

ATOMIC STRUCTURE

Rutherford's model of the atom

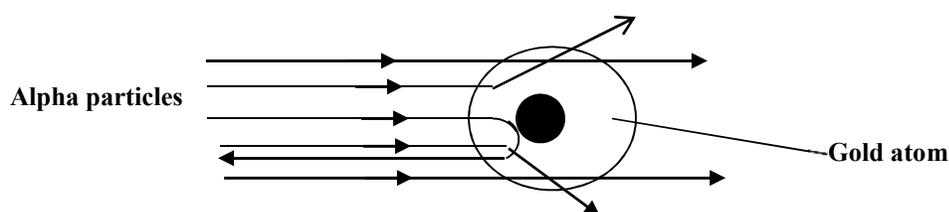
All the positive charge of the atom is concentrated in a small region called the nucleus of diameter less than 10^{-10}m . The negative charge surrounds the positive charge.

This was verified by Rutherford and his team. The experiment involved the scattering of alpha particles by a thin Gold foil.

Alpha particles emitted by a radioactive source were directed towards a thin gold foil. The scattered alpha particles were observed using a Zinc Sulphide detector. The detector was moved to different positions around the vessel in order to detect the alpha particles. This was done in an evacuated vessel to allow free movement of the alpha particle without obstruction by air molecules.

Observations

1. The majority of the alpha particles passed through undeflected.
2. A few of the alpha particles were scattered through small angles.
3. Very few alpha particles were deflected through angles greater than 90° .



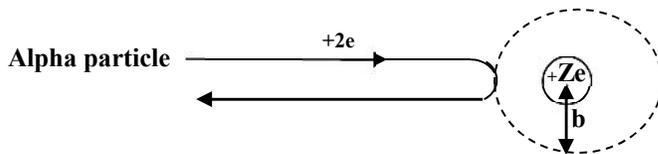
Conclusion

1. The alpha particles being positively charged, their scattering must be due to the positive charge in the gold atom.

2. Since the majority of the alpha particles passed through undeflected, most of the space inside the atom is empty.
3. Large angle scattering occurred whenever an alpha particle was incident almost head on to the nucleus.
4. Since very few alpha particles were scattered through large angles, it follows that the probability of a head on collision with the nucleus is small and it follows that the nucleus occupies only small proportion of the available space inside an atom.

Hence Rutherford concluded that atoms consist of a positively charged nucleus occupying a very small proportion of the volume of the atom with electrons orbiting the nucleus just like planets orbit the sun.

Closest distance of approach of alpha particles.



Where Z is the proton number or atomic number of the atom.

At closest distance of approach, all alpha particle's kinetic energy is converted into electrostatic potential energy of the alpha particle or nucleus system.

Hence

$$\frac{1}{2} mu^2 = \frac{2Ze^2}{4\pi\epsilon_0 b}$$

$$\frac{1}{2} mu^2 = \frac{Ze^2}{2\pi\epsilon_0 b}$$

$$b = \frac{Ze^2}{\pi\epsilon_0 mu^2}$$

Example

A beam of alpha particles of energy 4.2MeV is incident normal to a gold foil. What is the closest distance of approach by the particles to the nucleus of the gold atom?

(Atomic number of gold = 79)

$$\frac{1}{2}mu^2 = \frac{Ze^2}{2\pi\epsilon_0 b}$$

$$4.2 \times 1.6 \times 10^{-13} = \frac{79 \times (1.6 \times 10^{-19})^2}{2 \times \pi \times 8.85 \times 10^{-12} \times b}$$

$$b = 5.412 \times 10^{-14} \text{ m}$$

Summary, the atom consists of the following main particle: (i) the protons which are positively charged, (ii) the neutrons which carry no charge and the electrons which are found in orbits around the nucleus. The neutrons and protons make up the nucleus of the atom.

The Bohr model of the atom

Bohr postulated that:

- (i) Electrons in atoms can exist only in certain discrete orbits and while in these orbits, they don't radiate energy.
- (ii) Whenever an electron makes a transition from one orbit to another of lower energy, a quantum of electromagnetic radiation is given off.

The energy of the quantum of radiation emitted is given by $E = hf = E_i - E_f$, where E_i is energy of the electron in the initial orbit, E_f is the energy of the electron in the final orbit, h is Planck's constant and f is the frequency of emitted electron.

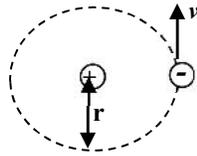
(iii) The angular momentum of an electron in its orbit in an atom is an integral multiple of $\frac{h}{2\pi}$

i.e. $mvr = \frac{nh}{2\pi}$, where $n = 1, 2, 3 \dots$

The orbit with the lowest energy is called the ground state. All physical systems are in physical equilibrium in the lowest energy state. Other high energy levels are called excited state.

Bohr's theory of the hydrogen atom

Consider an electron in a hydrogen atom to be in a circular orbit of radius , r , about the nucleus.



For circular motion, a centripetal force on an electron is $\frac{mv^2}{r} = \frac{e^2}{4\pi\epsilon_0 r^2}$

$$mv^2 = \frac{e^2}{4\pi\epsilon_0 r}$$

Hence kinetic energy, $T = \frac{1}{2}mv^2 = \frac{e^2}{8\pi\epsilon_0 r} \dots\dots\dots(i)$

The electric potential energy of the electron, $V(r) = \frac{e}{4\pi\epsilon_0 r} \times (-e) = \frac{-e^2}{4\pi\epsilon_0 r} \dots\dots\dots(ii)$

Total energy, $E = T + V(r) = \frac{e^2}{8\pi\epsilon_0 r} + \frac{-e^2}{4\pi\epsilon_0 r} = \frac{-e^2}{8\pi\epsilon_0 r} \dots\dots\dots(iii)$

From Bohr's postulates, $mvr = \frac{nh}{2\pi}$

Hence $v^2 = \frac{n^2 h^2}{4\pi^2 m^2 r^2} \dots\dots\dots(iv)$

Substitute equation (iv) in equation (i)

$$\frac{mn^2h^2}{8\pi^2m^2r^2} = \frac{e^2}{8\pi\epsilon_0r}$$

Hence $r = \frac{n^2h^2\epsilon_0}{\pi me^2}$(v)

Substitute equation (v) in equation (iii)

$$E = \frac{-e^2}{8\pi\epsilon_0\left(\frac{n^2h^2\epsilon_0}{\pi me^2}\right)} = \frac{-me^4}{8\epsilon_0^2n^2h^2}$$

Hence the allowed electron energies can be obtained from the equation

$$E_n = \frac{-me^4}{8\epsilon_0^2n^2h^2}, \text{ where } n \text{ is the principal quantum number,; } n = 1, 2, 3, \dots\dots$$

Note: (i) The energy of the electron is always negative. This means that work has to be done to move the electron to infinity where it is considered to have zero energy. The electron is therefore bound to the nucleus.

