Radioactivity

Inorganic Chemistry
(SEM 2H)

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RADIOACTIVITY

● Discovery :→ Radioactivity was first discovered by Henri Becquerel in 1896. He observed this phenomenon during study of correlation between fluorescence and X-rays. He used potassium uranyl sulfate as the fluorescent material. On exposure to sunlight, it emitted radiations which could penetrate paper, glass, aluminium sheets and ionise gases. He unexpectedly observed that this ~~emittion~~ emission is also occures at dark. He also observed that this radiation independant of the states of uranium.

The subject developed rapidly in the next few years. Marie Curie proposed the term 'radioactivity'.

● What is radioactivity :

Radioactivity is a phenomenon of spontaneous disintegration of certain nuclei to form new elements with the emission of 'active radiations'.

These active radiations usually consists of α-particles, β-particle and γ-rays ; they are called active as they affect photographic plates and intract with electric and magnetic fields.

● Natural radioactivity ⇒ Radioactivity is exhibited by a large number of naturally occuring elements — uranium, thorium and radium being the most common examples. Certain isotopes of lighter elements are also radioactive, e.g., ^{40}K, ^{14}C etc.

● Artificial radioactivity ⇒ Radioactivity is observed in some artificially obtained isotopes.

Aluminium target was bombarded by an alpha particle.

$$^{27}_{13}Al + ^{4}_{2}He \longrightarrow ^{30}_{15}P + ^{1}_{0}n$$

This artificially synthesized phosphorous is radioactive and that it decayed by positron emission.

$$^{30}_{15}P \longrightarrow ^{30}_{14}Si + ^{0}_{+1}e$$

Note :→ Natural radioactivity naturally decayed by α, β or γ particles but artificial radioactive materials decay positron and other modes of decays other than α, β, γ.

Characterisation of α, β and γ rays ⇒

Alpha rays : These consist of a steam of positively charged particles, called α-particles, which carry +2 charge and have a mass no. 4. These particles were shown by Rutherford to be identical with the nuclei of helium atom, that is, these are doubly charged helium ions He^{2+} (atomic no. 2, mass no. 4)

The charge to mass ratio of these particles was determined by ~~diffe~~ deflection in magnetic and electric fields (Thomson) (cathod ray expt.) and the accepted value is 4.787×10^{7} C/kg.

Charge of the α-particles was determined by Rutherford is 3.19×10^{-19} C and that of electron is 1.6×10^{-19} C.

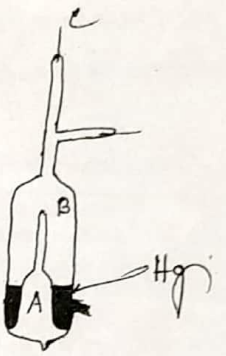
The mass of the α-particle may now be calculated. This is equal to $(3.19 \times 10^{-19} \text{ C} \div 4.787 \times 10^{7} \text{ C/kg})$ $= 6.67 \times 10^{-27}$ kg. This is four times the mass of a hydrogen atom $(1.67 \times 10^{-27}$ kg)

i.e., $\boxed{m_{\alpha\text{-particle}} = 4\, m_H}$

Identity with helium nuclei :-

The identity with helium ion was shown by another novel experiment done by Rutherford.

A quantity of purified radon gas (an α-emitter), was placed in placed in a thin wall tube A. The tube A is sealed by another tube B which is again connected with another spectrum tube C with arrangement for passing electric discharge.



The tube B is evacuated, and after a few days the gas is collected inside B was compressed by raising the mercury level. On passing a discharge in tube C, the spectrum of helium was obtained.

Control experiment showed that ordinary helium gas can't pass through the wall of A into B. α-particles, however, are able to do so.

Thus the identity of the α-particles as He^{2+} was established.

⟶

- When an alpha particle is ejected from within the nucleus, the nucleus of the mother element loses two units in atomic number, and four units in mass number.

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

- Properties of α-particles : α-particles affect the photographic plates, produce scintallation (ঝিলিমিলি) on a screen coated with zinc sulfide and can pass through the thin sheets of metals e.g. 1/100 mm aluminium. They also ionise gases when passing through it.

β-rays :-

Becquerel first measured the charge to mass ratio (e/m) for the β-particles (1900). His results indicated that β-particles were the same as cathode rays (consist of electrons or negatively charged particles).

Similarities between β-particles and electrons:

1. Both are negatively charged particles i.e., they are same in their electrical nature. 2. Their ~~mass/charge~~ charge to mass ratio (e/m) also same (1.7588×10^{11} C/kg).

Dissimilarities between β-particles and electrons:

1. β-~~rays~~ particles travel with much higher speeds than the electrons
2. The velocity of electron is const at the same time whereas β-particles have a wide range of velocity
3. After the ejection of an electron from an atom converts a neutral atom into a positively charged ion but leaves the nucleus undisturbed. Ejection of a β-particle changes the very composition of the nucleus and produces an atom of the next higher atomic number.

$$^{234}_{90}Th \longrightarrow {}^{234}_{41}Pa + {}^{0}_{-1}e \text{ (β-particle)}$$

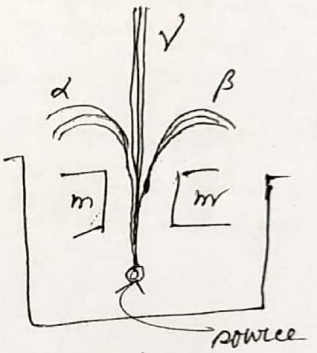
Properties of β-particle ⇒

β-rays consist of negatively charged particles. These are electrons, as confirmed by the determination of their charge to mass ratio — by applying electric and magnetic fields.

β-particles affect photographic plates and can penetrate 0.1 mm. thick aluminium foil. Their ionising power is comparitively weak, due to very small mass of the particles.

Though the speed of the β-particle is not constant but significantly the speed is high and ever may approach to the speed of light.
An average value of speed is 2×10^{10} cm/sec has been quoted by many workers.

(iii) Gamma rays ⟹ In 1900, Villard discovered the existence of some highly penetrating rays in radioactive radiations; these were unaffected by magnetic and electric fields. The exact nature of these rays was not known at first. It appears at 1903 the rays were mentioned by the term γ-rays, but controversy existed over their nature. A few scientists thought they were high speed particles while other thought them to be waves similar to X-rays. In 1914, Rutherford diffracted γ-rays by suitable crystals. This was a convincing proof of wave nature of γ-rays. Their results also showed that wavelength of γ-rays are same as that of short X-rays (electromagnetic wave)



Splitting of α, β, γ rays in the presence of magnetic field.

Properties :
The γ-rays are unaffected by electric and magnetic fields. They are electromagnetic radiations of wavelength 10^{-8} to 10^{-11} cm which is shorter than that of X-rays.
γ-rays have high penetrating properties — they can pass through even 5 cm of lead and 25 cm of steel. Being an electromagnetic wave γ-rays ~~are~~ have the velocity equal to the velocity of light.

They do not ionise gas directly, but a small portion of the γ-rays passing through a gas may be absorbed by the molecules — resulting in release of electrons. The secondary electrons cause ionisation.

