VI. Radioactivity:

Basis of radioactivity decay constant decay series – artificial radioactivity – radioisotopes- isotopes used in medicine – blood indicator (Gamma chamber)-detectors- non chamber- GM count scintillation chamber – liquid scintillation counter- electromagnetic radiations – spectrum – ionizing radiation – types charged. Particle radiation – electron beam- its properties – radiation protection- and basic principles of radiation protection- personnel monitoring devices (TLD,Film badge)

Radioactivity, a nuclear phenomenon, was first discovered by Henri Becquerel in 1896. Becquerel left some uranium salt on a photographic plate, wrapped in a black paper and was lying in a darkroom. When he developed the photographic plate, he found that the plate was affected. Later, he repeated the experiment with other salts of uranium and he concluded that uranium and its salts emit invisible radiations, which can pass through paper, wood, glass, etc., and affect the photographic plate. These radiations were found to have alpha (α), beta (β) particles, and gamma (γ) rays. Radioactivity is the process by which a nuclei undergo disintegration and emits either alpha or beta and gamma radiations. During the radioactive process, the atom changes its atomic number and chemical identity. An atom, with unstable nuclei and perform radioactivity is called radioisotope. The initial atom that undergoes disintegration is called parent and the end-product is called daughter. Radioactivity may be classified as natural and artificial. The phenomenon of spontaneous emission of rays, such as alpha (α), beta (β) particles, and gamma (γ) rays by heavy elements having atomic number greater than 82 is called natural radioactivity, e.g. radium-226 and potassium-40.

Artificial or induced radioactivity was discovered by Curie and Joliet in 1934, when they were studying the disintegration of light elements by α particles. They found that when light elements, such as boron and aluminum were bombarded with α particles, an unstable nucleus was formed and this nucleus disintegrated spontaneously. The artificial radioactive substance emits electrons, neutrons, positrons or γ rays. They follow the same laws of decay as natural radioactivity, e.g. cobalt- 60 and phosphorus-32.

NUCLEAR FORCES AND STABILITY

There are two forces acting inside the nucleus, namely, a week repulsive, force between protons and a strong exchange force between neutrons. The neutrons exchange pions between them. The strong exchange force keep the nucleus together and maintain the nucleus to a short distance 10~14 m. If a nucleus wants to be stable, it should overcome the repulsive forces. This means that the neutrons (N) must be higher than protons (Z) or N/Z ratio must be higher. The above ratio is equal to 1 for low atomic and 1.5 for higher atomic elements. Nuclei with odd number of neutrons and odd number of protons are unstable. But, nuclei with even number neutrons and even number of protons are more stable. Nuclear instability occurs whenever there is excess neutron or excess protons. An unstable nucleus attain stability by performing radioactivity.

RADIOACTIVE DISINTEGRATION

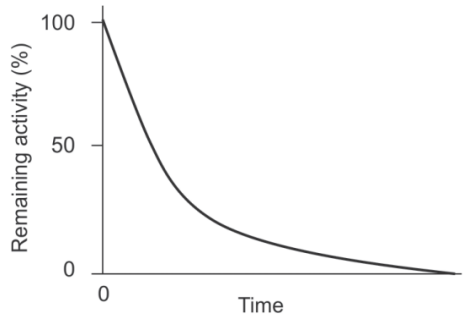
Rutherford and Soddy found that the rate at which a particular radioactive material disintegrates was independent of physical and chemical conditions. Their law states that the number of atoms that disintegrates in unit time is proportional to the number of radioactive atoms present at that

instant. Let N is the number of atoms at a particular time t, and dN atoms disintegrate in a time dt, then $\frac{dN}{dt} = \alpha N$ (or) $-\frac{dN}{dt} = \lambda N$

where, λ is a constant known as decay constant or disintegration constant. It is characteristic of each radionuclide. Decay constant refers the fraction of remaining atoms that decays per unit time and its unit is s^{-1}. The minus sign indicates that N is decreasing with time. After integration, the equation can be represented by a mathematical relation

$$N = N_0 e^{-\lambda t}$$

where, N_0 is the initial number of atoms, e is the base of natural logarithm (e = 2.719). The equation shows that the number of atoms of a given radioactive element decreases exponentially with time. From Figure, it is found that the disintegration takes place at a very rapid rate initially, with gradual increase of time it decreases and reaches zero. Theoretically, an infinite time is required to disintegrate all the atoms.



