MEASUREMENTS OF ENERGY OF GAMMA RADIATION

By

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Abstract

Gamma rays are electromagnetic radiation like x-rays and are the most energetic form of electromagnetic radiation with a very short wave length. theoretically i have measured the energy of interacted gamma rays using the NaI(Tl) and semiconductor detectors. The interaction and detection mechanism ,resolution of detector, detector efficiency for gamma measurement play greate role in increasing and decreasing the magnitude of the radiation energy .Gamma energy is proportional to the deposited energy by the photo electric ,compton and pair production interactions.

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Chapter 1

GAMMA-RAY INTERACTION WITH MATTER

1.1 Introduction

1.1.1 Gamma Ray Radiation

A gamma ray is a packet (or photon) of electromagnetic radiation emitted from the nucleus during radioactive decay and occasionally accompanying the emission of an alpha or beta particle. Gamma rays are identical in nature to other electromagnetic radiations such as light or microwaves but are of much higher energy. Examples of gamma emitters are cobalt-60, zinc-65, cesium-137, and radium-226. Because gamma radiation loses energy slowly, gamma rays are able to travel significant distances. Depending upon their initial energy, gamma rays can travel tens or hundreds of meters in air. Gamma radiation is typically shielded using very dense materials (the denser the material, the more chance that a gamma ray will interact with atoms in the material) such as lead or other dense metals. Gamma radiation particularly can present a hazard from exposures external to the body.

1.1.2 X-Ray Radiation

Like a gamma ray, an x-ray is a packet (or photon) of electromagnetic radiation emitted from an atom, except that the x-ray is not emitted from the nucleus. X-rays are produced

as the result of changes in the positions of the electrons orbiting the nucleus, as the electrons shift to different energy levels. Examples of x-ray emitting radioisotopes are iodine-125 and iodine-131. X-rays can be produced during the process of radioactive decay or as bremsstrahlung radiation. Bremsstrahlung radiation are x-rays produced when high energy electrons strike a target made of a heavy metal, such as tungsten or copper. As electrons collide with this material, some have their paths deflected by the nucleus of the metal atoms. This deflection results in the production of x-rays as the electrons lose energy.This is the process by which an x-ray machine produces x-rays. Like gamma rays, x-rays are typically shielded using very dense materials such as lead or other dense metals. X-rays particularly can present a hazard from exposures external to the body. Radiation, in our context, is energy in the form of high speed particles and electromagnetic waves. Radiation is further defined into ionizing and non-ionizing radiation.

a) Ionizing radiation is radiation with enough energy so that during an interaction with an atom, it can remove bound electrons, i.e it can ionize atoms. Examples are X-rays and electrons

b) Non-ionizing radiation is radiation without enough energy to remove bound electrons from their orbits around atoms. Examples are microwaves and visible light.

Gamma radiation is one of the three types of natural radioactivity. Gamma rays are electromagnetic radiation, like X-rays. The other two types of natural radioactivity are alpha and beta radiation, which are in the form of particles. Gamma rays are the most energetic form of electromagnetic radiation, with a very short wavelength of less than one-tenth of a nanometer. Gamma radiation is the product of radioactive atoms. Depending upon the ratio of neutrons to protons within its nucleus, an isotope of a particular element may be stable or unstable. When the binding energy is not strong enough to hold the nucleus of an atom together, the atom is said to be unstable. Atoms with unstable nuclei are constantly changing as a result of the imbalance of energy within the nucleus. Over time, the nuclei of unstable isotopes spontaneously disintegrate, or transform, in a process

known as radioactive decay. Various types of penetrating radiation may be emitted from the nucleus and/or its surrounding electrons. Nuclides which undergo radioactive decay are called radionuclides. Any material which contains measurable amounts of one or more radionuclides is a radioactive material. A nucleus which is in an excited state may emit one or more photons (packets of electromagnetic radiation) of discrete energies. The emission of gamma rays does not alter the number of protons or neutrons in the nucleus but instead has the effect of moving the nucleus from a higher to a lower energy state (unstable to stable).A photon can interact with matter by a number of competing mechanisms. The interaction can be with the entire atom, as in the photoelectric effect, or with one electron in the atom, as in the Compton effect, or with the atomic nucleus (as in pair production). The probability for each of these competing independent processes can be expressed as a collision cross section per atom, per electron, or per nucleus in the absorber. The sum of all these cross sections, normalized to a per atom basis, is then the probability that the incident photon will have an interaction of some kind while passing through a very thin absorber which contains one atom per cm^2 of area normal to the path of the incident photon. Detection of gamma radiation is one of the most important research tools in nuclear physics. Detection of gamma radiation yields information on various properties (excitation energies, angular moments, decay properties etc.) of states in nuclei. A knowldege of gamma-ray interaction is important to the nondestructive assayist in order to understand gamma-ray detection and attenuation. A gamma-ray must interact with adetector in order to be 'seen.' Although the major isotopes of uranium and plutonium emite gamma ray at fixed energies and rates ,the gamma-ray intensity measured out side a sample is always attenuated because of gamma-ray interactions with the sample. This attenuation must be carefully considered when using gamma-ray nondestructive assayist instruments.

1.2 Attenuation

As a photon makes its way through matter, there is no way to predicte precisely either how far it will travel before engaging in an interaction or the type of interaction it will engage in. In clinical applications we are generally not concerned with the fate of an individual photon but rather with the collective interaction of the large number of photons. In most instances we are interested in the overall rate at which photons interact as they make their way through a specific material.The interactions, either photoelectric or Compton, remove some of the photons from the beam in a process known as attenuation. Under specific conditions, a certain percentage of the photons will interact, or be attenuated, in a 1 unit thickness of material.

1.2.1 Linear Attenuation Coefficient

The linear attenuation coefficient (μ) is the actual fraction of photons interacting per 1 unit thickness of material. In our example the fraction that interacts in the 1 cm thickness is 0.1, or 10 percent, and the value of the linear attenuation coefficient is 0.1 per cm. Linear attenuation coefficient values indicate the rate at which photons interact as they move through material and are inversely related to the average distance photons travel before interacting. The rate at which photons interact (attenuation coefficient value) is determined by the energy of the individual photons and the atomic number and density of the material.

1.2.2 Mass Attenuation Coefficient

In some situations it is more desirable to express the attenuation rate in terms of the mass of the material encountered by the photons rather than in terms of distance. The quantity that affects attenuation rate is not the total mass of an object but rather the area mass. Area mass is the amount of material behind a 1 unit surface area .The area mass is the product of material thickness and density: Area Mass (g/cm^2) = Thickness

(cm)$\times$ Density (g/cm^3). The mass attenuation coefficient is the rate of photon interactions per 1 unit (g/cm^2) area mass. If we compare two pieces of material with different thicknesses and densities but the same area mass. Since both attenuate the same fraction of photons, the mass attenuation coefficient is the same for the two materials. They do not have the same linear attenuation coefficient values. The relationship between the mass and linear attenuation coefficients is Mass Attenuation Coefficient (μ/ρ) = Linear Attenuation Coefficient (μ) / Density (ρ). Notice that the symbol for mass attenuation coefficient (μ/ρ) is derived from the symbols for the linear attenuation coefficient (μ) and the symbol for density (r). We must be careful not to be misled by the relationship stated in this manner. Confusion often arises as to the effect of material density on attenuation coefficient values. Mass attenuation coefficient values are actually normalized with respect to material density, and therefore do not change with changes in density. Material density does have a direct effect on linear attenuation coefficient values. The total attenuation rate depends on the individual rates associated with photoelectric and Compton interactions. The respective attenuation coefficients are related as follows: $\mu(total) = \mu(photoelectric) + \mu(Compton)$. Let us now consider the factors that affect attenuation rates and the competition between photoelectric and Compton interactions. Both types of interactions occur with electrons within the material. The chance that a photon will interact as it travels a 1 unit distance depends on two factors. One factor is the concentration, or density, of electrons in the material. Increasing the concentration of electrons increases the chance of a photon coming close enough to an electron to interact. In a previous section (Characteristics and Structure of Matter) we observed that electron concentration was determined by the physical density of the material. Therefore, density affects the probability of both photoelectric and Compton interactions. All electrons are not equally attractive to a photon. What makes an electron more or less attractive is its binding energy. The two general rules are:

1. Photoelectric interactions occur most frequently when the electron binding energy is

slightly less than the photon energy.

2. Compton interactions occur most frequently with electrons with relatively low binding energies.

1.2.3 Exponential attenuation

Gamma rays were first identified in 1900 by Becquerel and Villard as a component of the radiation from uranium and radium that had much higher penetrability than alpha and beta particles. In 1909, Soddy and Russell found that gamma-ray attenuation followed an exponential law and that the ratio of the attenuation coefficient to the density of the attenuating material was nearly constant for all materials. 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

$$I = I_0 e^{-\mu_l L} \tag{1.2.1}$$

where μ_l is the attenuation coefficient (expressed in cm^{-1}). The ratio I/I_0. is called the gamma-ray transmission. Figure 1.1 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 a much lower fraction of incident gamma radiation than does a similar thickness of aluminum or steel. The attenuation coefficient in Equation 1.2.1 is called the linear attenuation coefficient.

