⑥ sets

381-

2 copy 7841942039

Chavan Swati T

|| Shri Ganeshai Namah ||

raane (Pat

Maya Patil. Inorganic

NUCLEAR CHEMISTRY

INTRODUCTION :

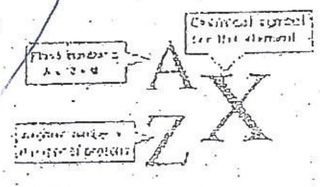
Nuclear chemistry is the branch of chemistry that deals with the study of the nucleus in an atom. The discovery of natural radioactivity by Becquerel was the begining of nuclear chemistry. The initial progress in this branch was done by Pierre Curie and Marie Curie by isolating natural radioactive elements and investigating their properties. Their investigations soon attracted the attention of several scientists all over the world. Today, nuclear science occupies an important place in scientific research as it has established its potential for several applications in the areas of energy, medical diagnosis and treatment, and warfare.

NUCLEAR NOTATION

Standard nuclear notation for an element shows the chemical symbol, the mass number and the atomic number of the isotope.

A → mass

Z → atomic



COMMONLY USED NOTATIONS IN NUCLEAR CHEMISTRY

Notation	Species	Notation	Species
α	${}^{4}_{2}He$	p	${}^{1}_{1}H$
β^-	${}^{0}_{-1}e$	d	${}^{2}_{1}H$
β^+	${}^{0}_{+1}e$	γ	chargless radiation
n	${}^{1}_{0}n$		

NUCLEUS AND NUCLEAR STABILITY

Nucleus is located at the centre of the atom and consists of protons and neutrons which are collectively called as nucleons. The attractive forces amongst nucleons are known as nuclear forces which determine the stability of nucleus. The stability of nucleus may be discussed in terms of any one of the following :

1. Mass defect and nuclear binding energy.
2. Packing fraction
3. Neutron-proton ratio
4. Nuclear Shell model.

1. Mass defect and Nuclear binding energy

Mass Defect (Δm)

The difference between the theoretical mass and observed mass of a nucleus is called as mass defect.

It is denoted by $\triangle$ m and is expressed in a.m.u.

$\triangle$ m = sum of masses of protons and neutrons − observed mass of nucleus.

Theoretical mass of one proton = 1.0078

Theoretical mass of one neutron = 1.0086

For example: The mass defect for $^{40}_{20}Ca$ whose mass is 39.972 a.m.u. will be

$$\triangle m = (20 \times 1.0078 + 20 \times 1.0086) - 39.975$$
$$= 40.3280 - 39.9750$$
$$= 0.3530 \text{ a.m.u.}$$

Nuclear Binding Energy.

Nuclear binding energy is defined as the energy released in binding the nucleons together in the nucleus.

OR.

It is the amount energy required to break the nucleus into its constituent nucleons. The unit of nuclear binding energy is MeV.

It is calculated by using following formula :

$$B.E. = 931 \times \triangle m \text{ MeV}$$

Where $\triangle$ m = mass defect.

It can be seen that the greater the mass defect: greater is the nuclear binding energy and hence greater is the stability of the nucleus.

Binding Energy Per Nucleon :

It is defined as the ratio of total binding energy of the nucleus to its mass number. It is also defined as the average amount of energy required to isolate one nucleon from its nucleus.

$$\text{B. E. per nucleon} = \frac{\Delta m \times 931}{A}\ \text{MeV} = \frac{\text{Total binding energy}}{\text{mass no.}}$$

Δm = mass defect

A = mass number

Calculate the mass defect, binding energy and binding energy per nucleon of $^{56}_{26}Fe$ having mass 55.9375 a.m.u.

Solution

Mass defect [illegible]

Δm = sum of masses of protons and neutrons – observed mass of nucleus

$= 56.46236 - 55.9375$

$= 0.52486$ a.m.u.

Binding energy

B. E. $= \Delta m \times 931$

$= 0.52486 \times 931$

$= 488.64$ MeV.

Binding energy per nucleon

$$\text{B. E. per nucleon} = \frac{\text{Total B. E.}}{A}$$

$$= \frac{488.64}{56}$$

$= 8.725$ MeV.

Examples to solve :

Q.1 Calculate the binding energy per nucleon for $^{4}_{2}He$. Its actual mass is 4.00260 amu.

Q.2 Calculate the nuclear binding energy for $^{184}_{74}W$. Its experimental isotopic mass is 184.006 amu.

Q.3 Calculate the average binding energies for $^{14}_{7}N$ and $^{15}_{7}N$ and predict their relative stability.

Q.4 The atomic weight of $^{84}_{36}Kr$ is 83.9115 amu. Calculate its binding energy.

Q.5 Calculate the average binding energy for $^{59}_{27}Co$. Its atomic mass is 58.93319 amu.

2. Packing Fraction

Packing fraction is defined as

$$\text{Packing fraction} = \frac{\text{Actual isotopic mass} - \text{Mass number}}{\text{Mass number}} \times 10^4$$

Packing fraction and Stability are related as :

Lower the packing fraction, greater is the stability of nuclei.

Example : Calculate the packing fraction of ^{40}Ar. (isotopic weight of Ar is 39.96238)

Solution

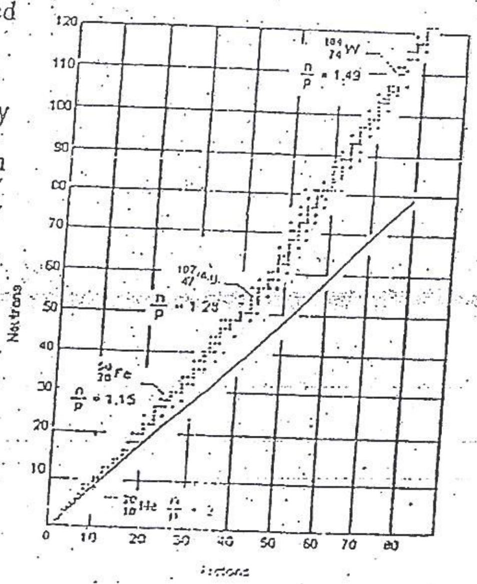
$$\text{Packing fraction} = \frac{39.96238-40}{40} \times 10^4$$

$$= -9.405$$

3. Neutron-Proton Ratio and Stability :

Nuclear stability is found to be related to the neutron to proton (N/Z) ratio.

The N/Z ratios for stable nuclei vary between 1 to 1.6. The elements lying within the stability limit (1–1.6) constitute the stability belt or stability zone. However, the elements whose nuclei do not fall within the stability limit are said to be unstable. The unstable nuclei, whose N/Z ratio is either less than 1 or greater than 1.6 are radioactive and disintegrate giving out α, β or γ rays in their attempt to attain stability. This is illustrated as : when we plot each stable nuclide on a graph with the number of protons (Z) on the horizontal axis and the number of neutrons (N) on the vertical axis, it is found that stable nuclei lie within a region known as belt of stability as shown in the graph.



The band of stability is the region in which stable nuclides lie in a plot of number of protons against number of neutrons. Nuclei outside the band of stability are generally radioactive (unstable).

The way an unstable nucleus disintegrates is decided by its position with respect to the actual N/Z plot of stable nuclei as given below :

1) Those to the left of the band of stability have a neutron–to–proton ration (N/Z) larger than that needed for stability decay by beta emission.
2) Those to the right of the band stability have N/Z ratio that is smaller than that needed for stability decay by either $\overset{\text{positron}}{\text{position}}$ emission or electron capture.
3) Heavier nuclei, especially those with Z greater than 83, often decay by alpha emission.

Types of Radioactive Decay

Type of Decay	Radiation	Nuclear Change		Usual Nuclear Condition
		Atomic Number	Mass Number	
Alpha emission (α)	${}^{4}_{2}He$	-2	-4	Z > 83
Beta emission (β)	${}^{0}_{-1}e$	+1	0	N/Z too large
Positron emission(β^+)	${}^{0}_{1}e$	-1	0	N/Z too small
Electron capture. (EC)	x rays	-1	0	N/Z too small
Gamma emission(γ)	${}^{0}_{0}\gamma$	0	0	Excited nucleus

4. Nuclear Shell Model

Nuclear Shell model is a nuclear model in which protons and neutrons exist in levels, or shells, analogues to the shell structure that exist for electrons in an atom. The shell structure is supported by the existance of periodicity in the nuclear properties. For example, elements with even number of protons and neutrons are more stable whereas elements with odd number of protons and neutrons are less stable. This suggests that like electrons, nucleon particles in the nucleus are paired. Magnetic fields of the two paired protons spinning in opposite direction cancel each other and develop attractive forces which are sufficient to stabilise the nucleus (This is discussed in detail in nucleon pairing).

