بسم الله الرحمن الرحيم

Sudan University of Sciences and Technology
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Study of Nuclear Radiation Counting Systems

دراسة أنظمة العد الإشعاعي النووي

A Thesis Submitted as Partial Fulfillment of the Requirements
for the Degree of Master of Sciences in Nuclear physics

BY

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بسم الله الرحمن الرحيم

الآيـــة

قال تعالى:

(وَسَخَّرَ لَكُم مَّا فِي السَّمَاوَاتِ وَمَا فِي الْأَرْضِ جَمِيعاً مِّنْهُ إِنَّ فِي ذَلِكَ لَآيَاتٍ لَّقَوْمٍ يَتَفَكَّرُونَ)

سورة الجاثية الآية (١٣)

Dedication

To my parents for their kind support and care

Acknowledgement

I am greatly indebted to my supervisor Dr. Ahmed ELhassan ELfaki, Sudan University of Sciences & Technology for his appropriate guidance, genuine help, and encouragement.

I am grateful to everybody, who assisted me at one time or another during this research.

Abstract

Nuclear radiation counting systems are used for measuring the nuclear radiation, depending on the application the counting systems can be roughly grouped into Single channel analyzer (SCA) systems and Multi-channel analyzer (MCA) systems. The measurement of radiation is distinguished into two categories. The first category is measuring the number of radiations or intensity which depends on the activity of the source of radiation. The second category is measuring the energy distribution of incoming radiation which is characteristic to the type of the source of radiation. The number of output pulses from detector is proportional to the number of incoming radiation so the intensity of radiation can be measured just by counting those electric pulses which are produced by the detector. The single channel analyzer system is used to carry out intensity measurements by using threshold window (one energy range only). On the other hand the spectrum of radiation can give information about the intensity at each energy level or energy peaks of the incoming radiation. The multi-channel analyzer is used to carry out energy distribution spectrum measurements. In terms of internal functioning, multi-channel analyzer is different from single channel analyzer. The multi-channel analyzer performs the same task with many of threshold windows, thus it doesn’t need to count pulses at each threshold window individually, therefore making the process faster.

المستخلص

أنظمة العد الإشعاعي النووي تستخدم لقياس الإشعاع النووي واعتمادا علي التطبيق يمكن تصنيف أنظمة العد النووي الي نظام تحليل وحيد القناة (SCA) و نظام تحليل متعدد القنوات(MCA). عموما قياس الإشعاع يتم بطريقتين الطريقة الأولي يتم فيها قياس شدة الإشعاع التي تعتمد علي النشاط الإشعاعي للمصدر والطريقه الثانية فيتم فيها قياس توزيع الطاقة (طيف الطاقة) التي يتميز بها مصدر الاشعاع. شدة الاشعاع يمكن قياسها بواسطة عد النبضات الكهربية الصادرة عن الكاشف الإشعاعي حيث نجد ان عدد تلك النبضات الكهربية يتناسب طرديا مع كمية الاشعاع الساقط علي الكاشف الإشعاعي .نظام تحليل وحيد القناة يقوم بقياس شدة الإشعاع بواسطة عد النبضات الكهربية الصادرة من الكاشف الإشعاعي عند نافذة طاقة وحيدة بينما نظام تحليل متعدد القنوات يقوم بقياس توزيع الطاقة (طيف الطاقة) للاشعاع الساقط علي الكاشف الإشعاعي . قياس طيف الطاقة للاشعاع يوفر معلومات عن الشدة لكل مستوي طاقة أو توزيع قمم الطاقة في طيف الاشعاع مما يمكن من تمييز نوع المصدر الإشعاعي الذي يصدر منه الأشعاع. نظام تحليل متعدد القنوات يتميز عن نظام تحليل وحيد القناة في أنه يقوم بقياس شدة الإشعاع عند عدد من نوافذ الطاقة مما يعطي معلومات عن الشدة لكل مستوي طاقة بشكل أسرع.

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Introduction

1.1 General View

Ionizing radiation that is associated with radioactivity cannot be directly detected by our senses. Ionization is the process whereby the radiation has sufficient energy to strip electrons away from atoms. The ionization results in the formation of free electrons and an ionized atom that has lost some of its orbital electrons. Examples of ionizing radiation include particles such as alpha and beta particles, and photon radiation such as X-rays and gamma rays. Neutrons and protons can also cause ionizations [1].

Since radiation can be harmful to our health, detectors are needed to sense the presence and intensity of radiation and convert it into an electrical signal to provide suitable alarm. The measurements of radiations can also be distinguished into two categories, the first is measuring the number of radiations or intensity and the second is measuring the energy distribution [2].

Nuclear counting systems are used for measuring the nuclear radiation. Depending on the application, the counting systems can be roughly grouped into: Single channel analyzer (SCA) systems and Multi-channel analyzer (MCA) systems. The intensity of radiation can be measured just by counting the electric pulses, which are produced by the detector. The number of output pulses from detector is proportional to the number of incoming radiation. The single channel analyzer (SCA) system is used to carry out this type of measurements.

A MCA is used for measuring the energy distribution (energy spectrum) of incoming radiation. The spectrum can give information about the intensity at each energy level or on the other hand energy peaks of the incoming radiation can be determined.

1.2 Problem statement

Ionizing radiation that is associated with radioactivity cannot be directly detected by our senses. Ionization is the process whereby the radiation has sufficient energy to strip electrons away from atoms. The ionization results in the formation of free electrons and an ionized atom that has lost some of its orbital electrons. Examples of ionizing radiation include particles such as alpha and beta particles, and photon radiation such as X-rays and gamma rays. Neutrons and protons can also cause ionizations. Since radiation can be harmful to our health, nuclear counting systems are needed to sense the presence, intensity and energy of radiation and to provide suitable alarm.

1.3 Objectives

The objectives of this research is to study and analysis of nuclear counting systems, that are used for measuring the nuclear radiation such as single channel analyzer (SCA) system and Multi-channel analyzer (MCA) systems. In addition to study ionization radiations, its interactions with matter and its detectors that is used in nuclear counting systems.

1.4 Research methodology

Review all topics that concern the subject such as ionization radiations, its interactions with matter, its detectors and study and analysis the basic structure of the nuclear counting systems.

1.5 Thesis Layout

This thesis contains five chapters. Chapter one is an introduction. Chapter two introduces an overview of different types of an ionizing radiation and its interaction with matter. Chapter three describes different types of radiations detector. Chapter four describes the types of nuclear counting systems and its basic structure. Chapter five gives the conclusion.

Chapter Two

Ionizing Radiation and interactions

2.1 Ionizing radiation

Radiation can be defined as the propagation of energy through matter or space. It can be in the form of electromagnetic waves or energetic particles. Radiations can be classified generally into two groups, non-ionizing radiations such as microwaves, visible light and radio waves, and ionizing radiations such as alpha particles, beta particles, neutrons, gamma rays and X-rays. The ionizing radiations have the ability to ionize the atoms or the molecules of the media they pass through [1]. Non-ionizing radiations do not have enough energy to ionize atoms in the material it interacts with.

Ionizing radiations can be classified into directly ionizing such as alpha and beta particles that interacts with the matter under the effect of the Coulomb force, and indirectly ionizing such as gamma rays that indirectly transfer energy to absorber atom. The ionizing radiation can be classified according to their electrical properties into charged radiations such as alpha and beta particles, and uncharged radiations such as gamma rays and neutrons.

Radiations are mainly classified into four groups:

- Heavy charged particles, such as alpha particles and protons.
- Light Charged particles, such as beta particles.
- Uncharged particles, such as neutrons.
- Electromagnetic radiations, such as gamma rays and X-rays.

2.2 Radioactivity

Radioactivity is the spontaneous disintegration of the nucleus of certain atoms with the emission of particles and radiant energy to form other, more stable atoms. The transformation of one element into another as a result of nuclear disintegration is called transmutation. Among the elements with atomic numbers from 1 to 83, there are some that have both stable isotopes and radioactive isotopes (radioisotopes). For elements with atomic numbers greater than 83, there are no stable isotopes and all are radioactive.

The radioactivity is activity of radioisotope source which is defined as rate of its decay and is given by the law of radioactive decay [2].

$$\frac{dN}{dt} = -\lambda N \qquad (2.1)$$

where

N= number of radioactive nuclei.

λ= decay constant.