1.2.4 Total Mass Attenuation Coefficient

The three interaction processes described above all contribute to the total mass attenuation coefficient. The relative importance of the three interactions depends on gamma

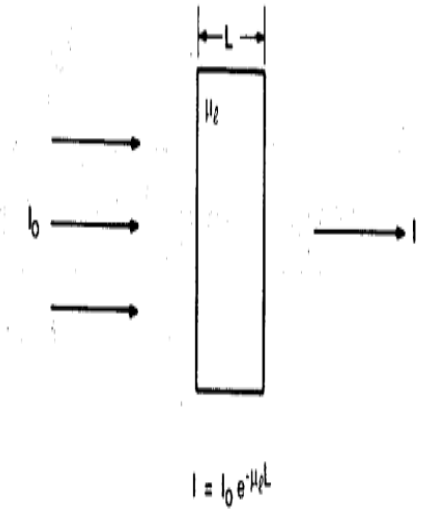

Figure 1.1: The fundamental law of gamma ray attenuation

ray energy and the atomic number of the absorber. All elements except hydrogen show a sharp, low energy rise that indicates where photoelectric absorption is the dominant interaction. The position of the rise is very dependent on atomic number. Above the low energy rise, the value of the mass attenuation coefficient decreases gradually, indicating the region where Compton scattering is the dominant interaction. The mass attenuation coefficients for all elements with atomic number less than 25 (iron) are nearly identical in the energy range 200 to 2000 keV. The attenuation curves converge for all elements in the range 1 to 2 MeV. The shape of the mass attenuation curve of hydrogen shows that it interacts with gamma rays with energy greater than 10 keV almost exclusively by Compton scattering. Above 2 MeV, the pair-production interaction becomes important for high Z elements and the mass attenuation coefficient begins to rise again. The interaction and transfer of energy from photons to tissue has two phases. The first is the "one-shot" interaction between the photon and an electron in which all or a significant part of the photon energy is transferred,the second is the transfer of energy from the

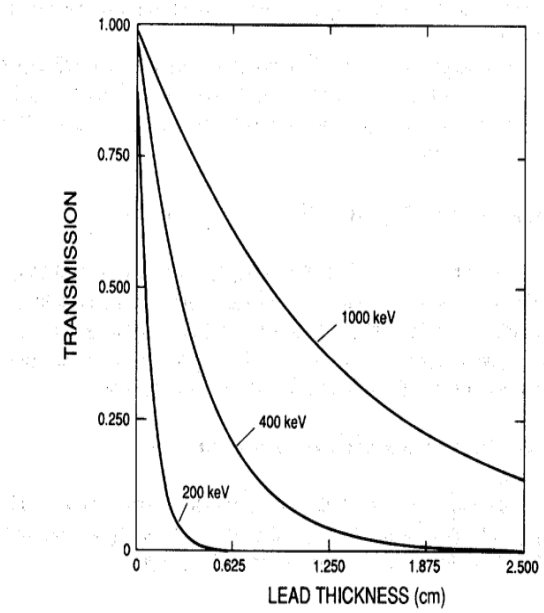

Figure 1.2: Transmission of gamma rays through lead absorbers

energized electron as it moves through the tissue. This occurs as a series of interactions, each of which transfers a relatively small amount of energy. Several types of radioactive transitions produce electron radiation including beta radiation, internal conversion (IC) electrons, and Auger electrons. These radiation electrons interact with matter (tissue) in a manner similar to that of electrons produced by photon interactions. In photoelectric interactions, the energy of the electron is equal to the energy of the incident photon less the binding energy of the electron within the atom. In Compton interactions, the relationship of the electron energy to that of the photon depends on the angle of scatter and the original photon energy. The electrons set free by these interactions have kinetic energies ranging from relatively low values to values slightly below the energy of the incident photons. As the electrons leave the interaction site, they immediately begin to transfer their energy to the surrounding material. Because the electron carries an electrical charge, it can interact with other electrons without touching them. As it passes through the material, the electron, in effect, pushes the other electrons away from its path. If the force on an electron is sufficient to remove it from its atom, ionization results. In some cases, the atomic or molecular structures are raised to a higher energy level, or

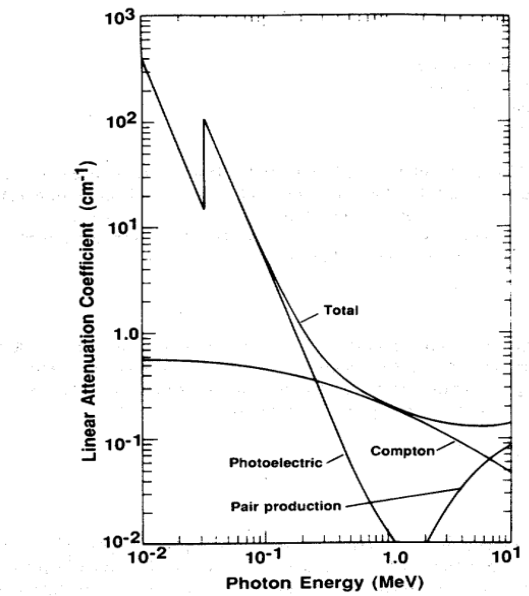

Figure 1.3: linear attenuation coeffcient of NaI showing contributions from photoelectric absorption, Compton scatterithng, and pair production.

excited state. Regardless of the type of interaction, the moving electron loses some of its energy. Most of the ionization produced by x- and gamma radiation is not a result of direct photon interactions, but rather of interactions of the energetic electrons with the material. For example, in air, radiation must expend an average energy of 33.4 eV per ionization. Consider a 50-keV x-ray photon undergoing a photoelectric interaction. The initial interaction of the photon ionizes one atom, but the resulting energetic electron ionizes approximately 1,500 additional atoms.

1.3 Interaction processes

Detection of gamma radiation is based on the interaction between the radiation and the detector material. The photon scatters from the electrons of the material and in each scattering process it loses a part of its energy. If the piece of material is large enough and the scatterings take place suitably, all the energy of the initial gamma ray is absorbed in the material. Thus, the energy of the photon is found by measuring the energy absorbed by the material. How this energy is determined,depends on the detector type and its

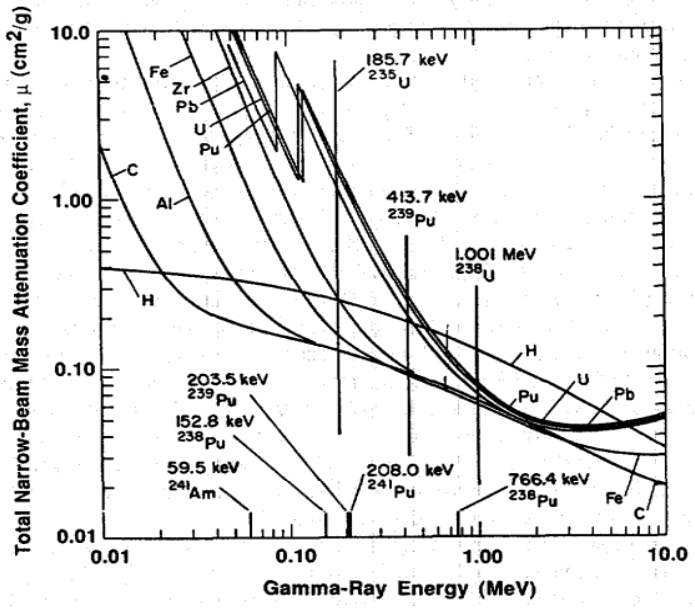

Figure 1.4: Mass attenuation coefficients of selected elements. Also indicated are gamma-ray energies commonly encountered in NDA of uranium and plutonium.

functioning. Probabilities of various processes depend on the energy of the photon, the used detector material and the size of the detector. If we recall that photons are individual units of energy. As an x-ray beam or gamma radiation passes through an object,three possible fates await each photon, as listed below:

a. It can penetrate the section of matter without interacting.

b. It can interact with the matter and be completely absorbed by depositing its energy.

c. It can interact and be scattered or deflected from its original direction

and deposite part of its energy. Photons Entering the Human Body will either Penetrate, be Absorbed, or Produce Scattered Radiation.There are two kinds of interactions through which photons deposite their energy; both are with electrons. In one type of interaction the photon loses all its energy; in the other, it loses a portion of its energy,and the remaining energy is scattered. Although alarge number of possible interaction mechanism are known for gamma rays in matter only three major types play an inportant role in radiation measurements with detectors and absorbers: 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.

1.3.1 Photoelectric Absorption

In the photoelectric (photon-electron) interaction a photon transfers all its energy to an electron located in one of the atomic shells. The electron is ejected from the atom by this energy and begins to pass through the surrounding matter. The electron rapidly loses its energy and moves only a relatively short distance from its original location. The photon's energy is, therefore, deposited in the matter close to the site of the photoelectric interaction.The energy transfer is a two-step process. The photoelectric interaction in which the photon transfers its energy to the electron is the first step. The depositing of the energy in the surrounding matter by the electron is the second step. Photoelectric interactions usually occur with electrons that are firmly bound to the atom, that is, those with a relatively high binding energy. Photoelectric interactions are most probable when the electron binding energy is only slightly less than the energy of the photon. If the binding energy is more than the energy of the photon, a photoelectric interaction cannot occur. This interaction is possible only when the photon has sufficient energy to overcome the binding energy and remove the electron from the atom.The photon's energy is divided into two parts by the interaction.A portion of the energy is used to overcome the electron's binding energy and to remove it from the atom.The remaining energy is transferred to the electron as kinetic energy and is deposited near the interaction site.Since the interaction creates a vacancy in one of the electron shells, typically the K or L, an electron moves down to fill in. The drop in energy of the filling electron often produces a characteristic

x-ray photon. The energy of the characteristic radiation depends on the binding energy of the electrons involved. Characteristic radiation initiated by an incoming photon is referred to as fluorescent radiation. Fluorescence, in general, is a process in which some of the energy of a photon is used to create a second photon of less energy. This process sometimes converts x-rays into light photons. Whether the fluorescent radiation is in the form of light or x-rays depends on the binding energy levels in the absorbing material.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 . 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. The probability of photoelectric absorption depends on the

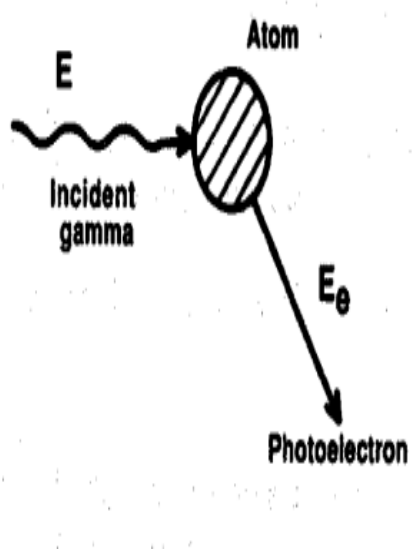

Figure 1.5: A schematic representation of the photo- electric absorption process

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 percent of the interactions involve K electrons), provided the gamma-ray energy exceeds the K-electron binding energy. The probability is given approximately by the next Equation which shows that the interaction is more important for heavy atoms like lead and uranium and low-energy gamma rays:

$$\tau \propto \frac{Z^4}{E^3} \tag{1.3.1}$$

whereτ = photoelectric mass attenuation coefficient. This proportionality is only approximate because the exponent of Z varies in the range 4 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 .

