Unit 27

Nuclear Physics

Teaching Periods 17 **Weightage %** 11

CERN (European Organization for Nuclear Research) is a research organization that operates the largest particle physics laboratory in the world, home to the Large Hadron Collider (LHC). Pakistan has made significant contributions to CERN's LHC project, including designing and manufacturing over 300 superconducting magnets, developing detector components like muon chambers and silicon trackers for the CMS experiment, participating in data analysis and simulations, and establishing a National Grid Computing Center to support LHC research. These contributions showcase Pakistan's expertise in advanced physics research and its collaboration with the global scientific community at CERN.

In this unit student should be able to:

- Recall the composition of atomic nuclei
- Describe isotopes in detail
- Explain that an element can exist in various isotopic forms each with a different number of neutrons.
- Explain the use of mass spectrograph to demonstrate the existence of isotopes and to measure their relative abundance
- Explain the process of radioactive decay
- State law of radioactive decay
- Identify the spontaneous and random nature of nuclear decay.
- Define the terms activity and decay constant and recall and
- Solve problems using $A = \lambda N$
- Infer and sketch the exponential nature of radioactive decay
- Describe the term half life and solve problems using the equation $\lambda = \frac{0.693}{T_{1/2}}$
- Define the terms unified mass scale, mass defect and calculate binding energy using Einstein's equation Illustrate graphically the variation of binding energy per nucleon with the mass number.
- Determine the release of energy from different nuclear reactions.
- Explain that atomic number and mass number conserve in nuclear reactions.
- Describe energy and mass conservation in simple reactions and in radioactive decay.
- Describe the phenomena of nuclear fission and fusion.
- Describe the fission chain reaction
- Describe the function of various components of a nuclear reactor.
- Explain the basic principle of nuclear reactor.
- Describe how the conditions in the interiors of the Sun and other stars allow nuclear fusion to take place and hence, how nuclear fusion is their main energy conversion process.
- Show awareness about nuclear radiation exposure and biological effects of radiation.
- Describe the term dosimetry.
- Describe the use of radiations for medical diagnosis and therapy.
- Explain the importance of limiting exposure to ionizing radiation.
- Describe the examples of the use of radioactive tracers in medical diagnosis, agriculture and industry.

Introduction:

In this chapter, we are going to explore nuclear physics. This field explores the properties and behavior of atomic nuclei, including radioactivity, nuclear reactions, and nuclear energy. First, we will learn about isotopes, which are like different versions of the same atom also see how scientists use mass spectrometers to find these isotopes. Then, we will learn radioactivity, understanding why some atoms emit radiation. Finally, explore the mysteries of nuclear reactions and the cool processes that make nuclei change, even discover how stars and the sun make energy, explore how we can create affordable nuclear energy with reactors, and see how nuclear radiation is used in our everyday lives.

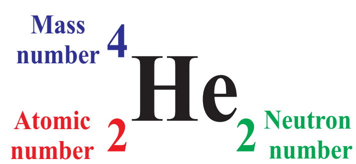
DO YOU KNOW?

Henri Becquerel discovered uranium's invisible energy, sparking curiosity. Rutherford's bold experiment revealed the dense nucleus at the atom's center, like a strong bowling pin, holding most of the atom's weight and binding it together with the powerful nuclear force

27.1 Atomic Nucleus and Isotope:

The atom is the building block of matter; an atom is composed of a positively charged nucleus, with a cloud of negatively charged electrons surrounding it, bound together by electrostatic force. and atomic nucleus is the small, dense region consisting of protons and neutrons at the center of an atom. Almost all of the mass of an atom is located in the nucleus, with a very small contribution from the electron cloud.

A = Z + N



All properties of a nucleus are determined by the number of protons and neutrons it has. A specific combination of protons and neutrons is called a nuclide and is a unique nucleus. The following notation is used to represent a particular nuclide.

$${}^{A}_{Z}X \ldots\ldots\ldots\ldots 27.1$$

Where X shows any nuclide, Z is atomic number and A is mass number. Table 1 lists these quantities and the symbols commonly used to represent them.

For example, a nuclide of aluminum has a mass number (A) of 27 and an atomic number (Z) of 13. Therefore, it has 13 protons and 14 neutrons (27 − 13 = 14) as shown in figure.27.1 and equation

$$A = Z + N \ldots\ldots\ldots\ldots\ldots..27.2$$

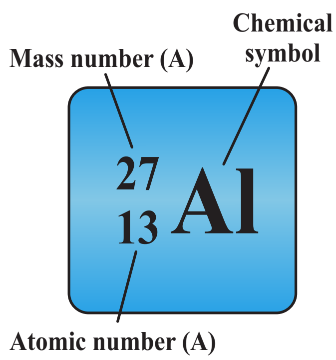


Figure 27.1
Element and its nuclides numbers

Isotopes:

Two or more forms of the same element that contain equal numbers of protons but different numbers of neutrons in their nuclei, and hence they differ in relative atomic mass but not in chemical properties.

Isotopes differ in relative atomic mass but not in chemical properties. For example, carbon has an atomic number of 6. This means that all carbon atoms have 6 protons. However, carbon has three naturally occurring isotopes: carbon-12, carbon-13, and carbon-14. Carbon-12 has 6 neutrons, carbon-13 has 7 neutrons, and carbon-14 has 8 neutrons.

Isotopes are of two types:

- ***Stable isotopes***: They do not show any radioactivity and are stable. For example, $_7N^{14}$ and $_7N^{15}$.
- ***Radioactive isotopes:*** They are unstable and show radioactivity. Some of the radioactive isotopes are $_6C^{14}$ for carbon, and $_{19}K^{40}$ for potassium.

Isotopic variations: different numbers of neutrons:

An element can exist in various isotopic forms, each with a different number of neutrons. Elements with low atomic numbers tend to have fewer isotopes, while elements with high atomic numbers tend to have more isotopes.

Every element on the periodic table naturally occurs in various isotopic forms, although some may be more prevalent than others. For instance:

- **Oxygen:** About 99.76% of oxygen in nature is Oxygen-16 (with 8 neutrons). However, Oxygen-17 and Oxygen-18 are also found in much smaller quantities.
- **Uranium:** The naturally occurring isotopes of uranium are Uranium-238 (99.3%) and Uranium-235 (0.7%). Uranium has 35 known isotopes. The most stable isotope of uranium is uranium-238, which has 146 neutrons.
- **Hydrogen:** Hydrogen has only three isotopes: protium, deuterium, and tritium. Protium has no neutrons, deuterium has one neutron, and tritium has two neutrons.

DO YOU KNOW?

The Isotopes have same Physical Properties, Despite having different masses like the isotopes of hydrogen have the same physical properties, such as:

- ✓ Boiling point
- ✓ Melting point:
- ✓ Density
- ✓ Solubility:
- ✓ Color: Colorless
- ✓ Odor: Odorless
- ✓ Taste: Tasteless

Self-Assessment Questions:

1. How many protons are there in the nucleus $^{197}_{79}Au$?
2. How do isotopes of an element differ from each other?
3. Give an example of two isotopes of the same element.

27.1.4 Mass Spectrograph:

A mass spectrograph is a device that can be used to separate isotopes of an element based on their mass and it works by accelerating charged particles through a magnetic field. The particles are then deflected by the magnetic field, and the amount of deflection is determined by the mass of the particle.

Bainbridge mass spectrograph is a type of mass spectrometer that uses a combination of electric and magnetic fields to separate Ions according to their charge-to-mass ratio. It is named after its inventor, Kenneth T. Bainbridge, who developed it in 1933.

Principle:

The fundamental principle behind the Bainbridge Mass Spectrograph is the application of magnetic and electric fields to separate and measure the masses of charged particles, typically Ions. This separation is based on the principles of magnetic deflection and kinetic energy.

The **Bainbridge mass spectrograph** consists of three main components: an ion source, a velocity selector, and a magnetic analyzer.

- The **ion source** is where the Ions are produced. The Ions are typically produced by bombarding a sample with electrons, which knocks electrons out of the atoms, creating positively charged Ions.
- The **velocity selector** is used to select Ions of a particular velocity. The Ions are passed through a region of electric and magnetic fields, which are adjusted so that only Ions of a certain velocity can pass through.
- The **magnetic analyzer** is used to separate the Ions according to their charge-to-mass ratio. The Ions are passed through a region of magnetic field, and the radius of their path is determined by their charge-to-mass ratio.

The Ions that are separated by the magnetic analyzer are then detected by a detector, such as a photographic plate or a computer.

A schematic diagram showing the construction of Bainbridge's mass spectrograph is shown in Figure 27.2.A beam of positive Ions produced in a discharge tube is collimated into a narrow beam by the two slits S_1 and S_2. After emerging from the slit, the positive Ions enter a velocity selector.

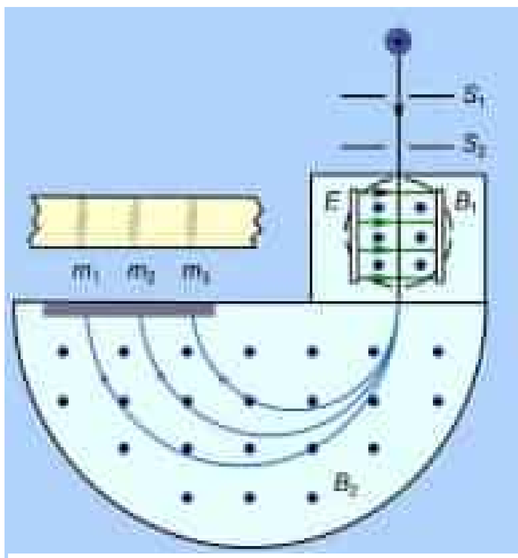


Figure 27.2 Bainbridge's mass spectrograph

The velocity selector consists of two plates E and B_1, between which a steady electric field is maintained in a direction at right angles to the ion beam. The electric field and the magnetic field of the velocity selector are so adjusted that the deflection produced by one is exactly equal and opposite to the deflection produced by the other so that there is no net deflection for Ions having a particular

$$Xe = B_1 ev \dots 27.3$$

$$v = \frac{X}{B_1} \dots\dots\dots\dots\dots 27.4$$

The Ions were accelerated to a known kinetic energy, ensuring that all Ions of different masses had the same kinetic energy. Positive ions entering the evacuated chamber are subjected to a perpendicular electromagnetic field of intensity B_2, causing them to follow curved paths. The curvature depends on their charge-to-mass ratio (e/m), with heavier ions curving less than lighter ones. This method is very accurate due to the linear mass scale. When a charged particle with mass m and charge e is accelerated through a potential difference V, it gains a velocity v, given by

$$\frac{1}{2}mv^2 = eV \quad or \quad v = \sqrt{\frac{2eV}{m}} \;\ldots\ldots\ldots\ldots 27.5$$

