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PHYSICS

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MODERN PHYSICS - II

THEORY AND EXERCISE BOOKLET

CONTENTS

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Syllabus :

Atomic nucleus; Alpha, beta and gamma radiations; Law of radioactive decay; Decay constant; Half-life and mean life; Binding energy and its calculation; Fission and fusion processes; Energy calculation in these processes.

NUCLEAR PHYSICS

It is the branch of physics which deals with the study of nucleus.

1. NUCLEUS :

(a) Discoverer : Rutherford

(b) Constituents : neutrons (n) and protons (p) [collectively known as nucleons]

1. Neutron : It is a neutral particle. It was discovered by J. Chadwick.
Mass of neutron,

$m_n = 1.6749286 \times 10^{-27}$ kg

2. Proton : It has a charge equal to +e. It was discovered by Goldstein.
Mass of proton, $m_p = 1.6726231 \times 10^{-27}$ kg

$(m_p \lesssim m_n)$

(c) Representation :

$_Z X^A$ or $^A_Z X$

where X ⇒ symbol of the atom
Z ⇒ Atomic number = number of protons
A ⇒ Atomic mass number = total number of nucleons.
= no. of protons + no. of neutrons.

Atomic mass number :

It is the nearest integer value of mass represented in a.m.u (atomic mass unit)

1 a.m.u = $\frac{1}{12}$ [mass of one atom of $_6C^{12}$ atom at rest and in ground state]

1.6603×10^{-27} kg ; 931.478 MeV/c^2

mass of proton (m_o) = mass of neutron (m_n) = 1 a.m.u.

Some definitions :

(1) Isotopes :
The nuclei having the same number of protons but different number of neutrons are called isotopes.

(2) Isotones :
Nuclei with the same neutron number N but different atomic number Z are called isotones.

(3) Isobars :
The nuclei with the same mass number but different atomic number are called isobars

(d) Size of nucleus : Order of 10^{-15} m (fermi)
Radius of nucleus ; $R = R_0A^{1/3}$
where $R_0 = 1.1 \times 10^{-15}$ m (which is an empirical constant)
A = Atomic mass number of atom.

(e) Density :

$$\text{density} = \frac{\text{mass}}{\text{volume}} \cong \frac{Am_p}{\frac{4}{3}\pi R^3} = \frac{Am_p}{\frac{4}{3}\pi (R_0A^{1/3})^3} = \frac{3m_p}{4\pi R_0^3} = \frac{3 \times 1.67 \times 10^{-27}}{4 \times 3.14 \times (1.1 \times 10^{-15})^3} = 3 \times 10^{17}\ \text{kg/m}^3$$

Nuclei of almost all atoms have almost same density as nuclear density is independent of the mass number (A) and atomic number (Z).

2. MASS DEFECT

It has observed that there is a differene between expected mass and actual mass of a nucleus.

$M_{expected} = z\, m_p + (A - Z)\, m_n$

$M_{observed} = M_{atom} - Zm_e$

It is found that

$M_{observed} < M_{erxpected}$

Hence, mass defect is defined as

Mass defect $= M_{expected} - M_{observed}$

$\Delta m = [Zm_p + (A - Z)m_n - [M_{atom} - Zm_e]$

3. BINDING ENERGY

It is the minimum energy required to break the nucleus into its constituent particles.

or

Amount of energy released during the formation of nucleus by its constituent particles and bringing them from infinite separation.

Binding Energy (B.E.) $= \Delta mc^2$

BE $= \Delta m$ (in amu) $\times$ 931.5 MeV/amu

$= \Delta m \times 931.5$ MeV

$= \Delta m \times 931$ MeV

Note : If binding energy per nucleon is more for a nucleus then it is more stable.