HALF-LIFE PERIOD

The half-life of a radioactive element is defined as the time taken for half the number of atoms to disintegrate. From the law of radioactive disintegration, $N = N_0 e^{-\lambda t}$

if T is the half-life, then t = T, N = $N_0/2$, substituting we get $N_0/2 = N0\ e^{-\lambda T}$

$1/2 = e^{-\lambda T}$ (or) $2 = e^{\lambda T}$

$\log_e 2 = \lambda T$, or $T = 0.6931/\lambda$

The half-life of a radioactive element is inversely proportional to the decay constant of that element. The following are the half-life value for some important radioisotopes used in medicine.

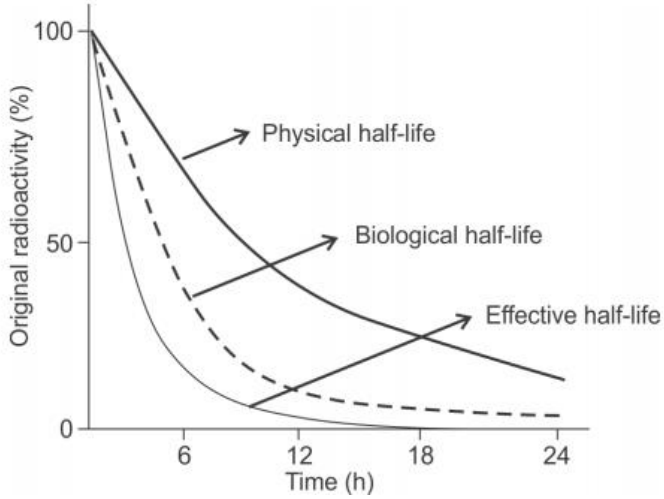
Radium-226	: 1622 years
Cobalt -60	: 5.26 years
Cesium-137	: 30 years
Iridium-192	: 73.8 days
Iodine -131	: 8.04 days
Technetium-99m	: 6 hours

The mean life or average life (T_a) is the average lifetime for the decay of radioactive atoms. It is defined as the lifetime of an imaginary source which decays at a constant rate equal to the initial activity. The mean life is related to the half-life as, $T_a = 1.44T$, so the mean life is directly proportional to the half-life.

BIOLOGICAL HALF-LIFE

The physical half-life is the time required for a nuclide to decay to half of its original activity. It is expressed by the relation $T_{½} = 0.693 / \lambda$, where λ is the decay constant. The biological half-life (T_b) is determined by the clearance of the radionuclides from the organ, tissue or body. The effective half-life (T_e) of a radionuclide in any organ consists of both radioactive decay and biological clearance. The relation between the effective, biological and physical half-life is given by $1/T_e = 1/T_b + 1/T_{½}$

For example, if a radionuclide has a physical half-life of 6 hours and a biological half-life of 3 hours, then $1/T_e = 1/6 + 1/3$, and $T_e = 2$ hours. The effective half-life is always less than either the physical or biological half-life



