SEMESTER IV
Paper: PHS-A-CC-4-9-TH
Fission and Fusion:mass deficit, relativity and generation of energy.

Fission and fusion: mass deficit, relativity and generation of energy. Fission - nature of fragments and emission of neutrons. Nuclear reactor: slow neutrons interacting with Uranium 235; Fusion and thermonuclear reactions driving stellar energy (brief qualitative discussions)

1 Fission & Fusion

1.1 Nuclear Fission-its characteristics aspects

The process of breaking up of the nucleus of a heavy atom into two more or less equal fragments with release of a tremendous energy is known as the nuclear fission.

A typical fission of the isotope $^{235}_{92}U$, carried out by Otto Hahn and Strasmann is represented as follows:

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow \left(^{235}_{92}U\right) \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n + Q$$

From the above nuclear reaction we shall now estimate the amount of energy released per fission.

Mass of $^{235}_{92}U$ = 235.11750 a.m.u
Mass of $^{1}_{0}n$ = 1.00898 a.m.u

Total intial mass = 236.12648 a.m.u

Again,
Mass of $^{141}_{56}Ba$ = 140.95770 a.m.u
Mass of $^{92}_{36}Kr$ = 91.92640 a.m.u
Mass of $3^{1}_{0}n$ = 3.0294 a.m.u

Total final mass = 235.91104 a.m.u

$\therefore$ loss in mass (or mass converted to energy)
= (236.12648 − 235.91104) a.m.u
= 0.21544 × 931.2 MeV
= 200.5 MeV
=amount of energy released per fission

The cause of liberation of such enoromous amount of energy during fission is clearly understood if we investigate the nature of binding energy per nucleon (ϵ) versus mass number (A) curve (Figure 1). It is found that the binding energy per nucleon for $^{235}_{92}U$ is about 7.6 MeV, while that of each of the fission fragments lying in the middle of the binding energy diagram is about $8.5MeV$.

Change in binding energy per nucleon =0.9 MeV. Hence, the energy released per fission of $^{235}_{92}U$ will be $0.9 \times 235 \approx 211MeV$. The mechanism of nuclear fission may be explained on the basis of the liquid drop model of the nucleus.

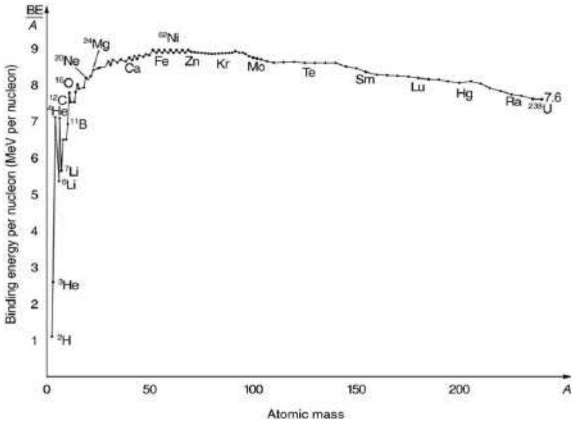

Figure 1: *A graph of average binding energy per nucleon, BE/A, for stable nuclei.*

1.2 Liquid drop theory of fission and the nature of fission fragments

In a liquid drop, the total energy of the particles inside the drop is not sufficient to overcome the forces that hold the particles together in the form of a droplet. But if some energy is added to the drop so as to set it into vibration, it would alternately elongate and contract. If the amplitude of vibration is sufficiently large, the drop might divide itself into two droplets. It was pictured by Bohr and Wheeler that such a situation arises in the $^{235}_{92}U$ nucleus, when bombarded by a thermal neutron and results in its fission. The repulsive forces between positive charges in the nucleus (Coulomb repulsion) are balanced by the binding forces between the nucleus. There is also a kind of surface effect like surface tension in the droplet.

Thus, the net binding energy E of a nucleus is given by

$$E_{net} = E_{Vol} - E_{Coulomb} - E_{surface} \tag{1}$$

When a nucleus is different is deformed, E_{net} decreses due to the increase in the surface area and if enough energy is added to the nucleus resulting in such distortions or vibrations, these may violently disrupt the nucleus to produce the fission. Figure (2) illustrates the percentage of fission fragments in many fissions.

The two peaks of the curve show that in most cases of fissions one particle has mass number ~ 94 and the other 140. The sharp fall at the centre corresponding to $A = 118$ shows that in extremely rare cases $^{235}_{92}U$ divides itself into two equal nuclei.