The unit of activity has been the curie (Ci), defined as exactly $3.7 X 10^{10}$ disintegrations/second. The curie is replaced by its SI equivalent Becquerel (Bq) which is defined as one disintegration per second. Thus:

$$1\ \text{Bq} = 2.703\ \text{X}\ 10^{-11}\text{Ci} \qquad (2.2)$$

There are three major products emitted by the decay of naturally occurring radioactive isotopes, alpha particles, beta particles, and gamma radiation.

An alpha particle, produced by alpha decay, is the nucleus of a helium atom, ${}^{4}_{2}He$. It contains two neutrons and two protons. In nuclear equations for alpha decay, alpha particles appear as a product. The following example shows the alpha decay of radium-226 to radon-222.

$$ {}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}He \qquad (2.3)$$

Nuclear equations are balanced when the number of nucleons (mass number) represented as reactants is equal to the number of nucleons represented as products, thus maintaining conservation of mass. Charge is maintained when the sum of the atomic numbers of the reactants is equal to the sum of the atomic numbers of the products.

Beta decay occurs when a beta particle is emitted from a nucleus. A beta particle has the properties of a high-speed electron and is represented in nuclear equations by the symbol ${}^{0}_{-1}e$. For example radioactive isotope thorium-234 is a beta emitter.

$$ {}^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e \qquad (2.4)$$

Like alpha decay, beta decay is accompanied by transmutation of the original isotope into an isotope of another element. The product of the decay of thorium-234 is protactinium-234. In beta decay, the atomic number increases by 1, while the mass number remains unchanged. The process can be considered as a breakdown of a neutron to an electron (which is emitted) and a proton (which increases the atomic number). Thus, there is one less neutron in the nucleus, but there is one more proton. Therefore, the mass number remains unchanged.

Gamma radiation is another product of radioactive decay. Gamma rays, which are similar to high-energy X rays, are not particles and do not have mass or charge. So the presence of gamma rays does not affect the balancing of nuclear equations.

The products of radioactive decay can be separated from each other by application of an electric or magnetic field to the path of the emanations. In an electric field, positively charged alpha particles are deflected toward the negative electrode, while negatively charged beta particles are deflected toward the positive electrode. In a magnetic field, alpha and beta particles move towards opposite poles. Since gamma rays have no charge, they are not affected by either electric or magnetic fields.

The half-life of a radioactive isotope is the time required for one-half of the nuclei in a given sample of that isotope to undergo radioactive decay. The half-life period can vary from a fraction of a second to billions of years. As example the isotope iodine-131 has a half-life of about 8 days.

2.3 Sources of Radiation

Sources of ionizing radiation are inside and surrounding us all the time and everywhere. All living creatures, from the beginning of time, have been, and are still being, exposed to radiation. This radiation comes from radionuclide's which occur naturally as trace elements in rocks and soils of the earth as a consequence of some radioactive decay.

Sources of radiation can be divided into two categories:

- Natural Background Radiation
- Man-Made Sources of Radiation

Natural background radiation comes from three sources:

- Cosmic Radiation

- Terrestrial Radiation
- Internal Radiation

Cosmic Radiation is Charged particles from the sun and stars. The earth, and all living things on it, is constantly bombarded by radiation from space. The charged particles interact with the earth's atmosphere and magnetic field to produce a shower of radiation, typically beta and gamma radiation. The dose from cosmic radiation varies in different parts of the world due to differences in elevation and to the effects of the earth's magnetic field.

Terrestrial sources are radioactive material found throughout nature. It is in the soil, water, and vegetation. Low levels of uranium, thorium, and their decay products are found everywhere. Some of these materials are ingested with food and water, while others, such as radon, are inhaled. The dose from terrestrial sources also varies in different parts of the world. There are three very important naturally occurring terrestrial radionuclide's include ^{238}U, ^{235}U and ^{232}Th. They are actually the parents of three long radioactive decay chains, which end in stable lead as follows:

- Uranium series, beginning with ^{238}U
- Thorium series, which originates with ^{232}Th
- Actinium series, which originates with ^{235}U

Internal Radiation comes from radioactive potassium-40, carbon-14, lead-210, and other isotopes inside our bodies from birth. The variation in dose from one person to another is not as great as the variation in dose from cosmic and terrestrial sources.

The four major sources of man-made radiation exposure are:

- Medical Radiation, such as diagnostic x-ray, nuclear medicine, and radiation therapy.
- Consumer Products, such as building materials, televisions, smoke detectors (americium) and road construction.
- Industrial applications
- Nuclear power

- Radioactive Fallout, which is radioactive material that has become airborne as a result of nuclear weapons testing in the atmosphere or as a result of large scale accidents of nuclear reactor.

2.4 Radiation interactions

An understanding of the mechanisms by which ionizing radiations interact with matter is fundamental to an understanding of the response of a specific type of detector. Ionizing radiations possess sufficient energy to eject electrons from neutral atoms such as alpha particles, beta particles, gamma rays, x-rays, and neutrons.

The following expressions are related to the interaction of radiation with matters and should be defined first:

The radiation stopping power is the average energy loss per unit path length and is usually expressed in MeV per cm.

The radiations range is the linear distance behind which no particle passes through the absorber material. It depends on type and energy of the particle and on the material through which the particle traverses.

The radiation path length is the total distance traveled by the particle in the absorber material where it is linear for heavy charged particles and non-linear for light charged particles.

The mean free path is the average length of the path that the radiation traveled without interaction with the absorber material.

The specific ionization is the average number of ion pairs (electron and positive ion pairs) formed per cm in the track of radiation.

The mean ionization energy is the average energy required to form one ion pair in the matter.

2.4.1 Heavy charged particles

Heavy charged particles interact with the matter under the effect of the Coulomb force (electrostatic force) between their positive charge such as alpha particle and the negative orbital electrons within the atoms of the absorber material. Under the effect of the Coulomb forces, the heavy charged particle interacts simultaneously with many orbital electrons of the absorbing medium atoms. Because of the large masses differences between the charged particles and the electrons, the energy transfer from the charged particle per collision is very small. The maximum energy transfer in one collision is about 1/500 of the particle energy per nucleon [2]. The charged particles lose their energies after many collisions within the matter. The particle's energy is decreased with through its path length and then finally stopped within the matter after losing its energy. At the end of its track, the particle accumulates z electrons and becomes a neutral atom [2].

The heavy charged particles have a linear path and a definite range in a given absorbing material. Depending on the energy transferred to the orbital electrons, either it bring the electrons to a higher orbits with less binding energies (atoms excitation), or remove the electrons (primary electrons) from the atoms this called primary atoms ionization. Atomic ionization produces ion pairs where each ion pair is composed of an electron and a positive ion of an absorber atom from which one electron has been removed. The energetic primary electrons, known as delta electron or delta rays, interact with the absorber atoms and lose their energy via secondary ionizations. The secondary ionization is very important for radiation detection where it increases indirectly the energy transfer to the absorbing medium.

The specific energy loss (linear stopping power) varies as inversely with particle energy. The rate of energy transfer is increased with decreasing charged particle velocity because it spends a greater time in the vicinity of any given electron. For the different charged particles that have the same velocity, the particle with the greatest charge (ze) will have the largest energy loss per track length unit. For different absorber materials, the specific energy loss depends on the product NZ. Linear stopping power will increases with increasing the atomic number of the absorber material (higher density material).

On the macroscopic level, for a certain absorbing material, with increasing the absorber thickness, the heavy charged particles losses more of their energies with a defined means range.

2.4.2 Beta particles

The beta particles interact with matter via Coulomb force (electrostatic forces). They lose their energy through the collisions with orbital electrons and consequently it either excites or ionizes the absorber atoms. Because both beta particles and electrons have the same mass, the energy loss per collision is larger comparing to that in case of heavy charged particles. Due to the large deviation in the direction of beta particle after collision, it follows much more tortuous path [2].

In addition to the energy loss due to atoms excitation and or ionization, particle energy may be lost by another radiative process called Bremsstrahlung radiation. When high speed charged particles pass close to the intense electric field of the absorber nuclei, the particle suffers strong and Bremsstrahlung radiation is emitted. The energy loss due to Bremsstrahlung radiation is more significant only in absorber materials of high atomic number.

Finally beta particles lose their energy inside the absorber and stop at the end of their tracks. Negative beta particles act as free electrons in the absorber, while positive beta particles (positrons) annihilate with free electrons and produce two photons which are very penetrable compare to the range of positron. These photons interact with matter and may lead to energy deposition in other locations far from the end of the positron track.