Further, it is found that nuclei with certain number of protons or neutrons are more stable. These numbers are called as magic numbers.

Magic number for protons : 2, 8, 20, 28, 50, 82, 114

Magic number for neutrons : 2, 8, 20, 28, 50, 82, 126, 184, 196.

The relatively higher stability of $^{208}_{82}Pb$ can be explained by magic numbers. It has magic number for protons = 82 and magic number for neutrons = 126.

Nucleon Pairing :

The nuclei $^{4}_{2}He$, $^{12}_{6}C$, $^{16}_{8}O$ and $^{24}_{12}Mg$ are very stable. The exception stability of these nuclei is attributed to the presence of even number of neutrons and even number of protons. Nucleons, like the electrons are assumed to be paired. Just as a pair of electrons is more stable than an unpaired electron in an electronic orbital, paired nucleons are stable. Complete pairing of all the protons (Z) and all the neutrons (N) is possible when a nucleus contains an even number of protrons and even number of neutrons. The complete pairing of like nucleons imparts extra stability to the nucleus. For example, the $^{16}_{8}O$ nucleus is more stable than the $^{17}_{8}O$ nucleus; in the former, all nucleons are paired, whereas in latter, one neutron must remain unpaired. The following table lists the number of stable isotopes that have even number of protons and even number of neutrons.

Number of stable isotopes	157	52	50	5
No. of protons	Even	Even	Odd	Odd
No. of neutrons	Even	Odd	Even	Odd

By comparision, there are only 5 stable isotopes having an odd number of protons and an odd number of neutrons.

Generally, the order of stability of nuclides in terms of pairing, is

Even Z – Even N > Even Z – Odd N = Odd Z – Even N > Odd Z – Odd N

Predicting the relative stabilities of Nuclides :

Question : One of the nuclides in each of the following pairs is radioactive; the other is stable. Which is radioactive and which is stable ? Explain.

(a) $^{208}_{84}Po$, $^{209}_{83}Bi$ (b) $^{39}_{19}K$, $^{40}_{19}Bi$ (c) $^{71}_{31}Ga$, $^{76}_{31}Bi$

Solution : The problem states that one nucleus is radioactive and the other stable. We must decide which is more likely to be radioactive or which is more likely to be stable. (a) Polonium has an atomic number greater than 83, so $^{208}_{84}Po$ is radioactive.

Bismuth-209 has 126 neutrons (a magic number), so $^{209}_{83}Bi$ is expected to be stable. (b) Of these two isoptopes, $^{39}_{19}K$ has a magic number of neutrons (20), so $^{39}_{19}K$ is expected to be stable. The isotope $^{40}_{19}K$ has an odd number of protons (19) and an odd number of neutrons (21). Because stable odd–odd nuclei are rare, we might expect $^{40}_{19}K$ to be radioactive; (c) Of the two isotopes, $^{76}_{19}Ga$ lies farther from the corner of the band of stability, so it is more likely to be radioactive. For this reason, we expect $^{76}_{19}Ga$ to be radioactive and $^{76}_{19}Ga$ to be stable.

Example to solve :

Q.6 Of the following nuclides, two are radioactive. Which are radioactive and which is stable ?

Explain (a) $^{118}_{50}Sn$ (b) $^{76}_{33}As$ (c) $^{227}_{89}Ac$

Predicting the type of radioactive decay :

Example : Predict the possible type of radioactive decay for each of the following radioactive nuclides.

(A) $^{47}_{20}Ca$ (B) $^{25}_{13}Al$

Answer :

A) The nucleus of calcium–47 has 20 protons and 47–20 = 47 neutrons. Since for Ca, N/Z ratio is too high (> 1), it decays by beta emission.

B) The nucleus of aluminium–25 has 13 protons and 25–13 = 12 neutrons. Since N/Z ration of Al is too small (< 1) it decays by positron emission or electron capture.

Example to Solve :

Q.7 Predict the type of decay for each of the following radioactive nuclides.

A) $^{13}_{7}N$ B) $^{26}_{11}Na$ C) $^{208}_{84}Po$ D) $^{76}_{31}Ga$

RADIOACTIVITY

The phenomenon of spontaneously and continuously emitting active radiations is called as radioactivity and the substance emitting such radiations is called as radioactive.

All the heavy elements from bismuth and few lighter elements posses radioactive properties.

Radioactive Rays

In 1905, Rutherford analysed that the radiations from a radioactive substances are composed of three important rays : 1. α rays 2. β rays 3. γ rays. The properties of these rays are discussed below :

1. α-Rays : These rays consist of material particles of mass four each and carrying two positive charges. They are the helium nuclei, ^4_2He. They have least penetrating power and they are therefore, easily absorbed by thin sheets of metal foil. They are emitted with a great velocity and have the greatest ionising power. They have a limited range in air. They produce luminacity in ZnS due to high kinetic energy.

2. β Rays : These rays consist of negatively charged particles identical with electrons. Thus β particle has a unit negative charge and a negligible mass($^0_{-1}e$). These are more penetrating than α-rays. They are emitted from radio-active substances with a very high velocity comparable to that of light. They have weak ionising power;

3. γ Rays : These are non-material rays like X-rays, i.e. electromagnetic radiations, and are unaffected by electric field. These have high penetrating power and can penetrate even quite thick layers of lead. They have very feeble ionising power. They have high energy and short wave-length.

DISINTEGRATION THEORY OF RADIOACTIVITY

The theory was given by Rutherford and Soddy in 1902. According to this theory, radioactive elements are unstable and undergo spontaneous breakdown from one chemical atom to another. This process continues till a stable non-radioactivative nuclear species is obtained. The emission of radioactive rays takes place during this process. This process is called as radioactive decay.

Rate of Radioactive Decay

The radioactive atoms in a sample of a radioelement disintegrate. But all the atoms do not disintegrate at the same time. The number of atoms which disintegrate in unit time is directly proportional to the total number atoms of radioactive element.

If the number of atoms of radioelement is 'N' at any instant then the rate of decay disintegration will be

$$\frac{-dN}{dt} \propto N \qquad (1)$$

The equation (1) can be written as

$$\frac{-dN}{dt} = \lambda N \qquad (2) \qquad \text{Where, } \lambda = \text{decay constant}$$

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

Integrating the equation between the limits N_0 (number of atoms present initially) and Nt (number of atoms present at time t) we get

$$\int_{N_0}^{Nt} \frac{dN}{N} = -\lambda \int_0^t dt$$

$$\ln \frac{Nt}{N_0} = -\lambda t \Rightarrow N_t = N_0 e^{-\lambda t} \qquad (4)$$

Conversion of equation -- (4) to $\log_{10}$, we get

$$\lambda = \frac{2.303}{t} \log_{10} \frac{N_0}{Nt}$$

Half Life Period ($t_{1/2}$)

The half life period of a radioactive element is defined as the time in which half the amount of the substance has disintegrated.

The half life period is related to decay constant and is not related to the initial concentration of the radioactive element. Half life period is related to decay λ constant as follow :

We know that

$$t = \frac{2.303}{\lambda} \log \frac{No}{Nt}$$

At half life period ($t_{1/2}$), the Nt will be $N_0/2$

$$\text{therefore } t_{1/2} = \frac{2.303}{\lambda} \log \frac{No}{No/2}$$

$$t_{1/2} = \frac{2.303}{\lambda} \log 2$$

$$t_{1/2} = \frac{0.693}{\lambda}$$

Thus, it can be seen that half life period of the radioactive element is not related to the initial concentration.

Example 1 : 100Kg of a radioelement disintegrates to 25 Kg in 120 years. Calculate the (i) decay constant (λ) and (ii) half life of the radioelement ($t_{1/2}$)

Solution - (i) $\lambda = \frac{2.303}{t} \log10 \frac{No}{Nt}$

$$= \frac{2.303}{120} \log10 \frac{100}{25}$$

$$= \frac{2.303}{120} \times 0.6021$$

Therefore $\lambda = 1.155 \times 10^{-2}$ year^{-1}

(ii) Half life $t_{1/2} = \frac{0.693}{\lambda}$

$$t_{1/2} = \frac{0.693}{1.155 \times 10^{-2}}$$

$$t_{1/2} = 60.0 \text{ years}$$

Example 2 : A radioactive element has a life of 34 hours. How long will it take for the radioactivity of a sample of this element to fall to (i) one tenth and (ii) one hundredth of its activity ?

