Radioactivity

Objectives

After going through the module, learner will be able to

- Understand and appreciate the concept that radioactivity
- Understand and appreciate the concept of half-life
- Calculate the decay constant of a radioactive substance
- Differentiate between half-life and average life of a radioactive substance
- Appreciate radioactivity laws for alpha, β^- or β^+ particle decay
- Understand the origin of gamma radiations from the nucleus

Content Outline

- Unit Syllabus
- Module-wise distribution of unit syllabus
- Words you must know
- Introduction
- Radioactivity
- Laws of radioactivity
- Decay constant and Half-life
- Alpha decay
- Beta decay
- Gamma decay
- Summary

Unit Syllabus

Unit 8

Atoms and Nuclei

Chapter 12 Atoms

Alpha particle scattering experiment, Rutherford's model of atom, Bohr model, energy levels, hydrogen spectrum

Chapter 13 Nuclei

Composition and size of nucleus, radioactivity, alpha, beta and gamma particles/rays and their properties, radioactive decay laws

Mass energy relations, mass defect, binding energy per nucleon and its variation with mass number, nuclear fission and nuclear fusion

Module Wise Distribution of Unit Syllabus -7 Modules

Module 1	• Introduction • Early models of atom • Alpha particle scattering and Rutherford's Nuclear model of atom • Alpha particle trajectory • Results and interpretations • Size of nucleus • What Rutherford's model could not explain
Module 2	• Bohr's model of hydrogen atom • Bohr's postulates • Electron orbits, what do they look like? • Radius of Bohr orbits • Energy levels, Energy states, energy unit eV • Lowest energy -13.6 eV interpretation • Velocity of electrons in orbits
Module 3	• The line Spectrum of hydrogen atom • de Broglie's explanation of Bohr 's second postulate of quantisation • Departures from Bohr model energy bands • Pauli's Exclusion Principle and Heisenberg's uncertainty principle leading to energy bands
Module 4	• Atomic masses and composition of nucleus • Discovery of neutron • Size of nucleus • Nuclear forces • Energy levels inside the nucleus

Module 5	• Mass and energy, Einstein's equation $E = mc^2$ • Mass defect • MeV • Nuclear binding energy • Binding energy per nucleon as a function of mass number • Understanding the graph and interpretations from it
Module 6	• Radioactivity • Laws of radioactivity • Half life • Rate of decay -disintegration constant • Alpha decay • Beta decay • Gamma decay
Module 7	• Nuclear energy • Fission • Controlled fission reaction • Nuclear Reactor • India's atomic energy programme • Nuclear Fusion – energy generation in stars • Controlled thermonuclear fusion

Module 6

Words You Must Know

Let us remember the words and the concepts we are familiar with:

- **Atom structure is an atom:** The smallest independent entity of an element .It consists of a small, central, massive and positive core surrounded by orbiting electrons.
- **Nucleus**: The central positive core of the atom is called the nucleus.
- **Size of an atom:** The size of an atom is of the order of 10^{-10} m, the size of a nucleus is of the order of 10^{-15} m.
- **Nucleons**. Nucleus is made up of neutrons and protons, they being the constituents of a nucleus are also called nucleons.
- **Mass number** If a nucleus has **Z number of protons** and **N number of neutrons**, then its mass number A.

$A = Z + N$

A nucleus of an element is represented as $_Z X^A$

- **Isotopes**: The atoms of an element, which have the same atomic number (Z), but different mass number (A), are called isotopes. For example $_1H^1$, $_1H^2$ and $_1H^3$ are isotopes. They have the same number of protons but different numbers of neutrons.
- **Isobars:-** The atoms which have the same mass number (A) but different atomic number (Z) are called isobars. They are the atoms of different elements for example $_1H^3$, $_2He^3$ are isobars.
- **Isotones:** The atoms, whose nuclei have, same number of neutrons, are called isotones.

  Nuclear size: The radius R , of a nucleus having mass number A is given by the expression

  - $R = R_0 A^{1/3}$, where $R_0 = 1.1 \times 10^{-15}$ m
- **Nuclear density:** Nuclear density = (mass of the nucleus/ volume of the nucleus) Nuclear density is independent of mass number.
- **Properties of a neutron:** A neutron is a neutral particle carrying no charge, and having mass slightly more than that of a proton. A neutron is stable inside the nucleus, but a free neutron is unstable and has a mean life of 1000 seconds.
- **Nuclear forces:** In spite of a Columbian repulsive force between protons, the nucleons stay inside a nucleus because of a strong attractive force called nuclear force.
  - Nuclear forces are the strongest forces in nature
  - Nuclear forces are short range forces
  - Nuclear forces are saturated forces
  - Nuclear forces are charge independent
  - Nuclear forces are spin dependent, non-central forces.

