Nucleus & Radioactivity

Isotopes

The atoms of same element whose nuclei have the same atomic number Z, but differ in their mass number A, are called the isotopes.

Eg. $_1H^1$, $_1H^2$, $_1H^2$

$_6C^{12}$, $_6C^{13}$, $_6C^{14}$

Neutron

Discovered by James Chadwick, English physicist in 1932, was awarded Nobel prize.

Produced by bombarding beryllium with α

$${}_{2}He^{4} + {}_{4}Be^{9} \longrightarrow {}_{6}C^{12} + {}_{0}n^{1} + Q.$$

Zero charge and mass greater than proton (collapsed H- atom - At extreme temperature and pressure the electron of the H atom was forced towards proton . Before the electrons bangs into the proton , it was stopped close to proton by nuclear energy .)

Properties

i. Fundamental particle in the atom except H-atom

ii. No charge and not deflected in E and B

iii. High penetrating power and low ionising power

iv. In free state , it is unstable and decays to p + β + $\bar{\upsilon}$

v. Spin ½ particles.

Classification of Neutrons

Classified according to their Kinetic energy.

i. Slow neutrons : 0 to 1000 eV . They are in thermal equilibrium with the medium through which they pass and are called thermal neutrons.

ii. Fast neutrons : 0.5 to 10 MeV . When pass through material , they are slowed down by collisions with the nuclei of the material and lose a part of their energy. Materials rich in hydrogen are very efficient in slowing down, are called moderators. Cd is a good absorber.

Isobars

Atoms of different elements having the same mass number, but different number of protons (atomic number) .

Eg: $_{18}Ar^{40}$ and $_{20}Ca^{40}$

$_{12}Mg^{24}$ and $_{11}Na^{24}$.

Isotones

Nuclei having equal no. of neutrons.

Eg. $_6C^{14}$, $_7N^{15}$, $_8O^{16}$

Isomeric nuclei or isomers.

Nuclei having same Z and A, but different from one another in their nuclear energy states and exhibits differences in their internal structure.

They are distinguished by their different life times.

Mirror Nuclei

Same A, but with proton and neutron number interchanged.

Eg. $_4Be^7$ and $_3Li^7$

Nuclear size

Smallest value of distance of closest approach is found to be 10^{-14} m to 10^{-15}m which is nuclear radius .

Formula for nuclear radius is

$R = r_o A^{1/3}$ where r_o = 1.3 fm

Atom size is 10,000 time nucleus

Atomic mass unit (a.m.u)

1a.m.u is equal to 1/12th mass of one $_6C^{12}$ atom.

12 $\times 10^{-3}$kg C contains 6.023 $\times 10^{23}$ atoms

1amu or 1u = 1.660 x 10^{-27}kg

Using $E = mc^2$ 1u ≡ 931MeV

Mass of proton = 1.007276 amu

Mass of neutron = 1.008665 amu

Nuclear mass

Expected mass of nucleus is sum of the mass of protons and neutrons present in it

$= Zm_p + (A-Z)m_n$.

Exptl value of nuclear mass is less than this expected value.

Mass defect Δm

Real nuclear mass $< Zm_p + (A-Z)m_n$.

Difference b/w real mass of nucleus and expected mass is called mass defect.

Nuclear density

Nuclear mass = A m_N

A – mass no.

mass of nucleon= 1.67 x 10^{-27}kg

Nuclear volume = (4/3) πR3

= (4/3) π $\{r_o A^{1/3}\}^3$

ρ_N = m_N / (4/3) πr_o^3

= 1.816 x 10^{17}kg/m^3.(≈ white dwarfs)

Binding energy

Energy equivalent to mass defect.

When nucleus is formed mass defect is converted into energy ($= \Delta mc^2$).

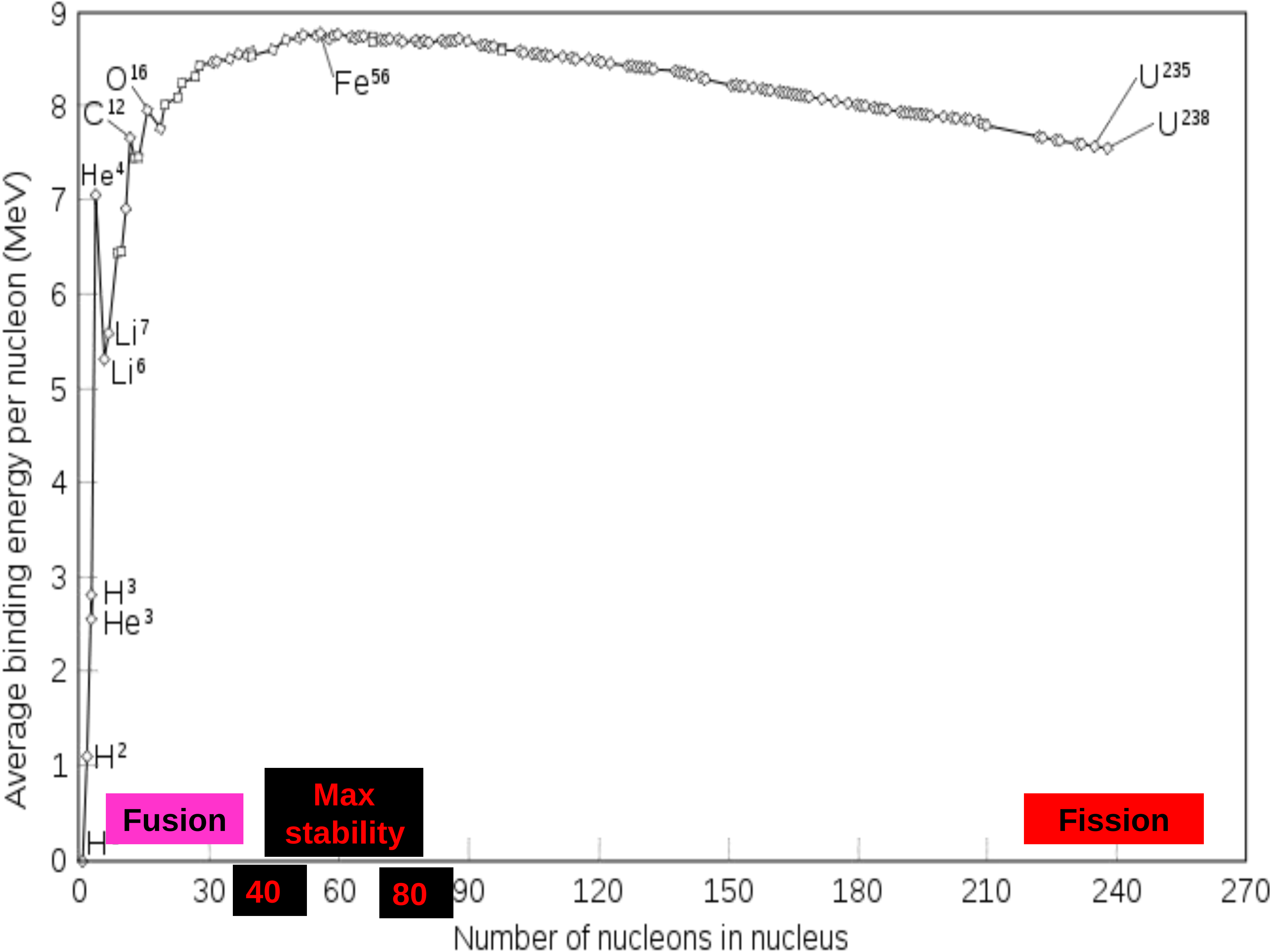
To disrupt a stable nucleus into its constituent protons and neutrons, miniumum energy required =B.E.

ie.if B.E is more,nucleus more stable

B.E /nucleon and Packing fraction .

B.E / nucleon = B.E / mass number

Packing fraction = $\Delta m / A$



Average binding energy per nucleon (MeV)
Number of nucleons in nucleus
0
1
2
3
4
5
6
7
8
9
0
30
40
60
80
90
120
150
180
210
240
270
H
H2
He3
H3
Li6
Li7
He4
C12
O16
Fe56
U235
U238
Fusion
Max stability
Fission

Discussion of graph

i. B.E/A increases with A and after attaining a flat max, it decreases.

ii. Max for intermediate (A) nuclei, (nucleons are most tightly bound)

iii. At multiple of 4 (4,8,12,16 …) shows sudden rise.

iv. B.E/A is 8MeV for nearly all elements except very light (fusion)and heavier (fission) elements.