For Example

If $\left(\frac{B.E_1}{A_1}\right) > \left(\frac{B.E_2}{A_2}\right)$

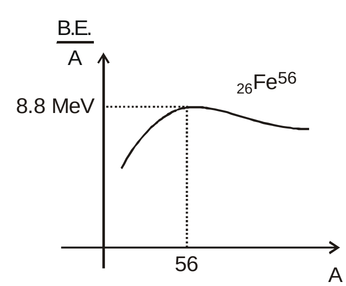
then nucleus 1 would be more stable.

3.1 Variation of binding energy per nucleon with mass number :

The binding energy per nucleon first increases on an averge and reaches a maximum of about 8.7 MeV for A. 50 $\rightarrow$ 80. For still heavier nuclei, the binding energy per nucleon

slowly decreases as A increases.

Binding energy per nucleon is maximum for $_{26}Fe^{56}$, which is equal to 8.8 MeV. Binding energy per nucleon is more for medium nuclei than for heavy nuclei. Hence, medium nuclei are highly stable.



- The heavier nuclei being unstable have tendency to split into medium nuclei. This process is called **Fission.**
- The Lighter nuclei being unstable have tendency to fuse into a medium nucleus. This process is called **Fusion.**

4. RADIOACTIVITY :

It was discovered by Henry Becquerel.

Spontaneous emission of radiations (α, β, γ) from unstable nucleus is called **radioactivity.**

Substances which shows radioactivity are known as **radioactive substance.**

Radioactivity was studied in detail by Rutherford.

In radioactive decay, an unstable nucleus emits α particle or β particle. After emission of α or β the remaining nucleus may emit γ- particle, and converts into more stable nucleus.

α- particle :

It is a doubly charged helium nucleus. It contains two protons and two neutrons.

Mass of α - particle = Mass of $_2He^4$ atom $- 2m_e = 4\, m_p$

Charge of α - particle = + 2e

β-particle :

(a) β^- (electron) :

Mass = m_e ; Charge = – e

(b) β^+ (positron)

Mass = m_e ; Charge = + e

positron is an antiparticle of electron.

Antiparticle :

A particle is called antiparticle of other if on collision both can annihilate (destroy completely) and converts into energy. For example : (i) electron (–e, m_e) and positron (+e, m_e) are anti particles, (ii) neutrino (ν) and antineutrino ($\bar{\nu}$) are anti particles.

γ-particle : They are energetic photons of energy of the order of Mev and having rest mass zero.

5. RADIOACTIVE DECAY (DISPLACEMENT LAW) :

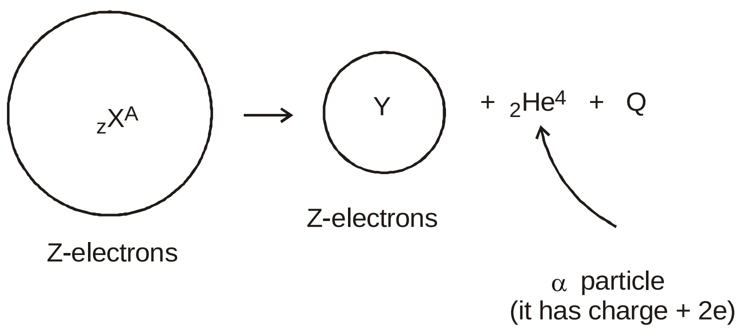
5.1 α - decay :

$${}_Z X^A \rightarrow {}_{Z-2}Y^{A-4} + {}_2He^4 + Q$$

Q value : It is definied as energy released during the decay process.

Q value = rest mass energy of reactans – rest mass energy of products.