When this charged particle moving with a velocity v enters a magnetic field B in a direction perpendicular to the field, the force acting on it due to the field is Bev acting in a direction at right angles to the direction of motion of the charged particle and that of the magnetic field. The particle, therefore, moves along a circular path of radius r given by

$$Bev = \frac{mv^2}{r} \;\ldots\ldots\ldots 27.6$$

Rearrange eq:27.6 for mass m and putting value of v from equation 27.5 $v = \sqrt{\frac{2eV}{m}}$),

$$m = \frac{Ber}{v} = \frac{Ber}{\sqrt{\frac{2eV}{m}}} \;\ldots\ldots\ldots 27.7$$

Squaring both sides and after re-arranging,

$$m = \left(\frac{er^2}{2V}\right) B^2 \;\ldots\ldots\ldots\ldots 27.8$$

The mass of each ion reaching the detector depends on the value of B^2. By changing B and keeping other variables constant, ions of different masses can be directed into the detector. This allows us to create a graph of detector readings versus B^2, identifying the masses and quantities of the ions present. Multiple peaks in the mass spectrum indicate different isotopes of the same element.

For instance, chlorine's mass spectrum shows two peaks corresponding to chlorine-35 and chlorine-37, demonstrating the presence of isotopes. The height of each peak reveals the relative abundance of each isotope, with more abundant isotopes producing taller peaks and less abundant ones producing shorter peaks. Comparing peak intensities helps determine the relative abundance of the isotopes.

27.2 Radioactive Decay:

Radioactivity is the process by which an unstable atomic nucleus loses energy by radiation. A material containing unstable nuclei is considered radioactive.

There are two types of radioactivity:

1. **Natural Radioactivity:** Natural radioactivity is the radioactivity that occurs naturally in the environment. It is caused by the decay of unstable isotopes of elements that are found in the Earth's crust, such as uranium, thorium, and potassium-40.

DO YOU KNOW?

Radioactivity was first discovered by Henri Becquerel back in 1896. He observed that a piece of uranium salt, wrapped in paper, emitted certain strong rays that could affect a photographic plate.

2. **Induced Radioactivity:** Induced radioactivity is the radioactivity that is created by bombarding a stable material with radiation, such as neutrons or protons. This can be done in a nuclear reactor or particle accelerator.

The main difference between natural and induced radioactivity is the source of the radiation. In natural radioactivity, the radiation comes from the unstable nuclei of the atoms themselves. In induced radioactivity, the radiation comes from outside the atoms, and is used to destabilize their nuclei.

Henri Becquerel discovery of radioactivity was that the rays were emitted without any external stimulation or excitation. In other words, uranium salt was naturally radioactive, meaning it produced these penetrating radiations all on its own, without any external forces influencing it. Further research by scientists like Madame Curie, Pierre Curie, and Rutherford confirmed that this phenomenon wasn't unique to uranium; it could also be observed in heavy elements like polonium, radium, and thorium.

27.2.1 Radioactive Decay Process:

The natural radioactivity observed was specific to heavy elements with atomic weights greater than about 206. Of the 2,500 identified types of atoms, around 90% are radioactive, meaning they change into other types of atoms over time. These unstable nuclides release energy and particles in much different way of decay types to become stable nuclides.

Alpha Decay:

All atomic nuclei with a proton number (Z) greater than 83 and a mass number (A) greater than 209 undergo spontaneous transformation into lighter nuclei by emitting one or more alpha particles, which are equivalent to helium-4 nuclei.

$$^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + ^{4+}_{2}He \ldots\ldots\ldots\ldots\ldots 27.9$$

where X is parent nuclei, Y is daughter nuclei and $^{4}_{2}He$ is alpha particle. Examples of alpha decays are:

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4+}_{2}He$$

In this example, an isotope U $^{-238}$ converts into Th $^{-90}$ with emission of alpha particle. Alpha decay is possible whenever the mass of the original neutral atom is greater than the sum of the masses of the final neutral atom and the neutral helium-4 atom.

Worked Example 27.1

The element radium was discovered by Marie and Pierre Curie in 1898.One of the isotopes of radium, $^{226}_{88}Ra$, decays by alpha emission. What isthe resulting daughter element?

Solution:

Step 1: Write down the known quantities and quantities to be found.

Given: The decay can be written symbolically as follows:

$$^{226}_{88}Ra \rightarrow Y + ^{4}_{2}He$$

Unknown: the daughter element (Y).

The mass numbers and atomic numbers on the two sides of the expression must be the same so that both charge and nucleon number are conserved during the course of this particular decay.

Mass number of Y = 226 − 4 = 222
Atomic number of Y =88 – 2=86

$$^{226}_{88}Ra \rightarrow {}^{222}_{86}Y + {}^{4}_{2}He$$

Step 2: The periodic table shows that the nucleus with an atomic number of 86 is radon,
Result: Thus, the decay process is as follows:

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

In this process, radium ($Ra^{-226)}$ transforms into radon (Ra^{-222}).

Beta Decay:

The beta-decay is a spontaneous process in which mass number of the nucleus remains unchanged, but the atomic number changes by unity ($\Delta Z = \pm 1$). The change in atomic number is due to emission of an electron, emission of positron or by capture of an orbital electron (K−capture). If the daughter nucleus doesn't have the right ratio of neutrons and protons to stay stable, it can change through beta decay to become more stable. There are three types of β−decay processes depending upon their mode of decay: β^{-}−decay (electron emission), β^{+}−decay (positron emission) and electron capture.

β^{-}−Decay (Electron Emission): General equation of electron emission is:

$$^{A}_{Z}X \rightarrow {}_{Z+1}{}^{A}Y + {}_{-1}^{0}e \;\ldots\ldots\ldots 27.10$$

Whenever, the number of neutron is more than the number of proton then negative beta decay happens. In this process, a neutron is transformed into a proton:

$$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}_{-1}^{0}e \;\ldots\ldots\ldots 27.11$$

Here is an example:

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}_{-1}^{0}e$$

This equation represents the decay of carbon-14 ($_6C^{14}$) into nitrogen-14 ($_7N^{14}$) with the emission of an electron.

β^{+}−Decay (Positron Emission):

Also known as positive beta decay. General equation of positron emission is:

$$^{A}_{Z}X \rightarrow {}_{Z-1}{}^{A}Y + {}_{+1}^{0}e \;\ldots\ldots\ldots\ldots 27.12$$

Whenever, the number of proton is more than the number of neutron then positive beta decay happens. In this process, a proton is transformed into a neutron:

$$^{1}_{1}p \rightarrow {}^{1}_{0}n + {}_{+1}^{0}e \;\ldots\ldots\ldots\ldots 27.13$$

Here is an example:

$$^{11}_{6}C \rightarrow {}^{11}_{5}B + {}_{+1}^{0}e$$

This equation represents the decay of carbon-11 ($_6C^{11}$) into boron-11 ($_5B^{11}$) with the emission of a positron (e^{+}).

Electron Capture: In this process an electron from K-shell of the atom is captured by the nucleus to form a new nucleus and a photon is emitted:

$$^{A}_{Z}X + {}_{-1}^{0}e \rightarrow {}_{Z-1}{}^{A}Y + hv \;\ldots\ldots\ldots 27.14$$

In this process, atomic number Z is decreased by one but mass number A remains the same. In this case a proton in the nucleus is converted into a neutron by capture of an orbital electron:

$$^{1}_{1}p + {}^{0}_{-1}e \rightarrow {}^{1}_{0}n \ldots\ldots\ldots\ldots 27.15$$

An example of electron capture is the decay of Krypton-81 into Bromine-81:

$$^{81}_{36}K + {}^{0}_{-1}e \rightarrow {}^{81}_{35}Br$$

In this reaction, the atomic number drops from 36 to 35, while the mass number stays at 81.

Gamma Decay:

The gamma decay is the spontaneous emission of electromagnetic photon from the nucleus. The emission of alpha or beta particles from the natural radioactive substance may leave the daughter nucleus in one or more excited states. When the nucleus in excited states goes to lower or ground state, then it emits gamma rays. During gamma decay, there is no change in mass number A or atomic number Z. An excited nucleus is denoted by an asterisk (*) after or over its usual symbol. Thus $_{38}S^{87*}$refers to $_{38}S^{87}$ in an excited state. The general equation for gamma decay is:

$$^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma \ldots\ldots\ldots 27.16$$

Here is an example of gamma-decay:

$(_{27}Co^{60*}) \rightarrow _{27} A^{60} + \gamma$

This equation represents the decay of an excited state of cobalt-60 ($_{27}Co^{60*}$) into the ground state of cobalt-60 ($_{27}Co^{60}$) with the emission of a gamma (γ) photon.

The summary of the radiations from nucleus is given in Table 27.1.

Table 27.1 Alpha, Beta and Gamma radiation

Particle	Symbols	Composition	Charge	Effect on parent nucleus
alpha	α ($^{4}_{2}He$)	2 protons, 2 neutrons	+ 2	mass loss; new element produced
beta	β^{-} ($^{0}_{-1}e$)	electron	− 1	no change in mass number; new element produced
	β^{+} ($^{0}_{1}e$)	positron	+ 1	
gamma	γ	Photon	0	energy loss

Self-Assessment Questions:

The isotope $^{56}_{26}Fe$ decays into the isotope $^{56}_{27}Co$.

1. By what process will this decay occur?
2. Write the decay formula for this process.

27.2.2 Law of Radioactive Decay:

The law of radioactive decay states that the rate of decay of a radioactive sample at any instant is directly proportional to the number of atoms present at that instant.

It implies that the larger the quantity of the radioactive material, the faster it will decay.

Let ΔN be the number of atoms disintegrating in a time Δt and N be the number of atoms present at that instant, then the rate of decrease $-\frac{\Delta N}{\Delta t}$ is proportional to N,

$\frac{\Delta N}{\Delta t} \propto -N$, $\frac{\Delta N}{\Delta t} = -\lambda N \ldots\ldots 27.17$

> **DO YOU KNOW?**
> The key thing to remember is that this natural radioactivity is entirely spontaneous and not affected by external factors. Artificial radioactivity is also spontaneous in nature.