Reason for variation in B.E

B.E is due to interaction of nucleons.

Surface nucleons B.E is less.

Surface to Volume ratio is greater for light nuclei (surface nuclons more in no)

Electrostatic repulsion introduce –ve BE which increases as the square of no. of protons, which is the reason for reductio in B.E of heavy nuclides.

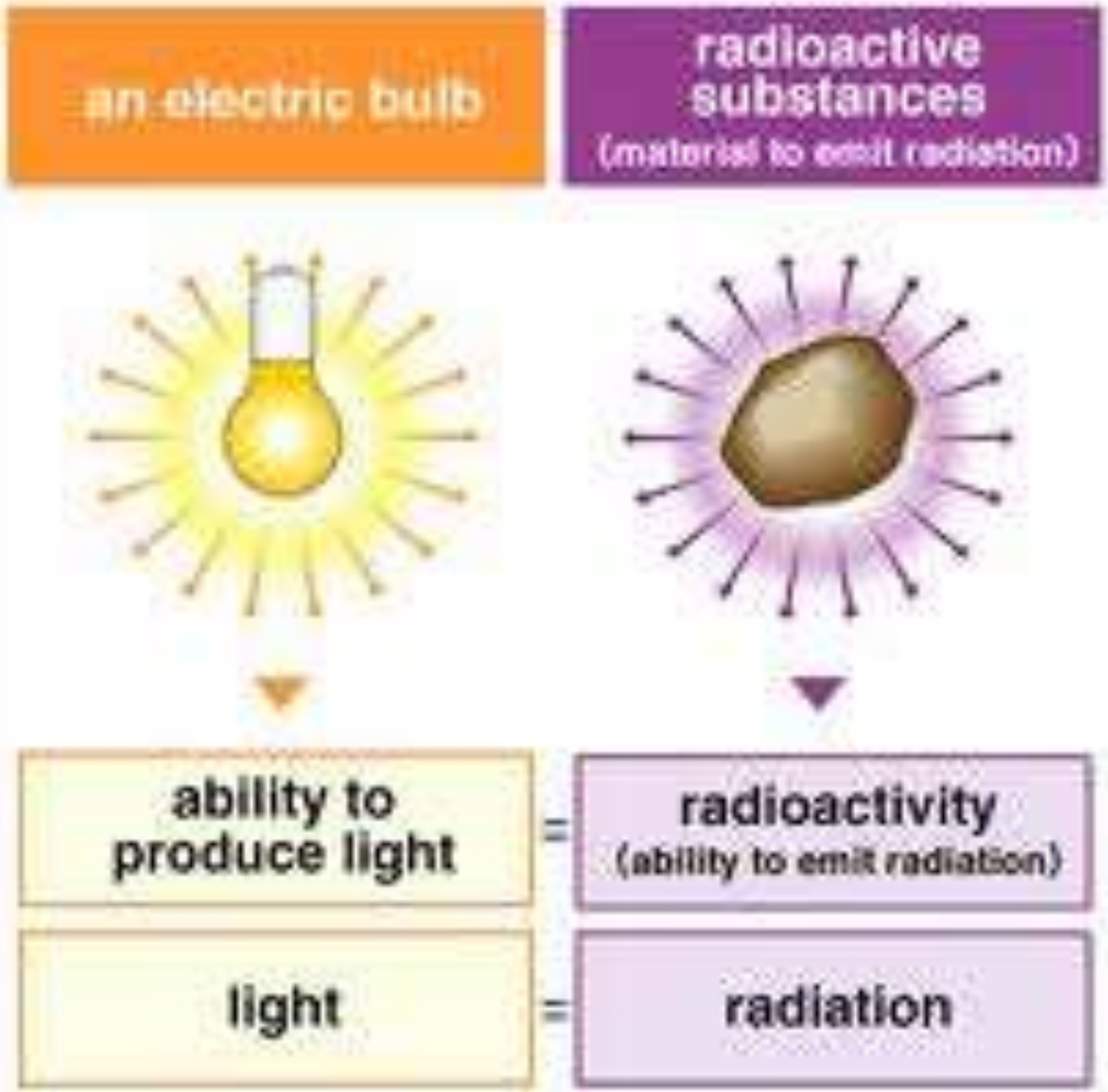
Balance of the 2 is seen in middle range

Significance of average B.E /nucleon =8MeV

It explains saturation nature of nuclear force.

One nucleon does not interact with all other nucleon but only with certain no which gives saturation

Note: if a nucleon was interacting with all other nucleons, B.E/nucleon would have increased linearly with A.



an electric bulb
radioactive substances
(material to emit radiation)
ability to produce light
=
radioactivity
(ability to emit radiation)
light
=
radiation

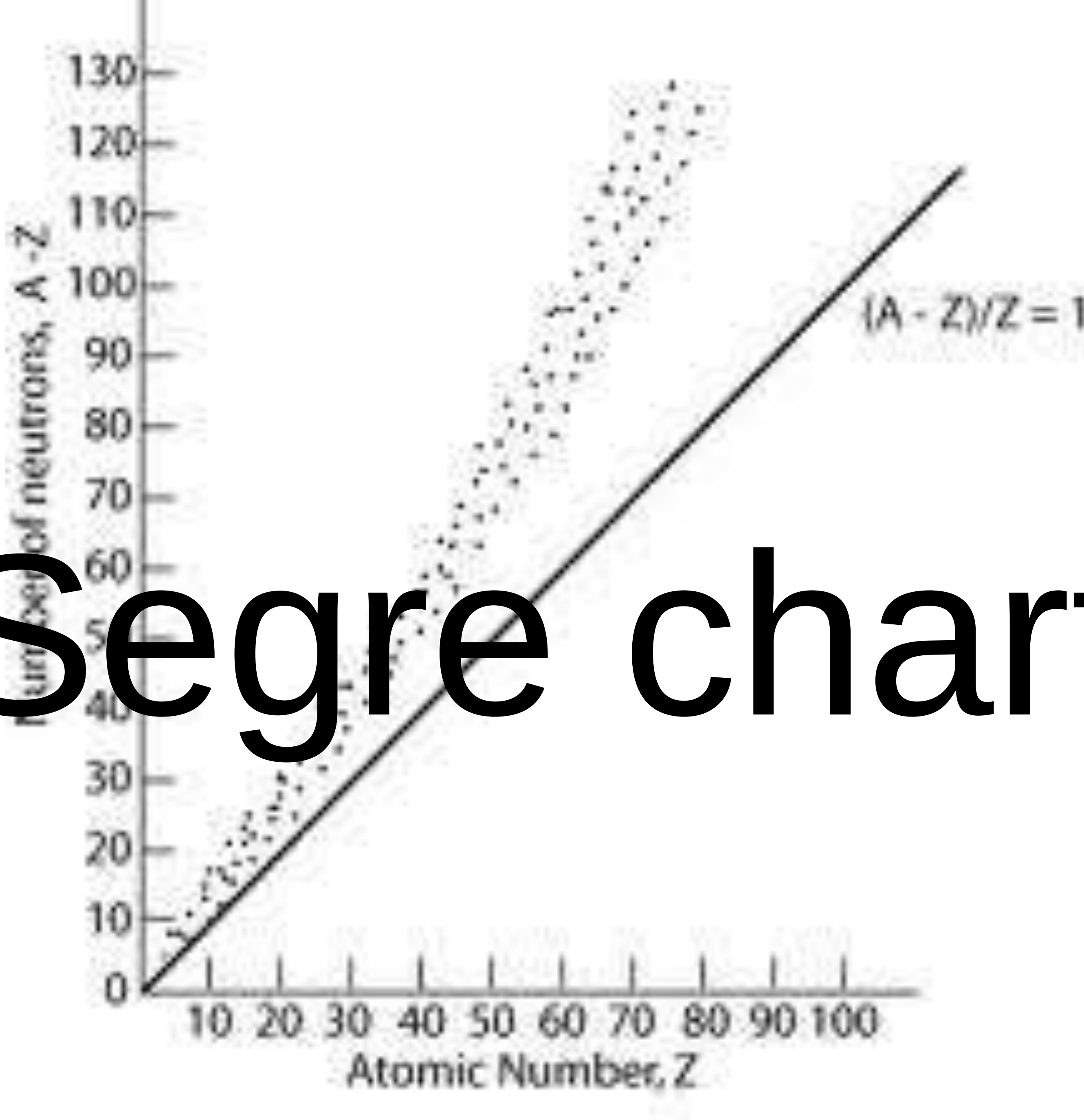

CAUTION
RADIOACTIVE
MATERIALS

What is radioactivity? Name two radioactive substances?