This energy is available in the form of increase in K.E. of the products



Let, M_x = mass of atom ${}_zX^A$

M_y = mass of atom ${}_{z-2}Y^{A-4}$

M_{He} = mass of atom ${}_2He^4$

Q value = $[(M_x - Zm_e) - \{(M_y - (Z-2)m_e) + (M_{He} - 2m_e)\}]\, c^2$

$= [M_x - M_y - M_{He}]\, c^2$

Considering actual number of electrons in α - decay

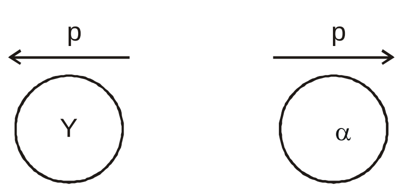
Q value = $[M_x - (M_y + 2m_e) - (M_{He} - 2m_e)]\, c^2$

$= [M_x - M_y - M_{He}]c^2$

Calculation of Kinetic energy of final products :

As atom X was initially at rest and no external forces are acting, so final momentum also has to be zero.

Hence both Y and α - particle will have same momentum in magnitude but in opposite direction.



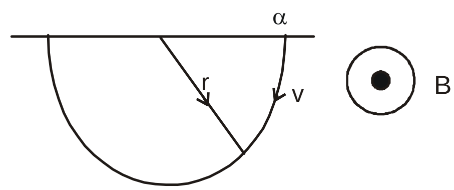
$p_\alpha^2 = p_Y{}^2$ $\quad 2m_\alpha T_\alpha = 2\, m_Y T_Y$ (Here we are representing T for kinetic energy)

$Q = T_y + T_\alpha$ $\quad m_\alpha T_\alpha = m_Y T_y$

$$T_\alpha = \frac{m_Y}{m_\alpha + m_Y} Q \quad ; \quad T_Y = \frac{m_\alpha}{m_\alpha + m_Y} Q$$

$$T_\alpha = \frac{A-4}{A} Q \quad ; \quad T_Y = \frac{4}{A} Q$$

From the above calculation, one can see that all the α-particles emitted should have same kinetic energy. Hence, if they are passed through a region of uniform magnetic field having direction perpendicular to velocity, they should move in a circle of same radius.

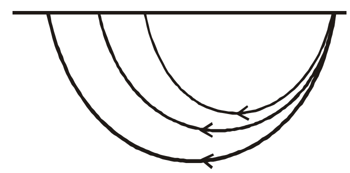


$$r = \frac{mv}{qB} = \frac{mv}{2eB} = \frac{\sqrt{2Km}}{2eB}$$

Experimental Observation :

Experimentally it has been observed that all the α-particles do not move in the circle of same radius, but they

move in 'circles having different radii.



This shows that they have different kinetic energies. But it is also observed that they follow circular paths of some fixed values of radius i.e. yet the energy of emitted α-particles is not same but it is quantized. The reason behind this is that all the daughter nuclei produced are not in their ground state but some of the daughter nuclei may be produced in their excited states and they emits photon to aquire their ground state.

$$X \longrightarrow Y^* \text{(excited state)} + \alpha + Q$$

$$\downarrow$$

$$Y + \text{photon } (\gamma \text{ particle})$$

The only difference between Y and Y* is that Y* is in excited state and Y is in ground state.

Let, the energy of emited γ- particles be E

$\therefore \quad Q = T_\alpha + T_Y + E$

where $Q = [M_x - M_Y - M_{He}]\, c^2$

$T_\alpha + T_Y = Q - E$

$$T_\alpha = \frac{m_Y}{m_\alpha + m_Y}(Q-E) \quad ; \quad T_Y = \frac{m_\alpha}{m_\alpha + m_Y}(Q-E)$$

5.2 β^- – decay :

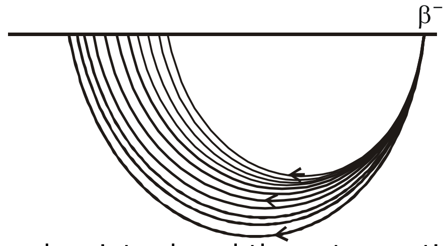
$${}_zX^A \longrightarrow {}_{Z+1}Y^A + {}_{-1}e^0 + Q$$

