Chapter 5.   The Measurement of Alpha, Beta and Gamma Radiations.

Peter A. Burns
Australian Radiation Laboratory

Abstract. Detection methods for nuclear radiations are based on the processes of excitation and ionization of atoms in the detection medium by the passage of a charged particle. The incident radiation may be a charged particle or may cause the release of a charged particle after some primary interaction. Detectors are usually of two types, those which produce a charge pulse following ionization of the medium and those which produce a burst of light photons which are then detected by a photomultiplier tube. By processing the electronic signals produced in suitable ways either the count rate of the source, the activity, or the dose equivalent to a person may be determined. In order to make these determinations it is necessary to understand the type of nuclear transformation of the radionuclide in question, the type and energy of the radiation being emitted and the processes involved when these radiations pass through the medium of the detector. Suitable choice of detectors and extrapolation from measured data to the quantity which is to be determined can then be made.

TYPES OF RADIOACTIVE DECAY

Alpha decay is the de-excitation of a radionuclide by the emission of two protons and two neutrons (a helium nucleus) from the nucleus. There is usually a small amount of residual energy which is emitted as a gamma ray or as is more often the case, by internal conversion, as an internal conversion electron plus an X-ray or Auger electron from the daughter nuclide.

Beta decay is the de-excitation of a radionuclide by the emission of an electron or positron and a neutrino from the nucleus. The de-excitation energy is shared between the electron and the neutrino in a way which is dependent on the atomic number and the energy of de-excitation. The daughter nucleus may be left in an excited state which will result either in the emission of a gamma ray or internal conversion may take place resulting in emission of an internal conversion electron plus an X-ray or Auger electron.

Electron capture occurs when an inner shell electron is captured by a nucleus. The new nucleus may be in an excited state and subsequently emit a gamma ray or through internal conversion an internal conversion electron plus an X-ray or Auger electron.

RADIATIONS EMITTED

As a result of these decay processes we are therefore likely to observe the following types of radiation following nuclear transformation. The energy of the radiations likely to be encountered when measuring heavier atomic number materials are as follows.

Alpha particles: Monoenergetic helium nucleii with energies in the range 3.5 to 9 MeV.

Beta particles: Electrons with a distribution of energies up to a maximum energy. The remaining energy for a particular transition is carried off by a neutrino. The range of energies encountered and measurable will be from 2 keV to 3500 keV.

Gamma rays: Monoenergetic photons with a range of interest from 10 keV to 2 MeV.

Internal Conversion Electrons: Monoenergetic electrons with an energy equal to that of the gamma ray converted, less the binding energy of the electron. Only conversions from the K shell and L shell are of interest.

X-rays: Monoenergetic photons resulting from the filling of a K shell or L shell vacancy which has been emptied as a result of either internal conversion or electron capture.

Auger electrons: Monoenergetic electrons resulting from a vacancy in the K-shell or L-shell whereby the excess energy results in the emission of an electron with an energy equal to the L-shell or K-shell binding energy.

THE PASSAGE OF RADIATION THROUGH MATTER

__Alpha particles__ Alpha particles loose energy by ionization and excitation of electrons of the absorber atom as a result of interactions with the electromagnetic field of the alpha particle. For alpha particles with an energy of several MeV the predominant mechanism for energy loss is by collision with outer shell electrons (i.e. ones with low binding energies). The absorber therefore appears as a cloud of electrons and the higher the atomic number of the material and the denser the material the denser the electron cloud.

If the alpha particle has a mass M and energy E_a and collides with an electron of mass m, then the maximum energy an electron may acquire is, by classical mechanics.

$$W \max = (4 \, mM/(m+M)^2)E_a$$

As M is much greater than m the following approximation applies

$$W \max = 4mE_a/M$$

For alpha particles with an energy of several MeV the maximum energy loss is approximately 2 keV (Dearnaley and Northrop 1966).

As the binding energy of the electron is much less than this it is justifiable to consider the collisions as occuring with free electrons. At each collision, an alpha particle loses approximately one thousandth of its energy so that deflections from a straight-line path are small. The range in a particular material is determined by a large number of collisions and is therefore well defined.

As can be seen from the above, alpha particles will loose small amounts of energy as they move in straight lines with only small deviations through the source material, the material between the source and detector (unless the source is in a vacuum) and finally in the detector itself. 5 MeV alpha particles will travel less than 30 microns in silicon (Marion 1960).