Solution -
$$\lambda = \frac{0.693}{t_{1/2}} = \frac{0.693}{34} \text{hr}^{-1}$$

i) If the initial activity $n_0 = 1$, then $n_t = 0.1$

$$\lambda = \frac{2.303}{t} \log_{10} \frac{N_o}{N_t}$$

$$t = \frac{2.303}{\lambda} \log_{10} \frac{N_o}{N_t}$$

$$t = \frac{2.303 \times 34}{0.693} \log10 \frac{1}{0.1}$$

$$t = \frac{2.303 \times 34}{0.693} \times 1$$

$$t = 113 \text{ hours}$$

ii) In this case, if $N_o = 1$, $N_t = 0.01$

$$t = \frac{2.303 \times 34}{0.693} \log10 \frac{1}{0.01}$$

$$t = \frac{2.303 \times 34 \times 2}{0.693}$$

$$t = 226 \text{ hours}$$

Example 3 : A sample of radioelement loses 90% of its activity in 6×10^3 s. Calculate the (i) decay constant and (ii) half life of the element.

Solution - i) If $N_o = 100$, then $N_t = 10$

$$\lambda = \frac{2.303}{t} \log_{10} \frac{N_o}{N_t}$$

$$\lambda = \frac{2.303}{6.0 \times 10^3} \log_{10} \frac{100}{10}$$

$$\lambda = 7.677 \times 10^{-4} \ s^{-1}$$

ii) half life $t_{1/2} = \dfrac{0.693}{\lambda}$

$$= \frac{0.693}{7.677 \times 10^{-4}}$$

$$= 903.0 \text{ s}$$

Problems on radioactive decay :

Q.8 ^{18}F undergoes 10% radioactive decay in 16.5 minutes. Calculate its $t_{1/2}$.

Q.9 The $t_{1/2}$ of $^{90}_{38}Sr$ is 20 years. If a sample of this nuclide has initial activity of 8000 disintegrations per minute today, what will be the activity after 80 years?

Q.10 ^{18}F undergoes 90% radioactive decay in 366 minutes. What is its $t_{1/2}$?

Q.11 The half life of Hg–203 is 49.6 days. How much of 0.200 mg sample of Hg–203 will remain after 6 months.

Q.12 Starting with 1 g of radioactive sample, 0.25 g is left after 20 days. Calculate the rate constant λ of the radioactive sample.

Q.13 Starting with 1.0 g of a radioactive sample, 0.25 g. of it is left after 5 days. Calculate the amount which was left after day.

Q.14 A radioactive element decays at such a rate that after 60 minutes only 25 percent of its original amount remains. Calculate λ and $t_{1/2}$ for this radioactive element.

UNITS OF RADIOACTIVITY

The first type of unit is Curie (Ci) which describe the intensity of radiation source.

One Curie is the amount of a radioactive substance which produces 3.7 x 10^{10} disintegrations per second. Thus, the weight of 1 Curie of U-238 is different from the weight of 1 Curie of K-40. The value of 3.7 x 10^{10} disintegrations per second (dps) is chosen as standard based on the fact that one gram of radium produces 3.7 x 10^{10} dps. Now, smaller units viz. millicurie (mci) and microcurie (uci) are often used.

1 mci = 3.7 x 10^7 dps.

1 uci = 3.7 x 10^4 dps.

1 Ci = 3.7 x 10^{10} dps

The S.I. unit of radioactivity is becquerel (bq.) It is defined as the amount of a radioactive isotope, which gives one disintegration per second.

Rutherford is a more recent unit. 1 Rutherford is equal to the amount of a radioactive isotope which gives 10^6 disintegrations per second.

Example : Half life of radium is 1580 years. Show that 1 gram of radium gives 3.7 x 10^{10} disintegrations per second.

Solution : If the number of items of radio element is N at any instant then the rate of disintegration is $-dN/dt = \lambda N$

Here $\lambda = \dfrac{0.693}{t_{1/2}}$

$$\lambda = \frac{0.693}{1580 \times 365 \times 24 \times 60 \times 60} = 1.391 \times 10^{-11}\ S^{-1}$$

[λ is required in the unit of second^{-1}]

We know that,

$$-\frac{dN}{dt} = \lambda N = \frac{1.391 \times 10^{-11} S^{-1} \times 6.023 \times 10^{23}\ mol^{-1}}{226\ g.mol^{-1}} = 3.7 \times 10^{10}\ \text{disintegration}\ S^{-1}\ g^{-1}.$$

[N is no. of atoms present in 1 gram of radium which is equal to $\dfrac{6.023 \times 10^{23}}{226}$]

Example-2 : The half-life of the nuclide ^{220}Rn is 54.5 s. What mass of this nucleus is equivalent to 1 millicurie (mci) ?

Solution :

$$\lambda = 0.693 / t_{1/2} = 0.693 / (54.5\ s) = 1.27 \times 10^{-2} S^{-1}$$

$$1\ mci = 3.7 \times 10^{7}\ \text{disintegration}\ S^{-1} = -dN/dt$$

Since $-dN/dt = \lambda N$

$$\therefore N = \frac{-dN/dt}{\lambda} = \frac{3.7 \times 10^{7} s^{-1}}{1.27 \times 10^{-2} s^{-1}} = 2.91 \times 10^{9}$$

This value for ^{220}Rn can be converted into mass as follows :

$$\text{Mass of nucleus} = \frac{2.91 \times 10^{9} \times 220\ g\ mol^{-1}}{(6.022 \times 10^{23}\ mol^{-1})} = 1.06 \times 10^{-12}\ g = 1.06 \times 10^{-15}\ kg$$

NUCLEAR REACTIONS

A nuclear reaction refers to a transformation of a target nucleus, usually at rest, by bombarding it with projectiles of light nuclei, or free nucleons, or photons of adequate energy.

The nuclear reaction is represented by an equation indicating the nuclear characteristics of the reactants and the products as

$$^{A1}_{Z1}X + ^{A2}_{Z2}a \rightarrow ^{A3}_{Z3}Y + ^{A4}_{Z4}b$$

Where, X = Target nucleus

a = Projectile effecting the reaction.

Y = Product or recoil nucleus

b = Ejectile

The first ever nuclear reaction in the laboratory was carried out in 1919 by Rutherford, when he bombarded nitrogen with α–particles :

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

Bethe's Notation :

A nuclear reation may be written in shorter form by using Bethe's notation. While representing the nuclear reaction according to Bethe's notation, the target nuclide is written first and the product last, with the projectile and ejectile articles inside the parenthesis, in the same order but separated by a comma.

The reaction $^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$ is thus represented as $^{14}_{7}N(\alpha P)^{17}_{8}O$

$^{79}_{35}Br(n,\gamma)^{80}_{35}Br$

Q.15 Write the Bethe's notation for the following reactions.

1) $^{79}_{35}Br + ^{1}_{0}n \rightarrow ^{80}_{35}Br + \gamma$

2) $^{14}_{7}N + ^{1}_{1}H \rightarrow ^{11}_{6}C + ^{4}_{2}He$

3) $^{11}_{5}B + ^{1}_{1}H \rightarrow ^{11}_{6}C + ^{1}_{0}n$

4) $^{238}_{92}U + ^{4}_{2}He \rightarrow ^{241}_{34}Pu + ^{1}_{0}n$

Nuclear reaⁿ is always accompanied by a release or absorption of energy known as Q value of reaⁿ. It is always placed at right hand side of the reaⁿ e.g. $^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H + Q$ (nuclear reaⁿ energy)

Q VALUE OF NUCLEAR REACTIONS :

Q Value refers to the energy associated with the nuclear reactions.

As in chemical reactions, nuclear reactions also involve energy changes represented by the symbol Q. The value of Q may be positive or negative. If Q is negative, the reaction is called endoergic i.e. energy is absorbed, and if Q is positive, the reaction is called exoergic i.e. energy is released.

The term Q is equivalent to enthalpy in a chemical reaction.

CALCULATION OF Q VALUE :

The value of Q for a nuclear reaction is calculated as

$$\boxed{Q = \Delta m \times 931 \text{ MeV}}$$

Where, Δm = Sum of mass of reactants – Sum of mass of products

Solved Example :

Problem : Find out the θ value of the following nuclear reaction.

