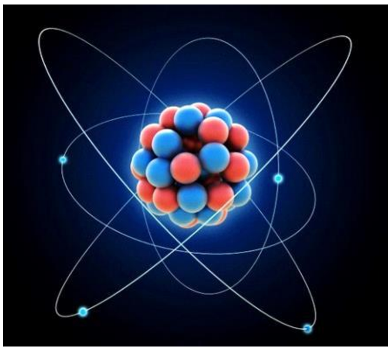
Nuclear physics

The nucleus was discovered in 1911 by Ernest Rutherford in Manchester, England. He and his coworkers took radiation known as alpha particles (see the following) and allowed them to hit a thin gold foil. Although most particles went through or were only slightly deflected, one particle in a thousand was bounced backward from the atoms in the foil. Rutherford compared the experiment to the process of shooting a bullet into a cloud of steam and occasionally finding a bullet bouncing back. The only conclusion that can be drawn in either case is that somewhere inside the atom (or cloud of steam) was a small dense body capable of deflecting fast-moving particles and making them change direction. Rutherford called this small, dense body the nucleus.

Basic properties of Nucleus:

Nuclei have certain time-independent properties such as size, charge, mass, intrinsic angular momentum (nuclear spin) and certain time dependent properties such as radioactive decay and artificial transmutations (Nuclear reactions).

- ✓ Primary constituents of nuclei are protons and neutrons.
- ✓ Nuclear mass is roughly the sum of the masses of its constituents (proton and neutron).
- ✓ Nuclear charge is $+q$ times the number of protons (Z)



The atomic nucleus is designated as $^{A}_{Z}X_{\mathrm{N}}$

Where
A → Mass number (N+Z)
N → Neutron number
Z → Atomic number (No. of protons)
X → Chemical symbol of the element.

Atomic masses are measured in atomic mass unit (*amu* or *u*)

$$1\ amu = \frac{1}{12} \times \text{atomic mess of } C^{12} = 1.66054 \times 10^{-27}\,\text{kg} = 931.49\ \text{MeV/c}^2$$

Atomic radius are measured using the following formula

$R = R_o A^{1/3}$, Where $R_o = 1.414 \times 10^{-15}$ m is the **atomic radius** of the hydrogen nucleus.

Calculation of Nuclear Radii & Ratios

$$R = r_0 A^{\frac{1}{3}} \qquad r_0 = 1.2\times10^{-15}$$

R radius of nucleus $\quad A$ nucleon number

$$\frac{R_1}{R_2} = \frac{A_1^{\frac{1}{3}}}{A_2^{\frac{1}{3}}} \qquad \frac{R_1}{R_2} = \left(\frac{A_1}{A_2}\right)^{\frac{1}{3}}$$

Example 1: What is the diameter of an oxygen nucleus (nucleon number 16)?

$$R_{\mathbf{O}} = r_0 A_{\mathbf{O}}^{\frac{1}{3}} = (1.2\times10^{-15})(16)^{\frac{1}{3}}$$
$$= (1.2\times10^{-15})\times(2.5198)$$
$$= 3.0238\times10^{-15}$$
$$\text{diameter} = 2\times3.0238\times10^{-15} = 6.0476\times10^{-15}$$

Ans. diameter of an oxygen nucleus is 6.05×10^{-15}m

Example 2: If the number of nucleons in a copper nucleus is 64 and the number of nucleons in an oxygen nucleus is 16, how much larger is a copper nucleus than an oxygen nucleus?

$$r_0 = 1.2\times10^{-15}$$

$$\frac{R_{\mathbf{Cu}}}{R_{\mathbf{O}}} = \left(\frac{A_{\mathbf{Cu}}}{A_{\mathbf{O}}}\right)^{\frac{1}{3}} = \left(\frac{64}{16}\right)^{\frac{1}{3}} = (4)^{\frac{1}{3}} = 1.59$$

A copper nucleus is 1.59 times larger than an oxygen nucleus

Constituents of Nucleus:

Proton → 1.6726×10^{-27} kg = 1.007176 u = 938.28 MeV/c^2

Neutron → 1.6750×10^{-27} kg = 1.008665 u = 939.57 MeV/c^2

${}_{1}^{1}H$ atom → 1.6736×10^{-27} kg = 1.007825 u = 938.79 MeV/c^2

Electron → 9.1095×10^{-31} kg = 5.486×10^{-4} u = 0.511 MeV/c^2

Types of Nuclei:

Nuclide → A specific nuclear species

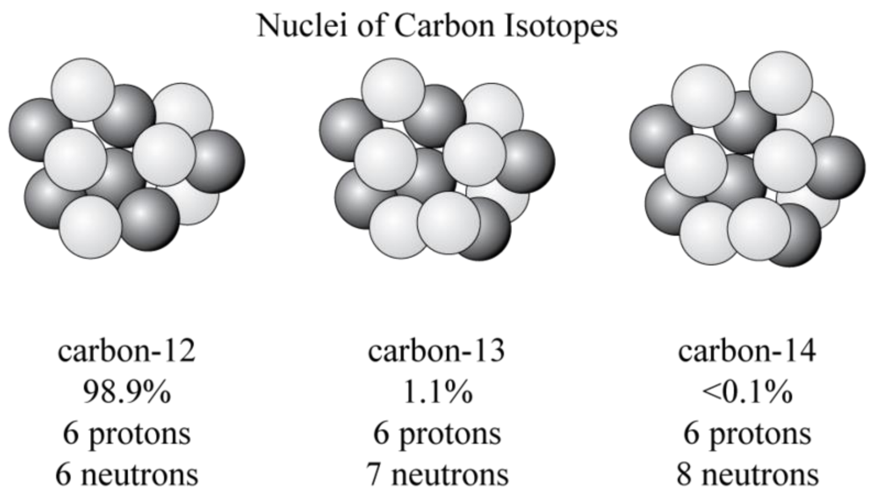
Nucleon → Neutron or proton

Isotopes → Nuclides of same Z and different N. Example: (${}_{8}^{16}O_{8}$, ${}_{8}^{16}O_{9}$, ${}_{8}^{16}O_{10}$)

Isotones → Nuclides of same N and different Z. Example: (${}_{7}^{14}N_{7}$, ${}_{8}^{15}O_{7}$, ${}_{9}^{16}F_{7}$)

Isobars → Nuclides of same atomic mass no (A). Example: (${}_{6}^{14}F_{8}$, ${}_{7}^{14}N_{7}$, ${}_{8}^{14}O_{6}$)

Isomers → Nuclide in an excited state with measurable half life. ${}_{8}^{16}O_{8}*$



Why electron cannot be in the nucleus?