In macroscopic level, beta particles suffer from absorption inside the absorber material or backscattering. For the majority of beta particles, the absorption curves (number of beta particles as a function of absorber thickness) have a near exponential shape.

Backscattering is a very important process that could affect significantly the specific energy lost in the matter and consequently the radiation detection. Some particle undergoes large angel deflections along their track which lead to backscattering process that lead to re-emerges of the particle from the absorber surface without depositing all their energy in the absorbing medium. This will affect significantly the detection processes.

2.4.3 Gamma Rays

The electromagnetic radiations such as gamma rays have no electric charge, no mass and their rest mass is zero. Gamma rays have originated from the nuclei, travel with the velocity of light, and are considered as a particles called photons. The relationship between energy (E), frequency (ν), and wavelength (λ) of photon is [2]:

$$E = h\nu = h\frac{c}{\lambda} \qquad (2.5)$$

Where, h is Planck's constant.

There are three main mechanisms of interaction of gamma ray with matter that play an important role in radiation detection processes known as photoelectric absorption, Compton scattering and pair production. These interaction mechanisms lead to the partial or complete transfer of gamma ray photon energy to electron energy. This leads to indirect ionization of the absorber atoms.

2.4.3.1 Photoelectric absorption

This mechanism of interaction is very important for gamma ray measurements. The photon interacts with the absorber atoms and photon absorption occurs. Depending on the photon energy, the most bonded orbital electron in K or L shell will absorb the photon energy to be removed completely from the atom with a kinetic energy given by [2]:

$$E_e = h\nu - E_b \qquad (2.6)$$

where

E_e = photo-electron kinetic energy.

$h\nu$ = photon energy.

E_b = electron binding energy

The photo-electrons are energetic electrons and interact with the matter exactly like beta particle. These electrons leave the atom and create an electron vacancy (excited atom) in their inner orbits, where either a free electron or an electron from a higher orbit of the atom fills this vacancy and generate X-ray. The generated X-rays interact with the absorber and produce another photo-electron via photo-electric absorption, with less binding energy electron (known as auger electron) than the original photo-electron. The probability of interaction between Photon and Electron is called the photoelectric cross section or photoelectric coefficient (τ). It depends on the photon energy (E) and the absorber atomic number (Z). Photoelectric absorption is the predominant mechanism of interaction for low energy photons (Eγ). It is enhanced with increasing the absorber atomic number (Z).

2.4.3.2 Compton scattering

The Compton scattering is an inelastic collision between the incident photon and the weak bonded electron (nearly free) in the outer shell of the absorber atoms. The incident photon dissipates a part of its energy and deflects with a scattering angle θ. The recoil electron is removed from the atom with a kinetic energy dependent on the amount of energy transferred from the photon. The energy transfer varies from zero when θ= 0 to a maximum value when θ=π where θ is scattering angle of the scattered photon.

The probability that Compton scattering will occur is called the Compton coefficient or Compton cross section, which decreases with increasing the energy of photon and increase with the atomic number Z of the absorber material.

2.4.3.3 Pair production

Pair production is the main interaction mechanism for the energetic photon. Practically, it becomes significant for the few MeV energy photons. Theoretically, it is possible for the photons with energy (Eγ) of 1.022 MeV, which is equivalent to two electron rest masses energy ($2 m_0$ C2) . The photon disappears in the nucleus of the absorber atoms and electron-positron pair is generated. The kinetic energy of the electron (Ee-) and the positron (Ee+) is given by [2]:

$$E_{e^-} = E_{e^+} = 0.5\left(E_\gamma - \left(m_0 C^2\right)_{e^-} - \left(m_0 C^2\right)_{e^+}\right) = 0.5\left(E_\gamma - 1.022 MeV\right) \tag{2.7}$$

Both electron and positron interact with the absorber as beta particles and finally come to rest after losing their kinetic energy. Then, the electron acts as a free electron and the positron interacts with electron and generates two inhalation photons.

In the macroscopic level, the incident photons may interact with the absorber material and their number decrease with increasing the thickness of the absorber. This phenomenon is known as radiation attenuation. Photons attenuation occurs due to the main interaction mechanisms of photons such as photoelectric effect, Compton Effect and pair productions effect, and the photons completely absorbing or scattering. The linear attenuation coefficient (μ) is the probability per unit length that the photon is interacted and removed from the beam. The linear attenuation coefficient is the sum of the probabilities of the three main interaction mechanisms (photoelectric, Compton scattering and pair production is given by [2] :

$$\mu = \tau(photoelectric) + \sigma(compton) + \kappa(pair) \tag{2.8}$$

Chapter Three

Radiation Detectors

3.1 Radiation detectors

The function of detector is to produce a signal for every particle entering into it. The physical properties and characteristic of the detector control the features of the detection system. There are three main radiation detectors categories as follow:

- Gas-filled detectors.
- Scintillation detectors.
- Semiconductor detectors.

Radiation detectors are also classified according to their detectors physical form into gas, liquid and solid detectors. And according to the nature of the detector output signal into current or light.

For radiation detection, there are some operating characteristics such as detection efficiency, energy resolution, background, proportionality of signal to energy deposited, pulse shape and time resolution or dead time. The functions and the applications of the different radiation detection systems are significantly dependent on these parameters.

The detection efficiency is defined as the ratio of the number of particles or photons recorded by the detector to the number of particles or photons emitted by the source, known as absolute efficiency (ε). It is defined also as the ratio of the number of particles or photons recorded by the detector to the number of particles or photons striking the detector, known as intrinsic efficiency (η), which is dependent on the solid angle (δ) of the source-detector geometric arrangement and given by [1]:

$$\eta = \delta . \varepsilon \tag{3.1}$$

The energy resolution is defined as the capability of the detector to distinguish between two particles or photons with different but close energies.

The resolving time is defined as the minimum time requires by the detection system to recover from recoding one event or interaction so it would be able to record another event. It is defined also as the minimum time in which the detection system cannot record any radiation interaction or signal because it is busy with processing the previous signal and known as the dead time.

3.2 Gas-filled detectors

Gas-filled detector is composed of enclosed gas volume between two electrodes (anode and cathode) where there is a potential difference as shown in Figure (3.1).

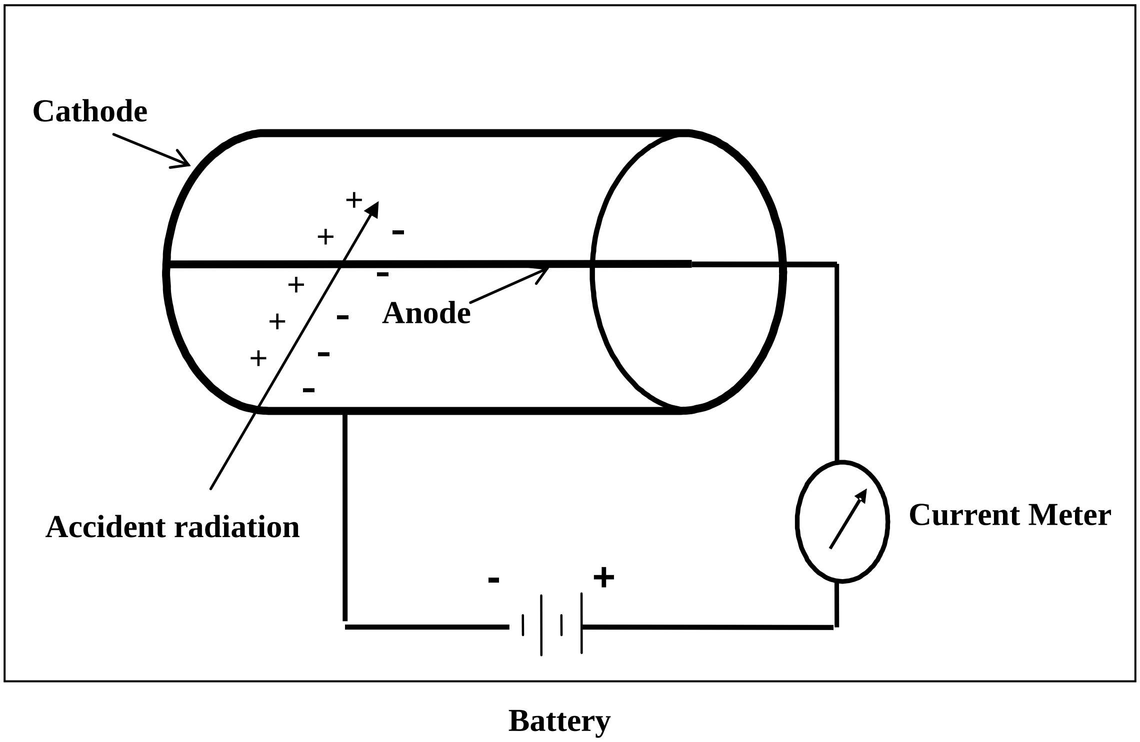

Figure (3.1): Gas-filled detectors [1].

