a positron that is at rest combines with a negatron (negative electron), their total mass is "annihilated" and converted to an equivalent amount of energy in accordance with $E= mc^2$, where E is the energy in ergs, m is the mass in grams, and C is the velocity of light in a vacuum. The energy is radiated in the form of two γ rays, each with energy of 0.51 MeV, moving in opposite directions.[33-39]

They display marked penetrating ability which depends on their, extremely high energy and short wavelength.

As described before, α rays differ from X ray only in their site

3.4 Working principles

Radiation gauges send ionizing radiation perpendicular through the strip. The passing strip absorbs a portion of the radiation on its way from the source below the strip to the detector above the strip. The radiation is reduced by the absorption coefficient μ as it passes through the measurement object (absorber). The intensity of the transmitted radiation is inversely proportional to the thickness and the density of the absorber material. The reduction of radiation intensity is evaluated based on a calibration curve which is stored in the measurement processor for each of the various strip materials to be measured. Figure 3.1 shows a sketch diagram for the general principles of gamma ray transmission systems for thickness measurements.

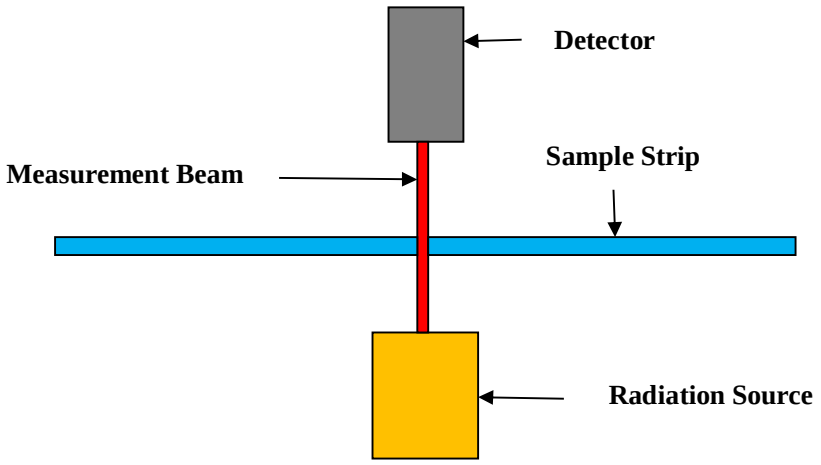


Fig.3.1 Sketch diagram for the general principles of gamma ray transmission systems for thickness measurements

3.5 Ionizing Radiation and Gamma ray sources

Radiation is a generalized term used to describe a variety of energy forms that are emitted from a body. For the purposes of this discussion, we will focus on ionizing radiation which involves charged particles or electromagnetic waves possessing sufficient energy to dislodge strongly held electrons from atoms or molecules.

3.5.1 ***Forms of Radiation***

Ionizing radiation comes in three primary forms: [13- 20];

α-Rays– Alpha radiation involves accelerated helium nuclei, composed of two protons and two neutrons. This particle has a high mass and a double positive charge. Due to its high mass, this form of radiation has low penetrating energy and a limited range. The primary source of formation is during the nuclear transformation process (radioactive decay), where a new element results.

β-Rays– Beta radiation involves accelerated electrons (or positrons). These particles have a low mass and a negative charge (positive for positrons). Beta rays have modest penetrating energy (more than alpha particles), but can be stopped by metals a few centimeters thick. The primary source of formation is during the nuclear transformation process (radioactive decay), where a neutron is converted to a proton (which remains in the nucleus) and an electron and an antineutrino are emitted.

Beta radiation can also be formed by an electron gun in the presence of high electric field potentials.

γ-Rays– Gamma rays are high energy photon emissions (electromagnetic waves), [21]. Gamma radiation has high penetrating energy and is the

primary form of radiation employed in strip thickness gauging systems. X-Rays are also a form of electromagnetic (gamma) radiation. Classically, Gamma Rays and X-Rays have been separated by their respective energy levels (with Gamma being of higher energy). However, a more common place distinction involves the means of their generation. We will examine the various aspects of these differences in the next section.

In fact, there are many forms of radiation (when considering the non-ionizing form), which include: neutron or proton emissions, acoustic, low energy electromagnetic radiation (i.e., thermal, black body, light, radio waves), etc. These forms of radiation are not considered within the scope of this discussion.

3.5.2 Naturally Occurring Gamma Rays (Isotope Sources)

Naturally occurring gamma rays are specifically produced by radioactive isotopes during the nuclear transformation process, where following the emission of alpha and / or beta radiation, the decaying nucleus releases excess energy (in the form of photons) to obtain an equilibrium, [13-20]. These photon emissions form very well defined spectral lines at specific energy levels and relative amplitudes, [13]. Common radioactive isotopes are: Americium 241, Cesium 137, Curium 244. Figure 3.2 shows the spectral characteristics of photonic radiation released by the radioactive isotope Americium 241.

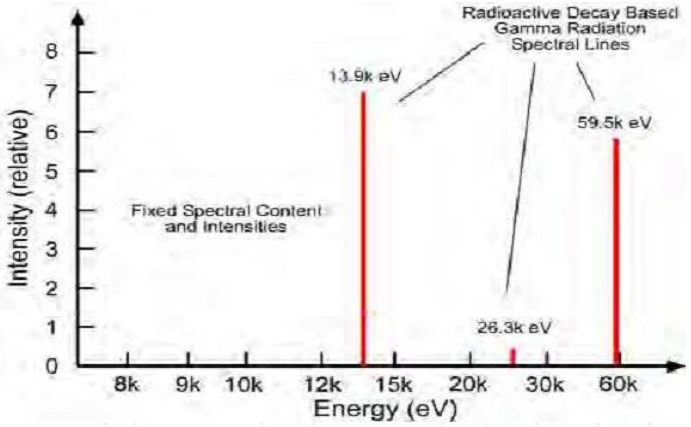


Fig 3.2, Spectral characteristics of photonic radiation released by the radioactive isotope Americium 241

3.6 Gamma Detectors

In order for a gamma ray to be detected, it must interact with matter that interaction must be recorded. Fortunately, the electromagnetic nature of gamma-ray photons allows them to interact strongly with the charged electrons in the atoms of all matter.

The key process by which a gamma ray is detected is ionization, where it gives up part or all of its energy to an electron. The ionized electrons collide with other atoms and liberate many more electrons. The liberated charge is collected, either directly (as with a proportional counter or a solid-state semiconductor detector) or indirectly (as with a scintillation detector), in order to register the presence of the gamma ray and measure its energy. The final result is an electrical pulse whose voltage is proportional to the energy deposited in the detecting medium.[31-34]

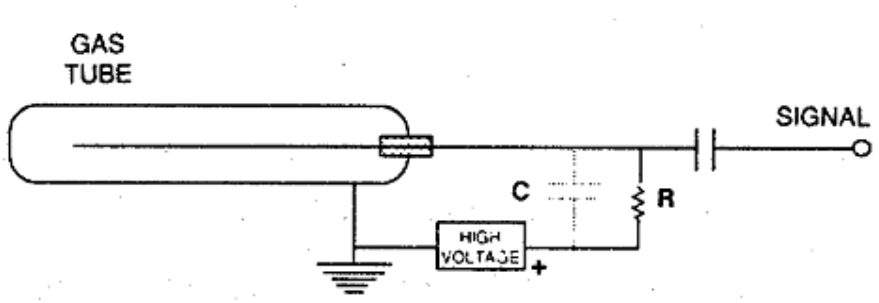
3.7 Types of Detectors

Many different detectors have been used to register the gamma ray and its energy. In NDA, it is usually necessary to measure not only the amount of radiation emanating from a sample but also its energy spectrum. Thus, the detectors of most use in NDA applications are those whose signal outputs are proportional to the energy deposited by the gamma ray in the sensitive volume of the detector.

3.7.1 Gas-Filled Detectors

Gas counters consist of a sensitive volume of gas between two electrodes. (Figure 3.1.) In most designs the outer electrode is the cylindrical wall of the gas pressure vessel, and the inner (positive) electrode is a thin wire positioned at the center of the cylinder. In some designs (especially of

ionization chambers) both electrodes can be positioned in the gas separate from the gas pressure vessel.



Fig(3-3)

The equivalent circuit for a gas-filled detector. The gas constitutes the sensitive (detecting) volume. The potential difference between the tube housing and the center wire produces a strong electric field in the gas volume. The electrons from ionizations in the gas travel to the center wire under the influence of the electric field, producing a charge surge on the wire for each detection event.

An ***ionization chamber is a*** gas-filled counter for which the voltage between the electrodes is low enough that only the primary ionization charge is collected. The electrical output signal is proportional to the energy deposited in the gas volume.

If the voltage between the electrodes is increased, the ionized electrons attain enough kinetic energy to cause further ionizations. One then has a ***proportional counter*** that can be tailored for specific applications by varying the gas pressure and/or the operating voltage. The output signal is still proportional to the energy deposited in the gas by the incident gamma ray photon, and the energy resolution is intermediate between NaI scintillation counters and germanium (Ge) solid-state detectors. Proportional counters have been used for spectroscopy of gamma rays

and x rays whose energies are low enough (a few tens of keV) to interact with reasonable efficiency in the counter gas. If the operating voltage is increased further, charge multiplication in the gas volume increases (avalanches) until the space charge produced by the residual ions inhibits further ionization. As a result, the amount of ionization saturates and becomes independent

of the initial energy gas. This type of detector is known

as the ***Geiger-Mueller (GM) detector.*** A GM tube gas counter does not differentiate among the kinds of particles it detects or their energies it counts only the number of particles entering the detector. This type of detector is the heart of the conventional β γ dosimeter used in health physics. Gas counters do not have much use in gamma-ray NDA of nuclear materials. The scintillation and solid-state detectors are much more desirable for obtaining the ~spectroscopic detail needed in the energy range typical of uranium and plutonium radiation (approximately 100-1000 keV).

3-7-2 scintillation detector

The sensitive volume of a scintillation detector is a luminescent material (a solid, liquid, or gas) that is viewed by a device that detects the gamma-ray-induced light emissions [usually a photomultiplier tube (PMT)]. The scintillation material may be organic or inorganic; the latter is more common. Examples of organic scintillators are anthracene, plastics, and liquids. The latter two are less efficient than anthracene

(the standard against which other scintillators are compared). Some common inorganic scintillation materials are sodium iodide (NaI), cesium iodide (CSI), zinc sulfide (ZnS), and lithium iodide (LiI). The most common scintillation detectors are solid, and the most popular are the inorganic crystals NaI and CSI. A new scintillation material, bismuth germanate ($Bi_4Ge_3O_{12}$), commonly referred to as BGO, has become

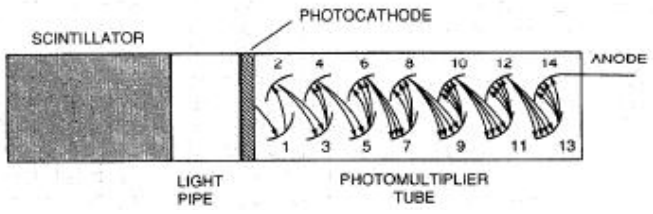
popular in applications where its high gamma counting efficiency and/or its lower neutron sensitivity outweigh considerations of energy resolution [3-4].