Electrons

Electron with energies less than 10 MeV loose energy mainly by excitation and ionization of the electron in the absorber. However as both electrons have the same mass, a large proportion of the energy of the incident electron

may be transferred and scattering will take place. Because of this
straggling, the range of an electron in a particular material is less well
defined than the range of an alpha particle.

Photons

Gamma rays and X-rays interact with matter in the same way, and only
differ in their method of production. For the range of energies of interest,
namely 10 keV to 2MeV, three types of interactions are important. The first
effect, which predominates at lower energies is the photoelectric effect.
This occurs when a photon interacts with an electron from an inner orbit. The
electron is ejected with an energy equal to that of the photon minus its
binding energy.

$$Ep = E_\gamma - E_b$$

Subsequently an X-ray will be emitted by the excited atom.

When the photon energy becomes much larger than the binding energy of the
K shell electrons, Compton scattering becomes the dominant process by which
energy is lost. Compton scattering may be considered as an elastic collision
between a photon and an atomic electron in which the electron binding energy
is very small compared with the photon energy. The energy is shared between
the scattered photon and the recoiling electron.

At photon energies above 1.02 MeV, pair production is possible, whereby
the photon disappears and an electron-position pair is created with total
kinetic energy equal to the photon energy less the rest mass energy of the two
particles. Subsequently annihilation of the positron yields two 511 keV
photons.

In each of these processes, photon are removed from a narrow beam by a
single interaction process, unlike the case of the slowing down of alpha or
beta particles. The number of photon absorbed in a thickness dx of absorber
is therefore proportional to dx and to the intensity of the beam at that
point, i.e.

$$I = Io \ e^{\mu x}$$

where Io is the original intensity, x is the thickness of absorber, μ is the
attenuation coefficient and I is the intensity of the emergent beam. An
approximate relationship for the photoelectric absorption coefficient is

$$\mu x = 10^{-33} \ NZ^5 \ E_\gamma^{-3.5} \qquad cm^{-1}$$

Thus μ increases rapidly with the atomic number (Z) of the absorber and
decreases rapidly with the energy of the incident photon, E_γ (Heitler
1944). N is the number of atoms.

When a photon of energy E_γ collides with an atomic electron and
undergoes Compton scattering, the energy of the scattered photon E_γ may be
expressed as follows:

$$E_\gamma = E_\gamma/(1 + [1 - \cos \theta] \ E_\gamma/mc^2)$$

where θ is the angle between the direction of the scattered photon and its
original direction of motion.

When the scattered angle is 180°, E_γ has its minimum value. This is
commonly called the "back scatter" condition and corresponds to a maximum
energy transfer to the absorber atom.

Compared to the photoelectric effect and the Compton effect the
probability of pair production is small in the energy region from 1.02 MeV to
2 MeV; it does not occur below 1.02 MeV.

Neutrons

When neutrons pass through matter they have essentially no interaction with electrons. The absorption of neutrons can only occur when nuclear reactions occur in the absorber. The type of reaction which takes place varies from one absorber to another and with the energy of the neutron. The processes which may occur are the following:

(1)   Scattering due to a collision with a nucleus with the transfer of kinetic energy. An important example of this type of collision is with hydrogen nuclei (protons), where because the masses are essentially equal, large amounts of energy may be transferred. The target nucleus may be left in an excited state and subsequently emit a gamma ray.

(2)   The neutrons may be captured by the nucleus which is then in an excited state. The excitation energy is usually released by gamma-ray emission.

(3)   If the excitation energy of the compound nucleus is sufficient, charged particles may be emitted. In some cases fission of the compound nucleus may occur.

The detection of neutrons relies on the excitation and ionization of atomic electrons produced by charged particles which result from the primary interaction process. Neutrons are therefore removed from the incident beam by a single interaction process and the absorber has a characteristic neutron capture cross-section.

Ionization by Charged Particles

Alpha particles, beta particles and the electrons released by primary interactions with photons lose their energy, when travelling through matter, to the atomic electrons of the absorber. Most of the electrons are ejected with a kinetic energy smaller than the ionization potential, I. For a given medium there is a parameter W, the mean energy per ion or electron produced, which is relatively independent of particle type and energy. Some values for electrons for common detector materials are as follows (Fulbright 1958).

Air	34.2 eV
Argon	26.3 eV
Methane	28.1 eV
Silicon	3.8 eV
Germanium	2.9 eV

The values are greater than the mean ionization potential for the medium as the energy is divided between excitation of atoms (without ionization) and emission of electrons. The number of ionization events produced relates to the initial energy of the charged particle and there will be a statistical fluctuation in this number which will be related to the mean energy required to produce an ion pair. For detectors using materials such as silicon or germanium there will be approximately ten times as many ion pairs produced than for detectors such as ionization chambers filled with argon or NaI(Tl) crystals. The energy resolution of these detectors is better because of the smaller statistical fluctuations in the number of ion pairs.

