NUCLEAR PHYSICS

Every atom has the nucleus. The nucleus of an atom consists of protons (positively charged) and neutrons (electrically neutral i.e. not charged). Protons and neutrons are collectively termed as nucleons. Electrons (negatively charged) revolve around the nucleus in their orbits / energy levels / shells at high speeds.

Comparison of nucleons with electrons

Particle	***Electron***	***Proton***	***Neutron***
Mass	$m_e = 9.110 \times 10^{-31} kg$	$m_p = 1836 m_e$	$m_n = 1839 m_e$
Charge	$q_e = -1.602 \times 10^{-19} C$	$q_p = +1.602 \times 10^{-19} C$	$q_n = 0\,C$

In a neutral, the number of protons equals to the number of electrons since in each atom, the magnitude of charge carried by the electron is equal to the magnitude of charge carried by the proton.

NOTE:

The protons and neutrons (nucleons) are held together by the following forces

1. *Nuclear forces (strongest)*
2. *Gravitational forces.*
3. *Weak interactions*
4. *Electromagnetic forces.*

Terminologies used in nuclear physics.

1. ***Atomic number**, Z.*
   This refers to the total number of protons in the nucleus of an atom.
2. ***Mass (Nucleon or Nuclear) number**, A.*
   This refers to the total number of protons and neutrons in the nucleus of an atom.
   I.e Mass number $=$ Number of protons $+$ Number of neutrons.

NB:

(i) *Mass number is also known as atomic mass*

(ii) *The nuclear symbol of the nucleus X of mass number, A and atomic number, Z is given by, $^{A}_{Z}X$.*

3. ***Nuclide**.*
   This refers to the term used to specify atom with a particular number of protons and neutrons.
   For example, $^{16}_{8}O$, $^{6}_{3}Li$, $^{7}_{3}Li$ etc. are different nuclides.
4. ***Isotopes**.*
   These refer to atoms of the same element with the same atomic number but different mass numbers.
   For example, (a) $^{6}_{3}Li$, $^{7}_{3}Li$ are isotopes of Lithium (b) $^{12}_{6}C$, $^{13}_{6}C$, $^{14}_{6}C$ are isotopes of Carbon.

NB:

(i) *Isotopes have different mass numbers because they have different neutrons.*

(ii) *Chemical properties of isotopes are identical (the same) since they have the same number of protons or electrons and therefore cannot be separated by chemical methods.*

5. ***Radioisotopes**.*

These refer to radioactive atoms of the same element having the same number of protons but different number of neutrons.

6. ***Relative atomic mass**, (A_r).*

This refers to the ratio of the mass of an atom to the a twelfth (12^{th}) mass of carbon -12 atom.

i.e. $A_r = \left(\dfrac{Mass\ of\ an\ atom}{\frac{1}{12} \times mass\ of\ carbon - 12} \right).$

NB:

Relative atomic mass is also known as atomic weight.

7. ***Unified atomic mass unit (U)**.*

This refers to a twelfth (12^{th}) mass of carbon -12 atom.

i.e. $1U = \frac{1}{12} \times\ mass\ of\ carbon\text{-}12\ atom.$

Calculation of U.

(i) ***In kilograms (kg)***

$1U = \frac{1}{12} \times\ mass\ of\ carbon\text{-}12\ atom,$

$1\ mole\ of\ carbon\text{-}12\ has\ a\ mass\ of\ 12\ g$,

$1\ mole\ contains\ 6.02 \times 10^{23} atoms$ *, and thus,*

$1\ \ atom = \left(\dfrac{12 \times 10^{-3}}{6.02 \times 10^{23}} \right) kg,$

$\Rightarrow\ 1U = \left(\frac{1}{12} \times \left(\dfrac{12 \times 10^{-3}}{6.02 \times 10^{23}} \right) \right) kg$ *and therefore,* $1U = 1.66 \times 10^{-27} kg.$

(ii) ***In joules (J)***

From Einstein's equation, $E = mc^2$ *, where, m is mass of 1U and c is the speed of an electromagnetic wave in the vacuum .*