- **Nuclear Size:** To confine an electron in a box of nuclear dimension, it must have energy more than 20 MeV. Whereas, electrons emitted during β^- decay have energies of only 2 or 3 MeV. On the other case for proton this box confinement energy is only 0.2 MeV.
- **Nuclear Spin**: Deuterium if consists two protons and an electron, its nuclear spin should be $\frac{1}{2} + \frac{1}{2} + \frac{1}{2} = \frac{2}{3}$ or, $\frac{1}{2} + \frac{1}{2} - \frac{1}{2} = \frac{1}{2}$. But it is actually 1.
- **Magnetic moment**: Magnetic moment of proton = 0.15% of electron. If electron is part of nucleus its magnetic moment ought to be of the order of magnitude of the electron. But it is only comparable to that of proton.
- **Electron- nuclear Interaction**: BE 8 MeV per particle for nucleon. If electron is inside the nucleus how can the other electrons is the atom remain outside?

Binding Energy:	Mass of H nucleus	= 1.007825 u
	Mass of Neutron	= 1.008665 u
	Expected mass of	= 2.016490 u

But mass of the atom is 2.014102 u. Thus (2.016490 – 2.014102) u or 0.002388 u mass is missing (→ Mass defect.)

Now, the energy needed to work up a deuterium nucleus into separate neutron and proton is 2.224 MeV. Thus Binding Energy can be defined as -

The energy equivalent to mass difference between the sum of the masses of individual nucleons (protons and neutrons) and the mass of the nucleus. That is the energy equivalent to the missing mass of a nucleus. It represents the energy needed to dissociate the nucleus into separate nucleons. The more the B.E. the more energy that must be supplied to break up the nucleus.

Therefore the binding energy E_b in of a Nucleus can be written as

$$E_B = [\, Z\, m_p + N m_n - m(A,Z)\,]\, c^2$$

or, $$E_B = [\, Z\, m_p + N m_n - m(A,Z)\,]\ 931.49 \text{ Mev/u}$$
$$= (\Delta m)c^2$$

Now average binding energy per nucleon

$$E_{B,avg}(A,Z) = \frac{E_{B\,Total}}{A}$$

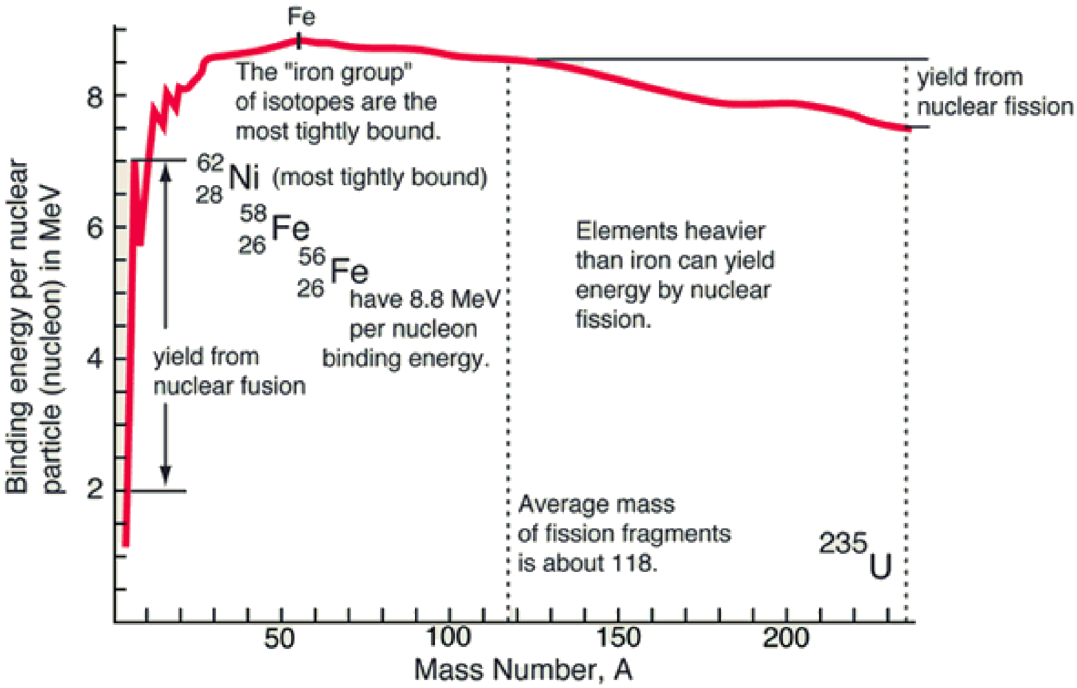
Thus, binding energy per nucleon is the energy that is needed to separate an proton or neutron form the nucleus. This is also called separation energy.

Problem: BE of the Neon isotope ${}^{20}_{10}Ne$ is 160.647 MeV. What is its atomic mass?

Sol^n : Here Z = 10, N= 10, m_p = 1.007825 u, m_n = 1.008665 u.

$$\therefore m(A,Z) = [(Z\,m_p + N m_n) - (E_B/931.49)]$$
$$= [(10\times 1.007825 + 10\times 1.008665) - (160.647/931.49)]$$
$$= 19.992 \text{ u}$$

B. E Curve: If we plot B. E per nucleon $E_{B,avg}$ in MeV as a function of mass number we get the curve rises sharply at first and then rises gradually until it reaches a maximum of 8.79 MeV at A= 56, Corresponding to ${}^{56}_{26}Fe$ and thereafter, drops slowly to about 7.6 MeV at the highest mass numbers. Thus, the nuclei with intermediate mass range are more stable and if higher mass number nuclei split into lighter ones or light nuclei joined together some energy will be released. The peaks in the curve show the existence of isobars.



Radioactivity

-Time dependent property of nucleus

The main features of radioactive decay are as follows:

1. When nucleus undergoes α or β decay, it's atomic number Z changes and it becomes the nucleus of a different element
2. The radioactive decay occurs naturally, i.e., without any external excitation.
3. Radioactive decay is a statistical process and does not involve cause-effect relationship.

