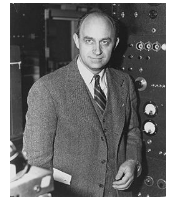
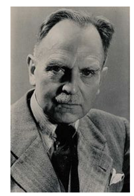
Historical Outline

- Rutherford described as the father of nuclear physics, bombarded alpha particles on Nitrogen to eject a proton and thus started the business of splitting atom in 1917
- James Chadwick is credited with discovering neutron in 1932. Being neutral, it can easily penetrate the Columb barrier and interact directly with the nucleus

Historical Outline



- Enrico Fermi, considered to be one of the most brilliant physicist, postulated and succeeded in producing transuranic elements by bombarding neutrons on Uranium. However, he did not realise that he had fissioned Uranium in 1934



- Otto Hahn, Fritz Strassman and Lise Meitner in 1938 conducted experiments similar to Fermi and were the first ones to postulate fission and pointed the large energy that will be released

Review of Nuclear Physics I

Chemical Energy ⇒ Rearrangement of Electrons

Nuclear Energy ⇒ Rearrangement of Nucleons

Rutherford's Model

Protons, Neutrons, Electrons

	Mass	Charge
Proton	$1.67261 X10^{-24}$ g	$+1.60219 X10^{-19}$ Columbs
Electron	$9.10956 X10^{-28}$ g	$-1.60219 X10^{-19}$ Columbs
Neutron	$1.67492 X10^{-24}$ g	0

Review of Nuclear Physics II

$^{A}_{Z}X$

Z - No of Protons

A - No of Protons + No. of Neutrons

Isotope – Same Z, different A

Radius of Nucleus = 10^{-15} m

Radius of Atom = 10^{-10} m

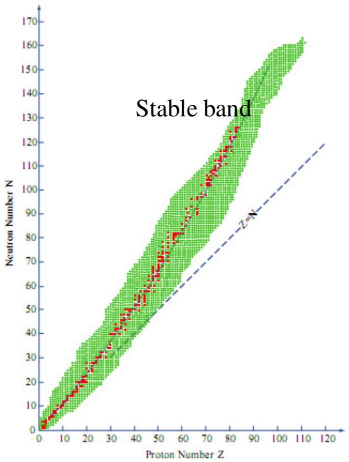
Density of Nucleus = 10^{17} Kg/m^3

Density of Atom = 10^{3} Kg/m^3

⇨ Enormous Hollow space

⇨ Large number of neutrons for collisions of occur.

Stability of Nucleus



The known nuclides. Stable nuclides are indicated by red dots and radioactive nuclides by green dots. The line of equal neutrons and protons is shown by the heavy dashed line.

- The stable isotopes are shown in Red
- The green ones are radioactive (unstable)
- The unstable ones move towards a stable isotope
- The ratio of N/P increase from 1 to 1.5 progressively as Z increases
- Fission products will be heavily neutron rich and hence will expel neutrons

Nuclear Reactions

$$ {}^{A_1}_{Z_1}x_1 + {}^{A_2}_{Z_2}x_2 \rightarrow {}^{A_3}_{Z_3}x_3 + {}^{A_4}_{Z_4}x_4 $$

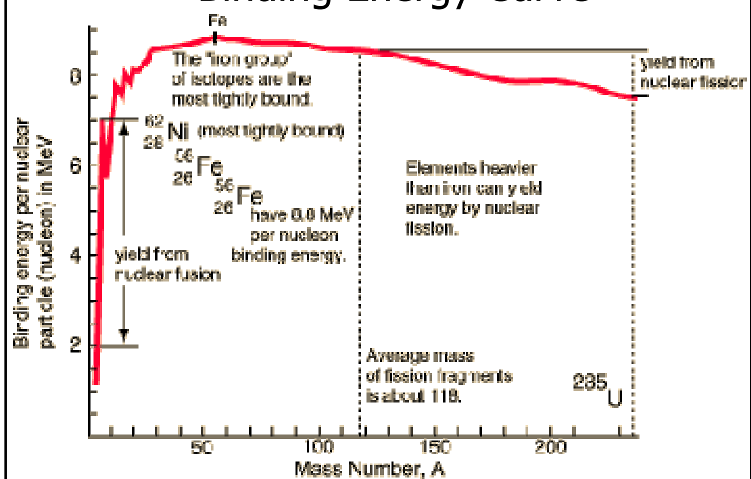
- $Z_1 + Z_2 = Z_3 + Z_4$ (Conservation of charge)
- $A_1 + A_2 = A_3 + A_4$ (Conservation of nucleons)
- In addition we shall have conservation of momentum and energy