PRODUCTION OF RADIOISOTOPES

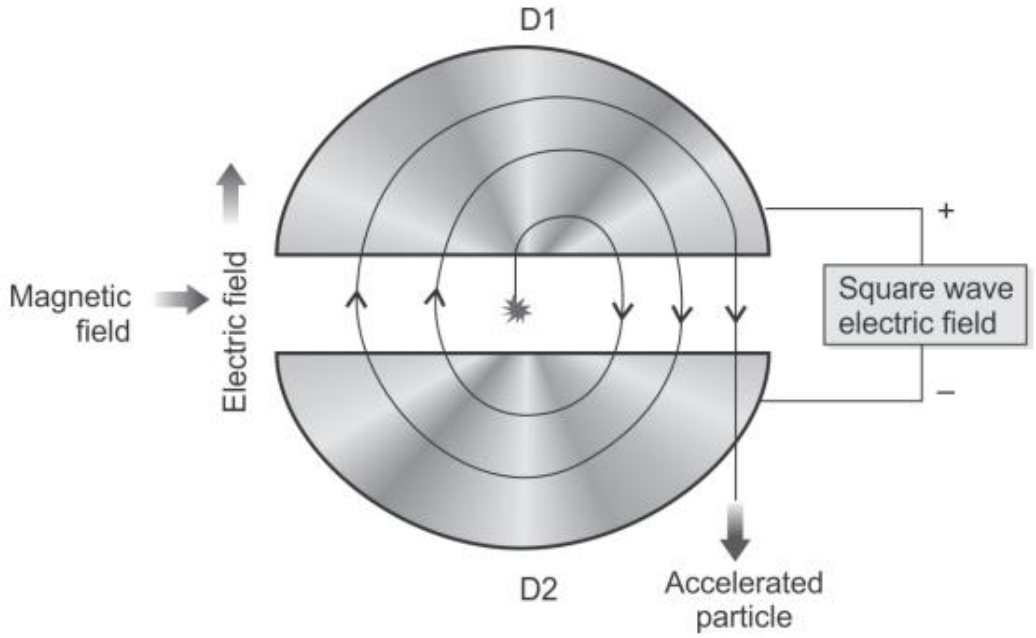
The majority of radioactive isotopes used in medicine are produced artificially by bombarding a stable target nucleus with suitable high energy particles. Alpha, proton and neutron are used as particles for bombarding the nucleus. Neutrons are found to be more effective in producing radioisotopes, using nuclear reactors. Radioisotope of an element is prepared by placing small quantities of the pure element, in small containers made of aluminum in an atomic reactor for a period of several weeks. The element is converted into radioactive isotope due to continuous bombardment by neutrons inside the reactor. For example, cobalt-60 is produced with (n,□) reaction.

$$_{27}Co^{59} + {}_{0}n^{1} \rightarrow {}_{27}Co^{60} + \gamma$$

In another method, radioisotopes are produced by bombarding the element with accelerated particle from a cyclotron.

CYCLOTRON

The spiral type of accelerator called cyclotron was first developed by Lawrence in 1930. It consists of a hollow cylinder divided into two sections D_1 and D_2. Each section is known as Dee because it resembles the letter D. They are kept separated and placed inside a vacuum chamber. The Dees are connected to a high frequency oscillator. The whole apparatus is placed between the pole pieces of a strong electromagnet. The magnetic field (B) is perpendicular to the plane of the Dee.



When a positive ion with charge q and mass m is emitted from the source, it is accelerated towards the Dee having the negative potential at that instant. Due to the magnetic field, the positive ion moves along a semi-circular path. By the time the particle arrives at the gap, the polarity of the Dee gets reversed and the particle is once again accelerated and enters the other Dee with a greater velocity describing a semicircle of greater radius. The charged particle of mass m describes a circular path of radius r when its velocity is v, then the centripetal force and centrifugal forces are equal;

$$Bqv = \frac{mv^2}{r} \text{ (or) } \frac{v}{r} = \frac{Bq}{m} = \text{constant}$$

where, Bq is the magnetic force and mv^2/r is the centripetal force for circular motion. The time taken (t) to describe a semi-circle is given by

$$t = \frac{\pi r}{v} = \frac{\pi rm}{Bqr} = \frac{\pi m}{Bq}, \text{ by substituting v,}$$

It is seen that 't' is independent of the radius (r) and velocity (v) of the particle. The period of motion of a charged particle is independent of velocity under a uniform magnetic field. This is the basic principle of cyclotron. If ω is the frequency of rotation, then

$2\pi v = \omega = v/r = Bq/m$ (or) $v = Bq/2\pi m$

Since Bq/2πm is a constant, then the frequency of rotation is a constant. The RF oscillator is adjusted to satisfy this condition in a given magnetic field B for the charge q. After spiralling several times within the Dees and acquiring large velocity (kinetic energy), the particle is finally extracted out through a window by means of a deflector plate.

The cyclotron can accelerate protons, deuterons, and alpha particles. At high velocities, Bq/2πm is not a constant due to relativistic mass variation of the particle. As the velocity increases, the mass also increases. That means the frequency of rotation of the particle decreases, and the particle takes longer time to complete its semi-circular path. It results in phase instability and the particle will not arrive at the gap just when the polarity reverses. However, this effect can be overcome by decreasing the frequency of the alternating voltage over short intervals to keep in step with the accelerated particles. This is the principle of synchrocyclotron.

