NUCLEI

~~Introduction.~~

Atomic Masses.

It is essential to determine mass of nucleus of atom. It can be determined by instrument called mass spectrometer.

Spectrometers are of two types:-

1> Aston Spectrometer.

2> Brain Bridge Spectrometer.

Atomic mass is least quantity which can't be measured in general unit of mass.

The unit for this purpose is a.m.u.

One a.m.u. is defined as $\frac{1}{12}^{th}$ of the mass of an atom of $_6C^{12}$ isotope.

1 amu is $\frac{1}{12}$ th of mass of an atom of $_6C^{12}$

$$1 \text{ mole of } C = 12 \text{ gm}$$

$$N \text{ atom} = 12 \text{ gm}$$

$$1 \text{ atom} = \frac{12}{N} \text{ gm}$$

$$1 \text{ amu} = \frac{1}{12} \times \text{mass of one atom.}$$

$$1 \text{ amu} = \frac{1}{12} \times \frac{12}{N} = \frac{1}{N} \text{ gm}$$

$$1 \text{ amu} = \frac{1}{6.022 \times 10^{23}} \text{ gm}$$

$$1 \text{ amu} = \frac{1}{6.022} \times 10^{-23} \text{ gm}$$

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$1\ amu = \frac{1000}{602} \times 10^{-24}$ gm

$\boxed{1\ amu = 1.660 \times 10^{-24}\ gm}$

$\boxed{1\ amu = 1.660 \times 10^{-27}\ kgm}$

Energy from 1 a.m.u.
Acc. einstein, each mass can be converted equivalent energy & vice-versa.

$$E = mc^2$$
$$E = 1\ amu \times (3 \times 10^8)^2$$
$$E = 1.660 \times 10^{-27} \times 9 \times 10^{16}$$
$$E = 1.494 \times 10^{-10}\ J$$
$$E = \frac{1.494 \times 10^{-10}}{1.6 \times 10^{-19}}\ eV$$
$$E = 9.31 \times 10^8\ eV$$
$$E = \frac{9.31 \times 10^8}{10^6}\ eV$$
$$\boxed{E = 931\ MeV}$$

$$\boxed{1\ amu = 931\ MeV}$$

Electron volt is the unit of energy.
One eV is the energy gained by an electron, when accelerated through a potential difference of one volt.

Composition Of Nucleus.

Meson, positron and natrino.

1> Proton - Electron Hypothesis.

In 1930, the emission of alpha and beta particles from the nuclei of radioactive elements. According to proton - electron hypothesis, the nucleus of an atom of mass number A and atomic number Z is made up of A protons and (A-Z) electrons. As every atom is electrically neutral, it must contain Z more electrons. They revolve around nucleus in circular orbits.

It was rejected as:—

i> Acc. to de-Broglie hypothesis and Heisenberg's uncertainty principle, if e^- is to exist inside nucleus, it should posses energy from 20 MeV to 200 MeV. But energy of e^- is emitted during β-decay is 2 MeV - 3 MeV. Therefore, existence of e^- inside nucleus isn't justified on basis of wave mechanics.

ii> The observed values of nuclear spin or angular momentum of nuclei rule out the possibility of existence of e^- inside nucleus.

iii> Exp., the values of magnetic moments of nuclei are much smaller than the magnetic moments of electrons. Therefore, electrons cannot exist inside the nucleus.

iv> The presence of a few electrons inside the nucleus and others revolving in orbits around the nucleus show dual role of electrons in the atomic structure, which is difficult to visualize.

Discovery of Neutron.
A neutron is a neutral particle carrying no charge, and having mass equal roughly to the mass of a proton. This particle was discovered experimentally by Chadwick in 1932.

i> Chadwick observed that when beryllium was bombarded with alpha particles, some neutral radiations were emitted, which could knock out protons from light nuclei like He, C and N.

ii> Application of the principles of conservation of energy and momentum showed that neutral radiation from bombardment of beryllium could not be photons. Chadwick solved this puzzle by assuming that these neutral radiations consisted of hitherto unknown neutral particles- which were called neutrons.

Chadwick estimated the mass of a neutron being roughly equal to mass of a proton.
Whereas a free proton is stable; a free ~~electron~~ neutron is unstable and has a mean life of 1000 second. Neutron is however, stable inside the nucleus.
Chadwick won 1935 Nobel Prize in Physics for his discovery of neutron.