(ii) Whenever an electron makes a transition from a higher energy level, n_i , to a lower energy level, n_f , the energy of the quantum of radiation emitted is

$$hf = E_i - E_f = \frac{-me^4}{8\epsilon_0^2n_i^2h^2} - \frac{-me^4}{8\epsilon_0^2n_f^2h^2} = \frac{me^4}{8\epsilon_0^2h^2} \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

Energy of the ground state:- $E_0 = \frac{-me^4}{8\epsilon_0^2h^2}, \text{ since } n = 1$

But $m = 9.11 \times 10^{-31}, \epsilon_0 = 8.85 \times 10^{-12}, h = 6.6 \times 10^{-34}$

$$E_0 = -2.18 \times 10^{-18} J$$

$$E_0 = -13.6 eV$$

Hence $E_n = \frac{-13.6}{n^2} eV$

$$E = hf = \frac{me^4}{8\varepsilon_0^2 h^2} \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

$$f = \frac{me^4}{8\varepsilon_0^2 h^3} \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

The wave number of the radiation emitted is $\sigma = \frac{f}{c} = \frac{me^4}{8\varepsilon_0^2 h^2 c} \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$

The term $\frac{me^4}{8\varepsilon_0^2 h^3 c} = R_H = \text{Rydberg constant}$

$$\sigma = R_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

Spectral lines of hydrogen atoms

Energy levels are grouped into shells. Electrons in one shell have nearly the same energy. The shells are denoted by letters K, L, M, N etc. where K shell corresponds to $n = 1$, L shell to $n = 2$, M shell to $n = 3$ and so on.

Transitions of electron from a high energy level to lower energy level cause electron to lose energy in form of electromagnetic waves. Transitions from other shells to K- shell emit spectra of wavelength grouped into what is called Lyman series.

Lyman series lie in the Ultra violet region of the spectrometer.

$$\sigma = R_H \left(\frac{1}{1^2} - \frac{1}{n_i^2} \right)$$

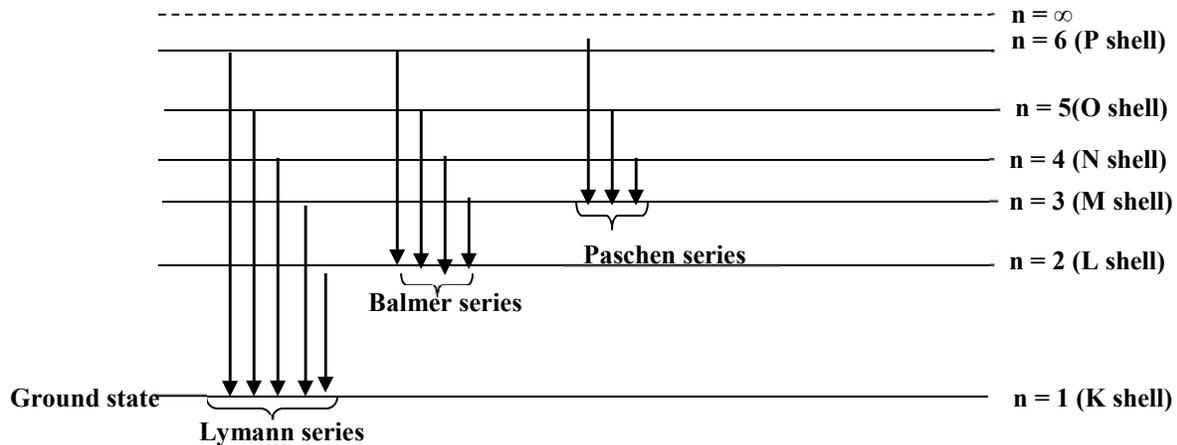
Where $n_i = 2, 3, 4, \dots$

Transitions from other high energy levels to the L- shell ($n = 2$), emits spectra of wavelengths referred to as Balmer series. Balmer series lie in the visible spectrum.

$$\sigma = R_H \left(\frac{1}{2^2} - \frac{1}{n_i^2} \right), \quad n_i = 3, 4, 5 \dots$$

Transition from other high energy levels to the M – shell ($n = 3$), emits spectra referred to as Paschen series which lie in the infra red region.

$$\sigma = R_H \left(\frac{1}{3^2} - \frac{1}{n_i^2} \right), \quad n_i = 4, 5, 6, \dots$$



Note Bohr's theory is too simple to explain spectra of more complicated atoms however, the following remain valid:

- (i) electrons exist outside the atomic nucleus
- (ii) existence of energy levels.
- (iii) Emission and absorption of radiation occur in discrete amounts called quanta.

Line emission spectra

When atoms like H_2 , neon etc. are excited due to some form of heat from a flame or electricity, electron transition may occur to higher energy levels. This makes the atom unstable since energy has increased. Electron transition may occur to a vacancy left in the lower energy level and radiation of a definite wavelength or

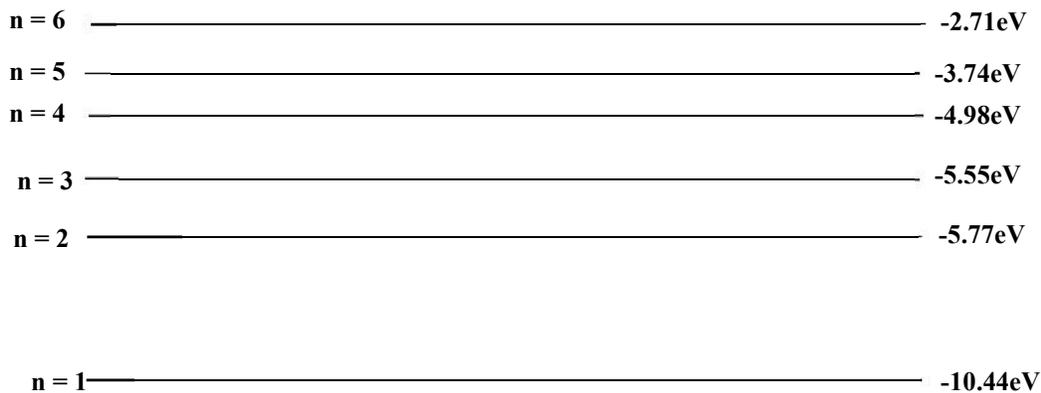
frequency is emitted. A line appear bright against a dark background. The lines are separated which give evidence that energy levels of the atoms are separate.