Alternatively, the magnetic field may be increased in increasing radius by having special design of magnet called hill and valley design. This will provide azimuthally varying magnetic field, so that the relativistic mass variation is taken care of. Of course, the increasing magnetic field may cause the particle to deviate the median plane in which it is revolving. Hence, optimal varying magnetic field is applied to keep the particle in the gap as well as in the median plane.

Medical Cyclotron Facility

The cyclotron is employed in medicine for particle acceleration, which is used for (i) radiotherapy and (ii) medical imaging. The cyclotrons used in medical imaging are negative ion accelerators, which accelerates both proton and deuteron for the production of positron radionuclides. The advantage of negative ion accelerators are (i) extraction with thin foil (5 μm) is possible, (ii) extraction efficiency is better, (iii) size is compact and simple, (iv) electron stripping does not induce radioactivity, etc. However, its vacuum requirement is stringent. They are available in the form of self-shielded design, which can reduce the radiation level up to 1–5 μSv/h. For self-shielding, high density polystyrene (HDP), lead and boronated water are used in 8 tanks as shield. This will attenuate both neutrons and gamma rays. A typical medical cyclotron consists of ion source system, RF system, vacuum system, magnetic system, extraction system and target (Fig.12.5.). In addition, power supply with UPS, cooling system, gas distribution, radio synthesis hot laboratory and quality control laboratory are required.

The ion source system allows hydrogen gas to flow across tantalum cathodes, where hydrogen gets ionized and accepts one electron and become negative ion. The ion source is mounted at the center of the cyclotron between the Dees. Two resonators with RF power system accelerate the particle under the influence of the azimuthally varying magnetic field. The Dees may be 2 or 4 and in the latter case, the particle is accelerated 8 times (one push and pull, for each gap). Vacuum (1.2×10^{-5} mbar) is required to avoid collision of accelerated particles and gas molecules as well as to insulate the Dees. The extraction carousels use 6 carbon foils, which remove 2 electrons and the accelerated particle becomes positive ion. The target body is made up of silver and has provision for liquid/gaseous target under helium gas cooling. The target material of water enriched with ^{18}O is used for 18F [Fluorodeoxyglucose (FDG), half-life 110 min] production through (p,n) reaction. The other positron emitters that can be produced in the medical cyclotron are ^{15}O, ^{13}N, ^{11}C. The cyclotron may produce 10 Ci activity in 2 hours under a beam current of 100 μA with particle energy of 16.5 MeV.

Cyclotron Produced Radionuclides

Cyclotron accelerators produce radionuclides by bombarding stable nuclei with high energy particles. Protons, deuterons and α particles are commonly used to produce radionuclides. Gallium-67 is an example of a widely used cyclotron-produced radionuclide. The production reaction is written as $^{68}Zn + p \rightarrow {}^{67}Ga + 2n$

where, Zn-68 is the target and a proton (p), accelerated to about 20 MeV, is the bombarding particle. Two neutrons are emitted during this reaction. In some cases, the nuclear reaction produces radionuclide's that decays and gives newer radionuclides, e.g. I-125, I-123, and Tl-201. The commonly used radionuclides and their characteristics are listed in Table

Nuclide	Photons (keV)	Production mode	Decay mode	Half-life
^{67} Ga	93,185,296,388	Cyclotron	EC	78 hours
$^{99\ m}$ Tc	140	Generator	IT	6 hours
^{111} In	173, 247	Cyclotron	EC	68 hours
^{123} I	159	Cyclotron	EC	13 hours
^{125} I	27, 36	Reactor	EC	60 days
^{131} I	364	Fission product	β	8 days
^{133} Xe	80	Fission product	β	5.3 days
^{201} Tl	70,167	Cyclotron	EC	73 hours
EC = electron capture, IT = isomeric transition				

Nuclear Reactor Produced Radionuclides

Nuclear reactors are also used to produce radionuclides. Neutrons, being uncharged, have an advantage of penetrating through the nucleus without being accelerated to high energies. The nuclear reactor uses two methods, namely, (i) nuclear fission and (ii) neutron activation, to produce radionuclides. The radionuclides, obtained from the fission process are molybdenum-

99 (Mo-99), iodine-131 (I-131), and xenon- 133 (Xe-133). Examples of radionuclides produced by neutron activation are P-32 and Cr-51.