METHODS OF DETECTION

Detection methods for nuclear radiation are based on the processes of ionization and excitation of atoms in the detection medium by the passage of a charged particle. If the incident radiation is not a charged particle there must first be an interaction of the type described above in which a charged particle is produced. That is, alpha and beta particles ionize the detection

medium directly whereas neutral particles or electromagnetic radiations interact in the detection medium or in a converter near the detector to produce a charged particle. Many methods exist by which ions, electrons or excited atoms can be detected and these have been adapted to solid, liquid or gaseous systems, both with and without an applied electric field. Many gaseous or solid detectors exist where the charged particles liberated by ionization are collected by electrodes under an applied electric field. In another important type of detector, excitation of atoms in liquid or solid detection media results in the emission of light photons which are detected by the cathode of a photomultiplier tube.

(a) Gaseous Ionization Detectors

The gaseous ionization chamber is one with a gaseous detection medium between two electrodes. When an electric field is applied, electrons and ions produced by radiation are collected, and give an electrical pulse which may be amplified and measured. Usually the chamber containing the gas is the cathode and is held at earth potential and the anode is a wire running through the gas and is held at some positive high voltage.

Approximately 10^{-7} seconds after the passage of a charged particle the gas will contain ions and electrons with energies which have been reduced by collision to below 10 eV (Dearnaley and Northrop 1966). These begin to drift towards the electrodes at a rate dependent upon the electric field. Electron mobilities are a thousand times greater than those of ions, giving rise to shorter collection times. Recombination occurs when electrons collide with positive ions and recombine. The rise time of the voltage pulse produced has two components due to the collection of electrons and ions respectively. The relative magnitudes of the fast and slow components of the pulse depends on the relative distance of the two electrodes from the path of the ionizing particle. With a wire anode the potential drop is concentrated near the anode and the major component of the pulse is due to fast collection of electrons.

If the voltage between the electrodes is increased the electrons travelling towards the anode acquire sufficient energy to cause secondary ionization thereby multiplying the number of electron-ion pairs available for collection. The number of electrons and therefore the voltage pulse will still be proportional to the energy of the incident radiation but the signal may now be 10^3 times larger. Such a chamber is called a proportional chamber. The output pulse rises to half amplitude in about 10^{-6} seconds, during which time the electrons are collected. The slow component of the pulse, corresponding to ion collection, takes much longer and the pulses are usually clipped short by an appropriate coupling time constant in the amplifier circuit. The counter requires a time of about 100 microseconds to recover completely after a pulse, as the slowly moving ion cloud modifies the collecting field for this period.

As the potential of the anode is raised further saturation of the chamber takes place and proportionality between the energy of the incident radiation and the number of ion pairs created no longer exists. Eventually the chamber becomes fully saturated and the output is independent of the energy or type of the incident radiation. The counter is then said to be operating in the Geiger region. The recovery time is of the order of 100 µsec and the rise time of the output pulse is approximately one microsecond.

(b) Scintillation Detectors

The scintillation detector relies on excitation of atoms in the detecting medium rather than on ionization. The excited atoms emit light photons which can then be detected by the cathode of a photomultiplier tube. The electron

released at the photocathode is multiplied at each stage of the tube resulting in a large current pulse at the anode. The detecting medium may be solid, liquid or gaseous, the solid being the most common type. Solid scintillation counters have high electron densities and high efficiencies for gamma rays in a relative small volume. This type of detector is also capable of relatively good energy response. Liquid scintillation systems are commonly used for alpha and beta particles with high efficiency where resolution is not critically important.

The luminescent emission in the detection medium occurs when an electron in an excited state returns almost immediately (within 10^{-8}s.) to a lower energy state either directly or via an intermediate state. This type of luminescence is called fluorescence. If while in the intermediate or metastable state the electron is raised back to its initial excited state by gaining thermal energy it may subsequently (after times longer than around 10^{-8}s.) reach the ground state by emission of radiation. This delayed emission is called phosphorescence and is temperature dependent. For a material to be a good scintillator the time lag between the fluorescent decay and the phosphorescent decay must be small. The scintillator material must also be transparent to its own luminescent radiation and the spectral distribution of this luminescent radiation must be matched to the response of the photocathode of the photomultiplier tube.

