Course Title**: MEDICAL NUCLEAR PHYSICS**

Course Code**: PHY 416**

**Course Outline**

* Production of Isotopes,
* Nuclear scanning and tracers,
* Nuclear magnetic resonance,
* Interaction of radiation with matter,
* X-rays and Gamma rays,
* Thompson scattering,
* Photoelectric effect,
* Compton Scattering,
* Pair production,
* Annihilation.

1.1 **INTRODUCTION TO THE NUCLEUS OF AN ATOM**

All nuclei are composed of two types of particles: ***protons*** and ***neutrons***. The only exception is the ordinary hydrogen nucleus, which is a single proton.

In describing some of the properties of nuclei, such as their charge, mass, and radius, we make use of the following quantities:

* the **atomic number, Z,** which is the number of protons in the nucleus,
* the **neutron number, N,** which is the number of neutrons in the nucleus,
* the **mass number, A,** which is the number of nucleons (i.e. sum of protons and neutrons in the nucleus).

The symbol we use to represent nuclei is:

where represents the chemical symbol for the element. For example, has the mass number 27 and the atomic number 13; therefore, it contains 13 protons and 14 neutrons. When no confusion is likely to arise, we omit the subscript Z because the chemical symbol can always be used to determine Z.

1.2 **CONCEPT OF ISOTOPE**

The nuclei of all atoms of a particular element must contain the same number of protons, but they may contain different number of neutrons. Nuclei that are related in this way are called ***isotopes***. ***The isotopes of an element have the same Z value but different N and A values***.

Carbon, for example, has four isotopes: , , , and . The natural abundance of is 98.9%, whereas that of isotope is only about 1.1%. Some isotopes do not occur naturally but can be produced in the laboratory through nuclear reactions.

1.2.1 **WHAT IS A RADIOISOTOPE?**

A *radioactive isotope*, also called *radioisotope*, *radionuclide*, or *radioactive nuclide* is any of several species of the same Z value (proton number) with different A value (atomic number) whose nuclei are unstable and dissipate excess energy by spontaneously emitting radiation in the form of alpha, beta, and gamma rays.

Most of the radionuclides found in nature are members of four radioactive series (Table.1), with each series consisting of a succession of daughter products all ultimately derived from a single parent nuclide. The nuclides in each chain decay by emitting α and/or β particles until a final (stable) nuclide is reached.



1.3 **PRODUCTION OF ISOTOPES**

Isotopes are ***naturally occurring*** or are ***artificially made***. The first ones are often stable, while the last ones are unstable or radioactive. There have been characterized about 1600 isotopes, either stable or unstable (radioactive).

Radioactive isotopes or radioisotopes have numerous applications in medicine, agriculture, industry and fundamental research.

At present there are up to 200 radioisotopes used on a regular basis, and most of them are produced artificially.

Artificially made radioisotopes, among which are those for medical use, are mainly produced by **research reactors**. Currently more than 80% of the medical radioisotopes are produced by research reactors. The remaining isotopes are made by **particle accelerators**, mostly with **circular accelerators (cyclotrons)** and sometimes with **linear accelerators (linacs)**, or by other methods.

**2.0 RADIOACTIVE TRACERS**

A ***radioactive tracer***, or ***radioactive label***, is a chemical compound in which one or more atoms have been replaced by a radioisotope so by virtue of its radioactive decay, it can be used to explore the mechanism of chemical reactions by tracing the path that the radioisotope follows from reactants to products. Medically, it is defined as a radioactive molecule that can be sent through the body’s circulatory or urinary system, with its progress followed by a radiation-sensitive machine.

As part of the medical subspecialty of Nuclear Medicine, various diagnostic procedures make use of a small amount of a radioactive isotope, usually injected into the patient’s bloodstream for the purpose of imaging some part of the body. The useful radiation from such isotopes is usually *gamma rays*, which can be detected outside the body. These gamma rays can be used to image internal organs or structures. An example is the imaging of blood flow in the heart muscle in *myocardial infusion imaging*. The radioisotopes used have short half-lives so that they are quickly eliminated from the body. While appropriate cautions must be observed with any use of ionizing radiation, the radiation doses in such procedures are very low and the risks have been carefully examined.

Technetium Tc is a very versatile radioisotope and the most commonly used radioisotope tracer in medicine.