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

Given the masses of ^{14}N, ^{4}He, ^{17}O and ^{1}H are 14.003074, 4.002603, 16.999133 and 1.007825 amu respectively.

Solution : Sum of the masses of reactants = 14.003074 + 4.002603

= 18.005677 amu

Sum of the masses of products = 16.999133 + 1.007825

= 18.006985 amu.

Δm = Masses of reactants – Masses of products

= 18.005677 – 18.006958

= – 0.001281 amu

Q = 931 × Δm MeV

= 931 x –00.001281

= –1.192 MeV

The θ value for the reaction is – 1.192 MeV and therefore reaction is endoergic.

Examples to Solve :

Q.16 Calculate Q value for the following nuclear reaction :

$$^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{14}Si + ^{1}_{1}H$$

The exact masses of ^{27}Al, ^{4}He, ^{30}Si and ^{1}H are 26.9815, 4.0026, 29.9738 and 1.0078 respectively.

Q.17 Calculate Q value for the following nuclear reaction.

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

Given the masses of $^{2}_{1}H$, $^{3}_{1}H$, $^{4}_{2}He$ and $^{1}_{0}n$ are 2.014, 3.016, 4.003 and 1.0086 respectively.

Q.18 Calculate the Q for the reaction :

$$^{232}_{92}Th + ^{4}_{2}He \rightarrow ^{235}_{92}U + ^{1}_{0}n$$

[^{232}Th = 232.0381, $^{4}_{2}He$ = 4.0026, ^{235}U = 235.0439, n = 1.0086]

THRESHOLD ENERGY OF A NUCLEAR REACTION :

When Q is negative, the reaction is endoergic and the energy required for the reaction is made available in the form of kinetic energy of projectile particle. For instance, let us consider the following reaction.

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

14.003074 amu 4.002603 amu 16.999133 amu 1.007825 amu.

We observe that the total mass of the reactants is 18.005677 amu and the total mass of products is 18.006958 amu. Therefore the mass difference is –0.001281 amu and hence Q value is --0.001281 x 931 or – 1.192 MeV. Since Q value of the reaction is negative, the reaction is endoergic and hence the energy required for the reaction is made available in the form of kinetic energy associated with the α–particle. The said reaction should therefore occur with an α– particle having an energy 1.192 MeV. However, when the α–particle strikes the nucleus, the composite system does not remain at rest, but moves forward with a certain kinetic energy. The minimum energy required for the reaction to occur is, therefore greater than the Q value. This energy is called as threshold energy (E_{th}) which can be calculated from the law of conservation of momentum.

If a particle of mass m and velocity v stikes head-on a nucleus of mass M, and is absorbed, the product nucleus whose mass is (m + M) moves in the same direction as the incident particle with a velocity v, then

$$m = (m + M)\nu,$$

$$v = \frac{m}{m+M} \qquad \text{.........}\ (1)$$

At the threshold energy (E_{th}), the minimum kinetic energy $\frac{1}{2}mv^2$ of the projectile needed for the excitation of the compound nucleus is,

$$\frac{1}{2}mv^2 = -Q + \frac{1}{2}(m+M)v^2$$

Therefore,

$$-Q = \frac{1}{2}mv^2 - \frac{1}{2}(m+M)v^2 \qquad \text{.........}\ (2)$$

Substituting eq. (2) in eq. (1), we get

$$-Q = mv^2 - mv^2\left(\frac{M}{m+M}\right) = E_{th}\left(\frac{M}{m+M}\right)$$

Where,
E_{th} = threshold energy
m = mass of projectile
M = mass of target

OR

$$E_{th} = -Q\left(\frac{m+M}{M}\right) \qquad \text{.........}\ (3)$$

The negative sign on the right-hand side of eq. (3) indicates that E_{th} has to be supplied from outside for the reaction to occur. For the reaction under consideration, the threshold energy E_{th} is, therefore,

$$E_{th} = -(-1.192)\left(\frac{14+4}{14}\right) = 1.53 \text{ MeV}$$

It is important to note that the threshold energy is of significance only for endoergic reactions. For exoergic reaction, it would appear that there need be no threshold.

Examples to Solve :

Q.19 The reactions $^{9}Be(P, n)^{9}B$ and $^{18}O(P, n)^{18}F$ have threshold energies of 2.059 and 2.590 MeV respectively. Find their Q values.

Q.20 Given the Q value for the reaction $^{14}N(\alpha, P)^{17}O$ to be −1.192 MeV. Find the threshold energy of the reaction.

Q.21 The threshold energies for the reactions $^{10}B(P, n)^{11}C$, $^{18}O(P, n)^{19}F$ and $^{23}Na(P, n)^{23}Mg$ are 3.016 MeV, 2.893 MeV and 5.061 MeV. Find the Q value for each of the reactions.

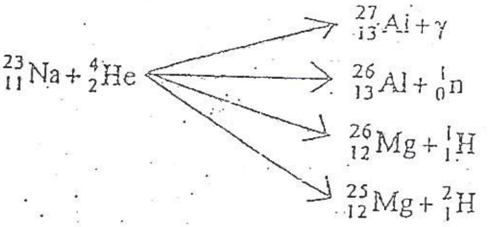
REACTION CROSS SECTION :

An important quantity in nuclear reaction is the reaction cross section (σ) which expresses the probability of occurance of a given type of a nuclear reaction.

If the nucleus of radius R represents a target of area πR^2 to an incident particle then the probability of an incident particle to strike the nucleus is proportional to this target area. Although this simple equation does not always hold good, nuclear reaction cross sections are generally of the magnitude of the target area. The unit in which the cross section is expressed is the barn(b) which corresponds to a value of 10^{-24} cm^2. By assuming that the reaction is possible only if the projectile passes through the area πR^2 of the target nucleus, we get

$$\sigma = \pi R^2 = \pi\left(A^{1/3} \times 1.4 \times 10^{-13}\right)^2 \text{ cm}^2 \qquad \ldots\ldots (1)$$

Many different kinds of reactions may occur as consequence of the collision of the projectile with the nucleus. For example,



We may imagine the total cross-section of the ($^{23}_{11}Na + ^{4}_{2}He$) reaction to be subdivided into areas corresponding to each of the different cross-sections; each reaction being assigned an area proportional to the probability of the particular reaction taking place under given conditions. For example, if the total cross section for $^{23}_{11}Na$ is 1b and that for the $^{23}_{11}Na(\alpha, d)^{25}_{12}Mg$ reaction is 1 millibarn, then out of every 1000 particles, only one will lead to the formation of $^{25}_{12}Mg$. Further the product yield for each possible reaction will show an energy dependence. For example, a particular reaction often predominates in an energy region.

When the energy of the incident particle is so low that its de-Broglie wavelength is larger than the radius of the target nucleus, the wavelength factor predominates in determining the probability of interaction. The maximum possible

Example : Calculate the effective neutron capture radius of a nucleus having cross section of 1.0 barn.

Solution : 1.0 barn = 1.0 x 10–24 cm2

The area, $A = \pi r^2$

Hence $r = \sqrt{A/\pi} = \sqrt{\dfrac{1.0 \times 10^{-24}}{3.14}} = 5.6 \times 10^{-13}\,\text{cm}$

Examples to Solve :

Q.22 Calculate the number of ^{198}Au nuclei produced per second in a sheet of Au, 0.3 mm (0.03 cm) thick and 5 cm^2 in area which has been exposed to a thermal neutron flux of 10^7 neutron cm^{-2} sec^{-1}. The capture cross section of ^{197}Au for thermal neutrons is 99 barns, density of Au is 19.3 g cm^{-3} and atomic weight is 197.2.

Q.23 A 0.02 cm thick gold foil is irradiated by thermal neutrons of flux 10^{20} nm^{-2} s^{-1} for 5 min. The product ^{198}Au has a half-life of 2.7 days. The density of gold is 19.3 g cm^{-3} and its cross section for neutron capture is 98.7 x 10^{-23} m^2. Find the number of radiogold atoms produced at the end of 5 min of irradiation.

Types of Reactions :-

CLASSIFICATION OF NUCLEAR REACTIONS :

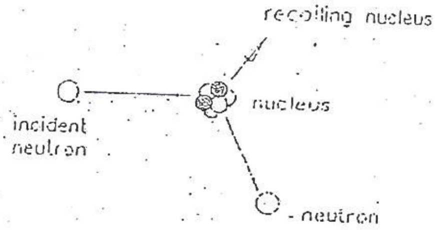
Nuclear reactions are classified into different categories on the basis of nature of projectile and ejectile.