- Uranium has all the isotope radioactive

There are five types of radioactivity so far for-

1) Alpha (α)-decay: $^{A}_{Z}\text{X} \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$ i.g., $^{238}_{92}\text{U} \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$
2) Beta (β^-)-decay: $^{A}_{Z}\text{X} \rightarrow {}_{Z+1}^{A}Y + e^-$ i.g., $^{14}_{6}\text{C} \rightarrow {}^{14}_{7}N + e^-$
3) Positron (β^+)-emission: $^{A}_{Z}\text{X} \rightarrow {}_{Z-1}^{A}Y + e^+$ i.g., $^{64}_{29}\text{Cu} \rightarrow {}^{64}_{28}Ni + e^+$
4) Gamma (γ)-decay: $^{A}_{Z}\text{X}^* \rightarrow {}^{A}_{Z}X + \gamma$ i.g., $^{87}_{38}\text{Sr}^* \rightarrow {}^{87}_{38}\text{Sr} + \gamma$
5) Electron (e^-)-capture: $^{A}_{Z}\text{X} + e^- \rightarrow {}_{Z-1}^{A}Y$ i.g., $^{64}_{29}\text{Cu} + e^- \rightarrow {}^{64}_{28}Ni$

Difference between X-ray and γ-ray:

X-ray produces due to the transition of orbital electron or due to acceleration of high energy electron.

γ-ray is a nuclear radiation that is emitted when excited atom losses energy and transit to the stable state.

Activity or Radioactivity:

The activity or radioactivity of a sample of any radioactive nuclide is the rate at which the nuclei of its constituent atoms decay. If N is the number of radioactive nuclei present in the sample at a certain time its activity A or R is given by

$$R = -\frac{dN}{dt} \qquad (1)$$

The minus sign is used to make R positive as $\frac{dN}{dt}$ negative.

- ✓ SI unit of Radioactivity is Becquerel. 1 Becquerel = 1 Bq = 1 decay/s
- ✓ Traditional unit of Radioactivity is Curie. 1 Curie = 1 Ci = 3.7×10^{10} disintegration /s = 37 G Bq.

Laws of Radioactive decay:

It has been observed experimentally that activity of a radioactive sample obeys exponential decay. If N is the number of nuclei in a sample at time t, then the rate of disintegration,

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

or, $$\frac{dN}{dt} = -\lambda N \qquad (2)$$

Here λ is the constant of proportionality known as *decay constant* or *disintegration constant*, which is a characteristic of a unique element.

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_0^t dt$$

or, $$[lnN]_{N_0}^{N} = -\lambda [t]_0^{Nt}$$

or, $$ln\,N - ln\,N_0 = -\lambda t$$

or, $$ln\frac{N}{N_0} = -\lambda t$$

$$\therefore\; N = N_0 e^{-\lambda t} \qquad (3)$$

This is the decay law and it gives the number N of **un-decayed nuclei** at time t in terms of the decay probability per unit time of the nuclide involved and the number of un-decayed nuclei at time t = 0.

$$\therefore\; R = -\frac{dN}{dt} = -\frac{d\,(N_0 e^{-\lambda t})}{dt} = \lambda N_0 e^{-\lambda t}$$

Because, at $t = 0$, $R = R_0 = \lambda N_0$ is the initial activity.

$$\therefore\; R = R_0 e^{-\lambda t} \qquad (4)$$

So activity of a radioactive material also falls off exponentially.

Half Life: It is defined as the time interval which the amount of the radioactive element reduces top one half of the initial amount. It is the time when activity of a specimen reduces to half of its initial activity.

i.e., $N = N_o/2$, or $R = R_o/2$, at $t = T_{1/2}$

$$\therefore\; N_0/2 = N_0 e^{-\lambda t}$$

or, $$T_{1/2} = \frac{ln2}{\lambda} = \frac{0.693}{\lambda}$$

i.e., $$T_{1/2} \propto \frac{1}{\lambda}$$

Average or mean Life:
The life of every atom present in the radioactive element is different. Thus the average life period of the atoms can be computed by adding the life period of all the atoms and then dividing it by the total number of atoms present initially. That is average lifetime,

$$\bar{T} = \frac{\int_{N_0}^{0} t\,dN}{\int_{N_0}^{0} dN}$$

$$= \frac{\int_0^\infty t\left(-\lambda N_0 e^{-\lambda t}\right)dt}{[N]_{N_0}^{0}}$$

$$= \frac{-\lambda N_0 \int_0^\infty t\left(e^{-\lambda t}\right)dt}{[0 - N_0]}$$

$$= \frac{-\lambda N_0 \int_0^\infty t\,(e^{-\lambda t})dt}{[0 - N_0]}$$

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

$$= \lambda\{[\frac{t\,(e^{-\lambda t})}{-\lambda}]_0^\infty - \frac{\int_0^\infty e^{-\lambda t}dt}{-\lambda}\}$$

$$= \lambda\left\{0 + \frac{\int_0^\infty e^{-\lambda t}dt}{\lambda}\right\}$$

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

$$= [\frac{e^{-\lambda t}}{-\lambda}]_0^\infty$$

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

$$\therefore\ \bar{T} = \frac{1}{\lambda}$$

Therefore the mean lifetime is the reciprocal of its decay probability per unit time. And we can also show that

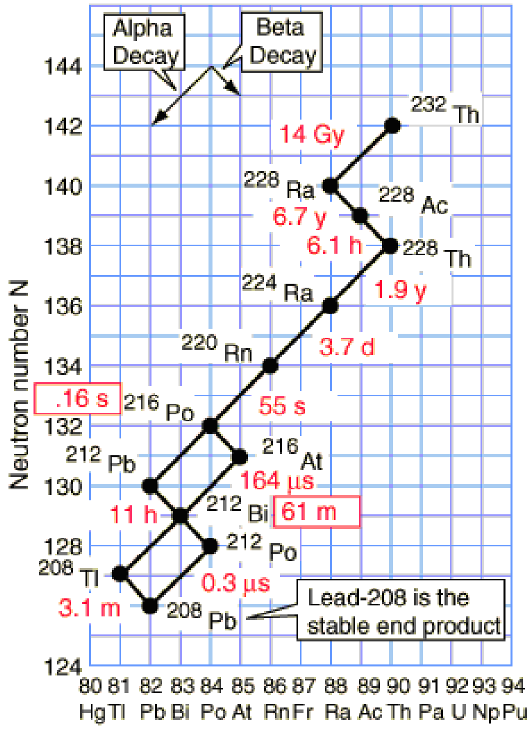
$$\therefore\ \bar{T} = \frac{1}{\lambda} = \frac{T_{1/2}}{0.693} = 1.44\,T_{1/2}$$