  Atomic mass unit: - One atomic mass unit is defined as $(1/12)^{th}$ of the mass of one $_6C^{12}$ atom.1 atomic mass unit = 1.66×10^{-27} kg

  eV energy gained by an electron when subjected to a potential difference of one volt.
- **Mass defect:** The difference between the sum of the masses of the nucleons constituting a nucleus and the rest mass of the nucleus is known as **mass defect.**
- **Binding energy:** Binding energy of a nucleus may be defined as the energy is required to break up a nucleus into its constituent nucleons and to separate them to such a large distance that they may not interact with each other.

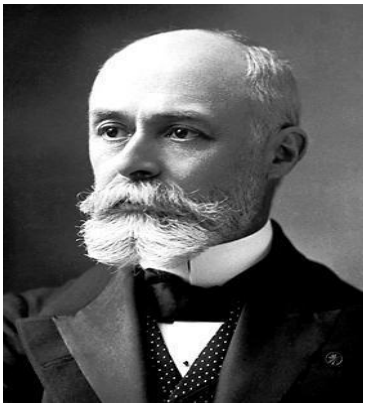
OR

The binding energy may also be defined as the surplus energy which the nucleons give up by virtue of their attractions when they become bound together to form a nucleus.

- **Binding energy per nucleon: -** "the average energy required for extracting one nucleon from the nucleus".

Introduction

H. Becquerel discovered radioactivity in 1896 purely by accident.



https://upload.wikimedia.org/wikipedia/commons/3/3a/Henri_Becquerel_1903.jpg

While studying the fluorescence and phosphorescence of compounds irradiated with visible light, Becquerel observed an interesting phenomenon.

After illuminating some pieces of **uranium-potassium sulphate** with visible light, he wrapped them in black paper and separated the package from a photographic plate by a piece of silver.

When, after several hours of exposure, the photographic plate was developed, it showed blackening due to something that must have been emitted by the compound and was able to penetrate both black paper and the silver**.**

Experiments performed subsequently showed that radioactivity was a nuclear phenomenon in which an unstable nucleus undergoes a decay in order to become stable.

This is referred to as radioactive decay.

Three types of radioactive decay occur in nature:

- **α - decay** in which a helium nucleus of helium is emitted;

- **β - decay** in which electrons or positrons (particles with the same mass as electrons, but with a charge exactly opposite to that of electron) are emitted;
- **γ -decay** in which high energy (hundreds of keV or more) photons are emitted.

What intrigued the scientists!!

- Emission was random;there was no predictability - as to when a particle would be radiated-there seemed to be utter confusion!!
- There were only protons and neutrons in the nucleus –how come an alpha particle emerged out,
- Where did the beta particle come from? Etc.

  In this module, we will learn about the phenomenon of radioactivity

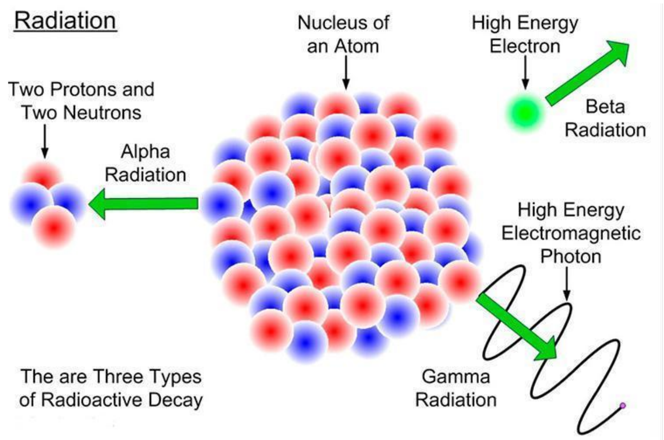
Radioactivity

We have seen from the binding energy per nucleon versus mass number curve that heavy nuclei have low binding energy per nucleon i.e they are less stable. Experiments performed thereafter showed that some invisible highly penetrating radiations are randomly though spontaneously emitted by heavy unstable nuclei. These substances were called radioactive substances.

The substances, which spontaneously emit penetrating radiations, are called radioactive substances.

Thus the **phenomenon of spontaneous emission of radiation by radioactive substances is called radioactivity**.