When gamma rays interact in scintillator material, ionized (excited) atoms in the scintillator material “relax” to a lower-energy state and emit photons of light. In a pure inorganic scintillator crystal, the return of the atom to lower-energy states with the emission of a photon is an inefficient process. Furthermore, the’ emitted photons are usually too high in energy to lie in the range of wavelengths to which the PMT is sensitive. Small amounts of impurities (called activators) are added to all scintillators to enhance the emission of visible photons. Crystal de-excitations channeled through these impurities give rise to photo is that can activate the PMT.

One important consequence of luminescence through activator impurities is that the bulk scintillator crystal is transparent to the scintillation light. A common example of scintillator activation encountered in gamma-ray measurements is thallium-doped sodium iodide [NaI(Tl)].

The scintillation light is emitted isotropically; so the scintillator is typically surrounded with reflective material (such as MgO) to minimize the loss of light and then is optically coupled to the photocathode of a PMT. (See Figure 3.2.) Scintillation photons incident on the photocathode liberate electrons through the photoelectric effect, and these photoelectrons are then accelerated by a strong electric field in the PMT. As these photoelectrons are accelerated, they collide with electrodes in the tube (known as dynodes) releasing additional electrons. This increased electron flux is then further accelerated to collide with succeeding electrodes, causing a large multiplication (by a factor of 104 or more) of the electron flux from its initial value at the’photoea hode surface. Fully, the amplified charge burst arrives at the output electrode (the ruiode) of the tube. The magnitude of this charge ,surge is

proportional to the initial amount of charge liberated at the photocath6de of the PMT, the constant of proportionality is the gain of the PMT. Furtliermore, by virtue of the physics of the photoelectric effect, the initial number of photoelectrons liberated at the photocathode, is proportional to the amount of light incident on the phototube, which, turn, is proportional to the amount of energy deposited in the scintillator by the gamma ray (assuming no light loss from the scintillator volume). Thus, an output signal is produced that is proportional to the energy deposited by the gamma ray in the scintillation medium. As discussed above, however, the spectrum of deposited energies (even for a monoenergetic photon flux) is quite varied, because of the occurrence of the photoelectric effect, Compton effect, and various scattering phenomena in the scintillation medium and statistical fluctuations associated with all of these processes. [20-39]



Fig(3-4)

Typical arrangement of components in a scintillation detector. The scintillator and photomultiplier tube are often optically linked by a light pipe. The dynodes (1-13 in the figure) are arranged to allow successive electron cascades through the tube volume. The final charge burst is collected by the anode and is usually passed to a preamplifier for conversion to a voltage pulse.

3-7-3 Solid state detectors

In solid-state detectors, the charge produced by the photon interactions is collected directly. The gamma-ray energy resolution of these detectors is dramatically better than that of scintillation detectors; so greater spectral detail can be measured and used for SNM evaluations. A generic representation of the solid-state detector is shown in Figure 3.3. The sensitive volume is an electronically conditioned region (known as the ***depleted region)*** in a semiconductor material in which liberated electrons and holes move freely. Germanium possesses the most ideal electronic characteristics in this regard and is the most widely used semiconductor material in solid-state detectors. As Figure 3.3 suggests, the detector functions as a solid-state proportional counter, with the ionization charge swept directly to the electrodes by the high electric field in the semiconductor, produced by the bias voltage. The collected charge is converted to a voltage pulse by a preamplifier. The most popular early designs used lithium-drifted germanium [Ge(Li)] as the detection medium. The lithium served to inhibit trapping of charge at impurity sites in the crystal lattice during the charge collection process. In recent years, manufacturers have produced hyper pure germanium (HPGe) crystals, essentially eliminating the need for the lithium doping and simplifying operation of the detector.

Solid-state detectors are produced mainly in two configurations: planar and coaxial. These terms refer to the detector crystal shape and the manner in which it. is wired into the detector circuit. The most commonly encountered detector configurations are illustrated in Figure 3.4. ***Coaxial detectors are*** produced either with open-ended (the so-called true coaxial) or closed-ended crystals Figure 3.5 (a-b). In both cases the electric field for charge collection is primarily radial, with some axial component present in the closed-ended configuration. Coaxial detectors can be

produced with large sensitive volumes and therefore with large detection efficiencies at high gamma-ray energies. In addition, the radial electric field geometry makes the coaxial (especially the open-ended coaxial) solid-state detectors best for fast timing applications. The ***planar detector*** consists of a crystal of either rectangular or circular cross section and a sensitive thickness of 1-20 mm [for example, Figure 3.5 (c)]. The electric field is perpendicular to the cross-sectional area of the crystal The primary effect of radiation damage is the creation of dislocation sites in the detector crystal. This increases the amount of charge trapping, reduces the amplitudes of some full-energy pulses, and produces low-energy tails in the spectrum photo peaks .In effect, the resolution is degraded, and spectral detail is lost. An example of this type of effect is shown in Figure 3.6 . It has been generally observed that significant performance degradation begins with a neutron fluency of approximately 10^9 n/cm2, and detectors become unusable at a fluence of approximately 10^{10}n/cm2 . However, the new n-type HPGe crystals are demonstrably less vulnerable to neutron damage. Procedures have been described in which the effects of the radiation damage can be reversed through iming (annealing) the detector crystal .

In the quiescent state, the reverse-bias-diode configuration of a germanium solid state detector results in very low currents in the detector (usually in the pico- to nanoampere range). This leakage current can be further reduced from its room temperature value by cryogenic cooling of solid-state medium, typically to liquid nitrogen temperature (77 K). This cooling reduces the natural, thermally generated electrical noise in the crystal but constitutes the main disadvantage of such detectors: the detector package must include capacity for cooling, and this usually involves a dewar for containing the liquid coolant. ‘In recent years, attempts have been made

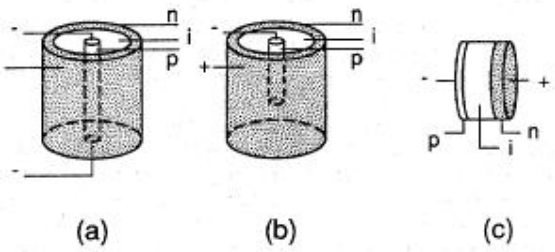


Fig (3-5)

Illustration of various solid-state detector crystal configurations: (a) open-ended cylindrical or true coaxial, (b) closed-ended cylindrical, and (c) planar. The p-type and n-type semiconductor materials are labeled accordingly. The regions labeled i are the depleted regions that serve as the detector sensitive volumes. In the context of semiconductor diode junctions, this region is referred to as the intrinsic region or a p-i-n junction.

to cool the detector material electronically .but these efforts are still in the experimental stages, and the capability is just beginning to be available commercially. Another popular solid-state detector material for photon spectroscopy is lithium drifted silicon [Si(Li)]. The lower atomic number of

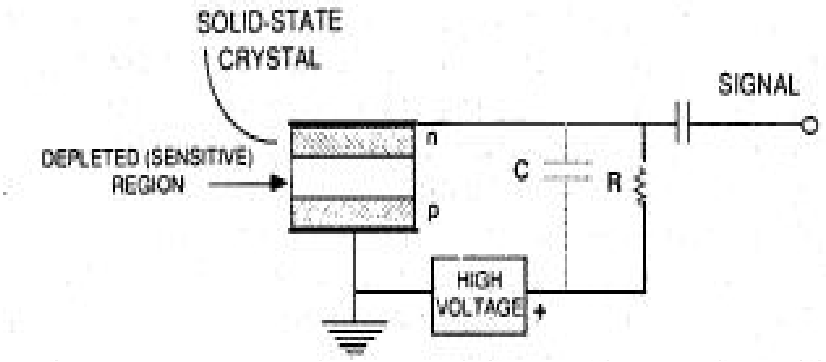


Fig (3-6)

Typical arrangement of components in a solid-state detector. The crystal is a reverse-biased p-n junction that conducts charge when ionization is produced in the sensitive region. The signal is usually fed to a charge-sensitive preamplifier for conversion to a voltage pulse (see Chapter 4).

silicon compared to germanium reduces the photoelectric efficiency by a factor of about 50 , but this type of detector has been widely used in the

measurement of x-ray spectra in the 1- to 50-keV energy range and finds some application in x-ray fluorescence (XRF) measurements. The low photoelectric efficiency of silicon above 50 keV is an advantage when measuring low-energy x rays and gamma rays, because it means that sensitivity to high-energy gamma rays is greatly reduced. Silicon detectors are most heavily used in charged-particle spectroscopy and are also used for Compton recoil spectroscopy of high-energy gamma rays.

Other solid-state detection media besides germanium and silicon have been applied to gamma-ray spectroscopy. In NDA measurements, as well as many other applications of gamma-ray spectroscopy, it would be advantageous to have high-resolution detectors operating at room temperature, thereby eliminating the cumbersome apparatus necessary for cooling the detector crystal. Operation of room-temperature semiconductor materials such as CdTe, Hg12, and GaAs has been extensively researched Their higher average atomic numbers, provide greater photoelectric efficiency per unit volume of material. However, these detector materials have enjoyed limited application to NDA problems to date, largely because it has not been possible to produce crystals sufficiently large for the total detection efficiencies needed in NDA applications. As crystal-growth technology improves, these detectors may become more attractive as convenient, high-resolution room-temperature detectors for gamma-ray spectroscopy of nuclear materials.[25-39].

3.8 Gamma interaction with materials

The collimated beam of radiation emitted by the radiation generator is directed (typically perpendicular) to one surface of the material. The incident radiation interacts with the material's atomic structures and is either passed, absorbed, scattered or involved in high energy

pair productions. The nature of this interaction is dependent on the spectral energy content of the applied radiation and the composition of the material. The resulting transmitted radiation appears as a dispersed beam pattern, having attenuated intensity and modified spectral content.[34-39]

3.9 Attenuation Effects Based on Form of Radiation

The nature of the material interaction is dependent on the form and energy content (wavelength) of the inbound radiation. A number of processes are involved (e.g., collision, photoelectric absorption, scattering, pair production) and their cumulative effect can be characterized as an energy dependent attenuation of the intensity, and a modification of the radiated pattern of the transmitted beam (through scattering processes), [20-22].

α -Particles – Due to their dual positive charge and their relatively large mass, Alpha particles interact strongly (through collision processes) with the material's atoms and are easily stopped, [22].

β-Particles – Due to their physical mass and negative charge, Beta particles also interact through collision / scattering processes. Elastic and inelastic scattering processes are associated with manner in which inbound, high energy electrons interact with the electric fields of the material's atoms, [20- 23].

Inelastic Scattering – A certain amount of the inbound radiation energy is dissipated through an ionization or excitation of the material atoms. Here, the inbound energy is sufficient to dislodge electrons from their shells, forming an ion, or shell electrons are excited to outer shells. Recombinational gamma spectra (electromagnetic)

is produced and radiated in all directions, when the excited or ionized electrons fall into the inner shells.

Elastic Scattering– This lesser (secondary) radiation tends to possess lower energy content and is also radiated in all directions. The radiation intensity is an increasing function of the material's atomic number. This attribute is well suited for measuring coating thicknesses on base materials (having different atomic numbers to the coating) via backscattering techniques.

γ-Rays– Gamma rays (electromagnetic energy) are attenuated through reductions in their quanta energies, via the combined processes of photoelectric absorption, scattering and pair production, [16]. The experienced attenuation is an exponential function of the inbound radiation energy spectra, and the material composition and thickness.

This relationship makes this form of radiation an attractive choice for material thickness measurement via a knowledge of the applied radiation, the material composition and an examination of the resulting transmitted radiation.