Phenomenon of spontaneous emission of powerful radiations from the nucleus of heavy elements.

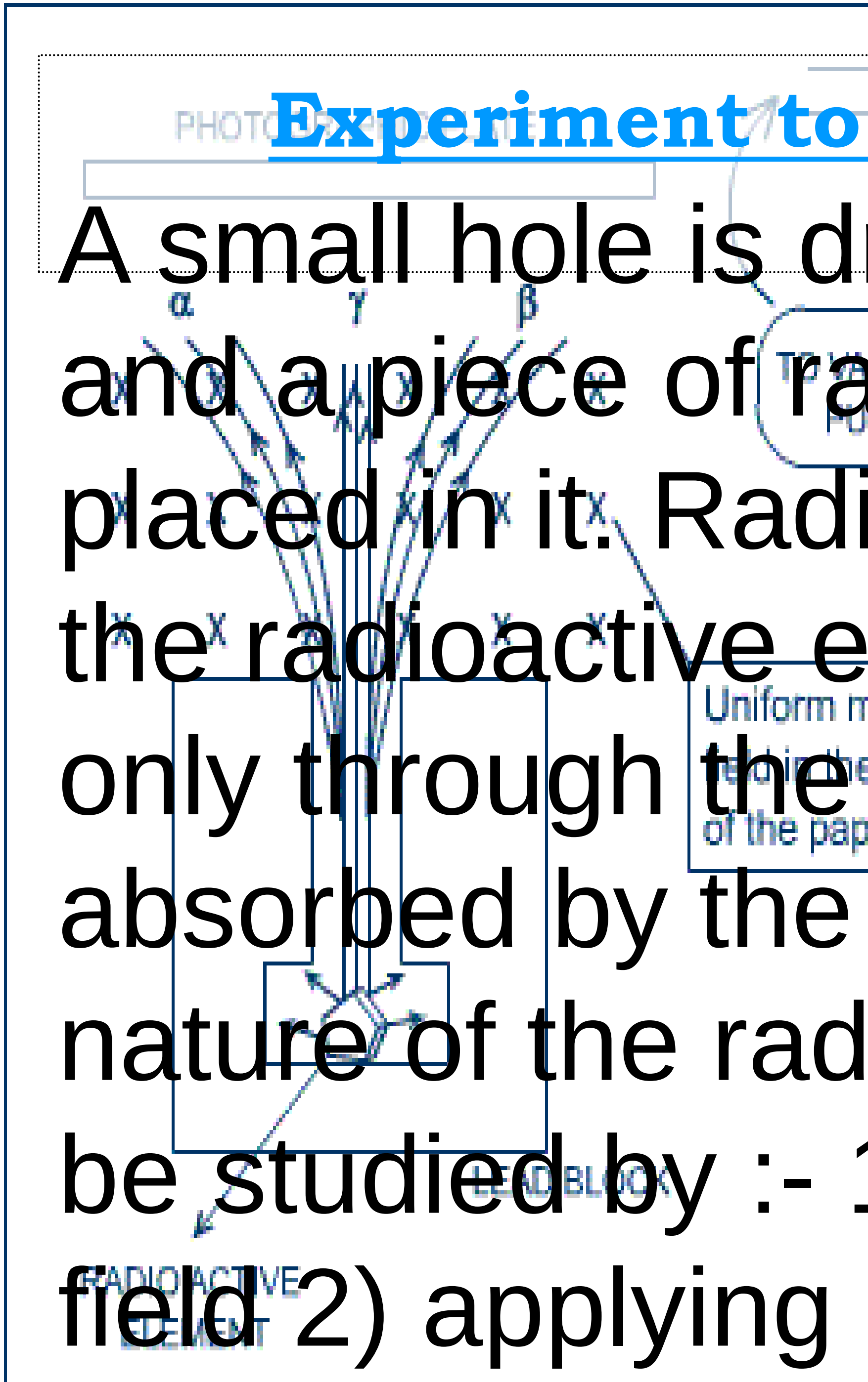
Radioactive elements : uranium, Thorium, Radium and Polonium

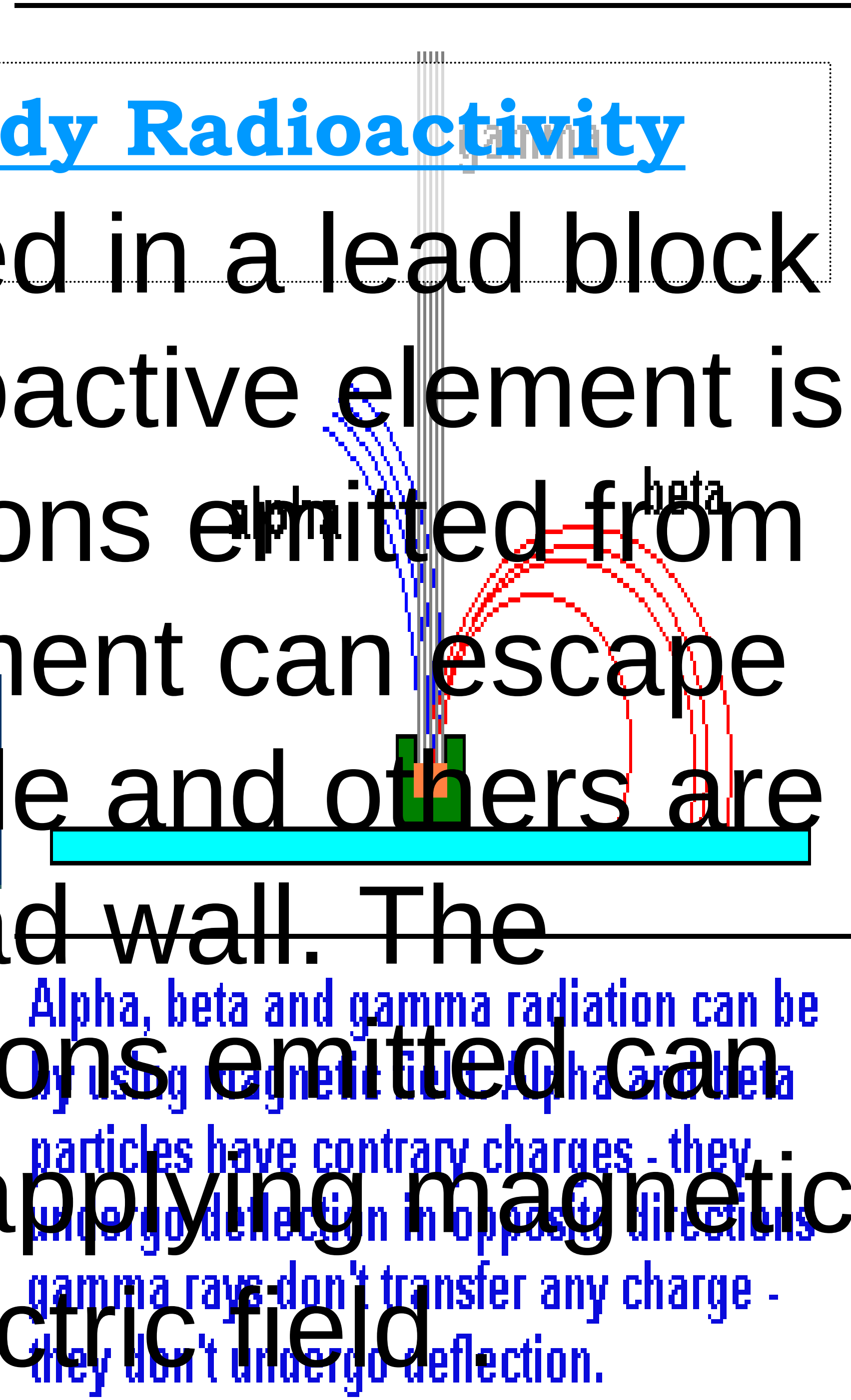
Segre chart



Number of neutrons, A - Z
130
120
110
100
90
80
70
60
50
40
30
20
10
0
(A - Z)/Z = 1
10 20 30 40 50 60 70 80 90 100
Atomic Number, Z

Experiment to study Radioactivity





A small hole is drilled in a lead block and a piece of radioactive element is placed in it. Radiations emitted from the radioactive element can escape only through the hole and others are absorbed by the lead wall. The nature of the radiations emitted can be studied by :- 1) applying magnetic field 2) applying electric field.