${}_{-1}e^0$ can also be written as ${}_{-1}\beta^0$

Here also one can see that by momentum and energy conversion, we will get

$$T_e = \frac{m_Y}{m_e + m_Y} Q, \quad T_Y = \frac{m_e}{m_e + m_Y} Q$$

as $m_e << m_Y$, we can consider that all the energy is taken away by the electron. From the above results, we will find that all the β-particles emitted will have same energy and hence they have same radius if passed through a region of perpendicular magnetic field. But, experimental observations were completely different. On passing through a region of uniform magnetic field perpendicular to the velocity, it was observed that β-particles take circular paths of different radius having a continuous spectrum.



To explain this, Paulling has introduced the extra particles called neutrino and antineutrino (antiparticle of neutrino).

$\bar{\nu} \rightarrow$ antineutrino, $\nu \rightarrow$ neutrino

Propeties of antineutrino ($\bar{\nu}$) & neutrino (n) :

(1) They are like photons having rest mass = 0
speed = c
Energy, $E = mc^2$

(2) They are chargeless (neutral)

(3) They have spin quantum number, $s = \pm \frac{1}{2}$

Considering the emission of antineutrino, the equation of β^- - decay can be written as

$$_ZX^A \longrightarrow _{z+1}Y^A + _{-1}e^0 + Q + \bar{\nu}$$

Production of antinuetrino along with the electron helps to explain the continueous spectrum because the energy is distributed randomly between electron and $\bar{\nu}$ and it also helps to explain the spin quantum number balnace (p, n and ± e each has spin quantium number ± 12)

During β^- - decay, inside the nucleus a neutron is converted to a proton with emission of an electron and antineutrino.

$$n \rightarrow p + _{-1}e^0 + \bar{\nu}$$

Let, M_x = mass of atom $_zX^A$
M_Y = mass of atom $_{z+1}Y^A$
m_e = mass of electron

Q value = $[(M_x - Zm_e) - \{(M_Y - (z + 1)m_e) + m_e\}]\ c^2 = [M_x - M_Y]\ c^2$

Considering actual number of electrons.

Q value = $[M_x - \{(M_Y - m_e) + m_e\}]\ c^2 = [M_x - M_y]c^2$

5.3 β^+ – decay :

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

In β^+ decay,inside a nucleus a proton is converted into a neutron, positron and neutrino.

$$p \rightarrow n + _{+1}e^0 + \nu$$

As mass increases during conversion of proton to a neutron, hence it requires energy for β^+ decay to take place,

$\therefore$ β^+ decay is rare process. It can take place in the nucleus where a proton can take energy from the nucleus itself.

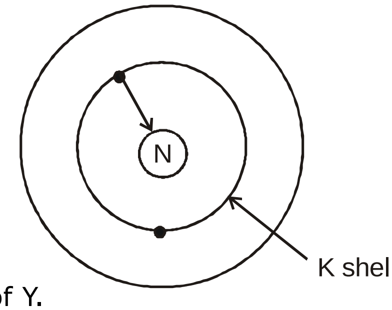
Q value = $[(M_X - Zm_e) - \{(M_Y - (Z - 1)\ m_e) + m_e\}]\ c^2 = [M_X - M_Y - 2m_e]\ c^2$

Considering actual number of electrons.

Q value = $[M_X - \{(M_Y + m_e) + m_e\}]\ c^2 = [M_X - M_Y - 2m_e]\ c^2$

5.4 K capture :

It is rare process which is found only in few nucleus. In this process the nuclues captures one of the atomic electrons from the K shell. A proton in the nucleus combines with this electron and converts itself into a neutron. A neutrino is also emitted in the process and is emitted from the nucleus.



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

If X and Y are atoms then reactions is written as :

$${}_{z}X^{A} \rightarrow {}_{z-1}Y^{A} + \nu + Q$$ + characteristic x-rays of Y.