3.10 Mass Attenuation Coefficient

The manner in which a composite / alloyed material responds to inbound photonic radiation can be characterized by the composite Mass Attenuation Coefficient (MAC), μ/ρ, of its elemental constituents (typically with units of(cm^2/g)). The MAC is a material density normalization of the Linear Attenuation Coefficient (LAC), μ, where ρ is the density of the material (in g/cm3), and the MAC is therefore an energy dependent constant that is independent of physical state (solid, liquid, gas).[37-39]

The reciprocal of the LAC, q, is often termed the Mean Free Path. The MAC is typically characterized as an energy cross-section, with the amplitude of attenuation being a function of applied photonic energy, [16]. Figure 3.2 provides a graphical representation of the MAC for the element Iron (Fe, Atomic No. 26). Radiation attenuation is composed of five primary processes:

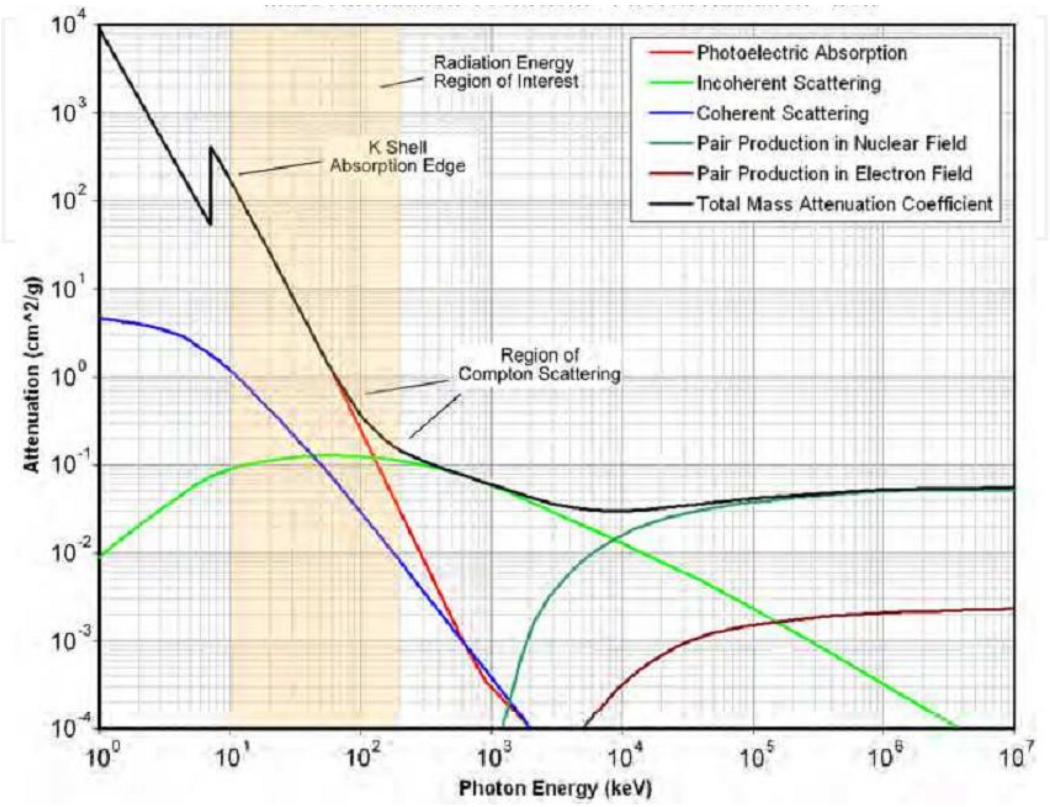


Fig.3.7: Graphical representations of the Mass Attenuation Coefficient, (μ/ρ), of the element Iron (Fe) as a function of the applied photonic energy.

Photoelectric Absorption This process is in effect at lower energies and involves the conversion of the inbound photon's energy to the excitation of the material atom's inner shell electrons (K or L), beyond their binding energies and dislodging them from the atom, to form an ion, [14]. These free electrons (photoelectrons) recombine with

free ions and radiate with a characteristic spectra of the material's constituent atoms (re combinational spectral lines). This radiation is emitted in all directions in the form of an X-Ray fluorescence (whose energy increases with atomic number). If the inbound radiation energy is below shell's binding energy, photoelectrons are not formed from that shell and an abrupt decrease in the material's absorption characteristics is noted (see the abrupt, sawtooth absorption edge in Figure 3.8).

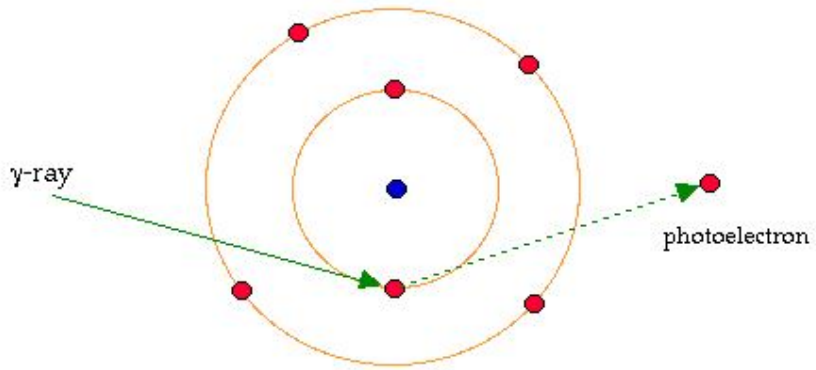


Fig (3-8) photoelectric effect

When photon energy fall into metal ,the metal absorb all energy .then some of energy going to rejected the electron from the surface and others carry the electron from the surface .

or

$$hf = \phi + K \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

Incoherent Scattering (Compton Scattering) This absorption process is in effect over a broad range of energies, and involves inelastic scattering interactions between the material atom's electrons and the inbound photonic radiation, [20]. The electrons are

transferred part of the inbound radiation energy (causing them to recoil) and a photon containing the remaining energy to be emitted in a different direction from the inbound, higher energy photon. The overall kinetic energy is not conserved (inelastic), but the overall momentum is conserved. If the released photon has sufficient energy, this process may be repeated. The Compton scatter radiation has a directional dependency that results in radiated lobes of having angular intensity dependencies.

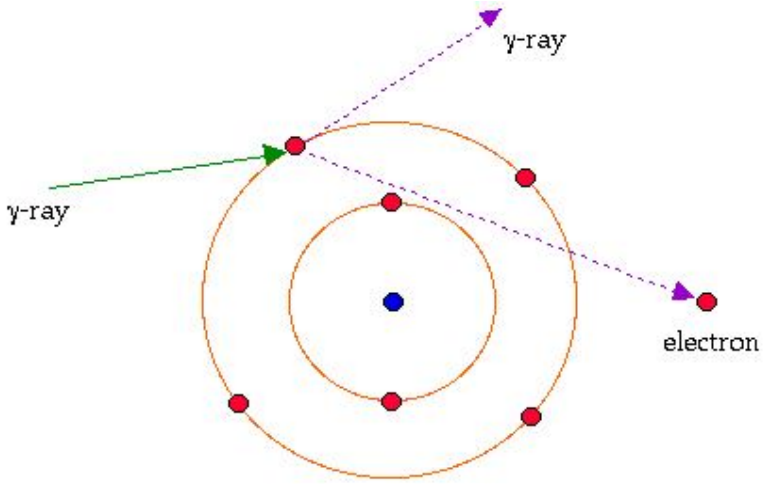


Fig (3-9) Compton scattering

In Compton scattering ,the incoming gamma rays photon is deflected through an angle o with respect to its original direction .the photon transfers apportion of its energy to the electron , which is then known a recoil electron. because all angles are possible, the energy transferred to the electron can vary from zero to a large fraction of the gamma ray energy .

using the law of conservation of momentum and energy photon is given by

$$hf = hf_0 + K \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

And the Compton shift is given by

$$\Delta\lambda = \frac{h}{m_0 C}\,(1 - \cos\emptyset)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.5)$$

Coherent Scattering (Rayleigh Scattering) This absorption process is in effect in the lower energy regions, and involves the elastic scattering interactions between the inbound photons and physical particles that are much smaller than the wavelength of the photon energy, [20].

Pair Production This absorption process is in effect only at very high energies (greater than twice the rest-energy of an electron (>1.022MeV)), and involves the formation of electron pairs (an electron and a positron), [13]. The electron pair converts any excess energy to kinetic energy, which may induce subsequent absorption / collisions with the material's atoms. This absorption process occurs only at very high energies, and therefore has no practical application in the forms of thickness measurement considered here.

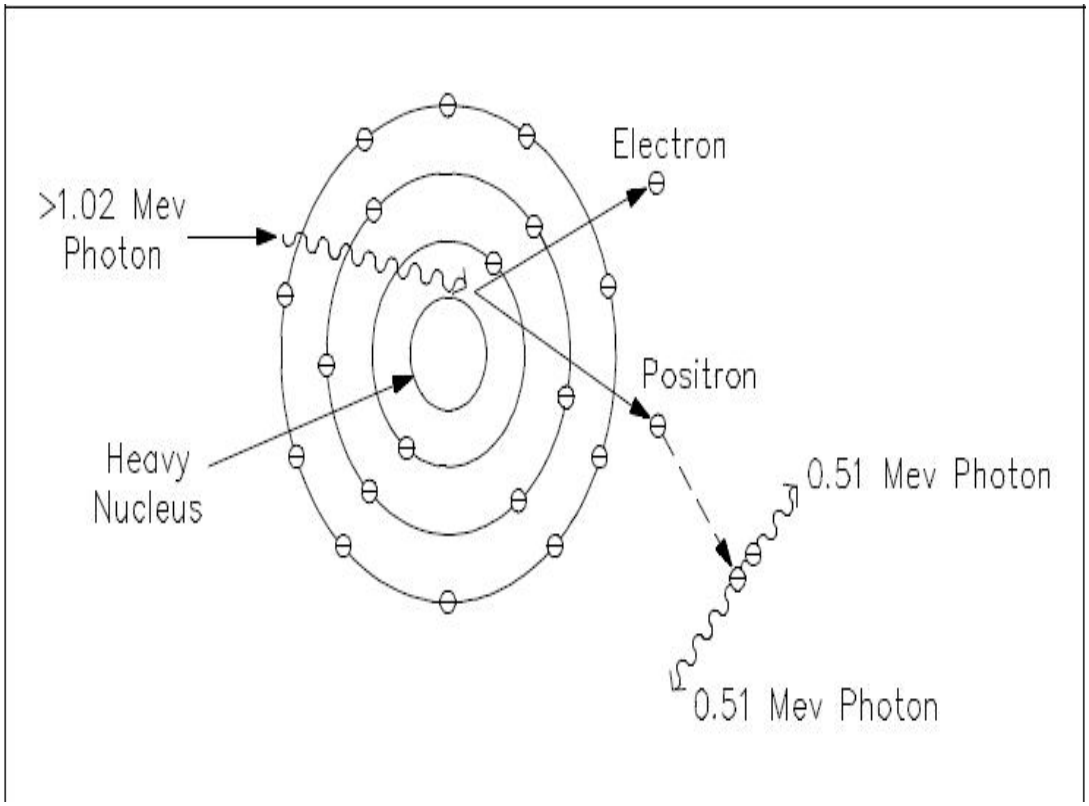


Fig (3-10) pair production

In pair production the energy is given by

$$hf = 2MC^2+K_1+K_2\ldots\ldots\ldots\ldots\ldots\ldots(3.6)$$

The summation of these components forms the MAC and precision cross-section data is openly published as tabulated lists by the National Institute of Standards and Technology (NIST) [16], for all the naturally occurring periodic table elements to an atomic number of 92 (Uranium).