Line absorption spectra.

An atom's energy can change by only discrete amounts. If a photon of energy, hf , is just enough to excite the atom, such that an electron can jump to one of higher energy levels, the photon will be absorbed. The intensity of the incident radiation is reduced since it has lost a photon. A dark line on a white background is observed, whose wavelength is that of the absorbed photon.

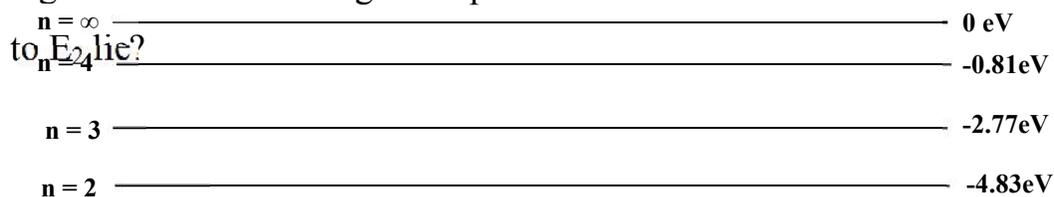
Example

1. The figure below represents the lowest energy levels of mercury.



- (i) Calculate the energy and wavelength of the photon emitted when the mercury atom's energy changes from E_6 to E_2 .
- (ii) Determine which energy levels in the mercury atom are involved in the emission of a line whose wavelength is 546nm.

2. The figure below shows some of the energy levels of a neon atom. In what region of the electromagnetic spectrum does the radiation emit in the transition E_3



Nuclear physics

The nuclei of atoms contain protons and neutrons. The collection of protons and neutrons together is called the nucleon.

A species of atoms with a specified number of protons and neutrons is called a nuclide. There are forces which bind the nucleons together. In some nuclides, the forces make the nucleons stay together permanently; however in some, the energy forces binding the nucleus affect some to the nucleons, this happens when the ration of neutrons to protons is big. When ration is big, the nucleus release excess energy to become stable.

The number of protons in the nucleus is called the atomic number while the number of protons and neutrons is the mass number.

An atom X, with atomic number Z and mass number A can be symbolised by ${}^A_Z X$

$A = Z + N$, where N = number of neutrons

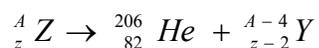
Radioactive decay

This is the spontaneous disintegration of unstable nuclei emitting alpha, α , beta, β and gamma, γ radiation

Alpha particles

An α -particle is a Helium atom that has two protons and two neutrons. When a nuclei decays by release of an α particles, it loses two protons and two neutrons i.e. mass number decreases by 4 and atomic number by 2.

Alpha particle symbol is ${}^4_2 He$



eg



Properties of α particles

They cause fluorescent in some materials

They blacken photographic plates

They readily ionise gases

They are easily absorbed by matter. The penetration of matter by α particles is unique in that the α particles can not be detected beyond their range.

They are deflected by electric and magnetic fields to a less extent than β particles. This means that they are heavier than β particles. In both magnetic and electric fields they are deflected in a direction opposite to that of the β particles. This indicates that they are positively charged.

They are emitted with speeds of the order 10^{-7} ms^{-1}

They are helium nuclei with mass $4U$ and charge $+2e$

Beta particles

These are electrons, the mass of the electron is much smaller than that of the proton

When an element decays by emitting a β particle it loses an electron. Hence the mass number remains the same but the atomic number increases by one.

A neutron is thought to consist of a proton and an electron. When a nucleus disintegrates, a neutron breaks down into an electron (β particle) which is emitted and a proton which increases the atomic number.

Properties of β particles

They have a much smaller fluorescent effect than α particles

They blacken photographic plates

They ionise gases more readily than α particles

They penetrate matter more easily than α particles but are absorbed completely by about 1 mm of Aluminium, or a few metres path of air. They don't have a definite range like α particles owing to successive deflection caused by collision with the atoms of the absorber.

They are deflected by electric and magnetic fields much more than α particles because they are lighter.

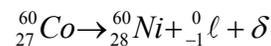
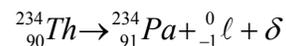
They are fast moving electrons. They move faster than cathode rays

Gamma rays

They are electromagnetic radiation with very short wave lengths. These are found to occupy a band the X-ray which are thought to have the shortest wave length known.

The main difference between γ - rays and X-rays is that γ -rays originate from energy changes in the nucleus in the atom while X rays originate from energy changes associated with electron structure of the atom.

Emission of γ rays has no effect on the mass of the nucleus. Emission of γ - rays is usually accompanied by α or β emission e.g.



Properties

Affect photographic plates

They are not deflected by magnetic and electric fields. This implies that they carry no charge

They travel in a vacuum with the speed of light

They are diffracted by light or X rays

Wave length of γ rays shorter than those of X rays

They cause photoelectric effect i.e. they eject electrons when they fall on certain metals

They have a greater penetrating power than β particles i.e. are absorbed by thick lead.

The Decay law

The rate of disintegration of a given sample at any time is directly proportional to the number of nuclide N , present at that time, t .

