SCHOOL OF STUDIES IN PHYSICS JIWAJI UNIVERSITY GWALIOR

Topic: Nuclear Fission: Mass and energy distribution of fission fragments

Nuclear Fission

Decay process in which an unstable nucleus splits into two fragments of comparable mass. In 1939, it was found by Hahn and Strassmann that heavy nuclei split into two or more lighter nuclei spontaneously or after the absorption of neutron or ϒ-photon.

1932: discovery of neutrons

1939: official discovery by Otto Hahn and Fritz Strassmann → fission of ^{235}U

↳ Lise Meitner! ($_{109}$Mn)

1942: first "chain reacting pile" (E. Fermi)

1945: first nuclear explosion in Alamogordo (New Mexico, USA)

1972: discovery of Oklo (Gabon): unique natural nuclear reactor ($1.8\ 10^{6}$ y ago)

→ very abnormal isotopic ratios of ^{235}U/^{238}U in uranium ores/

The minimum energy required for fission to take place is known as activation energy. For ^{235}U amount of energy required is 6.4 MeV. The fission reaction can be written as;

$$ {}^{A}_{Z}X \xrightarrow{Fission} {}^{A_1}_{Z_1}X + {}^{A_2}_{Z_2}X + E_F $$

Where, E_F represents energy released during the process and is given by

$$ E_F = M(Z,A)c^2 - \{M(Z_1,A_1) + M(Z_2,A_2)\}c^2 $$

Or, $E_F = B(Z_1,A_1) + B(Z_2,A_2) - B(Z,A)$

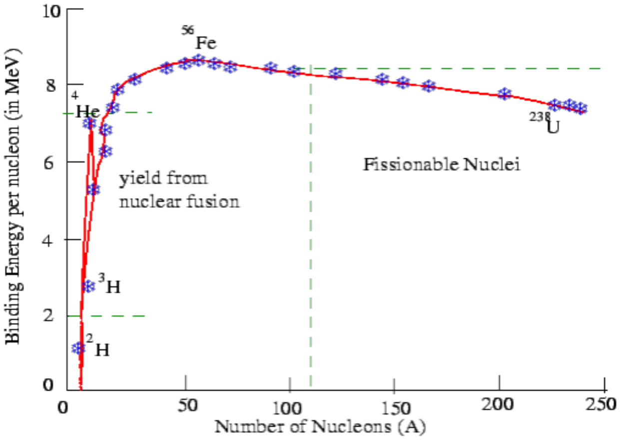
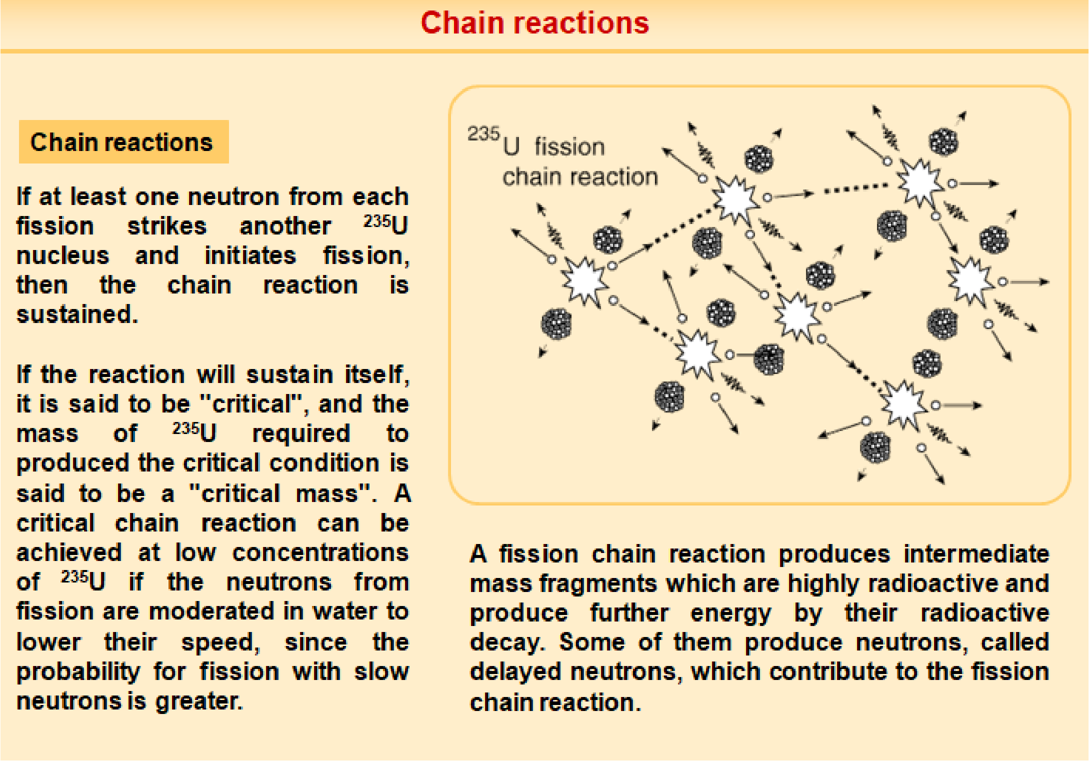