It is important to examine the nature of the material absorption characteristics within the region of radiation energy of interest (10keV – 200keV), see Figure(4.1). Here, the attenuation characteristics of the lower energy section are dominated by the photoelectric absorption. At energies higher than about 100keV, Compton Scattering becomes

the primary method of attenuation. Depending on the nature of a given element's atomic structure and atomic weight, the behavior of the MAC can vary widely.

3.11 Attenuation Characterization

If gamma ray passes through an absorber of thickness dx, its intensity *I* change. The change in intensity dI is proportional to the intensity *I* of γ – rays falling on the absorber and thickness of the absorber. The change in intensity is given by

$$dI \propto -Idx$$

$$dI = -\mu Idx \qquad (3.7)$$

Negative sing indicates that as x increases, *I* decrease. Here μ is constant of proportionality and is known as absorption coefficient or linear attenuation coefficient, [24- 25]. For a given absorber, μ depends upon the energy of gamma rays. Equation (3.7) can be written as

$$\frac{dI}{I} = -\mu dx$$

This on integration gives

$$In(I) = -\mu x + c \qquad (3.8)$$

When $x = 0, I = I_0$, here I_0 is the initial of γ – rays falling on the absorber from Eq. (3.8)

$$c = In\,(I_0)$$

Substituting for c in Eq.(3.7) , we get

$$In\left(\frac{I}{I_0}\right) = -\mu x$$

This equation can for also be written as

$$I = I_0 e^{-\mu x} \qquad (3\text{-}9)$$

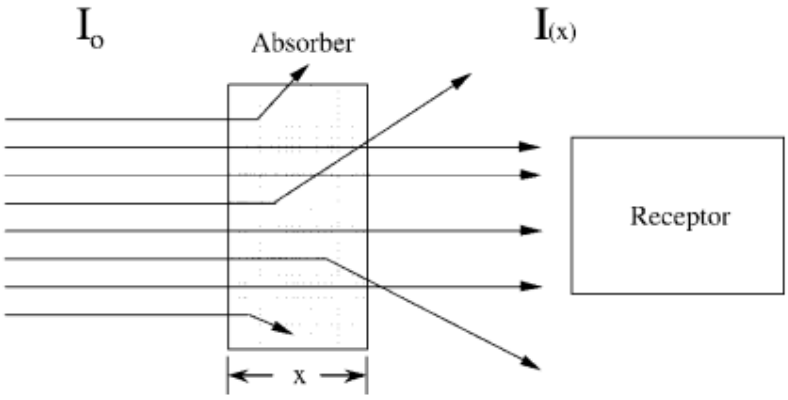


Fig (3-11) Illustration of attenuation of a photon beam in an absorber of thickness x

*3.11.1. **Mass Attenuation***

Use of the linear attenuation coefficient is limited by the fact that it varies with the density of the absorber, even though the absorber material is the same.

Therefore, the mass attenuation coefficient is much more widely used and is defined as

$$\frac{\mu}{\rho} \qquad (3\text{-}10)$$

Where ρ represents the density of the medium.

For a given gamma-ray energy, the mass attenuation coefficient does not change with the physical state of a given absorber. For example, it is the same for water whether present in liquid or vapor form, [24- 25]. The mass attenuation coefficient of a compound or mixture of elements can be calculated from

$$\left(\frac{\mu}{\rho}\right) = \sum_i w_i \left(\frac{\mu}{\rho}\right) \qquad (3\text{-}11)$$

Where the *W* factors represent the weight fraction of element *i* in the compound or mixture.

The linear attenuation coefficient is also equal to the product of the atomic density N_A and the total atomic cross section σ_A for all processes:

$$\mu = N_A \sigma_A \qquad (3\text{-}12)$$

The number of atoms $cm^{-3}$of an element is given by $N_A = (\rho/A)N_0$, where ρ is the density of the material in g cm^{-3}, A is the gram atomic weight, and N_0 is Avogadro's number.

Thus, we can write $\mu = \rho N_0 \sigma_A / A$, or

$$\frac{\mu}{\rho} = \frac{N_0 \sigma_A}{A} \qquad (3\text{-}13)$$

giving the relationship between the mass attenuation coefficient and the atomic cross section for photon interaction with any element. For a compound or mixture, one can add the separate contributions from each element to obtain μ.

311.2. Absorber Mass Thickness

In terms of the mass attenuation coefficient, the attenuation law for gamma rays now takes the form

$$\frac{I}{I_0} = e^{-(\mu/\rho)\rho t} \qquad (3\text{-}14)$$

The product ***pt,*** known as the mass thickness of the absorber, is now the significant parameter that determines its degree of attenuations. The thickness of absorbers used in radiation measurements is therefore often measured in mass thickness rather than physical thickness, because it is a more fundamental physical quantity, [24-25].

The mass thickness is also a useful concept when discussing the energy loss of charged particles and fast electrons. For absorber materials with similar neutron/proton ratios, a particle will encounter about the same number of electrons passing through absorbers of equal mass thickness. Therefore, the stopping power and range, when expressed in units of ***px,*** are roughly the same for materials that do not differ greatly in ***Z.***

3.11.3. Half-Value Layer

The concept of half-value layer (HVL) of an absorbing material for $\gamma - ray$ or x-radiations is important in the design of shielding for radiation protection. It is defined as the thickness of the absorber that reduces the intensity of a photon beam by one-half, [24-25].

The HVL depends on the energy of the radiation and the atomic number of the absorber. It is greater for high-energy photons and smaller for high-Z materials. For monoenergetic photons, the HVL of an absorber is related to its linear attenuation coefficient as follows:

$$HVL = \frac{0.693}{\mu} \qquad (3\text{-}15)$$

3.12 ***scattering cross section***

The probability for the occurrence of various processes initially through collision in atomic and nuclear physics are generally described in term of cross section for the process.

The cross section for Compton scattering has been calculated using the diras relativistic theory of the electron by klein and nishina in 1928 is given as

$$\frac{d\sigma}{d\Omega} = Zr_0^2 \left(\frac{1}{1+\alpha(1-cos\emptyset)}\right)^2 \left(\frac{1+\cos^2\emptyset}{2}\right)\left(1+\frac{\alpha^2(1-cos\emptyset)^2}{(1+cos^2\emptyset)[1+\alpha(1-cos\emptyset)]}\right)$$

...(3-16)

Where

$\alpha=h\upsilon/m_oc^2$, and r_o is the classical electron radius [24-25]

Chapter Four

Materials and Experimental Measurements

4.1 Introduction

Industrial measurements instruments that use radioisotopes are instruments that harness radioactive rays to measure such parameters as; thickness, level, density, moisture and the like. The advantage of such measuring instruments is that they are non contact, non-destructive and enable online, real-time high-speed measurements. Because the physical properties of radioisotopes make these instruments less susceptible to thermal, electrical and vibratory noise sources, these measuring instruments are widely used in such applications as, for example, the production lines at ceramic, glass, aluminum and iron industries.

4.2 The proposed Modality

In this work, an experimental facility which utilizes gamma transmission technique has been developed for routine determination of thickness defaults in metal and non metal samples such as; Alumina ceramic, borosilicate glass, aluminum and iron. It consists of ^{241}Am radioisotope source and NaI(Tl) detector coupled with single channel analyzer, characterized with relatively high sensitivity and with windows set at appropriate energy for determination of transmitted γ-counts from the sample.

The facility is based on principles of absorption and attenuation of low energy γ-rays which depend on the mean atomic number of elements and thus can be used to determine the thickness as well as the type of material. Sketched diagram for the proposed system is shown in figure 4.1.

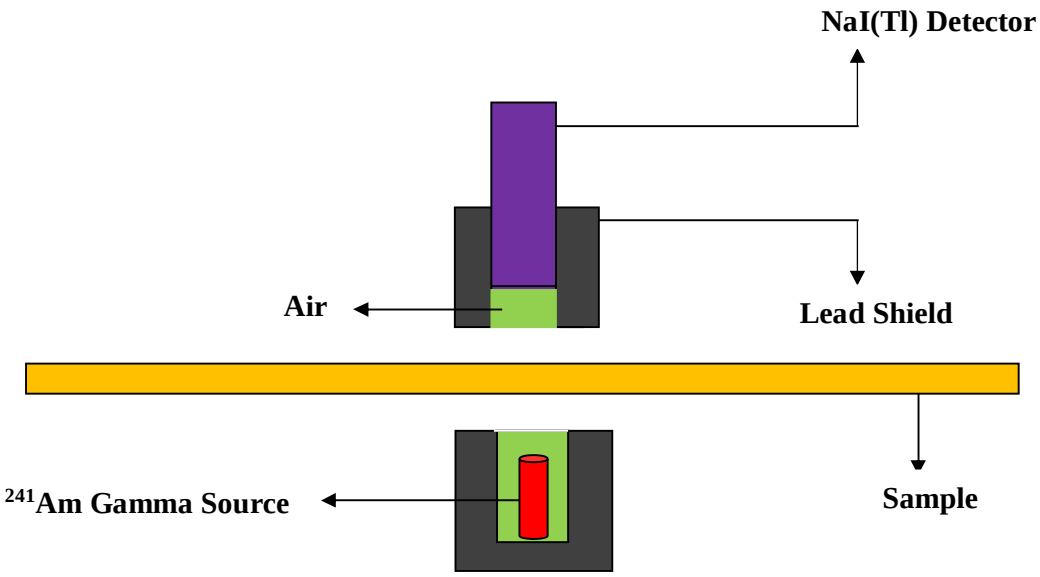


Fig.4.1. Sketch diagram for the gamma ray transmission-based system

4.3 Description of gamma transmission technique

When radiation emitted by a gamma ray source passes through matter (transmission), it is attenuated, the amount of attenuation being dependent on thickness, density and composition of the absorber. A scintillation detector, which is very sensitive to gamma radiation, is used to measure the attenuated radiation. This supplies a digital signal which is proportional to the intensity of the attenuated radiation. Also, the absorption of low –energy gamma radiation from ^{241}Am increases as a function of the atomic number of the material through which the radiation passes.

The samples under test; alumina ceramic, Borosilicate glass, Aluminum and Iron have different atomic numbers and thus give different absorption levels which are direct measures of sample density. Absorption of

Gamma-rays is widely used in non-destructive characterization of density. However, other methods could be used but the former has the following advantages;

i. Its simplicity for handling, instrumentation and processing;

ii. It can provide representative analysis without the need of sample preparation procedures;

iii. It can give an early indication of the mineral quality by allowing direct determination of concentration of sensitive elements and the derivation of important economic parameters, such as ash content values in samples in conveyor belts and in ores; and

iv. It is non-destructive, accurate, economic and low cost analytical tool [24-39]

4.4. NaI(Tl) Scintillation Detector

One of the most efficient methods of counting gamma rays and measuring their energies is their detection by a scintillation gamma ray spectrometer. This spectrometer employs a scintillation detector which is usually a thallium activated sodium iodide denoted by NaI (TI)] crystal as a scintillator.[25-39]

4.5 Experimental Arrangement

The experimental geometry of the nuclear-based system used is shown in figure (3.2) below. The ^{241}Am sources were used to provided the gamma (γ)-ray spectrometry which was detected with a thallium activated sodium iodide (NaI(Tl) -Canberra 200P detector, which operates at a bias voltage supply of 950 volts. The counting was done with the computer-assisted measuring and evaluation system

CASSY-S which consists of the CASSY Lab software (524 200) and Sensor-CASSY modules (524 010). The ^{241}Am sources was collimated and located 3cm below the sample, while the (NaI(Tl) detector was shielded with lead and located 3cm above the sample.