Radioactivity is a nuclear phenomenon, in which an unstable nucleus undergoes a decay called **radioactive decay**. Three types of radioactive decay occur in nature.



https://chernobylguide.com/wp-content/uploads/2016/02/alpha_and_beta_particles.jpg

- Alpha (α) decay, in this a helium nucleus, $_2He^4$ is emitted;
- β- decay, in this decay an electron or a positron (positron is a particle with the same mass as an electron, but with charge exactly opposite to that of an electron) is emitted;
- γ-decay, in this process high energy of the order of a few KeV or more, photons are emitted

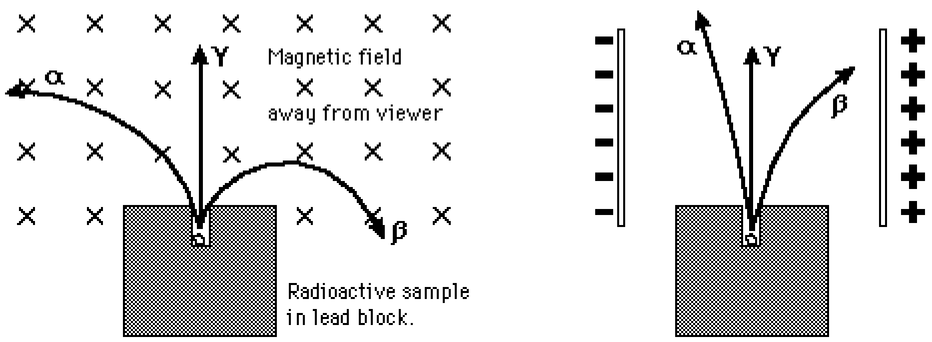
  Video for radioisotopes: -

  https://www.youtube.com/watch?v=cKJMk2Oiod0

  https://www.youtube.com/watch?v=KYDil96NR5Q

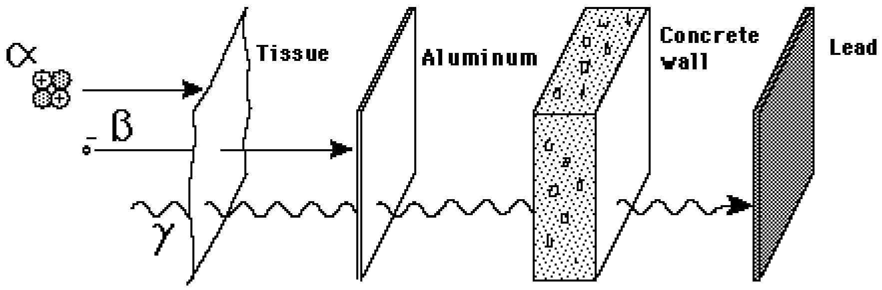
How Did They Find That There were Three Types of Radiations

Since radioactivity is natural and spontaneous, the emitted particles/radiations were discovered by using electric and magnetic fields. The track of the emitted particles was seen in evacuated glass chambers (cloud chambers) and irradiation of fluorescent plates and sheets by the emitted particle (Geiger counters).



http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/imgnuc/alpbet.gif

Another method that showed the three different types of radiation was absorption of radiation by thin sheets of different materials.



http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/imgnuc/radpen.gif

You may find out their unique properties and justify their use (alpha, beta and gamma radiations) in industry, medicine and manufacturing.

Laws of Radioactivity

Rules within unpredictability!!

According to Rutherford and Soddy:

- The disintegration is random. It is purely a matter of chance for any atom to disintegrate, i.e. it is not possible to predict which nuclei will disintegrate in a given interval of time.
- Radioactivity is a spontaneous process and is independent of all physical and chemical conditions and thus it can neither be accelerated nor retarded.
- During disintegration either an α-particle or a β-particle is emitted.
- Both of these particles are never emitted simultaneously. Also at a time an atom will not emit more than one α-particle or more than one β- particle.
- **The number of nuclei undergoing decay per unit time is directly proportional to the total number of undecayed nuclei present in the sample at that time**.

If N is the number no. of undecayed nuclei in the sample at any time,

ΔN is the number of nuclei disintegrating in time Δt, then, rate of decay is $\frac{\Delta N}{\Delta t}$ so that,

$$-\frac{\Delta N}{\Delta t} \alpha\, N$$

$$or, \quad \frac{\Delta N}{\Delta t} = -\lambda N$$

λ is called the radioactive decay constant or disintegration constant.Here ΔN is the number of nuclei that decay, and hence is always positive.dN is the change in N, which may have either sign.

Here it is negative, because out of original N nuclei, ΔN have decayed, leaving (N - ΔN) nuclei,

thus

$$\left(\frac{dN}{dt}\right) = -\lambda N$$

$$\left(\frac{dN}{N}\right) = -\lambda\, dt$$

Now on integrating both side of the above equation, we get

$$\int \frac{dN}{N} = -\lambda \int dt$$

Here N_0 is the number of radioactive nuclei in the sample at some arbitrary time t_0 and N is the number of radioactive nuclei at any subsequent time t.