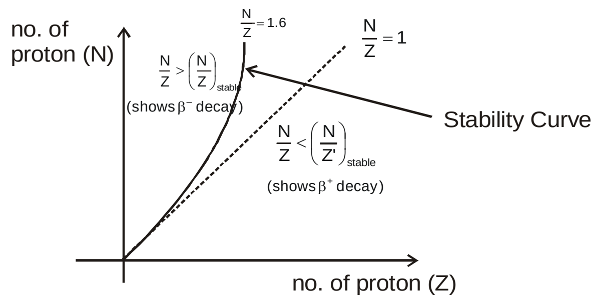
If X and Y are taken as nucleus, then reactions is written as :

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

Note : (1) Nuclei having atomic numbers from Z = 84 to 112 shows radioactivity.
(2) Nuclei having Z = 1 to 83 are stable (only few exceptions are there)
(3) Whenever a neutron is produced, a neutrino is also produced.
(4) Whenever a neutron is converted into a proton, a antineutrino is produced.

6. NUCLEAR STABILITY :

Figure shows a plot of neutron number N versus proton number Z for the nuclides found in nature. The solid line in the figure represents the stable nuclides. For light stable nuclides, the neutron number is equal to the proton number so that ratio N/Z is equal to 1. The ratio N/Z increases for the heavier nuclides and becomes about 1.6 for the heaviest stable nuclides.



The points (Z, N) for stable nuclides fall in a rather well-defined narrow region. There are nuclides to the left of the stability belt as well as to the right of it. The nuclides to the left of the stability region have excess neutrons, whereas, those to the right of the stability belt have excess protons. these nuclides are unstble and decay with time according to the laws of radioactive disintegration. Nuclides with excess neutrons (lying above stability belt) show β^- decay while nuclides with excess protons (lying below stability belt) show β^+ decay and K - capture.

7. NUCLEAR FORCE :

(i) Nuclear forces are basically attractive and are responsible for keeping the nucleons bound in a nucleus in spite of repulsion between the positively charge protons.

(ii) It is strongest force with in nuclear dimensions (F_n – 100 F_e)

(iii) It is short range force (acts only inside the nucleus)

(iv) It acts only between neutron-neutron, neutron-proton and proton-proton i.e. between nucleons.

(v) It does not depend on the nature of nucleons

(vi) An important property of nuclear force is that it is not a central force. The force between a pair of nucleons is not solely determined by the distance between the necleons. For example, the nuclear force depends on the directions of the spins of the nucelons. The force is stronger if the spins of the nucleons are parallel (i.e., both nucleons have m_s = +1/2 or −1/2) and is weaker if the spins are antiparallel (i.e., one nucleon has m_s = +1/2 and the other has m_s = – 1/2). Here m_s is spin quantum number.

8. RADIOACTIVE DECAY : STATISTICAL LAW :

(Given by Rutherford and Soddy)

Rate of radioactive decay $\propto$ N

where N = number of active nuclei = λ N

where λ = decay constant of the radioactive substance.

Decay constant is different for different radioactive substances, but it does not depend on amount of substances and time.

SI unit of λ is s^{-1}

If $\lambda_1 > \lambda_2$ then first substance is more radioactive (less stable) than the second one.

For the case, if A decays to B with decay constant λ

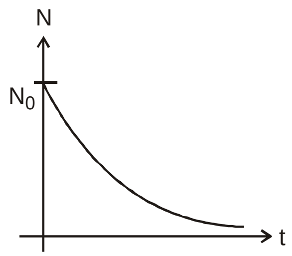
$$A \xrightarrow{\lambda} B$$

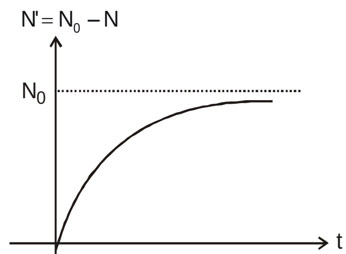
t = 0 N_0 0   where N_0 = number of active nuclei of A at t = 0

t = t   N   N'   where N = number of active nuclei of A at t = t

Rate of radioactive decay of A = $-\frac{dN}{dt} = \lambda N$

$$-\int_{N_0}^{N}\frac{dN}{N} = \int_0^t \lambda dt \Rightarrow N = N_0\, e^{-\lambda t} \text{ (it is exponential decay)}$$