$$Or, \qquad T_{1/2} = 0.693\bar{T}$$

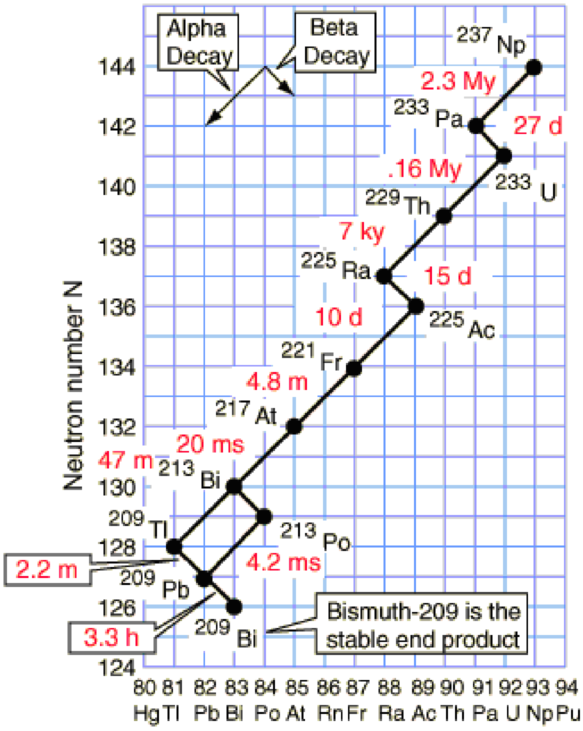
Radioactive Series: Most of the radio nuclides found in nature are members of radioactive series. As α-decay reduces the mass number of a nucleus by 4, there are 4 radioactive series that each ends in a stable daughter.

Mass Numbers	**Series**	**Parent**	**Half Life** (year)	**Stable End**
4n	Thorium	$^{232}_{90}Th$	1.39×10^{10}	$^{208}_{82}Pb$
4n+1	Neptunium	$^{237}_{93}Np$	2.25×10^{6}	$^{209}_{83}Bi$
4n+2	Urenium	$^{238}_{92}U$	4.51×10^{9}	$^{206}_{82}Pb$
4n+3	Actinium	$^{235}_{92}U$	7.07×10^{8}	$^{207}_{82}Pb$

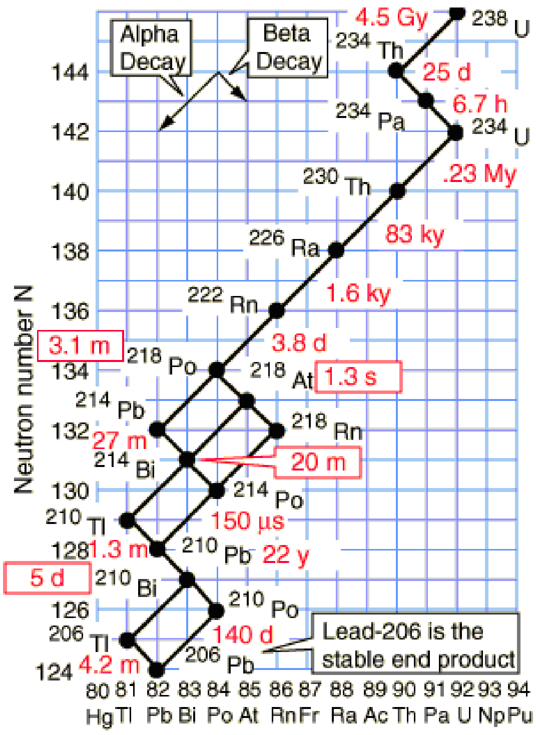
Thorium Series



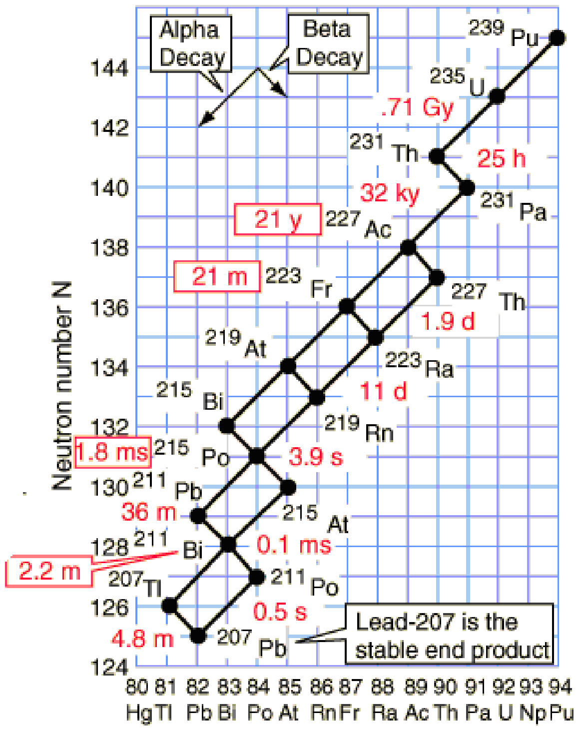
Neptunium Series



Uranium Series



Actinium (Uranium-235) Series



Nuclear Reaction (Artificial Radioactivity)**:**

Nuclear reaction refers to a process which occurs when a nuclear particle comes into close contact with one another during which energy and momentum exchange takes place.

In general nuclear reaction can be represented by an equation in the following form:

$$^{A}_{Z}X + x \rightarrow ^{A'}_{Z'}Y + y \qquad or \ \ ^{A}_{Z}X(x,y)^{A'}_{Z'}Y$$

where X is the target nucleus which is bombarded by the particle x. The resulting compound nucleus breaks up almost immediately by ejecting a particle y. leaving a residual nucleus Y. In most cases the projectiles are elementary particle, neutron (n), deuteron (d), α-particle, γ-ray, etc.