Gas-filled detectors have different shapes such as two parallel electrodes shape, cylindrical shape with a central rod as an anode and spherical shape but they are working based on the same principles.

When the incident radiations travel through the gas (the sensitive volume of the detector) and interact with the gas atoms and molecules, atoms excitation and ionization occur. The gas ionization produces electron-ion pairs and their number depends on the energy deposited during radiation gas interaction. If the applied voltage is zero or low ion pairs are recombined locally after their formation inside the gas sensitive volume. The electric field (E) between the detector electrodes will exert electric forces to move the negative electrons toward the anode and the positive ions toward the cathode.

Both, electrons and positive ions of the gas atom have the same charge and different masses where the positive ions are much heavier than the electrons. The acceleration (electric force/ mass) of an electron is thousands times higher than that of the positive ion, so the collection of the created electrons is thousands of times higher than that of the positive ions. The output signal is either current signal due to the collected charges (resistance, R, circuit) or pulse due the drop of the external circuit voltage (resistance-capacitor, R-C, circuit). There is a time difference between the output current signal due to electrons collection on the anode and the positive ions collection on the cathode. Practically, the output signal depends on the electrons charge collection to have a short responding time.

The gas filled counters structural material and designs are affected by their counting efficiency of the different radiation types. For charged particles, the counter windows should be thin to avoid particles absorption within the counter window. For beta particle, the counter is designed to stand a higher gas pressure that is necessary to stop the incident beta particle within the gas volume of the counter. For gamma ray, the counter walls are constructed from high atomic number materials where the counter response to gamma ray comes in most cases through its interaction with the counter walls.

As the applied voltage increases, the electric field strength increases and the recombination rate decreases up to become zero, so all created ions are collected. Up to this voltage, this region known as recombination region.

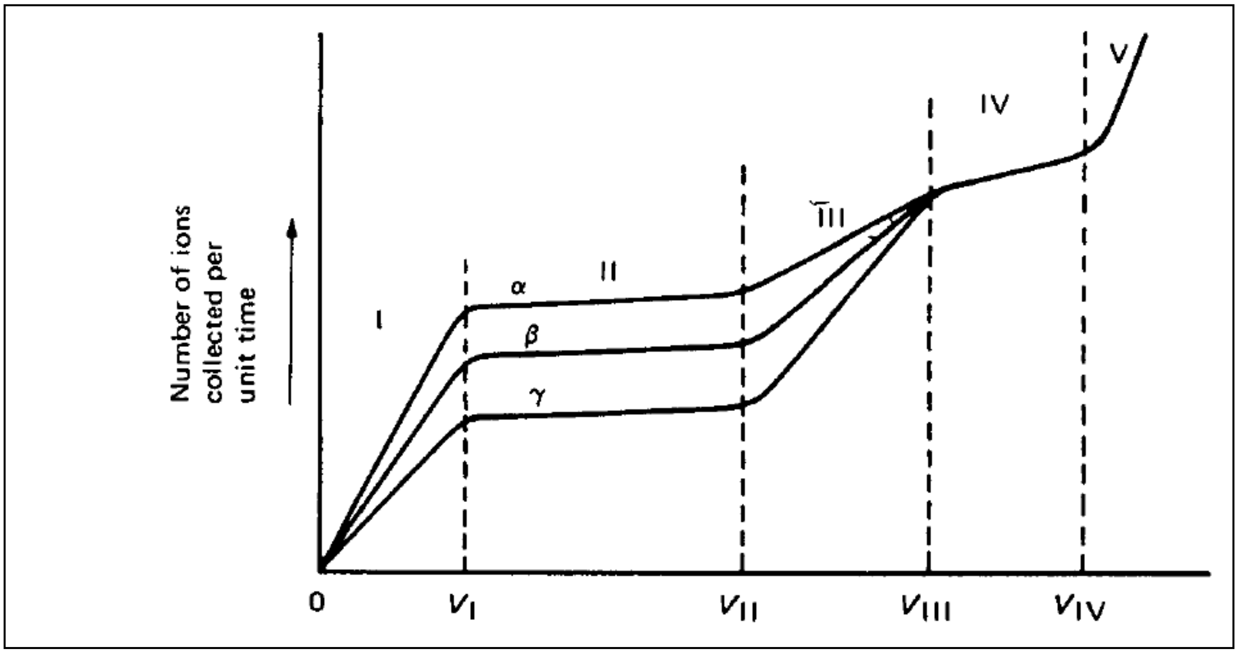

Figure (3.2): The response curve of the gas-filled detectors [1].

The response curve of the gas-filled detectors is shown above in Figure (3.2); it is divided into five regions as follow [1]:

I. Recombination region.
II. Ionization region.
III. Proportional region.
IV. Geiger-Muller region.
V. Continuous discharge region.

A gas filled detector may operates in any of these regions depending on the gas type, gas pressure, applied voltage, and counter size. According to the applied voltage, the gas-filled detectors are classified into:

- Ionization Chamber.
- Proportional Counter.
- Geiger-Muller (GM) counters.

3.2.1 Ionization Chamber

When applied voltage as shown in Figure (3.2) is high enough to collect electrons before recombination with the positive ions, the recombination rate becomes zero, and even with increasing the applied voltage the collected charge rate stays constant, this region is known as ionization chamber plateau or operating voltage. The detector output signal, either current or pulse, is exactly equivalent to the energy deposited divided by the energy required to ionize one gas atom, so there is no amplification. Therefore, the ionization chambers have the ability to distinguish between the different types of radiation and the same radiation with different energies. The energy resolution (the ability to distinguish between two photons or particles having close energies) of an ion chamber is quite good. Ionization chambers are very useful for the measurement of high radiation fields. The ionization chamber structure changes according to radiation types. It is basically a metal cylinder with a central anode and its inner walls are usually lined by an air equivalent material. For alpha particles detection, the entrance window of the detector should be thin to decrease particles absorption. For beta particle, the gas pressure increase to stop all particles inside the active volume of the chamber to ensure the complete particle energy deposit. For gamma rays, the detector should be lined by a high atomic number material to increase the probability of gamma rays interaction.

There are many applications of radiation detection systems based on ionization chamber such as calibration of radioactive sources and measurement of gases, such as radon, either incorporated in the filling gas of the chamber or sampled on a continuous flow through the gas.

3.2.2 Proportional Counter

As the applied voltage as shown in Figure (3.2) increases beyond the ionization chamber region range, the electric field strength will be strong enough not only to remove the electrons and positive ions of the primary ionization from the sensitive volume of the detector to the electrodes but also to accelerate the primary ionization electrons and positive ions. The accelerated electrons gain a relatively higher kinetic energy and produce a secondary ionization in the region beside the anode due to their collisions with the gas atoms. Also, the accelerated positive ions strike the cathode and create a secondary ionization. This multiplication process of primary ionization is known as Townsend avalanche [2]. The height of the output signals are linearly proportional to the energy dissipated and the primary ionization inside the counter. Therefore, the radiation detection and energy measurement are possible. As the applied voltage increases, the proportionality of the output signal to the dissipated energy and the primary ionization decreases. This range of voltage known as limited proportional region. The proportional counter can distinguish between the alpha particle and the electron particle, where the signal due to alpha particle will be bigger than that due to electron signal. From the characteristic curve of the proportional gas counter with an alpha/beta emitter mixed source the alpha signal count rate will increase to reach the plateau, known as alpha plateau. The length of the plateau depends on the source properties, being thin or thick, and the source-detector geometric arrangement, internal (located inside the counter), or external source. As the high voltage increases, the count rate will increase again due to the signals of beta particles, till reach another plateau where practically both Alpha and beta particles pulses are counted as shown in Figure (3.3) [1].