Fig. 1: Binding energy per nucleon *vs* number of nucleons

From the binding energy per nucleon (B/A) curve shown above it can be seen that B/A is maximum for ^{56}Fe. In heavier nuclei B/A decreases and can be increased by splitting heaver nuclei into smaller fragments. The fission fragments are usually unequal in size. Since heavy nuclei have large N/Z ratio, the fragments contains excess of neutrons. These neutrons are called Promt neutrons and are emitted as the fragments are formed. If fission is carried out by bombardment with incident particle, then it is known as induced fission.



Chain reactions

Chain reactions

If at least one neutron from each fission strikes another ^{235}U nucleus and initiates fission, then the chain reaction is sustained.

If the reaction will sustain itself, it is said to be "critical", and the mass of ^{235}U required to produced the critical condition is said to be a "critical mass". A critical chain reaction can be achieved at low concentrations of ^{235}U if the neutrons from fission are moderated in water to lower their speed, since the probability for fission with slow neutrons is greater.

A fission chain reaction produces intermediate mass fragments which are highly radioactive and produce further energy by their radioactive decay. Some of them produce neutrons, called delayed neutrons, which contribute to the fission chain reaction.

Symmetric Fission

Fission is known as symmetric fission if a nucleus breaks into two equal fragments. E.g., if ^{238}U splits two equal fragments with A = 119. The expected energy released in symmetric fission is $E_{FS} = M(Z,A) - 2M(Z/2, A/2) = B(Z/2, A/2) - B(Z,A)$. By binding energy formula, the binding energy of nucleus $^{A}_{Z}X$ can be written as;

$B(Z,A) = a_V A - a_S A^{2/3} - a_C \dfrac{Z(Z-1)}{A^{1/3}} - a_A \dfrac{(A-2Z)^2}{A} \pm \delta_0$. And for two fragments $^{A/2}_{Z/2}X'$;

$$B(Z/2, A/2) = a_V A - 2a_S (A/2)^{2/3} - 2a_C \frac{Z/2(Z/2-1)}{(A/2)^{1/3}} - a_A \frac{(A/2-Z)^2}{A} \pm 2\delta_0$$

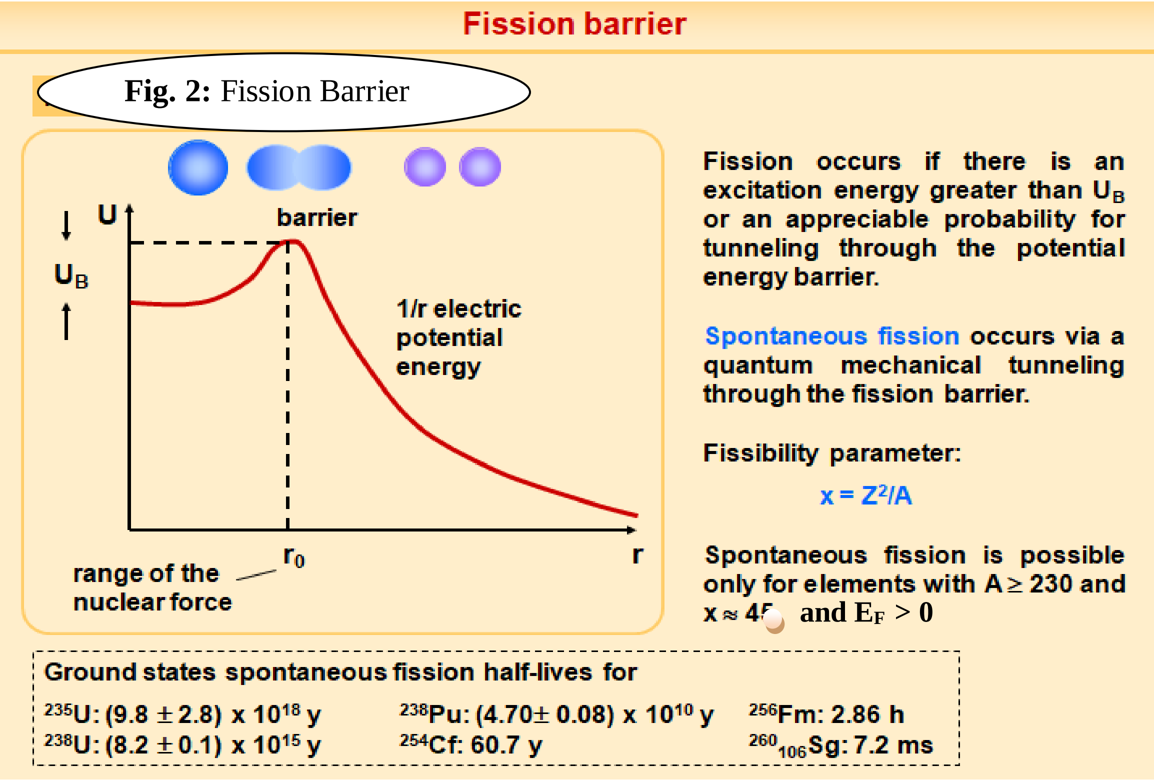
Neglecting the difference of pairing energy, we have