Mathematically

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

The negative sign indicates that N decreases as t increases

$$\frac{dN}{dt} = -\lambda N \quad \text{Where } \lambda \text{ is the decay constant}$$

Decay constant, λ , is defined as the fraction of the radioactive nuclei which decays per second.

$$\int \frac{dN}{N} = \int -\lambda dt$$
$$\ln N = -\lambda t + c$$

When $t = 0$, $N = N_0$, which is the original number of nuclei.

$$\text{Hence } \ln N_0 = c$$

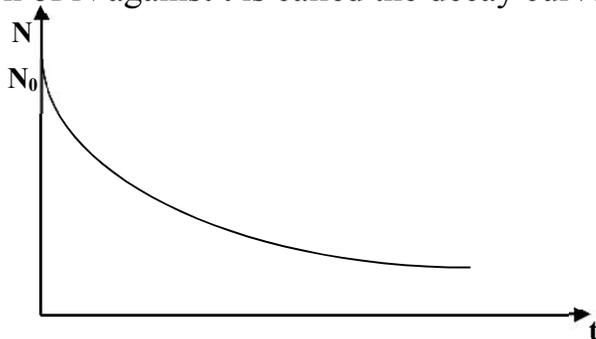
$$\text{Hence } \ln N = -\lambda t + \ln N_0$$

$$\ln \left(\frac{N}{N_0} \right) = -\lambda t$$

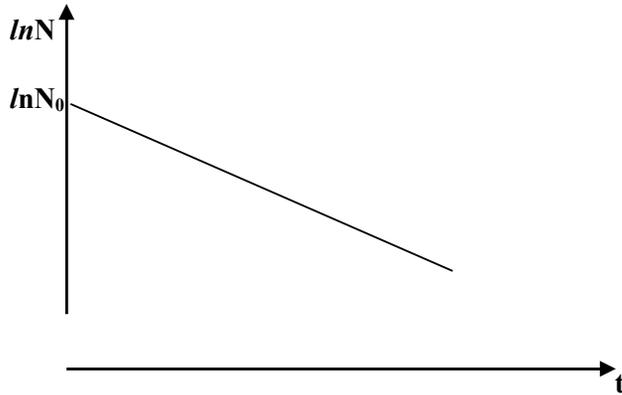
or

$$N = N_0 e^{-\lambda t}$$

A graph of N against t is called the decay curve



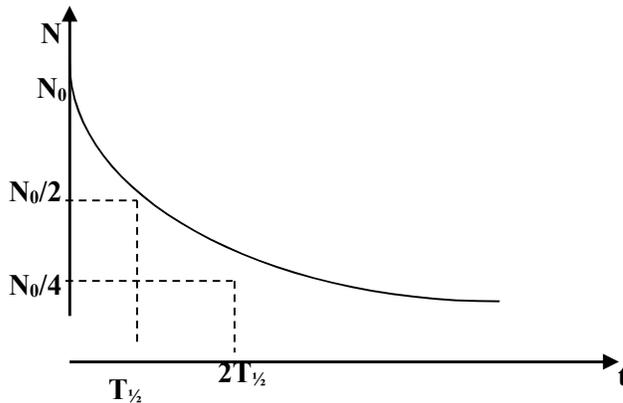
A graph of $\ln N$ against t is a straight line with a negative slope.



Half life ($T_{1/2}$)

The half life of a radioactive source is the time taken for half the number of radioactive nuclei present in the source to disintegrate.

Consider the decay curve of a radioactive source



Relationship between λ and ($T_{1/2}$)

When $t = T_{1/2}$, $N = N_0/2$

From

$$N = N_0 e^{-\lambda t}$$

$$\frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}}$$

$$\frac{1}{2} = e^{-\lambda T_{1/2}}$$

$$In \frac{1}{2} = In e^{-\lambda T_{1/2}}$$

$$In \frac{1}{2} = -\lambda T_{1/2}$$

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

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

Activity of a radioactive source

This is number of disintegration of a radioactive source per second.

$$\text{Activity } A = \frac{dN}{dt} = -\lambda N$$

The SI unit of activity is Becquerel (Bq)

1Bq = 1disintegration per second

A large unit of activity is curie (Ci)

$$3.70 \times 10^{10} \text{ Bq} = 1\text{Ci}$$

$$\text{Activity, } A = \frac{dN}{dt} = -\lambda N$$

$$N = N_0 e^{-\lambda t}$$

$$A = -\lambda N_0 e^{-\lambda t}$$

but $A_0 = -\lambda N_0$ = initial activity

when $t = 0$

hence

$$A = A_0 e^{-\lambda t}$$

Hence Half-life can also be defined as the time taken for the activity of the source to decrease to half the original value.

Example

1. The half life of a radio isotope is 5.27 years, calculate

i. Its decay constant

ii. The number of years it will take 75% of a given mass of isotope to decay

$$\lambda = \frac{0.693}{T_{\frac{1}{2}}} = \frac{\ln 2}{T_{\frac{1}{2}}} = \frac{\ln 2}{5.27 \times 365 \times 24 \times 3600} = 4 \times 10^{-9} \text{ s}^{-1}$$

(ii)

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

$$N = 0.25No$$

$$0.25No = Noe^{-\lambda t}$$

$$\ln 0.25 = -\lambda t = 4 \times 10^{-9} t$$

$$t = 3.31 \times 10^8 \text{ s}$$

$$t = 10.5 \text{ years}$$

2. The radio isotope ^{60}Co decays by emission of a β particle and a γ ray. Its half life is 5.3 years. Find the activity of the source containing 0.10 gm of ^{60}Co

$$A = \lambda N$$

$$\text{but, } \lambda = \frac{\ln \frac{1}{2}}{5.3 \times 365 \times 24 \times 3600} = 4.15 \times 10^{-9}$$

$$0.10 \text{ gm contain } \frac{\text{NA}}{60} \times 0.10 = \frac{6.02 \times 10^{23} \times 0.10}{60} \text{ atoms}$$

$$N = 1.003 \times 10^{21} \text{ atoms}$$

$$A = \lambda N$$

$$A = 4.15 \times 10^{-9} \times 1.003 \times 10^{21} = 4.16 \times 10^{12} \text{ disintegration s}^{-1}$$

Exercise:

A silver isotope $^{108}_{47}\text{Ag}$ has a half life of 2.4mins. Initially, a sample contain 2.0×10^6 nuclei of silver. Find the number of radioactive nuclei left after 1.2 minutes.

(ans: 1.412×10^6)

Carbon dating

The unstable isotope ^{14}C produced during nuclear reactions in the atmosphere as a result of cosmic ray bombardment give a small portion of ^{14}C in CO_2 in the atmosphere.

Plants take in CO_2 for photosynthesis. When a plant dies it stops taking in CO_2 and its ^{14}C decays to ^{14}N by β particle emission.

By measuring the activity of ^{14}C in the remains, the time when the plant died can be estimated.