Where negative sign indicates that there is decrease in N with time and λ is called ***decay constant*** or disintegration constant. It is defined as the ratio of the amount of the substance which disintegrates in a unit time to the amount of substance present. Isotopes with a large value of λ decay rapidly; those with small λ decay slowly.

We can write the above equation in derivative form as dN/N = −λdt. Let the number of radioactive atoms initially present be N_0 at t = 0; and at some time t, the number of radioactive atoms are N.

Applying the limits and integrating equation both sides:

Taking anti logarithm on both sides of above equation:

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

$$N = N_0 e^{-\lambda t} \ldots\ldots\ldots 27.18$$

This equation shows that the number of atoms of a given radioactive substance decreases exponentially with time.

27.2.3 The Spontaneous and Random Nature of Radioactive Decay:

Radioactive decay is both spontaneous and random.

Spontaneous process:

It is a process which cannot be influenced by environmental factors, Such as:

(i) Temperature
(ii) Pressure
(iii) Chemical conditions

Random process:

It is a process in which the exact time of decay of a nucleus cannot be predicted

The random nature of radioactive decay can be demonstrated by observing the count rate of a Geiger-Muller (GM) tube.

(i) When a GM tube is placed near a radioactive source, the counts are found to be irregular and cannot be predicted.
(ii) Each count represents a decay of an unstable nucleus.
(iii) These fluctuations in count rate on the GM tube provide evidence for the randomness of radioactive decay.

The nucleus has a constant probability, ie. the same chance, of decaying in a given time. Therefore, with large numbers of nuclei, it is possible to statistically predict the behavior of the entire group.

27.2.4 Activity (A):

Sometimes we are more interested in the decay rate A ($A = -\frac{\Delta N}{\Delta t}$) than in N itself. The **activity A** of a radioactive sample is the number of disintegrations (decays) occurring per unit of time.

If a radioactive sample contains N atoms at any time t, then its activity at time t is given as

$$A = -\frac{\Delta N}{\Delta t} \;\ldots\ldots\ldots 27.19$$

where negative sign shows that activity decreases with time. According to law of radioactive decay

$$\frac{\Delta N}{\Delta t} = -\lambda N$$

Therefore,

$$A = \lambda N$$

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

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

Putting $A_o = \lambda N_o$ in above equation, we get

$$A = A_0 e^{-\lambda t} \;\ldots\ldots\ldots 27.20$$

The equation $A = \lambda N$ and $A = A_0 e^{-\lambda t}$ are alternative forms of the law of radioactive decay. The total decay rate A of a sample of one or more radionuclide is called the activity of that sample. The SI unit for activity is the Becquerel (Bq), which corresponds to one disintegration per second. Another common unit is the curie (Ci), where 1 Ci is approximately equal to 3.7×10^{10} Bq.

Worked Example 27.2

A radioactive sample of radium ($^{226}_{88}Ra$) contains 3×10^{16} nuclei. The decay constant λ is $1.4 \times 10^{-11} s^{-1}$. What is the activity A of the sample? Convert answer in curies.

Solution:

Step 1: Write down the known quantities and quantities to be found.

Number of nuclei $N = 3 \times 10^{16}$, $\lambda = 1.4 \times 10^{-11} s^{-1}$

Unknown: A = ?

The activity A of the sample is given by:

$$A = \lambda N$$

Step 2: Putting the values,

$$A = 1.4 \times 10^{-11} \times 3 \times 10^{16} = (1.4 \times 3) \times 10^{-11+16} = 4.5 \times 10^{5}$$

$A = 4.5 \times 10^{5}$ Bq

Step 3: In order to convert above value in curies, we will divide it by the factor 3.7×10^{10} *Bq/Ci:*

$$A = \frac{4.5 \times 10^5 Bq}{3.7 \times \frac{10^{10} Bq}{Ci}} = 1.1 \times 10^{-5} Ci$$

Result: **A**=$1.1 \times 10^{-5} Ci$

27.2.6 Exponential Nature of Radioactivity:

Radioactive decay follows an exponential decay pattern. This means that the rate of decay proportionally decreases with the remaining amount of radioactive material and it can be visualized graphically by decay curve.

A decay curve is a plot of the number of radioactive parent nuclei remaining in a sample as a function of half-life. A typical decay curve for a radioactive sample is shown in Figure 27.3. After each half-life, half the remaining parent nuclei have decayed. This is represented in the circles to the right of the decay curve. The blue spheres are the parent nuclei (carbon-14), and the red spheres are daughter nuclei (nitrogen-14). Notice that the total number of nuclei remains constant, while the number of carbon atoms continually decreases over time.

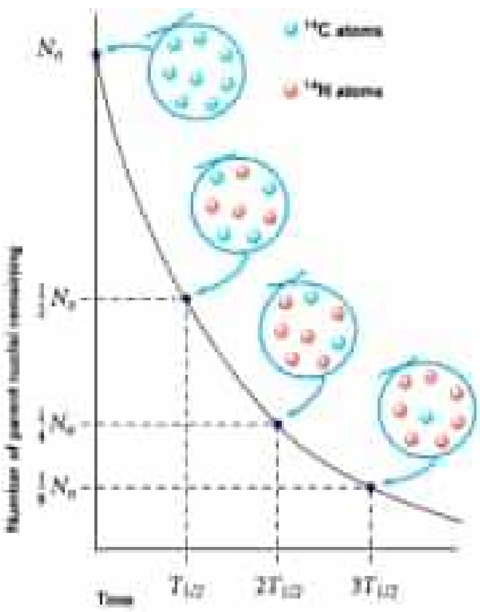


Figure: 27.3
decay curve for a radioactive sample

For example, the initial sample contains 8 carbon-14 atoms. After one half-life, there are 4 carbon-14 atoms and 4 nitrogen-14 atoms. By the next half-life, the number of carbon-14 atoms is reduced to 2, and the process continues. As the number of carbon-14 atoms decreases, the number of nitrogen-14 atoms increases.

The curve gets shallower and shallower as time goes on. This is because there are fewer and fewer radioactive nuclei left to decay, so the rate of decay slows down. This exponential decay is a characteristic feature of radioactive substances and is commonly used in radiocarbon dating and other applications in nuclear physics.

The key features of the exponential nature of radioactive decay include:

- The rate at which radioactive atoms decay is proportional to the quantity of the substance present.
- When plotted on a graph, the decay curve is a smooth, continuous curve that approaches but never reaches zero.
- The curve demonstrates a steeper decline at the beginning (short times) and a gradual decrease as time progresses.
- While we can't predict when a specific atom will decay, we can predict the probability of decay within a certain time frame.

27.2.7 Half-Life (t1/2):

The half-life of a radioactive substance is the time it takes for half of the initial amount of the substance to decay or transform into another element. It's a measure of the stability of an atom and the rate at which it loses its radioactivity.

Decay Constant (λ):

The decay constant, is a measure of the rate at which a radioactive substance decays. It's denoted by the symbol λ and represents the probability of decay per unit time.

Formula:

The half-life formula is:

t1/2 = ln(2) / λ

Where:

- t1/2 is the half-life
- ln(2) is the natural logarithm of 2 (approximately 0.693)

λ is the half-life constant (decay constant)

This shows that the half-life is inversely proportional to the decay constant. A higher decay constant means a shorter half-life, and vice versa.

Worked Example 27.3

A 50.0-g sample of carbon is taken from the pelvis bone of a skeleton and is found to have a carbon-14 decay rate of 200.0decays/min. It is known that carbon from a living organism has a decay rate of 15.0 decays/min-g and that C-14 has a half-life of 5730 years = 3.01×10^{9} min. Find the age of the skeleton.

Solution:

Step 1: Write down the known quantities and quantities to be found.

Given:A = 200 decays/min

Calculate the original activity A_0 from the decay rate and the mass of the sample:

$A_0 = 15$ decay/min-g × 50g = 7.5×10^2 decays/min

$T_{1/2} = 3.01 \times 10^9$min

Unknown: t = ?

Step 2: Age of skeleton can be found by the equation:

$$A = A_0 e^{-\lambda t}$$

Re-arranging,

$$t = \frac{\left(ln\frac{A}{A_0}\right)}{\lambda}$$

Step 3: Find the decay constant from the half-life:

$$\lambda = \frac{0.693}{T_{1/2}} = \frac{0.693}{3.01 \times 10^9} = 2.3 \times 10^{-10} min$$

Step 4: Age will be:

$$t = \frac{\left(ln\frac{200}{7.5\times10^2}\right)}{2.3\times10^{-10}} = \frac{1.32}{2.3\times10^{-10}} = 5.74\times10^9 min$$

Result: $t = 1.09\times10^4$ years.

Self-Assessment Questions:

1. The half-life of $^{131}_{53}I$ is 8.07 days. Calculate the decay constant for this isotope. What is the activity in Ci for a sample that contains 2.5×10^{10} iodine-131 nuclei?
2. A radioactive sample consists of 5.3×10^5 nuclei. There is one decay every 4.2 hrs.
   (a) What is the decay constant for the sample?
   (b) What is the half-life for the sample?

27.3 Mass Defect and Binding Energy:

When examining the nucleus of an atom, we find that its mass is actually less than the combined mass of its protons and neutrons. This discrepancy is due to the strong nuclear forces holding the nucleus together. To better understand this phenomenon, we need to learn some important terms.

Mass Defect and Binding Energy or the Hidden Energy within Atoms:

Two fundamental concepts that play a critical role in understanding atomic behavior are Mass Defect and Binding Energy.

Mass Defect:

Mass Defect refers to the difference between the total mass of individual protons, neutrons, and electrons in an atom and the actual mass of the atom.

