# Medical Physics
# **Nuclear Radiation**

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# Radiation

- Radiation is the emission or transmission of energy in the form of waves or particles.
- This includes: electromagnetic radiation, such as radio waves, microwaves, infrared, visible light, ultraviolet, x-rays, and gamma radiation (γ)
- Ionizing radiation is any type of particle or electromagnetic wave that carries enough energy to ionize or remove electrons from an atom (such as ultraviolet, x-rays, and gamma radiation (γ))
- Non-ionizing radiation is any type of electromagnetic radiation that does not carry enough energy to ionize atoms (to completely remove an electron from an atom). Such as radio waves, microwaves, infrared, and visible light

# Nuclear Radiation

- Nuclear radiation is defined as the particles or photons that are given off from a nucleus of the radioactive element.
- The particles and photons emitted by nuclear reactions are sufficiently energetic that they can remove electrons from atoms and molecules and ionize them.
- Therefore, Nuclear radiation is also known as ionizing radiation

# Discovery of radioactivity

- In 1896, Henri Becquerel discovered that uranium-containing crystals emitted rays that could fog photographic plates.
- He found that these “rays” originated from changes within the atomic nuclei of the U atoms.
- He proposed that the uranium atoms were unstable. These atoms emitted particles and/or energy to become more stable.
- For his discovery of radioactivity, Becquerel was awarded Nobel prize in Physics in 1903

## Discovery of radioactivity

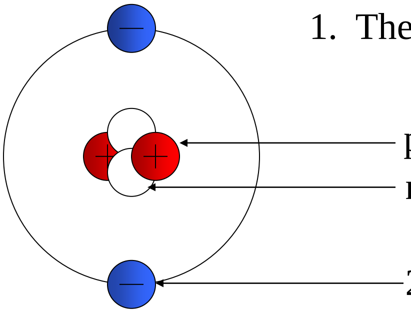
- In 1898, Pierre and Marie Curie discovered two elements, polonium and radium, which emitted high levels of radioactivity.
- They shared the Nobel prize in physics with Becquerel for discovering the radioactivity

## Atom

- All matters are made up of elements (e.g. carbon, hydrogen, etc.). The smallest part of an element is called an atom
- Every atom of any element has protons and neutrons in its nucleus.
- Atom of different elements contain different numbers of protons.
- The mass of an atom is almost entirely due to the number of protons and neutrons.

# Atom

- The atom consists of two parts:



1. The nucleus which contains:

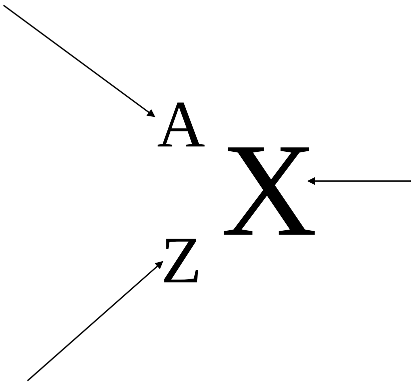
protons

neutrons

2. Orbiting electrons.

# Definitions

Mass number = # of protons + # of neutrons



$$^{A}_{Z}\mathrm{X}$$

Element symbol

Atomic number = number of protons

# Definitions

Number of protons = atomic number = Z

Number of neutrons = N

Mass number = A

# of protons + # of neutrons = mass number= A

Z+N=A

According to Z, N, A, elements are classified to

# Definitions

1- **Isotopes**---- Same Z, Different N, Different A

Example: $^{11}_{6}C$ , $^{13}_{6}C$ , $^{14}_{6}C$ -------- Z=6

Note: Isotopes are variants of a particular chemical element which differ in neutron number. They have the same symbol and same chemical and physical properties.

## Definitions

2- **Isobars** --------- Same A, different Z

Example: $^{40}_{19}K$ , $^{40}_{20}Ca$ ---------- A = 40

Note: Isobars are atoms (nuclides) of different chemical elements that have the same number of nucleons(P+N). They have different chemical and physical properties.

## Definitions

3- **Isotones**------Same N, different A and Z

Example: $^{39}_{19}K$ , $^{40}_{20}Ca$ -------- N=20

Note: Isotones are atoms (nuclides) of different chemical elements that have the same number of neutrons. They have different chemical and physical properties.

# Definitions

4- Isomeric state -------Same Z, N, and A, different energy levels

Example: $^{99m}_{43}\mathrm{Tc} \longrightarrow ^{99}_{43}\mathrm{Tc}$

Note: A nuclear isomer is a metastable state of an atomic nucleus caused by the excitation of one or more of its nucleons (protons or neutrons).