(b) Proton- neutron hypothesis.
By Heisenberg.
According to this hypothesis, a nucleus of mass number A and atomic number Z contains Z protons, and (A-Z) neutrons. As an atom is electrically neutral, therefore, number of peripheral electrons must be equal to Z, the number of ~~photons~~ protons inside the nucleus.

This hypothesis accounted for all the discrepancies of proton electron hypothesis.

mass of proton, $m_p = 1.6726 \times 10^{-27}$ kg $= 1.007$ amu
mass of neutron, $m_n = 1.6749 \times 10^{-27}$ kg $= 1.008$ amu.

A proton and a neutron may be regarded as two different states of the same particle, called nucleon.

As atom is neutral,

$$\text{no. of } e^- = \text{no. of } p^+$$

Atomic Number. of an element is the number of protons present inside the nucleus of an atom of the element. Represented by Z.

Mass Number. of an element is the total number of protons and neutrons present inside the atomic nucleus of the element. Represented by A.

$$\text{no. of } p^+ = Z \; ; \; \text{no. of } e^- = Z$$

$$\text{no. of nucleons} = A \; ; \; \text{no. of } n^0 = (A - Z).$$

Nuclide. is a specific nucleus of an atom, which is characterised by its atomic number Z, and mass A.

It is represented as $_Z X^A$ where X is symbol.

Nuclear Size.

Volume of a nucleus is directional to its mass number A.

$$\left(\frac{4}{3}\pi R^3\right) \propto A$$

$$R \propto A^{1/3}$$

$$\text{or} \quad \boxed{R = R_0 A^{1/3}}$$

R_0 = empirical constant $= 1.2 \times 10^{-15}$ m.

Atomic nuclei of different elements have different sizes.

Nuclear Density.

Density of nuclear matter is the ratio of mass of nucleus and its volume.

$$\text{Volume of nucleus} = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi (R_0 A^{1/3})^3$$

$$= \frac{4}{3}\pi R_0^3 A$$

$$\text{Density} = \frac{\text{mass of nucleus}}{\text{volume of "}} = \frac{mA}{\frac{4}{3}\pi R_0^3 A}$$

$$\boxed{\text{Density} = \frac{3m}{4\pi R_0^3}}$$

Density ρ of nuclear matter is the same for all elements.

$$\rho = \frac{3 \times 1.66 \times 10^{-27}}{4 \times 3.14 \times (1.2 \times 10^{-15})^3}$$

$$\rho = 2.29 \times 10^{17}\ kg/m^3.$$

Hence, matter in nucleus is very densely packed. Size of the nuclei are different, the heavier nuclei being bigger than the lighter ones. But density of nuclear matter is same for all nuclei. Value of nuclear density is far more greater than the atomic density.

Isotopes.

Isotopes of an element are the atoms of the element which have the same atomic number but different atomic weights.

Same no. of protons and same no. of electrons But as their atomic weights are different, they contain different no. of ~~el~~ neutrons.

Isotopes have same chemical but different physical properties.

The atomic weight of an element is the weighted average of the masses of all its isotopes.

Ex → $_6C^{10}$, $_6C^{12}$.

∴ Average atomic wt. of Ne (9:1) $= \frac{20\times9+22\times1}{9+1}$

$= 20.2$

Mass number A is always an integer, as it represents the number of nucleons in the nucleus.

Isobars.

Isobars are the atoms of different elements which have the same atomic weight, but different atomic numbers.

Isobars contain different no. of protons, different no. of electrons and also different number of neutrons.

for ex, $_{11}Na^{22}$, $_{10}Ne^{22}$ are isobars.

Chemical properties are different and physical properties may be identical.

Isotones.

Isotones are the ~~nucleus~~ nuclides which contains the same no. of neutrons, i.e., in their case, $(A-Z)=N$ is the same.

for ex, $_{17}Cl^{37}$ and $_{19}K^{39}$ are isotones.

Nuclear Binding Energy.

(a) Concept of binding energy.
Nucleons in every nucleus are bound together with short range interacting forces called nuclear forces.

Binding energy of a nucleus is the energy with which nucleons are bound in the nucleus. It is measured by the work required to be done to separate the nucleons an infinite distance apart from the nucleus, so that they may not interact with each other.
This difference between the sum of the masses of neutrons and protons forming a nucleus and mass of the nucleus is called mass defect. It is this mass defect which appears in the form of binding energy responsible for binding the nucleons together in the nucleus.

(b) Expression for Nuclear Binding Energy.