1.3.2 Compton Scattering

The interaction processe of compton scattering takes place between the incident gamma-ray photon and an electron in the absorbing material.It is an interaction in which only a portion of the energy is absorbed and a photon is produced with reduced energy.This photon leaves the site of the interaction in a direction different from that of the original photon, Because of the change in photon direction, this type of interaction is classified as a scattering process. In effect,a portion of the incident radiation 'bounces off' or is scattered by the material. This is significant in some situations because the material with in the primary x-ray beam becomes a secondary radiation source.The most significant object producing scattered radiation in an x-ray procedure is the patient's body.The portion of the patient's body that is with in the primary x-ray beam becomes the actual source of scattered radiation. This has two undesirable consequences.The scattered radiation that continues in the forward direction and reaches the image receptor decreases the quality (contrast) of the image, the radiation that is scattered from the patient is the predominant source of radiation exposure to the personnel conducting the examination.Compton scattering is the process whereby a gamma ray interacts with a free or weakly bound

electron ($E_\gamma >> E_b$) and transfers part of its energy to the electron . Conservation of energy and momentum allows only a partial energy transfer when the electron is not bound tightly enough for the atom to absorbed 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 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. Generally when a gamma of energy E_γ scatters from a free electron, After scattering, the gamma-ray departs at an angle θ with respect to its original direction. The energy of the scattered gamma-ray is lowered to $E_{\gamma'}$.That difference in gamma-ray energies is transferred to the electron, which recoils at an angle ϕ with respect to the original gamma-ray direction, and carries off an energy E_e. The laws of conservation of energy and momentum for the interaction are as follows:

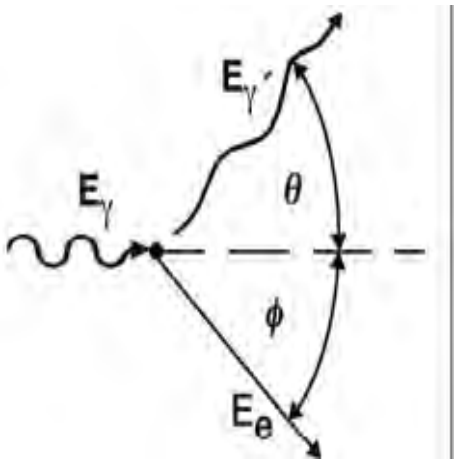

Figure 1.6: A schematic representation of compton scattering

Conservation of energy:

$$E_\gamma = E_{\gamma'} + E_e \tag{1.3.2}$$

Conservation of momentum: X direction:

$$\frac{h\nu}{c} = \frac{h\nu'}{c} cos\theta + cos\phi \tag{1.3.3}$$

Y direction:

$$0 = \frac{h\nu^{'}}{c} sin\theta - mv_e sin\phi \tag{1.3.4}$$

In equations (1.3.4), and (1.3.5), ν and $\nu^{'}$ are the frequencies of the incident and scattered gamma rays, respectively, and h is Planks Constant ($6.63 \times 10^{27} ergsec.$). Consequently, Also

$$E_\gamma = h\nu \tag{1.3.5}$$

$$E_{\gamma'} = h\nu^{'} \tag{1.3.6}$$

$Ee = mc^2 - m_0c^2$

where $m = \frac{m_0}{\sqrt{1-\frac{v_e^2}{c^2}}}$

For the electron, the rest mass is m_0, and the recoil velocity is v_e. Solving equations (1.3.3), (1.3.4) and (1.3.5) results in the well-known equation expressing the energy of the Compton-scattered gamma ray as a function of the scattering angle,θ.

$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0c^2}(1 - cos\theta)} \tag{1.3.7}$$

where

E_e = energy of scattered electron

E_γ = energy of incident gamma ray

$E\gamma^{'}$ = 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. where

$m_o c^2$ =rest energy of electron= $511kev$

ϕ =angle between incident and scattered gamma rays

This energy is minimum for a head-on collision where the gamma ray is scattered 180^0 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:

$$E_{\gamma'} = \frac{E_\gamma}{1 + 2\frac{E_\gamma}{m_0 c^2}} \tag{1.3.8}$$

For very small angle scatterings($\theta \simeq 0^o$), the energy of the, scattered gamma ray is

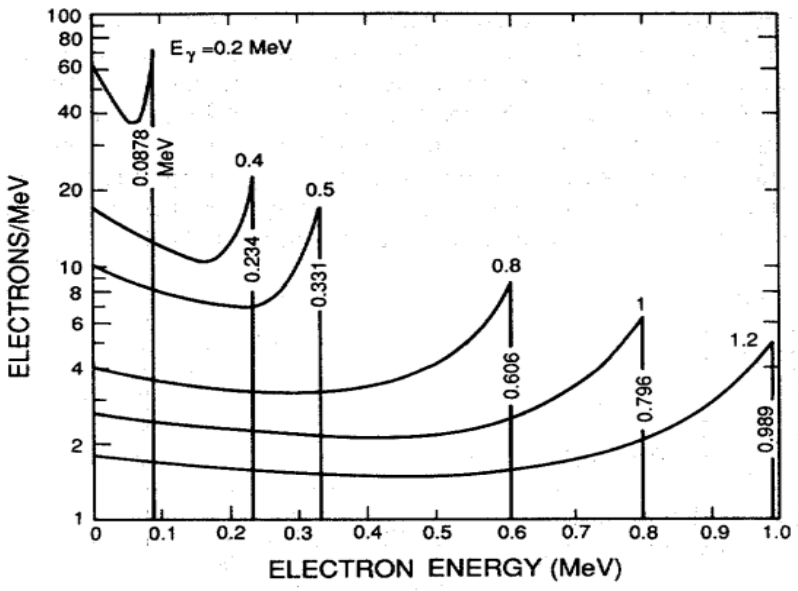

Figure 1.7: Energy of Compton-scattered electrons as a function of scattering angle and incident gamma-ray energy(E_γ). The sharp discontinuity corresponds to the maximum energy that can be transferred in a single scattering

only slightly less than the energy of the incident gamma ray and the scattered electron takes very little energy away from the interaction. The energy given to the scattered electron ranges from near zero to the maximum. When a Compton scattering occurs in a detector, the scattered electron is usually stopped in the detection medium and the detector produces an output pulse that is proportional to the energy lost by the incident gamma ray. Compton scattering in a detector produces a spectrum of output pulses from zero up to the maximum energy given by Equation 1.3.8. It is difficult to relate the

Compton scattering spectrum to the energy of the incident gamma ray. Figure (1.8) shows the measured gamma-ray spectrum from a monoenergetic gamma-ray source(^{137}Cs). The full-energy peak at 662 keV is formed by interactions where the gamma ray loses all of its energy in the detector either by a single photoelectric absorption or by a series of Compton scattering followed by photoelectric absorption. The spectrum of events below the full energy peak is formed by Compton scattering where the gamma ray loses only part of its energy in the detector. The step near 470 keV corresponds to the maximum energy that can be transferred to an electron by a 662 keV gamma ray in a single Compton scattering. This step is called a Compton edge.The small peak at 188 keV is called a backscatter peak. The backscatter peak is formed when the gamma ray undergoes a large angle scattering($\simeq 180$) in the material surrounding the detector and then is absorbed in the detector. The energy of the backscatter peak is given by Equation (1.3.8), which shows that the maximum energy is 256 keV. The sum of the energy of the backscatter peak and the Compton edge equals the energy of the incident gamma ray. Both features are the result of large angle Compton scattering of the incident gamma ray. The event contributes to the backscatter peak when only the scattered gamma ray deposites its energy in the detector it contributes to the Compton edge when only the scattered electron deposites its energy in the detector.

1.3.3 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. 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.Pair production is a photon-matter interaction that is not encountered in diagnostic procedures because it can occur only with photons with energies in excess of 1.022 MeV. In a pair-production interaction, the photon interacts with the nucleus in such a manner that its

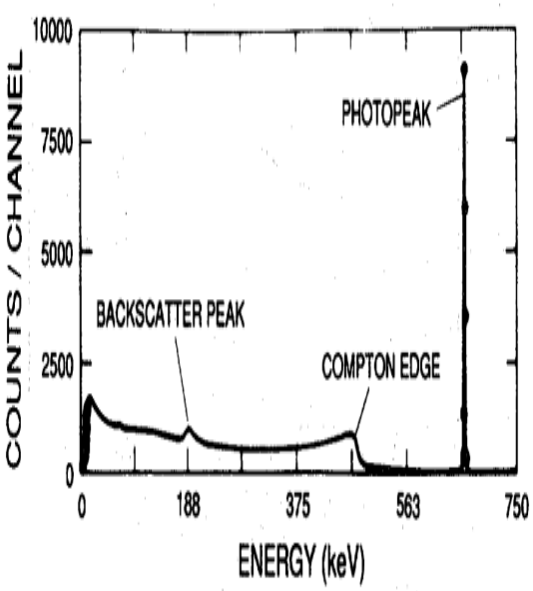

Figure 1.8: High-resolution spectrum of ^{137}Cs showing full-energy photopeak, Compton edge, and backscatter peak from the 662 keV gamma ray. Events below the photopeak are caused by Compton scattering in the detector and surrounding materials

energy is converted into matter.The interaction produces a pair of particles, an electron and a positively charged positron. These two particles have the same mass, each equivalent to a rest mass energy of 0.51 MeV.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. 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. These 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

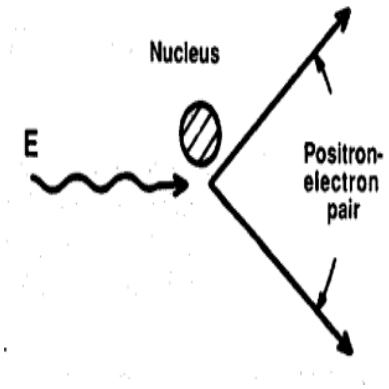

Figure 1.9: A schematic representation of pair production

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.These escape peaks may arise when samples of irradiated fuel,thorium, and ^{232}U are measured because these materials have important gamma rays above the pair-production threshold.Irradiated fuel is sometimes measured using the 2186-keV gamma ray from the fission product ^{144}Pr. The gamma-ray spectrum of ^{144}Pr in the single and double-escape peaks that arise from pair-production interactions of the 2186-keV gamma ray in a germanium 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. 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 percent of the interactions of 1.5 MeV gamma rays are through the pair-production process, and the fraction increases to 50 percent at 2.0 MeV. For carbon, the corresponding interaction fractions are 2 percent and 4 percent.