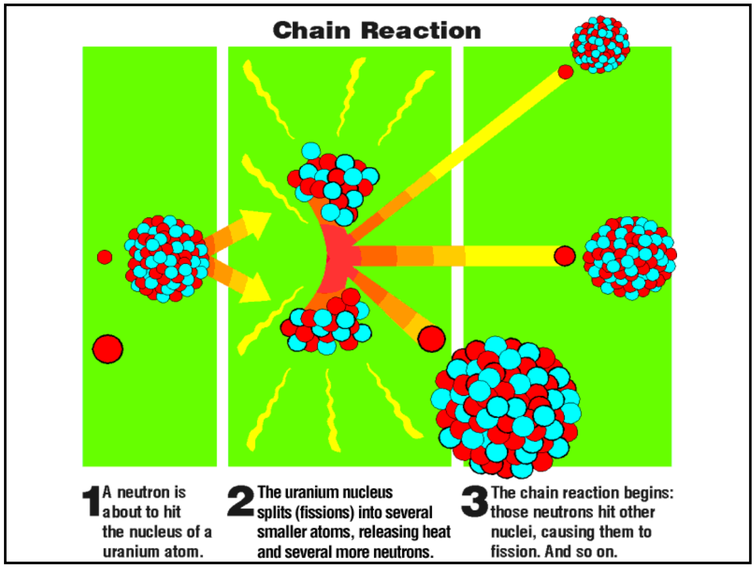
Concept of Binding Energy

$$ {}^1_1H + {}^1_0n \rightarrow {}^2_1H + \gamma(2.23MeV) $$

- Mass of the product nucleus is less than the sum of the masses of reactant nuclei by an equivalent of 2.23 MeV
- Another way of looking at this is that a proton and neutron, the constituents of deuterium nuclei, bind themselves by releasing binding energy of 2.23 MeV
- This implies that we need to supply 2.23 MeV to break deuterium nuclei into its constituents.

Binding Energy Curve





Fission Energetics

- ❑ Consider the following equation

$$^{233}_{92}U + ^{1}_{0}n \rightarrow ^{234}_{92}U + \gamma(6.6MeV)$$

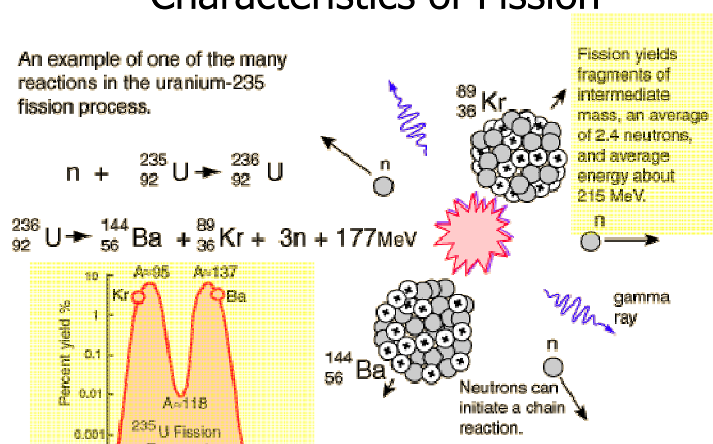
- ❑ Binding Energy of Last Neutron is 6.6 MeV
- ❑ Energy necessary to be supplied to induce fission is called Critical Energy for Fission

Isotope	Critical Energy for Fission (MeV)	Binding Energy of Last Neutron (MeV)
Th^{233}	6.5	5.1
U^{234}	4.6	6.6
U^{236}	5.3	6.4
U^{239}	5.5	4.9
Pu^{240}	4.0	6.4

Fissile and Fissionable Fuel

- ❑ Thus when neutron is absorbed in U^{233} the neutron deposits its binding energy in the compound nucleus, which is more than what is required to make U^{234} to fission.
- ❑ Those elements which can be fissioned by zero energy neutrons are called **fissile**
- ❑ Thus U^{233}, U^{235} and Pu^{239} are fissile
- ❑ On the other hand, Th^{233} and U^{238} need neutrons with 1.4 MeV and 0.6 MeV respectively for inducing fission. Hence these are called **fissionable** nuclei.
- ❑ Natural Uranium has 99.3% of U^{238} and 0.7% of U^{235}