$m = 1.66 \times 10^{-27} kg$ *and* $c = 3.0 \times 10^8 ms^{-1}.$

$1U = E = 1.66 \times 10^{-27} \times (3.0 \times 10^8)$ *and thus,* $1U = 1.494 \times 10^{-10} J.$

(iii) ***In Mega electron-volt. (MeV)** .*

$1MeV = 1.602 \times 10^{-13} J$ *, thus,* $\Rightarrow\ 1U = \left(\dfrac{1.494 \times 10^{-10}}{1.602 \times 10^{-13}} \right) \quad \therefore\ 1U = 931 MeV.$

Radioactivity.

This refers to the spontaneous instigation of an unstable nuclide to a stable nuclide by emission of alpha particles, beta particles and gamma rays.

*A nuclide which spontaneously breaks up to emit alpha particles, beta particles and gamma rays is known to a **Radioactive nuclide**.*

*A nucleus which undergoes a radioactive decay is called the **Parent nucleus** while the nuclei formed after the decay are called the **daughter nuclei**.*

Alpha, α-particles, beta, β-particles and gamma, γ-rays are the emissions associated with radioactivity.

In both α and β-emissions, the parent nucleus undergoes a change in atomic number and becomes a nucleus of a different element.

γ-rays are emitted as energy when the atom is unstable after either the emission of α or β or both particles to become stable.

Why is radioactivity spontaneous?

This is because the rate of decay cannot be controlled, increased or decreased. The decay happens on its own and is not affected by physical factors like temperature and pressure and it is not affected by chemical compensation.

Why is radioactivity random?

This is because it is impossible to predict which atom will decay at any given instant. Each atom has the same probability of decaying at any instant.

1. Alpha, α-particles ($^{4}_{2}He$).

An alpha, α-particle refers to a helium atom that has lost two of its orbital electrons.

Properties of an alpha particle.

It has a mass number 4 and atomic number 2.
It is positively charged since it has lost two electrons.
It is slightly deflected in a magnetic field according to Fleming's hand rule.
It is slightly deflected in an electric field towards a negatively charged plate since it is positively charged.
It moves slowly at a speed far less than that of electromagnetic radiations since it is massive.
It has a low penetration power and can be stopped by a thick sheet of paper.
It has a high ionization power i.e., it greatly ionizes gas.
It affects or blackens a photographic plate.
They cause fluorescence

Effect of alpha, α-particle decay on a nucleus.

Consider a nucleus, P with a mass number, A and atomic number, Z which emits an alpha particle. The decay series is as $^{A}_{Z}P \rightarrow {}^{A-4}_{Z-2}X + {}^{4}_{2}He$.
The daughter nucleus $^{A-4}_{Z-2}X$ *has a mass number reduced by 4 units and the atomic number reduced by 2 units.*

NUMERICAL EXAMPLE

1. *Uranium-238 ,* $^{238}_{92}U$ *decays emitting an alpha particle to form Thorium. Write down the decay series and hence state the atomic mass and proton number of thorium.*
2. $^{238}_{92}U$ *undergoes a decay by emitting an α-particle to form* $^{y}_{x}T$ *. Find the values of x and y and name T.*

2. Beta, β-particles ($^{0}_{-1}e$).

This refers to a fast moving electron.

Properties of a beta particle.

It has a mass number 0 and atomic number -1.
It is negatively charged since it is an electron in nature.
It is highly deflected in a magnetic field according to Fleming's hand rule.

It is highly deflected in an electric field towards a positively charged plate since it is negatively charged.
It sometimes moves at a speed slightly less than that of electromagnetic radiations since it is less massive compared to an alpha particle.
It has an intermediate penetration power and can be stopped by a thin sheet of aluminium foil.
It has an intermediate ionization power, less than that of an alpha particle.
It affects or blackens a photographic plate.
It produces fluorescence.

Effect of alpha, α-particle decay on a nucleus.