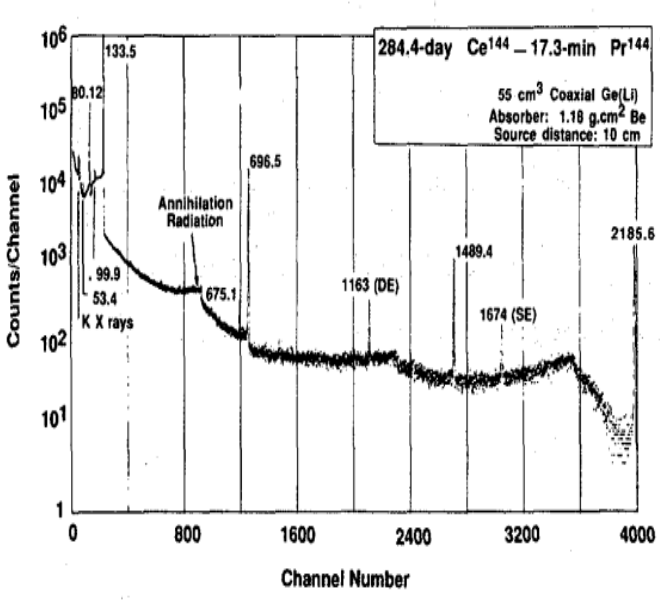

Figure 1.10: Gamma-ray spectrum of the fission-product ^{144}Pr showing single-escape (SE) and double-escape (DE) peaks (1674 and 1163) that arise from pair-production interactions of 2186- keV gamma rays in a germanium detector

Pair Spectrometer: For the detection and energy measurement of high energy gamma rays, where the pair production is larger than any of the other interaction process of gamma rays, a pair spectrometer is used for the energy measurement. The electron-positron pairs created by the incident gamma rays in a high material used as a radiator are deflected through 180^0 in opposite directions due to a magnetic field and enter two gamma ray counters arranged in coincidence. The coincidence pulses are recorded and counted electronically. It can be seen easily that the sum of the radii of the curvature of the two particles in the magnetic field is a linear function of the gamma energy. Writing W_e and W_p as the total energies of the electron and positron respectively, which are usually different , we have

$$E_\gamma = W_e + W_p = (P_e c^2 + m_0^2 c^4)^{1/2} + (P_p^2 c^2 + m_0^2 c^4)^{1/2} \tag{1.3.9}$$

where the P's are the momenta of the particles. If B is the magnetic induction field , we have $P_e = B_e r_e$ and $P_p = B_p r_p$ where r_e and r_p are the radii of curvature of the electron

and positron respectively. For $pc >> m_0c^2$ for both the particles , we then get,

$$E_\gamma = (P_e + P_p)c = B_e c(r_e + r_p) \tag{1.3.10}$$

which proves the statement made above. It is possible to measure the gamma ray energies upto about 100 MeV by this method.

1.4 A positron interaction that produces annihilation radiation

The annihilation process occurs when the antimatter positron combines with the conventional matter electron. In this interaction, the masses of both particles are completely converted into energy. The relationship between the amount of energy and mass is given by $E = mc^2$. The energy equivalent of one electron or positron mass is 511 keV. The energy that results from the annihilation process is emitted from the interaction site in the form of two photons, each with an energy of 511 keV. The pair of photons leave the site in opposite directions. With special imaging equipment it is possible to capture both photons and to determine the precise three dimensional location of the interaction site. Since the range of a positron, like that of an electron, is relatively short, the site of interaction is always very close to the location of the radioactive nuclei.

1.4.1 Ionization produced by a radiation electron

Electron Range: The total distance an electron travels in a material before losing all its energy is generally referred to as its range. The two factors that determine the range are

(1)the initial energy of the electrons

and

(2) the density of the material.

One important characteristic of electron interactions is that all electrons of the same energy have the same range in a specific material. Relationship of Electron Range to

Initial Energy in a Material with a Density of $1g/cm^3$ (Soft Tissue).In general, the range of electron radiation in materials such as tissue is a fraction of a millimeter. This means that essentially all electron radiation energy is absorbed in the body very close to the site containing the radioactive material.

1.4.2 Linear energy transfer

The rate at which an electron transfers energy to a material is known as the linear energy transfer (LET), and is expressed in terms of the amount of energy transferred per unit of distance traveled.Typical units are kiloelectron volts per micrometer ($keV/\mu m$). In a given material, such as tissue,the LET value depends on the kinetic energy (velocity) of the electron. The LET is generally inversely related to the electron velocity. As a radiation electron loses energy, its velocity decreases, and the value of the LET increases until all its energy is dissipated.The effectiveness of a particular radiation in producing biological damage is often related to the LET of the radiation. The actual relationship of the efficiency in producing damage to LET values depends on the biological effect considered. For some effects, the efficiency increases with an increase in LET, for some it decreases, and for others it increases up to a point and then decreases with additional increases in LET. For a given biological effect, there is an LET value that produces an optimum energy concentration within the tissue. Radiation with lower LET values does not produce an adequate concentration of energy. Radiations with higher LET values tend to deposite more energy than is needed to produce the effect; this tends to waste energy and decrease efficiency.

1.5 Photon interaction crossection

1.5.1 Photoelectric interaction crossection

The probability, and thus attenuation coefficient value, for photoelectric interactions depends on how well the photon energies and electron binding energies match. This can be considered from two perspectives. In a specific material with a fixed binding energy, a change in photon energy alters the match and the chance for photoelectric interactions. On the other hand, with photons of a specific energy, the probability of photoelectric interactions is affected by the atomic number of the material, which changes the binding energy. The Relationship between Material Atomic Number and Photon Energy That Enhances the Probability of Photoelectric Interactions

Dependence on photon energy

In a given material, the probability of photoelectric interactions occurring is strongly dependent on the energy of the photon and its relationship to the binding energy of the electrons. generally said that the probability of photoelectric interactions is inversely proportional to the cube of the photon energy ($1/E^3$).This general relationship can be used to compare the photoelectric attenuation coefficients at two different photon energies. The significant point is that the probability of photoelectric interactions occurring in a given material drops as the photon energy is increased. The other important feature of the attenuation coefficient photon energy relationship is that it changes abruptly at one particular energy:the binding energy of the shell electrons. The K-electron binding energy is 33 keV for iodine. This feature of the attenuation coefficient curve is generally designated as the K, L, or M edge. The reason for the sudden change is apparent if it is recalled that photons must have energies equal to or slightly greater than the binding energy of the electrons with which they interact. When photons with energies less than 33 keV pass through iodine, they interact primarily with the L-shell electrons. They do not have sufficient energy to eject electrons from the K shell, and the probability of interacting with the M and N shells is quite low because of the relatively large difference between the

electron binding and photon energies. However, photons with energies slightly greater than 33 keV can also interact with the K shell electrons. This means that there are now more electrons in the material that are available for interactions. This produces a sudden increase in the attenuation coefficient at the K-shell energy.A similar change in the attenuation coefficient occurs at the L-shell electron binding energy. For most elements, however, this is below 10 keV and not within the useful portion of the x-ray spectrum. Photoelectric interactions occur at the highest rate when the energy of the x-ray photon is just above the binding energy of the electrons.

Material atomic number

The probability of photoelectric interactions occurring is also dependent on the atomic number of the material. An explanation for the increase in photoelectric interactions with atomic number is that as atomic number is increased, the binding energies move closer to the photon energy. The general relationship is that the probability of photoelectric interactions (attenuation coefficient value) is proportional to Z^3. In general, the conditions that increase the probability of photoelectric interactions are low photon energies and high atomic number materials.

1.5.2 Compton interaction crossection

Compton interactions can occur with the very loosely bound electrons. All electrons in low atomic number materials and the majority of electrons in high atomic number materials are in this category. The characteristic of the material that affects the probability of Compton interactions is the number of available electrons. It was shown earlier that all materials, with the exception of hydrogen, have approximately the same number of electrons per gram of material. Since the concentration of electrons in a given volume is proportional to the density of the materials, the probability of Compton interactions is proportional only to the physical density and not to the atomic number, as in the case

of photoelectric interactions. The major exception is in materials with a significant proportion of hydrogen. In these materials with more electrons per gram, the probability of Compton interactions is enhanced.Although the chances of Compton interactions decrease slightly with photon energy, the change is not so rapid as for photoelectric interactions, which are inversely related to the cube of the photon energy.

Direction of Scatter

It is possible for photons to scatter in any direction. The direction in which an individual photon will scatter is purely a matter of chance. There is no way in which the angle of scatter for a specific photon can be predicted. However, there are certain directions that are more probable and that will occur with a greater frequency than others. The factor that can alter the overall scatter direction pattern is the energy of the original photon. In diagnostic examinations, the most significant scatter will be in the forward direction. This would be an angle of scatter of only a few degrees. However, especially at the lower end of the energy spectrum, there is a significant amount of scatter in the reverse direction, i.e.backscatter. For the diagnostic photon energy range, the number of photons that scatter at right angles to the primary beam is in the range of one-third to one-half of the number that scatter in the forward direction. Increasing primary photon energy causes a general shift of scatter to the forward direction. However, in diagnostic procedures, there is always a significant amount of back and side scatter radiation.