Several organic materials have been used to detect nuclear radiation. Aromatic hydrocarbons with linked benzene-ring structures, such as anthracene, stilbene and napthalene in pure crystal form are the most common. The fluorescent decay in organic scintillators is very fast; in anthracene for example the fluorescent lifetime is approximately 3.5×10^{-9} sec (Birks 1954). Organic scintillators are not very dense and therefore not very efficient for energetic gamma rays. Apart from organic crystals, a range of plastic scintillators are also available in various forms ranging from the sheets 125 microns thick to thick blocks. These materials also have fast fluorescence life times of generally less than 5 nanoseconds.

Inorganic crystals suitable as scintillators are primarily the alkali halides and their efficiency is improved by the addition small quantities of suitable impurities known as activators. Excited electrons migrate through the crystal until they encounter an impurity atom with a high probability of excitation which subsequently decays by emission of radiation. The fluorescent radiation is generally too low in energy to excite electrons in the host lattice of the scintillator so that the crystal is transparent to it. The activator may be chosen to give the emission spectrum most suited to the photomultiplier response curve. Common activators are thallium in alkali hadides such as sodium iodide and silver in zinc sulphide, with concentrations of the order of 0.1 per cent, which correspond to activator sites at intervals of about ten lattice spacings. In general, inorganic scintillators are denser and contain materials with higher atomic numbers than organic scintillators and are consequently more efficient at converting particle energy into light energy. However the decay time of the fluorescence is much longer. In thallium activated sodium iodide (NaI(Tl)) the characteristic fluorescence life time is 0.25 microseconds.

Liquid scintillators are commonly used, where for example the radionuclide to be measured and the detecting material are mixed together in a vial. This technique is commonly used to measure alpha and beta particles and can result in high efficiencies because of the geometric relationship between sample and detector. A sample prepared for liquid scintillation counting includes at least three components namely the material being counted, a solvent and a

scintillator. Often the physical or chemical nature of the sample, rather than the radionuclide in question, determines the solvents and additives used in sample preparation. A good scintillator should be sufficiently soluble at the working temperature of the system and should be chemically stable for a reasonable period of time. Under ideal conditions a good scintillator emits about 7 photons per keV of beta ray energy absorbed in the scintillator (Rapkin 1967). Therefore a low energy beta emitter such as tritium ($E_\beta = 18$ keV) produces less than 130 photons per event.

A commonly used liquid scintillator is 2, 5 – diphenyloxazole (PPO) which has a maximum in its fluorescence spectrum at 380 nanometers. Greater efficiency can be obtained when counting low energy beta emitters by using a secondary scintillator to absorb photons emitted at a shorter wavelength and re-emit them at a longer wavelength. If quartz window photomultipliers are available, optimum performance will be achieved in the absence of secondary scintillators. One of the most important secondary scintillators is 1,4-bis-2-(5- phenyloxazole)-benzene (POPOP).

The optimum scintillator concentration for a particular solvent may be determined by plotting count rate against scintillator concentration. At some point the count rate will reach a plateau and it is usual to operate well past this point. However too much scintillator interferes with the overall fluorescence process, with a consequent reduction in the count rate.

A good solvent must transfer energy efficiently from the point of an alpha or beta particle emission to a scintillator molecule. The solvent must also be transparent to the photons emitted, must not freeze at the working temperature and must be able to dissolve the sample by itself or with the help of a solubilizing agent. Toluene is the most commonly used solvent and typically 5 grams of PPO would be dissolved in one litre of solution. Sample solubility is a problem with toluene and leads to the use of other solvents such dioxane or the addition of solubilizing agents.

Quenching in liquid scintillation applies to any process which interferes with the performance of the liquid scintillation counting solution. Colour quenching occurs from absorbance of coloured materials in solution, while chemical quenching involves interference with the transfer of energy between the site of an event and a molecule of the scintillator. The most common quenching agent is dissolved oxygen. Quenching is evidenced by a shift in the observed spectrum to lower energies.

The efficiency and resolution of scintillation counters are determined by several factors. There are five consecutive processes involved in the operation of a scintillation counter and the statistical fluctuation in each of these affect the overall energy resolution of the system. These processes are:

(a) Excitation and ionization along the track of the nuclear radiation.
(b) Conversion of energy of excitation into light energy by the process of fluorescence.
(c) Transfer of the light through the scintillator material and on to the cathode of the photomultiplier tube.
(d) Absorption of light at the photocathode with emission of photoelectrons.
(e) Electron multiplication at successive dynodes of the photomultiplier.