Number of nuclei decayed (i.e., the number of nuclei of B formed)

$$N' = N_0 - N = N_0 - N_0 e^{-\lambda t}$$

$$N' = N_0(1 - e^{-\lambda t})$$

8.1 Half life ($T_{1/2}$) :

It is the time in which number of active nuclei becomes half.

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

After one half life, $N = \frac{N_0}{2}$

$$\frac{N_0}{2} = N_0 e^{-\lambda t} \Rightarrow t = \frac{\ln 2}{\lambda} \Rightarrow \frac{0.693}{\lambda} = t_{1/2}$$

$$t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$ **(to be remembered)**

Number of nuclei present after n half lives i.e. after a time t = n $t_{1/2}$

$$N = N_0 e^{-\lambda t} = N_0 e^{-\lambda n t_{1/2}} = N_0 e^{-\lambda n \frac{\ln 2}{\lambda}}$$

$$= N_0 e^{\ln 2^{(-n)}} = N_0 (2)^{-n} = N_0 (1/2)^n = \frac{N_0}{2^n}$$

{$n = \frac{t}{t_{1/2}}$. It may be a fraction, need not to be an integer}

or $$N_0 \xrightarrow[\text{half life}]{\text{after 1st}} \frac{N_0}{2} \xrightarrow{2} N_0\left(\frac{1}{2}\right)^2 \xrightarrow{3} N_0\left(\frac{1}{2}\right)^3 \ldots\ldots\ldots\ldots\ldots \xrightarrow{n} N_0\left(\frac{1}{2}\right)^n$$

8.2 Activity :

Activity is defined as rate of radioactive decay of nuclei

It is denoted by A or R $\quad A = \lambda N$

If a radioactive substance changes only due to decay then

$$A = -\frac{dN}{dt}$$

As in that case, $N = N_0 e^{-\lambda t}$

$$A = \lambda N = \lambda N_0 e^{-\lambda t} \Rightarrow A = A_0 e^{-\lambda t}$$

SI unit of activity : becquerel (Bq) which is same as 1 dps (disintegration per second)

The popular unit of activity is curis which is defined as

1 curie = 3.7×10^{10} dps (which is activity of 1 gm Radium)

specific activity : The activity per unit mass is called specific activity.

8.3 Average Life :

$$T_{avg} = \frac{\text{sum of ages of all the nuclei}}{N_0} = \frac{\int_0^\infty \lambda N_0 e^{-\lambda t} dt.t}{N_0} = \frac{1}{\lambda}$$

Ex.17 A radioactive nucleus can decay be two different processes. The half-life for the first process is t_1 and that for the second process is t_2. Show that the effective half-life t of the nucleus is given by

$$\frac{1}{t} = \frac{1}{t_1} + \frac{1}{t_2}$$

Sol. The decay constant for the first process is $\lambda_1 = \frac{\ln 2}{t_1}$ and for the second process it is $\lambda_2 = \frac{\ln 2}{t_1}$. The probability that an active nucleus decays by the first process in a time interval it is λ_1 dt. Similarly, the probability that it decays by the second process is λ_2 dt. The probability that it either decays by the first process or by the second process is λ_1 dt + λ_2 dt. If the effective decay constant is λ, this probability is also equal to λ dt. Thus

$$\lambda dt = \lambda_1 dt + \lambda_2 dt$$

or, $\quad \boldsymbol{\lambda = \lambda_1 + \lambda_2}$

or, $\quad \frac{1}{t} = \frac{1}{t_1} + \frac{1}{t_2}$ (To be remembered)

Ex.18 A factory produces a radioactive substance A at a constant rate R which decays with a decay constant λ to form a stable substance. Find (i) the no. of nuclei of A and (ii) Number of nuclei of B, at any time t assuming the production of A starts t = 0. (iii) Also find out the maximum number of nuclei of 'A' present at any time during its formation.