Consider a nucleus, P with a mass number, A and atomic number, Z which emits an alpha particle. The decay series is as ${}^{A}_{Z}P \rightarrow {}^{A}_{Z+1}X + {}^{0}_{-1}e$.
The daughter nucleus ${}^{A}_{Z+1}X$ *has the same mass number as the parent nucleus and the atomic number increased by 1 unit.*

NUMERICAL EXAMPLE

Carbon-14, ${}^{14}_{6}C$ *undergoes radioactivity by emission of 2 beta particles to become* ${}^{y}_{x}D$. *Write down the decay series and hence determine the values of x and y.*

3. Gamma, γ-rays.
A gamma ray refers to an electromagnetic radiation of a very short wavelength.

Properties of gamma, γ-rays

It has a mass number 0 and atomic number 0
It has no charge since its atomic mass and atomic number are equal to zero.
It is neither deflected in a magnetic field nor electric field since it carries no charge.
It moves at a speed of light in a vacuum i.e. $3.0\times10^{8}\,ms^{-1}$.
It has a very high penetration power and can only be stopped by a thin sheet of lead or a thick concrete wall.
It has a very ionization power.
It affects or blackens a photographic plate.
It produces fluorescence.

Effect of alpha, α-particle decay on a nucleus.

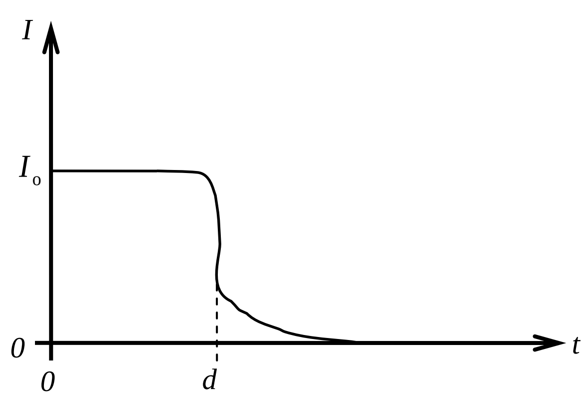
When a gamma ray is emitted, it is only energy which is released but the mass number and atomic number of the daughter nucleus remains the same as that of the parent nucleus.

Absorption of α-particles, β-particles and γ-rays by matter.

(a) Alpha particles

*Alpha, α-*particles emitters produce alpha particles of one energy only. Alpha particles are therefore called **mono-energetic** and have the same range of penetration to the absorber.
They are absorbed by a sheet of paper of some good thickness.

***Variation of intensity, I with thickness, t of the absorber for alpha particles*.**



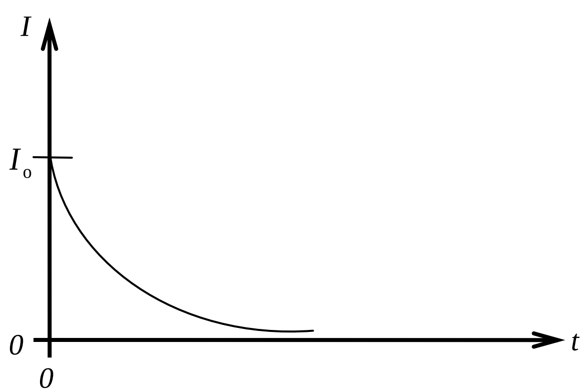
Features of the graph.

All alpha particles pass through a thin sheet of paper and so produce a constant intensity up to a thickness, d.
All alpha particles are absorbed at d and so there is a sharp drop in intensity.

(b) Beta particles

Beta particle emitters produce beta particles with a range of energies. They pass through a sheet of paper and can be absorbed by aluminium sheet at different thicknesses.

Variation of intensity, I with thickness, t of the absorber for alpha particles.