Binding Energy:

Binding Energy is the energy required to break apart the nucleus of an atom into its constituent protons and neutrons. Exploring the Connection: as shown in figure 27.4

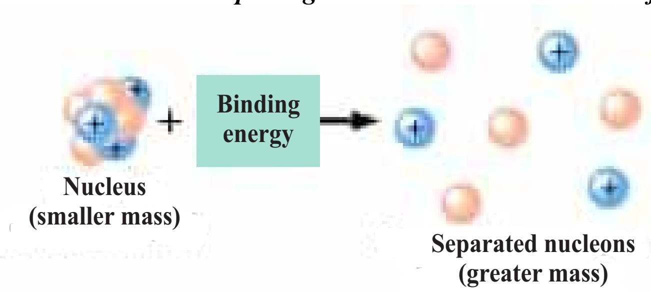


Figure 27.4. mass defect and binding energy of an atom

27.3.1 Unified Mass Scale and Mass Defect:

Unified mass scale:

It is also known as the **Unified Mass Scale** or **Atomic Mass Unit (amu)**, is a unit of measurement used in atomic and nuclear physics to express the mass of atoms and molecules on a scale that is convenient for working with atomic and molecular masses based on the carbon-12 isotope.

The Atomic Mass Unit (a.m.u) is defined as 1/12th of the mass of $_6C^{12}$atom (C−12). According to Avogadro's Hypothesis, the number of atoms in 12 gm of $_6C^{12}$ is equal to Avogadro number i.e., 6.023×10^{23}.

The mass of one carbon atom = $\frac{12}{6.023\times10^{23}} = 1.992678 \times 10^{-26}$kg.

Therefore 1 a.m.u is defined as:

$1\text{a.m.u} = \frac{1}{12} \times 1.992678 \times 10^{-26} = 1.660565 \times 10^{-27}$kg

For examples:

- Mass of a proton m_p = 1.007276 a.m.u= 1.67865×10^{-27}kg
- Mass of a neutronm_n = 1.008665 a.m.u= 1.67495×10^{-27}kg
- Hydrogen atom $_1H^1$ = 1.00784 a.m.u
- Chlorine atom = 35.47 a.m.u

Energy equivalent of a.m.u:

According to Einstein mass-energy relation, the energy equivalent to mass m given by: $E = mc^2$ where c is velocity of light.

Let mass m = 1 a.m.u = 1.680665×10^{-27}kg, c = 3×10^8 m/s. Then energy equivalent to 1 a.m.u is given as:

1 a.m.u = $1.680666 \times 10^{-27} \times (8 \times 10^8)^2 = 1.4925 \times 10^{-10}$ Joules

1 a.m.u= $\frac{1.4925\times10^{-10}}{1.602\times10^{-13}}$= 931.5 MeV

Where 1MeV =1.602×10^{-13}J. Energy equivalent to mass of electron, proton and neutron are:

m_e = 0.511MeV, m_p = 938.279MeV and m_n = 939.573MeV.

The mass and rest energy of all particles are given in the table 27.2.

Table 27.2 Mass and Rest energy of atomic particles

Particle	m (kg)	m (u)	E_R (MeV)
Proton	1.673×10^{-27}	1.007276	938.3
Neutron	1.675×10^{-27}	1.008665	939.6
Electron	9.109×10^{-31}	1.000549	0.5110

Binding Energy and Mass Defect:

Binding energy is the energy required to separate all the protons and neutrons in a nucleus as shown in figure 27.5. It is a measure of the stability of the nucleus. The mass defect, which is the difference between the mass of the nucleus and the sum of the individual masses of its protons and neutrons, is converted into binding energy according to Einstein's equation $E = mc^2$.

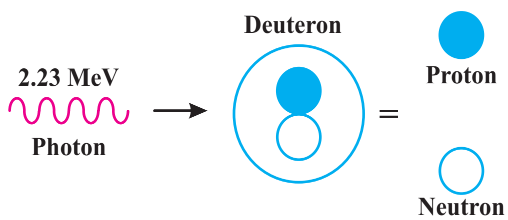


Figure 27.5 Splitting of nucleus

This energy is what holds the nucleus together, overcoming the repulsive forces between the positively charged protons. The mass of the nucleus so formed is less than the sum of the masses of the constituent protons and neutrons. This mass difference is called **mass defect** and is denoted by Δm.

If Z is the number of protons in the nucleus (Atomic number Z) and A is the atomic mass, then the number of neutrons in the nucleus is (A - Z). If m_p is the mass of the proton and m_n is the mass of the neutron, then:

Sum of the masses of the protons and neutrons = $Zm_p + (A - Z)m_n$.

If M_N is the actual mass of the nucleus, then Mass defect Δm is given by,

$$\Delta m = Zm_p + (A - Z)m_n - M_N \; \ldots\ldots\ldots 27.21$$

If mass defect is Δm then the binding energy of the nucleus according to Einstein mass energy relation is given as:

$$\text{Binding Energy} = E_B = \Delta mc^2$$

$$E_B = c^2[Zm_p + (A-Z)m_n - M_N]$$

where M_N is the mass of the nucleus, m_p the mass of the proton and m_n the mass of the neutron.

Worked Example 27.5

Calculate the mass defect and binding energy of deutron which contains one proton and one neutron. The mass of deutron nucleus is 2.0136 a.m.u, mass of a proton is 1.0073 a.m.u and mass of a neutron is 1.0087 a.m.u.

Solution:

Step 1: Write down the known quantities and quantities to be found.

mass of proton:1.0073 a.m.u, mass of neutron = 1.0087 a.m.u and mass of deutron = 2.0136 a.m.u.

Unknown: $\Delta m = ?$, $E_B = ?$

Step 2: The combined mass is of proton and neutron = [1.0073 + 1.0087] = 2.1060 a.m.u.

Step 3: Therefore, mass defect: $\Delta m = 2.1060 - 2.0136 = 0.0024$ a.m.u.

The biding energy is given by:

$$E_B = \Delta m \times 931.5 = 0.0024 = 2.2356 MeV$$

Result: $E_B = 2.2356 MeV$

27.3.2 Binding Energy Per Nucleon:

The binding energy per nucleon ($\overline{E_B}$) is the average energy required to release a nucleon from the nucleus. It is given mathematically as

$$\overline{E_B} = \frac{E_B}{A} \ldots\ldots\ldots 27.22$$

where A is the total number of nucleons in the nucleus.

The binding energy per nucleus $\overline{E_B}$ of a nucleus is more important than total binding energy E_B of the nucleus because $\overline{E_B}$ determines the stability of the nucleus. Higher is the value of the binding energy per nucleon, more stable is the nucleus. The nuclei with less binding energy per nucleon are comparatives less stable.

The graph between binding energy per nucleon and mass number of different nuclei is shown in Figure 27.6. Following are the main features of binding energy curve:

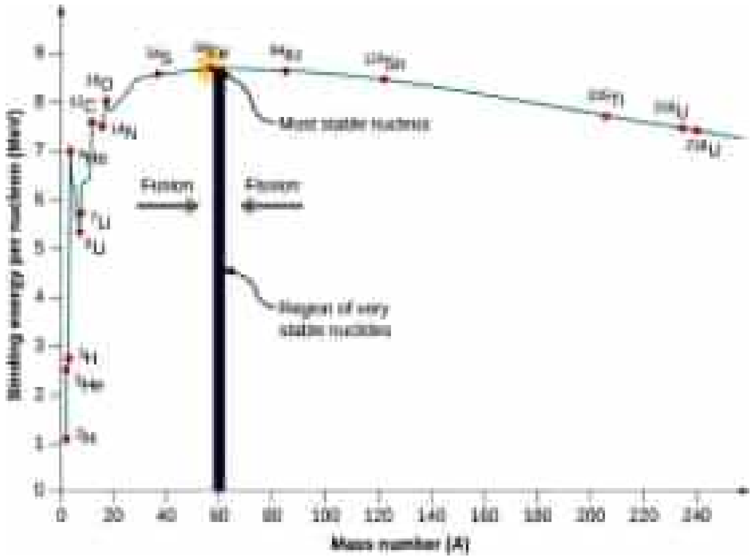


Figure 27.6 Binding energy per nucleon and mass number of different nuclei

- The binding energy per nucleon for light nuclei (i.e. $_aH^2$) is very small. The binding energy per nucleon increases rapidly for nuclei up to mass number 20.
- The curve possesses peaks corresponding to nuclei $_2He^4$,$_4Be^8$, $_6C^{12}$, $_8O^{16}$ and $_{10}Ne^{20}$.
- The peaks indicate that these nuclei are more stable than other nuclei in their neighborhood. ù After mass number 20 binding energy per nucleon increases gradually.
- The curve has average value of binding energy per nucleon of about 8.6 MeV for a very considerable range of mass number 10 to 120. In this range the curve is more or less flat.
- For mass number A = 6(i.e., $_{26}F^{56}$), the binding energy per nucleon is maximum and is equal to 8.8 MeV.

- The nuclei of intermediate masses (i.e. A=40 to 120) are most stable and a very high amount of energy has to be supplied to liberate each of their nucleons.
- The binding energy per nucleon has a low value for both very light and very heavy nuclei.
- In order to attain higher value of binding energy per nucleon, the lighter nuclei may unite together to form a heavier nucleus (process of nuclear fusion) or a heavier nucleus may split into light nuclei (process of nuclear fission). In both these nuclear processes, the resulting nucleus acquires greater value of binding energy per nucleon and large amount of energy is released.

27.4 Nuclear Reactions:

Any process that involves a change in the nucleus of an atom is called a nuclear reaction. Mathematically,

$$X + x \rightarrow Y + y + Q$$

where X is the target, x are the projectiles, y are the ejectiles and Y is called the residual(product) nucleus.

DO YOU KNOW?

Rutherford produced the first nuclear reaction in a laboratory experiment in 1919. He used 7.7 MeV alpha particles from the decay of ^{210}Po radioactive source on nitrogen and demonstrated the following nuclear changes:

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H + Q$$

The above equation is called Nuclear Reaction.

27.4.1 Energy Released from Nuclear Reactions:

The energy is either absorbed or emitted which is called **Q value** and it is equal to the mass defect. The Q value can also be define as the difference between the rest energies of X and x and the rest energies of Y and y:

$$Q = (m_X + m_x - m_Y - m_y)c^2 \ldots\ldots 27.23$$

The value of Q is taken as positive when the energy is released, and its corresponding reaction is called **exothermic.** Similarly, the value of Q is taken as negative when the energy is absorbed, and its corresponding reaction is called **endothermic**.

27.4.2 Conservation of Atomic and Mass Numbers:

Whenever there is a nuclear decay, there is always some physical quantities need to be conserved or remain constant. The following are rules for any nuclear reaction:

1. The total of the atomic numbers (Z) on the left is the same as the total on the right of the given equation because charge must be conserved.
2. The total of the mass numbers (A) on the left is the same as the total on the right of equation because nucleon number must be conserved.