Fission is not confined to Uranium alone. Under favourable conditions most of the heavy nuclei undergo fission. Again fission may also be induced by method other than neutron capture. The only point is that the nucleus must be fed with an energy greater than the activation energy. Fissions have actually been induced by α particles, protons, deuterons, γ rays or high energy $X-$rays. There may even be auto fission in Uranium.

1.3 Slow, fast and thermal neutrons

The neutrons having an energy less than $1eV$ are called slow neutrons. Those having an energy greater than 1.2 MeV are known as fast neutrons. When the neutrons come into thermal equilibrium with the substance through they pass, they are called thermal

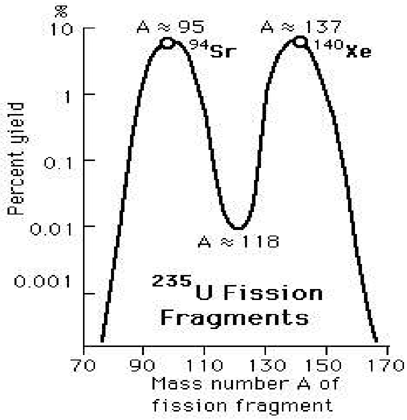

Figure 2: *Fission fragments*

neutrons. The velocities of thermal neutrons are given by Maxwellian velocity distribution formula. The neutrons having an energy within the range from 1eV to 1.2 MeV are called epithermal neutrons.

1.4 Prompt and delayed neutrons

Most of the neutrons (about 99%) that are emitted in the fission of Uranium are ejected almost instantaneously (within 10^{-14} sec) with the fission process. theses neutrons are prompt neutrons. Few other neutrons, however, are ejected rather late. They are actually emitted from neutron decay of the unstable fission fragments while reacting the stable state. Theses neutrons are called delayed neutrons and are of importance in the control of reactors.

The energy of the emitted neutrons varies from 0 to 1.7 MeV with an avarage energy of 2 MeV. The energy distribution of $^{235}_{92}U$ neutrons can be expressed as

$$n(E)dE = k \times e^{-E}\ sinh(2E)^{1/2}dE$$

where $n(E)dE$ is the no. of neutrons emitted in the energy range E and $(E + dE)$.

1.5 Effect of the incident neutron energy on the fission of nuclei

Experimentally, it has been observed that even-odd nuclei like ^{235}U, ^{239}Pu etc. can undergo fission more effectively with slow or thermal neutrons having energies between 0.03 eV and 10 eV. The cross-sections of fissions for these nuclei have been estimated to be 580 barns for ^{235}U and 750 barns for ^{239}Pu. On the contrary this cross section ranges upto 1.27 barns only with high energy ($\sim$ 2 Mev) neutrons. But for even-even nuclei like ^{238}U, ^{232}Th etc only the high energy neutrons can induce fission. For example, the fission cross-section is 0.5 barns for ^{238}U with the high energy neutrons.

1.6 Neutron emission in fission chain reaction

In each event of a fission reaction with heavy nuclei, the highly excited nuclei emit two or three promt neutrons. As suggested by Fermi, these prompt neutrons interact with neighbouring nuclei producing in turn, fission so that more neutrons are emitted. The result is an avalanche like build up of fission events. Such a fission reaction is called a

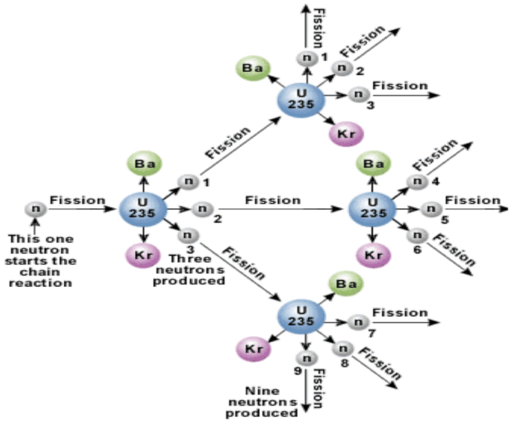

Figure 3: *Fission Chain reaction*

chain reaction. The continuous regeneration of active centres is the distinctive feature of such reactions, for the formation of each new centre is accompanied by a greater number of repeating links or chains of the reaction. It is the neutrons that play the role of active centres in this case of fission chain reactions. The average number of neutrons emitted per fission of ^{235}U is 2.46 and ^{239}Pu is 2.88 as indicated by experiments. A typical chain reaction of ^{235}U is shown in Figure (3).