A beta particle in sodium iodide looses 30 to 50 eV for each detectable photon produced, which represents a conversion efficiency from kinetic energy to light energy of about ten per cent. Other scintillators are less efficient. However at best one photoelectron is released from the photocathode of the photomultiplier for each 300 eV of energy dissipated in a crystal of NaI(Tl), while in organic scintillators the total energy dissipation is between 1 and 5 keV per photelectron. Thus it is more efficient to collect electrons liberated by ionization in an ionization detector than to collect light from an excitation process and then use a photomultiplier tube to give a flux of electrons at a photocathode.

The energy resolution of a scintillation counter for charged particles is determined principally by the fluctuation in the number of electrons produced at the photomultiplier cathode. For monoenergetic particles of about 5 MeV energy this sets an optimum of the full width at half maximum of the spectrum of nearly 150 keV, or 3 per cent, with an alkali halide phosphor. For gamma rays the resolution is worse because of the additional processes involved in transferring the energy of the gamma photon to charged particles. For a NaI(Tl) crystal the intrisic energy resolution is 6.6 per cent for gamma rays of energy 660 keV (Kelly et al. 1956).

(c) Solid State Detectors

Solid state counters are ionization chambers in which the charges released during the absorption of radiation constitute the signal in the same way as in gaseous ionization chambers. Semiconducting solids have a number of advantages over gaseous ionization chambers. Firstly their greater density and stopping power means that there is complete absorption of energetic beta particles and photons. Radiations which may travel several meters in air can be completely absorbed in millimeters in a semiconductor. Because the average energy needed to produce an ion-pair is low, e.g. 3.6 eV for silicon compared to 30 eV for gases and 300 eV for a scintillator-photomultiplier combination, the accuracy with which the total energy can be measured is greater than for other types of detectors. The available signal is therefore about eight times as large in silicon as in the other counters and the statistical fluctuations expressed as a percentage of the signal will be reduced by a factor of at least the square root of eight.

The use of semiconductor detectors introduces difficulties which must be overcome before the performance of solid state counters can be fully realized. The crystal lattice in a solid detector has a finite electrical conductivity so that any field applied to the detector causes a standing current through the detector. The size of this current must be kept small so that the level of noise generated is low and there is no interference with the collection of charge. A useful semiconductor material is one which has few free charge carriers and few trapping centres to delay or remove charge carriers from the signal. These criteria tend to be contradictory as materials with sufficiently low conductivities to have small standing currents tend to contain most traps. An additional problem is that of crystal uniformity. Unless a crystal is uniform as regards most of its basic semiconductor properties it is unlikely to act in an ideal way. A homogeneous counter has great advantages of flexibility and simplicity. The properties required by a good counter are summarized below:

(1) Low carrier density to minimize current noise.
(2) Freedom from traps to minimize loss of signal and various slow effects.
(3) High carrier mobilities for short pulse rise times.

(4) A low value for mean energy per ion pair.
(5) High atomic number for good stopping power.
(6) Long carrier lifetimes to allow efficient charge collection.

Some of these requirements are contradictory, for example (4) and (1) as (4) requires the energy gap between the valence band and the conduction band to be low, whereas (1) implies the opposite. This problem can be overcome by cooling the detector to reduce the free carrier density without increasing the energy gap. Long carrier lifetimes and freedom from traps imply a material where lattice defects and impurity concentrations have been reduced to a very low level. Silicon and germanium are the only materials in this category which are suitable in other respects for counters, and even these are not ideal as regards the requirements of low carrier density and high atomic number.

In order to apply an electric field to the detector it is desirable for electrodes to make contact with the semiconductor material in such a way that charge can be introduced or withdrawn without modifying the charge carrier concentrations anywhere in the counter. An ohmic contact necessarily involves a transition region between the metal electrodes and the high resistivity semiconductor whose function is to regulate the rate of movement of charge to maintain thermal equilibrium in the bulk semiconductor. The density of charge carriers must increase very substantially in passing from the semiconductor into the metal. A way of achieving this is by diffusing an impurity into the semiconductor through the electrode faces so that near the electrode the material has shorter lifetime and much higher carrier densities than in the bulk material. A second method is to alloy the impurity and recrystallize the material to obtain a graduated impurity concentration, but this method is more difficult to control than diffusion. A third method is to evaporate or electroplate a metal onto the surface of the semiconductor relying on surface states to form a surface barrier.

Most practical semiconductor detectors are rectifying junctions. The semiconductor rectifier is formed by creating an n-type and a p-type region in a semiconductor crystal. Some of the most commonly used semiconductor junction counters are now described.