Example

The activity of a sample of dead wood is 10 counts per minute, while for a living plant is 19 counts per minute. If the half life of ^{14}C is 5500 years, find the age of the wood sample.

$$A = A_0 e^{-\lambda t}$$

$$10 = 19 e^{-\lambda t}$$

$$-\lambda t = \ln\left(\frac{10}{19}\right)$$

but

$$\lambda = \frac{\ln 2}{T_{1/2}} = \frac{\ln 2}{5500} \text{ yr}^{-1}$$

Hence

$$-\frac{\ln 2}{5500} t = \ln\left(\frac{10}{19}\right)$$

$$t = 5093 \text{ years}$$

Exercise

Wood from a buried ship has a specific activity of $1.2 \times 10^2 \text{ Bq kg}^{-1}$ due to ^{14}C , whereas comparable living wood has an activity of $2 \times 10^2 \text{ Bq kg}^{-1}$. What is the age of the ship? (half life of $^{14}\text{C} = 5,7 \times 10^3$ years).

Radio isotopes

Radioisotopes are nuclides which are unstable and undergo radioactive decay emitting α or β particles or γ - rays during return to a stable form. ^{238}U , ^{226}Ra and ^{230}Th are examples of natural radioactive.

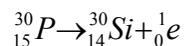
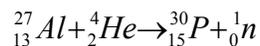
A greater number of radio isotopes are produced artificially by bombarding stable nucleus with high energetic particles such as protons, α -particles, deuterons and neutrons.

Artificial radioisotopes behave the same way as the natural radioactive materials in that each will emit its characteristic particle or radiation and each has a characteristic half-life.

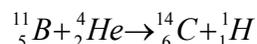
Examples

1. By bombarding

^{27}Al with α particles, one gets ^{30}P which decays by emission of a positron (0_1e)



2. Bombarding of boron $^{11}_5\text{B}$ with α particles to get $^{14}_6\text{C}$ which decays by emission of β particles.



then $^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + ^0_{-1}e$ with half life 5730 years.

3. Neutrons are ideal for bombardment of stable nuclei to produce radioisotope because they carry no charge and are therefore not deflected by either atomic electrons or nuclear charge.

They will penetrate the nucleus even when their energies are comparatively low.

Some uses of radioisotope

1. *Biological uses*

i. Radiotherapy

Radio cobalt ${}_{27}^{60}\text{Co}$ decays with emission of β particles together with very high energy γ -rays. The γ -rays have greater energy than is available with standard X-rays machines when properly shielded, the γ -rays are employed in the treatment of cancer.

The iodine isotope ${}^{131}\text{I}$ (half life 8 days) decays by γ -ray emission. This is injected into the blood stream of a patient having cancer of the thyroid and the γ -rays given off are concentrated right where they are needed. The speed with which the iodine isotope becomes concentrated in the thyroid provides a measure of the thyroid function.

ii. Tracers

Small quantities of low activity radioisotope are administered by injection into patients and their passage through the body and absorption by diseased tissue studied.

The radioisotope ${}^{59}\text{Fe}$ is administered into a patient's blood stream. Measurements of the radioactivity of a plasma sample will indicate the amount of dilution and hence the total number of red blood cells can be determined if some of the patients own red cells are labelled with ${}^{59}\text{Fe}$ or ${}^{51}\text{Cr}$ and returned into the blood stream.

In agriculture, traces have been used to study how fertilizers, hormones, weed killers and pesticides perform their functions. E.g. the radioisotope ${}_{15}^{30}\text{P}$ has been used to provide information about the best type of phosphate fertilizer to supply to particular crops and soil.

iii. Mutants

Radioisotopes have been used to induce plant mutations. This has led to improved seed varieties of crops like wheat, peas, beans with high yields and high resistance to crop disease.

iv. Sterilization

Medical instruments and equipments are sterilized by exposure to γ –rays. Gamma ray as are also being used to sterilize and preserve some food products. The method is safe as no radioactivity is induced in the material irradiated by γ -rays.

Radiation has also been used to eliminate agricultural pests by sterilizing them and therefore serving the reproduction chains.

v. Carbon dating

By measuring the residual activity of the quality $^{14}_6\text{C}$ remaining after death of an organism, we can determine how long ago the organism died.

2. Industrial uses

(i) Tracers

a) For investigation of flow of liquids in chemical plants or in underground water and sewerage pipelines. In the latter cases, a little radioactive solution is added to the liquid being pumped. Temporary high activity around a leak is detected from the ground above. The rate of flow of liquids can also be measured.

b) For study of wear in machinery such as of piston rings in motor engine.

Before the piston is put in place, it is irradiated with neutrons to form the radioisotope

^{59}Fe . As the piston rings wear out, the ^{59}Fe which comes off with the oil is tested using Geiger Muller counter. Through comparison of the initial

activity with the activity measured time, the rate of wear of the piston is deduced.

- c) Automatic control of thickness paper, plastic or metal sheeting as it gives through the production plant. The thickness is controlled by measuring the transmission of radiation through the sheet.

3. Diagnostic uses

Cobalt ⁶⁰ and other γ - rays emitters are used as alternatives to X rays set ups which are more elaborate to produce radiographs for examination of welded beams and metal castings.

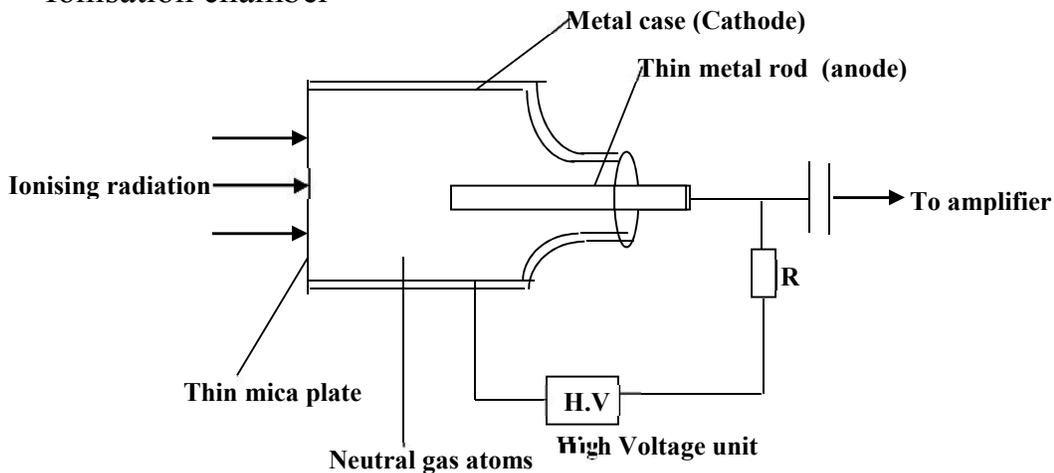
Detections of Nuclear radiation

The requirement for the detection of any nuclear radiation is that it must dissipate energy in the detector.