Uniform B is applied perpendicular to plane of the screen .

Radiations splitted into 3 parts.

Fleming's Left Hand Rule

Ray bends towards left is α - particle, the ray bends towards right in a semi-circle is β - particle and the ray goes in a straight undeflected is gamma ray.

Electric field is applied

- ray deflects towards the negative plate is alpha particle
- the ray deflects towards positive plate is beta particle
- the ray which goes undeflected is gamma ray.

Range of α – particles

The distance traveled within the medium before it gets stopped or loses ionising power completely is called the range of the alpha particle in the medium .

Range depends on the nature of medium , pressure, ionisation potential of the gas and initial energy of alpha particle.

Properties of α , β and γ radiations.

SL. No.	PROPERTY	α- PARTICLE	β-PARTICLE	γ - RAYS
1.	Identification.	Nuclei of helium.	Fast moving electrons.	Electromagnetic waves of short wavelength.
2.	Electric charge.	Positive charge(+2e).	Negative charge(-e)	No charge.
3.	Rest mass.	Equal to that of helium nucleus.	Equal to rest mass of electrons.	Zero rest mass.
4.	Speed	About $(1/10)^{th}$ the velocity of light (C).	0.99 C.	Equal to C

PENETRATION OF RADIOACTIVE EMANATIONS

alpha α

beta β

gamma γ

BARRIER

5.	Penetrating power.	Smaller than that of β -particle.	100 times that of α-particle .	100 times that of β -particle.
6.	Ionising power.	Higher than that of β -particle.	$(1/100)^{th}$ of that of α- particle .	$(1/100)^{th}$ of that of β -particle..
7.	Behaviour in E and B fields.	Deflected in electric and magnetic fields.	Deflected.	Not Deflected.
8.	Photographic plate.	Affect photographic plate.	Affect.	Affect.
9.	Fluorescence.	Produce fluorescence.	Produce.	Produce.

State the penetrating range of α ,β and ν

α – 2.7 cm to 8.62cm of air

β – 5mm of Al or 1mm of Pb.

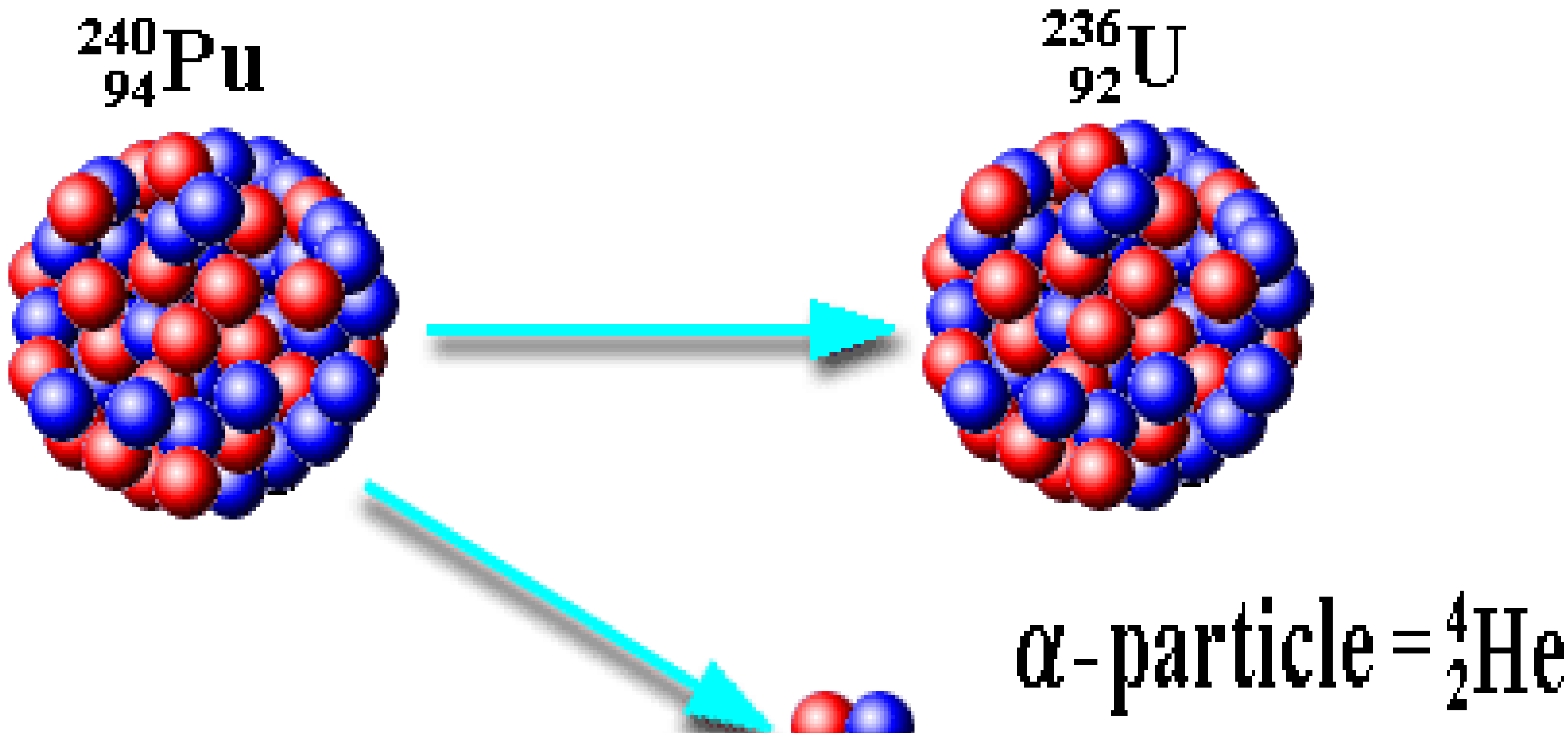
ν – 30cm of iron.

Radio activity is a nuclear phenomenon. comment

Emission of radiation from a fixed mass of radioactive substance is unaffected by chemical change or physical change like heating ,cooling, finely dividing etc.

ie. electrons outside nucleus has no role in radioactivity or it is nuclear.

Alpha Decay(α-decay)

