SENIOR SIX TERM 3

TOPIC 3/3: NUCLEAR PROCESSES

Competency: The learner appreciates that nuclear reactions involve high amounts of energy which can be both constructive and destructive.

Radioactivity

This is the spontaneous disintegration of unstable atoms with emission of particles like alpha, beta particles and gamma radiations.

The nuclei of some elements like uranium, thorium are unstable undergo radioactive decay in order to gain stability.

The three types of radiations can be identified by:

(i) Their different penetrating powers/abilities
(ii) Their ionizing powers
(iii) Their behavior in electric and magnetic fields.

Alpha – particles, ^4_2He

- They are the least penetrating with a range of a few centimeters in air and can be stopped by paper.
- They produce intense ionization in any gases through which they pass.
- They are deflected by both electric and magnetic fields.
- Their direction and size of deflection suggests that:
  i) They are positively charged
  ii) They are relatively heavier particles.
- Alpha particles are therefore a Helium nuclei containing 2 protons and 2 neutron

Beta – particles

- They are more penetrating than the alpha particles with a range of several centimeters in air and a few millimeters in aluminum.
- They are less ionizing than the alpha particles.

- They are more easily deflected than the alpha – particles, and their size and direction of deflection suggest that:
  i) They are negatively charged
  ii) They have a very small mass

Gamma rays

- They are highly penetrating
- They ionize gases to a very small extent
- They are not deflected by both the magnetic and electric fields, indicating that they are uncharged.

Rules governing radioactivity

1. When a radioactive substance decays by emission of alpha particle, its atomic number A reduces by 2 and it mass number Z reduces by 4
   i.e. ${}_{A}^{Z}X \rightarrow {}_{A-2}^{Z-4}Xy + {}_{2}^{4}He$
2. When a radioactive substance decays by emission of beta particle, its atomic number A increases by 1 and it mass number Z remains constant
   . ${}_{A}^{Z}X \rightarrow {}_{A+1}^{Z}Xy + {}_{-1}^{0}e$
3. When a radioactive substance decays by emission of gamma rays, both its atomic number A and it mass number Z remains constant
   ${}_{A}^{Z}X \rightarrow {}_{A}^{Z}Y + \gamma$

The decay law

It states that the rate of disintegration of the nuclei in a given time is propotional to the number of atoms present

Rate of decay,R = $-\lambda \frac{dN}{dt}$

where N- number of atoms present, t = time, λ is a constant and negative because the number of atoms are reducing

The decay law can also be xpressed as

$N = N_0e^{-\lambda t}$

where No is the intial number of disintegrating atoms.

The decay constant is the fractional number of atoms that are disintegrating per second

Half-life ($t_{½}$) is the time taken for the number of atoms in a radioactive element to reduce to half the original value.

From $N = N_0e^{-\lambda t}$

In $\frac{N_0}{N}$ = λt

At t = t ½ ; N = $\frac{N_0}{2}$

⇨ In $\frac{N_0}{N/2}$ = λt½

⇨ t½ = $\frac{In\ 2}{\lambda}$ = $\frac{0.693}{\lambda}$

Activity is the rate of dsintegration of a radioactive substance = λN

Example 1

A sample of radioactive material initially contains 10^{18} atoms. If the half-life of the material is 2 days, calculate the

(i) number of atoms remaining after 5days

$\lambda = \frac{0.693}{t_{\frac{1}{2}}} = \frac{0.693}{2} = 0.3465s^{-1}$

N = $10^{18}e^{-0.3467\ x\ 5}$ = 1.7684 x 10^{17}

(ii) percentage that decayed after 5days

Number of decayed atoms = $N_0 - N$

Percentage decayed = $\frac{N_0 - N}{N_0}\ x\ 100\%$ = $\frac{10^{18} - 1.7684\ x\ 10^{17}}{10^{18}}$x100% = 82.32%