(iii) Important characteristics of α, β, γ are listed below:—

	α-particles	β-particles	γ-particles
(i) charge	$+2e$	$-e$	0
(ii) Mass	$4m_H$	m_e	0
(iii) Speed (m/sec)	2×10^7	2×10^8	3×10^8
(iv) penetrating power	weak, $\frac{1}{100}$ mm. of Al.	medium, $\frac{1}{10}$ mm of Al	high, 25 cm steel, 5 cm lead.
(v) Deflection in electric and magnetic field.	Yes	Yes, opposite to the direction of deflection of α-particle.	No.

(iv) Positron ⟹

These are extremely short-lived particles (10^{-9} sec.) produced by the action of cosmic rays on matters. They are also emitted when very penetrating γ-rays are absorbed by lead, aluminium, etc.

The ejection of positron is possible by the conversion of a proton into a neutron

$$_1^1H \longrightarrow {}_0^1n + {}_{+1}^0e$$

Many artificial radioactive species are positron emitter.

$$_{51}^{120}Sb \longrightarrow {}_{50}^{120}Sn + {}_{+1}^0e$$

Positron bears the same mass and quantity of charge as the electron; but they are positively charged.

Pauli therefore postulated that alongwith the ejection of β-particle another tiny neutral particle called antineutrino is also ejected. This antineutrino has also a spin angular momentum of $\pm \frac{1}{2} \frac{h}{2\pi}$.

Neutron ⟶ proton + β-particle + Antineutrino ($\bar{\nu}$)

Similarly,

Proton ⟶ Neutron + Positron + Neutrino (ν)

Example:

$$^{234}_{90}Th \longrightarrow {}^{234}_{91}Pa + \beta^- + \bar{\nu}$$

$$^{30}_{15}P \longrightarrow {}^{30}_{14}Si + \beta^+ + \nu$$

Nuclear reactions Vs Chemical reactions

1. New elements are produced in a radioactive change. In some artificially induced nuclear reactions, neutrons are absorbed by a target nucleus producing an isotope. But chemical reactions involve some loss, gain or overlap of outer orbital electrons of the reactant atoms.

Such reactions cannot alter the composition of the nuclei, so that atomic numbers of the elements remain unchanged.

2. A radioactive change is always irreversible. Radioactive equilibrium is similarly different from chemical equilibrium as it is irreversible and independent of external conditions like Temp, press etc.

3. The rate of a radioactive change is independent of imposed external conditions like temp, pressure etc. It is also independent of the state of chemical combination of the radioelement. Moreover, a radioactive change occurs spontaneously and cannot be initiated by any external means.

4. In a radioactive change, the energy released per mole is about one million times greater than that liberated in a chemical change.

5. Different isotopes of the same elements show identical chemical properties since the electron numbers are same. But these isotopes show different nuclear properties. For example $^{12}_{6}C$ and $^{14}_{6}C$ possess similar chemical properties but their nuclear properties are widely different. $^{12}_{6}C$ is very stable but $^{14}_{6}C$ decays spontaneously by β-emission giving a stable nucleus of $^{14}_{7}N$.

Thus, radioactivity is totally different from a chemical change. The latter concerns the extranuclear electrons in an atom. So radioactivity can't be related to the extranuclear part of an atom. It is a nuclear property of the atom.

● **Nuclear instability — The cause of radioactivity :⇒**

Since radioactivity is a nuclear phenomenon it must be connected with the instability of the nucleus. Since nucleus of an element is composed by protons and neutrons, it must be said that the arrangement and number are the responsible factors for instability of nucleus.

Nuclear Scientists have studied this problem and concluded that there is two factors for stability or instability of the nucleus which is responsible for radioactivity.

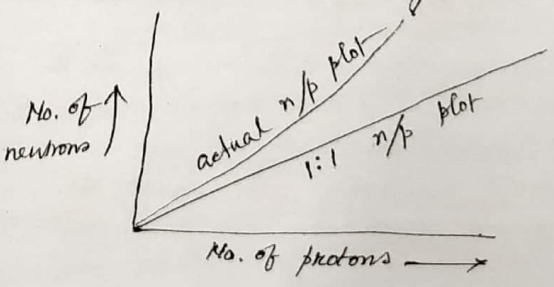
The factors are —— ① pairing of nuclear spins
② the ratio of no. of neutrons and no. of protons.

1) Pairing of nuclear spins :

Just as electrons spin around their own axes and just as electron spin-pairing leads to ~~chemical~~ stable chemical bonds, so also the nuclear protons and neutrons spin around their own axes, and pairing of spins of neutrons among neutrons, and pairing of spins of protons among protons leads to nuclear stability. When all the non-radioactive, that is, stable isotopes of elements are considered it is observed that nuclei with even number of protons and with even number of neutrons are the most abundant. It will be noted that even numbers lead to spin pairing, and odd number leads to unpaired spin. Nuclei with either of the proton number or the neutron number odd are slightly less stable than even numbered ones. The nuclear spin pairing is a minimum when odd numbers of both are present.

2) Neutron to proton ratio :-

Along with the odd or even number of protons and neutrons, the nuclear stability is also profoundly influenced by the relative numbers of protons and neutrons. The neutron/proton ratio (n/p) helps us to predict which way an unstable radioactive nucleus will decay.



The plot indicates that as the number of protons increases inside the nucleus more and more neutrons are needed to minimise the proton-proton repulsion and thereby to add to nuclear stability. Neutrons therefore serve as binding material inside the nucleus.

The way an unstable nucleus will disintegrate will be decided by its position with respect to the actual n/p plot of stable nuclei. When an isotope is located above this actual n/p plot it has too high an n/p ratio, and when it is located below the plot it has too low an n/p ratio. In either case the unstable nucleus should decay so as to approach the actual n/p plot. We now discuss the ~~case~~ two cases of decay:

(a) Neutron-to-proton ratio too high:

From the plot we saw that which are situated above the ~~plot~~ curve, they have high n/p ratio.

As neutron number is high then it is very essential to add proton(s) to the nucleus for stability. This is done by the following process —

One neutron ~~is~~ emitts β-radiation along with the formation of a proton.

$$^{1}_{0}n \longrightarrow {}^{1}_{1}H + {}^{0}_{-1}e$$

So, we may say that the elements which have high n/p ratio are β-emitter.

$$^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e \; ; \qquad {}^{133}_{53}I \longrightarrow {}^{133}_{54}Xe + {}^{0}_{-1}e$$

$n/p = 1.3$ $\qquad$ $n/p = 1.5$

(b) Neutron-to-proton ratio too low:

A nucleus deficient in neutrons will tend to attain nuclear stability by converting one of its protons to a neutron and this will be achieved either by the emission of a positron or by the capture of an electron.

Positron emission occurs with light isotopes (low n/p) of elements of low atomic number.

$$^{13}_{7}N \longrightarrow {}^{13}_{6}C + {}^{0}_{1}e$$

Orbital electron capture occurs with too light isotopes (too low n/p) of elements ~~of radioactivity~~

$$^{7}_{4}Be + {}^{0}_{-1}e(\text{electron}) \longrightarrow {}^{7}_{3}Li.$$

The net effect of the nuclear transformation resulting from orbital electron (K electron) capture is the same as that observed with positron emission. In both cases, a proton in the nucleus is converted to a neutron. On orbital electron capture as soon as the K-electron drops into the nucleus electrons move in successively from higher energy orbitals to fill in the vacancy in the K-shell. The excess energy in such transition is given off in the form of X-rays.