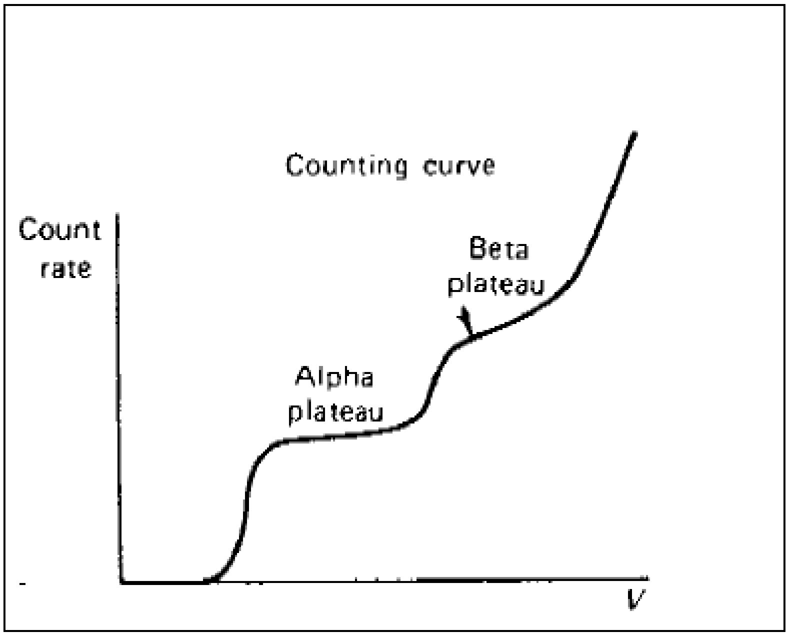

Figure (3.3): Alpha and beta plateau [1].

One of the most important environmental applications of proportional counters is the low background total alpha/beta gas flow proportional counter.

3.2.3 Geiger-Muller (GM) counters

As the applied voltage as shown in Figure (3.2) increases beyond the proportional counter region ranges, the gas multiplication increases greatly due to the strong applied electric field between the counter electrodes. G-M counter works under such principle in the same manner as the proportional counter. But the main difference in the G-M counter, is one that avalanche can produce another avalanche within the counter sensitive volume and spreads as chain reactions. So, the output pulses of G-M counter are not correlated to the original radiation properties because all pulses are the same regardless of the initial number of ion pairs produced by radiation. G-M counter can operate only as a simple counter and not as spectrometer because it cannot to differentiate between the different radiations energies.

G-M counter is used as simple economical radiation counter. One of the main disadvantages of the G-M counter is its long dead time comparing to any other counters. This limits its use to the low count rate (a few thousand pulses per second) situations.

G-M counter quenching is another problem that appears as a continuous output of multiple pulses. The negative ions are collected and produce the primary discharge of the counter, and then the positive ions slowly drift toward the cathode where they hit the cathode and produce free electrons. At the cathode surface, the positive ions are neutralized by combining with an electron released from the cathode, and the rest of electrons move toward anode leading to second discharge. Counter quenching is handled in two ways, externally through electronic circuit to decrease the high voltage after the primary discharge or internally by mixing quench gas with lower ionization energy to decrease the production of electrons at the cathode surface and to prevent counter quenching.

3.3 Scintillation detectors

Scintillators are materials (solid, liquids and gasses) that produce scintillations of light when ionizing radiation passes through them [1]. There are different types of scintillators that are classified into inorganic and organic-based scintillators. The interaction of different radiations with scintillators will ionize and excite its atoms and molecules. A large percentage of the absorbed energy will be transferred to heat. While, after a short time, a small percentage of the deposited energy will be released due to scintillator atoms de-excitation that produce fluorescence light (visible light pulses) known as scintillation. The light pulses (scintillations) are converted to photoelectrons that are magnified through the photomultiplier tube to electric signals.

The fluorescence process is prompt emission of visible light from a scintillator following its excitation due to energy absorption. Delayed fluorescence has the same emission spectrum as the prompt fluorescence but with much longer emission time. Phosphorescence process corresponds to the emission of longer wavelength visible light than that of the fluorescence and generally with much slower emission time. The quality and suitability of scintillator as radiation detector depend on its ability to convert as large fraction as possible of the incident radiation energy to prompt fluorescence and to minimize the delayed fluorescence and phosphorescence processes.

The quality of the scintillator as radiation detectors is dependent on the following properties:

- Linear response between the deposited energy and the output light pulse.
- Decay time between the energy absorption and the light emission.
- Radiation energy absorption efficiency.
- Scintillation efficiency of conversion of absorbed energy to light,
- Transparency to its fluorescence light.
- Its index of refraction.

The high quality scintillator should has a liner response, short decay time, a high absorption and scintillation (emission) efficiencies, a high transparency to its fluorescence photons, a good optical quality and an index of refraction near that of glass (1.5) to permit efficient coupling to the photomultiplier tube.

Radiation detection systems based on scintillation detectors consist of three main components; scintillator (including the sensitive volume of the detector), optical coupling system, photomultiplier tube and signal possessing electronic.

The outer surface of the scintillator (the sensitive volume of the detector) is optically isolated inside holding vessel where the outer surfaces constructed from reflecting materials. Of course the side of the scintillator facing the photomultiplier tube is transparent to allow the passage of the produced light pulses (scintillation) due to radiation interaction within the scintillator. The light emitted is isotropic and somehow has to be channeled towards the photomultiplier tube. Any loss at this stage reduces the signal pulse height, decreases the low energy sensitivity and degrades the energy resolution. The photomultiplier tube consists of photo-sensitive layer (photocathode) and dynodes where the applied positive voltage increases gradually for each dynodes and anode. The photons, produced in the scintillator hit the photocathode and release a number of electrons that gain a kinetic energy due to the potential difference between the photocathode and the first dynode and then hit the first dynode and release a number of electrons. The produced photoelectrons are internally multiplied due to increase of the applied voltage on the dynodes that generate a relatively large electric pulse output at the anode, which is nearly proportional to the energy absorbed in the scintillator. Therefore, radiation detection process with scintillation detectors will include energy absorption in the scintillator, conversion of the absorbed energy to light photons, collection of photons and emission of electrons by the photocathode, electron multiplication in the photomultiplier tube (PMT), and finally output electric pulses analysis.

The scintillation detectors allow the measurement of radiation intensity, with a higher efficiency for gamma rays, and the determination of the deposited energy. They can be used as a radiation counters to measure radiation intensity and spectrometer to measure radiation energy spectrum.

3.4 Semiconductor detectors

Semiconductors are not materials that have enough free charge carriers to behave as electrical conductors nor have a high resistivity as that of the electrical insulators. The solid crystal has three energy bands that are valence band, conduction band and forbidden band. For the electrical conductors, the width of the forbidden energy band is very small that allow the movement of the valence electrons to the conduction band, under the effect of any electric field strength higher than zero, where the electrons can move freely in the crystal lattice and carry electric current. For the electrical insulators, the width of the forbidden energy band is big enough to prevent the movement of the valence electrons to the conduction band, which is completely empty. For the semiconductor materials, the forbidden energy band is relatively narrow to prevent the movement of the electron to conduction band at low temperature. As temperature increases, some electrons gain enough energy to cross the forbidden band to the conduction band where electrons can carry the electric current under the influence of an electric field in the same way as the conductors.

Semiconductor crystal as a detector material should have the capability of supporting large electric field gradients, high resistivity, and exhibits long life and mobility for both electrons and holes. If the mobility is too small and life time is too short, most electrons and holes will be trapped at crystal lattice imperfections or recombine before they can be collected. The group IV elements silicon and germanium are the most widely used semiconductor crystal as radiation detectors. The conductivity of semiconductors increases with increasing the concentration of impurities, which create new energy levels that facilitate the movement of charge carrier within the crystal.

Semiconductors have four valence electrons in the upper energy level of the valence band, if they are doped with atoms (crystal impurity) with three valence electrons the positive holes will be existed in the crystal that is known as P-type crystal and the holes are the major current carrier. While, if they are doped with atoms with five valence electrons the excess electrons will be existed in the crystal that is known as N-type crystal and the electrons are the major current carrier. . The P-N diode structure has depletion region near the junction between N- and P-type semiconductor materials which is created by depletion of charge carriers. It is the sensitive volume of a P-N diode structure detector where the ionizing radiation interacts and the dissipated energy will produce electron-hole pairs directly or indirectly in the same way like gas filled detectors. The electron-hole pairs are swept to the P and N regions. The produced charge is linearly correlated to the energy deposited in the detector. Unbiased P-N junction can act like a detector but only with a very poor performance because the depletion region thickness is quite small, the junction capacitance is high, and the spontaneously electric field strength across the junction is low and not enough to collect the induced charge carriers that could be lost due to trapping and recombination. The performance of the P-N junction as a practically used radiation detector is improved by applying an external voltage that leads the junction to be reversed biased. As the applied voltage increases, the width of the depletion region and the sensitive volume increase and the performance of the detection is improved. The applied voltage should be kept below the breakdown voltage of the detector to avoid of changing detector properties.