Types of Nuclear Reactions:

a. Elastic Scattering: $^{A}_{Z}X(x,x)^{A}_{Z}X \quad ie., \ ^{A}_{Z}X + x \rightarrow ^{A}_{Z}X + x$

b. Inelastic Scattering: $^{A}_{Z}X(x,x)^{A}_{Z}X^{*} \quad ie., \ ^{A}_{Z}X + x \rightarrow ^{A}_{Z}X^{*} + x$

c. Radiative capture: $^{A}_{Z}X(x,\gamma)^{A'}_{Z'}Y \quad ie., \ ^{A}_{Z}X + x \rightarrow ^{A'}_{Z'}Y^{*} \rightarrow ^{A'}_{Z'}Y + \gamma$

d. Disintegration Process: $^{A}_{Z}X(x,y)^{A'}_{Z'}Y$ *ig.*, $^{14}N + \alpha \rightarrow ^{17}O + p$

e. Many Body reaction: $^{A}_{Z}X(x,y_1,y_2,y_3,\ldots)^{A'}_{Z'}Y$ *ig.*, $^{16}O\,(p,\,2p)^{15}N$

f. Photo disintegration: $^{A}_{Z}X(\gamma,y)^{A'}_{Z'}Y$

g. Nuclear fission: $^{A}_{Z}X(x,y)^{A'}_{Z'}Y$, where y and Y have comparable masses

h. Elementary particle reactions: These involve elementary particles.

i. Heavy ion reactions: Bombarding particle is heavier than $^{4}_{2}He$ nucleus

Conservation laws in Nuclear reactions: *Ref: Atomic and Nuclear Physics by S. N Ghoshal*

a. Conservation of mass number : $A + a = A' + a'$

b. Conservation of atomic number : $Z + z = Z' + z'$

c. Conservation of energy : $M_X c^2 + E_X + M_x c^2 + E_x = M_Y c^2 + E_Y + M_y c^2 + E_y$

d. Conservation of Linear momentum: $P_X + P_x = P_Y + P_y$

e. Conservation of angular momentum: Total angular momentum (I) conserved.

$$I_X + I_x + l_X \rightarrow I_Y + I_y + l_Y$$

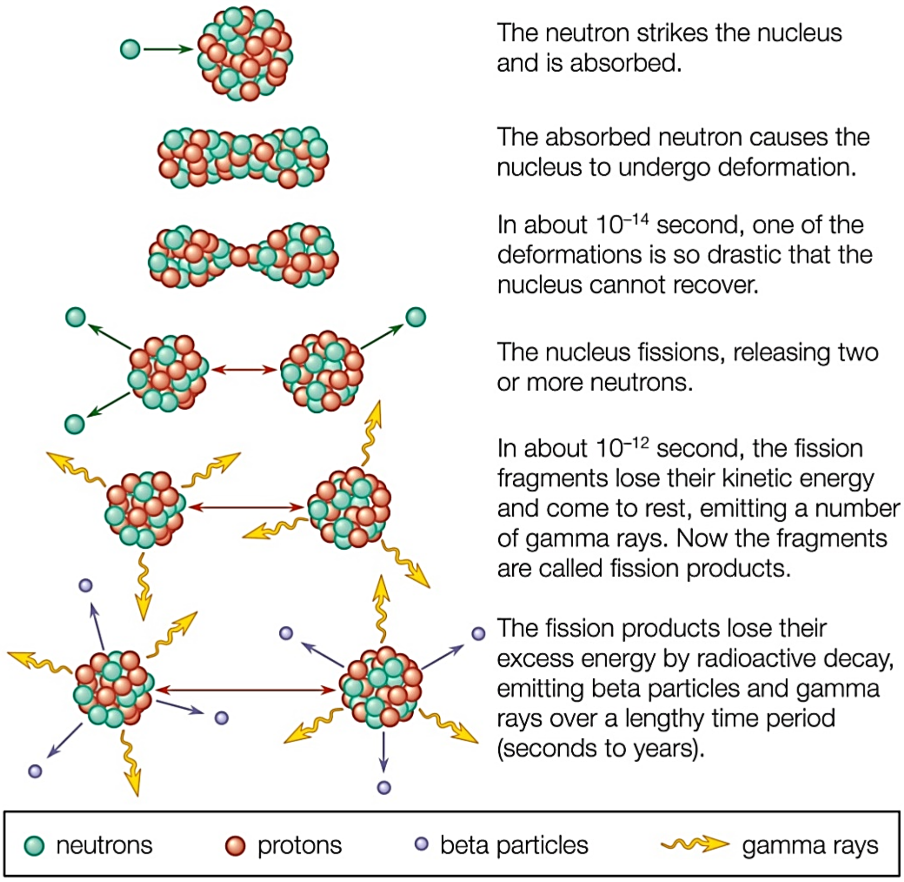
f. Conservation of Parity:

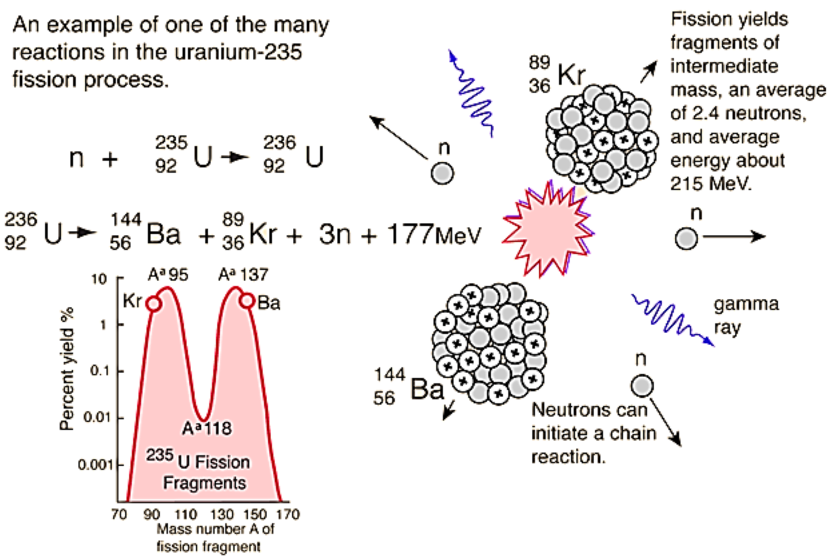
g. Conservation of isotopic spin :