**Technetium – 99m**

Technetium – 99m is a widely used radioactive tracer isotope in Nuclear Medicine. Its gamma ray energy of about 140keV is convenient for detection. The fact that both its physical half-life and its biological half-life are very short leads to very fast clearing from the body after an imaging process. A further advantage is that the gamma is a single energy, not accompanied by beta emission, and that permits more precise alignment of imaging detectors.

|  |  |
| --- | --- |
| Isotope | Half-lives in days |
|  |  |  |
| 99mTc | 0.25 | 1 | 0.20 |

Technetium – 99m is produced by bombarding molybdenum 98Mo with neutrons. The resultant 99Mo decays with a half-life of 66 hours to the metastable state of Tc. This process permits the production of 99mTc. For medical purposes, the 99mTc is used in the form of Tc.

The technetium isotope 99mTc is unusual in that it has a half-life for gamma emission of 6.03 hours. This is extremely long for an electromagnetic decay – more typical is 10-16 seconds. With such a long half-life for the excited state leading to this decay, this state is called a **metastable state**, and that is the reason for the designation 99m.

**ISOTOPE PRODUCTION METHODS**

Radioisotopes find wide-ranging applications in various fields, including industry, research, agriculture and medicine. Two major sources of artificial radioisotopes are accelerators and reactors.

Radioisotopes produced in reactors represent a large percentage of the total use of radioisotopes due to a number of factors.

1. The reactor offers large volume for irradiation.
2. Simultaneous irradiation of several samples.
3. Economy of production and possibility to produce a wide variety of radioisotopes.

The accelerator-produced isotopes relatively constitute a smaller percentage of total use. The accelerators are generally used to produce those isotopes which cannot be produced by reactor or which have unique properties.

1.3.1 **Production of radioisotopes with nuclear reactors**

The research reactors used for radioisotope production could be broadly classified into:

– enriched uranium, light water moderated, swimming pool type reactors

– natural uranium, heavy water moderated and cooled tank type reactors.

Radioisotopes are produced by exposing suitable target materials to the neutron flux in a nuclear reactor for an appropriate time. In swimming pool type reactors, the core is compact and visible, and is accessible from the top of the pool. Target materials to be irradiated are sealed in primary capsules, loaded in specially designed irradiation jigs and then lowered in predetermined locations in the core for irradiation. In swimming pool reactors, the core being easily accessible, loading and unloading of targets are easy, and can be carried out from top of the pool using simple devices. The irradiated targets are then loaded in appropriate shielding containers and transported to the radioisotope processing laboratories.

In the tank type reactors, the irradiation assemblies contain a large number of target capsules and are lowered using specially designed jigs. The irradiation assembly is lowered into a hot cell fitted with master slave manipulators for carrying out loading and unloading of target capsules subsequent to irradiation.

Production of quality radioisotopes with high specific activity will depend on the target as well as irradiation conditions.

The factors which decide the type of nuclear reaction that takes place and the rate of production are:

1. The energy of the neutrons and the neutron flux.
2. The characteristics and quantity of the target material.
3. The activation cross-section for the desired reaction.

Neutron flux is the product of neutron density and the average speed of the neutron and is expressed as n/cm2/sec. The neutron interaction with the nucleus of the target material can be expressed quantitatively in terms of nuclear cross section. It is a measure of the probability that a given nuclear reaction takes place. This can be expressed in terms of an imaginary cross-sectional area presented by nucleus around the nucleus to the beam of neutrons, perpendicular to the beam such that if and only if the neutrons pass through this area, the nuclear reaction takes place. The value of the cross-section varies with the energy of the interacting neutrons and from nucleus to nucleus. The maximum value of the cross-section is for thermal neutrons. The higher the cross-section; the higher the probability of radioisotope formation.

**Characteristics of the Target Material**

1. Substances which are explosive, pyrophoric, volatile, etc. are not permitted to be irradiated in reactor.
2. Targets should be stable under irradiation conditions.
3. Isotopically pure target gives high specific activity radioisotopes.
4. The physical form of the target should be such that the neutron flux depression is minimum.
5. The target should be in a suitable chemical form for post irradiation processing. Usually target in metallic form or oxides are preferred.
6. If the target is hygroscopic, it is preferable to preheat the target prior to encapsulation.

**Nuclear reactions leading to radioisotope production are**:

1. reaction: ***Radiative Capture***

Most of the reactor-produced radioisotopes are products of the reaction. This reaction is also referred to as ***radiative capture*** and is primarily a thermal neutron reaction. Some of the common radioisotopes produced by reactions are:

Here, the product is an isotope of the target element itself and hence cannot be chemically separated. Therefore the specific activity is limited by the neutron flux available in the reactor.