1.7 Nuclear Fusion

There are some nuclear reactions in which lighter nuclei fuse together and produce a heavier nucleus which occupies a higher position in the periodic table. The systhesis of elements by the fusion of light nuclei is called fusion. If any two particles can overcome Coulomb's potential barrier and come in the range of nuclear forces a finite probability exists that they will get fused together. These reactions are commonly known as thermo-nuclear reactions.

1.8 Nuclear reaction in stars

The condition for fusion reaction is fulfilled in the stellar core with large temperature. The central core temperatures of the stars like the Sun are $\approx 1.5 \times 10^7 \deg K$ and for the fusion of hydrogen nuclei a temperature of the order of $10^7 \deg K$ are required. It is well known, the stars are formed out of hydrogen clouds, which first cluster together and undergo a gravitational contraction leading to the formation of high temperature core material where the fusion reactions are triggered.

Proton-proton reactions are first started and they are the most fundamental of all reactions. H. A. Bethe in 1939 suggested that the production of stellar energy is by thermonuclear reactions in which protons are continuously transformed into helium nuclei. For comparatively low stellar temperatures he proposed the following:

$$
\begin{aligned}
&{}_1^1H + {}_1^1H \rightarrow {}_1^2D + {}_1^0e(\beta^+) + \nu \\
&{}_1^2D + {}_1^1H \rightarrow {}_2^3He + \gamma \\
&{}_2^3He + {}_1^1H \rightarrow {}_2^4He + {}_1^0e(\beta^+) + \nu
\end{aligned}
$$

so that by addition we have

$$4_1^1H \rightarrow {}_2^4He + 2_1^0e(\beta^+) + 2\nu$$

with an energy release of about 27 MeV.

This reaction is followed by a set of reactions

$$
\begin{aligned}
&{}_2^3He + {}_2^3He \rightarrow {}_2^4He + 2_1^1H \\
&{}_2^3He + {}_2^4He \rightarrow {}_4^7Be + \gamma \\
&{}_4^7Be + {}_{-1}^0e \rightarrow {}_3^7Li + \nu \\
&{}_3^7Li + {}_1^1H \rightarrow {}_2^4He + {}_2^4He \\
&{}_4^7Be + {}_1^1H \rightarrow {}_5^8B + \gamma \\
&{}_5^8B \rightarrow {}_4^8Be + {}_1^0e + \nu \\
&{}_4^8Be \rightarrow {}_2^4He + {}_2^4He \\
&{}_4^8Be + {}_2^4He \rightarrow {}_6^{12}C
\end{aligned}
$$

The entire class of low mass nuclei are built up from the elementary reactions of proton chain till ^{12}C is formed. When the fusion of light nuclei takes place, energy is released, because the mass of the product nucleus is usually smaller than the total mass of the fusing partners in the case of light elements. If we refer to the binding energy curve, we find that it rises sharply in the region $A = 1$ to $A = 20$. Proton-proton reaction is an important source of energy in sun. It predominates in stars of comparatively low temperatures.

For the main sequence stars (the sun is only a small star) Bethe suggested an alternative to proton-proton chain- the carbon nitrogen oxygen cycle (CNO cycle). The reactions in this cycle are the following:

$$
\begin{aligned}
&{}_6^{12}C + {}_1^1H \rightarrow {}_7^{13}N \\
&{}_7^{13}N \rightarrow {}_6^{13}C + {}_1^0e(\beta^+) + \nu \\
&{}_6^{13}C + {}_1^1H \rightarrow {}_7^{14}N \\
&{}_7^{14}N + {}_1^1H \rightarrow {}_8^{15}O \\
&{}_8^{15}O \rightarrow {}_7^{15}N + {}_1^0e(\beta^+) + \nu \\
&{}_7^{15}N + {}_1^1H \rightarrow {}_6^{12}C + {}_2^4He
\end{aligned}
$$

So that, on addition, we have again

$$4_1^1H \rightarrow {}_2^4He + 2_1^0e(\beta^+) + 2\nu + 27MeV$$

The above reactions form a cycle and the production of ^{12}C in a great majority of cases. THe entire reaction chain is completed in a fairly long time of 5×10^6 years. Due to large Coulomb barrier of ^{12}C nucleus, this reactions requires a slightly larger temperature of the core material.

In the above summary of the source of stellar energy we have seen that the fusion of four protons to form helium is only possible because of the high initial temperature and the fact that the carbon and nitrogen atoms act as true catalysts.

Books Suggested:

(1). Atomic and Nuclear Physics, Vol II; S. N. Ghosal

(2). Nuclear Physics, Theory and Experiment; R. R. Roy & B. P. Nigam

(3). Atomic and Nuclear Physics, An Introduction; T.A. Littlefield & N. Thorley