Because of the narrow energy band gap, 0.74 eV for germanium and 1.12 eV for silicon, semiconductor detectors are thermally sensitive. Practically both Ge and Si photon detector are cooled down with liquid nitrogen during operation to reduce the thermal charge carrier generation (noise) to acceptable limit. The narrow energy band gap of the semiconductor materials lets the energy required to produce an electron-hole pair is less than required to produce an electron-ion pair in a gas. This gives them the advantage of better energy resolution over the gas filled and scintillation detectors where the increase in the number of charge carrier in semiconductor detector leads to improved statistics and better energy resolution.

Chapter Four

Nuclear Counting System

4.1 Counting system types

Nuclear instruments can be grouped as those that measure the many type of radiations or particles emitted by radioactive sources or nuclear accelerators, such as alpha particles, beta particles, gamma, X-rays and neutrons. The energy of the particles or radiations is expressed in electron-volts (eV) and can range from below 1 eV to millions of eV (MeV). The choosing of the suitable detector and detection system depends on a various number of factors that have to be taken into account in choosing the optimum system for a particular application. The first consideration is the type of particle or radiation to be detected then the number of events to be counted and the energies are to be measured [3].

Nuclear counting systems are used for measuring the nuclear radiation. Depending on the application, the counting systems can be roughly grouped into: Single channel analyzer (SCA) systems and Multi-channel analyzer (MCA) systems. The measurements of radiations can also be distinguished into two categories, the first is measuring the number of radiations or intensity and the second is measuring the energy distribution.

The intensity of radiation can be measured just by counting the electric pulses, which are produced by the detector. The number of output pulses from detector is proportional to the number of incoming radiation. The single channel analyzer (SCA) system is used to carry out this type of measurements.

A MCA is used for measuring the energy distribution (energy spectrum) of incoming radiation. The spectrum can give information about the intensity at each energy level or on the other hand energy peaks of the incoming radiation can be determined.

4.2 Single Channel Analyzer (SCA) System

To measure the radiation intensity just counts the electric pulses that produced by the detector for several seconds or hours. But some other applications need to measure the radiation intensity only at certain range of energy, so certain electric pulses which have a certain range of amplitude are counted. The pulses that exceed the criteria will be ignored. The input signal from detector is fed to discriminator which has adjustable triggering levels. The lower triggering level is called the baseline and has lower values than the upper level. The difference between these levels is called the window of the single-channel analyzer [4].

A single channel analyzer system consists of High Voltage Power Supply (HVPS), Amplifier, Discriminator and Counter as shown in Figure (4.1).

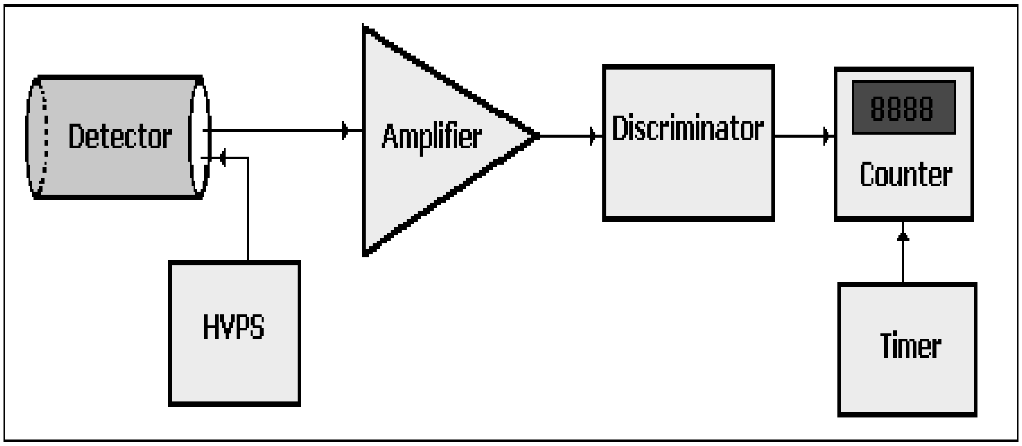

Figure (4.1): Configuration of SCA system

4.2.1 High voltage power supply

High voltage power supply (HVPS) is needed for polarizing the detector. The free electrons, which produced by ionization process, have to be captured and stored. There must be an electric field in order to push or attract the free electrons to the anode (positive electrode).

4.2.2 Amplifier

Amplifier has two functions, shaping and amplifying the electric pulses from detector. The peak of exponential pulses from detector is too sharp to be measured or distinguished and the tail is too long as shown in Figure (4.2). So, they have to be shaped as Gaussian pulses, which are more flat at the peak and have no long tails ,also this shaping improves the signal-to-noise ratio [5].

The second function of amplifier is to amplify the amplitude of the pulses. Output pulses of detector are in order of mVolt or even hundreds of µVolt, so it has to be amplified to become some Volts. The amplifier must have facility to change the gain factor of the pulse amplification.

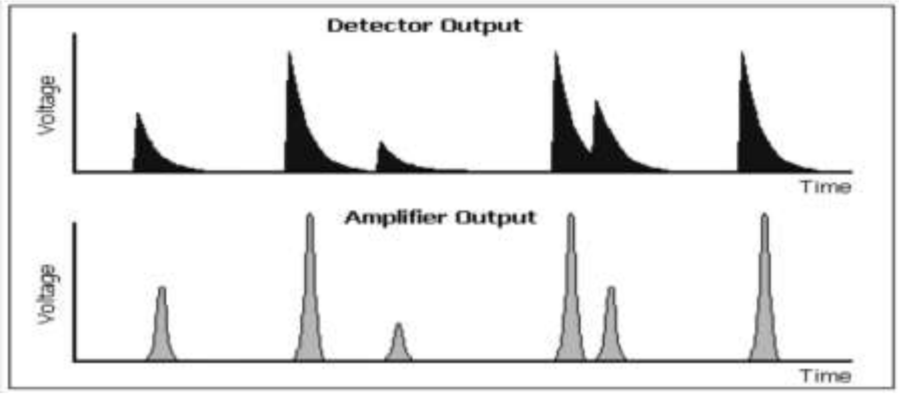

Figure (4.2): Output pulses from detector and amplifier

4.2.3 Discriminator

Discriminator has a function to discriminate the analog incoming pulses, which comes from the amplifier. The discriminator will produce logic signal, when the incoming pulse fulfills the energy range criteria, which is defined by the user selectable lower- and upper level.

As shown in Figure (4.3), the lower level and upper level are set at a certain position in order to count the middle energy radiation only. So, before carrying out the measurement, the energy levels of radiation that want to be counted have to be known. Then setting the lower level and upper level of the discriminator. The upper and lower discriminators can set externally by controlled potentiometers [6].

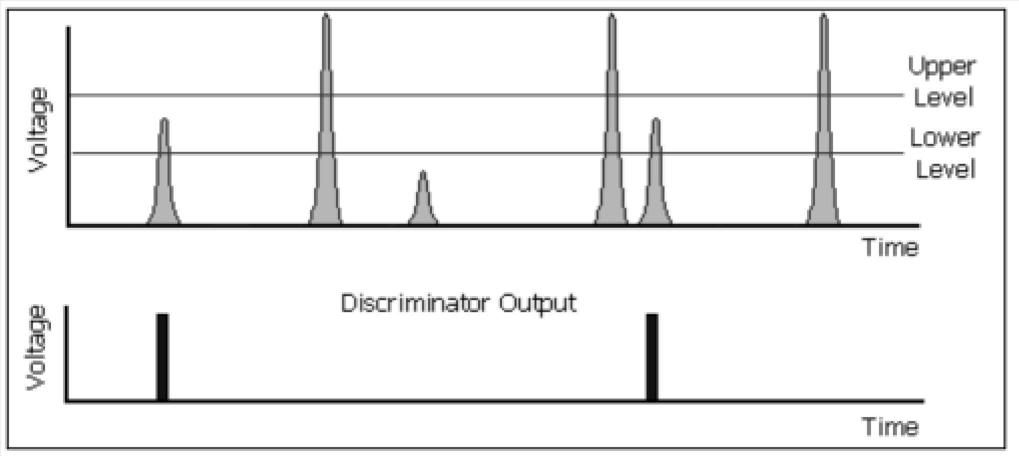

Figure (4.3): Pulse discrimination process in discriminator

4.2.4 Counters

Counters are used for counting the logic signal from the discriminator for certain interval time (counting time). The User sets the counting time through the timer in the order of seconds, minutes or hours. The simplest technique is combination of a clock generator with a counter. The clock pulses are counted between the start and stop signals, which produces a direct readout in real time [5].