1. followed by decay

In some cases reaction leads to a product with short half-life which decays by emission to the isotope of interest.

The product can be chemically separated from the target. This will enable us to obtain high specific activity or carrier free radioisotope.

1. reaction

In some cases the absorption of neutron leads to emission of a proton as outgoing particle. Such a reaction is termed as reaction, caused by fast neutrons having energy more than a particular value known as threshold energy. Hence, such a reaction is known as ***threshold reaction***.

Also in this case, the product nucleus can often be chemically separated from the target, thereby obtaining very high specific activity product.

1. reaction

This reaction is also a threshold reaction as neutrons having energy above a specific value (threshold energy) is absorbed by the nucleus causing an alpha particle to be ejected. In some very special cases, the reaction is caused by thermal neutrons as well.

1. Multistage reactions
2. Fission reaction

Fission of Uranium atom by thermal neutron leads to the formation of a number of radioisotopes. Each fission provides two fission fragments, light (mass no around 95) and heavy (mass no around 140), with the release of about 2.4 neutrons/fission. In fact the nuclear reactors work on the principle of controlled nuclear fission.

**Rate of Production of Radioisotope in a Nuclear Reactor**

When a target is undergoing irradiation in a reactor, a nuclear reaction takes place leading to the production of radioisotope.

The rate of production is expressed as:

where

 is the number of atoms present in the target;

 is the activation cross-section

 is the number of activated atoms at an instant of time.

Thus, the rate of production is independent of time. Once the radioisotope is produced, it starts decaying with its own half-life. The net rate of increase of radioactive nuclei is the difference between the rate of production and the rate of decay.

or

The solution of equation (iii) gives,

The activity of the sample is defined as

where is time of irradiation in seconds. Equation (5) shows that the growth of activity in a target under irradiation is exponential and reaches a saturation value limited by the neutron flux in the reactor.

**Reactor-produced radioisotopes and their medical applications**

The underlisted are some reactor-produced radioisotopes and their applications in medicine.

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| **Radioisotope** | **Medical Application** |
| Caesium-131 (9.7 d):  | Used for brachytherapy, emits soft x-rays. |
| Caesium-137 (30 yr): | Used for low-intensity sterilisation of blood. |
| Cobalt-60 (5.27 yr): | Formerly used for external beam radiotherapy, now almost universally used for sterilizing. Co-60 is used for brain cancer treatment. |
| Iodine-125 (60 d): | Used in cancer brachytherapy (prostate and brain), also diagnostically to evaluate the filtration rate of kidneys and to diagnose deep vein thrombosis in the leg. It is also widely used in radioimmuno-assays to show the presence of hormones in tiny quantities. |
| Iodine-131 (8 d): | Widely used in treating thyroid cancer and in imaging the thyroid; also in diagnosis of abnormal liver function, renal (kidney) blood flow and urinary tract obstruction. A strong gamma emitter, but used for beta therapy. |
| Iron-59 (46 d): | Used in studies of iron metabolism in the spleen. |
| Molybdenum-99 (66 h): | Used as the 'parent' in a generator to produce technetium-99m. |
| Phosphorus-32 (14 d): | Used in the treatment of polycythemia vera (excess red blood cells). It is a beta emitter. |
| Potassium-42 (12 h): | Used for the determination of exchangeable potassium in coronary blood flow. |
| Samarium-153 (47 h): | Sm-153 is very effective in relieving the pain of secondary cancers lodged in the bone. Also very effective for prostate and breast cancer. It is a Beta emitter. |
| Sodium-24 (15 h): | For studies of electrolytes within the body. |
| Strontium-89 (50 d): | Very effective in reducing the pain of prostate and bone cancer. Beta emitter. |
| Technetium-99m (6 h): | Used to image the skeleton and heart muscle in particular, but also for brain, thyroid, lungs (perfusion and ventilation), liver, spleen, kidney (structure and filtration rate), gall bladder, bone marrow, salivary glands, heart blood pool, infection and numerous specialised medical studies. Produced from Mo-99 in a generator. The most common radioisotope for diagnosis, accounting for over 80% of scans. |

**Cyclotron-produced radioisotopes and their medical applications**

The underlisted are common cyclotron produced radioisotopes and their applications in medicine.