Radioactive Disintegration series :

There are forty or nearly forty naturally occuring radioactive elements. They appear towards the end of the periodic table. Detailed investigation reveals that these elements form three distinct family of successive disintegration products. The elements within a ~~series~~ family are said to form a series. They are :

(1) The thorium series : It begins with $^{232}_{90}Th$ and ends with $^{208}_{82}Pb$. The mass numbers of the members in the series are given by $4n$, where n is an integer. So this is also called $4n$-series.

(2) The Uranium series : It begins with $^{238}_{92}U$ and ends with $^{206}_{82}Pb$. The mass numbers of different members corresponds to $4n+2$. ~~series~~ This is also called $(4n+2)$-series.

(3) The actinium series : It begins with $^{235}_{92}U$ (known as actinouranium) and ends with $^{207}_{82}Pb$. ~~There~~ The series is named after actinium, the first discovered member of this series. This series is called $(4n+3)$ series also.

● Group displacement law : from R.L.D.

● Unit of Radioactivity :

S.I. unit is becquerel, Bq.

1 Bq = 1 disintegration per second (dis sec^{-1})

The oldest unit is curie (Ci).

1 Ci = 3.7×10^{10} dis s^{-1}.

$\therefore$ $\boxed{1\ Ci = 3.7 \times 10^{10}\ Bq}$.

1 mCi = 3.7×10^{7} dis s^{-1}, 1 μCi = 3.7×10^{4} dis s^{-1}.

Again 1 Ci = 37×10^{9} Bq

= 37 GBq. (giga becquerel).

Another unit is Rutherford (rd)

1 rd = 10^{6} dis s^{-1}.

● Rate of radioactive disintegration :→

Rutherford and Soddy observed that Uranium and Thorium decayed in an exponential manner with time. This means that the rate of loss of activity at any instant is proportional to the amount of activity actually present at that time. Now the rate of loss of activity must be proportional to the number of atoms which disintegrate in a unit time-interval.

Let n be the total numbers of atoms of the radioelements present in a radioactive species at any time t, counted from any arbitarily taken starting time (t=0). Of dn atoms disintegrate between the very small time interval between t and dt+t, then the rate of disintegration at time t is equal to $-dn/dt$; the negative sign indicates that n decreases with time. This rate is proportional to the total number of atoms present at time t, i.e., n.

Therefore —

$$-\frac{dn}{dt} \propto n$$

$$\Rightarrow -\frac{dn}{dt} = \lambda n$$

$$\Rightarrow \lambda = -\frac{dn}{dt.\, n}$$

λ is a proportionality constant.

When $dt = 1$, $\lambda = -\frac{dn}{n}$; this is the fraction of total number of atoms which disintegrate at unit time.

This constant is called disintegration const or decay constant, characterizing each radioelement. Its magnitude is unaffected by the physical condition or state of chemical combination of a radioelement.

$$\frac{dn}{n} = -\lambda dt$$

Integrating $\ln n = -\lambda t + I$ (I = const. of integration)

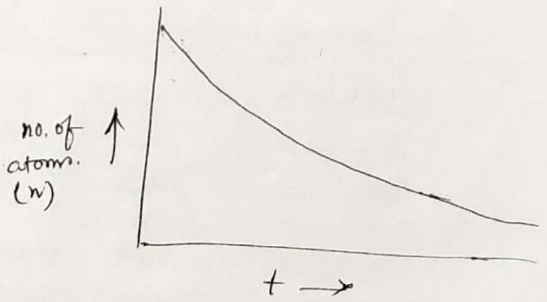
Let n_0 be the number of atoms of the radioelement present at the moment from which we started to count the time. This corresponds to $t = 0$ for the particular observation.

$$\ln n_0 = -\lambda \cdot 0 + I \Rightarrow I = \ln n_0$$

$$\therefore \ln n = -\lambda t + \ln n_0$$

$$\Rightarrow \ln \frac{n}{n_0} = -\lambda t$$

$$\Rightarrow \boxed{n = n_0 e^{-\lambda t}}$$



Limitation :

The rate law shows that a radio element will take infinite time to decay completely, i.e., when n will become zero. However, the law is valid in nature and it may not applicable to a small number of atoms.

Half-life of Radioelement :-

The half-life is the time required for the activity of a given amount of radioelement to decay to half of its initial value.

The time is independent of the amount of radioactive substance taken initially and is characteristic of each radioactive element. It provides a measure of the rate at which an element disintegrates.

We have, $\ln \frac{n}{n_0} = -\lambda t$

$\Rightarrow \ln \frac{n_0}{n} = \lambda t$

$\Rightarrow \frac{2.303}{\lambda} \times \log \frac{n_0}{n} = t$

At $t = t_{1/2}$, $n = n_0/2$

$\therefore \frac{2.303}{\lambda} \log \frac{n_0}{n_0/2} = t_{1/2}$

$\Rightarrow t_{1/2} = \frac{2.303}{\lambda} \log 2 = \frac{2.303 \times 0.3010}{\lambda}$

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

The above expression shows that the half-life is independent of n_0, i.e., the amount of radioelement taken initially.

Average Life Period :-

The equations for radioactive decay reveal that a definite fraction of the atoms present at any instant will decay in unit time; this fraction is related to the decay const λ. But it is not possible to foretell which particular atoms will disintegrate in a particular time interval. Thus, some of the atoms will die very early, while some others will have a very long life. In fact, the life of any radioactive atom may have all possible values from zero to infinity. It is now possible to determine an average life of an aggregate of large number of atoms.

Average life period of an atom of radioelement tells us the average span of time after which the atom will disintegrate.

Suppose n_0 atoms of a radioelement are present in an aggregate at some arbitarily assumed zero time.

Between the very small time interval between t and $t+dt$, dn atoms are found to disintegrate.

Since dt is small, each of these dn atoms may be considered to have a life-time of t. So, the total life-time of all the dn atoms is $t\,dn$.

$$\therefore \quad t_{av} = \frac{t_1 dn_1 + t_2 dn_2 + t_3 dn_3 + \cdots}{dn_1 + dn_2 + dn_3 + \cdots} = \frac{\sum t\,dn}{n_0}$$

$$= \frac{\int_{n_0}^{0} t\,dn}{n_0}$$

$$= \frac{1}{n_0} \int_0^{\infty} t(-\lambda n\,dt)$$

$$= \frac{1}{n_0} \int_0^{\infty} -\lambda t\, n_0 e^{-\lambda t}\,dt$$

$$= -\lambda \int_0^{\infty} t\, e^{-\lambda t}\,dt$$

$$= -\lambda \left\{ t \cdot \int_0^{\infty} e^{-\lambda t}\,dt - \int_0^{\infty} \left[\frac{d}{dt}(t) \int_0^{\infty} e^{-\lambda t}\,dt \right] dt \right.$$

$$= -\lambda \left\{ t \cdot \left[\frac{e^{-\lambda t}}{-\lambda} \right]_0^{\infty} - \int_0^{\infty} \left[\frac{e^{-\lambda t}}{-\lambda} \right]_0^{\infty} dt \right.$$

$$= -\lambda \left[t \cdot \left[\frac{e^{-\lambda t}}{-\lambda} \right]_0^{\infty} \right\} + \frac{1}{\lambda} \cdot \left[\frac{e^{-\lambda t}}{-\lambda} \right]_0^{\infty}$$

$$= -\frac{\lambda}{\lambda} \left[t e^{-\lambda t} + \frac{1}{\lambda} e^{-\lambda t} \right]_0^{\infty}$$

$$= -\frac{1}{\lambda}$$

$$= \frac{1}{\lambda}$$ (negative sign is neglected and time unit is signless)

And (−) sign indicates merely the decreasing trend of dN nuclides with time.