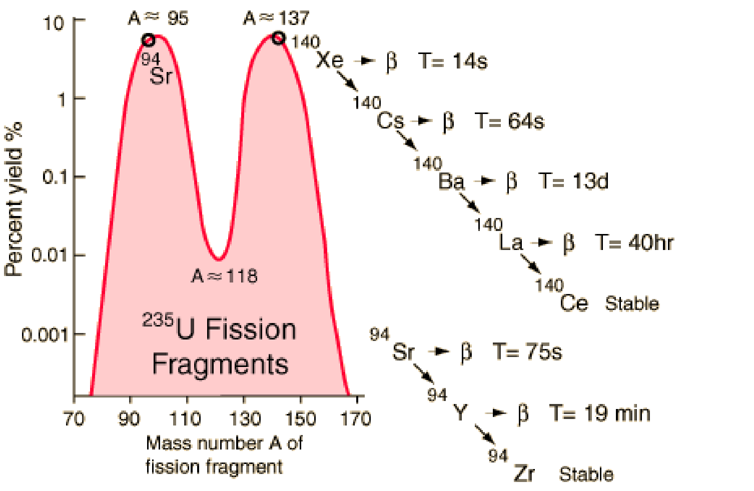
Nuclear Fission:

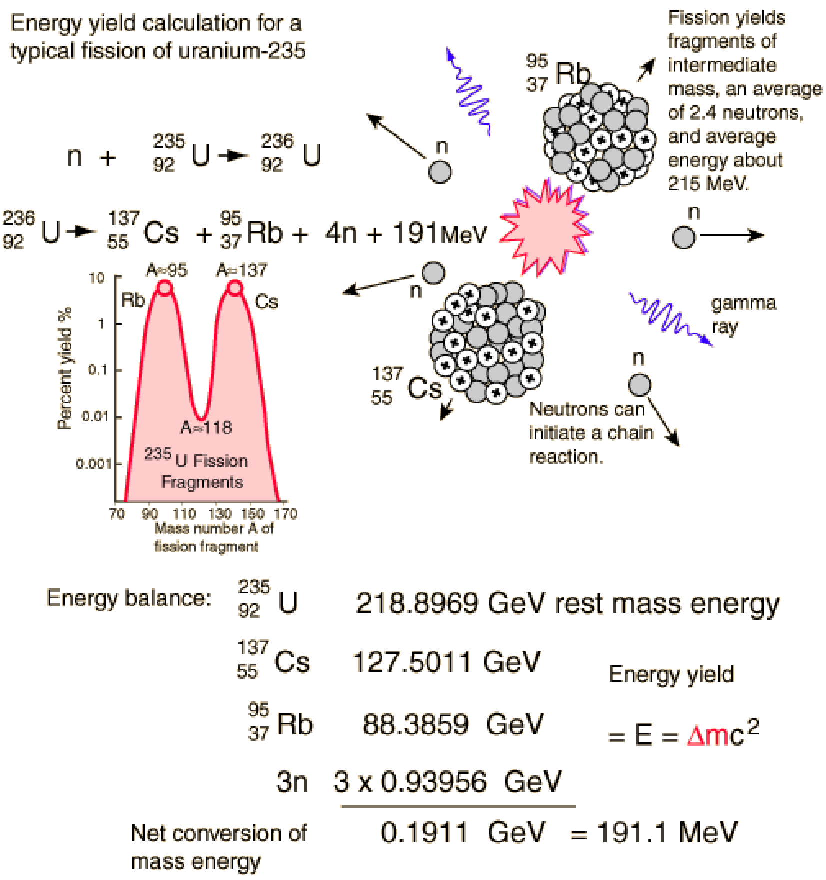
The process of disintegration of a heavy nucleus into two nuclei of comparable masses is termed as nuclear fission. Fission occurs for heavy nucleus because of the increased Coulomb forces between the protons.

Fission may also be termed as **induced nuclear reaction**, when a neutron absorbed by a heavy nucleus, forms a highly excited compound nucleus, that may quickly undergo fission. The fission of ^{235}U by bombarding neutrons is an example of induced fission.





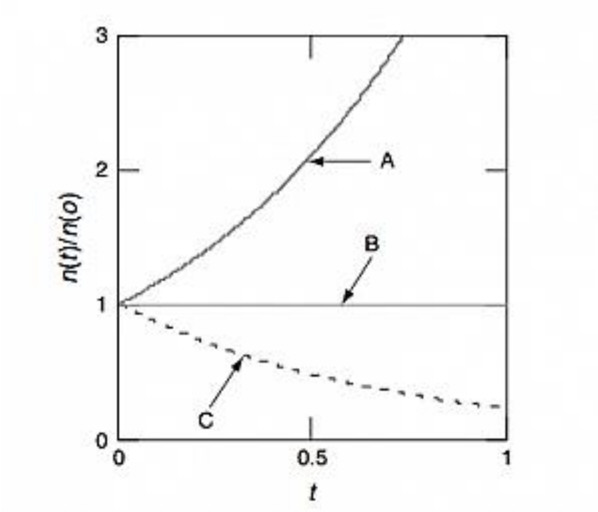




Chain reaction: As fission leads to other neutrons, the secondary neutrons can further cause fission and a sort self-sustaining sequence of fission should be possible. This is called chain reaction.

- If two few neutrons cause further fission they will slow down and stop. This is the **sub-critical situation**.
- If precisely one neutron per fission causes fission, energy will be released at a constant rate. This is the **critical situation** and is used in nuclear reactor.
- If the frequency of fission increases, the energy release will be so rapid that an explosion will occur which is the case in the **atomic bomb** and this is the **supercritical situation**.

NB: 1 m^3 block of U liberate 10^{12} kWh energy in less than 0.01 seconds.