Sol. $$\text{Factory} \xrightarrow[\text{constant}]{R} A \xrightarrow[\text{decay}]{\lambda} B$$

Let N be the number of nuclei of A at any time t

$$\therefore \frac{dN}{dt} = R - \lambda N \qquad \int_0^N \frac{dN}{R - \lambda N} = \int_0^t dt$$

On solving we will get

$N = R/\lambda \, (1 - e^{-\lambda t})$

(ii) Number of nuceli of B at any time t, $N_B = R\,t - N_A = Rt - R/\lambda\,(1 - e^{-\lambda t}) = R/\lambda\,(\lambda t - 1 + e^{-\lambda t})$

(iii) Maximum number of nuclei of 'A' present at any time during its formation = $\frac{R}{\lambda}$

Ex.19 ***A radioactive substance "A" having N_0 active nuclie at t = 0, decays to another radioactive substance "B" with decay constant λ_1. B further decays to a stable substance 'C' with decay constant λ_2. (a) Find the number of nuclei of A, B and C after time t, (b) What would be answer of part (a) if $\lambda_1 >> \lambda_2$ and $\lambda_1 << \lambda_2$***

Sol. The decay scheme is as shown

$$A \xrightarrow{\lambda_1} B \xrightarrow{\lambda_2} C \text{ (stable)}$$

	A	B	C
t = 0	N_0	0	0
t	N_1	N_2	N_3

Here N_1, N_2 and N_3 represent the nuclei of A, B and C at any time t.

For A, we can write

$$N_1 = N_0 e^{-\lambda_1 t} \qquad \text{...(1)}$$

For B, we can write

$$\frac{dN_2}{dt} = \lambda_1 N_1 - \lambda_2 N_2 \qquad \text{...(2)}$$

or, $$\frac{dN_2}{dt} + \lambda_2 N_2 - \lambda_1 N_1$$

This is a linear differential equation with integrating factor

$$\text{I.F.} = e^{\lambda}2^{t}$$

$$e^{\lambda_2 t}\frac{dN_2}{dt} + e^{\lambda_2 t}\lambda_2 N_2 = \lambda_1 N_1 e^{\lambda_2 t}$$

$$\int d(N_2 e^{\lambda_2 t}) = \int \lambda_1 N_1 e^{\lambda_2 t} dt$$

$$N_2 e^{\lambda_2 t} = \lambda_1 N_0 \int e^{-\lambda_1 t} e^{\lambda_2 t} dt \qquad \text{...using (1)}$$

$$N_2 e^{\lambda_2 t} = \lambda_1 N_0 \frac{e^{(\lambda_2 - \lambda_1)t}}{\lambda_2 - \lambda_1} + C \qquad \text{...(3)}$$

At t = 0, $N_2 = 0$ $\qquad 0 = \dfrac{\lambda_1 N_0}{\lambda_2 - \lambda_1} + C$

Hence $C = \dfrac{\lambda_1 N_0}{\lambda_1 - \lambda_2}$

Using C in eqn. (3), we get

$$N_2 = \frac{\lambda_1 N_0}{\lambda_2 - \lambda_1}(e^{-\lambda_1 t} - e^{-\lambda_2 t})$$

and $N_1 + N_2 + N_3 = N_0$

$\therefore$ $N_3 = N_0 - (N_1 + N_2)$

(b) For $\lambda_1 >> \lambda_2$ $\qquad N_2 = \dfrac{\lambda_1 N_0}{-\lambda_1}(-e^{-\lambda_2 t}) = N_0 e^{-\lambda_2 t}$