Types of nuclear reactions :

1) Elastic scattering
2) Inelastic scattering
3) Photonuclear reactions
4) Radioactive capture
5) Special nuclear reactions
    i) Evaporation
    ii) Spallation
    iii) Fragmentation
    iv) Stripping reactions
    v) Fission

1) Elastic Scattering :

This is analogous to billiard ball type collision. In these reactions, the incoming projectile particle strikes the target nucleus thereby loosing some of its kinetic energy in translating the target nucleus. The direction of the incoming particle gets deflected by angle θ after the striking as in the scattering of the billiard ball. The energy the projectile loses is gained by the target nucleus which moves away at an increased speed.



During elastic scattering, the target nucleus and the projectile retain their individual identities. An example of elastic scattering is $^{9}Be(n, n)^{9}Be$.

The amount of energy transferred to the target nucleus by the projectile is calculated as

$$E_M = \frac{4mM\cos^2\theta}{(m+M)^2} E_m$$

Where, E_M = K.E. gained by the target nucleus of mass M.

E_m = Initial K.E. of the projectile of mass m.

θ = Angle between initial and final path of the projectile.

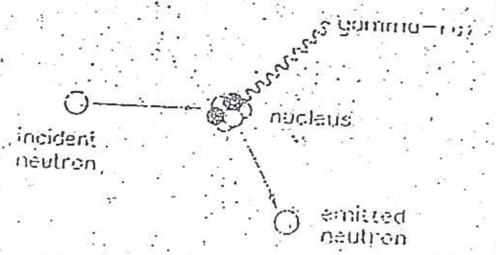
There is no change in the total potential energy and the kinetic energy is conserved during an elastic scattering.

The slowing down of fast neutrons by a moderator in a nuclear reactor is mainly by elastic scattering.

2) Inelastic Scattering :

In these reactions, projectile strikes the target nucleus thereby loosing some of its kinetic energy in raising the potential energy of the target nucleus. The target nucleus gains the energy and is raised to an excited state and then decays releasing the energy as gamme radiation. During inelastic scattering the target nucleus and the projectile retain their individual identities. An example of inelastic scattering is $^{14}_{7}N(P, P)^{12}_{7}N^{*}$ (* denotes excited state).

Here, the kinetic energy of the system is not conserved.



In the foregoing two processes (elastic and inelastic scattering), the reactants and the products are same.

3) Photonuclear reactions :

Nuclear reactions initiated by γ-photons of high energy are called as photonuclear reactions. Photonuclear reactions are endoergic in nature. An ejectile particle in photonuclear reactions is more often n or P but with some very high energy photons, d, t, or α or even a mixture of particles is liberated as ejectile. An example of photonuclear reaction is

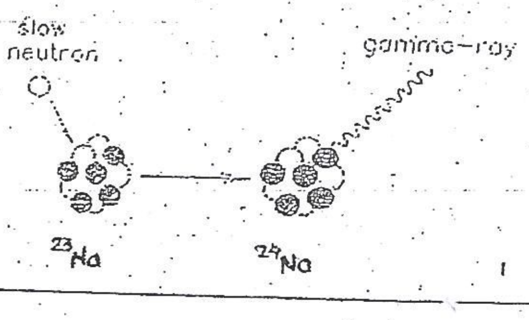
$$^{9}_{4}\mathrm{Be} + \gamma \rightarrow 2\,^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n}$$

(γ,γ'), (γ,P), (γ,n), $(\gamma,2n)$, (γ,α) are some of the principle types of photonuclear reactions.

4) Radiative Capture Reactions :

During radiative capture, target nucleus emits radiations in the form of one or more photons after the projectile capture. The most common radiative capture reactions are (n,γ) reactions in which the projectile neutron is captured by the target nucleus and emits only a gamma photon/s. (n,γ) reactions results in the product nucleus with one mass unit higher. Some examples of radiative capture reactions are; $^{23}\mathrm{Na}(n,\gamma)^{24}\mathrm{Na}$; $^{31}\mathrm{P}(n,\gamma)^{32}\mathrm{P}$; $^{179}\mathrm{Au}(n,\gamma)^{180}\mathrm{Au}$.

This reaction which occurs in most materials is the most important one for neutrons with low energy. (P,γ) reactions are the other common radiative capture reactions.



5) Special Nuclear Reactions :

Special nuclear reactions are the reactions involving high energy projectiles. The target nucleus is partly torn apart giving products lighter by several units, unlike in the above (1 to 4) reactions in which the product nucleus differs from the target nucleus only by a few units of mass. Some of the important types of these reactions are explained below;

i) *Evaporation reactions :*

The nuclear reactions in which several nucleons or their combinations are ejected from the target nucleus are called as evaporation reactions. Some examples of nuclear reactions are $^{133}Ca(\alpha, 4n)^{133}La$

$^{27}Al(d, P\alpha)^{24}Na$

ii) *Spallation :*

Spallation involve expulsion of a large number of nucleons. In spallation, the excitation energy of the target nucleus is sufficient high and results in the emission of several particles such as α-particles and protons leaving behind a product nuclei of sufficiently smaller masses than the target. These reactions generally involve proton or neutron as a projectile.

Some examples of spallation are; $^{63}Cu(P, P3n9\alpha)^{24}Na$; $^{79}Bi(P, P7n7\alpha)^{44}Sc$

iii) *Fragmentation :*

In fragmentation, a target on heavy excitation breaks into a light and a heavy fragment having about the same N/Z ratio as in the target nucleus. The light and heavy fragment thus produced decays by β^- and evaporation respectively.

iv) *Stripping reactions :*

Stripping is a direct interaction process in which the projectile leaves behind one of its nucleons in the target nucleus without the formation of the compound nucleus. In many of the nuclear reactions, it is observed that projectile does not react as a whole with the target nucleus, but one or more constituents of the projectile alone are trapped by the target nucleus. Stripping, thus produces heavier products than the target nucleus.

Some of the stripping reactions of the $^{27}_{13}Al$ are listed below :

$$^{27}_{13}Al \xrightarrow{+P} {}^{28}_{14}S$$

$$^{27}_{13}Al \xrightarrow{+\alpha} {}^{31}_{15}P$$

$$^{27}_{13}Al \xrightarrow{+3\alpha} {}^{39}_{19}K$$

v) Nuclear Fission :

2011

Nuclear fission is a process in which a heavy nucleus excited by a neutron or by other means splits into two smaller fragments of approximately equal mass. Nuclear fission is generally accompanied by emission of one or more neutrons.

The nuclei with mass number over 200 when bombarded with subtatomic particles like neutrons or other particles with sufficient energy show fission process.

Thermal neutrons are effective to carry out fission of $^{241}_{90}Th$, $^{233}_{92}U$, $^{235}_{92}U$, $^{242}_{93}Np$ while fast neutrons produce fission in $^{232}_{90}Th$, $^{231}_{91}Pa$ and $^{242}_{94}Pu$.

A typical nuclear fission is splitting of U-235.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{143}_{54}Xe + ^{90}_{38}Sr + 3\,^{1}_{0}n + 200\ \text{MeV}$$

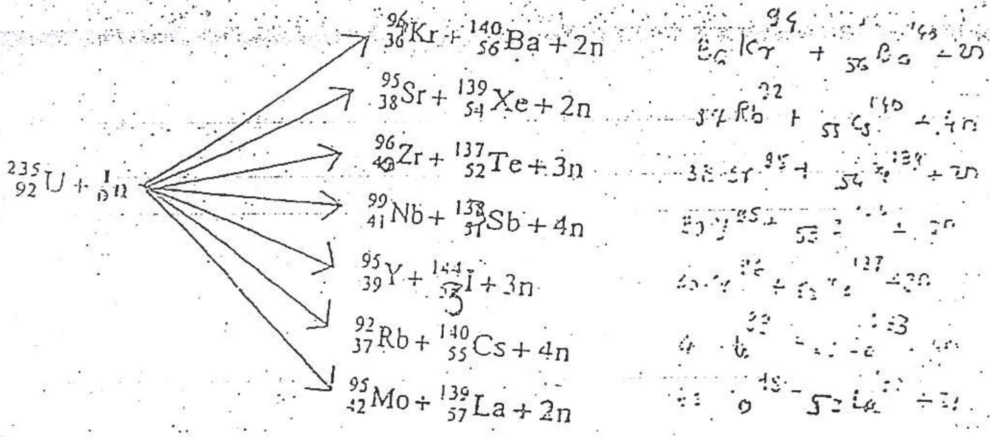
This fission is achieved by bombarding U-235 nuclei with thermal neutrons.