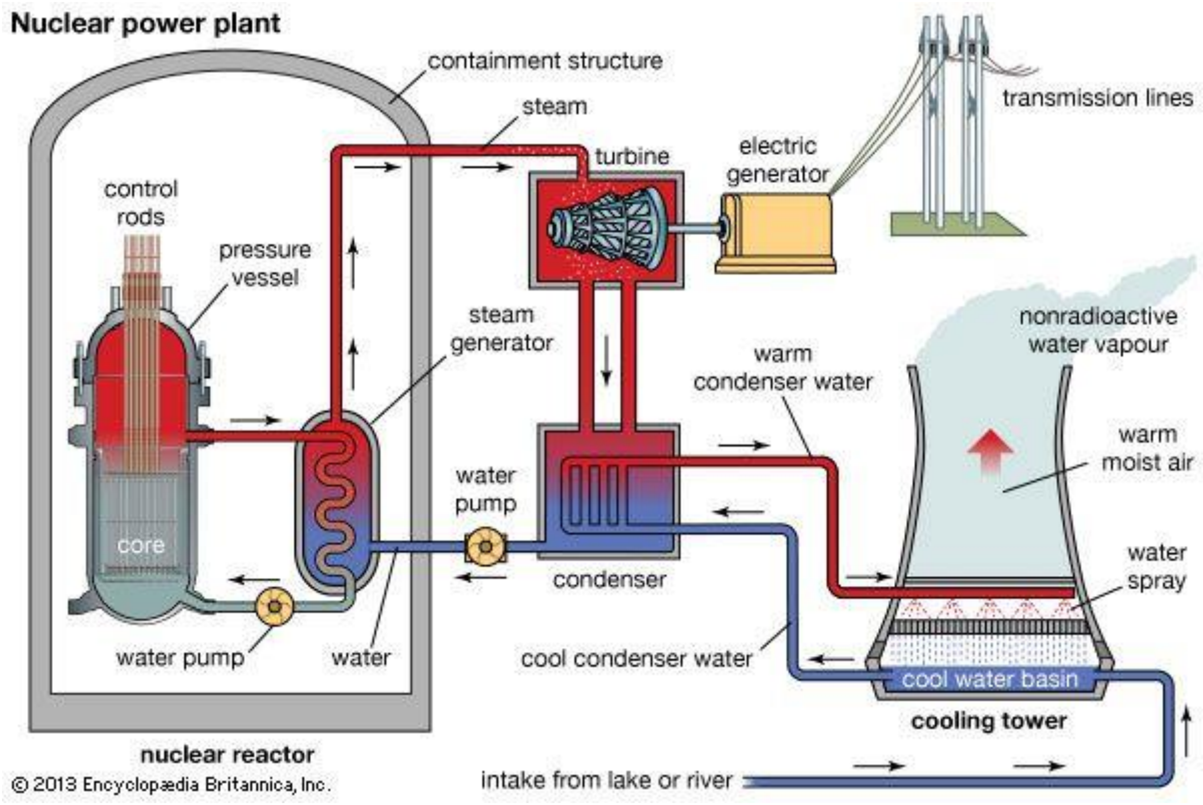


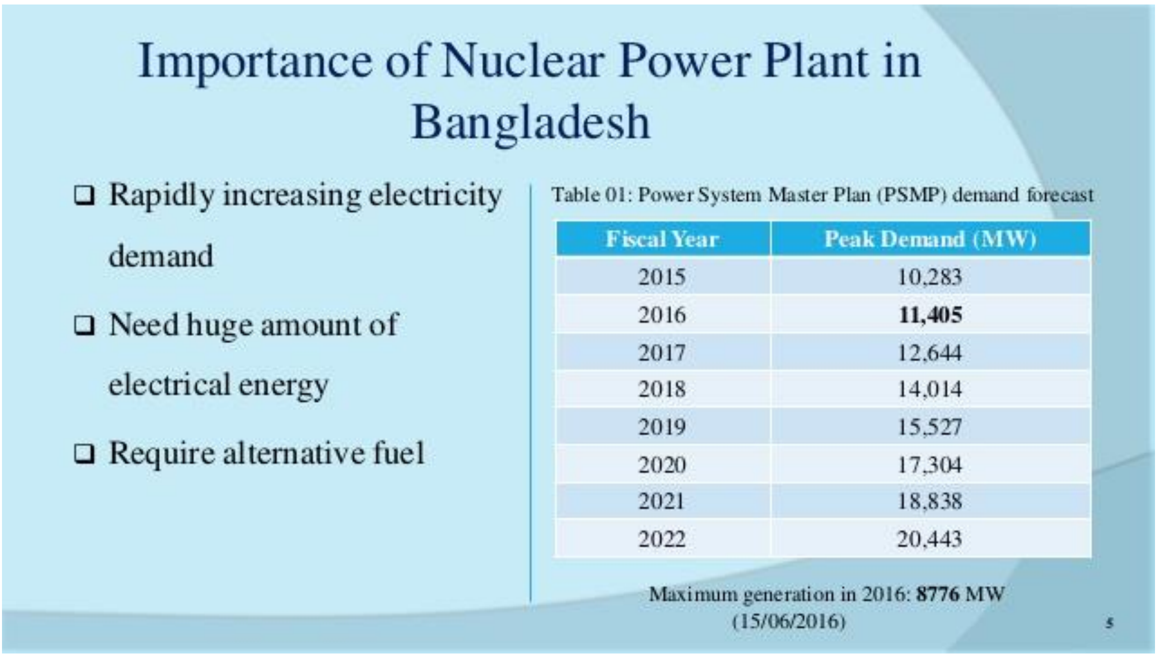
Reactor criticality. A – supercritical state; B – critical state; C – subcritical state

The basic classification of states of a reactor is according to the **multiplication factor as eigenvalue** which is a measure of the change in the fission neutron population from one neutron generation to the subsequent generation.

- **k_{eff} < 1**. If the multiplication factor for a multiplying system is **less than 1.0**, then the **number of neutrons is decreasing** in time (with the mean generation time) and the chain reaction will never be self-sustaining. This condition is known as **the subcritical state**.
- **k_{eff} = 1**. If the multiplication factor for a multiplying system is **equal to 1.0**, then there is **no change in neutron population** in time and the chain reaction will be**self-sustaining**. This condition is known as **the critical state**.
- **k_{eff} > 1**. If the multiplication factor for a multiplying system is **greater than 1.0**, then the multiplying system produces **more neutrons** than are needed to be self-sustaining. The number of neutrons is exponentially increasing in time (with the mean generation time). This condition is known as **the supercritical state**.

The definitions described above are fully applicable to a reactor at **zero power level**, that is at such power level in which **all thermal considerations** are not important to the chain reaction (let say **from zero power to 1% of rated power**).