Problem 1 : 2.00 g of $^{210}_{82}Bi$ decays at such a rate that 0.500 g of it is left after 10 days. Calculate (a) the radioactive decay rate constant, λ (b) the amount left after five days and (c) the half-life of the isotope.

⟹ (a) We have, $n = n_0 e^{-\lambda t}$

$\frac{n}{n_0} = e^{-\lambda t}$

$\Rightarrow \ln \frac{n}{n_0} = -\lambda t$

$\Rightarrow \log \frac{n}{n_0} = \frac{-\lambda t}{2.303}$

$\Rightarrow \lambda = \frac{2.303 \times \log \frac{n_0}{n}}{t}$

Here $\frac{n}{n_0} = \frac{0.500}{2.00}$ g

$t = 10$ days.

$\therefore \log\left(\frac{n_0}{n}\right) = \frac{\lambda t}{2.303}$

$\Rightarrow \log\left(\frac{0.5}{2.0}\right) = \frac{\lambda \times 10 \text{ days}}{2.303}$

$\Rightarrow \lambda = 0.138 \text{ days}^{-1}$

(b) Now $t = 5$ days.

$2.303 \log \frac{n_0}{n} = \lambda t$

$\Rightarrow 2.303 \log \frac{2.00}{n} = 0.138 \text{ days}^{-1} \times 5 \text{ days}$

$\Rightarrow n = 1.00$ g.

(c) $t_{1/2} = \frac{0.693}{\lambda} = \frac{0.693}{0.138 \text{ days}^{-1}}$

$= 5$ days.

Problem-2 : The half-life of radium is 1590 years. How long will it take for 1 g of the element to lose 0.1 g?

⟹ $\lambda = \frac{0.693}{1590 \text{ y}}$ $\quad N = 1.0 - 0.1$ g $= 0.9$ g.

$\therefore \lambda t = 2.303 \log\left(\frac{N_0}{N}\right)$

$\Rightarrow t = 2.303 \log\left(\frac{1}{0.9}\right) \times \frac{1590 \text{ y}}{0.693}$

$= 2385$ y.

Isotopes :

Isotopes of an element are atoms of the same element with different atomic weights.

Isotopes possess identical chemical properties because of their identical electronic structure.

Isotopes of a particular element have the same no. of protons but varying no. of neutrons inside the nuclei.

Examples — Cl-35 and Cl-37, O-16 and O-18, H-1 and H-2.

Isobars :

There are some species which possess the same atomic wt. but different atomic numbers. Such species are called isobars.

Isobars have different chemical properties since they possess different electronic conf^{n}, i.e., they are the members of different groups in periodic table.

Examples — Ar - 40 & Ca - 40, Pt-196 & Hg-196.

After the emission of a β-particle, the product nucleus and the reactant nucleus are the isobars of each other.

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

Nuclear isomers :

A third case may arise where nuclei with the same atomic weight and the same atomic number may vary only in their radioactive properties. Such species are known as isobaric isotopes or as nuclear isomers.

Example :— Zinc - 68 on being bombarded by deuteron gives off a proton and leads to Zn-69. This freshly synthesised Zn-69 emitts γ-radiation till another nuclear isotope Zn-69 is obtained, which decays by β-emission.

$$Zn-68 + {}^{2}_{1}D \longrightarrow Zn-69(m) + {}^{1}_{1}H$$

Here Zn-69 (m) (γ-emitter) $\xrightarrow{-\gamma\text{ ray}}$ Zn-69 (can emit β-ray)

and Zn-69 (β-emitter) are nuclear isomers.

Isotones :-

Some radioactive elements may have in their nuclei the same number of neutrons. Such species are called isotones.

$^{226}_{88}Ra$ & $^{227}_{89}Ac$ are the examples of such class.

Seperation of isotopes :

The seperation factor : The seperation factor, S, signifies the extent of enrichment in any seperation procedure. Suppose a ~~cont~~ mixture contains n_1 atoms of light isotope and n_2 atoms of the heavier isotope (per gm of mixture, say). Let the corresponding numbers be n_1' and n_2' after a particular seperation process. The seperation factor for the process is then given by —

$$S = \frac{\text{Ratio of atoms after seperation}}{\text{Ratio of atoms before seperation}} = \frac{n_1'/n_2'}{n_1/n_2}$$

Methods for Seperation :⟶

There are various way to seperate ~~isotopes~~ isotopes. They may be physical procedure or chemical procedure. On this content, the name of the methods are given below —

① Gaseous diffusion method ② Thermal diffusion method ③ The electromagnetic method ④ Electrolytic method. ⑤ Distillation method ⑥ Centrifugal seperation ⑦ Ion-migration method ⑧ Gas-liquid chromatography.

⑨ Szilard – chalmers seperation.

Gaseous diffusion method (by Graham):

Two isotopic species diffuse through a porous membrane at rates which are inversely proportional to the square root of their respective molecular weights, say M_1 and M_2:

$$\frac{\text{Rate}_1}{\text{Rate}_2} = \left(\frac{M_2}{M_1}\right)^{1/2}$$

[The kinetic energies of two ideal gases 1 & 2 at a given T being the same $\frac{1}{2} M_1 V_1^2 = \frac{1}{2} M_2 V_2^2$

$$\Rightarrow \frac{V_1}{V_2} = \left(\frac{M_2}{M_1}\right)^{1/2}$$

Thus the molecules containing the lighter isotope will diffuse more rapidly than the others, resulting in some separation. The separation factor, s, for the process would be $s = \left(\frac{M_1}{M_2}\right)^{1/2}$; where M_1 is mol. wt. for heavier isotope and M_2 is the mol. wt. for the lighter isotope.

Thus, s will be theoritically equal to $2^{1/2}$ or 1.41 for a mixture of D_2 and H_2; but s will fall gradually with higher molecular weights.

For $^{235}UF_6$ and $^{238}UF_6$, s is only $\left(\frac{352}{349}\right)^{1/2} = 1.0043$.

The actual value is still less for several practical difficulties. To obtain practical separation, a cascade ~~metho~~ system involving many successive diffusion stages at reduced pressure is used and the enriched material is recycled many times. ^{20}Ne and ^{22}Ne; ^{12}C and ^{13}C; $^{235}UF_6$ and $^{238}UF_6$ have been separated by this method. The method is used for the large scale enrichment of ^{235}U for reactors. About 4000 diffusion stages are required to obtain 99 percent $^{235}UF_6$.

Uses of isotopes ⟹

Isotopes have been of varied utility. The use of isotopes may be broadly classified under the heads: (a) reaction mechanism studies (b) structure elucidation (c) uses in analytical chemistry (d) age determination of minerals and rocks and relics (e) medicinal uses (f) agricultural uses (g) industrial uses.

a) Reaction mechanism Studies :- (Example of Tracer technique See R.L.D.)