4.3 Multi-Channel Analyzer (MCA) Systems

In the single-channel analyzer (SCA) system, the radiation intensity is measured in one energy range only. For sure, the measurements can be repeated with different position of lower level and upper level, and then the result is plotted as a spectrum. Actually this method was applied for spectroscopy applications, when the analog to digital conversion techniques had not been invented. The single-channel analyzer (SCA) has the drawback that it needs quite a long time to obtain a spectrum too long when short-lifetime isotopes are involved in the experiments. The multichannel analyzer grouping the input signal according to its amplitude by converting the amplitude of single into a digital signal that is processed in a small internal computer [4].

The measurements in MCA systems apply different approach. Instead of measuring the radiation intensity (counting the number of electric pulses) several times with different energy level, the radiation energy is measured directly by measuring the amplitude of each electric pulse by conversion of the pulse amplitude into a digital number. The Analog to Digital convertor (ADC) converse the pulse amplitude into a digital number. The digital number is in binary form. The multi-channel analyzer (MCA) uses memory to record the number of pulses converted in each channel [7].

The configuration of MCA system as shown in Figure (4.4), specially the analog parts, is similar to the SCA system. The only difference is the MCA module. The Figure (4.5) shows the conversion of analog pulses from amplifier to be a spectrum.

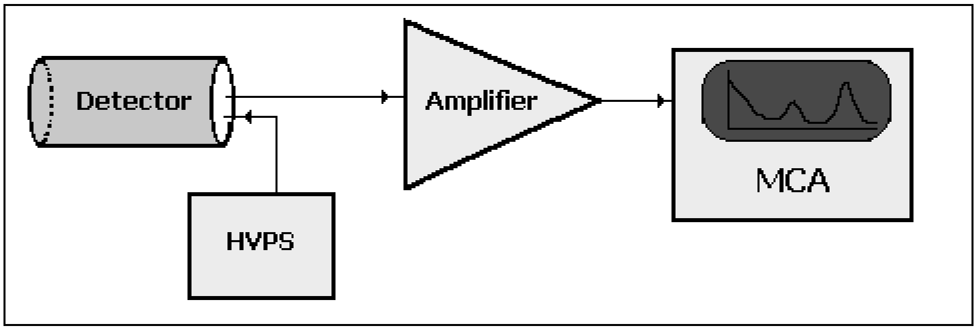

Figure (4.4): Configuration of MCA system

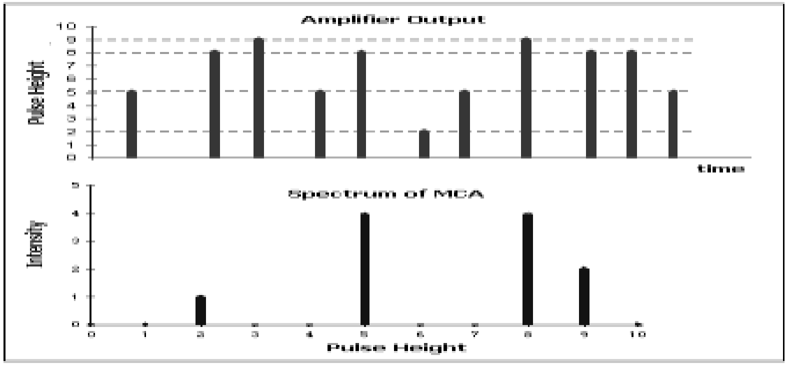

Figure (4.5): Conversion of analog pulses to be a spectrum

As shown in the below Figure (4.6), the energy spectrum of radiation emitted from Cs137(662 keV) and Co60 (1173 keV and 1332 keV) sources.

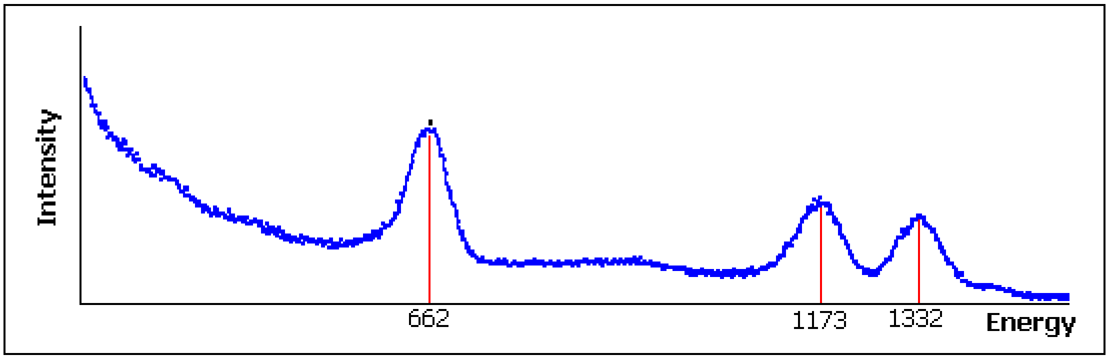

Figure (4.6): energy spectrum of Cs137 and Co60 sources

4.3.1 MCA module

The MCA module is rather complicated comparing to other modules such as amplifier or discriminator. Basic concept of the MCA module itself can be described as shown in Figure (4.7).

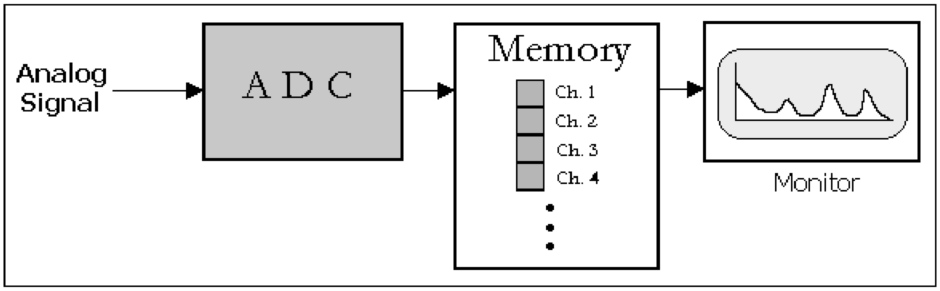

Figure (4.7): Block diagram of the MCA module

The most important component of the MCA module is the analog to digital converter (ADC) part. It measures the voltage of the incoming analog signal at a certain frequency (sampling frequency). The measurements results are in binary number. If the incoming analog signal crosses the threshold (is greater than the lower level) the ADC starts to find the amplitude of the incoming pulse. If amplitude of the pulse is less than the upper level and the width of the pulse is no longer than a predefined value, then the amplitude of that pulse is hold and it will be used as a memory address. This is the so called channel number. On the contrary, if the amplitude is too big or the pulse width is too long then it will be discarded. The content of a memory at a certain channel number, which is correlated to the amplitude of the pulse, is read from the memory, incremented by one and written back to its initial location in the memory. The ADC needs a finite time to acquire the signal then the input pulse may not be too short and it should have a gradually rounded peak [8].

Those steps above are repeated every time a pulse is recognized until the counting time has elapsed. During this time, with less priority, the contents of memory of every channel number are displayed on the monitor. The most important things in that process above are the sampling frequency and the resolution.

So in terms of internal functioning, multi-channel analyzer (MCA) is different from SCA. MCA performs the same task with many of threshold windows. Thus it doesn’t need to count pulses at each threshold window individually, therefore making the process faster [9].

As mentioned, the ADC measures the voltage of the incoming analog signal at a certain frequency. The sampling frequency of an ADC has to be much higher than the frequency of the signal, otherwise amplitude of the pulse will be found incorrectly as shown in Figure (4.8).