For example, in following nuclear reaction, the total atomic number and mass number remain same on both sides of the equation:

$$^{A}_{Z}X = ^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He \ldots\ldots 27.24$$

In above reactions, Z=92 on the left side which is equal to 90+2=92 on the right side. Similarly, A=238 on the left side which is equal to 234+4=238 on the right side.

27.4.3 Conservation of Mass and Energy:

According to Einstein's mass-energy relationship ($E = mc^2$), in all nuclear reactions, the total sum of mass and energy must conserve. This means the total mass on the left side of the equation (before the decay) is equal to the total mass on the right side (after the decay), plus the Q value.

The Q value represents the mass difference before and after the decay, and this difference is converted into energy according to the mass-energy relationship ($E=mc^2$). This released energy is typically in the form of kinetic energy of the decay products, such as alpha particles, beta particles, or gamma rays.

So, the equation that represents the conservation of mass and energy in radioactive decay can be expressed as:

Total mass before decay=Total mass after decay+Q-value

This equation underscores the principle that while mass may appear to decrease due to the emission of particles; the lost mass is accounted for in the form of energy released during the decay process.

27.4.4 Nuclear Fission and Fusion:

The uranium nucleus, upon absorbing a neutron, underwent a process of splitting into two roughly equal parts. This revelation was striking because, up until then, known nuclear reactions had only involved the ejection of tiny fragments, such as neutrons, protons, or alpha particles, from a nucleus.

Nuclear Fission:

The splitting of a heavy nucleus (A > 230) into two medium-mass nuclei in a nuclear reaction with the release a huge amount of energy due to mass defect is called **nuclear fission**. For example, when a uranium nucleus (U-235) is bombarded by a slow moving neutron (called thermal neutron), the U-235 nucleus splits into two medium-mass nuclei with the release of huge amount of energy as shown in figure 27.7.

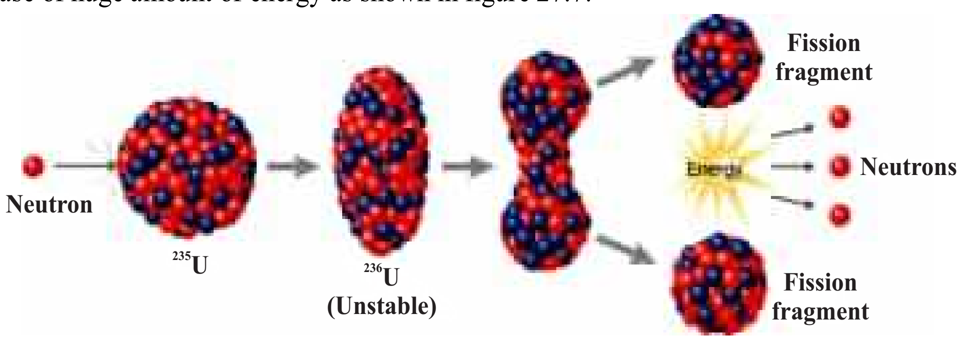


Figure 27.7 Heavy nuclei splits into two light nuclides (nuclear fission process)

This fission reaction is given below:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U^{*} \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n + 200MeV \;\ldots\ldots 27.25$$

Where * on $\mathbf{U}^*$ represents that U-236 is in excited state. Two things are worth noting in this fission reaction. First, a huge amount of energy (about 200 MeV per U -235 nucleus) is released in the process.

Secondly, on the average 2 to 3 neutrons are released in the process. The released neutrons can further cause splitting of ${}_{92}U^{235}$nuclei and lead to self-sustaining nuclear fission.

When nuclear fission takes place, it is found that the sum of the masses of fission products is very slightly less than the sum of the masses of reactant products. As a result, there occurs a mass defect (m) in nuclear fission. This mass defect is converted into energy according to the relation $E = mc^2$. The energy released in the above fission can be determined from the mass defect that occurs in the process.

Total mass before fission:

mass of U-235 = 235.043933 a.m.u
mass of neutron = 1.008665 a.m.u
sum of masses before fission = 236.052598 a.m.u

Total mass after fission:

mass of two fragments = 232.812000 a.m.u
mass of 3 neutrons = 3.025995 a.m.u
sum of masses after fission = 235.837995 a.m.u
Mass defect Δm= 236.052598-235.837995 = 0.214603 a.m.u
Therefore, energy released per fission of U-235 = 0.214603 X931.5 =**200 MeV**

Nuclear Fusion:

The process of nuclear fusion is just the reverse of nuclear fission. But the energy released per unit mass in nuclear fusion is much greater than the energy released per unit mass in nuclear fission. When two light nuclei are combined to form a heavy nucleus, the mass of the product nucleus is slightly less than the sum of the masses of the light nuclei fusing together.

The process of combining two light nuclei to form a heavy nucleus with the release of huge amount of energy due to mass defect is known as nuclear fusion.

This mass defect results in the release of a huge amount of energy according to the relation $E = mc^2$. When two nuclei of heavy hydrogen or deuterium (${}_1H^2$) are combined, the following reaction is possible:

$${}_1^2H + {}_1^2H \rightarrow {}_1^3H + {}_1^2H + 4MeV \ldots\ldots 27.26$$

figure 27.8 shows the nucleus of tritium (${}_1H^3$) so formed can again fuse with a deuterium nucleus (${}_1H^2$) to give the following reaction:

$${}_1^3H + {}_1^2H \rightarrow {}_2^4H + {}_0^1n + 17.6MeV \ \ldots\ldots\ldots 27.27$$

The net result of these two nuclear reactions is that three deuterium (${}_1H^2$) nuclei fuse together to form a helium nucleus (${}_2He^4$) and a neutron with the release of 21.6 MeV (4.0 + 17.6 = 21.6 MeV). This energy of 21.6 MeV is obtained in

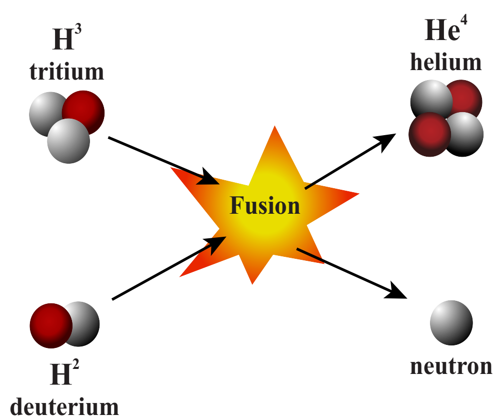


Figure 27.8 process of nuclear fusion

the form of kinetic energy of proton ($_1H^1$) and a neutron $_0n^1$.

Note that energy released in the fusion reaction is 21.6 MeV which is very much less than the energy of about 200 MeV released in the fission of $_{92}U^{235}$ nucleus. But this does not mean that fusion is a weaker energy source than fission. The sun and other stars are very hot so nuclei are moving fast enough for fusion to take place and the energy released keeps the temperature high so that further fusion reactions can occur. But on earth, such high temperatures are not attained in a controlled manner. However, the temperature produced by a fission bomb (atom bomb) is close to 10^8K. Therefore, **fission bomb** can be used to cause the fusion process.

The practical problems involved in producing energy from fusion to make a practical and cost-effective form of power is: Temperature, Pressure and confinement.

27.4.5 Fission Chain Reaction:

The nuclear fission which once started continues till all the atoms of the fissionable material are disintegrated is called chain reaction. Figure 27.9 shows how chain reaction is initiated in uranium by a single neutron. When a single neutron initially causes the fission of $_{92}U^{235}$ nucleus, 3 neutrons are released along with huge amount of energy. These 3 neutrons in turn cause three more nuclei to split, thereby liberating a total of 9 neutrons and so on. The process proceeds very quickly and in a very short time the whole of the uranium undergoes fission. For the fission to be self-sustaining, the number of emitted fission neutrons should be more than the incident ones. Under such conditions, the fission neutrons keep on increasing, thus maintaining the chain reaction. A very common term, called **neutron multiplication factor** (or **reproduction factor**), is often used in chain reaction. It is represented by k:

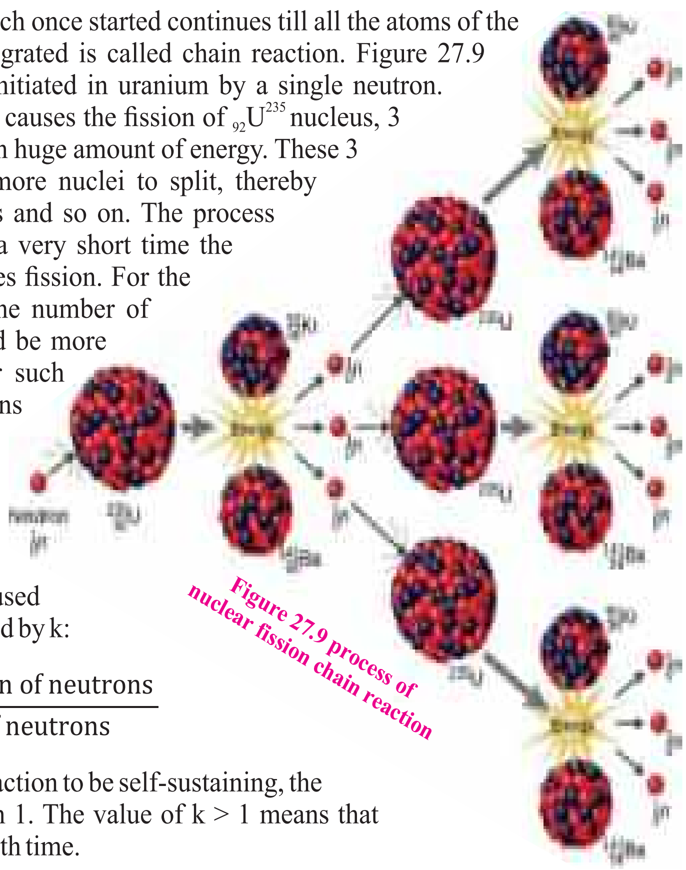


Figure 27.9 process of nuclear fission chain reaction

$$k = \frac{\text{rate of production of neutrons}}{\text{rate of loss of neutrons}}$$

Obviously, for chain reaction to be self-sustaining, the value of k must be greater than 1. The value of k > 1 means that neutrons increase or multiply with time.