(iii) activity of the sample after 5days

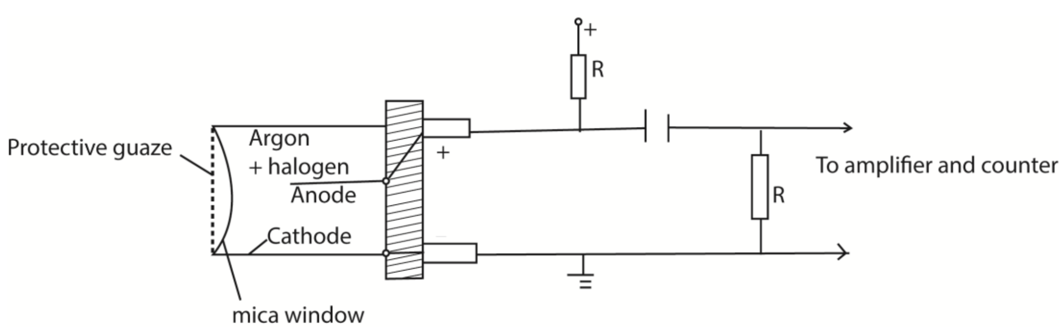
Activity, A = λN = 0.3465 x 1.7684 x 10^{17} = 6.127506 cx 10^{16}

Radioactive detector

A. Geiger Muller Tube (GMT)

The GMT is used to detect the presence of X- rays, Gamma rays, beta particles and if the window of the tube used is very thin, it detects even alpha particles.

Structure



The thin mica window allows the passage and detection of the weak penetrating alpha particles. The GM tube is first evacuated then filled with Neon, Argon plus Halogen gas which is used as a quenching agent.

Mode of operation

Mode of operation

- When an ionizing particle enters the tube through the window, argon atoms are ionized.

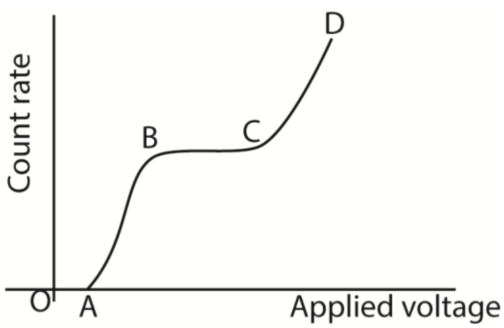
- The electrons move to the anode while the positive ions drift to the cathode.
- A discharge occurs and the current flows in the external circuit.
- A p.d is obtained across a large resistance, R which is amplified and passed to the scale.
- The magnitude of the pulse registered gives the extent to which ionization occurred.

Note:

- The anode wire must be very thin so that the charge on it produces an intense electric field close to its surface.
- This electric field is used to accelerate the electrons towards it from the cathode.

Characteristics of a GMT

The graph below is obtained when the counter rate is plotted against the operating voltage.



OA – the operating voltage is not enough to attract the ions to the respective electrodes and hence the counter registers no reading. This voltage (i.e. at A) is called the threshold voltage.

AB – the applied p.d not enough to attract all electrons; hence increasing the p.d increases the number of electrons being attracted and hence increase in counter rate.

BC – here the count rate is constant. This is called the plateau region.

- Between BC, all the negative ions are able to reach the anode because the operating voltage is large enough to attract them.

- Full avalanche is obtained along the entire length of the anode.

- Here the tube is said to be operating normally.

CD: - The count rate increases rapidly because the quenching process becomes ineffective and eventually a continuous discharge occurs which might damage the tube.

Definitions.

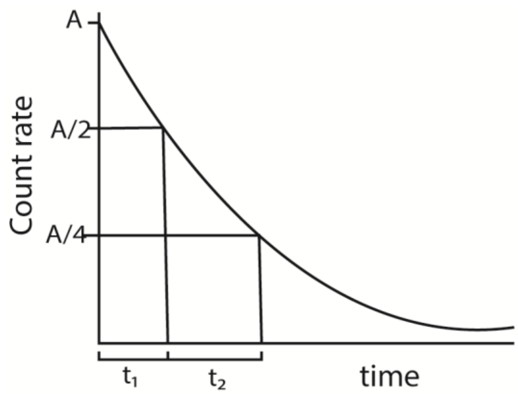
Dead time. This is the time taken by the positive ions to move from the anode to the cathode. During this time the tube is insensitive to the arrival of further ionizing particles.