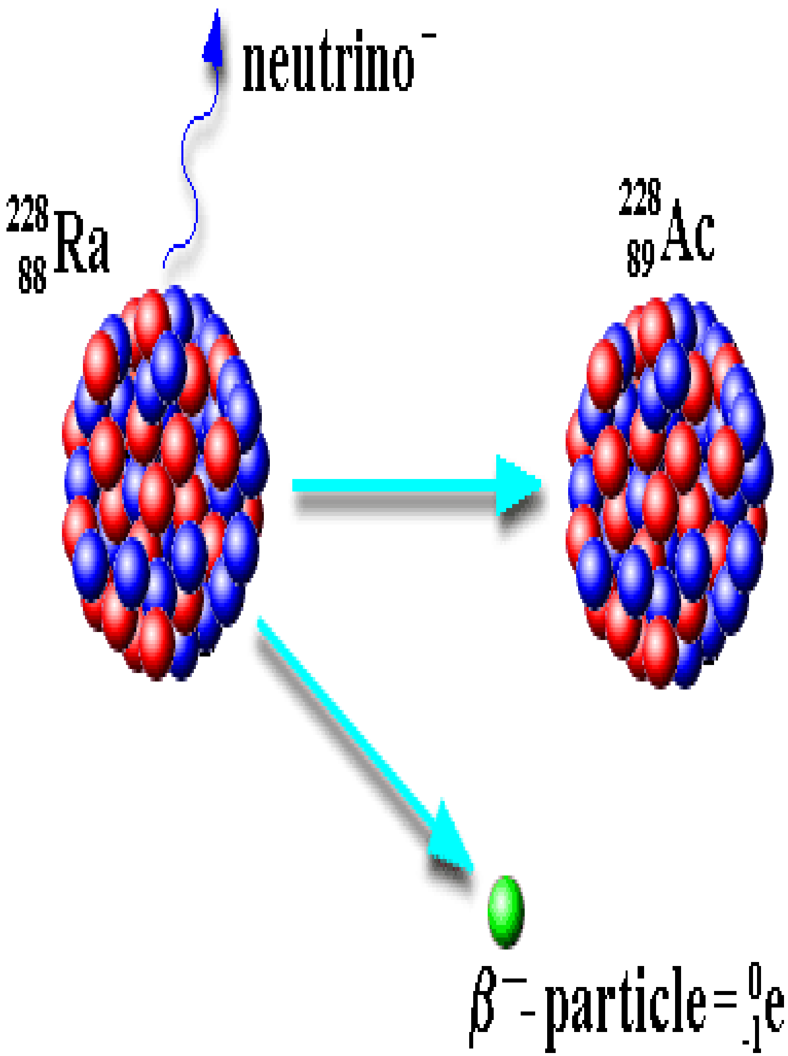


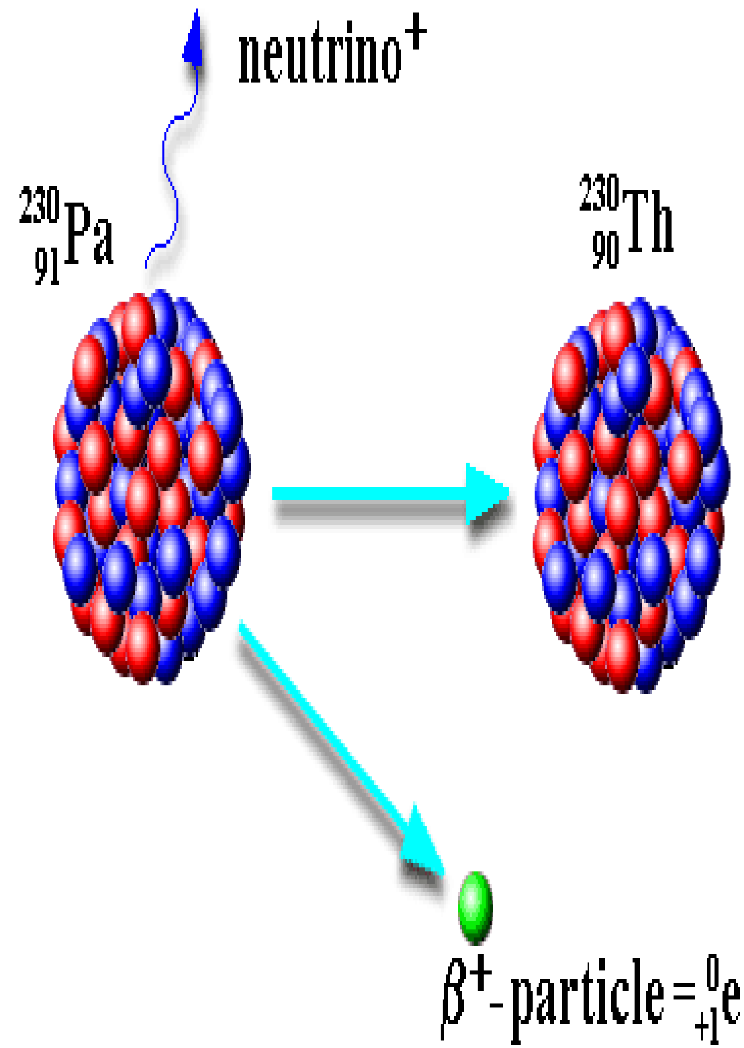
$$^{238}_{92}U \longrightarrow {}^{4}_{2}\alpha + {}^{234}_{90}Th$$

- **Unstable due to low B.E/ nucleon**
- **To achieve greater stability by reducing size, they emit alpha which has a high value of binding energy. When alpha particles are emitted the B.E/ nucleon increases**
- **Becomes more stable.**

Spontaneous Alpha Decay of a ^{239}Pu Nucleus

Beta Decay (β-decay)





β - decay

unstable due to higher or lower neutron to proton ratio, than that of a stable nucleus.

Emits β-particles and thus the neutron to proton ratio is decreased.

No electron in the nucleus. How will you account for β emission ?

Neutron is converted into a proton and an electron. When a parent nucleus X emits a β-particle, the daughter nucleus produced will have the same mass number but the atomic number will be increased by 1

$$ {}_{0}n_{1} \rightarrow {}_{1}p_{1} + {}_{-1}e^{o} + \bar{\upsilon} $$

β – decay and neutrino theory

β emission can be represented as,

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

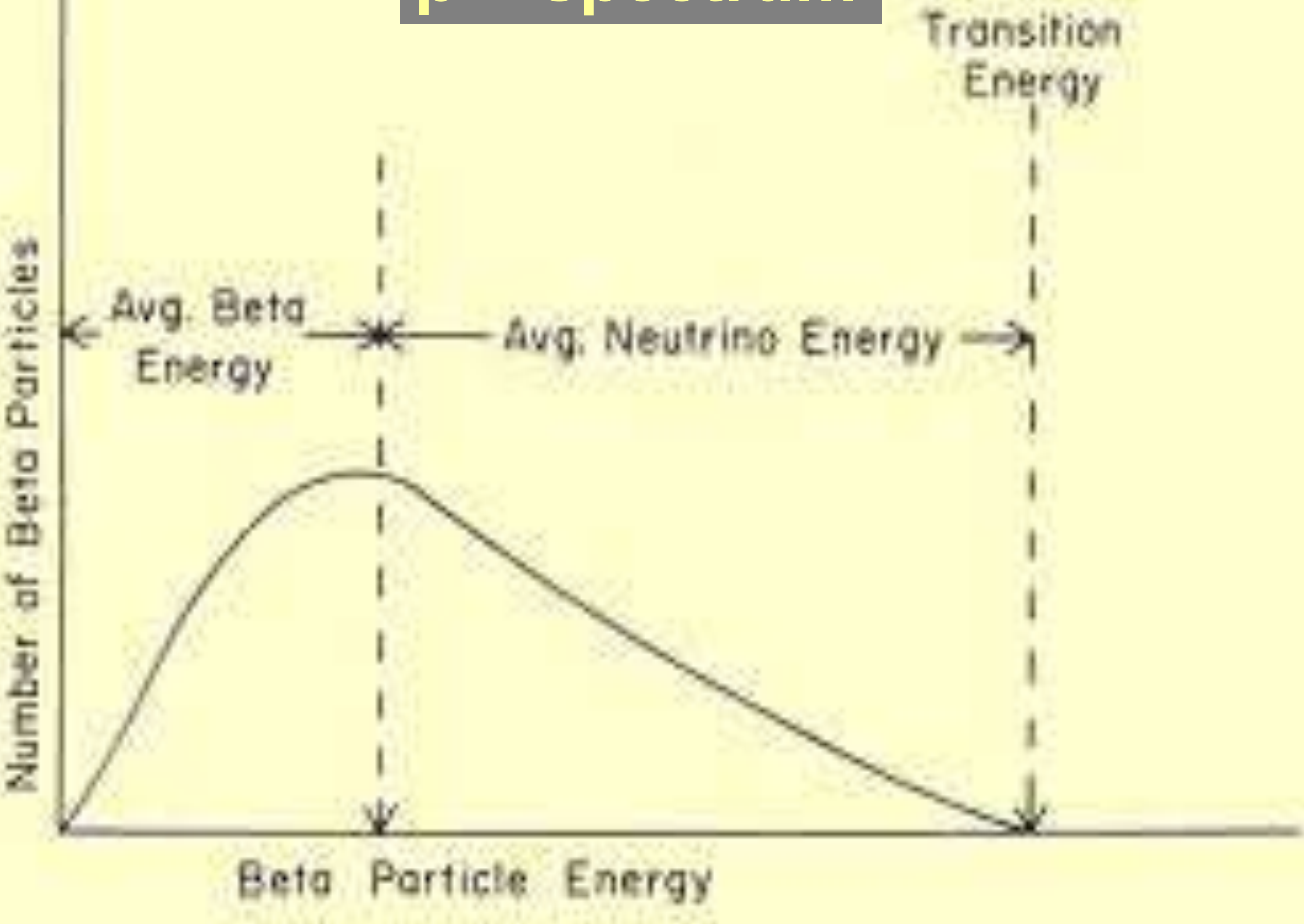
where Q is the energy released.