There are two types of fission chain reactions (according to neutron multiplication factor k):

1. **Controlled chain reaction:**

A controlled chain reaction is a chain reaction in which the number of neutrons produced can be controlled. This allows for a sustained release of energy, which can be used for beneficial purposes, such as generating electricity. A chain reaction can be controlled by systematically removing some of the fission neutrons from the reaction vessel. The apparatus in which controlled chain reaction takes place is called a **nuclear reactor**.

DO YOU KNOW?

The atomic bombs dropped on Hiroshima and Nagasaki during World War II utilized uncontrolled chain reactions.

2. **Uncontrolled chain reaction:**

An uncontrolled chain reaction is a chain reaction in which the number of neutrons produced cannot be controlled. This results in a sudden and rapid release of energy, which can be destructive. For example, atomic bomb.

27.4.6 Nuclear Reactor:

A nuclear reactor is a device in which controlled fission chain reaction takes place. A nuclear reactor is also known as nuclear pile or atomic pile.

Such a system was first achieved with uranium as the fuel in 1942 by Enrico Fermi.He used uranium-235 isotope that releases energy through nuclear fission. The schematic diagram of nuclear reactor is shown in figure 27.10

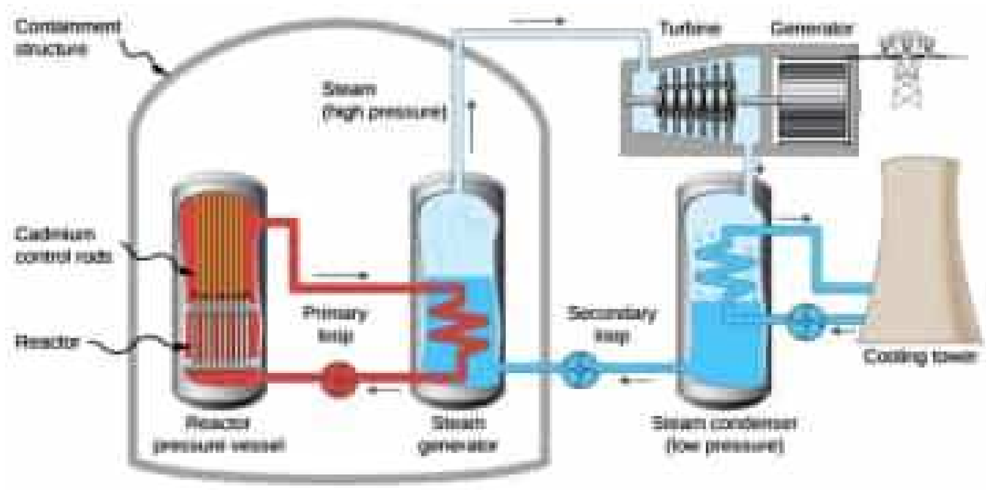


Figure 27.10 schematic diagram of Nuclear reactor

The following are the main components of the nuclear reactor:

Fissionable Substance:

Nuclear reactors use fuel, typically enriched uranium or plutonium, to sustain the fission chain reaction. The U-235 is fissionable, but uranium from ore typically contains only about 0.7 percent of U-235, with the remaining 99.3 percent being the U-238 isotope. Because uranium-238 tends to absorb neutrons, reactor fuels must be processed to increase the proportion of U-235 so that the reaction can sustain itself. This process is called **enrichment**.

Moderator:

The function of the moderator is to slow down the highly energetic neutrons produced in the process of fission of U-235 to thermal energies. Heavy water (D_2O), graphite, beryllium, etc., are used as moderators. Ideally, moderators have low atomic weight and low absorption cross-section for neutrons.

Control Rods:

Control rods are made of materials like boron or cadmium that absorb neutrons, regulating the rate of the fission chain reaction. By adjusting the position of control rods within the reactor core, operators can control the power output and maintain stability.

Coolant:

Coolant circulates through the reactor core to transfer heat away from the fuel and other reactor components. Common coolants include water, heavy water, or gases like helium or carbon dioxide. The heated coolant then transfers its thermal energy to a secondary loop containing water, which turns into steam. This steam drives turbines connected to generators, producing electricity.

Protective Shield:

In a nuclear reactor, there are many types of harmful radiations emitted which are dangerous for all living things. In order to protect from these radiations, the reactor is surrounded by a massive biological shield.

27.4.7 Nuclear Fusion in Sun and Stars:

Every second, the sun fuses around 500 million metric tons of hydrogen in its core. The core of the sun is incredibly hot, with temperatures reaching about 20 million degrees Celsius, while its surface temperature is around 5 million degrees Celsius.

The sun is a star which is primarily made up of hydrogen (about 75%), helium (about 25%), and trace amounts of other elements. It produces energy through a process called nuclear fusion, where hydrogen atoms combine to form helium atoms, releasing light and heat in the process.

The fusion in the sun can take place in two different reaction sequences, the most common of which, the **Proton-Proton (PP) Cycle** and the other one is **Carbon-Nitrogen-Oxygen (CNO) Cycle**.

The Proton-Proton Cycle involves the fusion of protons (hydrogen nuclei) to form helium as shown in figure 27.11. Hans Bethe was the first to work out the detailed steps of the PP cycle in 1938. The PP cycle is a

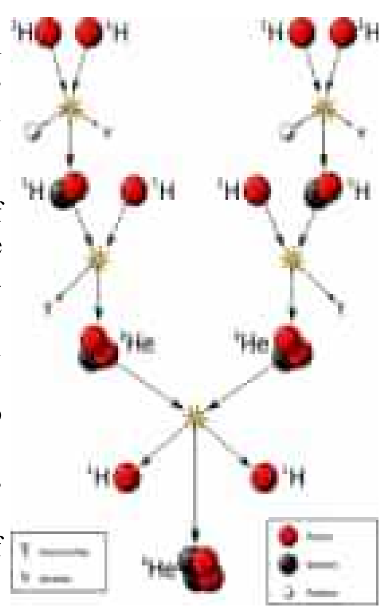


Figure 27.11
Proton-proton cycle to form helium

very efficient way to generate energy in the Sun. In the p–p chain, two protons first fuse to produce a deuterium nucleus which combines with another proton to yield ${}^3_2He$. Two ${}^3_2He$ nuclei fuse and form ${}^4_2He$ and two protons. These reactions can be represented by the equations

$${}^1_1H + {}^1_1H \rightarrow {}^2_1H + {}^0_1e + \nu + Q$$
$${}^1_1H + {}^2_1H \rightarrow {}^3_2He + \gamma + Q$$
$${}^3_2He + {}^3_2He \rightarrow {}^4_2He + {}^1_1H + {}^1_1H + Q \ldots\ldots\ldots 27.28$$

The net Q value of the chain reactionsisabout 26 MeV.

The Carbon-Nitrogen-Oxygen (CNO) cycle was independently suggested by Carl von Weizsacker and Hans Bethe in the late 1930s. The CNO cycle is a series of nuclear fusion reactions that convert hydrogen into helium as predicted in figure 27.12, and it is the primary source of energy in stars that are more than 1.3 times as massive as the Sun. This cycle uses carbon, nitrogen, and oxygen as catalysts to convert hydrogen to helium:

$${}^{12}_6C + {}^1_1H \rightarrow {}^{13}_7N + \gamma$$
$${}^{13}_7N \rightarrow {}^{13}_6C + e^+ + \nu_e$$
$${}^{13}_6C + {}^1_1H \rightarrow {}^{14}_7N + \gamma$$
$${}^{14}_7N + {}^1_1H \rightarrow {}^{15}_8O + \gamma$$
$${}^{15}_8O \rightarrow {}^{15}_7N + e^+ + \nu_e$$
$${}^{15}_7N + {}^1_1H \rightarrow {}^{12}_6C + {}^4_2He + \gamma$$

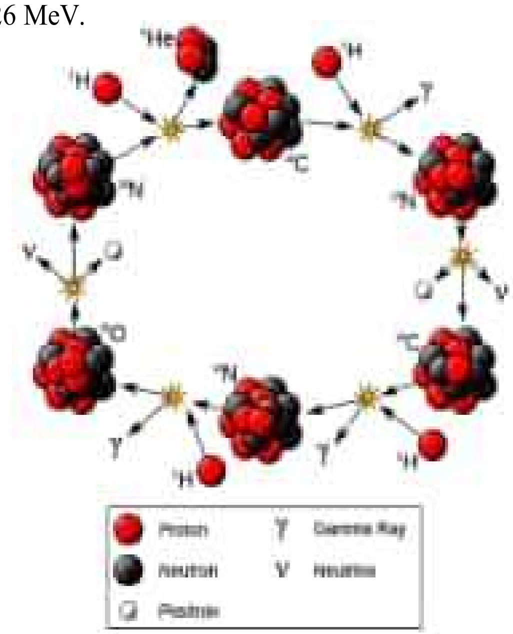


Figure 27.12
The Carbon-Nitrogen-Oxygen (CNO) cycle

In the CNO cycle, four protons fuse, using carbon, nitrogen and oxygen isotopes as a catalyst, to produce one alpha particle, two positrons and two electron neutrinos. Combining all the above reactions, the net reaction for the CNO cycle comes out to be

$$4{}^1_1H \rightarrow {}^4_2He + 2\beta^+ + 2\vartheta + 26.7MeV \ldots\ldots\ldots 27.29$$

We see that the net energy release is nearly same for both cycles.

27.5 Radiation Exposure:

Radiation refers to the transmission of energy in the form of waves or particles. This energy spectrum contains a vast range, from gentle radio waves and visible light to the more impactful X-rays, gamma rays, and even cosmic rays. The key factor influencing its impact is the **dose**, measured in units like milli-sieverts (mSv).

27.5.1 Nuclear Radiation Exposure and its Biological Effects:

Exposure is defined as the amount of ionization produced in a unit mass of dry air at standard pressure (STP). Its unit is 1 roentgen = 1R = 2.58 X 10^{-4} C/kg.

There are two main types of radiation exposure: **external** and **internal**.

1. **External radiation** exposure occurs when a person is exposed to radiation from a source outside the body, such as an X-ray machine or a nuclear power plant.
2. **Internal radiation** exposure occurs when a person ingests or inhales radioactive material, which can then accumulate in the body and emit radiation.

Radiation exposure can also be measured in other units, including sieverts (Sv), millisieverts (mSv), and microsieverts (μSv).