In a nucleus $_ZX^A$,
Z = no. of protons = charge no.
A = mass no. = no. of p^+ + no. of n^0.
m_p = mass of proton
m_n = " " neutron
m_N = mass of nucleus $_ZX^A$

∴,
Mass defect, $\Delta m = \left[Zm_p + (A-Z)m_n - m_N\right]$
Using Einstein's mass-energy equivalence,
$$B.E. = \Delta m \cdot c^2$$

$$B.E. = [Zm_p + (A-Z)m_n - m_N]c^2$$

If m is mass of the atom $_ZX^A$ containing Z electrons each of mass m_e,

$$m(_ZX^A) = m_N(_ZX^A) + Zm_e - \frac{B.E. \text{ of electrons}}{c^2}$$

for hydrogen atom of mass m_H containing one e^-,

$$m_H = m_p + m_e - \frac{B.E. \text{ of one electrons}}{c^2}$$

The B.E. of e^- is much smaller ≈ eV to keV, rest mass energy of a nucleon ≈ 10^3 MeV.

$$m(_ZX^A) = m_N(_ZX^A) + Zm_e$$

$$m_H = m_p + m_e$$

$$B.E. = [Zm_p + Zm_e + (A-Z)m_n - m_N - Zm_e]c^2$$

$$B.E. = [Z(m_p+m_e) + (A-Z)m_n - (m_N + Zm_e)]c^2$$

$$\boxed{B.E. = [Zm_H + (A-Z)m_n - m(_ZX^A)]c^2}$$

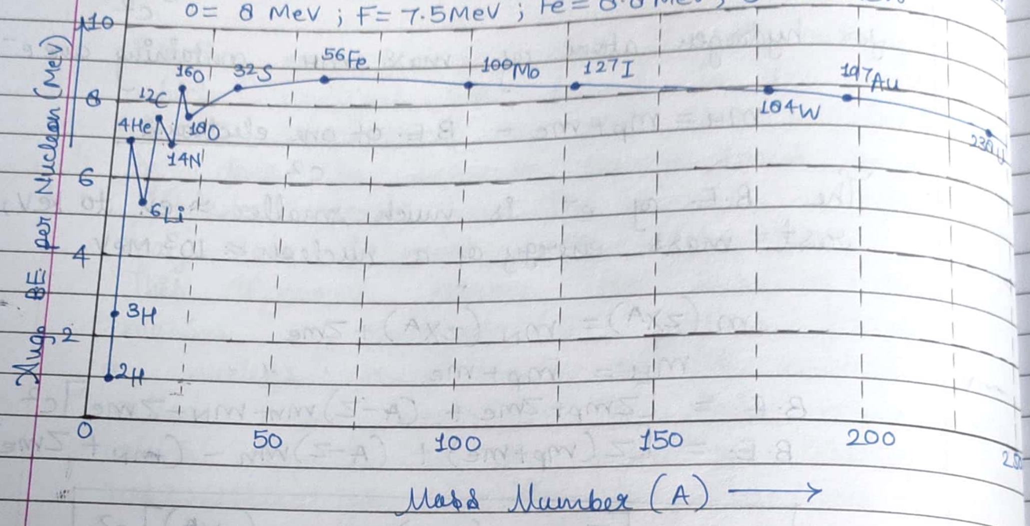
Expression for B.E.

(c) Average B.E. per nucleon of a nucleus.

It is the average energy we have to spend to remove a nucleon from the nucleus to infinite distance. It is given by total binding energy divided by the mass no. of the nucleus.

H = 1.085 MeV; He = 7.03 MeV; Li = 5.5 MeV; C = 7.9 MeV; N = 7.2 MeV

O = 8 MeV; F = 7.5 MeV; Fe = 8.8 MeV; U = 7.6 MeV.



This curve reveals that:

1> Average B.E./nucleon for light nuclei like $_1H^1$, $_1H^2$, $_1H^3$, is small.

2> For mass no. 2 to 20, there are many sharply peak corresponding to He, C and O. These peaks indicates these nuclei are more stable than their corresponding neighbouring nuclei.

3> B.E. per nucleon for Fe^{56} is 8.8, therefore Fe is greater stable in the earth.

4> On the basis of B.E. per nucleon, it is easy to understand nuclear fission or nuclear fusion.

Binding Energy of α- particle.

The nucleus of Helium atom is known as α- particle.