Energy of scattered radiation

When a photon undergoes a Compton interaction, its energy is divided between the scattered secondary photon and the electron with which it interacts. The electron's kinetic energy is quickly absorbed by the material along its path. In other words, in a Compton interaction, part of the original photon's energy is absorbed and part is converted into scattered radiation. The manner in which the energy is divided between scattered and absorbed radiation depends on two factors-the angle of scatter and the energy of the

original photon.

The relative importance of the interaction events can be summarized by the following gragh

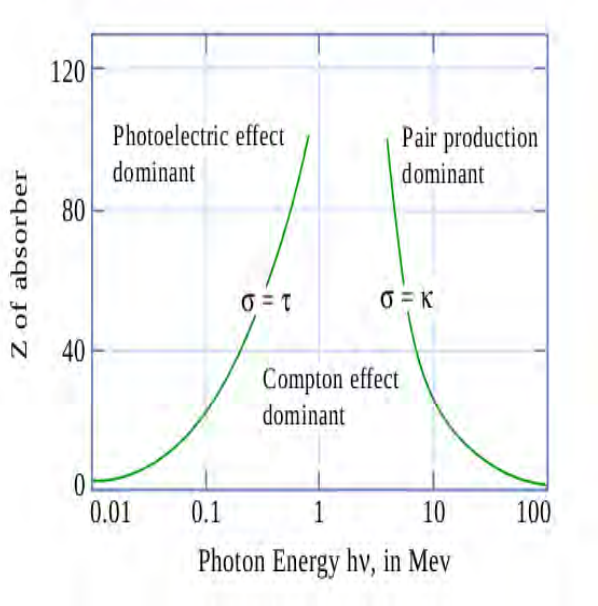

Figure 1.11: Relative importance of the three major types of gamma-ray interaction. The lines show the values of Z and h for which the two neighboring effects are just equal.

Chapter 2

ENERGY MEASUREMENT

2.1 Gamma-Ray Spectroscopy Using NaI(Tl)

beta particles will usually be absorbed in the surrounding material and not enter the scintillation detector. This absorption can be assured with aluminum absorbers. There is always some beta absorption by the light shield encapsulating the detector. The gammas, however, are quite penetrating, and will easily pass through the aluminum light shield. Generally there are two unknowns that we would like to investigate about a gamma source. One is measuring the energies of the gamma rays from the source. The other is counting the number of gamma-ray photons that leave the source per unit of time. The energy of the photoelectron E_e released by the interaction is the difference between the gamma-ray energyE_γ and the electron binding energy E_b:

$$E_e = E_\gamma - E_b \tag{2.1.1}$$

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.

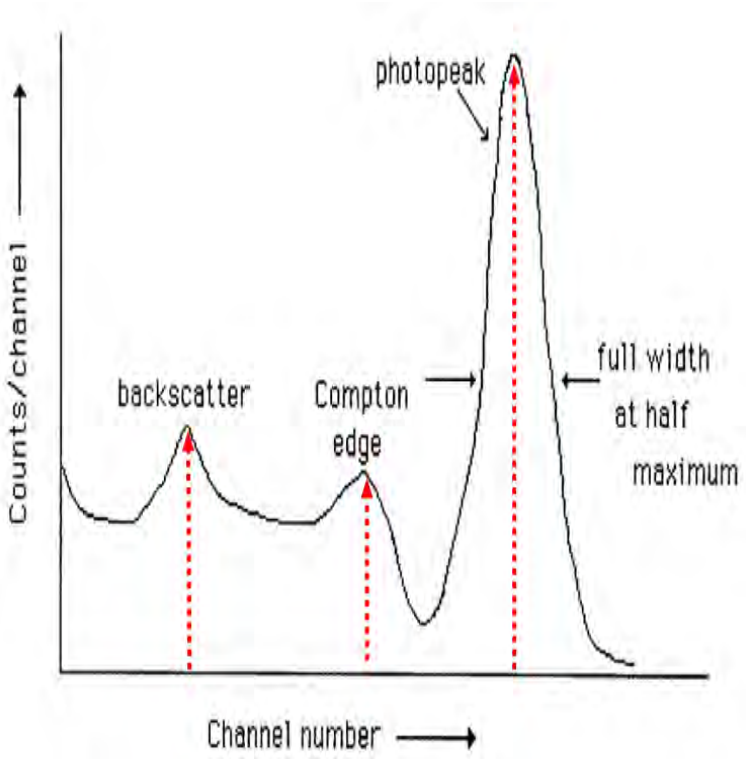

Figure 2.1: Na(Tl) Spectrum for Cs^{137}

BACKGROUND: Gamma ray detection is a slightly complicated, multi-step process, the gamma ray enters a NaI(Tl) scintillator crystal where it produces a rapidly moving free electron that in turn, loses its energy by excitation of the ions in its path as it travels through the crystal. This excitation energy is given off in various ways, one them being emission of visible light (fluorescence). Thus a single high energy gamma ray entering the scintillator produces a flash of low energy photons. These photons are directed to the photosensitive surface of a photomultiplier tube, where they eject electrons via the photoelectric effect. The electrons are collected in the photomultiplier and amplified to yield a current pulse, which is converted to a voltage pulse whose height is proportional to the number of photoelectrons and is thus proportional to the number of photons reaching the tube, which in turn is proportional to the initial energy of the fast electron. When

a radioactive source is placed near the scintillator, the photomultiplier produces a series of pulses, each corresponding to the decay of a single nucleus. The amplitude of each pulse is related to the energy of the electron freed by the gamma ray. These pulses are studied using either a single- or multi-channel analyzer. A single channel analyzer (SCA) counts on the number of voltage pulses whose height falls within a given (adjustable) window of values, while a multi-channel analyzer (MCA) sorts the pulses according to height and the counts the number in each window to give a spectral (energy) distribution of the fast electrons. The above figure shows a typical MCA spectrum. In order to relate this spectrum to the nuclear decay, we need to understand how gamma rays interact with matter.

2.1.1 Energy Calibration

Since the MCA is recording voltages resulting from scintillator light, we must correlate the size of the voltage pulses with the energy of the gamma rays. The voltage is proportional to gamma ray energy and we need to determine the proportionality constant. The software that controls the MCA provides this capability. It allows us to identify features of a known spectrum to establish the constant. We can then take the spectrum of a different nucleus and identify the gamma ray energies we observe. The photopeak is created when the gamma-ray photon interacts in the scintillator via the photoelectric effect. The photon encounters an orbital electron that is tightly bound to a nucleus. The entire energy of the photon is transferred to the electron, causing the electron to escape from the atom. The gamma-ray photon disappears in the process. As the photoelectron travels through the scintillator, it loses its energy by causing additional ionization. At the end of the process, the number of ionized atoms is proportional to the original energy of the photon. As the electrons re-fill the vacancies in the ionized atoms, visible light photons are generated. This is the source of the scintillation, where in the number of visible photons is proportional to the original energy of the gamma-ray. Consequently, the event populates

the photopeak in the spectrum. This peak is often called the full-energy peak, because a two-step interaction, a Compton scattering followed by a photoelectric interaction, also contributes a small number of events to the full-energy peak.The Compton interaction is a pure, kinematic collision between a gamma-ray photon and what might be termed a free electron in the NaI(Tl) crystal. By this process, the incident gamma-ray photon gives up only part of its energy to the electron as it bounces off the free electron. The recoiling electron loses energy by causing ionization as it travels through the crystal. Thus the number of visible photons in the resulting scintillation is proportional to the recoil energy of the Compton electron. The amount of energy transferred from the gamma-ray photon to the recoiling electron depends on whether the collision is head-on or glancing. For a head-on collision,the gamma ray transfers the maximum allowable energy for the Compton interaction. Although it involves a photon and an electron,the interaction is similar to a billiard-ball collision. The reduced energy of the scattered gamma ray can be determined by solving the energy and momentum conservation equations for the collision. The solution for these equations in terms of the scattered gamma-ray energy can be written as

$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_o c^2}(1 - cos\theta)} \tag{2.1.2}$$

where $E_{\gamma'}$ is the reduced energy of the scattered gamma-ray, γ', in MeV, θ is the scattering angle for the direction of γ' relative to the direction ofthe incident gamma-ray, γ, E_γ is the energy of the incident gamma-ray, , in MeV,γ $m_o c^2 = 0.511$ MeV is the equivalent energy of the rest mass, m_o, of the electron, and c is the speed of light. For a head-on collision, the gamma-ray is scattered backwards along its initial trajectory, and $\theta = 180$. For this condition, the backscattered gamma-ray energy becomes

$$E_{\gamma'} \cong \frac{E_\gamma}{1 + 4E_\gamma} \tag{2.1.3}$$

2.1.2 Interaction and detection mechanisms for gamma rays with matter

When entering a crystal,gamma rays produce fast charged electrons by three different processes, the photoelectric effect, the Compton effect (Compton scattering) and pair production. It is these fast electrons, which give rise to scintillations, not the gamma ray. The observed spectral distribution will thus depend on the detailed interaction process of the gamma rays in the crystal. Consider a beam of mono-energetic gamma rays striking the scintillator. For our purposes the most important energy loss mechanism is the photoelectric effect. When a gamma ray strikes an ion in the crystal, it is absorbed and all of its energy is transferred to one of the bound electrons, which is freed and moves rapidly through the crystal. Since the energy of the gamma ray (typically about 0.5 MeV) is much greater than the binding energy of the electron of the ion (typically 10 to 100 eV), the energy of the freed electron can be considered equal to that of the incoming gamma. (Especially since the energy resolution of the detector is only about 10 percent.) Thus the photoelectric effect results in a peak, called the photopeak, in the photomultiplier spectrum at an energy equal to that of the gamma 2 incoming gamma ray. In Compton scattering, the gamma ray is not absorbed, but rather scattered through an angle by an electron, which recoils and carries away some of the gamma rays energy E. (The scattered gamma ray then escapes from the scintillator; the probability that a gamma ray Compton scatters in a typical size scintillator is quite small (1 to 10 percent), which means we are unlikely to detect a gamma ray that has undergone two Compton scatterings.) The gamma rays initial wavelength is $\lambda = hc/E = 1240/E$ nm, where E is in eV. The change in wavelength is: $\Delta\lambda = h/mc(1 - cos\theta) = 0.00243(1 - cos\theta)nm$, where h is Plancks constant, m is the mass of the electron and c is the speed of light. From this equation we can see that the energy loss of the gamma ray will vary from zero (when$\theta = 0^0$) to a maximum corresponding to a wavelength shift of 0.00486 nm (when $\theta = 180^0$). This maximum energy loss is called the Compton edge. The energy distribution of Compton scattered