Radiopharmaceuticals should have desirable characteristics for nuclear imaging as given below:

1. The physical half-life should be in few hours, equal to duration of preparation and injection. It should decay to a stable daughter.

2. It should emit gamma rays (50–300 keV), without alpha, beta particles and very low energy photons. The energy is high enough to exit the patient and low enough for collimation.

3. It should have monoenergetic gamma energy, for easy scatter elimination. Decay by isomeric transition and electron capture is preferable.

4. It is easily attached to a pharmaceutical at room temperature, but no effect on its metabolism. It should localize largely and quickly in the target of interest.

5. It should have high specific activity, with low toxicity and is readily available at the hospital site.

6. It is easily eliminated from the body with an effective half-life similar to duration of examination.

TECHNETIUM GENERATOR

Tc-99m emits gamma energy of 140 keV with a half-life 6 hours and has 90% of clinical use. Its energy is suitable for easy absorption and collimation by a thin crystal with good spatial resolution. Its half-life and pure gamma emission helps to inject large activity to the patient, resulting in reduced noise in the image. It is obtained from Mo-99 on daily basis from the generator, which is a lead shielded container. It contains an exchange column of alumina beads, in which the parent 99Mo compound is absorbed. Mo-99m is produced by nuclear fission of U-235, and is in the form of ammonium molybdenate (NH_4^+ MoO_4^-) and has a half-life of 67h. When it is supplied to the hospitals, the Tc-99m activity has built up to a maximum, equal to the parent (Mo). The daughter and parent decay together with the half-life of the parent, 67 h. Hence, they are said to be in transient equilibrium. The ammonium molybdenate is loaded onto the alumina column (porus) and the Mo-99 decays to Tc-99m. Sterile isotonic saline (0.9%) is passed through the column to remove Tc-99m. This process is called elusion and takes only few minutes. The Mo-99 is not soluble in saline and hence remains in the column. When the saline is passed through the column, the chloride ions easily exchange with the TcO_4^- ions, producing sodium pertechnetate Na^+ ($^{99m}TcO_4^-$). This flows under pressure and is collected in sterile rubber caped vial. After the elusion, the Tc-99m decays with half-life of 6 h.Tc-99m is used in clinical medicine as sodium pertechnetate- 99m which is used for imaging tissues, e.g. thyroid, gastric mucosa and salivary glands, due its similarity to iodine and chloride ions. It is blocked from thyroid by administration of potassium per chlorate, and can be used for cerebral blood flow, and testicular imaging. It is mixed with bran porridge for gastric emptying studies.

IODINE-131

Iodine-131 is a reactor produced radionuclide, highly reactive and an excellent label. It is easily trapped and metabolized by the thyroid organ. It is the first radionuclide used for imaging and it is inexpensive, and has long half-life of 8.06 d. It decays by beta emission to stable Xenon-131, average beta energy (90%) is 192 keV, and the dominant photon energy is 364 keV (82% abundance). It gives a whole body dose of 0.5–3.5 rad per mCi and thyroid dose of 100–2000 rad per mCi. It is clinically administered as iodide, much less satisfactory isotope for imaging today, because of the high radiation dose to the patient. When iodine is administered as iodide ion, it is readily absorbed from the GI tract and distributed in the extracellular fluid. It is concentrated in the salivary glands, thyroid, and gastric mucosa. It is mainly excreted through urine (35–75% in 24 hours). Iodine is trapped and organified by the normal thyroid and has an effective half-life of 7 days. Nowadays Iodine-123 is replacing iodine 131, which is a cyclotron produced and more expensive radionuclide. It can be labeled with hippuran for renal imaging study