(i) Isotopes have played a key role in the evolution of reaction mechanisms, particularly in organic chemistry. Let us consider the photosynthesis reaction.

$$6CO_2 + 6H_2O \longrightarrow C_6H_{12}O_6 + 6O_2$$

We have to know whether the oxygen gas originates from the oxygen of CO_2 or from the oxygen of H_2O, has been settled by the use of oxygen-18. It is definitely established by mass spectrometric analysis of the oxygen that any O-18 introduced into water showed up as O_2 gas. CO_2 with O-18 could not influence the evolved oxygen. Therefore it is evident that the elementary oxygen given out by green plants is formed from water, and not from carbon dioxide.
Due to such work Calvin was awarded Nobel prize in 1961.

(ii) When H_2O_2 reacts with strong oxidant such as PbO_2, MnO_4^-, $Cr_2O_7^{2-}$ etc. oxygen gas is produced:

$$PbO_2 + H_2O_2 \longrightarrow PbO + H_2O + O_2$$

It was a strong controversy whether the O_2 comes entirely from H_2O_2 or partly from the oxidant:

$$PbO\boxed{O + O}OH_2 \longrightarrow PbO + H_2O + O_2$$

$$PbO\,O + \boxed{O - O}_{H}^{H} \longrightarrow PbO + H_2O + O_2$$

O-18 labelled H_2O_2 was used and mass spectroscopic analysis of the O_2 produced in the reaction proved that the O_2 comes from H_2O_2. Thus O-O linkage (of H_2O_2) is destroyed during the reaction.

(b) Structure Elucidation :

(i) PCl_5 :

The point of interest related to whether all the five Cl were equivalently bonded to P. PCl_3 was allowed to react Cl labelled with Cl-36 isotope, a β-emitter.

$$PCl_3 + {}^*Cl_2 \longrightarrow P{}^*Cl_5$$

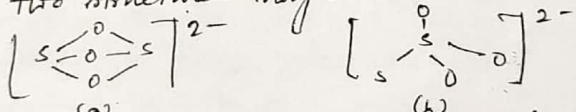
The activity originally associated with ${}^*Cl_2$ will distribute uniformly over all the five Cl provided they are all equivalent in $P{}^*Cl_5$. The pentachloride was then hydrolysed :

$$P{}^*Cl_5 + H_2O \longrightarrow POCl_3 + 2H{}^*Cl$$

Interestingly all the activity was found in the $H{}^*Cl$ and none with the $POCl_3$. Thus 3 Cl of PCl_5 are equivalent while the other two are different. Thus a distinction could be made between three equatorial chlorines and two axial chlorine of the trigonal bipyramidal PCl_5.

(ii) Thiosulfate ion :

The following two structures may be considered :



(a) (b)

(a) has a μ-trioxo str. making the two sulphurs equivalent while (b) has two non-equivalent sulphurs. Labelled thiosulphate was prepared by reacting non-radioactive sulphite with radioactive ^{35}S (a β-emitter)

$$SO_3^{2-} + {}^{35}S \longrightarrow {}^{35*}SSO_3^{2-} \text{ (or } {}^*SSO_3^{2-})$$

$AgNO_3$ and radioactive thiosulphate were then reacted

$$AgNO_3 + {}^*SSO_3^{2-} \longrightarrow Ag_2{}^*S_2O_3$$ [redacted]

Now

$$Ag_2{}^*S_2O_3 + H_2O \longrightarrow Ag_2{}^*S + H_2SO_4$$

The entire radioactivity came down with $Ag_2{}^*S$ ppt. Thus the non equivalent structure (b) is confirmed and same can be drawn when active sulfite was boiled with acid water.

$${}^*S_2O_3^{2-} \xrightarrow[\text{acid soln}]{\text{boiled with}} {}^*S + SO_3^{2-}$$

ⓐ Radiocarbon dating :→

Radiocarbon dating or carbon dating, is a method that uses the naturally occuring radioisotope carbon-14 to determine the age of carbonaceous materials up to about 58000 to 62000 years.

This theory was developed by W.F. Libby and was awarded the Nobel prize in 1960.

He has developed this method of determining the age of organic material based on the accurate determination of the ratio of C-14 to C-12.

C-14 is produced in the atmosphere by the interaction of neutrons (from cosmic rays) with ordinary nitrogen;

$$^{14}_{7}N + ^{1}_{0}n \longrightarrow ^{14}_{6}C + ^{1}_{1}H .$$

The carbon-14 ultimately goes over to C-14 dioxide. A steady state concentration of one ^{14}C to 10^{12} ^{12}C is reached in the atmospheric CO_2. This CO_2 is taken in or given out by plants or plant-eating elements or human beings so that they all bear this ratio. When a plant or animal is died the steady state is disturbed since there is no fresh intake of atmospheric CO_2 and the dead matter is out of equilibrium of atmosphere. The ^{14}C continues to decay so that after a number of years only a fraction of it is left in the dead matter. Therefore the ratio of the $^{14}C/^{12}C$ drops from the steady state ratio in the living matter.

$$^{14}_{6}C \longrightarrow ^{14}_{7}N + ^{0}_{-1}e \quad (t_{1/2} = 5760\ y).$$

By measuring this ratio by mass spectroscopy and comparing it with the ratio in living plants one can estimate when the plant died.

Problem: A piece of wood was found to have $^{14}C/^{12}C$ ratio 0.7 times that in a living plant. Calculate the approximate period when the plant died ($t_{1/2} = 5760\,y$)

$$\Rightarrow \lambda = \frac{0.693}{5760\,y} = 1.20 \times 10^{-4}\,y^{-1}$$

Now, $\log \frac{N_0}{N} = \frac{\lambda t}{2.303}$ $\qquad N = N_0 e^{-\lambda t}$

$$\Rightarrow \log \frac{1.00}{0.70} = \frac{1.20 \times 10^{-4}\,y^{-1} \times t}{2.303}$$

$$\Rightarrow t = \ldots = 2970 \text{ years}.$$

Age determination of rock/ore :——

A knowledge of the rate of decay of certain radioactive isotopes helps to determine the age of various rock deposits. Let us consider a uranium containing rock formed many years ago. The uranium started to decay giving rise to the uranium-238 to lead-206 series. The half-lives of the intermediate members being small compared to the U-238 ($4.5 \times 10^9\,y$), it is reasonable to assume that those uranium atoms that started decaying many many years ago must have been completely converted to the stable lead-206 during this extra long period. The U-238 remaining and the Pb-206 formed must together account for the U-238 present at 'zero' time, that is, when the rock solidified.

Thus both N_0 and N are known and λ is known from a knowledge of the half-life of U-238. Therefore age of the rock can be calculated.

If we consider that the rock solidified when the earth also solidified, we can easily determine the age of the earth following the above process.

[N.B. – In radiocarbon dating, we have an approximation that the intensity cosmic rays (which are responsible for neutron source) is same throughout the earth]

Problem:- A sample of uranium ($t_{1/2} = 4.5 \times 10^9$ y) ore is found to contain 11.9 g of uranium-238 and 10.3 g of Pb-206. Calculate the age of the ore.

$$\lambda = \frac{0.693}{4.5 \times 10^9 \text{ y}} = 0.154 \times 10^{-9} \text{ y}^{-1}$$

11.9 g of U-238 = 0.05 mole of U-238

10.3 g of Pb-206 = 0.05 mole of Pb-206

∴ At 'zero' time the mole of U-238 = 0.05 + 0.05
= 0.10 mole.