Setting $t_0 = 0$

Rewriting the above equations we get,

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_{t_0}^{t} dt$$

From calculus

$$\int \frac{1}{x} dx = \log x$$

And we know that

$$\log a - \log b = \log\left(\frac{a}{b}\right)$$

log x may also be written as ln x

So we have

$$\log N - \log N_0 = -\lambda t$$

Therefore, we get

$$\text{Log}\left(\frac{N}{N_0}\right) = -\lambda t$$

Now take antilog on both sides

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

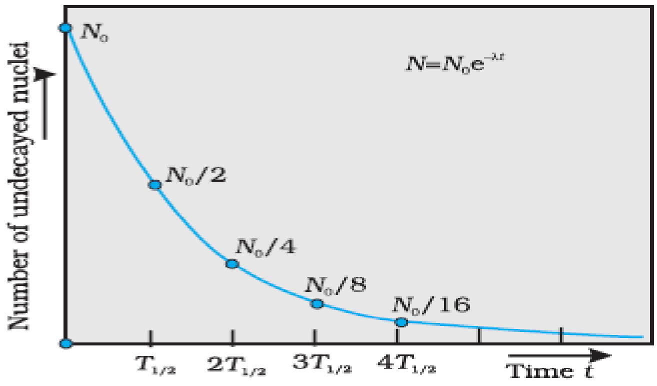
We get the relation:

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

From the equation $N(t) = N_0\, e^{-\lambda t}$, we see that

- The radioactive decay is exponential

- The number of active nuclei in a radioactive sample decreases exponentially with time.
- The disintegration is fast in the beginning but becomes slower and slower with the passage of time.
- The larger the value of decay / disintegration constant λ, the higher is the rate of disintegration.
- A radioactive sample will take infinitely long time to disintegrate completely.
- We see that N = 0 , only when t = infinity. The variation of the number of undecayed nuclei (N),with time t.



Exponential decay of a radioactive species. After a lapse of $T1/2$, the population of the given species drops by a factor of 2.

Decay Constant and Half Life

Decay Constant

In the equation $N(t) = N_0 e^{-\lambda t}$

If we put t = 1/λ, we get

$N(t) = N_0 e^{-1}$

$N(t) = N_0/e$

$= 0.368 N_0$

Decay/disintegration constant can be defined as **the reciprocal of time interval during which, the number of active nuclei in a radioactive sample reduces to 36.8 percent of its initial value**

OR

As $\left(\frac{dN}{dt}\right) = -\lambda N$

$-\left(\frac{dN}{dt}\right)/N = \lambda$

Decay/disintegration constant can be defined as **the ratio of the instantaneous rate of disintegration to the number of active nuclei present in the radioactive sample at the given instant.**

Value of λ depends upon the nature of the radioactive sample.

Half- Life

Different radionuclides differ greatly in their rate of decay. A common way to characterize this feature is through the notion of half-life (T).

Half-life of a radioactive substance is the time in which the number of undecayed nuclei will reduce to half of its initial value.

If N_0 is the initial number of radioactive atoms present, then in half-life time T, the number of undecayed radioactive atoms will be $N_0/2$ and in next half-life $N_0/4$ and so on.

That is

when t = T, $N = \frac{N_0}{2}$

From this relation: $\mathbf{N(t) = N_0 e^{-\lambda t}}$

We get, $N_0/2 = N_0 e^{-\lambda T}$

$$\mathbf{2 = e^{\lambda T}}$$

Taking the logarithm both sides, we get

$\log_e 2 = \lambda T \log_e e$

We know, $\log_e e = 1$

and

$\log_e 2 = 2.303 \log 2$

Therefore, $\lambda T = 2.303 \log 2$

$T = 2.303\ (0.3010)/\lambda$

$T = 0.6931/\lambda$

Thus **half-life of a radioactive substance is inversely proportional to the decay constant of the substance.**

Significance of half-life: - The value of the half-life of a radioactive substance gives an idea of the relative stability of that isotope/substance. An isotope having a longer half-life is more stable than the one with shorter half-life.

Video for finding half-life: -

Example

Tritium has a half-life of 12.5year undergoing beta decay. What fraction of a sample of pure tritium will remain undecayed after 25 years?

Solution

After 12.5 years half $\left(\frac{1}{2}\right)$ of the initial sample will remain undecayed.In the next 12.5 years $\left(\frac{1}{2}\right)$ of these nuclei will decay. Hence one fourth of the initial quantity of the sample will remain undecayed.