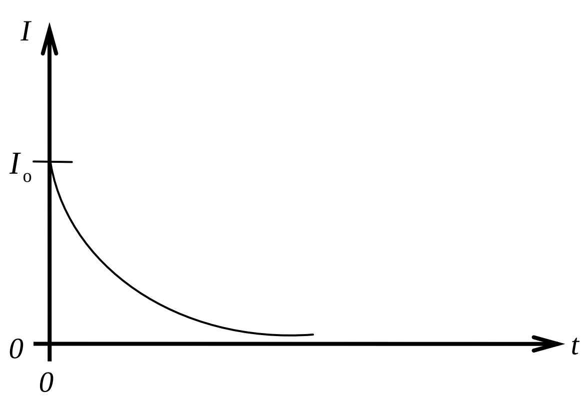
Features of the graph

Over a given range of thickness, beta particles are absorbed and so loss of energy which results into a decrease in intensity.
Since beta particles have a range of energies, the absorption is therefore exponential.

(c) Gamma rays

Gamma ray emitters produce gamma rays of more than one wavelength. Gamma rays pass through both a thick sheet of paper and a sheet of aluminium foil. They are absorbed by a thin piece of lead.

Variation of intensity, I with thickness, t of the absorber for alpha particles.

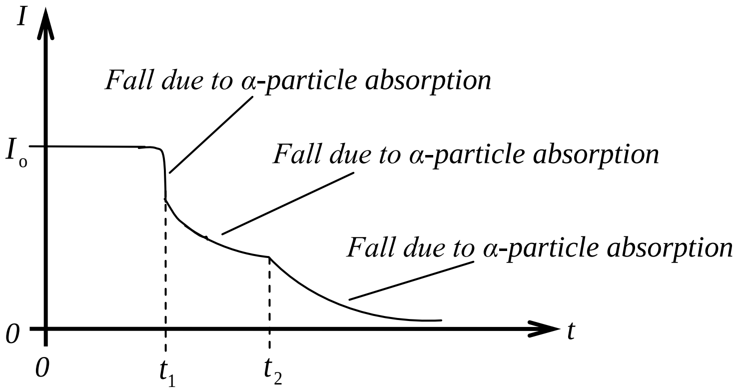


Features of the graph

In most cases, a gamma ray quantum loses all its energy in a single event. Therefore, the fractional intensity of the beam falls by a fixed amount each time it traverses any given small thickness of the absorber. The graph thus is exponential.

NB:

For all the on the same axes diagram, the variation of intensity, I with thickness, t of the absorber is as below.



Alpha, beta and gamma radiations all pass through a very thin sheet of paper hence no loss of intensity to a thickness, t_1.

At t_1, *all alpha particles are absorbed and hence a sharp drop in intensity.*

The beta particles have a range of energies and so are absorbed exponentially up to a thickness, t_2.

They are absorbed by a thin piece of lead and so intensity, I varies with thickness, t exponentially.

NUMERICAL EXAMPLES

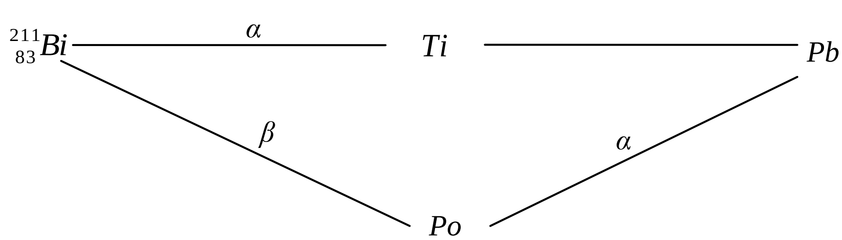
1. *The following is part of Uranium-238 decay series.* $^{238}_{92}U \xrightarrow{(i)} {}^{234}_{90}Th \xrightarrow{(ii)} {}^{234}_{91}Pb$. *Name the particles emitted at each of the two stages (i) and (ii).*

2. (a) *A source emits two types of radiations simultaneously. The radiations pass through the absorber of different thicknesses. Sketch a graph of intensity of the radiation detected against the thickness of the absorber.*
   (b) *Explain the features of the graph in (a) above.*

3. *The nucleus of* $^{37}_{17}Cl$ *emits an alpha particle and two beta particles. Show that the final nucleus is an isotope of chlorine.*

4. *In a naturally occurring radioactive decay series, there are several examples in which a nucleus emits an alpha particle followed by two beta particles.*
   (a) *Show that the final nucleus is an isotope of the original one.*
   (b) *What is the change I the mass number between the original and final nucleus.*

5. *Part of the actinium radioactive decay series can be represented as follows.*



In the symbols above, the arrows indicate the modes of decay.