P=2
N=2

$m_p = 1.6 \times 10^{-27}$ kg
$m_n = 1.6 \times 10^{-27}$ kg

actually,

$m_p = 1.00813$ a.m.u.
$m_n = 1.00893$ a.m.u.

$$m_c = 2m_p + 2m_n$$
$$= 2[1.00813 + 1.00893]$$
$$= 2[2.01706]$$
$$= 4.03412 \text{ a.m.u.}$$
$$m_a = 4.00389 \text{ a.m.u.}$$
$$\Delta m = m_c - m_a$$
$$= 4.03412 - 4.00389$$
$$= 0.03023 \text{ a.m.u.}$$

This mass converted into energy known as binding energy.

$$1 \text{ a.m.u.} = 931 \text{ MeV}$$
$$B.E.\ \alpha = 0.03023 \times 931$$
$$B.E.\ \alpha = 28.14 \text{ MeV}$$
$$B.E. \text{ per nucleon} = \frac{28.14}{4}$$
$$= 7.03 \text{ MeV}$$

Therefore, B.E. per nucleon of every atom is a different quantity, the element which has greater B.E. per nucleon is more stable. and element which has less B.E. per nucleon is less stable.

(d) Importance of Binding Energy Curve.

i) Energy can be released when a heavy nucleus ($A \simeq 240$) breaks into two roughly equal fragments. This process is called Nuclear Fission.

ii) Energy can be released when two or more lighter nuclei fuse together to form a heavy nucleus. This process is called Nuclear Fusion.

Hence, the importance of binding energy curve is that it led us to the possibility of release of nuclear energy by nuclear fission and nuclear fusion. These phenomena of nuclear ~~fusion~~ fission and nuclear fusion were actually discovered later.

When mass defect (Δm) is in a.m.u., energy released in MeV can be calculated directly by multiplying mass defect with 931 (MeV). There is no need to apply $E = (\Delta m)c^2$.

Packing Fraction:-

Packing fraction of a nucleus is defined as the mass excess per nucleons. Thus,

$$\text{Packing fraction} = \frac{\text{Mass excess}}{\text{Mass number}} = \frac{M-A}{A}$$

Where, M is actual mass.
A is mass no.

for $A < 20$, ~~B.E.~~ P.F. = +ve.
As A increases, P.F. = −ve.
passes a flat minimum and then rises gradually, becoming +ve again at values of A of about 180.

Nuclear Forces.

Nuclear forces are the strong forces of attraction which holds together the nucleons (neutrons and protons) in the tiny nucleus of an atom, inspite of strong electrostatic forces of repulsion between protons.

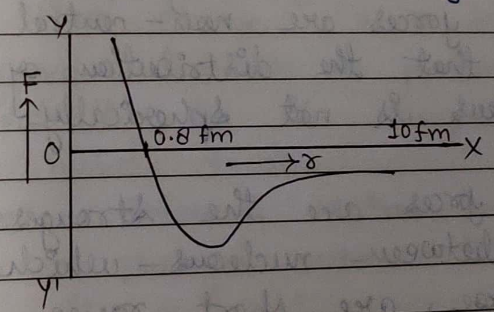
Important Characteristics :-

1> Nuclear forces act between a pair of neutrons, a pair of protons & also between a neutron, proton pair, with the same strength. This shows that nuclear forces are independent of charge.

2> Nuclear forces are the strongest forces in nature. Their magnitude is 100 times of electrostatic forces, 10^{38} times of gravitational forces between nucleons. That is why, nucleons are held together in a nucleus inspite of electrostatic force of repulsion between protons.

3> The nuclear forces are very short range forces.

4> The variation of nuclear forces with distance between nucleons is not known exactly.



i> Nuclear forces are negligible, when distance between nucleons is more than 10 fermi.

ii> Nuclear forces do not obey Inverse Square law.

iii> ~~The~~ When distance between nucleons becomes less than 0.8 fermi, the nuclear forces become strongly repulsive.

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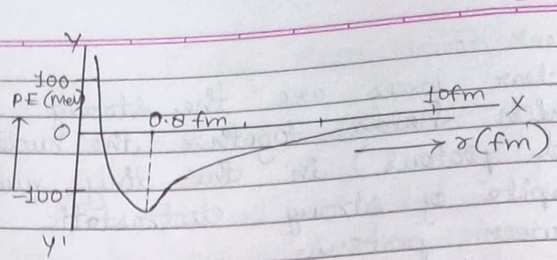


Above graph shows a rough plot of potential energy between a pair of nucleons with distance (r) between them.
The P.E. is minimum at a distance, $r_0 = 0.8$ fm. At this distance, force between nucleons is zero. For distances larger than 0.8 fm, negative P.E. goes on decreasing. The nuclear forces are attractive. For distances less than 0.8 fm, negative P.E. decreases to zero and then becomes positive. The nuclear forces are repulsive.