Nuclear Fission – A chain reaction :

When the U-235 splits, approximately 2 to 3 neutrons are released. If the neutrons from each nuclear fission are absorbed by other U-235 nuclei, these nuclei split and release even more nuetrons. Thus, a chain reaction occurs. A nuclear chain reaction is a self sustaining series of nuclear fissions caused by the absorption of neutrons released from previous nuclear fissions. The chain reaction of nuclear fissions is the basis of nuclear power and nuclear reactors.

Fission Products :

Different types of fission of the same nucleus (U-235) producing different primary products are possible. The fission fragments of U-235 thus are not a unique but could be one of about 30 possible pairs such that the mass number of lighter fragment ranges in between 85-105 and that of heavier fragment ranges in between 130-160. Following are some of the possibilities.



$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{96}_{36}Kr + ^{140}_{56}Ba + 2n$$
$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{95}_{38}Sr + ^{139}_{54}Xe + 2n$$
$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{96}_{40}Zr + ^{137}_{52}Te + 3n$$
$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{99}_{41}Nb + ^{138}_{51}Sb + 4n$$
$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{95}_{39}Y + ^{144}_{53}I + 3n$$
$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{92}_{37}Rb + ^{140}_{55}Cs + 4n$$
$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{95}_{42}Mo + ^{139}_{57}La + 2n$$

How exactly the nucleus splits depends on the energy acquired by the fissile nucleus.

Fission: product and yield

β^- **– decay of primary products :**

As most of primary fragments are neutron rich, they display β^- activity and continue to decay by successive β^- emissions till a stable nuclide isobaric with the primary fragment is obtained. This is illustrated for a typical fission frgament pair as

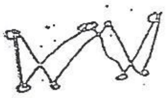
$$ {}^{236}_{92}\mathrm{U} \begin{cases} {}^{99}_{41}\mathrm{Nb} \xrightarrow{\beta^-} {}^{99}_{42}\mathrm{Mo} \xrightarrow{\beta^-} {}^{99}_{43}\mathrm{Tc} \xrightarrow{\beta^-} {}^{99}_{44}\mathrm{Ru}\ \text{(stable)} \\ {}^{133}_{51}\mathrm{Sb} \xrightarrow{\beta^-} {}^{133}_{52}\mathrm{Te} \xrightarrow{\beta^-} {}^{133}_{53}\mathrm{I} \xrightarrow{\beta^-} {}^{133}_{54}\mathrm{Xe} \xrightarrow{\beta^-} {}^{133}_{55}\mathrm{Cs} \end{cases} $$

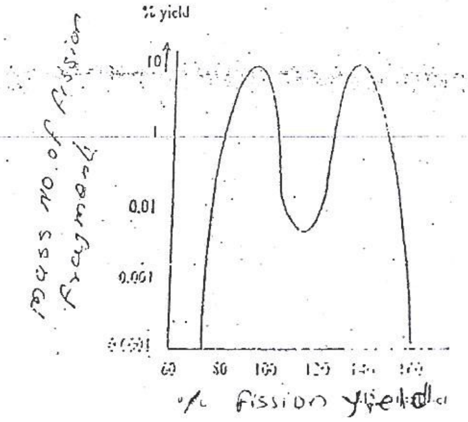
FISSION YIELD :

A term that is used in describing mass distribution between the fragments is called as cumulative chain fission yield and is described by the following equation.

$$ Y(A) = \frac{\text{Number of product nuclei of mass A}}{\text{Total number of nuclei fissioned}} \times 100 $$

Where, Y(A) is fission yield for the fragment with mass A. Experimently, the yield of fragment with any mass number is given by the yield of the final stable isotope of that mass number. A typical fission mass yield curve is shown below where mass number of fission fragment is plotted against percentage fission yield.





Fission yield, frequency distribution of the fission products generated in the fission of U-235

From the curve it is evident that the isotopes obtained are with mass numbers 72–162. The yields are above 1% range from 85-105 for lighter fragments while 130-150 for heavier fragment. The maximum yields (around 7%) are from 90-100 for lighter fragments while 134-144 for heavier fragment.

It can also be seen from the graph that the yield for symmetrical fission where both the fragments have mass 117 is lowest being around 0.05 per cent.
0.005

FISSION ENERGY :

The tremendous amount of energy is released during nuclear fission. The reason for this is a loss in mass. The energy released during a fission event can be calculated using the exact mass difference between the reactants and the products. Let's consider the following fission process;

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

Here, total mass of reactants = 235.044 + 1.0086 = 236.0526 amu.

Total mass of products = 140.908 + 91.905 + 3.0258 = 235.8388

Hence, mass defect, Δm = 236.0526 – 235.8388 = 0.2138 amu

The fission is thus accompanied by a loss of mass of 0.2138 amu, which is converted into energy.

Since, 1 amu = 931 MeV

Therefore, energy released = 0.2138 x 931 = 199.0478 MeV

Thus 199.0478 MeV of energy is released in above process.

Let us consider another case where ^{95}Mo and ^{139}La are two stable end products of fission. The reaction is

$$^{235}_{92}U + ^{1}_{0}n \rightarrow \left[^{236}_{92}U\right] \rightarrow ^{95}_{42}Mo + ^{139}_{57}La + 2^{1}_{0}n$$

For this reaction, the total mass of the reactants = 236.0526 amu and the total mass of the products = 235.8329 amu. Thus, the mass difference = 0.2197 amu. The energy released = 0.2197 x 931 = 204.54 MeV.

Another method for calculating the fission energy is based on the binding energy per nucleon (BE/A) values. By taking a value of 7.6 MeV for uranium and 8.5 MeV for the fission products, we obtain the binding energy of the ^{236}U compound nucleus = 236 x 7.6 MeV, the binding energy of the fission fragments = 236 x 8.5 MeV. Therefore, the energy released per fission = 236(8.5 – 7.6) = 212 MeV.

If a mole of ^{235}U is made to undergo complete fission, the energy released is 200 x 6.02 x 10^{23} MeV or 4.3 x 10^{12} kcal or 2.2 MW of electric power / day. In comparison with this figure, the energy released when 1 mole of carbon undergoes combustion is only 94 kcal.

Solved Examples :

Example : Estimate the energy released (in MeV) if the fragments of nuclear fission of, $^{235}_{92}U$ viz, $^{94}_{38}Sr$ and $^{140}_{54}Xe$, further emit β^- particles to give $^{94}_{40}Zr$ and $^{140}_{58}Ce$, respectively. Atomic masses of U, Zr and Ce are 235.7437, 93.6061 and 139.9053 respectively.

Solution : The neutron induced nuclear fission is

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{94}_{38}Sr + ^{140}_{54}Xe + 2\,^{1}_{0}n$$

Further distintegration reactions are as follows :

$$^{94}_{38}Sr \rightarrow ^{94}_{40}Zr + 2\,^{0}_{-1}\beta$$

$$^{140}_{54}Xe \rightarrow ^{140}_{58}Ce + 4\,^{0}_{-1}\beta$$

The overall fission reaction is

$$^{235}_{92}U \rightarrow ^{94}_{40}Zr + ^{140}_{58}Ce + 6\,^{0}_{-1}\beta + 2\,^{1}_{0}n$$

Mass defect = ΔM = Masses of reactants – Masses of prducts

$$= 235.7437 - [93.6061 + 139.9053 + 6(0.00055) + 2(1.00867)]$$

$$= 0.2137 \text{ a.m.u.}$$

Energy released = 0.2137 a.m.u. x 931.0 MeV/a.m.u. = 198.95 MeV

Plutonium as Fissionable material .

Ordinary uranium consists only of about 0.7 per cent of ^{235}U. At the same time, it is extremely difficult to isolate ^{235}U from the other isotopes present in ordinary uranium. It was found that plutonium which does not occur in nature but which can be prepared from the more abundant (99.3%) isotope ^{238}U, undergoes fission readily like ^{235}U.