electrons is essentially a constant. So the Compton spectrum produced by a photomultiplier tube is an almost flat plateau from zero energy up to the Compton edge where it drops off sharply (at a rate limited by the energy resolution of the tube). Consider, for example, a 622 keV gamma ray from a ^{137}Cs decay. Its initial wavelength is 0.00199 nm. If it is Compton scattered through $\theta = 180^0$ the wavelength becomes 0.00199 + 0.00486 = 0.00685 nm corresponding to an energy of 181 keV. The lost energy, 622 - 181 = 441 keV, is transferred to the electron from which it scattered and is observed as a Compton edge at 441 keV. For smaller scattering angles, the transferred energy will be less, extending down to zero for $\theta = 0^0$. The discussion above refers to gamma rays that are Compton scattered by electrons within the scintillator. It is also possible for a gamma ray to be Compton scattered into the scintillator from an interaction outside the scintillator. In this case the observed signal is from the scattered gamma and not from the recoiling electron. The scattered gamma ray could then be detected through the photoelectric effect. For ^{137}Cs the Compton scattered gamma rays will have energies ranging from 181 keV up to the full 622 keV. However, because of the geometry of the detector, most of the gamma rays scattered into the scintillator will have been scattered through a large value of θ. But $cos\theta$ varies only slowly with for near 180^0. which means that these gamma rays will all have energies near 181 keV. The resulting energy peak is called the backscatter peak. It can be enhanced by placing a sheet of lead around the outside of the scintillator. The third interaction mechanism is pair production. If the incoming gamma ray energy is above $1.02MeV = 2mc^2$, the rest mass of an electron-positron pair, the gamma ray can spontaneously create an electron-positron pair and be totally absorbed. If both the electron and positron lose all of their kinetic energy while still in the scintillator, they would produce a photomultiplier pulse corresponding to an energy $2mc^2$ below the gamma ray energy E. (Of course, either might escape the crystal after partial loss of kinetic energy.) But the spectrum is actually more complicated since if the positron has been slowed down and stopped in the crystal, it will annihilate with an electron, emitted two gamma rays,

each of energy mc^2. One, or both, of these gamma rays may be absorbed in the crystal, and thus contribute to the height of the photomultiplier output pulse. Pair production therefore produces a full energy peak (E), a one-escape peak ($E - mc^2$) and two escape peak ($E - 2mc^2$), depending upon whether both annihilation photons are absorbed in the scintillator or one, or both, escapes. The final question to consider is that of the relative importance of the three interaction mechanisms, which depend in different ways upon the energy of the gamma ray. For low energy rays, the photoelectric effect predominates. Since the photopeak directly yields the energy of the gamma ray, most scintillators are designed to maximize the photopeak. In the NaI(Tl) scintillator we use, a small amount of the heavy metal thallium is added for this purpose when the crystal is grown. (The strength of the photoelectric effect depends strongly on the number of electrons bound to the ion.) As E increases, the photoelectric absorption deceases rapidly, while the Compton scattering decreases much more slowly and predominates above several hundred keV. The absorption coefficient for pair production rises rapidly above the threshold E = 1.02 MeV and exceeds the Compton scattering, while photoelectric absorption becomes negligible.

2.1.3 Energy resolution:

The resolution of adetector is ameasure of how much narrow the peaks are. a commonly used measure is the 'Full Width at Half Maximum ' ,FWHM.It is just the width of the photo peak at which the values are 1/2 the maximum value. A NaI(Tl) detector has an energy resolution of only about 10 percent. [More advanced detectors such as high purity germanium detectors have as much as 30 times greater resolution, but are much more expensive.] When a beam of mono-energetic gamma rays strikes the scintillator, there is a fluctuation from gamma ray to gamma ray in the height of the voltage pulse from the photomultiplier, which shows up as a broadening of the photopeak. The pulse height variation is chiefly due to statistical fluctuations in the number of electrons emitted at the cathode of the photomultiplier when a flash of photons arrives from the scintillator, but

is also due to the occasional escape of electrons, X-rays or gamma rays from the crystal, all of which depend on how large the NaI crystal is. The fractional full width of a peak at half its maximum height (FWHM) is a convenient measure of the resolution of the instrument.

The resolution of a spectrometer is a measure of its ability to resolve (i.e., separate) two peaks that are fairly close together in energy.fig 2.1 shows the gamma spectrum that was plotted for the ^{137}Cs source. The resolution of the photopeak is calculated from the following equation:

$$percentageresolution = \frac{\delta E}{E} \times 100percent \tag{2.1.4}$$

Where δE is the Full Width of the peak at Half of the Maximum count level (FWHM) measured in number of channels, and E is the channel number at the centroid of the photopeak.

2.1.4 detector efficiency:

Detector efficiency is defined as the percentage of ionizing radiation hitting the detector that is measured.

The basic definition of absolute photon detection efficiency is

$$\varepsilon_{tot} = \frac{totalnumberofdetectedphotonsinthefullenergypeak}{totalnumberofphotonsemittedbythesource} - \tag{2.1.5}$$

For the discussion to follow, we will be concerned with only full-energy events and thus with the full-energy detection efficiency. This total efficiency can be expressed as the product of four factors:

$$\varepsilon_{tot} = \varepsilon_{geom}\varepsilon_{sample}\varepsilon_{int}\varepsilon_{absp} \tag{2.1.6}$$

The geometric efficiency ε_{geom} is the fraction of emitted photons that are intercepted by the detector. For a point source this is given by ε_{geom}=$\frac{A}{4\Pi \times r^2}$ where A is the cross-sectional area of the detector and r is the source-to-detector distance. This factor is essentially independent of photon energy. It manifests the well-known inverse-square law

for counting rates as a function of source-to-detector distance. The absorption efficiency ε_{absp} takes into account the effects of intervening materials (such as the detector housing, special absorbers, etc.) that absorb some of the incoming radiation before it interacts with the detector volume. This term is especially important (it should be $\ll 1$) for low-energy photons for which absorption effects are most pronounced. It has the mathematical form

$$\varepsilon_{absp} = exp[-\Sigma\mu_i(E_\gamma)\rho_i x_i] \tag{2.1.7}$$

where μ_i, ρ_i and x_i are the mass absorption coefficient, density, and thickness of the ith intervening material, and the summation is over all types of intervening materials.

The sample efficiency ε_{sample} is the reciprocal of the sample self-absorption cor- rection .This quantity is the fraction of emitted gamma rays that actually emerge from the sample material. For example, in a slab of thickness x and transmission T equal to $exp[-(\mu\rho x)_s]$, the sample efficiency is

$$\varepsilon_{sample} = \frac{1 - exp[-(\mu\rho x)_s}{\mu\rho x} = \frac{T-1}{lnT} \tag{2.1.8}$$

This factor clearly depends on the composition of each sample. The intrinsic eficiency ε_{int} is the probability that a gamma ray that enters the detector will interact and give a pulse in the full-energy peak. In simplest terms, this efficiency comes from the standard absorption formula

$$\varepsilon_{int} = 1 - exp(-\mu\rho x) \tag{2.1.9}$$

where μ is the photoelectric mass attenuation coefficient, and ρ and x are the density and thickness of the sensitive detector material. This simple expression underestimates the true intrinsic efficiency because the full-energy peak can also contain events from multiple Compton scattering interactions. In general,ε_{int} is also a weak function of r because of the detection of off-axis incident gamma rays.

2.2 semiconductor detectors

Semiconductors also produce photoelectrons when high-energy rays or particles strike the detector material. The most common X-ray and gamma-ray detectors use lithium-drifted silicon Si(Li) or lithium-drifted germanium Ge(Li). In these detectors, Li is incorporated into the semiconductor lattice by annealing the semiconductor with Li at a high temperature ($\simeq 500^{O}$). A voltage of approximately 1000 V is placed across the semiconductor material with two electrodes, and the electron cascade produced by a photoelectron is detected as an electrical pulse at the anode. In addition to being more robust than gas-filled or scintillator detectors, these semiconductor detectors also provide a much higher resolution. Their only disadvantage is the need for cooling, usually with liquid nitrogen, to decrease the dark noise of the detector and current-to-voltage preamplifier.