The gamma-transmission technique requires a gamma source, which were provided by a lower energy source ^{241}Am. ^{241}Am source has a half-life of 432.20 years, gamma intensity o f 35.90 % and energy of about 60keV. The transmitted intensity through the samples placed between the source and the detector were counted in the multi channel analyzer (MCA connected to a NaI (Tl) detector. The detail information on the radio isotope sources and samples used are given below in Table 3.1 and Table 3.2.

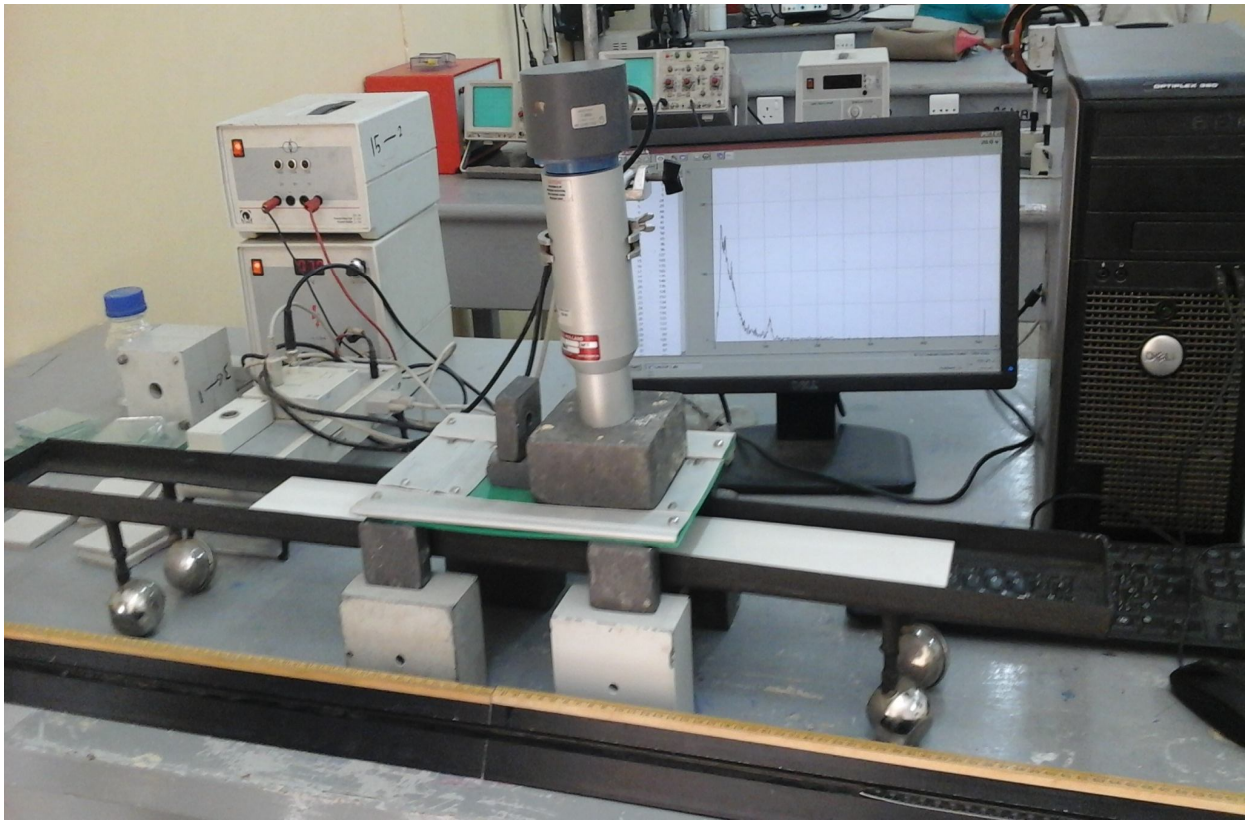


Fig. 4.2, Experimental Arrangement

Table 4.1: Radioisotope source used

Radioisotope	Half-life (Years)	Date of production	Activity at the date of production (kBq)	Gamma intensity (%)	Approximate Energy (keV)
^{241}Am	432.2	July 1st, 2004	36.5	35.90	60.0

Table 4.2: Materials used

Sample	μ/ρ	Density (ρ)	Thickness	Gamma Energy
Alumina Ceramic (Al_2O_3)	6.7	4.02 g/cm^3	1cm	13kev
Borosilicate glass SiO_2	0.358	2.6 g/cm^3	1cm	40kev
Aluminum (Al)	3.296	2.7 g/cm^3	1cm	20kev
Iron (Fe)	0.3708	7.9 g/cm^3	1cm	17kev

5.5.1 Analytical procedures

A cylindrical sample container which fits well into the detector geometry was used. It has a height of 11.0 cm and 2.2 cm in diameter. The source position was kept constant throughout the measurement at the top of the container and the position of the sample container made reproducible on the detector by placing a graphical sheet on which the bottom outline of the container were traced on top of the detector window.

The background intensity and the intensities with and without samples I and I_0 respectively were measured with the counter of the SCA in each case for the samples under test. The counting time was 20 seconds and each measurement was repeated ten times with standard deviation of 1.2 and 1.1 for I and I_o respectively.

Chapter Five

Results and Discussions

5.1 Introduction

Several measurements were carried out to evaluate the performance of the proposed gamma ray transmission-based sensor for detection of thickness defaults in metallic and non metallic samples such as; Alumina ceramic, Borosilicate glass, Aluminum and Iron. The results were analysed using SigmaPlot10 software, [30].

Based on the measurement procedures discussed in chapter three, here we present the results in terms of transmitted flux with respect to samples under test. The variation of the transmitted flux with energy was also considered to explore the possibility of discrimination between materials under test.

Firstly we used the proposed system to measure the background radiation since it represents an essential factor that should be considered to count the background flux of photons that contribute to our measured transmitted photons from the ^{241}Am source. Figure 1.4 shows background flux of photons. As presented, the background photon flux peaks at 233 photon.cm^{2}.s^{-1}. The rest of measurements are analyzed considering this value.

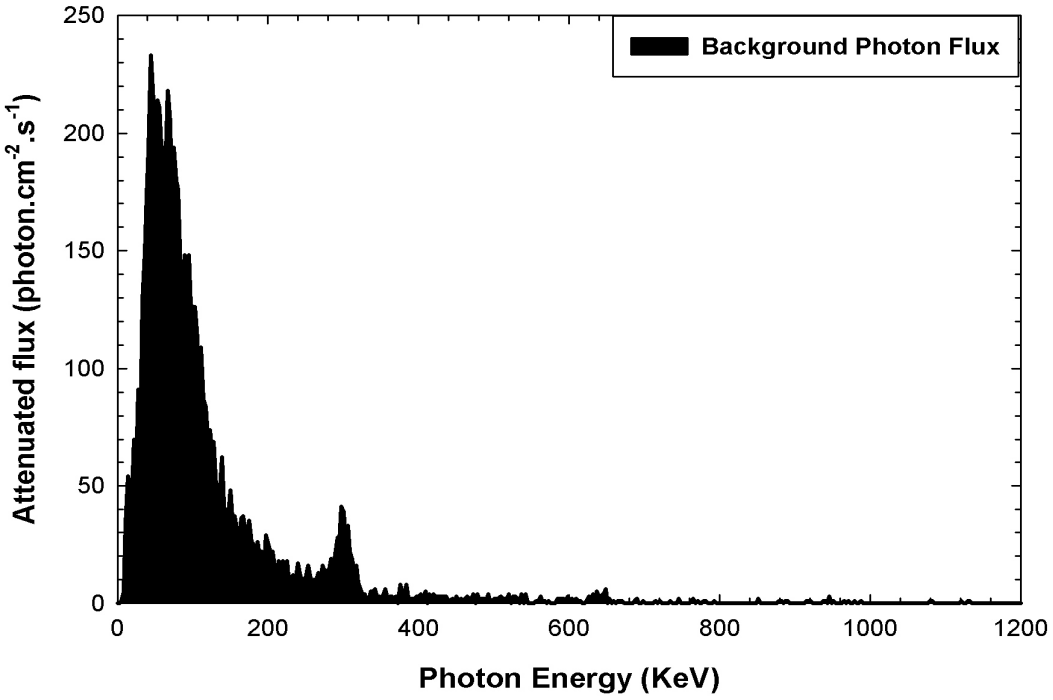


Fig 5.1 Background flux of photons

5.2 Transmitted Intensity

The variations of the transmitted intensity with respect to material thickness were presented in figures [5.2(a), 5.2(b)], [5.3(a), 5.3(b)], [5.4(a), 5.4(b)] and [5.5(a), 5.5(b)] , respectively.

5.2.1 Alumina Ceramic

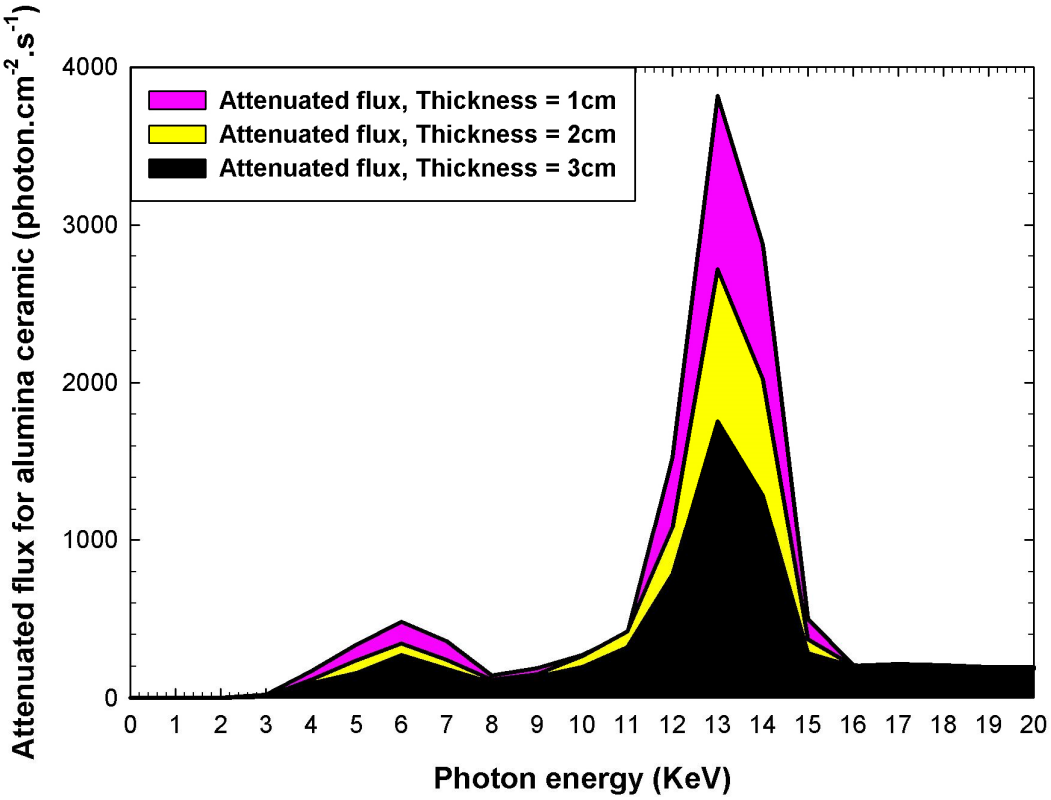


Fig 5.2(a) Transmitted intensity as a function of thickness for alumina ceramic

Table 5.1 Relationship between thickness(x) and transmitted flux I_x for Alumina Ceramic for energy 13KeV (Average density=4.02 g.cm^{-3})

Thickness t ±*0.1cm*	*Transmitted Intensity photon.cm^{-2}.s^{-1}*
1	*3818*
2	*2715*
3	*1756*

As shown in figure 5.2(a) and table (5.1) the transmitted intensity was significantly reduced with the increasing of thickness. This is reasonable since Beer-Lambert law states clearly the transmitted intensity is inversely proportional to the material thickness. The alumina ceramic sample at 1cm, 2cm and 3cm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) approximately by factors of 7, 11 and 17, respectively. Figure 5.2(b) reconfirms the current findings in terms of variations of the highest transmitted intensities with respect to change in thickness.