5) The nuclear forces show saturation properties, i.e., each nucleon interacts with its immediate neighbours only.

6) The nuclear forces are dependent on spin or angular momentum of nuclei.

7) Nuclear forces are non-central forces. This shows that the distribution of nucleons in a nucleus is not spherically symmetric.

Nuclear forces are the strongest attractive forces between nucleons which are independent of charge, are short range, non-central, non-conservative forces, not obeying inverse square law.

Nature of Nuclear Forces.
Yukawa in 1936 postulated that "nuclear forces between nucleons arise on account of continuous exchange of particles called mesons between the nucleus.
Later on, these particles were detected experimentally. They were found to have a mass about 270 times the mass of an electron. Three types of ~~el~~ mesons were detected.
(i) Mesons carrying no charge were called neutral pi meson (π^0).
(ii) Mesons carrying unit positive charge each were called positive pi meson (π^+) and,
(iii) Mesons carrying unit negative charge each were called negative pi meson (π^-).

According to meson theory or Yukawa theory of nuclear forces,
i> All nucleons consist of identical cores surrounded by a pulsating cloud of π meson.
ii> Mesons or pions may be neutral (π^0) or carry either charge (π^+ or π^-).
iii> The difference between a proton and a neutron is essentially in the composition of their respective meson clouds.
iv> The force between neutron and proton is due to exchange of charged meson between them, i.e.,

$$p^+ + \pi^- = n^0$$
$$n^0 + \pi^+ = p^+$$

Thus, proton and neutron continuously exchange their nature by absorbing and emitting π mesons. Thus,

$$n^0 \longrightarrow p^+ + \pi^- \text{ and } p^+ \longrightarrow n^0 + \pi^+.$$

v> The forces between a pair of neutrons or a pair of protons are the result of the exchange of neutral meson (π^0) between them, i.e.,

$$p \longrightarrow p' + \pi^0 \quad \text{or} \quad p + \pi^0 \longrightarrow p'$$
$$n \longrightarrow n' + \pi^0 \quad \text{or} \quad n + \pi^0 \longrightarrow n'$$

In both the cases, a proton or a neutron is converted into a new state after emitting or absorbing the π^0 meson.
Thus, exchange of π meson between nucleons keeps the nucleons bound together. It is responsible for nuclear forces.

Nuclear isn't a fundamental force of nature. It is a secondary effect of the strong force that binds quarks together to form neutrons and protons. Infact, when protons and neutrons are subjected to collisions at energies of many GeV ($= 10^9$ eV), their behaviour is explained by assuming that neutrons and protons are made up of quarks. Like electrons, quarks are thought to be indivisible.

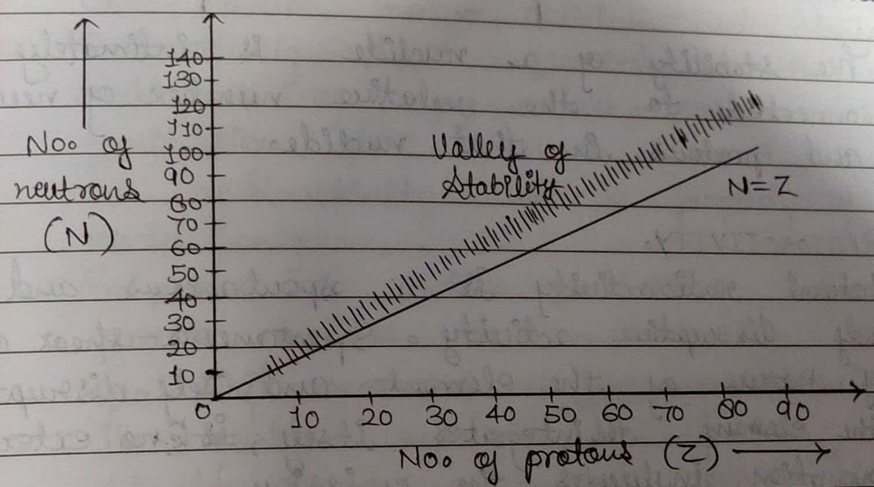
Nuclear Stability.
The very large repulsive electric forces between protons should cause the nucleus to fly apart. Nuclei are able to stay ~~s~~ together through nuclear force.

There are 2500 different nuclides. Out of which 280 are stable and rest unstable.