Note: There is another way of finding the fraction of sample that remains undecayed

Let T be the half-life of the sample, and t is the time which has lapsed

T	**N**	$\frac{N}{N_0}$
1T	$\left(\frac{N_0}{2}\right)$	$\left(\frac{1}{2}\right)$
2T	$\left(\frac{1}{2}\right)\left(\frac{N_0}{2}\right)$	$\left(\frac{1}{2}\right)^2$
3T	$\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{N_0}{2}\right)$	$\left(\frac{1}{2}\right)^3$
4T	$\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{N_0}{2}\right)$	$\left(\frac{1}{2}\right)^4$
5T	$\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{N_0}{2}\right)$	$\left(\frac{1}{2}\right)^5$

Thus we can generalize as

$$\left(\frac{N}{N_0}\right) = \left(\frac{1}{2}\right)^n$$

Where n is the number of half-lives, i.e. n = $\frac{t}{T}$

This expression can be used to find the fraction of the sample that remains undecayed after a given time (when time given is a multiple of half-life)

For **graph between log N versus time-**

https://www.khanacademy.org/science/in-in-class-12th-physics-india/nuclei/v/exponential-decay-and-semi-log-plots

Mean Life or Average Life of a Radioactive Substance

As the process of disintegration is random and spontaneous, so all the nuclei of a radioactive substance **do not** disintegrate at the same time.

While one nucleus may decay right in the beginning and some other may decay at the end of the process. So the lifetime of the different nuclei is different, varying from zero to infinity.

Mean life = $\frac{Sum\ of\ the\ lives\ of\ all\ the\ nuclei}{total\ number\ of\ nuclei}$

Relationship Between Decay Constant and Mean Life

The mean life of a radioactive substance is equal to the sum of life time of all atoms divided by the number of all atoms

$$mean\ life(\tau) = \frac{Sum\ of\ the\ lives\ of\ all\ the\ nuclei}{total\ number\ of\ nuclei} = \frac{1}{\lambda}$$

And half-life T = $\frac{0.6931}{\lambda}$

$T = 0.6931\tau$

Or

$\tau = 1/\lambda$

Thus T = 0.693/ λ = 0.693 τ

Example

The half-life of a given radioactive substance is 138.6days.

a. What is the mean life of this substance?
b. After how much time will a given sample of this radioactive substance get reduced to 12.5 percent of its initial value?

Solution

a. T = 138.6 days

   Using the formula, T = $\frac{0.693}{\lambda}$ = 0.693 τ

   $\tau = \frac{T}{0.693} = \frac{138.6}{0693}$ = **200 days**

b. $\frac{N}{N_0} = \frac{12.5}{100} = \frac{1}{8}$

$$\left(\frac{N}{N_0}\right) = \left(\frac{1}{2}\right)^n$$

$$\left(\frac{1}{8}\right) = \left(\frac{1}{2}\right)^n$$

$$\left(\frac{1}{2}\right)^n = \left(\frac{1}{2}\right)^n$$

So n = 3, as $n = \frac{t}{T}$

Thus t = 3T= 3 × 138.6= 415.8days

Activity of a Radioactive Substances

The activity of a radioactive sample is the total decay rate of the sample which is equal to the number of disintegrations taking place per second in the sample.

The activity of radioactive substances means the rate of decay (or the number of disintegration /sec). This is denoted by

$$A = \left|\frac{dN}{dt}\right| = \left|\frac{d\left(N_0 e^{-\lambda t}\right)}{dt}\right| = \lambda N$$

If A_0 is the activity at time t = 0, then,

$$A_0 = \lambda N_0$$

$$\therefore \frac{A}{A_0} = \frac{N}{N_0} = e^{-\lambda t},$$

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

Units Activity of a Radioactive Substances

The SI unit for activity is Becquerel, written as (Bq) and it is equal to 1 decay per second.

Other units of activity are i) Curie, written as (Ci) ii) Rutherford written as (Rd)

1 Ci = 3.7×10^{10} decays per second

1 Rd = 10^{6} decays per second

To say it in words this implies

- **Curie:** It is defined as the activity of radioactive substance which gives 3.7×10^{10} disintegration /sec which is also equal to the radioactivity of 1g of pure radium.
- **Rutherford:** It is defined as the activity of radioactive substance which gives rise to 10^6 disintegration per second.
- **Becquerel:** In S.I. system , the unit of radioactivity is Becquerel

1 Becquerel = 1 disintegration per second

Think About This

Why do we have three units to show the activity of a radioactive sample?

What is meant by activity of a sample is 50 Becquerel?

Alpha Decay

- In Alpha decay an unstable nucleus transforms into a new nucleus by emitting an Alpha particle.
- In α decay, the mass number of the product nucleus, also called daughter nucleus is four less than that of the parent (decaying) nucleus, while the atomic number decreases by two.
- In general, the α decay of a nucleus $_{Z}X^{A}$ results in a daughter nucleus $_{Z-2}Y^{A-4}$ as per the equation given below

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

- From Einstein's mass energy equivalence relation and energy conservation' it is clear that this spontaneous decay is possible only when the total mass of the decay products is less than the mass of the initial nucleus.