The formation of an electron-hole pair in a semiconductor such as silicon or germanium requires an energy of only about 3 eV; consequently, when these crystals are used as solid-state ionization chambers, they can provide large signals for very little energy deposition in the medium. Solid-state devices can therefore be particularly advantageous for applications at low energies. They were, in fact, developed initially in nuclear physics for high-resolution measurements of energy, and for obtaining ranges and stopping power of nuclear fragments. More recently, silicon strip detectors and pixels have gained wide acceptance in both nuclear and particle physics for precision measurement of positions of charged particles. Because the number of free charge carriers produced in semiconductors is so large, and both electrons and holes have high mobility, very thin wafers of crystal (about 200-300 μ m) suffice for achieving good signals, even for minimum-ionizing particles. The performance of these detectors is quite linear in that the output signal is proportional to the ionization loss, provided that an imposed electric field within the medium is large enough to prevent recombination of the charge carriers. This can be

achieved by using very pure semiconductors of high-resistivity, and operating these detectors as diodes with a reverse bias of about 100 V. The semiconductor wafer is sandwiched between very thin conducting electrodes (thickness of tens of $\mu gm/cm^2$), which can be deposited in electrically separated stripes (or other patterns) on the surface of the wafer. Detectors $5 \times 5cm^2$ in area are quite common; they often have 20-50 μ m stripes, and are used in series (just like planes of MWPCs) to determine charged-particle trajectories to position-accuracies of the order of several μ m in the transverse direction. Such devices can be used to measure small impact parameters and thereby determine whether some charged particle originated from a primary colli- sion or was the decay product of a particle that traveled a small distance from the original interaction, and then decayed. Two silicon detectors positioned in series can be used to determine the kinetic energy and velocity of any low-energy particle or nuclear fragment, and therefore its rest mass. This determination is made by placing a very thin wafer in front of a thicker detector that can stop that particle. The velocity is deduced from the stopping power measured in the thin wafer, and the mass from the range or from the total kinetic energy loss in the thicker crystal (or array of thin wafers).

2.2.1 Measurement of a single gamma-ray spectrum with a Ge detector

The functioning of a Ge detector is based on the use of the depletion region formed between two different (p and n type) semiconductor materials. In normal electronics components this region is small, but in the Ge detector it is made massive with the help of reverse bias. The bias is typically 3000-4000 V. The operation of the detector is based on interaction of gamma rays and the semiconductor within this depletion region. When a photon enters the depletion region and interacts there, it excites electrons to the conduction band and electron-hole pairs are formed. The number of electron-hole pairs is directly proportional to the energy absorbed in the material. The charges are collected to the electrodes. As

with the scintillation detectors, the pulse obtained in collection of charges is very small. Therefore, the Ge detector is equipped with a preamplifier mounted next to the Ge crystal. A Ge detector can not be operated at room temperature, because thermal electrons mask all weak signals. Thats why the Ge detector is cooled down by liquid nitrogen

Chapter 3

GAMMA-RAY DETECTORS

3.1 Introduction

3.1.1 Gamma Ray Detector

he gamma ray detector is a scintillation detector consisting of a scintillation crystal, a photomultiplier tube, and a preamplifier assembled in a single unit supplied by a Mechtronics Nuclear. 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. During operation, the crystal absorbs energy from a gamma event and produces a proportional flash of light. The light flash causes the photomultiplier tube cathode to emit a proportional quantity of electrons. These are attracted from dynode to dynode through the tube with a multiplication effect at each successive dynode due to secondary emission. The highly intensified burst of electrons which arrives

at the anode of the tube, still proportional to the energy of origin, is transferred to form a charge at the input capacitor in the preamplifier. The amplifier responds by creating a positive output pulse which retains the basic proportional significance. There are two connectors on the photomultiplier tube base:

Anode Output:

Connects photomultiplier output pulses to the amplifier. This output pulse is always negative and has an amplitude depending on the input pulse and the HV of the photomultiplier. The connection between the photomultiplier output and the amplifier input is always made with a 50 ohm coaxial cable.

HV:

Connects the high voltage power supply to the photomultiplier tube, using HV BNC for the white HV cable.

Amplifier:

The amplifier is an ORTEC unit. Usually we find the model 575A. The amplifier accepts both positive or negative input pulses and provides both pulse shaping and amplitude expansion of these pulses. The amplifier gain is set via a control knob setting and there are both unipolar positive and bipolar positive going outputs on BNC connectors. The function of the amplifier is to produce positive output pulses of suitable amplitude and shape so that they can be fed into the pulse height analyzer.

MultiChannel Pulse Height Analyzer:

The multichannel analyzer is a PC containing an ORTEC model 916A pulse height analyzer card (MCA) run by the Maestro II software package. The MCA card contains an Analog to Digital Converter (ADC), single channel analyzer (SCA), multichannel scaler (MCS), and a dualported memory. The card, along with the standard software, transforms the personal computer into a multichannel analyzer. An input of 0 to 10 volt positive pulses from a shaping amplifier is the only external signal necessary for pulse height analysis operation. The software is located in the MCA directory and is started by typing

MCA on the command line. The MCA has been set up for the input voltage range of 0 to 10 Volts to correspond to channel 0 (0 V) and channel 512 (10 V). High Voltage Supply the high voltage supply for the gamma ray detector is usually a Hewlett Packard Model 6522A using the positive HV output connector. The supply can furnish an output of 0 2000 V DC. We normallly run the photomultiplier somewhere between 800-1000 Volts.

Oscilloscope:

Any mobile scope may be used to display the pulses being input to the multichannel pulse height analyzer. In this chapter, we will present some general information on types of gamma-ray detectors that are used in nondestructive assay (NDA) of nuclear materials.

3.2 Types of detectors

Many different detectors have been used to register the gamma ray and its eneqgy. 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.

3.2.1 scintilation detector (scintilation detectors)

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 inor- ganic 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 ma- terial, 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. 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 photons 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.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 10^4 or more) of the electron flux from its initial value at the photocathode surface. Finally, the amplified charge burst arrives at the output electrode (the anode) of the tube. The magnitude of this charge is proportional to the initial amount of charge liberated at the photocathode of the PMT. The constant of proportionality is the gain of the PMT. Furthermore, 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 in 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 pro portional to the energy deposited by the gamma ray in the scintillation medium.

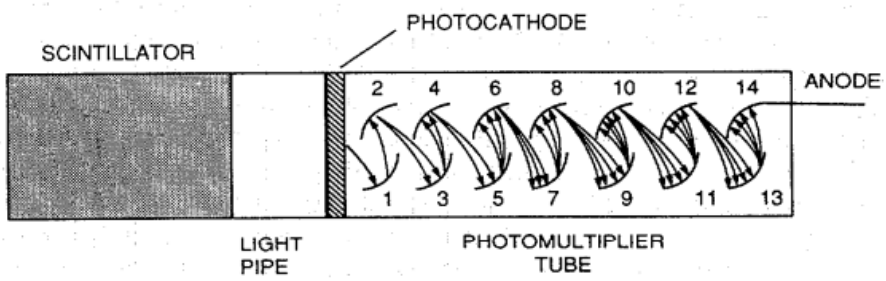

Figure 3.1: scintilation detector

3.2.2 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. The sensitive volume as shown in the figure below 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. The Figure below 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 hyperpure germanium (HPGe) crystals, essentially eliminating the need for the lithium doping and simplifying operation of Solid-state detectors are produced mainly in two configurations: planar and coaxial.

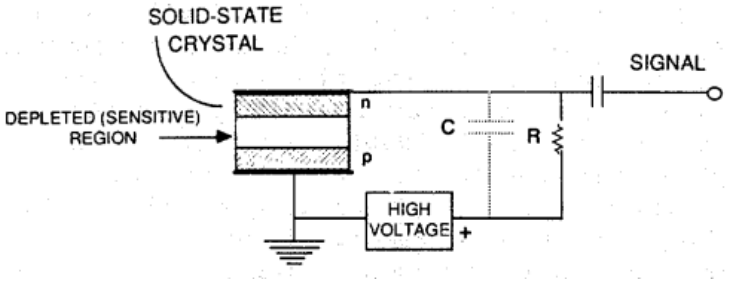

Figure 3.2: solid state detector

These terms refer to the detector crystal shape and the manner in which it is wired into the detector circuit. Coaxial detectors are produced either with open-ended (the so-called true coaxial) or closed-ended crystals . In both cases the electric field for charge collection is primarily radial, with some axial compo nent 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 eiectric 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 . The electric field is perpendicular to the cross-sectional area of the crystal. The crystal thickness is selected on the basis of the gamma-ray energy region relevant to the application of interest, with the small thicknesses optimum for low-energy measurements (for example in the L-x-ray region for special nuclear material). Planar detectors usually achieve the best energy resolution, because of their low capacitance; they are preferred for detailed spectroscopy, such as the analysis of the complex low-energy gamma-ray and x-ray spectra of uranium and plutonium. Because of their high resolution, semiconductor detectors are relatively sensitive to performance degradation from radiation damage. The amount of damage produced in the detector crystal per unit of incident flux is greatest for neutron radiation. Thus, in environments where neutron levels are high (such as accelerators, reactors, or instruments with intense neutron sources), the most significant radiation damage effects will be

observed. Furthermore, radiation damage effects can be of concern in NDA applications where large amounts of nuclear material are continuously measured with high-resolution, gamma-ray spectroscopy equipment for example, in measurements of plutonium isotopics in a high-throughput mode. 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 photopeaks. In effect, the resolution is degraded, and spectral detail is lost. Another popular solid-state detector material for photon spectroscopy is lithium- drifted silicon [Si(Li)]. The lower atomic number of 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 applica- tions of gamma-ray spectroscopy, it would be advantageous to have high-resolution detectors operating at room temperature, thereby eliminating the cumbersome appa- ratus necessary for cooling the detector crystal. Operation of room-temperature semi- conductor materials such as CdTe,HgI_2, and GaAs has been extensively researched. Their higher average atomic numbers, provide greater photoelectric efficiency per unit volume of material.

3.3 characterstics of detected spectra

In gamma-ray spectroscopy applications, the detectors produce output pulses whose magnitudes are proportional to the energy deposited in the detecting medium by the incident

photons. The measurement system includes some method of sorting all of the generated pulses and displaying their relative numbers. The basic tool for accom- plishing this task is the multichannel analyzer (MCA). The end result of multichannel analysis is a histogram (spectrum) of the detected output pulses, sorted by magnitude. The pulse-height spectrum is a direct representation of the energy spectrum of the gamma-ray interactions in the detection medium and constitutes the spectroscopic information used in gamma-ray NDA.

3.3.1 Spectral Features

A more realistic representation of a detector-generated gamma-ray spectrum from a monoenergetic gamma-ray flux is shown in the Figure below. The spectral features labeled A-G are explained below.