The causes of dissipation of energy by nuclear radiation are

- i. Ionisation of atoms in the detector e.g in ionisation chamber and G.M. Tube
- ii. Excitation of atoms without removal of orbital elections e.g. in scintillation counter.

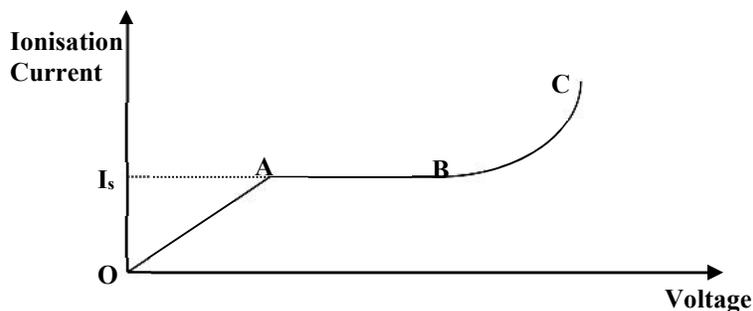
Ionisation chamber



Mode of action

When ionising radiation enters the chamber through the mica window, it ionises the neutral gas atoms. Ion pairs are produced as a result of collision. The positive ions produced drift to the cathode and the negative ions to the anode resulting in an ionisation current which is amplified and measured with the micrometer. A high voltage is set to a value that a constant current I_s flows. In this setting, the energy (intensity) of the incoming radiation is proportional to I_s .

A graph of ionisation current against voltage V has the following features.



Features of the graph

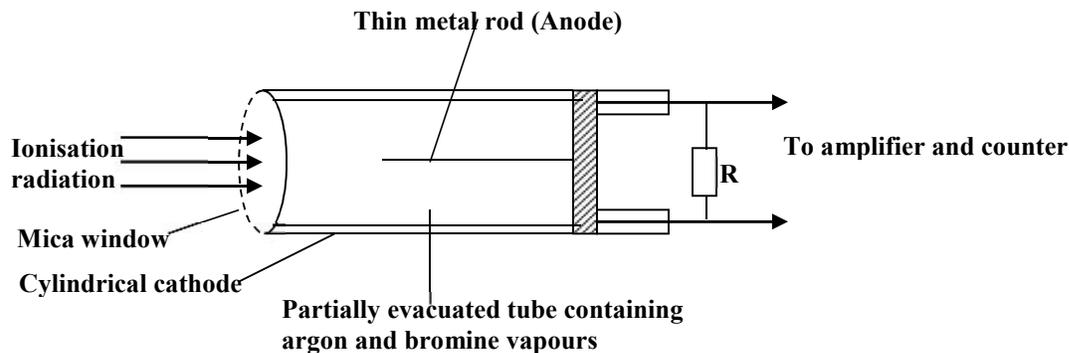
Region OA: The applied voltage is low. The positive ions and electrons produced by collisions of incoming radiation with the neutral gas atoms have a high chance of recombining since their velocities are low. The current produced is proportional to the voltage.

Region AB (Saturation region): All ions pairs produced per second travel and reach the respective electrodes. This results in constant current or saturation current $I_s = ne$.

In this region, the energy lost by the incoming particles is proportional to I_s . This is the region in which the ionisation chamber is normally operated.

Region BC (Gas amplification): because of the high voltage, the electrons produced by ionisation of the neutral gas atoms, acquire sufficient energy to cause ionisation themselves (secondary ionisation). This results in rapid multiplication of ions in the chamber, and hence the rise in ionisation current.

The Geiger Muller tube or counter

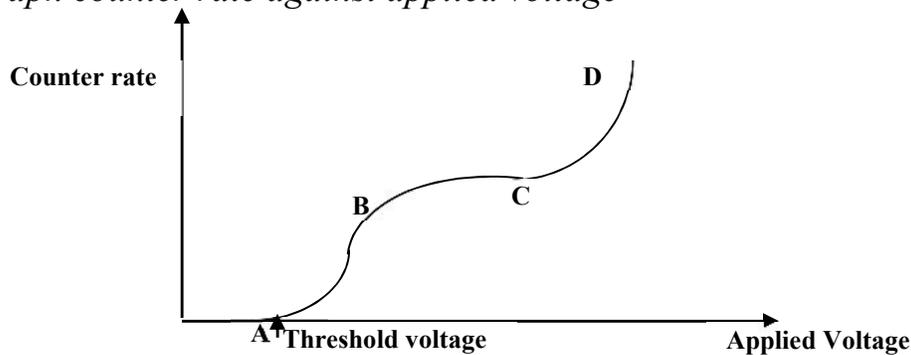


When the radiation enters the tube, it causes ionisation of the gas atoms. The electrons produced are accelerated to such a high energy that they also cause more ion pairs by repeated collisions. When the electrons reach the anode, the pulse is produced which is amplified and detected by a rate meter. The positive ions in the chamber are accelerated towards the cathode and if these ions reach the cathode, they will cause secondary discharge, which will give a false impression of an arrival in the chamber of another ionising particle. This is prevented by using a quenching agent like bromine.

During the quenching process, an electron from the bromine molecule is transferred to the organ ion neutralising it. In this way a tube is made to receive next ionising particle.

In a G.M tube the time taken by the positive ions to travel to the cathode is known as the dead time. The number of pulses per unit time (counter rate) corresponds to the activity of the source of radiation

A graph counter rate against applied voltage



Below a certain value of p.d known as *threshold voltage*, no counts are recorded at all since the number of ions produced per second is not enough to produce sufficient current which can result in a pd of sufficient magnitude to be detected.

Between A and B, magnitude of pulse developed in the tube depends on the initial ionisation of the tube and energy of the incident particles.