The most common type of diffused junction detector is made by diffusing phosphorous into p-type silicon to create a thin n-type region. A thick ohmic contact is made on the other side of the detector by diffusing aluminium to give a heavily doped p-type layer.

Most commercial available surface barrier detectors are made from n-type silicon where the surface is allowed to oxidise giving an inversion layer with properties very like a p-type layer. Because the oxidation occurs at room temperature the rectifier is made without the heating which causes deterioration of the carrier lifetime (unlike the diffused junction detector). The oxidised layer is then covered with gold by evaporation to form a thin rectifying contact. A thick layer of evaporated aluminium is used to form an ohmic contact to the base of the rectifier.

To produce a lithium drifted junction detector a slice of p-type silicon between 1 mm and 10 mm with a resistivity in the range 1000 to 2000 ohm is diffused with lithium to produce a thicker detector than is possible with phosphorous diffused junction detectors. Lithium drifting in germanium is also possible and because of the higher atomic number of germanium the cross sections for photoelectric absorption of gamma rays are high enough to make a useful detector.

Diffused junction detectors are available in planar form in thicknesses up to 1 mm and are used in many health physics applications where robustness is more important than resolution. Surface barrier detectors offer better resolution than diffused junction detectors and can be obtained in thicknesses up to 2 mm; however they are more easily damaged. Lithium drifted detectors are available in planar form of greater than 10 mm in thickness or in coaxial form where an annular ring of lithium drifted germanium encloses a p-type core. In the co-axial form a cylindrical detector of germanium up to 6 cm in diameter and 6 cm long may be constructed. Such a device is about 30°/o efficient when compared to a 7.5 cm by 7.5 cm NaI(Tl) detector for cobalt-60 gamma rays from a point source at 25 cm.

SIGNAL PROCESSING FOR COUNTING

All the above devices ultimately produce a charge pulse at their output, in the form of a pulse of electrons at the detector anode. This pulse must be taken, shaped and amplified through various conditioning electronic circuitry in order to be recorded in the counting device. If the anode is biased at some positive high voltage then the charge pulse usually first passes through a series capacitor known as a decoupling capacitor to eliminate the D.C. potential. The charge may then be collected on a capacitor in parallel with a resistor to form a pulse whose size in volts is proportional to the charge of the incident pulse. The time constant of the RC network must be much longer than the rise time of the charge pulse so that the output pulses will have a sharp rise time with long tails and resemble a sawtooth pattern. By conditioning these signals through integrating and differentiating circuits with appropriate time constants, discrimination is obtained so that only the fast rising edge of the input pulse causes an output pulse. The amplifiers producing these pulses have variable gain so that a sufficiently large output pulse can be obtained. The output pulses are usually near Gaussian in shape and the height of the pulse is proportional to the height of the fast rising edge of the input pulse. A second output is often provided on most amplifiers where the unipolar pulse with a near Gaussian shape is differentiated again to produce a bipolar pulse which crosses the base line in the middle of the pulse. The unipolar pulse is used when the energy of the incident radiation is the most important criteria whereas the bipolar pulse is used when the time the radiation is detected is most important, such as in coincidence counting. The crossover point of the bipolar pulse is less dependent on the amplitude of the pulse, as far as time walk of the pulse is concerned, than a unipolar pulse, as it represents the time when maximum charge collection occurred.

Output pulses from the amplifier may then be counted through a single channel analyser if limited energy resolution or noise discrimination is required or through a high resolution anologue to digital converter into a multi channel analyser when the ultimate in energy resolution is required.

MEASUREMENTS OF COUNT RATE - PRACTICAL CONSIDERATIONS
Alpha Particles
Source preparation is the most important consideration when a sample is to be counted for alpha particles. In order to obtain resolution when measuring alpha particles not only must the resolution of the detector be adequate but any material which might lead to self absorption within the source and to absorption between the source and the detector must be eliminated. Extremely thin sources counted in a vacuum will yield the ultimate in resolution. In most situations when it is necessary to differentiate alpha particles from different nuclides the ultimate in resolution is not required and a resolution of 50 to 100 keV F.W.H.M. should be adequate. If the nuclide to be counted is known, resolution of alpha particle energies may not be necessary and counting efficiency may be the most important criteria.

The material to be counted may be airborne particulate matter, in liquid form or in solid form. Airborne particles are usually collected on a filter paper and may then be counted directly. Some loss of resolution will result because of absorption in the filter paper, but in most situations this will not be sufficient to prevent the identification of various nuclides if a good quality resolution surface barrier or diffused junction detector is used and the samples are counted in a vacuum. If greater efficiency is required larger area detectors may be used but a loss of resolution will result.