(a) Write down the atomic number numbers of Ti, Po and Pb in this series.
(b) What is the possible mode of decay for the stage Ti to Pb?

Exponential law of radioactive decay.

This states that, the rate of decay of a radioactive substance is proportional to the number of nuclides present.

I.e. $\frac{dN}{dt} \propto N$ *, where N is the number of nuclides present at any time t.*

Expression for decay equation.

From, $\frac{dN}{dt} \propto N$ *. Since N reduces as time, t increases, then,*

$-\frac{dN}{dt} \propto N$ *, hence* $-\frac{dN}{dt} = \lambda N$ *, where λ is the decay constant.*

$\Rightarrow \quad \frac{dN}{dt} = -\lambda N \quad \Rightarrow \quad \frac{dN}{N} = -\lambda dt$ *and so,* $\int \frac{1}{N} dN = -\lambda \int dt \quad \Rightarrow \quad InN = -\lambda t + c$.

When $t = 0, \quad N = N_o$ *hence* $InN_o = -\lambda(0) + c \quad \Rightarrow \quad c = InN_o$

$\Rightarrow \quad InN = InN_o - \lambda t \quad \Rightarrow InN - InN_o = -\lambda t \quad \Rightarrow \quad In\left(\frac{N}{N_o}\right) = -\lambda t \quad \therefore \quad N = N_o e^{-\lambda t}$.

Terms used in decay law.

1. ***Decay constant (λ).***

This refers to the fractional number of atoms which decay per second.
The S.I unit of decay constant is per second (s^{-1} *).*

Other units *are per minute, per hour, per day, per year, etc.*

From, $\frac{dN}{dt} = \lambda N \quad \Rightarrow \quad \lambda = \frac{1}{N}\left(\frac{dN}{dt}\right)$.

2. ***Activity (A).***

This is the rate of decay of a radioactive nuclide. i.e. $A = \frac{dN}{dt}$.

Activity is measured in counts per second (s^{-1} *) or Becquerel (Bq).*

NB:

(i) $1\,Bq = 1\,count\ per\ second$.

(ii) A Becquerel refers to the rate of decay where one atom decays in one second.

Other units of activity are; counts per minute, counts per hour, counts per day, counts per year, etc.

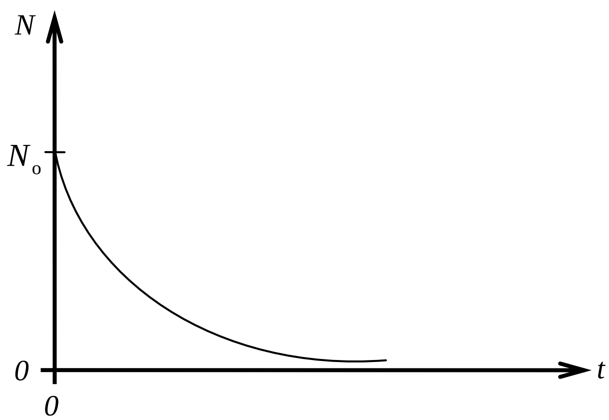
Note:

(a) *Number of counts = Number of nuclides decaying.*

(b) *From* $\lambda = \frac{1}{N}\left(\frac{dN}{dt}\right)$ *and* $A = \frac{dN}{dt}$ *then,* $\lambda = \frac{A}{N} \quad \Rightarrow \quad A = \lambda N$.