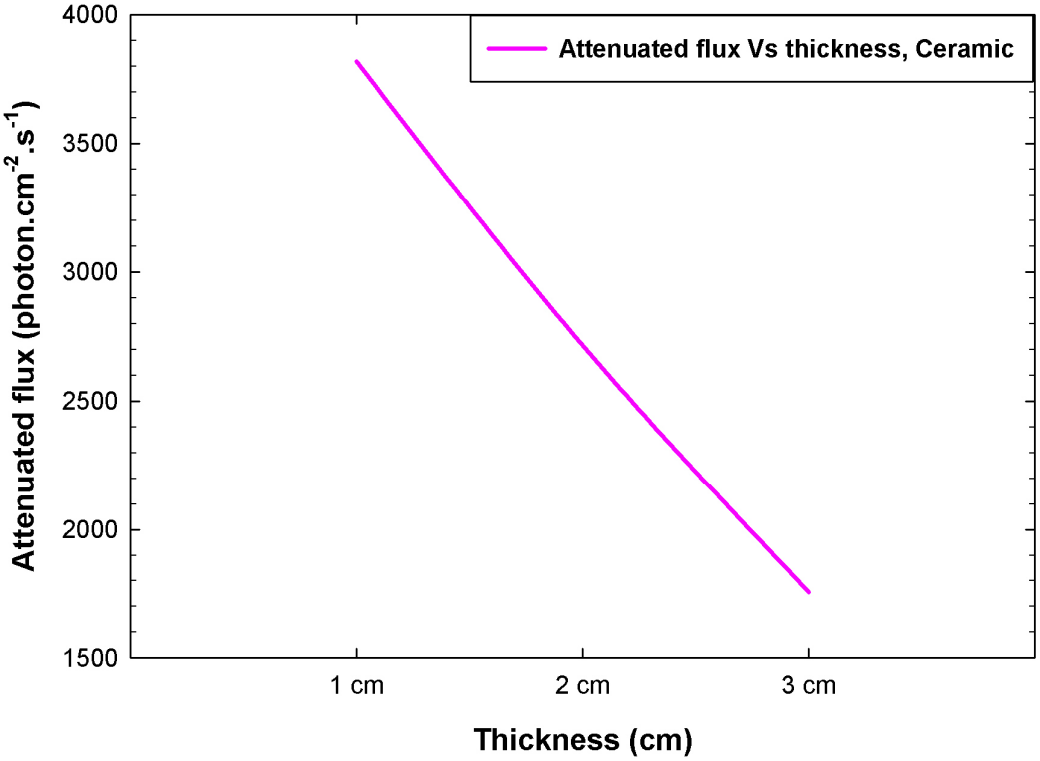


Fig 5.2(b) Peaks of transmitted intensity as a function of thickness for alumina ceramic

This should be explain on theoretical bases $I = I_0 e^{-\mu x}$

5.2.2 Borosilicate Glass

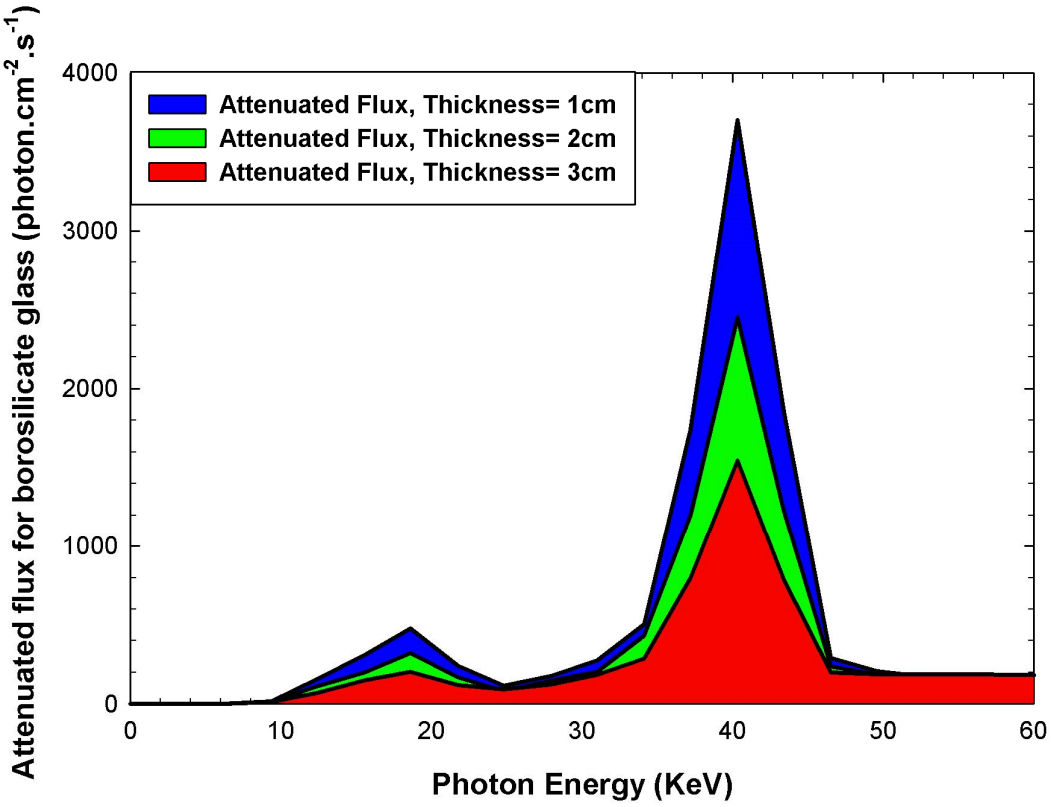


Fig. 5.3(a)Transmitted intensity as a function of thickness for Borosilicate glass

Table 5.2 Relationship between thickness(x) and transmitted flux I_x for Borosilicate glass energy 40KeV (Average density=2.6 g.cm^{-3})

Thickness ±*0.1cm*	*Transmitted Intensity* *photon.cm^{-2}.s^{-1}*
1	*3702*
2	*2450*
3	*1543*

As shown in figure 5.2(a) and table (5.2) the transmitted intensity was significantly reduced with the increasing of thickness. This is reasonable

since Beer-Lambert law states clearly the transmitted intensity is inversely proportional to the material thickness. The borated glass sample at 1cm, 2cm and 3cm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) approximately by factors of 8, 12 and 19, respectively. Figure 5.3(b) reconfirms the current findings in terms of variations of the highest transmitted intensities with respect to change in thickness.

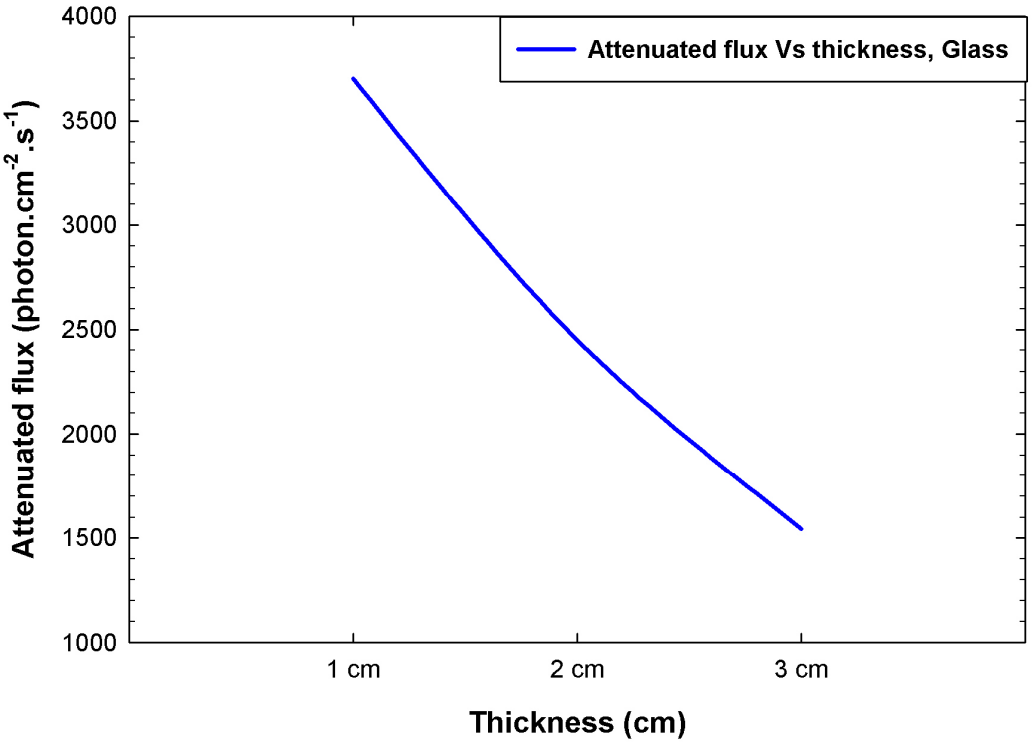


Fig 5.3(b) Peaks of transmitted intensity as a function of thickness for Borosilicate glass