For $\lambda_1 << \lambda_2$ $\qquad N_2 = \dfrac{\lambda_1 N_0}{\lambda_2}(e^{-\lambda_1 t}) = 0$

9. NUCLEAR FISSION :

In nuclear fission heavy nuclei of A, above 200, break up into two or more fragments of comparable masses. The most attractive bid, from a practical point of view, to achieve energy from nuclear fission is to use $_{92}U^{236}$ as the fission material. the technique is to hit a uranium sample by sample by slow moving neutrons (kinetic energy ≈ 0.04 eV, also called thermal neutrons.) A$_{92}$ U^{235} nucleus has large probability of absorbing a slow neutron and forming $_{92}U^{236}$ nucleus. This nucleus then fissions into two parts. A variety of combinations of the middle-weight nuclei may be formed due to the fission. For example, one may have

$$_{92}U^{235} + _0n^1 \rightarrow _{92}U^{236} \rightarrow X + Y + 2_0n^1,$$

or $$_{92}U^{235} + _0n^1 \rightarrow _{92}U^{236} \rightarrow X' + Y' + 2_0n^1$$

and a number of other combinations.
• On an average 2.5 neutrons are emitted in each fission event.
• Mass lost per reaction 0.2 a.m.u.
• In nuclear fission the total B.E. increases and excess energy is released.
• In each fission event, about 200 MeV of energy is released a large part of which appears in the form of kinetic energies of the two ragements. Neutrons take away about 5 MeV.

Ex. $^{235}_{92}U + _0n^1 \rightarrow ^{236}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3_0n^1 + \text{energy}$

Q value = $[(M_U - 92\,m_e + m_n) - \{(M_{Ba} - 56\,m_e) + (M_{Kr} - 36\,m_e) + 3m_n\}]\,c^2$
= $[(M_U + m_n) - (M_{Ba} + M_{Kr} + 3m_n)]\,c^2$

• A very important and interesting feature of neutron-induced fission is the chain reaction. For working of nuclear reactor refer your text book.

10. NUCLEAR FUSION (THERMO NUCLEAR REACTION) :

(a) Some unstable light nuclei of A below 20, fuse together, the B.E. per nucleon increases and hence the excess energy is released. The easiert thermonuclear reaction that can be handled on earth is the fusion of two deuterons (D – D reaction) or fusion of a deuteron with a triton (D – T reaction).

$$_1H^2 + _1H^2 \rightarrow _2He^3 + _0n^1 + 3.3\,\text{MeV}\,(D-D)$$

Q value = $[2((M_D - m_e) - \{(M_{He^3} - 2m_e) + m_n\}]c^2 = [2M_D - (M_{He^3} + m_n)]c^2$

$$_1H^2 + _1H^2 \rightarrow _1H^3 + _1H^1 + 4.0\,\text{MeV}\,(D-D)$$

Q value = $[2(M_D - m_e) - \{(M_T - m_e) + (M_H - m_e)\}]c^2 = [2M_D - (M_T + M_H)]c^2$

$$_1H^2 + _1H^3 \rightarrow _2He^4 + n + 17.6\,\text{MeV}\,(D-T)$$

Q value = $[\{(M_D - m_e) + (M_T - m_e)\} - \{(M_{He^4} - 2m_e) + m_n\}]c^2 = [(M_D + M_T) - (M_{He^4} + m_n)]c^2$

Note

• In case of fission and fusion, $\Delta m = \Delta m_{atom} = \Delta m_{nucleus}$
• These reactions take place at ultra high temperature ($\cong 10^7$ to 10^8). At high pressure it can take place at low temperature also. For these reactions to take place nuclei should be brough upto 1 fermi distance which requires very high kinetic energy.
• Energy released in fusion exceeds the energy liberated in the fission of heavy nuclei.