This difference in mass appears as kinetic energy of the products.

The disintegration energy or the Q- value of a nuclear reaction is

$$Q = \left[m_x - \left(m_y + m_\alpha\right)\right]c^2$$

If the initial nucleus is at rest, then Q is also the kinetic energy gained in the processes. the kinetic energy of the products.

For spontaneous alpha decay, Q > 0, thus it is an exothermic process.

One example of alpha decay is

$92238U \longrightarrow 90234Th + 24He$

For decay:-

https://www.khanacademy.org/science/in-in-class-12th-physics-india/nuclei/v/mass-defect-and-binding-energy/v/half-life/v/types-of-decay

Example

Show that the kinetic energy of an alpha particle, emitted in an alpha decay, if the parent nucleus is at rest, is, (A – 4)Q/A, where A is the mass number of the parent nucleus and Q is the total energy of the decay.

Solution

Consider the α decay

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

Given that the parent nucleus is at rest.

Let v_α and v_y be the velocities of the α particle and the daughter nucleus.

By **conservation of momentum**

$m_y v_y + m_\alpha v_\alpha = 0$

$m_y v_y = - m_\alpha v_\alpha$

The energy of the decay, Q, appears in the form of kinetic energy of the daughter nucleus and the alpha particle. So

$$\frac{1}{2}\left(m_Y v_y^2\right) + \frac{1}{2}\left(m_\alpha v_\alpha^2\right) = Q$$

Substituting the value of v_y from equation $m_Y v_y = m_\alpha v_\alpha$ we get

$$\frac{\frac{1}{2}\left(m_\alpha^2 v_\alpha^2\right)}{m_Y} + \frac{1}{2}\left(m_\alpha v_\alpha^2\right) = Q$$

$$\frac{1}{2}\left(m_\alpha v_\alpha^2\right)\left(m_\alpha + m_Y\right) = Q m_Y$$

Kinetic energy of alpha particle = $\frac{1}{2}\left(m_\alpha v_\alpha^2\right) = \frac{Q m_Y}{\left(m_\alpha + m_Y\right)}$

Kinetic energy of alpha particle = $\frac{1}{2}\left(m_\alpha v_\alpha^2\right) = \frac{Q(A-4)}{A}$

Hence proved.

Beta Decay

In β decay,

- A nucleus spontaneously emits **an electron** (β^- decay) or a **positron** (β^+ decay).
- The mass number A remains unchanged,
- The atomic number z of the nucleus **increases** by 1.
- Is *accompanied b*y the emission of an antineutrino ($\bar{\nu}$).
- For a parent nucleus $_{Z}X^{A}$ results in a daughter nucleus Y as per the equation given below

$_{Z}X^{A} \rightarrow {}_{Z+1}Y^{A} + {}_{-1}e^{0} + (\check{\nu})$.

- The basic nuclear process underlying β⁻ decay is the conversion of a neutron to proton as shown in the equation given below

  $n \leftrightharpoons p + e^{-} + (\check{\nu})$

  A common example of β⁻ decay is

  $1532P \longrightarrow 1632S + \; - 10e + \check{\nu}$

  β⁺ DECAY:-

  In β⁺ decay the mass number A remains unchanged,

- The atomic number z of the nucleus **decreases** by 1.
- β⁺ decay is accompanied by the emission of **neutrino ν** of a nucleus $_{Z}X^{A}$ results in a daughter nucleus Y as per the equation given below

  $$_{Z}X^{A} \rightarrow {}_{Z+1}Y^{A} + {}_{+1}e^{0} + \nu$$

- The basic nuclear process underlying β⁺ decay is the conversion of a proton to neutron as shown in the equation given below

  $$p \leftrightharpoons n + e^{+} + \boldsymbol{\nu}$$

- A common example of a β⁺ decay is

  $1122Na \longrightarrow 1022Ne \; ++ \; 10e + \nu$

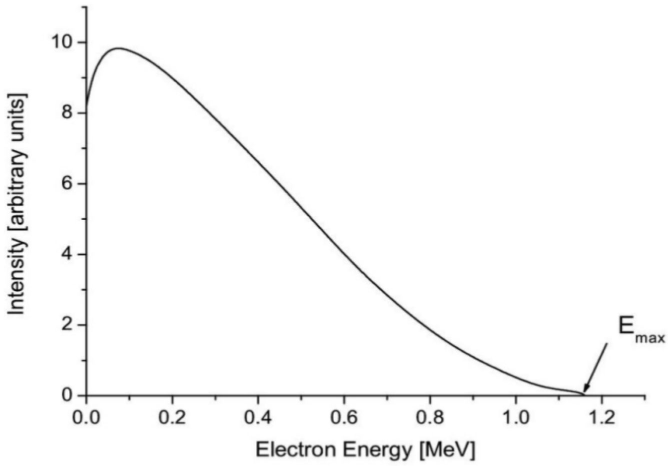
  Decay of a proton to a neutron is possible only inside the nucleus, since protons have smaller mass than neutrons.