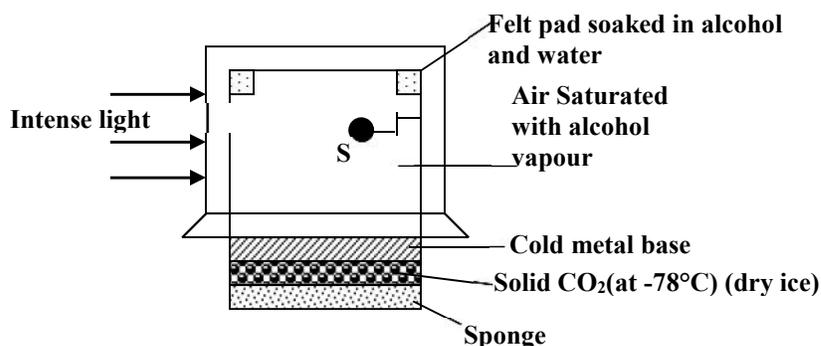
Between B and C, the plateau region, the counter arte is almost constant. All the region when the tube is said to be normally operated

Beyond C, the counter rate increases rapidly with voltage due to incomplete quenching one incident particle may start a whole chain of pulses.

Cloud Chamber

There two types:

(1) *Diffusion type chamber*

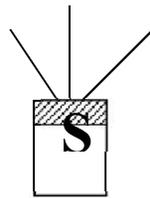


Mode of operation

Alcohol vaporised in the warm upper part of the chamber. It diffuses towards the cold part of the chamber. Above the cold metal base, there will be a layer of air super saturated with alcohol and water vapour.

The shield surrounding the radioactive source is removed. The radiation from S ionises the air molecules. The ions provide nuclei for condensation and their paths are seen by means of the intense light directed in the chamber. The tracks of the ions can be photographed. The chamber is cleared of ions by supplying a p.d between the top and bottom of the chamber.

The type of radiation emitted by the radioactive source can be deduced from the tracks formed. α particles proceed without deviation except at the end of their range. They ionise copiously and have well defined range.



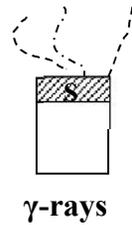
α -

β -particles proceed along tortuous tracks because they are light and are easily deflected by collision with atoms.

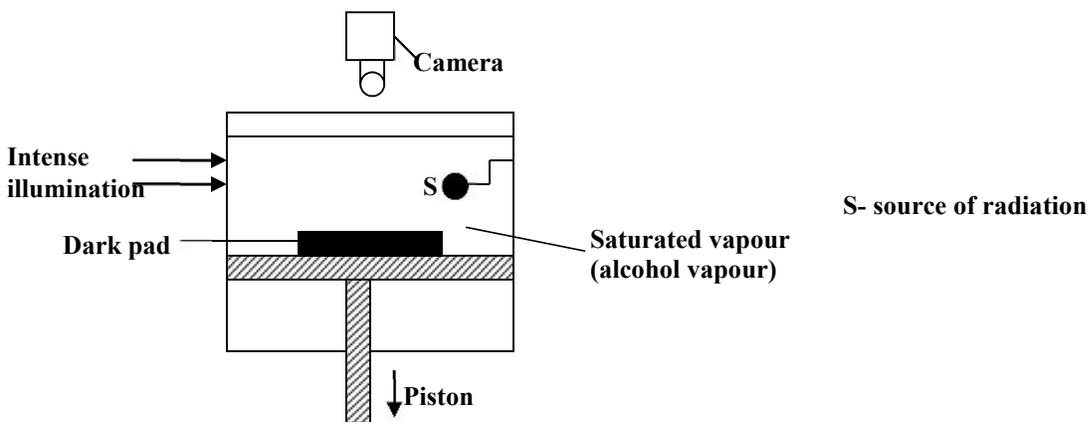


γ -rays give rise to diffuse ionisation.

β -



(2) Expansion cloud chamber



Mode of operation

The air inside the chamber undergoes adiabatic expansion by pumping on it. The air cools down as a result. After a few adiabatic expansion, condensation takes on the residual ions (or dust nuclei). The chamber is cleared of these ions by application of a p.d between the top and bottom of the chamber.

The gas in the chamber is then subjected to a precise adiabatic expansion so that the gas becomes super saturated. The shield S is removed, condensation takes place on the ions formed radiation emitted by S. The tracks of emissions of S are photographed and emissions identifies.

Example

A source of α particles has an initial activity of 2×10^5 disintegrations per second. When the α particles enter an ionisation chamber, a saturation current of 2×10^{-7} A is obtained. If the energy required to produce an ion pair is 32eV. Find the energy of one α -particle

$$I = ne$$

$$n = \frac{I}{e} = \frac{2 \times 10^{-7}}{1.6 \times 10^{-19}} = 1.25 \times 10^{12}$$

$$\text{Energy lost per second} = 1.25 \times 10^{12} \times 32 = 4 \times 10^{13} \text{ eV}$$

$$\text{Energy of one } \alpha\text{-particle} = \frac{4 \times 10^{13}}{2 \times 10^5} = 2 \times 10^7 \text{ eV}$$

NUCLEAR ENERGY

Einstein's mass- energy relation

If the mass of the closed system changes by an amount of m , the energy of the system changes by an amount, $E = mc^2$, where c is the speed of light in a vacuum.

The above relation is Einstein's mass- energy relation.

For a given mass, there is energy released.

Recall that $1\text{U} = 1.66 \times 10^{-27} \text{kg}$.

If the mass changes by 1U , then the energy changes is

$$E = mc^2 = 1.66 \times 10^{-27} \times (3 \times 10^8)^2 = 1.494 \times 10^{-10} \text{ J} = 934 \text{ MeV}$$

Binding Energy

The protons and neutrons of an atom are called nucleons. The energy needed to take all the nucleus a part so that they are completely separated is called the binding energy of the nucleus.

Hence from Einstein's mass-energy relation, it follows that the mass of the individual nucleons is greater than that of the nucleus in which they are together. The difference in mass is a measure of binding energy.