Recovery time. This is the second period of insensitivity. During this period, pulses are produced but not large enough to be detected. In this time, argon ions are being neutralized by the quenching gas before they reach the anode.

Threshold voltage is the voltage below which there is no sufficient gas amplification to produce pulse high enough to be detected

Experiment to determine a half-life of radioactive substance using GM- tube

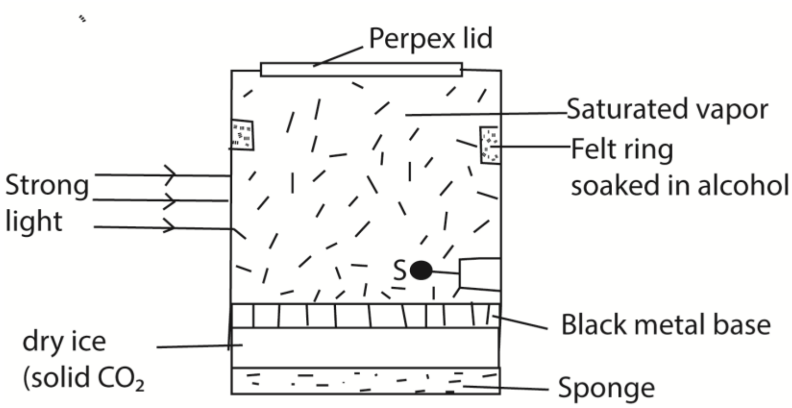
- Switch on the GM-tube, note and record the background count rate, A.
- Place a source of ionizing radiation near the GM-window.
- Note and record the count rate recorded the count rate at equal intervals.
- For each count rate recorded subtract the background count rate to get the true rate.
- Plot a graph of the count rate against time.



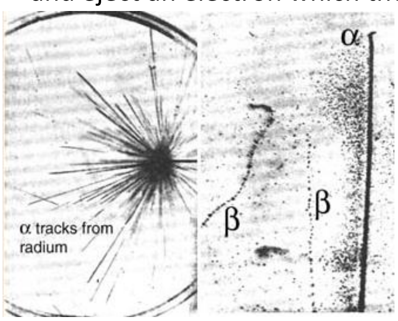
Find time t_1 taken for the activity to reduce to A/2 and t_2 taken for activity to reduce to A/4 from A/2

Half-life = $\frac{1}{2}(t_1 + t_2)$

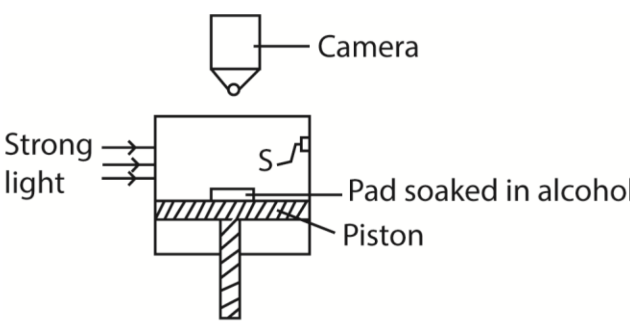
B. The diffusion cloud chamber



- The base of the chamber is maintained at low temperature, about -80^0c by the solid carbon dioxide while the top of the chamber is at room temperature, and so there is a temperature gradient between the top and the bottom of the chamber.
- The air at the top of the chamber is saturated with alcohol vapor from the felt ring. This vapor continuously diffuse downwards into the cooler regions so that the air at the chamber is super saturated with alcohol vapor.
- Radiations from the radioactive source S cause the ionization of the vapor.
- The ionizations from the radioactive source S cause condensation of the vapor on the ions formed, hence the path of the ionizing radiations are traced by series of small droplets of condensation.
- The thickness and length of the path indicate the extent to which ionization has taken place.
- Alpha particles produce short, thick, continuous straight tracks
- Beta particles which are less massive produce longer, thin but straggly paths owing to collisions with gas molecules
- Gamma radiations are uncharged and for ionization to take place, it must collide with an atom and eject an electron which then ionizes the vapor.