So, If an unstable nucleus has excess neutrons than needed for stability, the neutron converts into protons. If an unstable nucleus has excess protons than needed for stability, proton converts into neutron as per the equations given above

Now the question arises, why neutrinos or antineutrinos are emitted?

The energy spectrum of emitted beta particles is found to be continuous, indicating that beta particles carry all possible values of energy, from zero to a maximum value. Most of the beta particles emitted have energies less than the maximum energy. Thus the conservation of energy is violated.

The conservation of energy and angular momentum led to the postulate that beta decay is always accompanied by the emission of another particle of zero rest mass and zero charge, called neutrino or antineutrino.



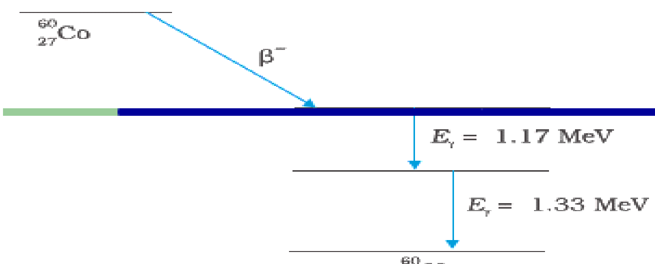
Gamma Decay

It is understood that like in an atom, a nucleus also has discrete energy levels, the ground state and the excited states.

- Atomic energy levels spacing's are of the order of eV, while nuclear level spacing's are of the order of MeV.
- When a nucleus in the excited state spontaneously decays to its ground state or to the lower energy state, a photon with energy equal to the difference in the two energy levels is emitted. This is called **gamma decay.**
- This is electromagnetic **radiation** much like light or heat waves. The wavelength of the photons emitted is less than that of X-rays.
- No new nuclei are formed in this decay.

Typically, a gamma ray is emitted when an α or a β decay results in a daughter nucleus in an excited state. This then returns to the ground state by emission of a **single photon or successive transitions involving more than one photon.**

The diagram below shows the successive emission of gamma rays, from the de-excitation of $_{28}Ni^{60}$ nuclei formed from β- decay of $_{27}Co^{60}$.



Decay of $_{27}Co^{60}$ nucleus followed by emission of two γ rays from de

excitation of the daughter nucleus to obtain $_{28}Ni^{60}$

Simple Explanation of α-Decay , β-Decay and γ-Decay

α- emission:

A proton in a nucleus has a binding energy of nearly 8 MeV; so to come out of a nucleus, it requires an energy of 8 MeV; but such an amount of energy is not available to a proton; hence proton as such cannot come out of nucleus on its own. On the other hand, the mass of α-particles is subsequently less than the total mass of 2 protons + 2 neutrons. According to Einstein's mass energy equivalence relation, sufficient energy is released in the formation of an **α**- particle within the nucleus. This energy appears in the form of kinetic energy of **α**-particles. With this kinetic energy, **α**-particle hits the wall of the nucleus again and finally escapes out. The process may be represented as

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

β-emission:

β-particles are not the constituents of the nucleus, then the question is why and how are they emitted by radioactive nuclei.

Pauli, in 1932, suggested that at the time of emission of a β-particle, a neutron in the nucleus is converted into a proton, a β-particle and antineutrino. This may be expressed as

$$n \leftrightharpoons p + e^{-} + (\check{\nu})$$

$$_{Z}X^{A} \rightarrow {}_{Z+1}Y^{A} + {}_{-1}e^{0} + (\check{\nu}).$$

Antineutrino is a massless and charge less particle. The energy of the above process is shared by β-particles and antineutrino; that is why the energy of β-particles ranges from 0 to a certain maximum value.

γ-emission:

When α and β-particles are emitted from a nucleus, the residual nucleus is left in an excited state. The excited nucleus returns to its ground state by emission of **γ-**photon. Thus γ-photon is emitted either with α- emission or with β-emission. It is an electromagnetic radiation .they travel with the speed of light, have very small wavelength .and high frequency,

Example

In the reactions given below, what is the particle x, also find the values of y, z, a and c.