The prepartion of plutonium from uranium involves the following three steps:

$$^{235}_{92}U + ^{1}_{0}n \xrightarrow[\text{by neutron}]{\text{Bombardment}} ^{239}_{92}U$$

(Excited nucleus)

$$^{239}_{92}U \xrightarrow[\text{a }\beta\text{-particle}]{\text{Emission of}} ^{239}_{93}Np + ^{0}_{-1}e$$

$${}^{239}_{93}\mathrm{Np} \xrightarrow[\text{another } \beta \text{ particle}]{\text{Emission of}} {}^{239}_{94}\mathrm{Pu} + {}^{0}_{-1}\mathrm{e}$$

Plutonium, being chemically different from uranium, can be separated relatively easily. The discovery of plutonium has solved the problem of release of nuclear energy through nuclear fission.

Problems with Uranium-238 :

U-238 is not suitable for chain reaction. This is because U-238 nuclei do not break untill the energy of bombarding neutrons is above 1.2 MeV. Such neutrons are called as fast neutrons. On the other hand U-235 which is commonly used for fission can be fissioned by slow neutrons. U-238 when bombarded by slow neutron forms excited unstable isotope U-239, which decays further to plutonium as mentioned in the above section.

Q.24 Complete the following nuclear reactions by writing the missing terms.

1) ${}^{6}_{3}\mathrm{Li} + {}^{2}_{1}\mathrm{H} \ldots \rightarrow 2\,{}^{4}_{2}\mathrm{He}$

2) ${}^{3}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + \ldots\ldots$

3) ${}^{30}_{15}\mathrm{P} \rightarrow {}^{30}_{14}\mathrm{Si} + {}^{0}_{+1}\mathrm{e} \ldots$

4) ${}^{2}_{1}\mathrm{H} + \gamma \rightarrow {}^{1}_{1}\mathrm{H} + \ldots\ldots$

5) ${}^{27}_{13}\mathrm{Al} + \alpha \rightarrow {}^{30}_{15}\mathrm{P} + {}^{1}_{0}\mathrm{n} \ldots$

6) ${}^{7}_{3}\mathrm{Li} + \ldots\ldots \rightarrow {}^{7}_{4}\mathrm{Be} + {}^{1}_{0}\mathrm{n}$

7) ${}^{232}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n}$

8) ${}^{14}_{7}\mathrm{N} + \ldots\ldots \rightarrow {}^{14}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H}$

9) ${}^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\mathrm{e} \ldots$

10) ${}^{239}_{93}\mathrm{Np} \rightarrow {}^{239}_{94}\mathrm{Pu} + \ldots\ldots$

11) ${}^{27}_{13}\mathrm{Al} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{27}_{12}\mathrm{Mg} + \ldots\ldots$

12) ${}^{55}_{25}\mathrm{Mn} + {}^{1}_{1}\mathrm{H} \rightarrow \ldots\ldots + {}^{1}_{0}\mathrm{n}$

13) ${}^{63}_{29}\mathrm{Cu} + {}^{2}_{1}\mathrm{H} \rightarrow \ldots\ldots + {}^{1}_{0}\mathrm{n}$

14) ${}^{23}_{11}\mathrm{Na} + {}^{1}_{1}\mathrm{H} \rightarrow \ldots\ldots + {}^{1}_{0}\mathrm{n}$

15) ${}^{59}_{27}\mathrm{Co} + {}^{1}_{0}\mathrm{n} \rightarrow \ldots\ldots + {}^{4}_{2}\mathrm{He}$

16) ${}^{96}_{42}\mathrm{Mo} + {}^{2}_{1}\mathrm{H} \rightarrow \ldots\ldots + {}^{1}_{0}\mathrm{n}$

17) ${}^{246}_{96}\mathrm{Cm} + {}^{13}_{6}\mathrm{C} \rightarrow \ldots\ldots + 5\,{}^{1}_{0}\mathrm{n}$

18) ${}^{253}_{99}\mathrm{Es} + {}^{4}_{2}\mathrm{He} \rightarrow \ldots\ldots + {}^{1}_{0}\mathrm{n}$

19) ${}^{238}_{92}\mathrm{U} + {}^{14}_{7}\mathrm{N} \rightarrow \ldots\ldots + 5\,{}^{1}_{0}\mathrm{n}$

20) ${}^{209}_{83}\mathrm{Bi} + {}^{54}_{24}\mathrm{Cr} \rightarrow \ldots\ldots + 2\,{}^{1}_{0}\mathrm{n}$

21) ${}^{239}_{94}\mathrm{Pu} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{242}_{96}\mathrm{Cm} + \ldots\ldots$

22) ${}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{133}_{51}\mathrm{Sb} + \ldots\ldots + \ldots\ldots$

23) ${}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{146}_{57}\mathrm{La} + \ldots\ldots + \ldots\ldots$

24) ${}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{139}_{54}\mathrm{Xe} + \ldots\ldots + \ldots\ldots$

25) ${}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{140}_{55}\mathrm{Cs} + \ldots\ldots + \ldots\ldots$

Q.25 Complete the following nuclear reactions.

1) .... $(\alpha,2n)\,^{211}_{85}At$ 2) $^{96}_{42}Mo$ (......, n) $^{97}_{43}Tc$

3) $^{55}_{25}Mn\,(n,\gamma)$......... 4) $^{241}_{96}Am$ (α, ...) $^{244}_{97}Bk$

5) $^{27}_{13}Al$ (......., n) $^{30}_{15}P$

Q.26 Classify the following nuclear reactions

1) $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{133}_{51}Sb + ^{99}_{41}Nb + 4\,^{1}_{0}n$

2) $^{9}_{4}Be + ^{1}_{0}n \rightarrow ^{9}_{4}Be + ^{1}_{0}n$

3) $^{31}_{15}P + ^{1}_{0}n \rightarrow ^{32}_{15}P + \gamma$

4) $^{9}_{4}Be + \gamma \rightarrow ^{8}_{3}Li + ^{1}_{1}H$

5) $^{14}_{7}N + ^{1}_{1}H \rightarrow ^{14}_{7}N^{*} + ^{1}_{1}H$

6) $^{79}Br + ^{1}_{1}H \rightarrow ^{44}Sc + ^{1}_{1}H + 7\,^{1}_{0}n + 7\alpha$

7) $^{27}_{13}Al + ^{1}_{1}H \rightarrow ^{28}_{14}Si$

NUCLEAR FUSION

A reaction in which two lighter nuclei combine to form a heavier nucleus accompanied by release of energy is called nuclear fusion. An example of fusion reaction is -

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6\ MeV$$

When the two nuclei to be fused are brought together, they experience a very large coulombic repulsion. Thus, the fusion can occur only by making one nucleus collide with another highly energetically, that is, the kinetic energy of each nucleus should be kept very high so as to overcome the repulsive coulombic potential energy barrier between them. This requires a very high temperature, of the order of millions of degrees.

Since, the kinetic energy needed to overcome the coulombic repulsion increases rapidly with the atomic number, the lighter the nuclei, the greater the chance for them to approach closely. Thus, hydrogen isotopes are the best elements for bringing out the nuclear fusion.

A nuclear fusion reaction is highly exoergic. Nuclear fusion reactions are called as thermonuclear reactions.

Fusion energy :

A nuclear fusion reaction releases a tremendous amount of energy consequent to the conversion of mass into energy. Fusion reactions are more energetic that fission reactions. The fusion of 1 gm of deuterium would result in the energy equivalent to that of 65 tonnes of TNT.

Nuclear fusion and stellar energy :

Stars produce tremendous amount of light and energy. Nuclear fusion are the source of such energies. The surface of the stars is extremely hot. For example, the temperature on the cooler star like sun is 15 million degrees Kelvin. E. Salpeter suggested the following proton–proton chain reaction to account for the sun's energy.

$${}^1_1H + {}^1_1H \rightarrow {}^2_1H + \beta^+ + \cancel{\nu}\ \vartheta$$

(neutrino)

$${}^1_1H + {}^2_1H \rightarrow {}^3_2He + \gamma$$

$${}^3_2He + {}^3_2He \rightarrow {}^4_2He + 2{}^1_1H$$

Overall $$4{}^1_1H \rightarrow {}^4_2He + 2\beta^+ + 2\nu + 2\gamma$$

It is believed that 3.685×10^{10} tonnes of hydrogen is consumed per minute on the sun for this fusion process. Even at this loss of rate the sun will be able to offer its life giving energy to our beautiful earth for may be another 100 billion years.