|  |  |
| --- | --- |
| **Radioisotope** | **Medical Application** |
| Carbon-11, Nitrogen -13, Oxygen-15, Fluorine-18: | These are positron emitters used in PET for studying brain physiology and pathology, in particular for localising epileptic focus, and in dementia, psychiatry and neuropharmacology studies. They also have a significant role in cardiology. F-18 in FDG (fluorodeoxyglucose) has become very important in detection of cancers and the monitoring of progress in their treatment, using PET. |
| Cobalt-57 (272 d): | Used as a marker to estimate organ size and for in-vitro diagnostic kits. |
| Copper-64 (13 h): | Used to study genetic diseases affecting copper metabolism, such as Wilson's and Menke's diseases, for PET imaging of tumours, and also cancer therapy. |
| Copper-67 (2.6 d): | Beta emitter, used in therapy. |
| Fluorine-18 (110 min) as FLT (fluorothymidine), F-miso (fluoromisonidazole), 18F-choline: | It decays with positron emission, so used as tracer with PET, for imaging malignant tumours. |
| Gallium-67 (78 h): | Used for tumour imaging and locating inflammatory lesions (infections). |
| Iodine-123 (13 h): | Increasingly used for diagnosis of thyroid function, it is a gamma emitter.  |
| Iodine-124 (4.2 d): | It is used as a tracer. It has longer life than F-18. One-quarter of decays are positron emission so used with PET. Also used to image the thyroid using PET. |

Seminar

MAGNETIC RESONANCE IMAGING

Explain the Physics of MRI

2.0 **INTERRACTION OF RADIATION WITH MATTER**

When a beam of radiation of any kind penetrates matter, some of the radiation may be absorbed completely, some may be scattered and some may pass straight through without any interaction at all.

There are two broad kinds of process by which a particle travelling through matter can lose energy:

1. In the first kind the energy loss is gradual; the particle loses energy nearly continuously through many interactions with the surrounding material.
2. In the second kind the energy loss is catastrophic; the particle moves without any interaction at all through the material until, in a single collision, it loses all its energy.

2.1 **ATTENUATION COEFFICIENT**

Consider a slab of material through which a beam of photon is passing. If at some distance into the material, particles are moving through the slab of material, then after penetrating an extra distance , the number of particle reduces to

This exponential attenuation law follows from the fact that:

1. over any short distance, the probability of losing a particle from the beam is proportional to the number of particles left.
2. Where there are many particles many will be lost, but as the number left decreases so does the rate of loss.

The quantity is known as the ***linear******attenuation coefficient***; **it is a measure of how rapidly the original photons are removed from the beam**. A large value of means that the original photons are removed after travelling only a small distance.

**Example:**

The linear attenuation coefficient for 200 keV x-rays in lead is . What is the fraction of such photons remaining after penetrating a lead sheet of thickness 2.0 mm?

Solution:

The exponential law can also be written in terms of attenuation length. **Attenuation length** or **mean free path**, , is the average distance travelled by a photon before it is absorbed. It is the reciprocal of linear attenuation coefficient .

So that

Another parameter of interest is **half thickness**, . Half thickness is the distance over which one half the initial beam is absorbed. It is related to the linear attenuation coefficient and mean free path by:

Since photons interact with individual atoms, the probability that a photon will interact somewhere within a slab of matter depends on the total number of atoms ahead of it along its path. So the attenuation of radiation depends on the amount of material in the beam's path and not on how it is distributed. It is useful, therefore, to describe the attenuation process in a way that does not depend on the density of material, only on what kind of stuff it is. We can achieve that by defining the **mass attenuation coefficient** which is related to the linear attenuation coefficient by:

where ρ is the density of the material. This means that the mass attenuation coefficient is the same for ice, liquid water and steam whereas the linear attenuation coefficients will differ greatly. The total attenuating effect of a slab of given type material can be described by quoting the mass attenuation coefficient, which is characteristic of the material’s chemical composition and the photon energy, together with the material’s density and its thickness. We now have yet another way of writing the attenuation law:

The product is the areal density (mass per area) of a thickness of the attenuating material measured in . It is also called the density-thickness. It is often quoted instead of the geometrical thickness .

For some purposes, it is useful to use the **atomic attenuation coefficient,** . It is defined as the fraction of an incident radiation beam that is attenuated by a single atom, its unit is expressed in . It is expressed as:

where is the number of absorber atoms per . Note that the dimensions of is , the unit of area. For this reason, the atomic attenuation coefficient is almost always referred to as the **cross-section** of the absorber.