C. The Wilson cloud chamber



Mode of action

When the piston is quickly moved, the air in the chamber is saturated with alcohol vapour undergoes an adiabatic expansion and it cools.

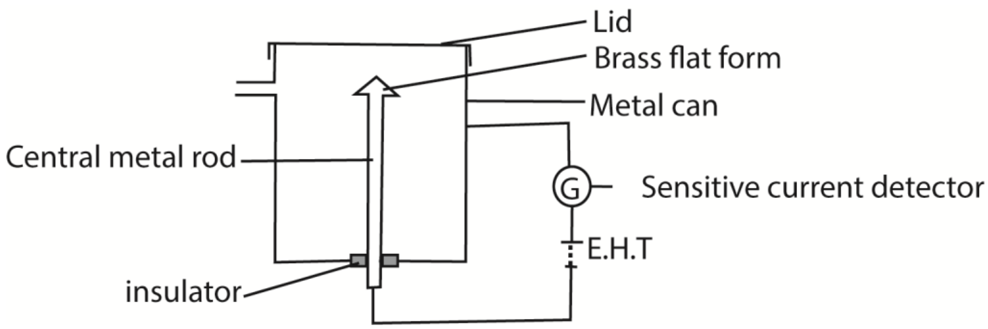
The dust particles are carried away leaving behind air which is dust free. This is the subjected to controlled expansion making it super saturated.

It is then simultaneously subjected to ionizing radiation from a source, S. the vapour condenses on the ions formed to form water droplets around the ions

These are then illuminated and photographed by the camera.

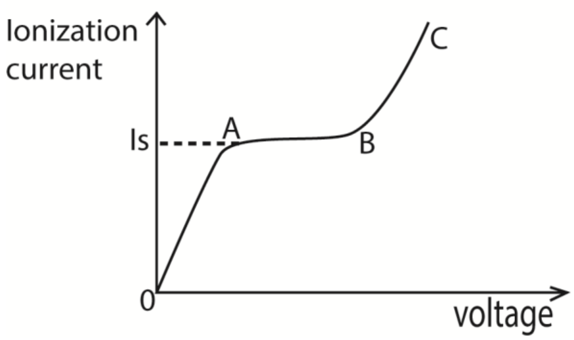
The nature of the path formed reveals the type of ionizing agent.

D. Ionizing Chamber



- A radiation source on the brass flat form causes ionization of air in the chamber producing electrons and positive ions.
- The electrons move to the metal can and positive ions drift to the central metal rod.
- Movement of the ions to the electrodes causes discharge and current pulse flows in external circuit.
- The current sensitive detector detects current.
- The magnitude of current detected shows the extent to which ionization takes place.

A graph of ionization current against voltage



Region OA:

Current detected increases gradually but p.d is not large enough to prevent recombination of the ions.

Region AB. (saturation region)

Current is almost constant, all ions reach the electrode before recombination but there is no secondary ionization.

Region BC (gas amplification)

Current increases rapidly for small increase (change) in p.d because secondary ionization takes place due to primary ions being produced. This implies many ion pairs, thus a larger current detected.

Artificial radiations

These can be produced by

- Bombarding a nucleus of stable element with neutrons in a nuclear reactor
- Bombarding a nucleus of stable element with a charged particle such as alpha or beta particles.