This should be explain on theoretical bases $I = I_0 e^{-\mu x}$

5.2.3 Aluminum

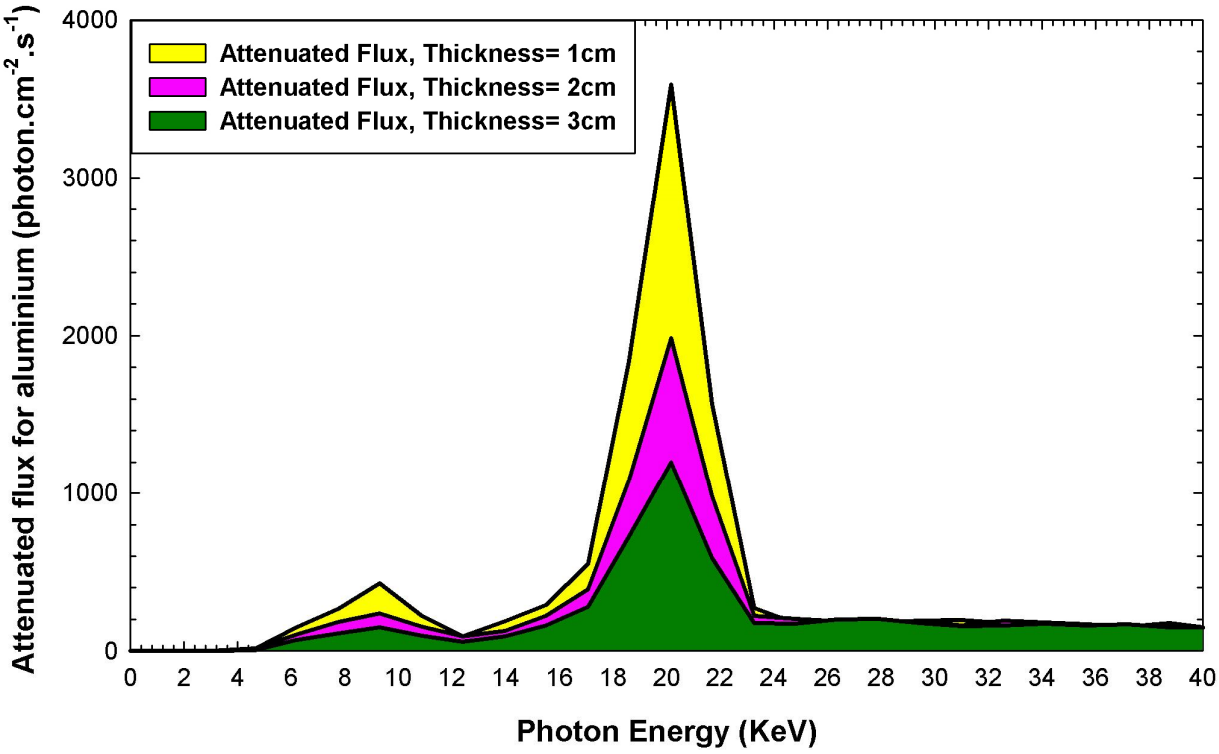


Fig. 5.4(a)Transmitted intensity as a function of thickness for Aluminum

Table 5.3 Relationship between thickness(x) and transmitted flux I_x for Aluminum for energy 20KeV (density=2.7 g.cm^{-3})

Thickness ±*0.1cm*	*Transmitted Intensity* *photon.cm^{-2}.s^{-1}*
1	*3591*
2	*1983*
3	*1196*

As shown in figure 5.4(a) and table (5.3) the transmitted intensity was significantly reduced with the increasing of thickness. This is reasonable since Beer-Lambert law states clearly the transmitted intensity is

inversely proportional to the material thickness. The Aluminum at 1cm, 2cm and 3cm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) approximately by factors of 8, 15 and 25, respectively. Figure 5.4(b) reconfirms the current findings in terms of variations of the highest transmitted intensities with respect to change in thickness.

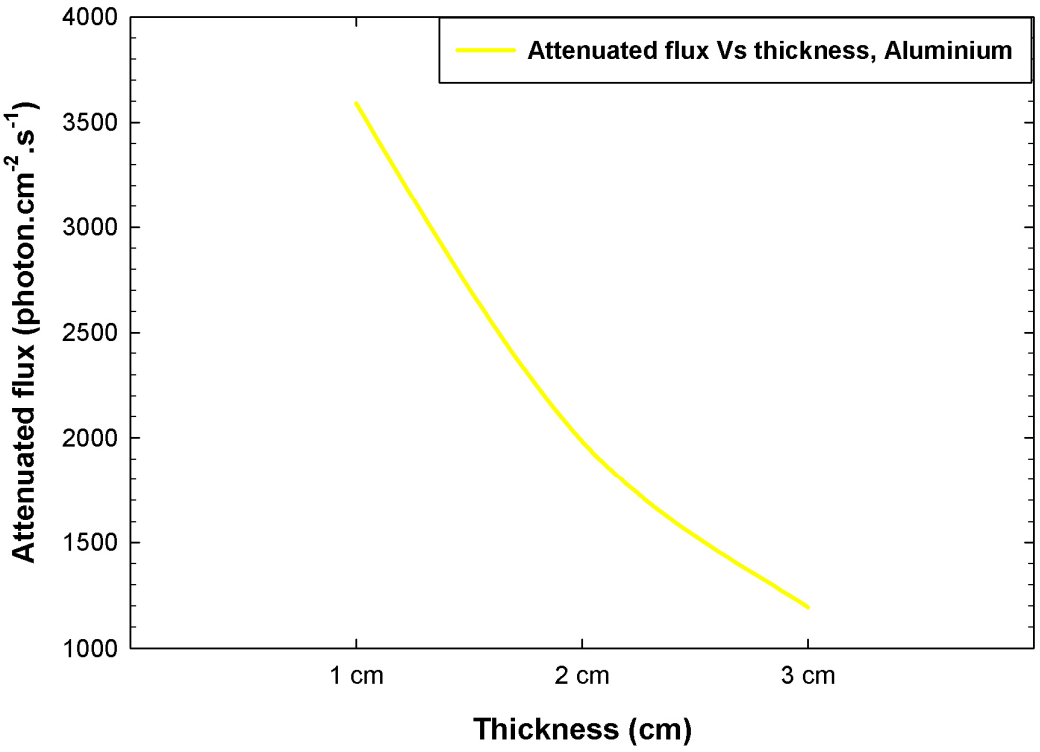


Fig. 5.4 (b) Peaks of transmitted intensity as a function of thickness for Aluminum

This should be explain on theoretical bases $I = I_0 e^{-\mu x}$

5.2.4 Iron

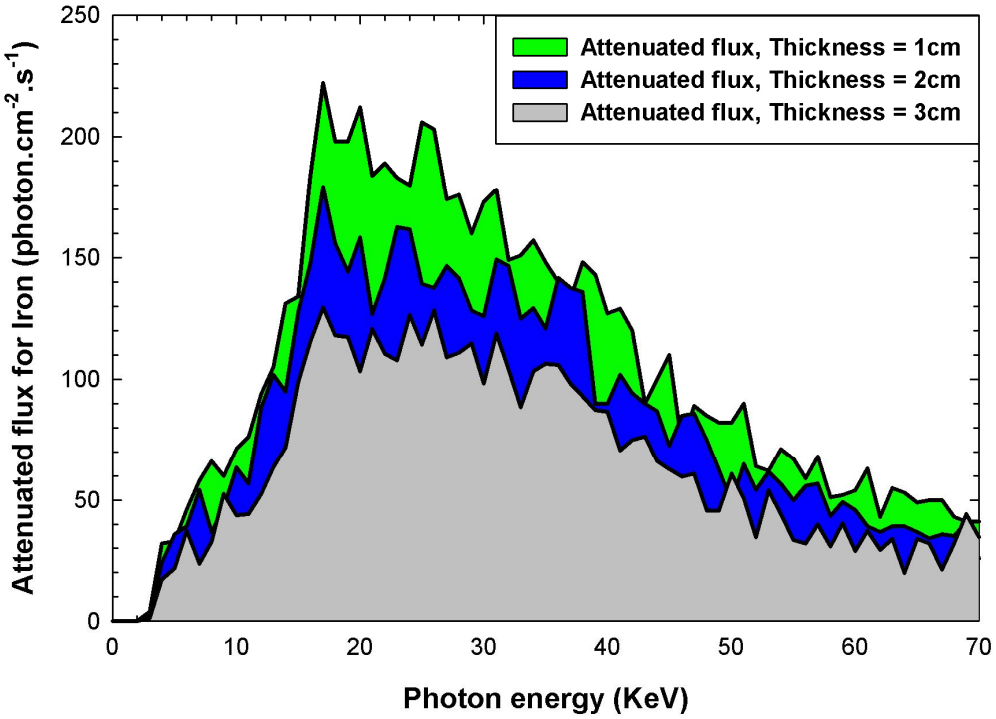


Fig. 5.5(a)Transmitted intensity as a function of thickness for Iron

Table 5.4 Relationship between thickness(x) and transmitted flux I_x for Iron for energy 17KeV for (Density=7.9 g.cm^{-3})

Thickness ±*0.1cm*	*Transmitted Intensity* *photon.cm^{-2}.s^{-1}*
1	*222*
2	*179*
3	*129*

As shown in figure 5.5(a)and table (5.4) the transmitted intensity was significantly reduced with the increasing of thickness. This is reasonable

since Beer-Lambert law states clearly the transmitted intensity is inversely proportional to the material thickness. The Iron sample at 1cm, 2cm and 3cm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) approximately by factors of 135, 167 and 232, respectively. Figure 5.5(b) reconfirms the current findings in terms of variations of the highest transmitted intensities with respect to change in thickness.

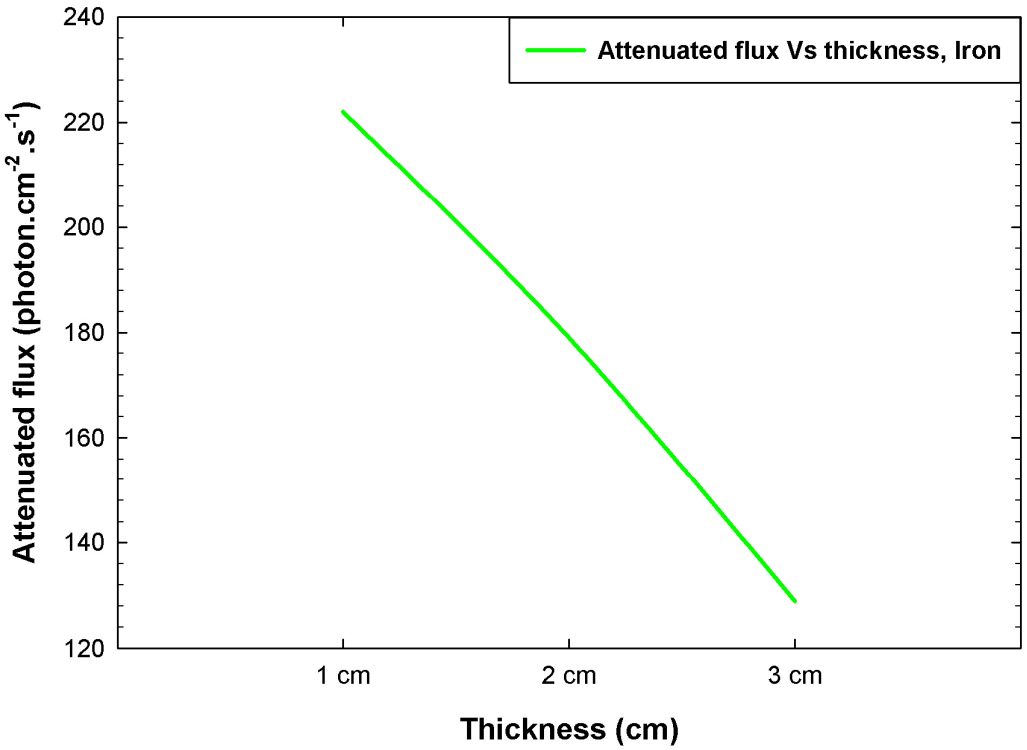


Fig. 5.5 (b) Peaks of transmitted intensity as a function of thickness for Iron

This should be explain on theoretical bases $I = I_0 e^{-\mu x}$

5.3 Sensitivity of the proposed system

The practicality of using the system to detect thickness flaws in millimeter range was calculated considering a scenario that a thickness change by 1mm is present along the sheet of each sample. Figure 4.6 shows the sensitivity of the system in terms of transmitted flux with respect to thickness variations (1cmm, 0.9cm and 1.1 cm). The results for Alumina ceramic, borated glass, aluminum and iron were presented in Tables (4.5), (4.6) ,(4.7) and (4.8) respectively. These results were plotted in figure (4.6)