According to this eqn, β particles emitted must have same energy .

Magnetic sprctrograph study shows continuous β –spectrum (energy 0 to max).

(max energy of spectrum is characteristic of the radioactive atom emitting β)

β - spectrum



Transition Energy
Avg. Beta Energy
Avg. Neutrino Energy
Number of Beta Particles
Beta Particle Energy

β – spectrum and confusions ???

1. All particles from a particular radioactive sample should emit β particles having same energy. But only a few β particles are emitted with the maximum value of energy. What about remaining energy?
2. Conservation of angular momentum . How ?
3. Conservation of linear momentum?

β – spectrum and confusions ???

2. Conservation of angular momentum . How ?

How is it possible for a nucleus of even mass number and therefore integral spin give daughter of same mass and integral spin and emit electron of spin ½ $h/2\pi$? (Similarily for odd nuclei)

3. Also apparent failure of coservation linear momentum?

β – spectrum and neutrino theory

In 1930 Pauli proposed that if an uncharged particle of zero mass and spin ½ is emitted in β – decay together with electron , above discrepancies can be settled.

Particle was named neutrino. (which carries difference in energy)

There are two type of β (negatron and positron) and hence neutrino and antineutino.

Lacking charge and mass and not electromagnetic in nature , the **neutrino** can pass unimpeded through vast amounts of matter.

neutrino has to pass through over 100 light years of solid iron on the average before interacting. (can pass through earth)

Neutino theory – by Fermi

Both β and neutrino are created in the nucleus and ejected simultaneously

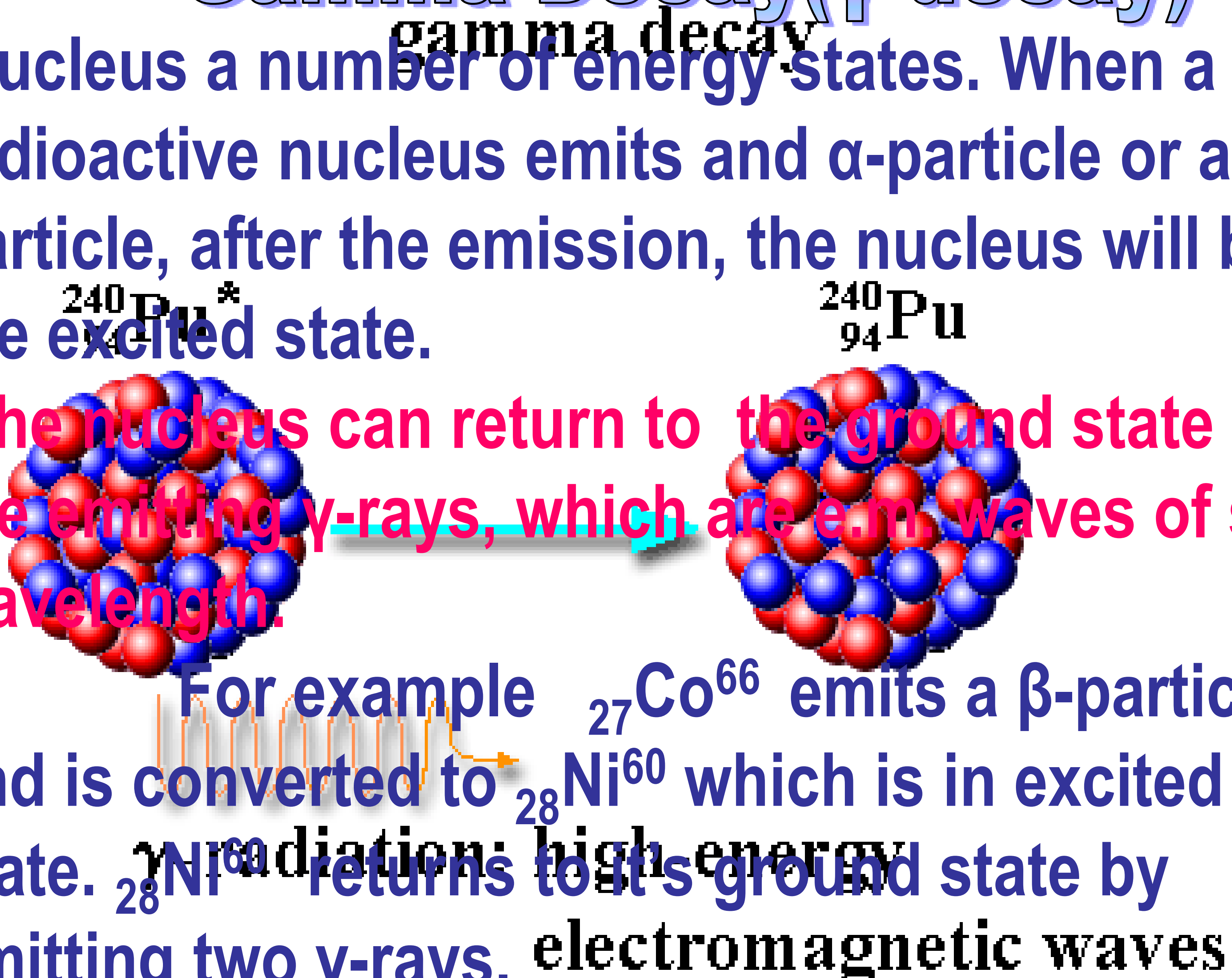
Total energy of these particles is a constant, which is the end point energy observed in the spectrum.

β carry max energy when energy of the neutrino is zero, and other cases less than maximum .

Total energy may be shared in any proportion which is the reason for continuous spectrum .

Gamma Decay(γ-decay)

Nucleus a number of energy states. When a radioactive nucleus emits and α-particle or a β-particle, after the emission, the nucleus will be in the excited state.



The nucleus can return to the ground state by the emitting γ-rays, which are e.m. waves of short wavelength.

For example $_{27}Co^{66}$ emits a β-particle and is converted to $_{28}Ni^{60}$ which is in excited state. $_{28}Ni^{60}$ returns to it's ground state by emitting two γ-rays.

SODDY FAJAN'S DISPLACEMENT LAW

- In radioactive transformations either an alpha or beta particle is emitted by the atom at one time. Never both or more than one.
- When a radioactive atom emits an alpha particle, the mass no. of the new element will be less by 4 units and atomic no. less by 2 units than those of the parent atom.
- When a radioactive atom emits a beta particle, the new atom formed has the same mass no. but the atomic no. increases by 1 .

Radioactive decay law or Rutherford and soddy theory

States that rate of disintegration is directly proportional to the total number of atoms present at that time .

Consider a sample contains N un decayed nuclei .

Let dN nuclei disintegrate in dt second.

$$dN/dt \quad \alpha \quad -N$$

-ve sign signifies that number of nuclei decreases with time .