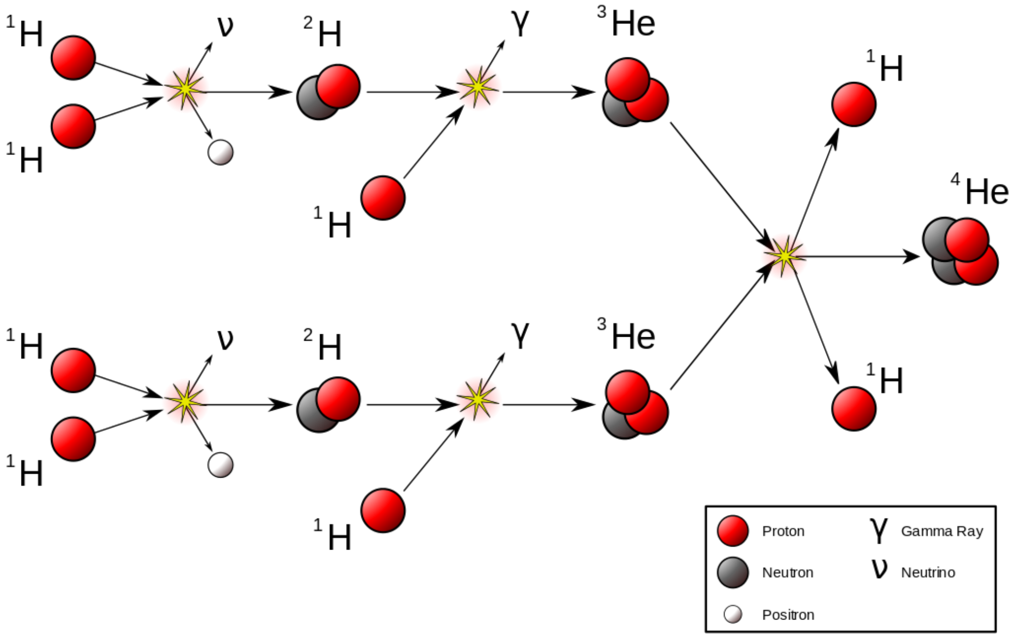
Rooppur Nuclear Power Plant is an under-construction 24000 MW nuclear power plant in Bangladesh. The nuclear power plant is being constructed at Rooppur (Rupppur), adjoining Paksey, in the Ishwardi Upazila of Pabna District, on the bank of the river Padma. It will be the country's first nuclear power plant, and the first of two units is expected to go into operation in 2023. It is being built by the Russian Rosatom State Atomic Energy Corporation.

Figure 03: Image of Rooppur Nuclear Power Plant

Nuclear fusion:

It is the process of fusing light nuclei together to form a single nucleus e.g., the fusion of hydrogen to form deuterium or helium. All these reactions occur at very high temperatures (~10^9 °C) and are called thermonuclear reactions.

Energy emitted by stars arises from nuclear fusion reactions. The proton-proton chain described below is one of the important cycles for producing energy in stars.



The possible mechanism used for producing very high energy is the self sustained fission explosions. In this case, the temperature of atomic explosion acts as a trigger for the fusion process to start and subsequently tremendous amount of energy is released. This is the principle of hydrogen bomb which is an uncontrolled fusion reaction.

The core of the sun is believed to be at a temperature of about 15 million K, which allows the proton-proton cycle to occur there.

Fusion reactor: Enormous energy produced in fission. Like this the fusion of light nuclei can produce more energy. Nuclear fusion promises to become the ultimate source of energy on the earth, safe, relatively nonpolluting, and with the oceans themselves supplying limitless fuel.

Applications of Radioactivity:

1. Radiometric dating: In evaluation of the ages of ancient objects.
2. Elemental analysis by artificial radioactivity: Element presents in a sample can be identified and quantified.
3. Application in medical science: Different isotopes such as ^{3}He, ^{14}C, ^{99m}Tc, etc. are widely used in medical research, diagnostics and treatment.
4. Industrial applications:
5. Agriculture:
6. Power generation:

Etc.

Problem: All Examples +

1. Find the number of alpha-decays that occur in a one gram sample of thorium [$^{232}_{90}Th$] in one year if the disintegration constant λ of $^{232}_{90}Th$ is 1.58×10^{-18} sec^{-1}. Also calculate the activity of one gm of $^{232}_{90}Th$. What would be the volume of helium gas produced by 1 gm of $^{232}_{90}Th$ in one year?
2. A 1.00 g sample of samarium emits alpha particles at a rate of 120 particle/sec. The responsible isotope is $^{147}_{62}Sm$, whose natural abundance in bulk samarium is 15%. Calculate the half-life for the decay process. Molar mass of samarium = 150.35 g.
3. Calculate the activity of ^{40}K in 100 kg man assuming that 0.35% of the body weight is potassium. The abundance of ^{40}K is 0.012%; its half-life is 1.31×10^{9} years.
4. An old wooden piece has 25.6% of radioactive carbon as compared to ordinary wood. Find its age, if its half-life is 5760 years.
5. The ratio of $^{235}_{92}U$ to $^{238}_{92}U$ in natural uranium deposits today is 7.2×10^{-3}. What was this ratio two billion years ago? Given, half-life of $^{235}_{92}U = 0.704 \times 10^{9}$ y and half-life of $^{238}_{92}U = 4.47 \times 10^{9}$ y.
6. A neutron breaks into a proton, electron and neutrino. Calculate the energy released in the process in MeV.
7. A city requires on the average 100 megawatts of electrical power per day and this is to be supplied by a nuclear reactor of efficiency 20%. Using U-235 as a nuclear fuel, calculate the amount of fuel required for one day’s operation. Energy released per fission of U-235 nuclide is 200 MeV.

8. A deuterium nucleus fuses with tritium nucleus to produce ^{4}He and a secondary neutron in the following reaction ${}_{1}^{2}H+{}_{1}^{3}H\rightarrow{}_{2}^{4}He+{}_{0}^{1}n+\Delta E$. Suppose through this reaction, you want to produce 100 MW of power. Calculate the mass of ${}_{2}^{4}$He that will be produced per unit time.

9. What is the power output of a reactor fueled by uranium-235 if it takes 30 days to use up 10 Kg of fuel and if each fission gives 200 MeV of energy?

10. A fusion reactor uses deuterium as fuel to give 200 MW power output. Find the fuel consumption per day if the reactor works with 25% efficiency. Given the masses of ${}_{1}^{2}$H =2.0141 *amu* and ${}_{2}^{4}$He=4.002603 *amu*.

11. In the interior of the sun a continuous process of 4 protons fusing into a helium nucleus and a pair of positrons is going on. Calculate [a] the release of energy per reaction and [b] the rate of consumption of hydrogen to produce 1 MW of power. Given mass of ${}_{1}^{1}$H=1.007825 *amu*, $m_{\beta^+} = 5.5 \times 10^{-4}$ *amu*.