Now $2.303 \log \frac{N_0}{N} = \lambda t$

$$\Rightarrow t = \frac{2.303 \log \frac{0.10}{0.05}}{0.154 \times 10^{-9} \text{ y}^{-1}}$$

$$= 4.5 \times 10^9 \text{ years}.$$

(iii) Medicinal uses of Radioisotopes:

Purpose of study	Isotopes used.
1. Thyroiditis (Goitre) → Hyper, Hypo	1. ^{131}I
2. Brain tumour, is very difficult to detect. Some of the dye is adsorbed by this.	2. Such dye is fluorescein. (called Rose bengal) contain ^{131}I.
3. Bone imaging	3. ^{18}F (as NaF), ^{85}Sr (as chloid) ^{99m}Tc (as methylene diphosphate)
4. Cerebrospinal fluid	4. ^{111}In (as chloride)
5. Kidney disorder	5. ^{99m}Tc (as dimercapto succinic acid) ^{131}I (as hippuran)
6. Liver/Spleen	6. ^{99m}Tc (as sulfer colloid) ^{131}I (as Rose Bengal) ^{198}Au (as colloidal gold)
7. Metabolism	7. ^{24}Na, ^{42}K (as chlorides)
8. Lung Ventilation	8. ^{67}Ga (as citrate).

Some tiny particles present in nucleus

In 1935, a Japanese theoritical physicist, predicted the existence of another nuclear particle called meson (meso means middle, in Greek), with a mass in between that of electron and proton. Since then three kinds of mesons have been found in both cosmic rays and Laboratory. One variety, called μ-meson, has been shown to have mass 206 times that of electron and a charge which may be negative or positive.
The second variety, called π-meson, has a mass about 270 times that of electron and a charge which may be positive, negative or zero. The third variety, called K meson, has mass about 970 times that of electron and a charge that may be positive, negative or zero.
Nuclear particles with mass larger than that of proton have also been obtained. These particles are called hyperons. The masses of hyperons have been found to be about 2180, 2330 and 2580 times that of the electon at rest. Some of these particles are neutral and others are positively or negatively charged.

Meson and hyperons are very short-lived. Mesons, depending upon their catagory decompose into other mesons, electrons, positrons, neutrino, antineutrinos, γ rays etc. Hyperons break down to other hyperons, mesons, neutrons and protons.

~~At the time of Rutherford,~~

(iii) Nuclear forces :— As is well known, the protons and neutrons are packed together in a very small nuclear space. A question immediately arises: What is the nature of forces which blinds the protons and neutrons together in such a small nucleus ?

If electrostatic forces (Coulombic forces) alone were involved, the repulsion between the protons would render the nucleus very unstable and liable to disintegration. Since this does not happen except in the case of heavier elements which are radioactive, it is evident that there must be some attractive force between proton and neutron, neutron and neutron and even between proton and proton, which must be stronger than the repulsive forces due to positive charge of the protons. These attractive forces are called nuclear forces.

These forces are also termed as short-range forces because they operate through the short distance viz., 0.10 fermi° (10^{-13} cm = 1 fermi°).

The exact nature of the nuclear forces is not well defined. These forces are believed to be associated with the interconversion of protons and neutrons.

Hideki, Yukawa, suggested in 1939, that π-mesons oscillate between neighbouring nucleons (protons and neutron) with a velocity close to that of light. They interact with protons and neutrons as a result of which a proton may change into neutron and a neutron may change into proton, for a part of the time,

proton + negative π-meson $\rightleftharpoons$ Neutron

Neutron + positive π-meson $\rightleftharpoons$ proton.

There is thus an exchange of meson between neighbouring nucleons. This results in an attraction between neutron and proton.

How the exchange of meson between two nucleons leads to attractive force may be understood by considering a crude analogy in which the two nucleons.

are taken as two dogs and the meson as a piece of bone which each of them is trying to ~~steal~~ snatch from the other. In the scuffle, the bone is rapidly exchanged between two dogs. Since neither of them is prepared to part with the bone, the latter keeps the two dogs bound together.

(II) Nuclear size :—

From the experiments on scattering of neutrons, Rutherford obtained an expression

$$r = R_0 A^{1/3}$$

R_0 = const $= 1.5 \times 10^{-13}$ cm

A = mass number, r = radius of the nucleus.

Problem : (a) Estimate the radius of $^{27}_{13}Al$ nucleus.

(b) Why is the atomic radius of Al comparitively so much large ?

$\Longrightarrow$ (a) $A = 27$, $R_0 = 1.5 \times 10^{-13}$ cm

$$r = (1.5 \times 10^{-13} \text{ cm}) \times (27)^{1/3} = 4.5 \times 10^{-13} \text{ cm}$$

$$= 4.5 \text{ fermi}.$$

(b) Atomic radius of Al, by defination, is taken as the distance between the centre of its nucleus and the outermost shell of electrons. This distance is tremendously large as compared to the radius of the nucleus. To quote an analogy, if the nucleus is of the size of a cricket ball, the outermost shell of electrons would be nearly 2 kilometer from the nucleus. This explains why the atomic radius is very large compared to the nuclear radius.

Atomic mass unit (a.m.u.)

According to the latest convention, the mass of the standard carbon atom, $^{12}_{6}C$, is taken to be 12 a.m.u.
Thus 1 a.m.u. is exactly $\frac{1}{12}$ th of the mass of $^{12}_{6}C$ atom.

$$\therefore 1 \text{ a.m.u} = \frac{1}{12} \times \text{mass of a } ^{12}_{6}C \text{ atom}$$

$$= \frac{1}{12} \times \frac{12 \text{ g/mole}}{6.023 \times 10^{23}/\text{mole}}$$

$$= 1.66 \times 10^{-24} \text{ g}.$$

Mass of proton = 1.007277 a.m.u.
" " electron = 0.0005486 "
" " neutron = 1.008665 "

∴ Nucleons has mass ≈ 1 a.m.u.

Problem: Calculate the density of a nucleus of mass number A.

⇒ The nucleus of mass no. A would contains A nucleons.

∴ mass of the nucleons = $A \times 1 \text{ amu}$

$$= A \times 1.66 \times 10^{-27} \text{ Kg}.$$

$$r_0 = R_0 A^{1/3}$$

$$= 1.5 \times 10^{-15} \text{ m} \times A^{1/3}$$

Volume of the nucleus $= \frac{4}{3} \pi r_0^3$

$$= \frac{4}{3} \times \pi \times \left(1.5 \times 10^{-15} \times A^{1/3}\right)^3$$

$$= \frac{4}{3} \pi \left(1.5 \times 10^{-15}\right)^3 A \text{ m}^3$$

Hence density of the nucleus $\rho = \frac{m}{V}$

$$= \frac{A \times 1.66 \times 10^{-27} \text{ Kg}}{\frac{4}{3} \pi \left(1.5 \times 10^{-15}\right)^3 A \text{ m}^3}$$

$$= 1.77 \times 10^{17} \text{ Kg/m}^3$$

i.e., density of nucleus is tremendously high.

Problem : Calculate the average density of the nuclear material in the $^{12}_{6}C$ nuclide, given that the nuclear radius is equal to 3 f. Compare this density with that of water. (1 a.m.u. $= 1.66 \times 10^{-27}$ kg)

⇒ We know that the density ρ is given by $\rho = \frac{m}{V}$ where m is the mass and V is the volume. Assuming that the nucleus is spherical, $V = \frac{4}{3}\pi r^3$ where r is the nuclear radius.