$dN/dt = -\lambda N$ $dN/N = -\lambda dt$

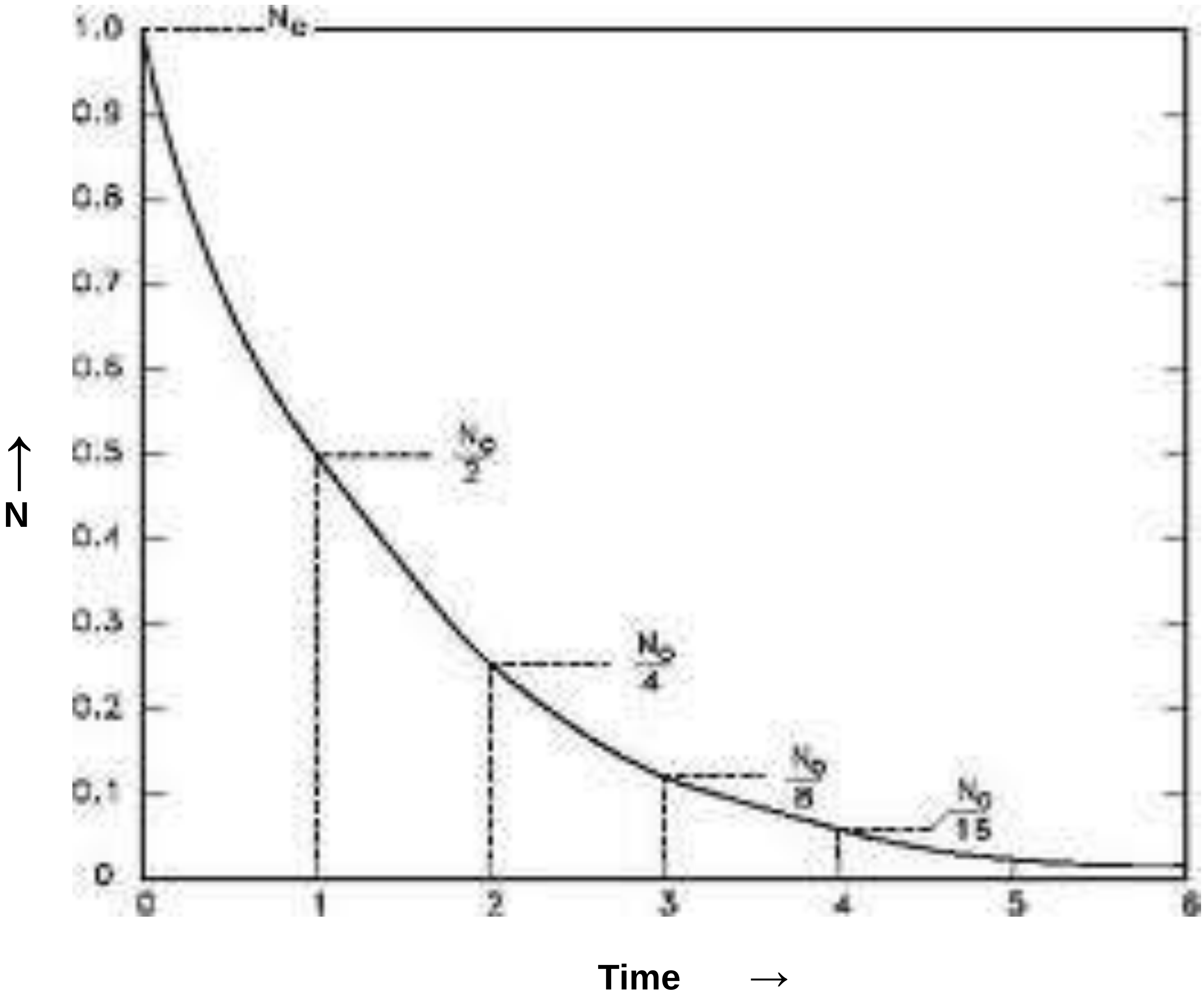
Let at time t = 0, no. of undecayed nuclei be N_0.and at time t, no. is N

$$\int_{N_0}^{N} dN/N = -\lambda \int_{0}^{t} dt$$

$$\log_e N - \log_e N_o = -\lambda t.$$

$$\text{Log}_e(N/N_o) = -\lambda t.$$

$$\mathbf{N = N_o\, e^{-\lambda t}}$$



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
N_0
$\frac{N_0}{2}$
$\frac{N_0}{4}$
$\frac{N_0}{8}$
$\frac{N_0}{15}$
0
1
2
3
4
5
6
N
Time →

Definition for decay constant

$dN/dt = -\lambda N \qquad \lambda = \dfrac{-dN/dt}{N}$

Decay constant of a radioactive substance is defined as the ratio of its instantaneous rate of disintegration to the number of atoms present (**$N = N_o e^{-\lambda t}$**)at that time .

If $t = 1/\lambda$, **$N = N_o e^{-\lambda 1/\lambda} = N_o/e$**

$= N_o/ 2.718 \quad = 0.368\ N_o.$

Radio active decay constant λ may be defined as the reciprocal of time when the number of atoms of radioactive substance decreases to 0.368 of the number present initially.

Half life $T_{1/2}$

Time at which undecayed nuclei falls to half of its original number.

$T = T_{1/2}$ $N = N_o/2$

$\mathbf{N = N_o\, e^{-\lambda t}}$ $\log_e(N/N_o) = -\lambda t.$

$\log_e N_o/2N_o = -\lambda\, T_{1/2}$

$\log_e 2 = \lambda\, T_{1/2}$

$$\mathbf{T_{1/2} = 0.693/\lambda}$$

Half life of some elements are shorter than 10^{-15}s and some as long as 10^{10}years ≈ age of universe

Average or Mean life τ

The mean of the ages of the atoms of the radioactive element is called average or mean life it is equivalent to reciprocal of decay constant λ.

τ = Total lives of all the atoms / Total no. of atoms.

$$\tau = 1/\lambda$$

$$= T_{1/2} / 0.693$$

$$= 1.44\, T_{1/2}$$

$$T_{1/2} = 0.693/\lambda$$

Let N_0 be the total no. of radioactive atoms in the beginning and N after a time t.

Let dN disintegrate b/w t and t+δt.

(if δt is very small , each of these atoms had a life of t)

Total life of dN atoms = (dN)t

Total life of N_o atoms T $= \int_0^\infty t(dN)$

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

$dN/dt = N_o e^{-\lambda t}$ omitting –ve sign as it merely indicates the decrease

$dN = N_o e^{-\lambda t} dt (-\lambda)$

Mean life = $\tau = T/N_0 = \lambda \int_0^\infty t e^{-\lambda t} dt$

Integrate by parts will give result $\tau = 1/\lambda$

Activity of radioactive substance

Is the rate of decay of the nucleus.

If N is the number of radioactive nuclei present in a sample, out of which a small fraction dN decays in a small interval dt,

Activity $A = -dN/dt = \lambda N$

$$= \lambda N_o e^{-\lambda t} = A_o e^{-\lambda t}$$

Units of Activity

SI unit – Becquerel (Bq)

1Bq = 1 disintegration /second(small unit)

Activity of a radioactive sample is said to be 1Bq , if it undrgoes one disintegration in 1sec.

1 curie (Ci) = 3.7×10^{10} Bq

1Ci = 37 GBq. (is the activity of 1g radium)

1Rutherford (Rd) = 10^{6} Bq.

RADIOISOTOPES

Isotopes of elements with atomic number less than 82, which are radio active are called radioisotopes.

They are prepared artificially. Artificial radioactivity was discovered by I.Curie and F.Joliot.

Eg. $_{27}Co^{60}$, $_{6}C^{14}$, $_{19}K^{40}$, $_{15}P^{32}$

A*l* after bombarding with α particles showed continuous emission of radiations.(even after source of alpha particles was taken away).

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

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

Radio active phosphorous differ from the normal phosphorous only in the mode of preparation .

Such isotopes prepared articficially and are radioactive are called radioisotopes.


^{131}I
^{3}H
^{51}Cr
^{111}In
^{32}P
^{35}S
^{125}I
^{14}C
^{33}P

Tracer technique or tagging

Process of deliberately adding a small quantity of radio isotope with the substance to be investigated and tracing the path of radio isotope by means of radioactive detector is known as tracer technique.