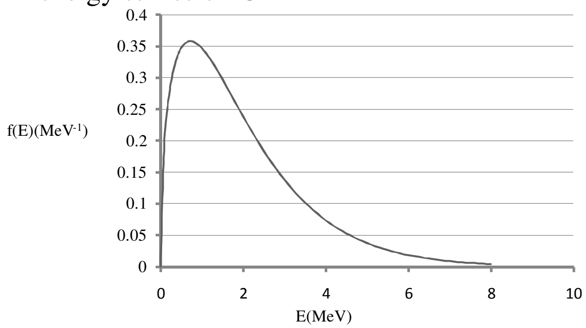
Characteristics of Fission



The number of neutrons released per fission event is denoted by $\overline{\nu}$

Prompt Neutron Spectrum

- Most Probable energy = 0.73 MeV
- Average Energy = 1.98 MeV
- A large fraction of neutron are above the threshold energy to fission U^{238}



Fission and Capture

- A neutron colliding with U^{235} does not guarantee a fission reaction
- There is a finite probability that the neutron will be captured with no fission
- If the probability fission and capture are F and C, then we can define the multiplication of neutron in the fuel, η, as

$$\eta = \frac{F\overline{\nu}}{F+C} = \frac{\overline{\nu}}{1+\frac{C}{F}} = \frac{\overline{\nu}}{1+\alpha}$$

- Since $\alpha < 1$, $\eta < \overline{\nu}$

Isotope	$\overline{\nu}$	η
U^{233}	2.49	2.29
U^{235}	2.42	2.09
Pu^{239}	2.87	2.11

Interaction with the fuel-I

- It has been noticed that as the energy of the colliding neutron is high the probability of reaction is poor
- This is attributed to the reduced time a neutron spends in the zone of interaction
- It is inversely proportional to the speed of the neutron
- In addition to these, there are resonances that attributed to quantum mechanical interactions. The variation is shown in the next slide

Interaction with the fuel-II

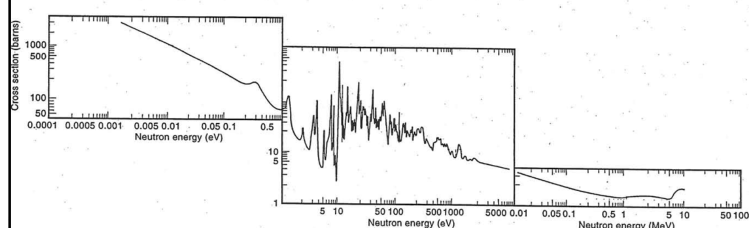
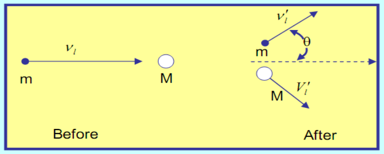


Figure 1. Microscopic cross section of ^{235}U. Source: BNL-325.

- As the interaction decreases rapidly with increase in energy, and that the energy of the prompt neutrons are high, we need to slow them down
- This is done by the use of moderator
- The energy is reduced by collision process and bulk of the slowing is through elastic collision process

Moderation



Trajectories of a neutron and its target nucleus before and after a scattering event as seen from the laboratory reference system.

Element	A	α	N
H	1	0	18
D	2	0.111	25
Be	9	0.640	86
C	12	0.716	114
U	238	0.983	2172

- For a neutron colliding with a nucleus of mass A, the maximum Energy Loss can be shown to be αE_0, where

$$\alpha = \left(\frac{A-1}{A+1}\right)^2$$

- **H as H_2O and D as D_2O are used as moderators**

Overall Multiplication

- We had seen that the fuel multiplies neutron by a factor η
- However, as many other materials are used, such as moderator, structure and control materials, neutron is also absorbed by them
- If the probability of a neutron being absorbed in fuel is f, then the overall multiplication denoted by k_∞ can be written as (∞ denotes that there is no leakage)

$$k_\infty = \eta f$$

- $k_\infty = 1$ implies that the population of neutrons remains steady and the system is called **critical**
- If $k_\infty < 1$ the system is called **sub-critical** and if $k_\infty > 1$ the system is called **Super-Critical**