Biological Effects of Radiation:

When radiation is absorbed by matter, especially living tissue, it can induce significant changes. The biological effects of radiation are diverse and depend on several factors, including:

- **Type of radiation:** Each type interacts differently. Alpha particles, while unable to penetrate deeply, cause disorder within cells they reach. Beta particles travel farther but deposit less energy, while gamma rays can pierce through tissues, potentially affecting multiple organs.
- **Dose absorbed:** This quantifies the energy deposited per unit mass of tissue. Higher doses generally translate to more pronounced effects.
- **Duration of exposure:** Acute (short-term) exposure like an X-ray differs from chronic (long-term) exposure from environmental sources or occupational hazards.
- **Individual sensitivity:** Age, health status, and genetic predispositions can influence susceptibility.

The biological effects of radiation include:

- **Acute radiation syndrome (ARS):** High-dose exposure can trigger ARS, a complex condition affecting multiple organ systems with symptoms like nausea, vomiting, hair loss, and bone marrow suppression.
- **Cancer risk:** Chronic low-dose or high-dose exposures can increase the risk of various cancers, depending on the affected tissue.
- **Genetic effects:** Germ cell mutations can lead to congenital disabilities in offspring.
- **Reproductive issues:** Fertility can be impaired, and miscarriage risk may increase.
- **Developmental effects:** Early exposure inutero can affect fetal development, causing physical and cognitive impairments.

27.5.2 Dosimetry:

Dosimetry is the science of measuring and quantifying radiation dose. It is a field of physics that deals with the interaction of radiation with matter and the biological effects of radiation exposure.

Dosimetry is derived from the Greek word ‘dos’, meaning ‘gift’ or ‘a giving’. In the context of physics, it represents the scientific discipline that quantifies the amount of radiation ‘given’ to or absorbed by an object or body. The goal is to determine potential biological effects, ensuring safe limits and monitoring radiation exposure.

Key Components of Dosimetry:

1. **Absorbed Dose:** The amount of radiation energy absorbed per unit mass of the material. Measured in Gray (Gy), it is a pivotal metric in understanding radiation’s effect on tissues.

2. **Equivalent Dose:** Not all radiation types have the same biological impact, even if their absorbed doses are identical. To account for this, radiation weighting factors are introduced to derive the equivalent dose. Measured in Sievert (Sv), it provides a more biologically relevant dose metric.
3. **Effective Dose:** Considering that different tissues have varying sensitivities to radiation, tissue weighting factors are used. The effective dose, also in Sieverts (Sv), offers a measure that summarizes the potential overall harm to the whole organism.
4. **Operational Dose Quantities:** These are practical quantities used for routine monitoring in radiological protection. They are designed to estimate effective dose or equivalent dose to a particular tissue. Examples include ambient dose equivalent and personal dose equivalent.

Dosimetry is performed using devices known as **dosimeters**, which can be worn by people working with or around radioactive materials to monitor their exposure levels. These devices can measure and record the dose of radiation over time.

27.5.3 Medical Uses of Nuclear Radiation:

Medical use of nuclear radiation is quite common in today's hospitals and clinics. It contains various diagnostic and therapeutic applications that control the properties of ionizing radiation to diagnose and treat diseases. Some examples include:

Imaging:

- **X-rays:** The workhorse of medical imaging, X-rays utilize electromagnetic radiation to reveal fractures, bone structures, and internal injuries.
- **CT scans:** Combining multiple X-ray images, CT scans provide detailed cross-sectional views of organs and tissues, aiding in diagnosing tumors, infect Ions, and internal bleeding.
- **PET scans:** Positron emission tomography (PET) utilizes radioactive tracers to map metabolic activity within the body, uncovering cancerous tumors and other metabolic disorders.

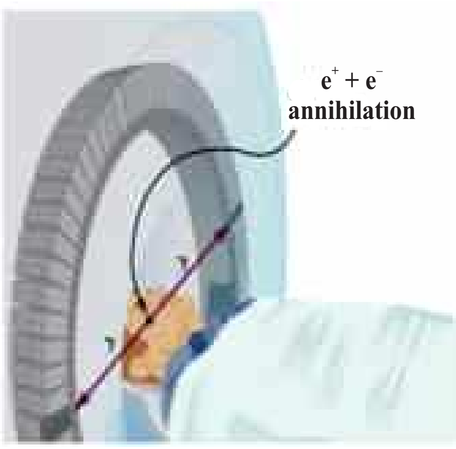


Figure 27.13 The CT scan

Nuclear medicine procedures:

- **Bone scans:**
  Radioactive tracers identify bone diseases like osteoporosis and cancer metastases.
- **Thyroid scans:**
  Radioactive iodine helps diagnose and treat thyroid disorders.
- **Lung scans:**
  Technetium-99m helps assess lung function and detect blood clots.

Treatment:

- **Radiotherapy:** Harnessing the destructive power of radiation, targeted beams are used to shrink and destroy cancerous tumors with remarkable precision. This non-invasive therapy plays a crucial role in treating various cancers, often in conjunction with surgery and chemotherapy.
- **Brachy therapy:** Radioactive implants placed directly within tumors deliver high doses of radiation locally, minimizing damage to surrounding tissue. This approach is particularly effective for treating prostate, cervical, and head and neck cancers.
- **Radioisotope therapy:** Radioactive isotopes are used to treat specific conditions like hyperthyroidism (radioactive iodine) and blood disorders (radioactive phosphorus).

Other Applications:

- **Pain management:** Radiofrequency ablation utilizes radio waves to heat and destroy nerve tissue, offering pain relief for chronic conditions like back pain and arthritis.
- **Sterilization:** Medical instruments and equipment are sterilized using gamma radiation, ensuring sterility and preventing infections.

27.5.4 Exposure of radiation:

This process creates charged particles (Ions) and free radicals, which can disrupt molecular structures and biological processes. Examples of ionizing radiation include:

- **X-rays:** Electromagnetic radiation produced by high-energy electron beams or X-ray tubes. X-rays are commonly used in medical imaging, security screening, and industrial applications.
- **Gamma rays:** High-energy electromagnetic radiation emitted by radioactive decay processes, such as those occurring in radioactive isotopes like cobalt-60 and cesium-137. Gamma rays are used in medical imaging (gamma cameras), radiation therapy, and sterilization processes.
- **Alpha particles:** Alpha particles are emitted during the decay of heavy elements like uranium and radium and have low penetrating power but can cause significant damage if inhaled or ingested.
- **Beta particles:** Beta particles can penetrate deeper into tissues than alpha particles but are less damaging. They are used in medical imaging (positron emission tomography) and radiation therapy.
- **Neutrons:** Neutrons can induce nuclear reactions and are used in neutron activation analysis, neutron radiography, and certain types of cancer therapy.
- **Cosmic rays:** High-energy particles from outer space continuously bombard Earth's atmosphere, generating secondary radiation that reaches the surface.
- **Industrial applications:** Gauges, sterilization processes, and smoke detectors often employ ionizing radiation for various industrial purposes.

These forms of ionizing radiation have various applications in medicine, industry, research, and other fields but require careful handling and monitoring to minimize risks to human health and the environment.

27.5.5 Uses of Radioactive Tracers:

One of the most important uses of nuclear radiation is the location and study of diseased tissue. This can be done by radioactive tracers. **Radioactive tracers** are radioactive substances that are used to track the movement and behavior of specific molecules or compounds in various systems. These tracers emit radiation that can be detected through biochemical reactions, metabolic pathways, fluid flow, and environmental transport. Some examples of the uses of radioactive tracers include:

Medical Imaging:

- **Positron Emission Tomography (PET):** Radiotracers labeled with positron-emitting isotopes (e.g., fluorine-18, carbon-11) are injected into the body and used to visualize metabolic activity, blood flow, and receptor binding in tissues. PET imaging is valuable for diagnosing and monitoring diseases such as cancer, heart disease, and neurological disorders.