$$E_{FS} = a_S A^{2/3}(1-2^{1/3}) + \frac{a_C}{A^{1/3}} Z\left[Z\left(1-\frac{1}{2^{1/3}}\right)+(2^{1/3}-1)\right]$$

Since $a_C = 0.585$ MeV and $a_S = 13.1$ MeV. Therefore,

$$E_{FS} = \overset{\substack{\boxed{\text{Surface tension term}}\\ \Uparrow}}{\boxed{-3.42A^{2/3}}} + \boxed{0.22\frac{Z^2}{A^{1/3}}} \Rightarrow \boxed{\text{Coulomb repulsion term}}$$

The surface tension term tries to retain nucleus as such. But the Coulomb force are destructive forces and favour fission. When ‘Z’ increases Coulomb repulsion increases dominates over surface tension. The nucleus does not remain stable and thus undergo spontaneous emission.



Fission barrier

Fig. 2: Fission Barrier

Fission occurs if there is an excitation energy greater than U_B or an appreciable probability for tunneling through the potential energy barrier.

Spontaneous fission occurs via a quantum mechanical tunneling through the fission barrier.

Fissibility parameter:

$x = Z^2/A$

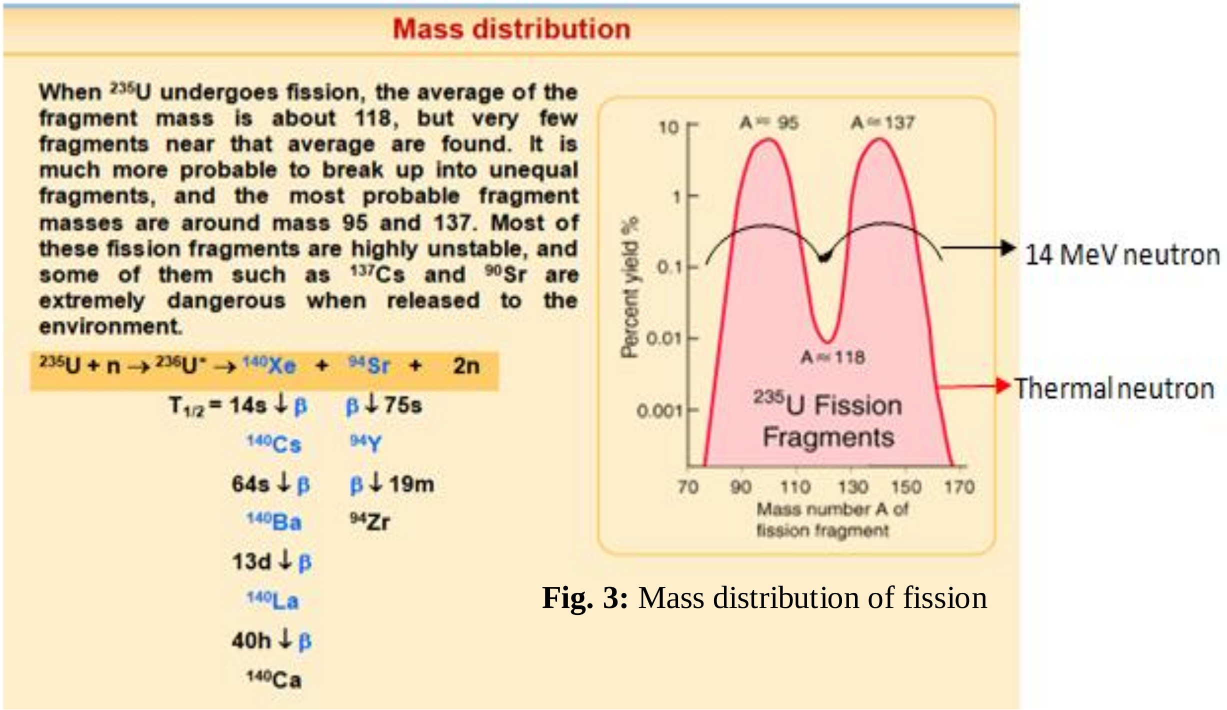
Spontaneous fission is possible only for elements with $A \geq 230$ and $x \approx 45$ and $E_F > 0$