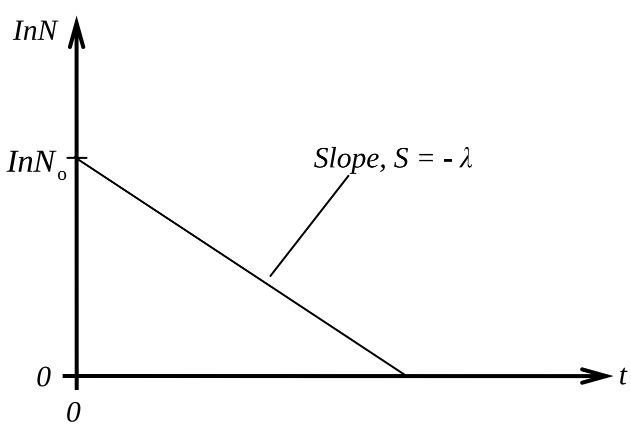
(c) *Equation* $N = N_o e^{-\lambda t}$ *shows that the number of nuclei remaining at any time, t varies exponentially with time, t*

A graph of number of decaying nuclides, N against time, t (Decay curve).



From, $N = N_o e^{-\lambda t}$, $\Rightarrow log_e N = log_e \left(N_o e^{-\lambda t}\right)$ *and so,* $log_e N = log_e N_o - \lambda t$ *or,* $InN = InN_o - \lambda t$.

A graph of In N against time, t .

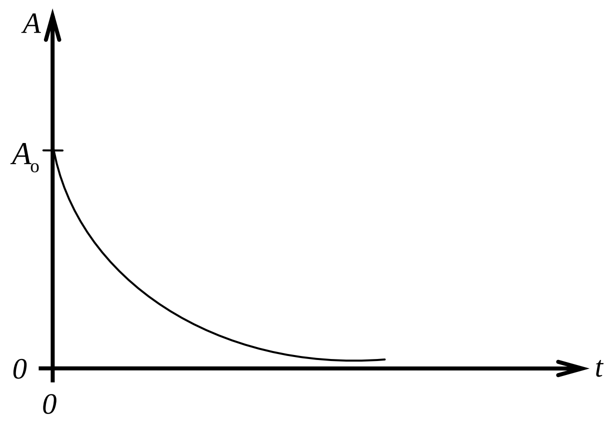


Equation for activity, A.

From $A = \frac{dN}{dt}$ *and* $\frac{dN}{dt} = \lambda N$, $A = \lambda N$ *but* $N = N_o e^{-\lambda t} \quad \Rightarrow \quad A = \lambda N_o e^{-\lambda t}$. *At* $t = 0$,

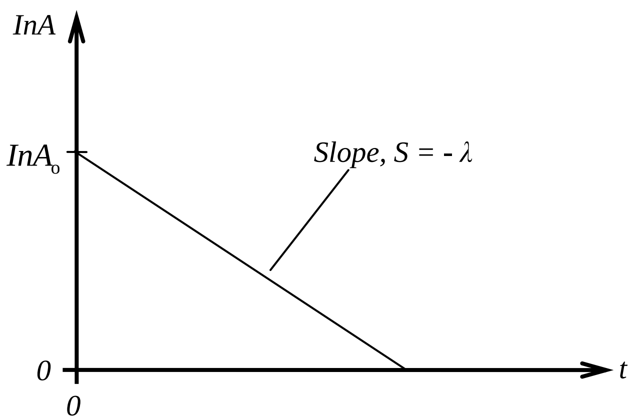
$A_o = \lambda N_o$ *(original activity) from which,* $A = A_o e^{-\lambda t}$.

A graph of Activity against time, t .



From, $A = A_o e^{-\lambda t}$, $\Rightarrow$ $log_e A = log_e\left(A_o e^{-\lambda t}\right)$ *and so,* $log_e A = log_e A_o - \lambda t$ *or,* $InA = InA_o - \lambda t$ *which is the equation of a straight line with a negative gradient.*

A graph of In N against time, t .



Half-life (*$T_{1/2}$*).

This refers to the time taken for half the number of radioactive nuclei present to decay.

The graph below illustrates how half life is arrived to.