Used in medicine and agriculture

USES OF RADIOISOTOPES

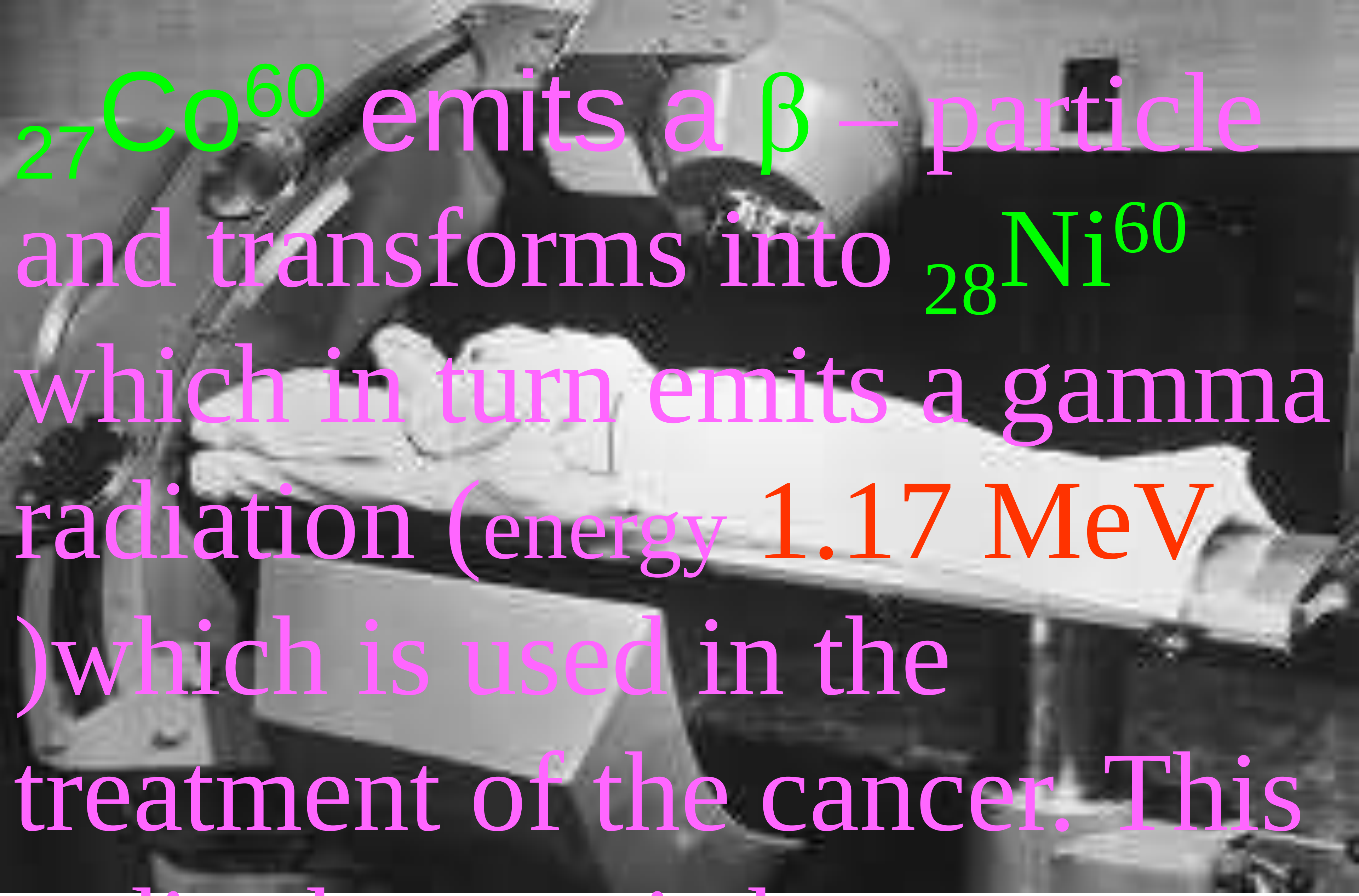
Medical

i. radiation therapy (Co-60) - to kill cells in a tumour. (inhibition of growth)

ii. Diagnosis (radio Nacl, radio Fe, radio I) - used as tracers to detect suspected brain tumour and blood clots before become dangerous.

iii. Radio cardiology (radio Nacl) to test blood circulation .

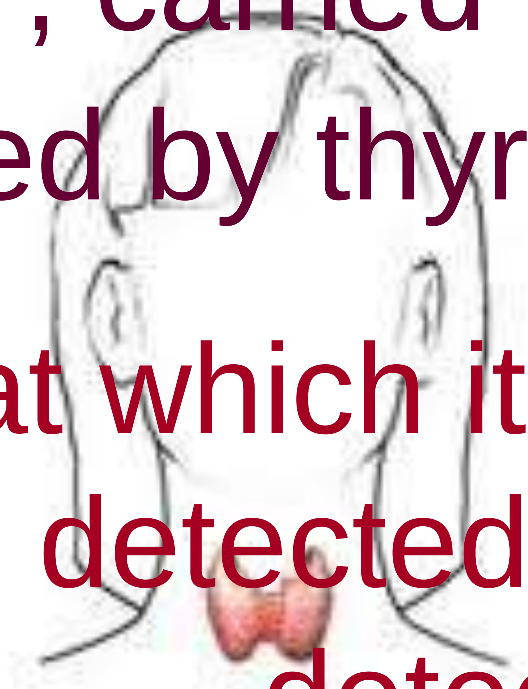
iv. Sterilisation(gamma rays)



$_{27}Co^{60}$ emits a β – particle and transforms into $_{28}Ni^{60}$ which in turn emits a gamma radiation (energy 1.17 MeV)which is used in the treatment of the cancer. This radio therapy is known as

Gamma from Co - 60

I^{131} has half life 8 days. If fed to a patient , carried by blood and collected by thyroid.



Rate at which it is collected can be detected by radiation detectors.

Radio iodine for goitre treatment

Rate of accumulation depend on the condition of the gland.

USES OF RADIOISOTOPES

Scientific

i. Projectiles for nuclear reactions (α).

ii. Radioactive tracers in agriculture

iii. Age of rocks, fossils (Carbon dating)

USES OF RADIOISOTOPES

industrial

i. Locate obstuction in gas,oil or water pipes

ii. Controll the thickness of paper, plastic sheet etc (manufacture).

iii. Radiography : γ from Co^{60} used to Check crack in welding, pipes etc.

Radio carbon dating

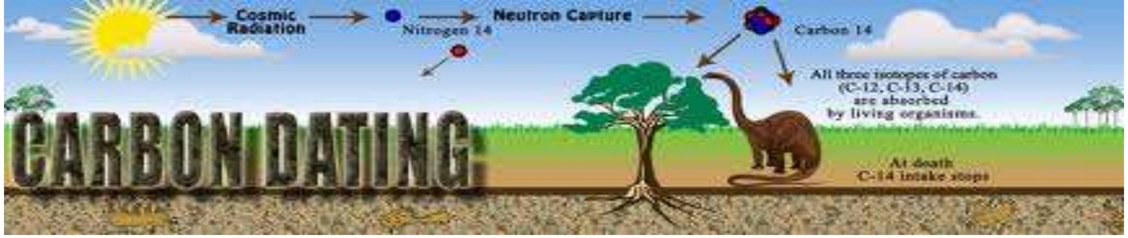
In a plant when alive, though c14 present decays, ratio of c^{14} to c^{12} remains constant due to the uptake from atmosphere.

When dies c^{14} start disintegration and ratio decreases with time exponentially.

By noting the % of c^{14} in a sample age can be determined . (half life of c14 = 5760 years)

Rock dating

- Half life of U^{238} – 5×10^9 years
- End product of series is Pb.(intermediate elements have short lives)
- In a rock after billions of years only major elements present in appreciable qty will be U^{238} and Pb.
- Relative proportion of the two in a sample enables to estimate how long back the rock contained only U^{238},gives age of rock.


Cosmic Radiation
Nitrogen 14
Neutron Capture
Carbon 14
All three isotopes of carbon
(C-12, C-13, C-14)
are absorbed
by living organisms.
CARBON DATING
At death
C-14 intake stops

Radiation measurement – 3 types.

i. Source activity – curie (Ci) = 37GBq.

ii. Exposure - rontgen (R) : one R is the quantity or exposure of radiation that produce 1.61 x 10^{15} ion pairs in 1kg of dry air at STP.

iii. Absorbed dose(rad): one rad is that amount of radiation absorbed in a material which increases its energy by 0.01joule /kg.

rad / day	Effect
0 - 25	No observable effect.
25 – 50	Possibility of slight blood changes.
50 - 100	Vomiting, fatigue, loss of apetite, moderate blood changes etc.
100 – 200	Vomiting , severe blood changes accompanied by hemorrhage etc
200 – 400	Chances of permanent damage in the body .
400 – 600	50% chance of death. Survivors to suffer permanent damage.
600 and more.	100% death !!!.......

Biological effects of nuclear radiations – 2 types

Radioactive radiations (α, β and γ cause ionisation and excitation of atoms of living cells due to which living cells are altered or destroyed.

1. Somatic effects (short term recoverable and long term irrecoverable)
2. Genetic effects (later generations)

Safety precautions at Nuclear plants.

i. Reactors in thick concrete walls to prevent gamma or neutrons.

ii. Nuclear materials in thick lead containers with narrow mouth (plug).

iii. Lead lined aprons and gloves.

iv. Handle with mechanical tongs.

v. Wear badges and periodic checking.

vi. Periodic compulsory check up