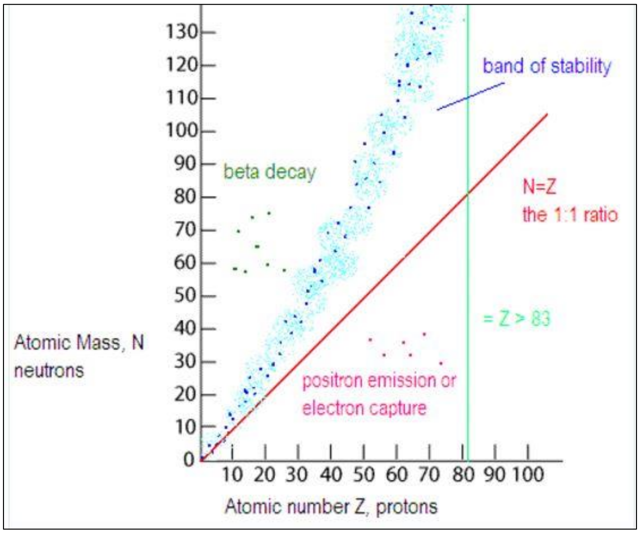
# Stability of nuclides

- As mentioned previously, nucleus consists of protons and neutrons which are called nucleons. protons have positive charge while the neutrons have no charge (neutral).
- There are two forces work in nucleus

1- Coulomb repulsive force between protons

2-Nuclear force (attractive) between nucleons. It is so strong that it cancel the effect of the force of repulsion between the protons and helps bind the nucleus together.

# Stability of nuclides



The graph shows that nuclides with more than 20 protons must have more neutrons than protons in order to be stable. Why?? Because Extra neutrons mitigate the effect of repulsive force between the protons

# Stability of nuclides

- If nucleus is stable, it does not spontaneously emit any kind of radioactivity (radiation).
- If the nucleus is unstable, it has the tendency of emitting some kind of radiation, (i.e., it is radioactive). Therefore the radioactivity is associated with unstable nucleus:

Stable nucleus – non-radioactive

Unstable nucleus – radioactive

- Unstable nuclides can become stable by releasing different types of particles
- This process is called **radioactive decay** and the elements which undergo this process are called **radioisotopes/radionuclides**.

## Radioactive Decay

Types of radioactive decay

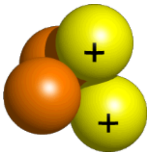
1. alpha decay (α)
2. beta minus decay (-β)
3. positron decay (+β)
4. gamma decay(γ)
5. electron capture
6. fission

## Alpha decay (α)

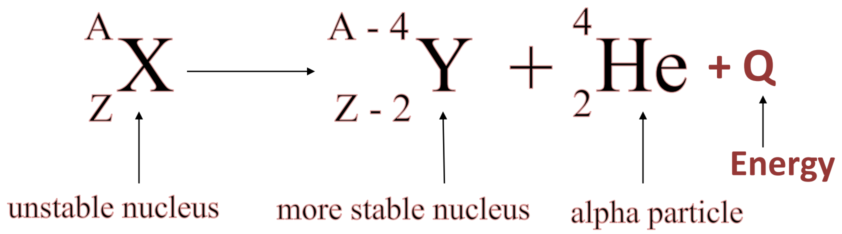
- Radioactive nuclei eject alpha particles in order to reach the stable state. This decay occurs only in heavy nuclei (Z > 83).

- Characteristics of alpha particle(α) :

1. a helium nucleus ( )
2. two protons and two neutrons
3. charge +2e
4. can travel a few inches through air
5. can be stopped by a sheet of paper, clothing.



# Alpha decay (α)



$$ {}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He + Q $$

unstable nucleus

more stable nucleus

alpha particle

Energy

Example: Uranium ⟶ Thorium + α + Energy

$$ {}^{234}_{92}U \longrightarrow {}^{230}_{90}Th + {}^{4}_{2}He + Q $$

# Beta decay (-β)

- This type of decay occurs in neutron rich nuclei. one neutron converts to proton and electron, then the electron (beta particle) will be ejected from the radioactive nucleus.

- Characteristics of Beta particles (- β)

1. Beta particles have the same charge (-e) and mass as "normal" electrons.
2. Can be stopped by glass plate, aluminum foil or a block of wood.

# Beta decay (-β)

$$\underset{\text{unstable nucleus}}{\underset{\uparrow}{{}^{A}_{Z}X}} \longrightarrow \underset{\text{more stable nucleus}}{\underset{\uparrow}{{}^{A}_{Z+1}Y}} + \underset{\text{Beta particle}}{\underset{\uparrow}{{}^{0}_{-1}\beta}} + \underset{\textbf{Energy}}{\underset{\uparrow}{Q}}$$

Ex: molybdenum $\longrightarrow$ Technetium + β + energy

$${}^{99}_{42}\text{Mo} \longrightarrow {}^{99\,m}_{43}\text{Tc} + {}^{0}_{-1}\beta + Q$$

# Positron decay (+β)

- This type of decay occurs in proton rich nuclei only if Q >1.02 Mev. If Q less, Electron capture will occur
- One proton converts to neutron and positron, then the positron (Beta plus particle) will be ejected from the radioactive nucleus.