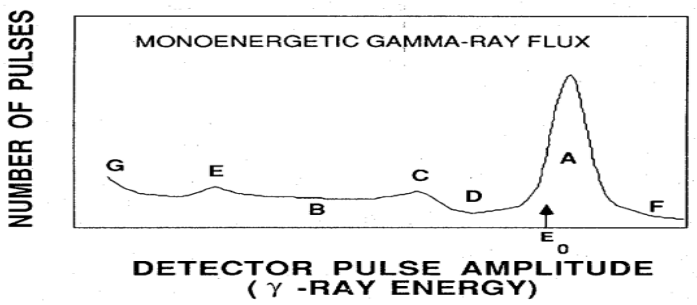

Figure 3.3: Detector pulse amplitude ($\gamma - rayenergy$)

A. The Full-Energy Photopeak This peak represents the pulses that arise from the full-energy, photoelectric interactions in the detection medium. Some counts also arise from single or multiple Compton interactions that are followed by a photoelectric interaction. Its width is determined primarily by the statistical fluctuations in the charge produced from the interactions plus a contribution from the pulse-processing electronics.Its centroid represents the photon energy E. Its net area above background represents the total number of full-energy interactions in the detector and is usually proportional to the mass of the emitting isotope.

B. Compton Background Continuum These pulses, distributed smoothly up to a maximum energy E_C , come from interactions involving only partial photon energy loss in the detecting medium. Compton events are the primary source of background counts under the full-energy peaks in more complex spectra.

C. The Compton Edge This is the region of the spectrum that represents the maximum energy loss by the incident photon through Compton scattering. It is a broad asymmetric peak corresponding to the maximum energy (E_C) that a gamma- ray photon of energy E. can transfer to a free electron in a single scattering event. This corresponds to a head-on collision between the photon and the electron, where the electron moves forward and the gamma-ray scatters backward through 180.

D. The Compton valley For a monoenergetic source, pulses in this region arise from either multiple Compton scattering events or from full-energy interactions by photons that have undergone small-angle scattering (in either the source materials or intervening materials) before entering the detector. Unscattered photons from a monoenergetic source cannot produce pulses in this region from a single interaction in the detector. In more complex spectra, this region can contain Compton-generated pulses from higher-energy photons.

E. BackScatter Peak This peak is caused by gamma rays that have interacted by Compton scattering in one of the materials surrounding the detector. Gamma rays scattered by more than 110-120 will emerge with nearly identical energies in the 200 to 250-keV range. Therefore, a monoenergetic source will give rise to many scattered gamma rays whose energies are near this minimum value.

F. Excess-Energy Region With a monoenergetic source, events in this region are from high-energy gamma rays and cosmic-ray muons in the natural background and from pulse-pileup events if the count rate is high enough. In a more complex spectrum, counts above a given photopeak are primarily Compton events from the higher-energy gamma rays.

G. Low-Energy Rise This feature of the spectrum, very near the zero-pulse-height-amplitude region, arises typically from low-amplitude electronic noise in the detection system that is processed like low-amplitude detector pulses are. This noise tends to be at rather high frequency and so appears as a high-count-rate phenomenon. Electronic noise is usually filtered out of the analysis electronically, so this effect does not usually dominate the displayed spectrum. In more complex gamma-ray spectra, containing many different photon energies, the Compton-edge and backscatter peak features tend to ' wash out,' leaving primarily full-energy peaks on a relatively smooth Compton background.

Chapter 4

summary

Gamma rays are electromagnetic radiation, like X-rays.Gamma rays are the most energetic form of electromagnetic radiation, with a very short wavelength of less than one-tenth of a nanometer. Gamma radiation is the product of radioactive atoms. Depending upon the ratio of neutrons to protons within its nucleus, an isotope of a particular element may be stable or unstable. gamma-ray must interact with adetector in order to be 'seen.' 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. If we recall that photons are individual units of energy. As an x-ray beam or gamma radiation passes through an object,three possible fates await each photon, as listed below:

a. It can penetrate the section of matter without interacting.

b. It can interact with the matter and be completely absorbed by depositing its energy.

c. It can interact and be scattered or deflected from its original direction

and deposite part of its energy. when gamma ray make an interaction three events will exist i.e photo electric absorption,compton scaterin and pair production In the photoelectric (photon-electron) interaction a photon transfers all its energy to an electron located in one of the atomic shells. The electron is ejected from the atom by this energy and begins to pass through the surrounding matter. The electron rapidly loses its energy and moves only a relatively short distance from its original location. The photon's energy is,

therefore, deposited in the matter close to the site of the photoelectric interaction.The energy transfer is a two-step process. The photoelectric interaction in which the photon transfers its energy to the electron is the first step. The depositing of the energy in the surrounding matter by the electron is the second step.

The interaction processe of compton scattering takes place between the incident gamma-ray photon and an electron in the absorbing material.It is an interaction in which only a portion of the energy is absorbed and a photon is produced with reduced energy.This photon leaves the site of the interaction in a direction different from that of the original photon, Because of the change in photon direction, this type of interaction is classified as a scattering process. In effect,a portion of the incident radiation 'bounces off' or is scattered by the material.

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 . 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.

The gamma ray detector is a scintillation detector consisting of a scintillation crystal, a photomultiplier tube, and a preamplifier assembled in a single unit supplied by a Mechtronics Nuclear. 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.

Many different detectors can be used to register the gamma ray and its eneqry. some of these detectors are Gas-Filled Detectors,scintilation detector (scintilation detectors) ,solid state detectors. Detectors have the following basic properties

- Radiation interacts in material
- Energy converted to photons

- Photons collected by photodetector
- Photodetector produces electrical signal

Detector efficiency depends upon:

- the type of detector (GM, Nal Scintillation, Plastic Scintillation, Proportional)
- the detector size and shape (larger areas and volumes are more sensitive)
- the distance from the detector to the radioactive material
- the radioisotope and type of radiation measured (alpha, beta and gamma radiation and their energies)
- the backscatter of radiation toward the detector (the denser the surface,the more scattering)
- the absorption of radiation before it reaches the detector (by air and by the detector covering)

Factors Affecting Detector Efficiency:

1. Some radiation go directly from the radioactive material into the detector.
2. Some radiation will backscatter off the surface into the detector.
3. Some radiation are absorbed by the detector covering.
4. Some radiation travels away from the detector.
5. The distance of the detector determines hay much radiation will strick the detector.

References

[1].R. D. Evans, The Atomic Nucleus (McGraw-Hill Book Co., New York, 1955). [2].G. F. Knoll, Radiation Detection and Measurement (John Wiley and Sons, New York, 1979).

[3].E. Storm and H. Israel, Photon Cross Sections from 0.001 to 100 MeV for Elements 1 through 100, Los Alamos Scientific Laboratory report LA-3753 (1967).

[4].J. H. Hubbel, Photon Cross Sections, Attenuation Coefficients, and Energy Ab- sorption Coefficients from 10 keV to 100 GeV; National Bureau of Standads report NSRDS-NSB 29 (August 1969).

[5].G. F. Knoll, Radiation Detection and Measurement (John Wiley and Sons, Inc ... New York, 1979).

[6]. F. Adams and R. Dams, Applied Gamma-Ray Spectrometry (Pergamon Press New York, 1975).

[7].C. E. Moss, E. J. Dowdy, and M. C. Lucas, Bismuth Germanate Scintillators: Applications in Nuclear Safeguards and Health Physics, Nuclear Instruments and Methods A242,480 (1986).

[8].P. E. Koehler, S. A. Wender, and J, S. Kapustinsky, Improvements in the Energy Resolution and High-Count-Rate Performance of Bismuth Germinate, Nuclear Instruments and Methods A242,369 (1986).

[9].J. B. Birks, The Theory and Practice of Scintillation Counting (Pergamon Press, Oxford, 1964).

[10].H. W. Cramer, C. Chasman, and K. W. Jones, 'Effects Produced by Fast Neu- tron Bombardment of Ge(Li) Gamma-Ray Detectors;' Nuclear Instruments and Methods 62, 173 (1968).

[11].P. H. Stelson, J. K. Dickens, S. Raman, and R. C. Trammell, Deterioration of Large Ge(Li) Diodes Caused by Fast Neutrons, Nuclear Instruments and Methods 98,481 (1972).

[12]. R. Baader, W. Patzner, and H. Wohlfarth, Regeneration of Neutron-Damaged Ge(Ll) Detectors Inside the Cryostat, Nuclear Instruments and Methods 117, 609 (1974).

[13].R. H. Pehl, Germanium Gamma-Ray Detectors, Physics Today 30, 50 (Nov., 1977).

[14].J. M. Marler and V. L. Gelezunas, Operational Characteristics of High-Purity Germanium Photon Spectrometers Cooled by a Closed-Cycle Cryogenic Refrig- erator, IEEE Transactions on Nuclear Science NS 20, 522 (1973).

[15].E. Sakai, Present Status of Room-Temperature Semiconductor Detectors, Nu- clear Instruments and Methods 196, 121 (1982).

[16].P. Siffert et al., Cadmium Telluride Nuclear Radiation Detectors: IEEE Trans- actions on Nuclear Science NS 22, 211 (1975).

[17].U. Fano, On the Theory of Ionization Yield of Radiation in Different Sub- stances: Physics Review 70, 44 (1946); Ionization Yield of Radiation II: The Fluctuations in the Number of Ions, Physics Review 72, 26 (1947).

[18].A. F. Muggleton, Semiconductor X-Ray Spectrometers, Nuclear Instruments and Methods 101, 113 (1972).

[19].H. Seyfarth, A. M. Hassan, B. Hrastnik, P. Goettel, and W. Delang, Efficiency Determination for some Standard type Ge(Li) Detectors for Gamma Rays in the Energy Range from 0.04 to 11 MeV, Nuclear Instruments and Methods 105, 301 (1972).

Declaration

This project is my original work, has not been presented for a degree in any other University and that all the sources of material used for the project have been dully acknowledged.

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Signature:– – – – – – – – – – – –

Place and time of submission: Addis Ababa University, June 2011

This project has been submitted for examination with my approval as University advisor.

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