CsI or CaF_2 crystals coupled to PM tubes could be used for such measurements with resolutions of only several hundred keV but with high efficiency due to the relatively large area detectors which can be obtained. Plastic scintillators may be used in place of CsI crystals at the expense of resolution but with a large saving in cost.

Liquid and solid samples will usually require chemical treatment so that a precipitate or filtrate can be obtained for counting. Counting the samples is then similar to that mentioned above for air filters. Another possibility is that after the initial chemical treatment the radioactive solution is dissolved in a liquid scintillation solution. Liquid scintillation counters can produce resolutions of several hundred keV for alpha particles but their greatest advantage comes from having nearly 100°/o counting geometry. In addition, good discrimination against background can be achieved in liquid scintillation counting systems yielding good overall system sensitivity.

The sensitivity is determined by the efficiency of the counting system and by the background noise level above which any real counts must be seen. Discrimination against background may be achieved by several means. Increased resolution at the expense of some efficiency may so reduce the background count rate in the region of interest that the overall sensitivity increases. In liquid scintillation systems discrimination against background may be achieved by using two PM tubes to view the vial containing the solution and recording only those events which are detected by both tubes.

Beta Particles

Beta particles may also be counted by liquid scintillation and for low energy beta particles this is often the most practical method. More energetic beta particles may be able to penetrate the window of an ionization or proportional chamber and be counted efficiently by such detectors. Energy resolution is not a consideration with beta particles as they are not monoenergetic and discrimination on the basis of energy is virtually impossible. Liquid scintillators enable discrimination to be made between alpha and beta particles because of the different rise times of the pulses produced, with alpha particles having a slower rise time. However discrimination on the basis of energy is more difficult as 5 MeV alpha particles will not produce pulses ten times bigger than 0.5 MeV beta particles due to saturation along the alpha particle track. The criteria for a good beta counter are usually high efficiency and low background. Sample preparation is also an important consideration as self absorption within the source may significantly effect efficiency.

γ-Rays

The counting of samples which emit gamma radiation opens up a much wider range of possibilities than for samples which emit either alpha or beta particles. Very high resolutions are attainable when measuring gamma or X-radiations with solid state detectors and measurements with poorer resolution but higher efficiency are possible with NaI(Tl) crystals. It should not be assumed that by using a high resolution detector on a monoenergetic source that the resulting spectrum will have a single peak on a

flat background, as several effects may occur which will lead to the absorption in the detector of energy from sources other than that of the monoenergetic photon. Most of these effects have been given specific names, e.g.

The Backscatter Peak is due to Compton scattering outside the detector and the subsequent detection of the scattered photon.

The Compton Edge is due to Compton scattering inside the detector and the subsequent escape from the detector of the scattered photon.

The Escape Peak is due to the photoelectric absorption of the photon and the subsequent escape of the characteristic X-ray of the detector.

Characteristic X-rays of the daughter nuclide may be present if the radionuclide decays by electron capture or if internal converison of the gamma photon occurs.

Characteristic X-rays of the shielding material will be present due to photoelectric absorption of the gamma photon in the shielding and subsequent detection of the emitted X-ray.

Sum peaks occur, particularly in efficient detection systems, when two photons are detected simultaneously. This may be accidental summing when photons originating from different atoms are detected simultaneously. This type of summing is dependent on detector efficiency and count rate. Summing may also occur when two photons originating from the same atom are detected together. The two photons may be an X-ray from an electron capture process and a gamma photon or two gamma photons if gamma rays are emitted in cascade from the same atom. This type of summing is dependent on detector efficiency and independent of count rate.

In order to assess the count rate due to a gamma photon in a spectrum it is necessary to integrate the area under the peak, make due allowance for the contribution from the background continuum under the peak and subtract it. If a sufficiently large number of points are available it is possible to fit a function to the peak shape and to the background so as to ascertain the peak area. In most spectral analysis the greatest difficulty lies determining the background contribution in order to yield a reproducible peak area. It is particularly difficult to devise an automatic peak fitting routine which will yield consistent answers in all situations. Other problems arise when trying to assign individual areas to peaks which are not resolved by the detector and appear as a merged peak.