Conversion and Breeding-I

- When the neutron is captured in U^{238} , it results in U239, which undergoes two β decays as follows

$${}^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{92}U \xrightarrow{\beta^-,\ 23.5\min} {}^{239}_{93}Np \xrightarrow{\beta^-,\ 2.35 day} {}^{239}_{94}Pu$$

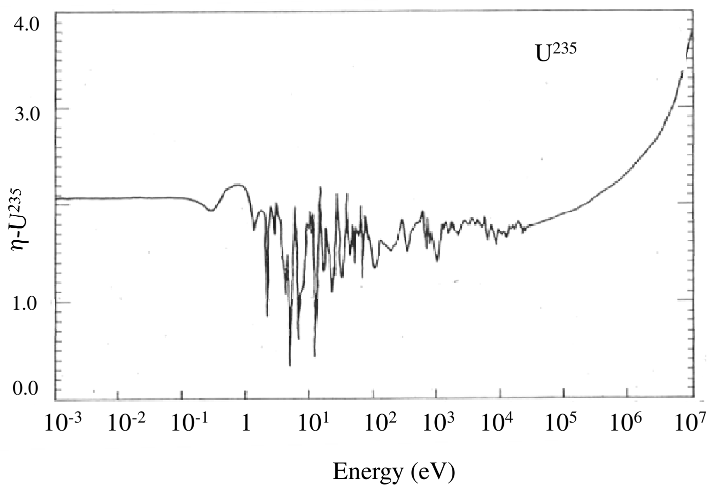
- Thus we see that the non-fissile U^{238} has been converted into a fissile Pu^{239}
- Similar conversion is also possible to get Th^{232} converted into U^{233} with the following reaction

$${}^{232}_{90}Th + {}^{1}_{0}n \rightarrow {}^{233}_{90}Th \xrightarrow{\beta^-,\ 22.2\min} {}^{233}_{91}Pa \xrightarrow{\beta^-,\ 27.4 day} {}^{233}_{92}U$$

- For this purpose, Th^{232} and U^{238} are also called fertile elements

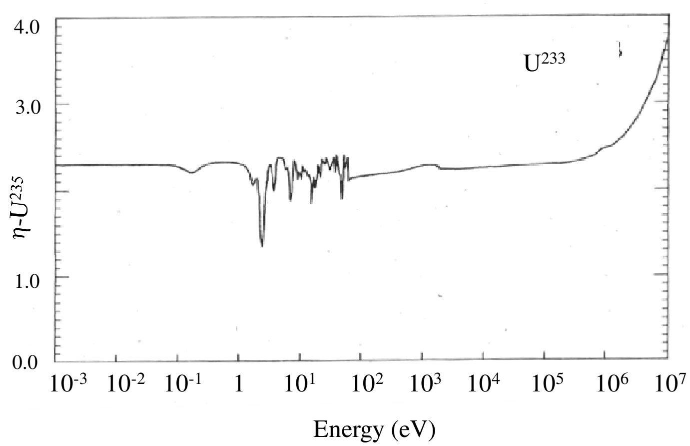
Conversion and Breeding-II

- We noted that for every neutron absorbed in fuel, we get η number of second generation neutrons
- Thus η-1 have to be absorbed elsewhere other than fuel to keep the reactor steady
- While we can use control material to absorb the excess neutrons, it will be useful if the excess is diverted into fertile elements. So that fuel can be generated
- It has been seen that if a high energy neutron is allowed to cause fission, η increases and gives possibility of breeding fuel
- This is precisely the motivation of having fast reactors



Fast Reactor

- In fast reactor neutrons are not allowed to slow down by moderators
- The excess neutrons are directed at the fertile blanket
- As the probability of reaction is low, the fuel has to be highly enriched.
- Usually Sodium is used as the coolant
- Hence these are Liquid Metal Fast Breeder Reactors



Power Reactors

Type	Moderator	Coolant	Pressure (bar)	Maximum Temp (C)	Eff. %
Pressurized Water Reactor	Light Water	Light Water	150	320	33
Boiling Water Reactor	Light Water	Light Water	70	250	33
Pressurised Heavy Water Reactor	Heavy Water	Heavy Water	80	320	32
Gas Cooled Reactor	Graphite	Carbondioxide	15	410	35
High Temperature Gas Reactor	Graphite	Helium	45	800	45
Liquid Metal Fast Reactor	-------	Sodium	1	580	42