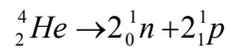
Example

Find the binding energy of a helium nucleus ${}^4_2\text{He}$

Mass of ${}^4_2\text{He} = 4.0015\text{U}$

Mass of ${}^1_0n = 1.0087\text{U}$

Mass of ${}^1_1p = 1.0073\text{U}$



mass on the right hand side = $(2 \times 1.0087) + (2 \times 1.0073) = 4.032\text{U}$

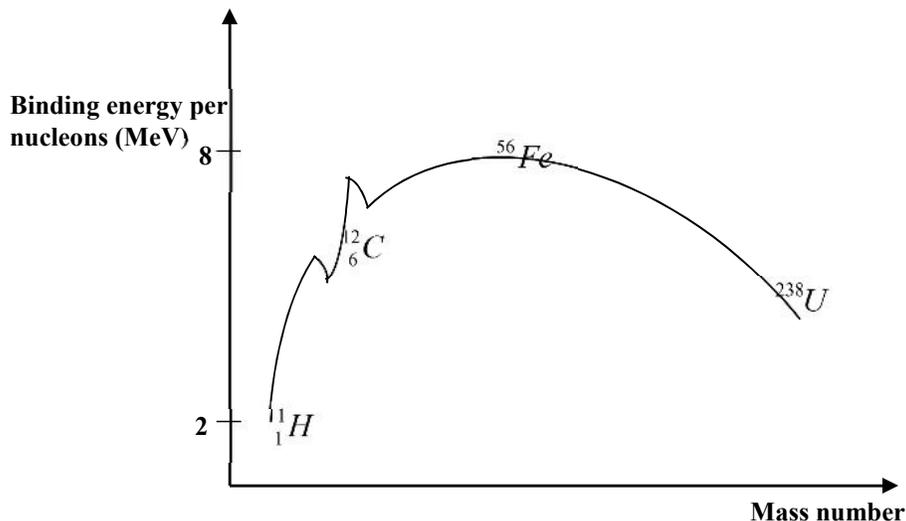
Change in mass, $m = 4.032 - 4.0015 = 0.0305\text{U}$

But $1\text{U} = 931\text{MeV}$

Hence binding energy = $931 \times 0.0305 = 28.4\text{MeV}$

Binding energy per nucleons is the ratio of the binding energy to the atomic mass of the nucleus.

The binding energy per nucleons of elements of the periodic table varies with mass as shown below.



The higher the binding energy per nucleon, the more stable the nucleus.

Excluding the nuclei lighter than ^{12}C , the graph indicates that the average binding energy per nucleon is fairly constant for a great majority of nuclei. The average value is about 8MeV per nucleon. The pitch occur at approximately the ^{56}Fe nucleus which is therefore one of the most stable nuclei.

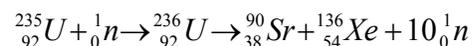
Nuclear fusion and fission

Nuclear fission

A nuclear fission reaction involves bombarding of the heavy nucleus with a highly energetic particles such as neutrons, protons, deuterons and alpha particles. The heavy nucleus splits into lighter nuclei of higher binding energy per nucleon. The mass deficiency which results is accounted for by the energy released in accordance to Einstein's mass-energy relation. In most nuclear fission reactions, neutrons are used to induce a reaction because of being neutral, they can penetrate the nucleus.

When ^{235}U splits, it produces nuclei that are lighter and hence have higher binding energy.

Examples of nuclear fission



Find the energy released by 1kg.

Mass of ^{235}U = 235.0439U, Mass of ^{90}Sr = 89.9073U,

Mass of ^1n = 1.0087U, Mass of ^{136}Xe = 135.907U

Mass on left hand side = 235.0439+1.0087 = 236.0526U

Mass on right hand side = 89.9073 + 135.907 + 10x1.0087 = 235.9013U

Change of mass, m = 236.0526 - 235.9013 = 0.1513U

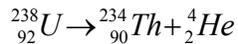
Energy released by a nucleon of U235 = 0.1513x931Mev = 140.8603MeV

$$\text{Energy released by 1kg of } ^{235}\text{U} = \frac{1000}{235} \times 6.025 \times 10^{23} \times 140.8603 = 3.61 \times 10^{26} \text{ MeV}$$

In the above example, when the emitted neutrons encounter with other Uranium nuclides, they bombard the uranium and more splitting occurs with the release of more energy. The produced neutrons are called fission neutrons, and when this occurs, the reaction is called a chain reaction. In a chain reaction, a lot of energy is produced and unless this energy is controlled, the reactions may cause an explosion. Chain reaction is applied in making nuclear bombs.

Exercise

^{238}U disintegrates by emission of an α -particle according to the equation



calculate (i) the total energy released in the disintegration (4.2315MeV)

(ii) the kinetic energy of the alpha particles, with the nucleus being at rest before disintegration.(4.16MeV)

Mass of $^{238}\text{U} = 238.1249\text{U}$, Mass of $^4\text{He} = 4.00387\text{U}$,

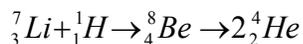
Mass of $^{234}\text{Th} = 234.11650\text{U}$, $1\text{U} = 930\text{MeV}$

Nuclear fusion

A lot of energy is released when the nuclei of lighter elements fuse together to form a heavy nucleus. The fusing together of nuclei to form a heavy nucleus is called nuclear fusion.

Example

Formation of alpha particles when lithium fuses with hydrogen.



Mass of $^7\text{Li} = 7.0160\text{U}$, mass of $^1\text{H} = 1.0078\text{U}$,

Mass of $^4\text{He} = 4.0026\text{U}$, $1\text{U} = 931\text{MeV}$

solution

Mass on left hand side = $7.0160 + 1.0078 = 8.0238\text{U}$

Mass on right hand side = $2 \times 4.0026 = 8.0052U$

Change of mass = $8.0238 - 8.0052 = 0.0186U$

Energy released = $0.0186 \times 931 \text{ MeV} = 17.317 \text{ MeV}$

Energy released by 1kg of the reactants = $\frac{1000}{8} \times 6.025 \times 10^{23} \times 17.317 = 1.304 \times 10^{27} \text{ MeV}$

Exercise:

Calculate the energy released by the reactant of two deuterium fusing to form helium according to the equation. $2 {}_1^2H \rightarrow {}_2^3He + {}_0^1n$

Mass of ${}_1^2H = 2.01421U$,

Mass of ${}_2^3He = 3.0160U$,

Mass of ${}_0^1n = 1.0087U$,

$1U = 931 \text{ MeV}$

The sun contains a considerable amount of hydrogen. It is believed that the energy of the sun is due to nuclear fusion of the hydrogen atoms. Fusion is capable if the nuclei concerned are able to approach each other close enough and if the temperatures are very high. These conditions are achieved in the sun.