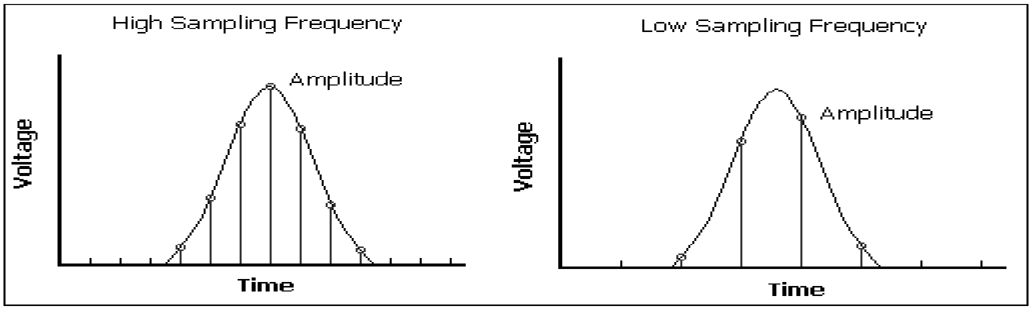

Figure (4.8): Voltage measurements with certain sampling frequency

The important parameter for analog to digital converter (ADC) used in detector systems is the resolution of an ADC which is the capability to distinguish between very close analog values. For example, a 10 bits ADC converts an analog signal into 1024 digital steps. If we assume a 10 Volt input range, the resolution is about 10 mVolt. It means that two pulses with amplitude 1110 mVolt and 1120 mVolt will be recognized as two different values and will be stored in the different channel number, but two pulses with amplitude 1110 mVolt and 1115 mVolt will be stored in the same channel number. Direct related to this parameter is the number of memory location. A 10 bits ADC needs 1024 memory locations and 12 bits ADC needs 4096 memory locations [8].

There are at least three parameters, which can prescribe the performance of a MCA system, namely the resolution, the integral and differential non-linearity. Those parameters are depended on two things, the detector itself and the electronic parts such as amplifier and MCA module.

4.3.2 Resolution

Resolution of the system shows how precise the system can distinguish between two consecutives energy peaks. This parameter is often measured as Full Width at Half Maximum (FWHM). A good resolution system has very narrow FWHM so it can resolve a very small different of energy peak as shown in Figure (4.9).

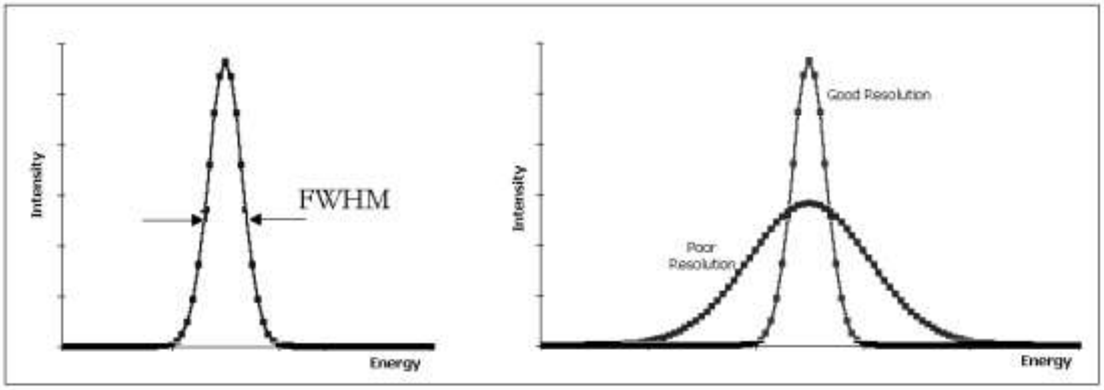

Figure (4.9): Resolution of the MCA system

As mentioned, radiation is converted into electric pulses, whose amplitudes are proportional to the radiation energy. In the ADC the amplitude of the pulse is converted to the channel number. So, ideally the radiation energy should be linear to the channel number.

4.3.3 The integral non-linearity

The integral non-linearity (INL) is a parameter that is used to determine the maximum deviation of that correlation to the linear line as shown in Figure (4.10).

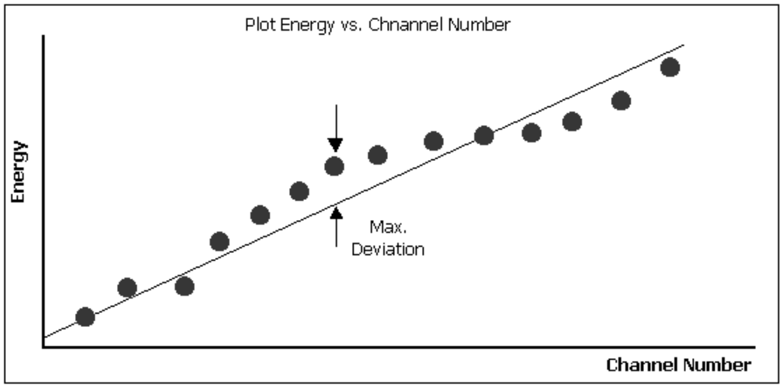

Figure (4.10): Integral non-linearity

Basically, MCA system measures intensity of incoming radiation at each energy level. If energy distribution of the incoming radiation is flat, the source emits the same intensity for every energy level, the spectrum will be a horizontal line.

4.3.4 The Differential non-linearity

Differential non-linearity (DNL) is a parameter that used to determine the maximum deviation of the measurements to the horizontal line as shown in Figure (4.11).

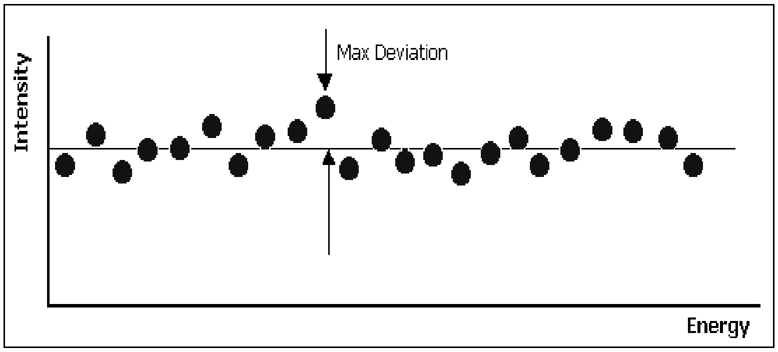

Figure (4.11): Differential non-linearity

4.4 Radiation Measurement Unit

Two types of measurements of the radiation's energy are generally used. The exposure rate, which is the amount of radiation energy that reaches an object's surface in a given time period. The absorbed dose, which is the amount of radiation energy that is actually absorbed by the material through which it passes. The curie (Ci) is a measure of the activity of the sample that is the number of nuclear disintegrations per second. In the SI system of units, the curi has been replaced by the Becquerel (Bq) disintegration per second.

The activity of a source is one way to describe the amount of radiation present. But there is another type of radiation unit that is related to the interaction of radiation with living tissue. As radiation passes through matter, it interacts and in general deposits energy in the matter. A rad of radiation will deposit 100 ergs of energy for each gram of tissue it passes through. The word rad was originally an acronym meaning radiation absorbed dose. Recently SI replaced the rad with the gray (Gy). A gray of radiation will deposit 10,000 ergs of energy for each gram (or 1 J/Kg) of tissue it passes through (100 rad = 1 Gy) [10].

The energy deposited per gram of tissue may be the same but the damage is different. That due to for some types of radiation deposits a relatively large amount of energy during each interaction, while other different types of radiation lose only a small amount of energy in each interaction.

The rem (roentgen equivalent unit) is the standard old unit for radiation damage and the sievert (Sv) is the new SI unit. 100 rem= 1 Sv. The amount of radiation present in Gy, is multiplied by an RBE (relative biological effectiveness) factor to yield the amount of radiation damage in sieverts. The RBE for X rays, gammas and betas is 1, protons it is 10 and for alpha it is 20. Thus the same number of rads or grays of alphas are much more damaging than the equivalent amount of gammas.

Chapter Five

Conclusion

There are two terminologies in radiation, intensity and energy. The intensity is used for describing the number of radiation per unit time that emitted by the source and absorbed by the detector. The intensity of the radiation depends on the activity (Currie or Becquerel) of the source. The term of energy is used for describing the strength (Kev) of each radiation that emitted by the source. The radiation energy is characteristic to the type of the source.

The intensity of radiation can be measured just by counting the electric pulses, which are produced by the detector. The number of output pulses is proportional to the number of incoming radiation. The single channel analyzer (SCA) system is used to carry out this type of measurements.

Multi-Channel Analyzer (MCA) is used for measuring the energy distribution (energy spectrum) of incoming radiation. The spectrum can give information about the intensity at each energy level or on the other hand energy peaks of the incoming radiation can be determined.

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