Labeled compounds	Clinical use
Methylene diphosphonate (MDP)	Bone imaging
Hexamethyl propylene amine oxime (HMPAO)	Cerebral imaging
Dimercaptosuccine acid (DMSA) and Mecapto-acetyltriglycine (MAG3)	Renal study
Iminodiaacetic acid (HIDA)	Biliary study
Human serum albumin (HSA) colloidal particles (0.5 µm size)	Liver, spleen and red morrow imaging
HAS macroaggregates (15–100 µm microspheres)	Lung perfusion study
Diethylene triamine pentacetic acid (DTPA) aerosol (5 µm particles)	Lung ventilation study
Auologous red cells	Cardiac function study
Tetrofosmin or sestamibi	Cardiac perfusion study

OTHER RADIONUCLIDES

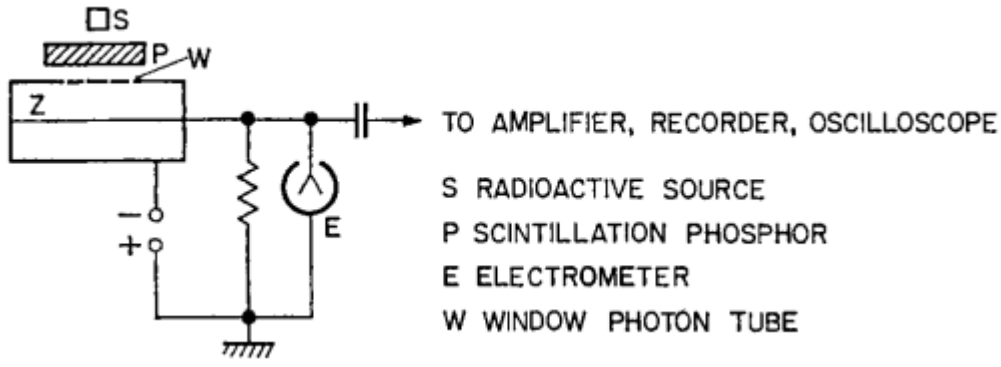
Apart from technetium and iodine, there are radionuclides that have very useful features and clinical applications. That includes Xenon-133 (113Xe), Krypton-81m (81mKr), Gallium-67 (67Ga), Indium-111(111In), Indium-111m (111mIn), and Thallium-201 (201Tl), etc. 113Xe is a reactor produced radionuclide, having half-life of 5.2 d, emits beta and low energy gamma rays of 81 keV. It is an inert gas, soluble in blood, used for lung ventilation imaging. 81mKr is a generator produced inert gas, has half-life of 13 s and emits gamma rays of 190 keV. It is inhaled with air for pulmonary ventilation study. 67Ga is a cyclotron produced radionuclide, with half-life of 78 h, emits gamma rays of energies 93,185 and 300 keV, respectively. It is used as gallium citrate to detect tumors and abscesses. 111In is a cyclotron produced radionuclide, has a half-life of 67 h, emits gamma rays of 173 and 247 keV energies. It is used for labeling white blood cells and platelets, to detect abscess and thromboses. ^{111m}In is a

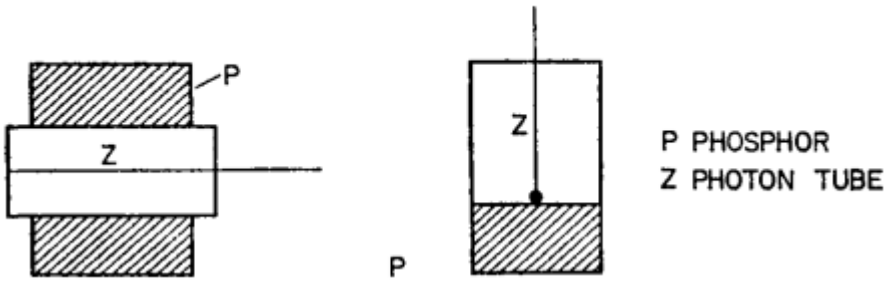
generator produced radionuclide, having a half-life of 100 m with gamma energy of 390 keV. It is often used as replacement to indium-111. ^{201}Tl is a cyclotron produced radionuclide, has a half-life of 73 h and emits X-rays of energy 80 keV. It is used as thallous chloride in myocardial perfusion imaging.

Generally, a radiopharmaceutical is formed by mixing the radionuclide with a compound to be labeled at room temperature. Of course, it may require additional chemicals. It may require sterile work station, shielded syringes and a glove box, in a room filled with sterile air and positive pressure. As a part of quality control, these pharmaceuticals are tested for their radiochemical purity, chemical purity, sterility and pyrogen, before injected to the patient.