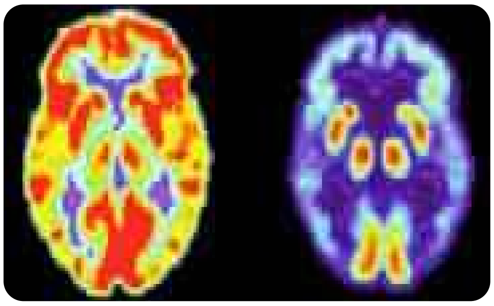


Figure 27.14 Positron Emission Tomography

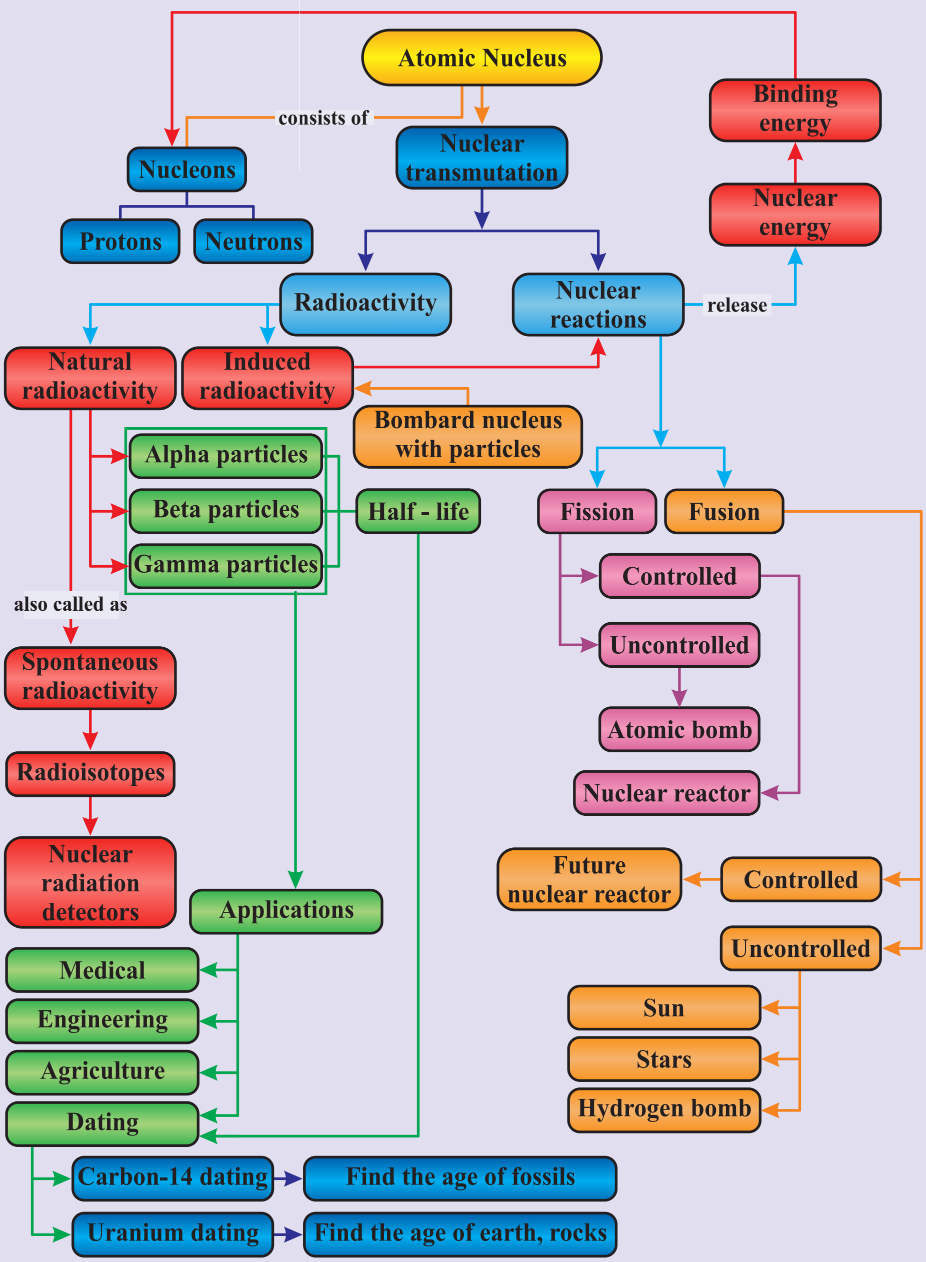
Industrial Processes:

- **Flow Visualization:** Radiotracers are injected into fluids or gases to track flow patterns and detect leaks or blockages in industrial pipelines, heat exchangers, and reactors. This technique is used in industries such as petrochemicals, food processing, and nuclear power.
- **Process Optimization:** Radiotracers are used to monitor and optimize chemical reactions, mixing processes, and material transport in industrial processes. By tracking the movement of tracers, engineers can identify bottlenecks, improve efficiency, and ensure product quality.
- **Soil Fertility and Nutrient Uptake:** Radioactive isotopes like phosphorus-32 (^{32}P) are used to study nutrient uptake in plants. By tagging fertilizers with these tracers, scientists can track how nutrients move through the soil and are absorbed by plants. This information helps in optimizing fertilizer application, ensuring that crops receive the right amount of nutrients.
- **Environmental Impact Assessments:** Radioactive tracers help in studying the environmental impact of agricultural practices. For instance, they can be used to trace the movement of pollutants or contaminants from agricultural fields to water bodies, enabling better management practices to protect the environment.

SUMMARY

- Variants of a particular chemical element that have the same number of protons but different numbers of neutrons, resulting in different atomic masses is known as isotopes.
- Mass Spectrograph (Analytical device) used to measure the charge to mass ratio of ions, useful in identifying isotopic compositions and molecular structures.
- The process (radioactivity decay) by which an unstable atomic nucleus loses energy by emitting radiation, resulting in the transformation of one element into another
- Activity measures the rate of decay of a radioactive substance, while the decay constant is a probability factor that describes the likelihood of an atom decaying per unit time.
- The time required for half of the radioactive atoms in a sample to decay, a characteristic property of each radioactive isotope.
- The energy (Binding Energy) required disassembling a nucleus into its individual protons and neutrons, indicating the stability of the nucleus.
- Fission is the splitting of a heavy nucleus into lighter nuclei with the release of energy, while fusion is the combining of light nuclei to form a heavier nucleus, also releasing energy.
- A self-sustaining sequence of nuclear fission reactions, where the neutrons produced by each fission event causes further fissions is known as chain reaction
- A device (Nuclear Reactor) used to initiate and control a sustained nuclear chain reaction, commonly used for energy production.
- The absorption (Nuclear Radiation Exposure) of energy from nuclear radiation by living tissues, which can cause cellular damage and increase cancer risk.
- Dosimetry is the measurement and calculation of the absorbed dose of radiation by the human body, crucial for assessing exposure and ensuring safety.
- Strategies include time minimization, distance maximization, and shielding, along with regulatory measures to protect individuals from harmful radiation levels is called Limiting exposure to ionizing radiation.

CONCEPT MAP


Atomic Nucleus
consists of
Nucleons
Protons
Neutrons
Nuclear transmutation
Binding energy
Nuclear energy
Radioactivity
Nuclear reactions
release
Natural radioactivity
Induced radioactivity
Bombard nucleus with particles
Alpha particles
Beta particles
Gamma particles
Half - life
Fission
Fusion
Controlled
Uncontrolled
Atomic bomb
Nuclear reactor
also called as
Spontaneous radioactivity
Radioisotopes
Nuclear radiation detectors
Applications
Future nuclear reactor
Controlled
Uncontrolled
Medical
Engineering
Agriculture
Dating
Sun
Stars
Hydrogen bomb
Carbon-14 dating
Find the age of fossils
Uranium dating
Find the age of earth, rocks

EXERCISE

Section (A): Multiple Choice Questions (MCQs)
Choose the correct answer:

1. Identify particle x in the following nuclear reaction $^{9}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + x$
   (a) Electron (b) proton (c) neutron (d) photon
2. In the equation $^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{15}P + X$,The correct symbol for X is:
   (a) $^{-1}_{0}e$ (b) $^{1}_{1}H$ (c) $^{4}_{2}He$ (d) $^{1}_{0}n$
3. Beta rays emitted by a radioactive material are:
   (a) Electromagnetic radiations (b) The electrons orbiting around the nucleus
   (c) Charged particles emitted by the nucleus (d) Neutral particles
4. The number of α and β particles emitted in the following radioactive decay is:
   $$^{200}_{90}X \rightarrow ^{168}_{80}Y + ^{?}_{?}X$$
   (a) 8 and 6 (b) 6 and 8 (c) 8 and 8 (d) 6 and 6
5. If radium has half-life of 5 years. Thus for a nucleus in a sample of radium, the probability of decay in ten years is:
   (a) 50% (b) 75% (c) 100% (d) 60%
6. Emission of β particles by an element affects its mass number **A** in the following way:
   (a) Increases by 1 (b) decreases by 1
   (c) Increases by 2 (d) remains the same
7. As the number of nucleons in a nucleus increases, the binding energy per nucleon:
   (a) Increases continuously with mass number
   (b) Decreases continuously with mass number
   (c) remains constant with mass number
   (d) First increases and then decreases with increase of mass number
8. Moderator in a nuclear reactor slows down the neutrons to:
   (a) Decrease the probability of escape (b) Increase the probability of nuclear fission
   (c) Decrease the probability of absorption (d) all of the above
9. Emission of β^{+} particles by an element affects its atomic number Z in the following way:
   (a) Increases by 1 (b) decreases by 1
   (c) Increases by 2 (d) remains the same
10. The half life period of a radioactive element is 100 days. After 400 days, 16 g of the element will be reduced to
    (a) 8g (b) 4g (c) 2g (d) 1g

Section (B): CRQs (Short Answered Questions):

1. Why are protons and neutrons necessary for the stability of an atomic nucleus?
2. How do isotopes of an element differ and why are these differences significant?
3. Name the two methods of controlling a chain reaction.
4. Why is nuclear decay described as spontaneous and random?
5. Explain what happens during the nuclear fusion process.

6. How are activity and decay constant related in radioactive materials?
7. What is meant by binding energy and binding energy per nucleon?
8. Why is the concept of half-life important in studying radioactive substances?
9. Explain the process of positron emission.

Section (C): ERQs (Long Answered Questions):

1. What is radioactivity? State the law of radioactive disintegration. Show that radioactive decay is exponential in nature.
2. Explain the main differences between alpha, beta, and gamma emissions.
3. A fission reactor produces energy to drive a generator. Describe briefly how this energy is produced.
4. Define Q-value of a nuclear reaction and its significance.
5. Describe the construction and working of GM counter.
6. Discus nuclear reactions induced by neutrons. Why are neutrons preferred to other particles?
7. What is a nuclear reaction? Explain nuclear fission and fusion.
8. How do the Sun and stars produce energy? What is the proton-proton cycle? Explain with details.

Section (D): Numerical:

1. In 9.0 days the number of radioactive nuclei decreases to one-eighth the number present initially. What is the half-life (in days) of the material? **[Ans: 3 days]**
2. The $^{32}_{15}P$ isotope of phosphorus has a half-life of 14.28 days. What is its decay constant in units of s^{-1}? **[Ans: $5.62\times10^{-7}s^{-1}$]**
3. Find the binding energy (in MeV) for lithium $^{7}_{3}Li$ (atomic mass = 7.016 003 u). **[Ans: 39.2 MeV]**
4. The binding energy of a nucleus is 225.0 MeV. What is the mass defect of the nucleus in atomic mass units? **[Ans: 0.2415 u]**
5. A copper penny has a mass of 3.0 g. Determine the energy (in MeV) that would be required to break all the copper nuclei into their constituent protons and neutrons. Ignore the energy that binds the electrons to the nucleus and the energy that binds one atom to another in the structure of the metal. For simplicity, assume that all the copper nuclei are $^{63}_{29}Cu$ (atomic mass = 62.939 598 u). **[Ans: 1.51249×10^{25}MeV]**
6. Write the β^+ decay process for each of the following nuclei with their proper chemical symbols including Z and A for each daughter nucleus: (a) $^{18}_{9}F$(b) $^{15}_{8}O$. **[Ans: (a) $^{18}_{9}F \rightarrow {}^{18}_{8}O + e^+ + \nu_e$ (b) $^{15}_{8}O \rightarrow {}^{15}_{7}N + e^+ + \nu_e$]**
7. A device used in radiation therapy for cancer contains 0.50 g of cobalt $^{60}_{27}Co$ (59.933 819 u). The half-life of $^{60}_{27}Co$ is 5.27 years. Determine the activity of the radioactive material. **[Ans: 2.10×10^{13}decays/second (Bq)]**