${}_6C^{11} \rightarrow {}_yB^{z} + x + \nu$

${}_6C^{12} + {}_6C^{12} \rightarrow {}_aNa^{20} + {}_2He^{4}$

Solution

In the equation

$\mathbf{{}_6C^{11} \rightarrow {}_yB^{z} + x + \nu}$

A neutrino is released, so x **is a positron with mass number 0 and charge number +1.**

By applying principle of charge conservation and mass number

11= z + 0 + 0. Thus, **z = 11**

6 = y + 1+0

y = 5

For the equation ${}_6C^{12} + {}_6C^{12} \rightarrow {}_aNa^{20} + {}_2He^{c}$

Considering the mass numbers

12 + 12 = 20 + c

c = 4

Also atomic number

6 + 6 = a + 2

a = 10

Example

The sequence of decay of a radioactive nucleus D is

$D \ \alpha\rightarrow D_1 \ \beta\rightarrow D_2 \ \alpha\rightarrow D_3 \ \alpha\rightarrow D_4$

If mass number and atomic number of D_2 are 176 and 71 respectively, what are their values for D and D_4?

Solution

Mass number of an alpha particle = 4

Atomic number of an alpha particle =2

D_4 is formed on emission of two alpha particles from D_2,

So the mass number of D_4 = 176 – 8 =168

The atomic number of D_4= 71 – 4 = 67

Charge number of a beta particle is -1, and its mass number is 0. Let the mass number of D be A and its charge number be z,

$A = 176 + 4 = 180$

$z = 71 + 2 + (-1) = 72$

Summary

- **Radioactivity:** The phenomenon of spontaneous emission of radiations by radioactive substances is called radioactivity**.**
- The substances, which spontaneously emit penetrating radiations, are called **radioactive substances.**
- **Laws of radioactivity:** According to Rutherford and Soddy
  - The disintegration is random. It is purely a matter of chance for any atom to disintegrate, i.e. it is not possible to predict which nuclei will disintegrate in a given interval of time.
  - Radioactivity is a spontaneous process and is independent of all physical and chemical conditions and thus it can neither be accelerated nor retarded.
  - During disintegration either an α-particle or a β-particle is emitted. Both of these particles are never emitted simultaneously. Also at a time an atom will not emit more than one α-particle or more than one β- particle.
  - The number of nuclei undergoing decay per unit time is directly proportional to the total number of undecayed nuclei present in the sample at that time,
- The number of active nuclei in a radioactive sample decreases exponentially with time as per the formula

  $N(t) = N_0 e^{-\lambda t}$
- **Decay constant (λ):** Decay/disintegration constant can be defined as the reciprocal of time interval during which, the number of active nuclei in a radioactive sample reduces to 36.8 percent of its initial value

  OR

  Decay/disintegration constant can be defined as the ratio of the instantaneous rate of disintegration to the number of active nuclei present in the radioactive sample at the given instant. Value of λ depends upon the nature of the radioactive sample.
- **Half-life:** Half-life (T) of a radioactive substance is the time in which the number of undecayed nuclei will reduce to half of its initial value.

- **Relation between half-life and decay constant:-**

  T = 0.693/ λ

- $\left(\frac{N}{N_0}\right) = \left(\frac{1}{2}\right)^n$

  Where n is the number of half-lives, i.e. n = t/T

- **Mean life (τ):** Mean life = (Sum of the lives of all the nuclei) / total number of nuclei τ = 1/λ
- T = 0.693/ λ = 0.693 τ
- **Activity of a radioactive substance:** The activity of a radioactive sample is the total decay rate of the sample which is equal to the number of disintegrations taking place per second in the sample.

  The activity of the radioactive sample R = $-\left(\frac{dN}{dt}\right) = \lambda N$

  $R(t) = R_0 e^{-\lambda t}$

- The SI unit for activity is " Becquerel", written as (Bq)

  1 Bq = 1 decay per second.

- **α decay:** In α decay, the mass number of the product nucleus, also called daughter nucleus, is four less than that of the parent (decaying) nucleus, while the atomic number decreases by two.

  $_ZX^A \rightarrow {}_{Z-2}Y^{A-4} + {}_2He^4$

- The disintegration energy or the Q- value of a nuclear reaction (alpha decay)is

  $Q = (m_x - m_y - m_{He}) C^2$

- Kinetic energy of alpha particle = Q(A- 4)/ A
- In β^- decay, the mass number A, remains unchanged, the atomic number z of the nucleus increases by 1. β^- decay is accompanied by the emission of an antineutrino

  $_ZX^A \rightarrow {}_{Z+1}Y^A + {}_{-1}e^0 + \mathbf{v}$

- In β^+ decay, the mass number A remains unchanged, the atomic number z of the nucleus decreases by 1. β^+ decay is accompanied by the emission of neutrinos (**ν**).

  $_ZX^A \rightarrow {}_{Z+1}Y^A + {}_{+1}e^0 + \mathbf{v}$

- Gamma ray is emitted when an α or a β decay results in a daughter nucleus in an excited state. This then returns to the ground state by emission of a single photon or successive transitions involving more than one photon. No new particle is formed in gamma decay