Now, $r = 3f = 3 \times 10^{-15}$ m

$$m = (12 \text{ a.m.u})(1.66 \times 10^{-27} \text{ kg/a.m.u})$$
$$= 12 \times 1.66 \times 10^{-27} \text{ kg}.$$

$$\rho = \frac{12 \times 1.66 \times 10^{-27} \text{ kg}}{\frac{4}{3}\pi (3 \times 10^{-15} \text{ m})^3} = 1.76 \times 10^{17} \text{ kg/m}^3$$

$$\frac{\rho}{\rho_{water}} = \frac{1.76 \times 10^{17} \text{ kg/m}^3}{1000 \text{ kg/m}^3} = 17.6 \times 10^{14}$$

Notice the fantastically high nuclear density compared with that of water.

● Relation between Energy and a.m.u. :—

According to Einstein's mass-energy relationship,

$$E = mc^2$$

$$\therefore E = 1.66 \times 10^{-27} \text{ kg} \times (3 \times 10^8 \text{ m s}^{-1})^2$$
$$= 1.4925 \times 10^{-10} \text{ J} \quad [\text{as } J = \text{kg m}^2 \text{ s}^{-2}]$$
$$= \frac{1.4925 \times 10^{-10} \text{ J}}{1.602 \times 10^{-19} \text{ J/eV}} \quad [1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}]$$
$$= \frac{1.4925 \times 10^{-10} \text{ J}}{1.602 \times 10^{-13} \text{ J/MeV}}$$
$$= 931.65 \text{ MeV}.$$

1 eV = (charge of electron)(1 volt)
$= 1.602 \times 10^{-19}$ Coulomb $\times$ 1 volt
$= 1.602 \times 10^{-19}$ J.

$\therefore$ 1 a.m.u. $\equiv$ 931.65 MeV. (MeV = Million electron volt. 1 MeV = 10^6 eV)

i.e., from 1 a.m.u. mass we can observe 931.65 MeV energy.

Packing Fraction :→

It has been observed that isotopic masses of elements are close to but not exactly equal to whole numbers. The mass numbers, however, are invariably whole numbers.

Aston expressed the variation of isotopic mass from mass number of the isotope in terms of a quantity called packing fraction which is defined as —

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

Packing fraction may have a negative or positive sign. The negative sign of packing fraction means that the isotopic mass is less than the mass number of the isotope. In such cases, some mass gets transformed into energy in the formation of that nucleus, in according to Einstein eqn. $E = mc^2$. Such nuclei, are therefore stable. A positive packing fraction, on the other hand, would imply a tendency towards instability. But this is not quite correct especially for elements of low atomic masses.

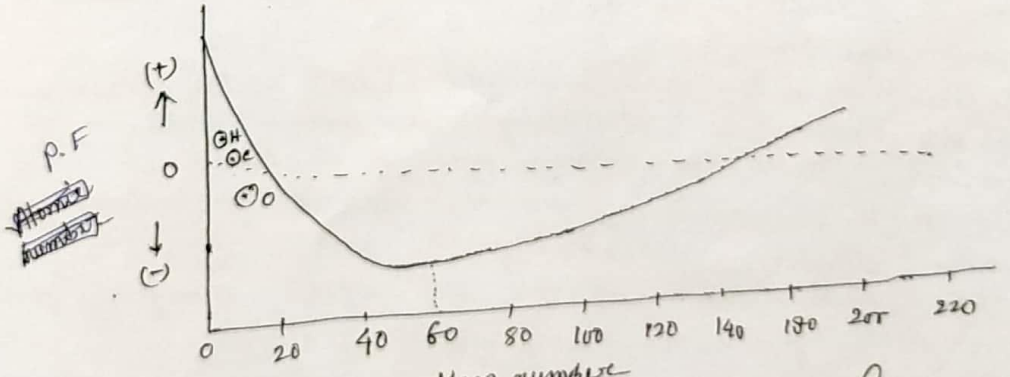


fig: A plot of packing fraction against the corresponding mass number of various element.

It has been observed that hydrogen, helium, carbon and oxygen atoms of mass number 1, 4, 12 and 16 respectively, do not fall on this curve. The packing fraction of H, He and C, although positive, have small values. These elements are therefore stable. ~~The transition elements~~ The packing fraction of oxygen with mass number 16 and isotopic mass 15.999 is negative. The O atom is therefore stable. The transm elements with mass numbers in the neighbourhood of 45, such as Mo, Te, Ru, Rh, Pd, Ag, have lowest packing fractions with a negative sign which indicate their high stability. The packing fraction beyond mass number 200 becomes positive and increases with increase in mass number. This indicates increasing instability of these elements. Elements beyond 230 mass numbers are radioactive and undergo spontaneous disintegration.

A quantitative measure of stability of a nucleus, however, become possible with the development of concept of mass defect.

Mass defect, binding energy of the Nucleus :-

It has been found that the actual isotopic mass of an element is almost invariably less than the sum of the masses of protons, neutrons and electrons present in it. This difference between the two is known as mass defect.

Suppose A is the mass number and Z is the atomic number of an element. Evidently, its atom contains Z protons, (A-Z) neutrons and Z electrons.

Let m_p, m_n and m_e are the masses of proton, neutron and electron respectively.

The atomic mass M' of the isotope, therefore, should be given by

$$M' = Z m_p + Z m_e + (A-Z) m_n$$
$$= Z(m_p + m_e) + (A-Z) m_n$$
$$= Z m_H + (A-Z) m_n \quad (\text{as } m_p + m_e = m_H)$$

i.e., mass of Hydrogen.

Suppose the actual mass is M, is less than M'

$\therefore$ Mass defect $= M' - M = \Delta M$

or $\Delta M = Z m_H + (A-Z) m_n - M$

The quantity ΔM represents the loss of mass in the formation of the nucleus of the atom. The loss of mass is equivalent of the energy released in the formation of the given nucleus from individual protons and neutrons. The release of the energy results in the stability of the nucleus.

The energy released in the formation of a nucleus from its constituent nucleons is called the binding energy of the nucleus. This much energy will naturally be required to breakup the nucleus into its component nucleons.

If mass defect $= \Delta M$ a.m.u.

$\therefore$ Binding energy $= \Delta M \times 931.5$ MeV

The binding energy of the nucleus when divided by number of nucleons gives the mean binding energy. This is the measure of the stability of the nucleus.

Greater the binding energy per nucleon, the more stable is the nucleus.

Problem: Calculate the binding energy per nucleon of oxygen atom $^{16}_{8}O$ which has a mass of 15.994910 a.m.u.

Mass of neutron = 1.008665 a.m.u., mass of proton = 1.007277 a.m.u. and mass of electron = 0.0005486 a.m.u.

$\Rightarrow$ Oxygen atom contains 8 protons, 8 neutrons and 8 electrons.

Mass of 8 neutrons $= 8 \times 1.008665 = 8.069320$ a.m.u.

" 8 protons $= 8 \times 1.007277 = 8.058216$ "

" 8 electrons $= 8 \times 0.0005486 = 0.0043888$ "

Total mass of 16 nucleons and electrons,

$M' = 16.1319248$ a.m.u.

Actual mass of oxygen atom, $M = 15.994910$ a.m.u. (given)

$\therefore$ Mass defect, $\Delta M = M' - M = 0.1370148$ a.m.u.