Ground states spontaneous fission half-lives for

^{235}U: $(9.8 \pm 2.8) \times 10^{18}$ y
^{238}U: $(8.2 \pm 0.1) \times 10^{15}$ y
^{238}Pu: $(4.70 \pm 0.08) \times 10^{10}$ y
^{254}Cf: 60.7 y
^{256}Fm: 2.86 h
$^{260}_{106}$Sg: 7.2 ms

Mass and energy distribution of fission products

The mass distribution of fission products is represented via fission yield shown in the Fig. 2 in which percentage yield of different products is plotted against mass number. The yeild of a given mass number can be found by measuring the long lived nuclei near the end of the chain or that of stabble end products. The fission yeild represents the probability of forming that nuclide. The curve shows two peaks corresponding to light and heavy group of products. The distribution must be symmertic about the centre that is for every heavy fragment there must correspond light fragment. From the figure it is clear that fission induced by thermal neutrons is highly assymetric. However, by increasing the energy of incidient neutron the probability of symmetric fisssion increases.



Mass distribution

When ^{235}U undergoes fission, the average of the fragment mass is about 118, but very few fragments near that average are found. It is much more probable to break up into unequal fragments, and the most probable fragment masses are around mass 95 and 137. Most of these fission fragments are highly unstable, and some of them such as ^{137}Cs and ^{90}Sr are extremely dangerous when released to the environment.

$^{235}U + n \rightarrow {}^{236}U^* \rightarrow {}^{140}Xe + {}^{94}Sr + 2n$

$T_{1/2}$ = 14s ↓ β	β ↓ 75s
^{140}Cs	^{94}Y
64s ↓ β	β ↓ 19m
^{140}Ba	^{94}Zr
13d ↓ β	
^{140}La	
40h ↓ β	
^{140}Ca	

Fig. 3: Mass distribution of fission

The kinetic energy of fission products can be determined by measuring the inonization produced in approprate ionization chamber. Considering the nucleus undergoing fission to be at rest and if neutrons emitted can be neglected. Then by law of conservation of momentum we have

$$m_1 v_1 = m_2 v_2$$

$$\frac{m_1}{m_2} = \frac{v_2}{v_1}$$

$$\frac{E_1}{E_2} = \frac{m_2}{m_1} \longrightarrow \boxed{\text{By using } E = mv^2/2}$$

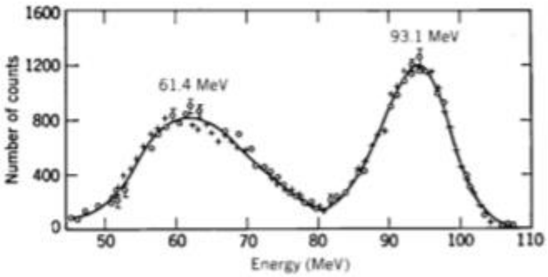


Fig. 4: Energy diistribution of fission fragments

The masses are inversely proportional to kinetic energy. When K.E. distribution has been measured the mass distribution can be obtained. The K.E. distribution has two peaks as well. when two fragments are formed they are in highly excited states, thereby de-excite by emission of ϒ-rays or neutrons or by β -decay. The peaks near at 60 MeV and 95 MeV show the nature of assymetric fission. When energy of incidient neutrons is increassed the probability of symmetric fission increases. With 90 MeV of incidient neutron only one peak is observed corresponding to division into two equal framents.