Fusion Power :

Fusion reactions can serve as power source and produce electricity if these can be conducted in a controlled manner in a reactor. The naturally occuring deuterium can be used in such a reactor.

$${}^2_1H + {}^2_1H \rightarrow {}^3_2He + {}^1_0n + \text{energy}$$

$${}^2_1H + {}^2_1H \rightarrow {}^3_1H + {}^1_1H + \text{energy}$$

The fusion of Li with a proton is a promising fusion reaction for the energy production

$${}^6_3Li + {}^1_1H \rightarrow {}^3_2He + {}^4_2He + \gamma$$

In a fusion power reactor being experimented, the deuterium-tritium fusion produces high energetic neutrons. This neutron energy can be absorbed by a lithium shield. The heated lithium can then be made to exchange its heat with water to generate steam.

Radiochemical analysis

Cold Fusion :

Two chemists, B. Stanley Pons of the University of Utah (U.S.A.) and Martin Fleischmann of the University of Southampton (England) announced in 1989 their success in effecting cold nuclear fusion. They claimed that the passage of current between a platinium anode and a palladium cathode in a 0.1 M LiOD Solution in D_2O produced nuclear fusion at room temperature along with a large amount of heat. They proposed deuterium-deuterium fusion through two paths.

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n$$

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{1}H + ^{1}_{1}H$$

If the cold fusion is real, it would solve the global problem as there is a vast amount of deuterium in nature.

Problems in performing nuclear fusion :

The production of extremely high temperature required for fusion in the laboratory is difficult and expensive. Even if such a temperature is produced no reaction vessel can withstand with such a high temperature.

COUNTERS

A counter is a device which is used to calculate the number of particles emitted by a radioactive nuclei and other nuclear processes.

Counters are of two types :

1) Ionization counters and
2) Scintillation counters.

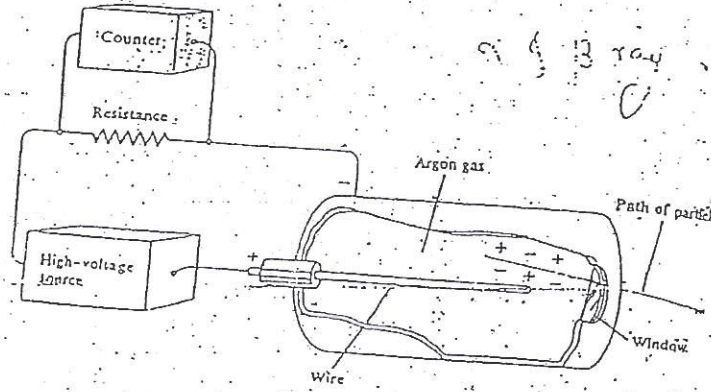
Ionization counters depend on the production of ions in matter. Scintillation counters detect the production of scintillations, or flashes of light. A Geiger-Muller counter (ionization counter) and Scintillation counter is described below:

GEIGER-MULLER COUNTER (G. M. COUNTER)

A Geiger-Muller counter is a kind of ionization counter used to count particles emitted by a radioactive nuclei or other nuclear processes. It was invented by Geiger and Muller, two German Scientists.

It consists of a metal cylinder filled with a gas such as argon. The cylinder is fitted with a thin glass or plastic window on one side through which radiation enters. A wire runs down the center of the cylinder and is insulated from the cylinder. The cylinder and wire are connected to a high-voltage source so that the cylinder becomes the negative electrode (cathode) and the wire the positive electrode (anode).

α & β ray detected



Working :

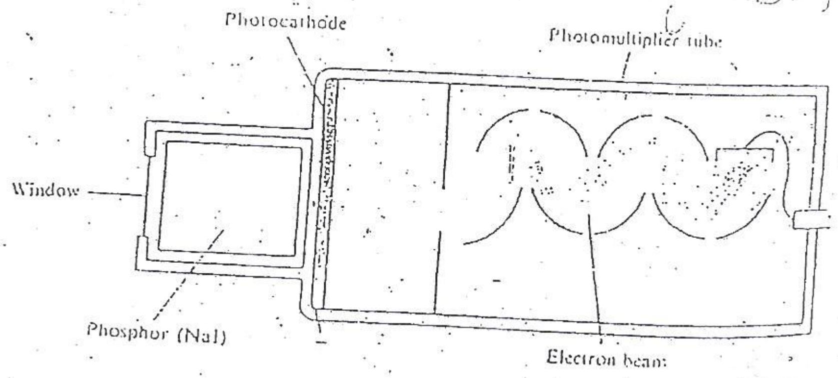
Normally the gas in the cylinder is an insulator and hance no current flows through it. However when the radiation passes the window of the tube and enters into the gas, it causes ionization of the gas. Free electrons released due to ionization are quickly accelerated to the wire. As they are accelerated to the wire, additional atoms of the gas get ionized from collisions with these electrons and more electrons are set free. As a result, an avalanche of electrons is created which produces a pulse of current that is detected by electronic equipment. The pulse of electric current produced are then counted by compairing these counts with counts using a standard of known radiation source under the same conditions, the radiation of the test source can be measured.

Alpha and beta particles are directly detected by a G. M. Counter. To detect neutrons, boron trifluoride is added to the gas in the tube. Neutrons react with boron-10 nuclei to produce alpha particles, which can then be detected.

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}He$$

SCINTILLATION COUNTER

A Scintillation counter is a device that detects nuclear radiations from flashes of light generated in a material by the radiation. A Phosphor is a substance that emits flashes of light when struck by radiation. A sodium iodide crystal containing thalium (I) iodide is used as a phosphor. Rutherford had used Zinc sulfide as a phosphor to detect α-particles. The gamma rays are detected by a Scintillation Counter.



Working :

Radiation passes through the window into phosphor (here, NaI). Phosphor emits a flash of light when struck by radiation. Flashes of light from the phosphor fall on the photocathode, which ejects electrons by the photoelectric effect. These electrons are accelerated towards a specially prepared photoactive dynode by applying a suitable voltage. When these electrons strike the dynode, electron multiplication occurs through the generation of secondary electrons. The multiplication process is repeated in several dynode stages in order to achieve a significant electric pulse at the final collecting dynode.

To a good approximation, the size of the pulse output is proportional to the energy deposited by the particle or γ-photon in the Scintillation detector.

Liquid Scintillation Counters :

Another useful application of the scintillation counter is liquid scintillation counting in which the radioactive sample is dissolved in the solution of Scintillation (phosphor). This counting method is particularly useful in the case of low energy β-emitters such as ^{14}C and ^{3}H, leading to 100% detection efficiency. Some commonly used liquid scintillators are p-terphenyl, 2,5-diphenyl oxazole (PPO) and 2,2'-phenylene bis-(S-phenyl oxazole) (POPOP).

APPLICATIONS OF RADIOACTIVE ISOTOPES

There are numcrous applications of radioactive isotopes in science, medicine and technology. These applications can be classified into three categories as follws:

1) Applications in which the nuclear properties of the isotopes of an element serve as an indicator to the behaviour of the chemical species (tracer methods).
2) Applications in which the age of the sample is determined by estimating a specific isotope in that sample (dating techniques).
3) Applications in which radionuclides act as radiation sources (a) to produce a chemical change in a material or (b) to develop some measuring devices.

Here, we will look at the applications of radioactive isotopes in chemical analysis and ^{14}C–dating.

A) TRACER TECHNIQUE

Tracer technique is the method of using an isotope of an element to study a chemical, biological or physical system. A radioactive isotope used in such a technique is referred as tracer. The advantage of a radioactive tracer is that it behaves chemically just as a non radioactive isotope does, but it can be detected in exceedingly small amounts by measuring the radiation emitted.

The tracer method can be applied to a variety of investigations such as

1. Physical processes such as evaporation, condensation, solubility, etc.
2. Chemical processes, especially reaction mechanisms.
3. Structural investigations.
4. Kinetics of reactions.
5. Biological processes.
6. Disease diagnosis.

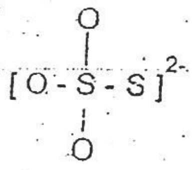
As an illustration of the use of radioactive tracers, let us consider some of the above investigations.

Structural Study :

The thiosulphate ion, $S_2O_3^{2-}$ may be represented by one of the following structures;

1. $[O-S-O-S-O]^{2-}$

2.



$[O-\overset{O}{\underset{O}{S}}-S]^{2-}$

Neutron Activation Analysis (NAA)