Nuclear stability depends on:-

i) The stability of a nucleus is determined by the value of its b.e. per nucleon. Higher the B.E./nucleon, more stable is the nucleus.

ii) The stability of a nucleus is also determined by its neutron to proton ratio.
Light nuclei are stable only if they contain about the same number of protons and neutrons. Heavy nuclei, on the other hand, are stable only when they have more neutrons than protons. Thus, heavy nuclei are neutron rich compared to lighter nuclei. This is as if neutrons help to stabilize a nucleus.



More the no. of p^+ in the nucleus, greater is the electrical repulsive force between them. ∴, more neutrons are needed to provide the strong attractive forces necessary to keep the nucleus stable. The long narrow region in which contains the cluster of short lines representing stable nuclei is referred to as the valley of stability.

iii> The stability of a nuclide is also determined by the consideration whether it contains an even or odd no. of protons and neutrons.

Even/odd no. of protons and neutrons in stable nuclei :—

No. of stable nuclei	No. of protons (Z)	No. of neutrons (N)
165	even	even
57	even	odd
53	odd	even
6	odd	odd

The stability of a nuclide is intimately connected to the relative number of neutrons and protons in that nuclide.

RADIOACTIVITY.

Natural radioactivity is a spontaneous and self disruptive activity. Spontaneous – sheer out of nature of the element and self disruptive – the element disintegrates itself; ~~it~~ i.e. no external provocation influences the emission.

Radioactivity is, therefore, the property by virtue of which a heavy element disintegrates itself without being forced by any external agent to do so.

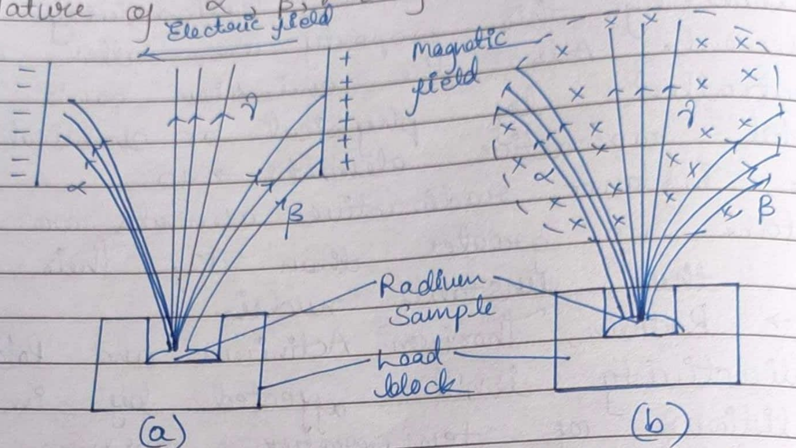
The phenomenon was discovered by a French physicist, Henry Becquerel in 1896. He observed that Uranium salts possessed a peculiar property of affecting a photographic plate even when the

plate was in a light proof package. This, he though, must be due to certain active radiations emitted by uranium salts. These radiations were called Becquerel rays. The phenomenon of emission of active radiations by an element was termed radioactivity. The element exhibiting this property was called radioactive element. Also, the emission can't be controlled by physical or chemical means.
Total radioactive elements → 40.
for instance, radioactive elements are having atomic no. greater than 82. Their nuclei are thus, unstable nuclei.
Ex → Radium, Thorium, Actinium and Polonium, etc.
Radioactivity isn't affected by imposed conditions of temperature, pressure, chemical combination, etc. Therefore, e^- aren't responsible.
The radioactivity must be property of heavy nuclei only.
Emission of active radiations indicates that parent nucleus is unstable.
Stability decreases as we move to heavier nuclei.
The mutual repulsion of protons reduces the binding effect of nuclear forces. This is the main cause of relative instability of heavy nuclei.
Radioactivity results from this instability.

Three types of radiations :—
One kind of radiations with least penetrating power (i.e., the one which would stop first) named α-rays.
The other kind with a comparatively larger penetrating power was called β-rays.

The last kind with maximum penetrating power was called γ-rays. All three types need not necessarily be emitted by one radioactive element.

Nature of α, β, γ rays :—



The α-rays are deflected through smaller angle towards the negative plate. The β-rays are deflected through larger angles towards the positive plate. The γ-rays remain undeflected.
It's concluded that α-rays consist of a stream of positively charged particles, where β-rays consists -ve. γ-rays could be waves or ~~undeflect~~ uncharged particles.
γ-rays have no mass so they were waves.
Same results on magnetic field.