But 1 a.m.u $\equiv$ 931.5 MeV of energy

$\therefore$ Binding of the nucleus $= 0.1370148$ a.m.u. $\times$ 931.5 MeV/a.m.u

$= 127.62$ MeV

$\therefore$ Binding energy per nucleon $= \frac{127.62}{16}$ MeV $= 7.976$ MeV.

$= 7.976$ MeV.

$= 7.976 \times 1.6 \times 10^{-13}$ Joule.

Note : 1 eV
= (electronic charge) × (1 volt)
= 1.6×10^{-19} coulomb × 1 volt
= 1.6×10^{-19} C.V
= 1.6×10^{-19} Joule (as 1 coulomb volt = 1 J)

$\therefore$ 1 MeV = $1.6 \times 10^{-19} \times 10^6$ J = 1.6×10^{-13} J.

Problem : Calculate packing fraction, mass defect and energy released in the formation of Argon atom $^{40}_{18}Ar$.
Isotopic mass of Ar = 39.96238 a.m.u.

⇒ Argon atom, evidently, contains 18 protons, 18 electrons (viz., 18 hydrogen atoms) and 22 neutrons.

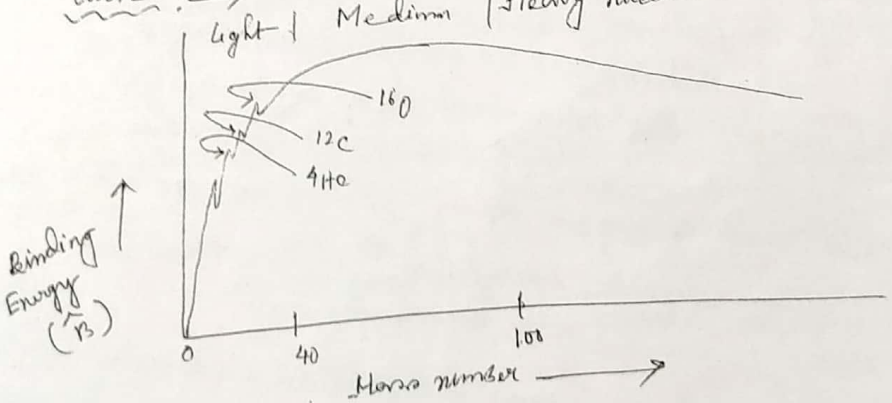
Packing fraction = $\frac{39.96238 - 40}{40} \times 10^4 = -9.4025$

$M' = 18 \times 1.007825 + 22 \times 1.008665 = 40.33148$ a.m.u.
(mass of one H)

$\therefore$ Mass defect = $M' - M = 0.36910$ a.m.u.

Energy released = 0.36910 a.m.u. × 931.5 MeV/a.m.u.
= 343.816 MeV.

● Characteristic features of the nuclear binding energy curve :→



① For the light nuclides (A < 30) :

The maxima for $\bar{B}$ vary periodically for the values of A which are the integral multiples of four. These nuclides are : ^4_2He, $^{12}_6C$, $^{16}_8O$, $^{20}_{10}Ne$, $^{24}_{12}Mg$ and $^{28}_{14}Si$, which are very much stable. In this group, only ^8_4Be is an exceptional one and it actually disintegrates into two α-particles ($^8_4Be \longrightarrow 2\ ^4_2He$)

Thus, the nuclides constructed by the α-particles as the blocking units are stabler compared to the neighbouring ones.

(ii) Medium nuclides ($A = 30 - 90$):

There is a rise of $\hat{B}$ from 8.0 MeV (for $A = 16$) to ~8.20 MeV (for $A = 28-32$), then it remains almost constant ($\hat{B} = 8.5 \pm 0.2$) upto $A \simeq 90$. The region of transition metals, e.g., iron, cobalt, nickel, etc. at around $A = 50 - 60$ lies at the centre of the plateau. This range ($A = 30-90$) characterised by $\hat{B} = 8.5 \pm 0.2$ MeV per nucleon gives the largest zone of the most stability. The value, $\hat{B} = 8.5 \pm 0.2$ is considered to be a diagnostic parameter in predicting the stability of the nuclides.

(iii) Heavy nuclides ($A > 90$):

After zirconium, $\hat{B}$ fall down gradually from ~8.7 MeV to ~7.5 MeV at $A \simeq 210$. Upto $A = 210$, the nuclides are stable but after this limit the nuclides becomes very much unstable. In fact, $^{209}_{83}Bi$ is the heaviest nuclide known to be stable.

Hence it can be concluded that the stable nuclides ($A > 30$) possess $\hat{B}$ in the range 7.5 – 8.5 MeV. The nuclides ($A > 90$) having $\hat{B}$ less than 7.5 MeV are radioactive.

(iv) Nuclear fission and fusion:

To obtain the maximum stability region characterised by $\hat{B} = 8.5 \pm 0.2$ the heavier nuclides undergo radioactive changes in such a way that the product nuclides may come to that stability region. This is why $^{}_{82}Pb$ is the end product of all naturally occurring radioactive series. The stable isotopes of lead lie in the most stable region. This is why, the heavier nuclides (e.g., $^{235}_{92}U$, $\hat{B} \simeq 7.6$ MeV) undergo fission to produce the nuclides having $\hat{B} \simeq 8.5$ MeV. In this process, a huge amount of energy will be released. e.g.- per fission of ^{235}U atom, the energy will be released = $(8.5 - 7.6) \times 235 = 211.5$ MeV

Similarly, if the lighter atoms (e.g. ^{1}H) having low $\hat{B}$ values are fused to generate the elements having higher $\hat{B}$ values. It can be concluded that the nuclides will undergo changes in the directions which lead to $\hat{B} = 8.5 \pm 0.2$ MeV/nucleon.

The Nuclear Models ⇒

Our knowledge about the nuclear structure made progress only after the discovery of neutron by James Chadwick in 1932. Two models have been suggested regarding the nuclear structure. These are briefly discussed below —

1. Liquid Drop Model :

The nuclear model is statistical in nature and was developed by N. Bohr and J. Wheeler. It treats the nucleus as a homogeneous entity containing a certain number of nucleons, each of nucleons being assumed to interact strongly with all its neighbours.

Bohr tried to compare properties of a nucleus with a drop of liquid and found many similarities, Some of these are given below —

1. A liquid drop has a large number of molecules just as a nucleus has a large number of nucleons.
2. Both the liquid drop and the nucleus are homogeneous and incompressible. The density, charge and other properties are the same throughout the liquid drop and the nucleus except at the surface boundaries. It can be easily visualised that the nuclear volume $\propto$ nuclear mass $\propto A$, where A is the mass number —

   Thus radius $r \propto A^{1/3}$

   $\Rightarrow r = R_0 A^{1/3}$ $\quad R_0 = 1.5 \times 10^{-13}$ cm

3. Heat of vaporisation of a liquid corresponds to binding energy of nucleons in a nucleus.
4. Evaporation of a liquid drop corresponds to radioactive emission from a radioactive isotope.
5. Surface tension in a liquid arises from the fact that the surface molecules in a drop are not so tightly bound as are the molecules in the interior. There is evidence to show that this is so in the case of nucleons present in a nucleus as well.
6. In a liquid drop, molecules are influenced only be those which lie in immediate neighbourhood. This means that intermolecular forces are short-range forces only. The same case as in the nucleus. The nucleon-nucleon forces operate within short range only.

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Thank you