Uses of Radioistopes and radioactivity

In industry

- Sterilization of food
- Detecting leakages in pipes
- Determining thickness of paper
- Determining the rate of wear

In medicine

- Treatment of cance
- Tracer of disease
- Sterilizing medical equipment

Health hazards

- May cause cancers
- Eye damage
- Cause sterility
- Cause mutation

Unified Atomic Mass unit U

Definition: the Unified Atomic Mass Unit (U) is one – twelfth the mass of one atom of carbon – 12 ($^{12}_{6}c$)

Derivation

1mole of a substance contains 6.02 x 10^{23}atoms

12g of carbon-12 contains 6.02 x 10^{23} atoms

Mass of 1 atom of carbon-12 = $\frac{12\ x\ 10^{-3}}{6.02\ x\ 10^{23}}$ kg

= 12U

∴1U = 1.66 x 10^{-27}kg

But 1 kg change in mass produces 9 x 10^{16} joules and 1 Mev = 1.6 x 10^{-13}joules

$$1U = \frac{1.66\ x\ 10^{-27}\ x\ 9\ x\ 10^{16}}{1.6\ x\ 10^{-13}} = 931MeV$$

Binding energy (B)

The mass of the nucleus of atom is always less than the total mass of its constituent nucleons (protons and neutrons). The difference in mass is called the mass defect.

Mass defect = (mass of nucleons) - mass of the nucleons mass of the nucleus

The reduction in mass is because when the nucleons are combining to form the nucleus, some of the mass is released as energy in the form of gamma rays.

In order to break the nucleus and separate the nucleons, the same amount of energy which was released has to be supplied to the nucleus. This is called the Binding energy.

Definition:

Binding Energy is the minimum energy required to break the nucleus into its constituent particles and completely separate them from each other.

Binding energy = (mass defect in kg) X (speed of light)^2

Example 2

The mass of lithium ${}^{7}_{3}Li$ is 7.01818U. Calculate

(i) The binding energy of lithium atom

Solution

Number of protons = 3

Number of neutrons = 7-3 = 4

Mass of nucleons = (3 x 1.0081 + 4 x 1.009) = 7.067U

Mass defect = mass of nucleons – mass of nucleus

= 7.060 – 7.01818

= 0.04252U

But 1U= 931eV

Binding energy = 0.04252 x 931 = 39.58612eV

(ii) The binding energy per nucleon of lithium atom

Given mass of proton = 1.0081U

Mass of neutron = 1.009U

Mass of electron = 0.00055U

1U = 931eV

Binding energy per nucleon = $\frac{Binding\ energy}{mass\ number}$

$= \frac{39.58612\text{eV}}{7}$

$= 5.65516eV$

Example 3

Given that the mass of ${}^{210}_{84}Po$ = 209.992U, ${}^{206}_{82}Pb$ = 205.964U, ${}^{4}_{2}He$ = 4.02U and 1U = 931eV;

(i) State whether it is possible for ${}^{210}_{84}Po$ to undergo alpha decay.

${}^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + {}^{4}_{2}He$

Total mass on RHS = 203.964 + 4.02 = 209.984U

Since there is a loss in mass, the reaction is possible and the loss in mass in mass is the energy released.

(ii) Calculate the mass defect of the reaction

Mass defect (loss in ass = 209.992 – 209.984 = 0.008U

(iii) Find the total energy released in the above reaction

0.008U = 0.008 x 931MeV =7.448MeV

Example 4

When a fast moving neutron hits uranium, ${}^{235}_{92}U$ the nucleus breaks up into ${}^{95}_{57}Mo$, ${}^{139}_{57}La$, 2neutrons and 7electrons.