Using equation (2.7), we can rewrite equation (2.1) as:

The linear attenuation coefficient for a mixture of materials or an **alloy** is given by

where

**Example**:

Aluminum bronze, an alloy containing 90% Cu (atomic weight=63.57) and 10% Al (atomic weight = 26.98) by weight, has a density of 7.6. What are the linear and mass attenuation coefficients for 0.4MeV gamma rays if the cross sections for Cu and Al for this quantum energy are 9.91 and 4.45 b? .

**Solution**

The number of Cu atoms per in the alloy is

and for Al, it is given by

The linear attenuation coefficient therefore is

The mass attenuation coefficient is

**Example**

Compute the thickness of Al and Pb to transmit 10% of a narrow beam of 0.1 MeV gamma radiation.

**Solution**:

For Aluminum

In similar manner, we have for Lead

**PHOTOELECTRIC EFFECT**

Photoelectric effect is the emission electron from a matter when a photon interacts with it. Photons can interact with an atom either by ionising it (ejecting an electron) or by exciting it (leaving all the electrons inside the atom). The atomic photoelectric effect involves the absorption of a photon by an atomic electron which is then ejected from the atom. This can occur only when the incoming photon has energy greater than the ionisation energy of the electron to be removed. Since an atom is much more massive than an electron the ejected electron takes practically all the energy and momentum of the photon.

The kinetic energy, of the ejected electron is then

The ejected electrons are known as photoelectrons and, since the atom is ionised, the process is one form of photoionisation.

**POSITRON EMISSION TOMOGRAPHY (PET)**

* Positron emission tomography (PET) is a nuclear medicine functional imaging technique that is used to observe metabolic processes in the body.
* The system detects pairs of gamma rays emitted indirectly by a positron-emitting radionuclide (tracer), which is introduced into the body on a biologically active molecule.
* The radiation source in this case is a positron emitter radioisotope (e.g., fluorine-18 or gallium-68) that is attached to a pharmaceutical and ingested.
* These positron emitters have short half lives and usually require a hospital to have an accelerator facility to prepare the radioisotopes.
* An emitted positron is very rapidly annihilated by an electron to form a pair of gamma rays.
* The energy and momentum of these gamma rays must satisfy the laws of conservation of energy and momentum.
* If both the electron and positron were at rest, then the total momentum must remain zero (hence the need for two identical gamma rays traveling in exactly opposite directions) and the total energy must equal the total rest energy of the electron and positron. This energy is equivalent to 511 KeV for each gamma ray.
* Thus the net result of each decay event is the production of a pair of 511 KeV gammas that leave the body in opposite directions.
* PET detectors 180° apart around the source to be imaged are set to look for the coincident arrival of 511 KeV gamma ray signals.
* A computer processes the data to construct an image of the distribution of the radionuclide in the patient.

**THE GAMMA CAMERA**



**COMPTON SCATTERING**

Scattering of x-rays by matter can be classified into two types.

1. Thomson scattering or coherent scattering
2. Compton scattering or incoherent scattering

In Thomson scattering, the incident x rays and the scattered x-rays have the same wavelength. So, this scattering is called *coherent scattering*. There is only change in the direction of the incident x-rays.

In Compton Scattering, the scattered x-rays consists of two wavelengths, one the incident wavelength and the other a radiation of longer wavelength. So, Compton scattering is an example of *incoherent scattering*.



According to Planck, the radiation is emitted in packets of energy called quanta. Planck thought that once the photons are emitted, they spread out in the form of waves.

But Einstein boldly asserted that the photons maintain their particle nature during their propagation also. Einstein also argued that the photons preserve their identity until they were absorbed by a body.

Compton Effect is an experiment to prove that photon is born as a particle, propagates as a particle and dies as a particle.

The scattering of a photon by an electron is called *Compton Effect*. The Compton Effect represents one of the most conclusive evidences of the particle properties of electromagnetic radiation. The experimental results of the Compton effect form an important verification of the quantum theory.

**Compton Scattering Experiment**

In 1923, Arthur Holly Compton discovered that when a homogenous beam of x-rays of sharply defined frequency were incident on a light element like Carbon or Aluminium, the x-rays suffered a change of frequency of scattering.

The scattered beam contained two wavelengths. One scattered beam has the same wavelength as the incident beam or primary beam while the second beam had a wavelength longer than that of the primary beam.

This change of wavelength is due to the loss of energy of the incident x-rays due to elastic interaction and is called Compton Effect.

From Special theory of relativity, an object whose rest mass is and is moving with velocity will have relativistic mass given by

Now,