- Characteristics of positron particles (+ β)

1. Positron is antiparticle of an electron/beta
2. Has same size as an electron but with a positive charge.
3. It will collide with any electron. The result of the collision is the annihilation of the electron and positron, and the creation of gamma ray photons

# Positron decay (+β)

$$\underset{\text{unstable nucleus}}{\underset{\uparrow}{{}^{A}_{Z}X}} \longrightarrow \underset{\text{more stable nucleus}}{\underset{\uparrow}{{}^{A}_{Z-1}Y}} + \underset{\text{positron particle}}{\underset{\uparrow}{{}^{0}_{+1}\beta}} + \underset{\textbf{Energy}}{\underset{\uparrow}{Q}}$$

Ex: Fluorine ⟶ oxygen + positron + Q

$${}^{18}_{9}F \longrightarrow {}^{18}_{8}O + {}^{0}_{+1}\beta + Q$$

# Gamma decay(γ)

- Gamma decay is an emission of nuclear photon from excited nucleus. The unstable nucleus has excess of energy. It expels this energy as Gamma ray in order to be stable
- The nuclide retains its identity.
- Characteristics of gamma ray (γ)

1. Gamma rays are electromagnetic radiation with high frequency. (have NO mass and NO charge)
2. Most Penetrating, can be stopped by 1m thick concrete or a several cm thick sheet of lead

# Gamma decay(γ)

$$^{A*}_{Z}X \longrightarrow \, ^{A}_{Z}X + \gamma + Q$$

unstable nucleus stable nucleus Gamma

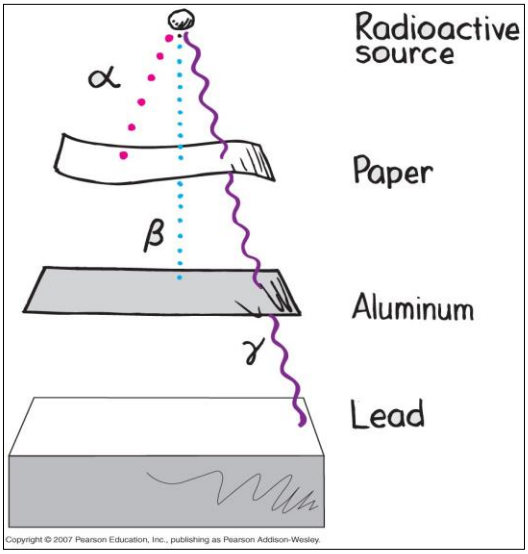
- Ex: *Technetium $\longrightarrow$ Technetium + γ + Q

$$^{99\,m}_{43}Tc \longrightarrow \, ^{99}_{43}Tc + \gamma + Q$$

# Gamma decay(γ)

- Note: Both Gamma and X-rays are electromagnetic radiation. But they come from different sources
- Gamma photons are ejected from the excited nucleus while X-ray is result of the transition of orbital electrons.

# Penetration of radiation



- Which one is more penetrating? Why ?Beta, Alpha, Gamma
- The answer would be Gamma because
- it has no charge
- it has speed of light

## The range of charged particles (Alpha, Beta, positron)

- The range of charged particles at a given energy is defined as "the average distance they travel before they come to rest".
- The range of a 4 MeV alpha particle in air is about 3 cm, and they can be stopped by a thin piece of paper
- 4 MeV beta particles have a maximum range of about 1,700 cm in air whereas they have a maximum range of about 2 cm in water and about 0.26 cm in lead

## Conservation of Energy

- The law of conservation of energy states that the total energy of an isolated system remains constant— (it is said to be conserved over time). Energy can neither be created nor destroyed; rather, it transforms from one form to another.
- Einstein's equation : $E = mc^2$

E: energy, C: speed of light($3 \times 10^8$ m/s),m: mass

# Conservation of Energy in nuclear reactions

- In nuclear reactions, matter changes to energy, but the total amount of mass and energy together does not change.
- When the radionuclide undergoes radioactive decay, it loses a tiny amount of mass (mass of daughter is less than the mass of its parent.
- What happens to the lost mass?. It is converted to energy.
- How much energy? The energy could be estimated from the $E = \Delta mc^2$
- The change in mass is tiny, but it results in a great amount of energy.

# Conservation of Energy in nuclear reactions

$$E = \Delta mc^2$$

- E: energy,
- C: speed of light(3 x$10^8$ m/s)
- $\Delta$m: mass difference between the parent nucleus and the daughter.
- The equation gives the energy released

- In a nuclear reaction, mass decreases and energy increases. However, the sum of mass and energy is always conserved in a nuclear reaction. Mass changes to energy, but the total amount of mass and energy combined remains the same.