Calculate the energy released by 10grams of uranium in the reaction

[${}^{235}_{92}U$ = 235.044U, ${}^{95}_{57}Mo$ = 94.906U, ${}^{139}_{57}La$ = 138.906U, ${}^{1}_{0}n$ = 1.009U, ${}_{-1}^{0}e$ = 0.005U, 1U = 1.66 x 10-27kgJ]

Solution

${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{95}_{57}Mo + {}^{139}_{57}La\ 2{}^{1}_{0}n + 7{}_{-1}^{0}e$

Mass defect = (235.044 + 1.009) – (94.906 + 138.906 + 2 x 1.009 + 7 x 0.005)

= 0.188U

= $(0.188\ x\ 1.66\ x\ 10^{-27})$kg

= 3.1208 x 10^{-28}kg

From $E = mc^2$

Energy released = 3.1208 x 10^{-28} x $(3 \times 10^{8})^{2}$

= 2.81 x 10^{-11}J

1mole mole ${}^{235}_{92}U$ contains 6.02 x 10^{23} atoms

235g contain 6.02 x 10^{23} atoms

10g contain $\frac{6.02\ x\ 10^{23}}{235}$ = 2.562 x 10^{22} atoms

But 1 atom releases 2.81 x 10^{-11}J

∴ 2.562 x 10^{22} atoms release 2.81 x 10^{-11} x 2.562 x 10^{22} = 7.1992 x 10^{11}J

Example 5

Given that ${}^{235}_{92}U$ = 238.12492U, ${}^{234}_{90}Th$ = 234.1165U, ${}^{4}_{2}He$ = 4.0038U, 1U = 933MeV

(i) Show that the nucleus of uranium can disintegrate by releasing an alpha particle

${}^{235}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$

Total energy on the RHS = 234.1165 + 4.0038 = 238 .1203U

Since there is a loss in mass, the reaction is possible and the loss in mass in mass is the energy released.

(ii) Calculate the energy released in the process

Energy released = 238.12492 - 238 .1203

= 0.00462U

=0.00462 x 933MeV

= 4.31046MeV

(iii) Calculate the kinetic energy gained by the alpha particle.

Let Q = total energy released

Q = $K.E_{Th} + K.E_{\alpha}$

= $\frac{1}{2}m_{Th}v_{Th}^2 + \frac{1}{2}m_{\alpha}v_{\alpha}^2$ ……………………………… (i)

From conservation of momentum

Initial momentum = final momentum

$0 = m_{Th}v_{Th} + m_{\alpha}v_{\alpha}$

$v_{Th} = -\frac{m_{\alpha}v_{\alpha}}{m_{Th}}$ ……………………………………………… (ii)

Substitute Eqn. (ii) into Eqn. (i)

Q = $\frac{1}{2}m_{Th}\left(-\frac{m_{\alpha}v_{\alpha}}{m_{Th}}\right)^2 + \frac{1}{2}m_{\alpha}v_{\alpha}^2$

= $\frac{1}{2}\frac{m_{\alpha}^2v_{\alpha}^2}{m_{Th}} + \frac{1}{2}m_{\alpha}v_{\alpha}^2$

Factorize $\frac{1}{2}m_{\alpha}v_{\alpha}^2$

Q = $\frac{1}{2}m_{\alpha}v_{\alpha}^2\left(\frac{m_{\alpha}}{m_{Th}} + 1\right)$

= $\frac{1}{2}m_{\alpha}v_{\alpha}^2\left(\frac{m_{\alpha} + m_{Th}}{m_{Th}}\right)$

$\frac{1}{2}m_{\alpha}v_{\alpha}^2$ = Q$\left(\frac{m_{Th}}{m_{Th} + m_{\alpha}}\right)$

Kinetic energy gained by alpha particle

$\frac{1}{2}m_{\alpha}v_{\alpha}^2$ = Q$\left(\frac{m_{Th}}{m_{Th} + m_{\alpha}}\right)$

$= 4.31046\left(\frac{234}{234+4}\right)$

$= 4.238MeV$

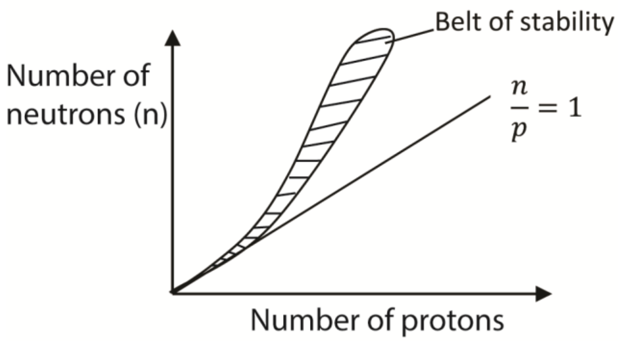
Nuclear stability

The nuclear stability depends on the number of neutrons and protons present in a nucleus.