Table 4.5 Relationship between thickness(x) and transmitted flux I_x for alumina Ceramic for energy 13KeV (Average density=4.02 g.cm^{-3})

Thickness ±*0.1mm*	*Transmitted Intensity photon.cm^{-2}.s^{-1}*
9	*5681.08*
10	*3818*
11	*2565.9*

Table 4.6 Relationship between thickness(x) and transmitted flux I_x for Borosilicate glass or energy 40KeV (Average density=2.6 g.cm^{-3})

Thickness ±*0.1mm*	*Transmitted Intensity photon.cm^{-2}.s^{-1}*
9	*4062.8*
10	*3591*
11	*3373.2*

Table 5.7 Relationship between thickness(x) and transmitted flux I_x for Aluminum energy 20KeV (density=2.7 g.cm^{-3})

Thickness ±*0.1mm*	*Transmitted Intensity photon.cm^{-2}.s^{-1}*
9	*8744.5*
10	*3591*
11	*1474*

Table 5.8 Relationship between thickness(x) and transmitted flux I_x for Iron energy 17KeV (Density=7.9 g.cm^{-3})

Thickness ±*0.1mm*	*Transmitted Intensity photon.cm^{-2}.s^{-1}*
9	*297.5*
10	*222*
11	*165.6*

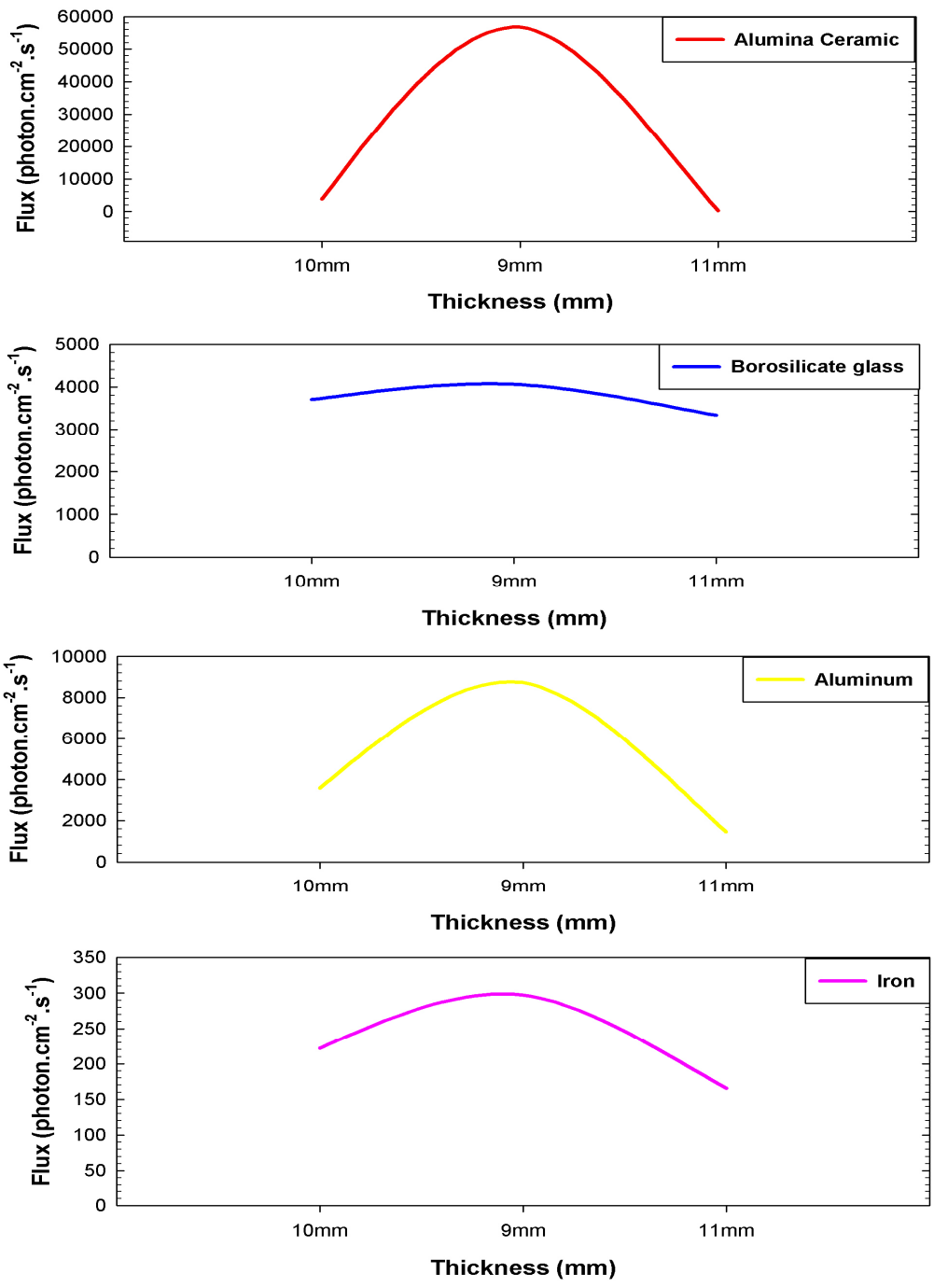


Fig. (5.6) The sensitivity of the system in terms of transmitted flux with respect to thickness variations

As shown in figure (5.6) The alumina ceramic sample at 10mm, 9mm and 11mm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) by factors of 7, 5 and 11, respectively.

The borated glass sample at 10mm, 9mm and 11mm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) approximately by factors of 8, 7 and 8.8, respectively.

The Aluminum at 10mm, 9mm and 11mm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) approximately by factors of 8, 3.4 and 20.3, respectively.

The Iron sample at 10mm, 9mm and 11mm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) by factors of 135, 100 and 181, respectively.

These results demonstrate clearly the possibility of using the proposed gamma-transmission-based sensor for thickness detection in millimeters ranges. A change by 1mm for all four samples produced detectable transmitted flux.

5.4. Material discrimination

The measured values at which transmitted intensity peaks for each sample were plotted against the corresponding energies to determine the performance of the system in discriminating between the four samples under investigation. The results are shown in figure (4.7)

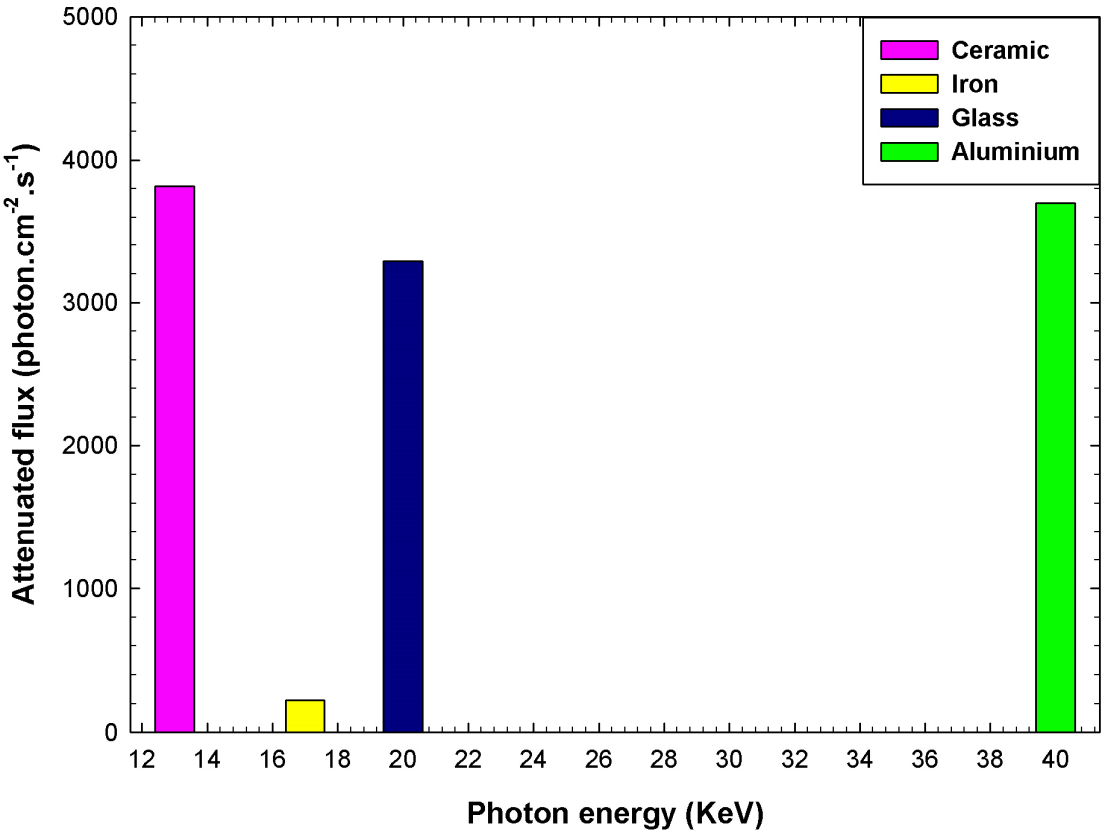


Fig (5.7) Peaks of transmitted flux for each sample plotted against the corresponding energies

As presented, for Alumina ceramic, borated glass, aluminum and iron, the transmitted flux peaks at the energies, 13 KeV, 40 KeV, 20 KeV and 17 KeV, respectively. These results suggest the possibility of using such energies to identify each of the four samples used.

Chapter Six

Conclusions and Recommendations

Conclusions

The objective of research was to develop a simple gamma transmission-based non destructive system and explore its practicality in providing a precise and accurate thickness measurement of flat rolled products such as; ceramic, glass, aluminum and iron. The research was also oriented to explore the possibility of using such system to discriminate samples with respect to their density. The proposed system is composed of ^{241}Am photon source, NaI(Tl) scintillation detector, signal processing unit, shielding and a monitor.

The results confirmed the sensitivity of the system for detection of flaws in both thickness scales. The alumina ceramic sample at 1cm, 2cm and 3cm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) approximately by factors of 7, 11 and 17, respectively. While at 9mm and 11mm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) by factors of 5 and 11, respectively. The borated glass sample at 1cm, 2cm and 3cm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) approximately by factors of 8, 12 and 19, respectively. While at 9mm and 11mm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) approximately by factors of 7 and 8.8, respectively.

The Aluminum at 1cm, 2cm and 3cm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) approximately by factors of 8, 15 and 25, respectively. While at 9mm and 11mm

thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) approximately by factors of 3.4 and 20.3, respectively. The Iron sample at 1cm, 2cm and 3cm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) approximately by factors of 135, 167 and 232, respectively. While at 9mm and 11mm thicknesses has reduced the source intensity (3×10^4) the source energy line (60KeV) by factors of 100 and 181, respectively.

These results demonstrate clearly the possibility of using the proposed gamma-transmission-based sensor for thickness detection in millimeters ranges. A change by 1mm for all four samples produced detectable transmitted flux.

On the other hand, the performance of the proposed system in discriminating between the four samples was explored and the results showed that, for Alumina ceramic, borated glass, aluminum and iron, the transmitted flux peaks at the energies, 13 KeV, 40 KeV, 20 KeV and 17 KeV, respectively. These results suggest the possibility of using such energies to identify each of the four samples used.

Recommendations

Further experimental measurements are needed to verify the feasibility of utilizing other different gamma sources such as ^{60}Co and ^{137}Cs. Further studies on the applicability of the proposed system for different flat rolled industrial products are needed.

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