THE MEASUREMENT OF DOSE EQUIVALENT

In many circumstances it is desirable to know the dose equivalent to a person from exposure to gamma or beta radiations (alpha particles will not penetrate the dead layer of skin). Monitors using detectors of the type mentioned previously may be constructed and calibrated so that determination of dose equivalent is possible. However, very few monitors are calibrated in terms of dose equivalent, and most are calibrated in terms of exposure or absorbed dose. Briefly the differences between these terms are as follows:

(i)   Exposure is defined as the ionization in air in a free air ionization chamber and is measured in coulomb per kilogram of air (old unit-Roentgen).

(ii) Absorbed Dose is defined as the energy absorbed per unit mass of matter. The absorber may be any sort of material and the units are joule per kilogram or Gray (old unit-rad).

(iii)   Dose Equivalent is defined as the absorbed dose in man with due
        allowance for the relative biological effect of various type of
        radiation which basically arised because of the different linear
        energy transfer function of different types of radiation. The units
        for dose equivalent are the Sievert (old unit-rem) which is one Gray
        multiplied by the appropriate Quality Factor.

In counting measurements the basic aim is to take the charge pulse output
from a detector and put it through a network with a reasonably fast time
constant to create a voltage pulse which may then be counted. When measuring
exposure rate or absorbed dose rate the basic aim is to take the charge pulses
from the detector and put them through a network with a reasonably long time
constant to produce a current which gives a continuous reading on a meter.

Ionization chambers are suitable for measuring exposure rate as the
ionization produced is proportional to the exposure by definition. The gas in
the chamber may be air or a gas with similar characteristics and if the
chamber walls, particularly the front entrance window, are air equivalent
material the response of the detector will be constant over a wide range of
photon energies.

Proportional chambers can be made to work in the same way as ionization
chambers as the gas amplification taking place in the chamber does not destroy
the relationship between the initial ionization and the charge collected at
the anode. The amplication can be used to advantage in building a monitor
with good sensitivity.

Geiger tubes no longer maintain the relationship between initial
ionization and charge collected at the anode as each event produces the same
charge at the anode regardless of energy. The calibration of such a detector
is therefore valid over a limited range of energies. This may not necessarily
present problems and may be outweighed by the fact that monitors with geiger
tube detectors are usually light, rugged and cheap.

Scintillators such as NaI(Tl), plastic scintillation or anthracene
crystals connected to PM tubes may also be used as exposure or absorbed dose
monitors. The current at the anode of the PM tube will be proportional to the
number and energy of photons in the detector and the measurement circuitry
used to measure this current may then be calibrated. The response of such
detectors to photons of various energies may be constant over a wide range
depending on detector type and thickness and type of housing material.
However this should be investigated for each detector.

Apart from hand held monitors there are several devices for integrating
total exposure which are designed to be worn by personnel. Some of the more
common ones are as follows.

Quartz fiber dosemeters act as a capacitor which is charged up with a
separate charger. Ionization within the chamber will cause ions to be
collected, discharging the detector. The amount of discharge is proportional
to the total exposure whereas most hand held monitors indicate exposure rate
which then must be interpreted to determine total exposure to personnel.

As with quartz fiber dosemeters, film integrates total exposure in the
emulsion of the film. This can later be read by developing the film and
measuring the degree of blackening. The response of film with photon energies
will depend on the emulsion characteristics and is usually not constant below
approximately 100 keV.

Thermoluminescent dosemeters also integrate total exposure, this time by trapping electrons released by excitation into the conduction band of a crystal lattice. Subsequent heating of the material releases the electrons which then lose energy as photons when they fall back to the valence band. The initial excitation is proportional to the number and energy of incident radiation particles or rays and is dependent on the TLD material. Such materials may have a response with energy which is flat over a wide range. Thermoluminescent dosimetry (TLD) is discussed in more detail in later chapters.

SUMMARY

A large variety of detectors and monitors have been developed to cater for the different measurement situations which arise in practice. This proliferation of detector and monitor types, many of which have been developed for particular purposes, necessitates careful consideration when selecting a device to perform a particular monitoring operation.

Firstly it is important to decide what quantity is to be determined, whether it be the activity of a particular radionuclide or the dose equivalent to a worker or some part of a worker.

Secondly, a detector must be selected which is sufficiently sensitive to the type of radiation being emitted and with a known response to that radiation. In real measurement situations the source to be measured is never in the ideal point source geometry. Consideration must therefore be given to the effect of source geometry and source self absorption on the measurement. If due consideration is given to the form of the radioactive source, the types of radiation emitted, the interaction of these radiations with the detector and the interpretation of the measurement in terms of the required quantity then it should be possible to make accurate and soundly based measurements.

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