Geiger Scintillation Counters

The first attempt at the electrical counting of scintillations was by Krebs (1941). He used a photosensitive Geiger-Müller counter to view the scintillations from a zinc sulphide screen irradiated with Po210 α-particles. Such photosensitive counters can be constructed with a high sensitivity of up to 12 quanta cm"2 sec"1 for ultraviolet radiation of 260 π\μ. The arrangement used by Krebs is shown in Fig. 1.3 (see also Krebs 1955). Improved photo sensitive Geiger-Müller tubes, and improved geometrical arrangements (Figure) to increase the detection efficiency and make the devices sensitive to β-rays and γ-rays, have been subsequently developed by Mandeville and Albrecht (1950). However, the Geiger-Müller scintillation counter does not compare in utility or performance with the modern photomultiplier scintillation counter. In particular, it suffers from the relatively slow response (by present standards) of the gas counter, it does not properly differentiate between different types of radiation, and it does not provide information about the energy of the incident radiations.





ELECTROMAGNETIC RADIATIONS

The absorption of electromagnetic radiations (X-rays and y-rays) by matter differs fundamentally from that of charged particles. The latter dissipate their energy continuously in a sequence of many ionization and excitation events, and penetrate a certain distance, the range, into the absorber in doing so. Electromagnetic radiations, on the other hand, are absorbed or scattered in single events. A beam of well-collimated γ-rays incident on an absorber undergoes a true exponential attenuation: those collimated γ-rays

which penetrate the absorber have had no interaction: those which undergo single interactions are eliminated from the beam.

The most important of the interactions which can occur are

(i) the Compton effect,

(ii) the photo-electric effect, and

(iii) pair production.

The fraction/of the incident quanta which are absorbed, i.e. undergo one of these interactions, in their passage through a scintillator of thickness d is $f = 1 - \exp(-\mu d)$

where μ is the linear attenuation coefficient, in cm^{-1}, μ is made up additively of the linear attenuation coefficients corresponding to each of the three types of interactions, a the Compton linear attenuation coefficient, τ the photoelectric linear attenuation coefficient and κ the pair production linear attenuation coefficient, so that $\mu = \sigma + \tau + \kappa$

Each of these quantities depends on the energy of the electromagnetic radiation, and on the nature of the absorber. At low energies τ is the largest component, but it decreases rapidly with increasing E, though with heavy elements it may still be appreciable up to a few MeV. A decreases steadily with increasing E. κ is zero at energies below 1.02 MeV, and at higher energies it increases steadily with increasing E. The mass attenuation coefficient ($cm^2\ g^{-1}$) is given by μ/ρ, where ρ is the density (g cm^{-3}) and the absorber superficial thickness is ρd (gcm^{-2}). The component linear attenuation coefficients σ, τ and κ can similarly be expressed as mass attenuation coefficients. The mass attenuation coefficient is more fundamental than the linear attenuation coefficient since it is independent of the density and physical state of the absorber. This is because the fundamental interactions can be expressed as cross-sections per atom ${}_{\alpha}\sigma$, ${}_{\alpha}\tau$ and ${}_{\alpha}\kappa$ which sum to a total atomic cross-section ${}_{\alpha}\mu$ ($cm^2/atom^{-1}$).

where N_0 is Avogadro's number, A the atomic weight of the absorber. When an absorber (scintillator) is a mixture or compound of different elements whose mass attenuation coefficients are (μ_1/ρ_1), (μ_2/ρ_2). · · the total mass attenuation coefficient is given by

$$\frac{\mu}{\varrho} = \frac{\mu_1}{\varrho_1} w_1 + \frac{\mu_2}{\varrho_2} w_2 + \cdots$$

where w_1, w_2... are the fractions by weight of the elements in the absorber. This equation is applicable also to the individual processes represented by σ, τ and κ.

blood indicator (Gamma chamber)-detectors- non chamber- GM count scintillation chamber – liquid scintillation counter- electromagnetic radiations – spectrum – ionizing radiation – types charged. Particle radiation – electron beam- its properties – radiation protection- and basic principles of radiation protection- personnel monitoring devices (TLD,Film badge)