Stability of light nucleus is most likely when number of protons = number of neutrons, e.g. ${}^{12}_{6}C, {}^{14}_{7}N$…

Stability of heavy nuclei is most likely to occur when the nucleus has more neutrons than protons, e.g. ${}^{206}_{82}Pb$.

A graph of the number of neutrons against the number of protons to show the stability zone



Unstable isotope are found below and above the stability belt. Disintegration produces new isotopes which are closer to stability belt than the original isotopes

Mode of decay

(i) the nuclei above the belt of stability are rich in neutrons and hence disintegrate in such a way that one of the neutron is converted to a proton
i.e. [$^1_0n \rightarrow {}^1_1H$ or $^1_1p + {}_{-1}^{0}e$] or such nuclei emit a β-particle.

Example
(a) $^{24}_{11}Na \rightarrow {}^{24}_{12}Mg + {}_{-1}^{0}e$
(b) $^{14}_{6}C \rightarrow {}^{14}_{7}N + {}_{-1}^{0}e$

(ii) The nuclei lying below the belt of stability are deficient in neutrons and hence disintegrate in such a way that one of their proton is converted into a neutron. The conversion can be done by any of the following two ways
(a) emission of positron: $^1_1H \rightarrow {}^1_0n + {}_{+1}^{0}e$
(b) electron capture process
$^1_1H + {}_{-1}^{0}e(electron) \rightarrow {}^1_0n$

(iii) $^{208}_{82}Pb$ and $^{209}_{83}Bi$ are the heaviest stable nuclei. Nuclei having higher number of protons or neutrons disintegrate by loss of α (^4_2He), ${}_{+1}^{0}e$, ${}_{-1}^{0}e$ or by fission process.

The higher the binding energy the more stable the nucleus.

Binding energy per nucleon is the ratio of energy required to break a nucleus into free neutrons and protons to the mass number.

i.e. binding energy per nucleon = $\frac{Binding\ energy}{Mass\ number}$

Nuclear fission

This is the splitting of a heavy nucleus into two or more light nuclei accompanied by the release of energy.

Sufficient excitation energy for the nucleus to split may be provided by particle bombardment of the nucleus with protons, neutrons or electrons. E.g.

$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{95}_{57}Mo + ^{139}_{57}La\ 2^{1}_{0}n + 7^{\ 0}_{-1}e$ + energy

Neutrons are preferred as bombarding particles because they do not carry charge and therefore can penetrate deeper into the nucleus.

Uses of nuclear fission

1. To provide electricity
2. To manufacture atomic bombs.

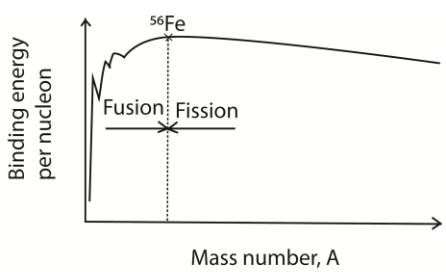
Nuclear fusion

It is the union of two lighter nuclei to produce heavier nucleus of higher binding energy per nucleon accompanied by release of energy, e.g.

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

Nuclear fusion takes place at high temperature because the nuclei need a lot of kinetic energy to overcome their electrostatic repulsion.

A sketch of Variation of Binding energy per nucleon with mass number relating nuclear fusion and nuclear fission



Note that:

- Two Small nuclei with atomic mass less than 56 each fuse to give a heavier nuclei with smaller mass by higher binding energy to increase stability of nucleon
- A nucleus with atomic mass higher than 56 split to form lighter nuclei of higher binding energy per nuclei.

Thank you
Dr. Bbosa Science