Nuclear fission

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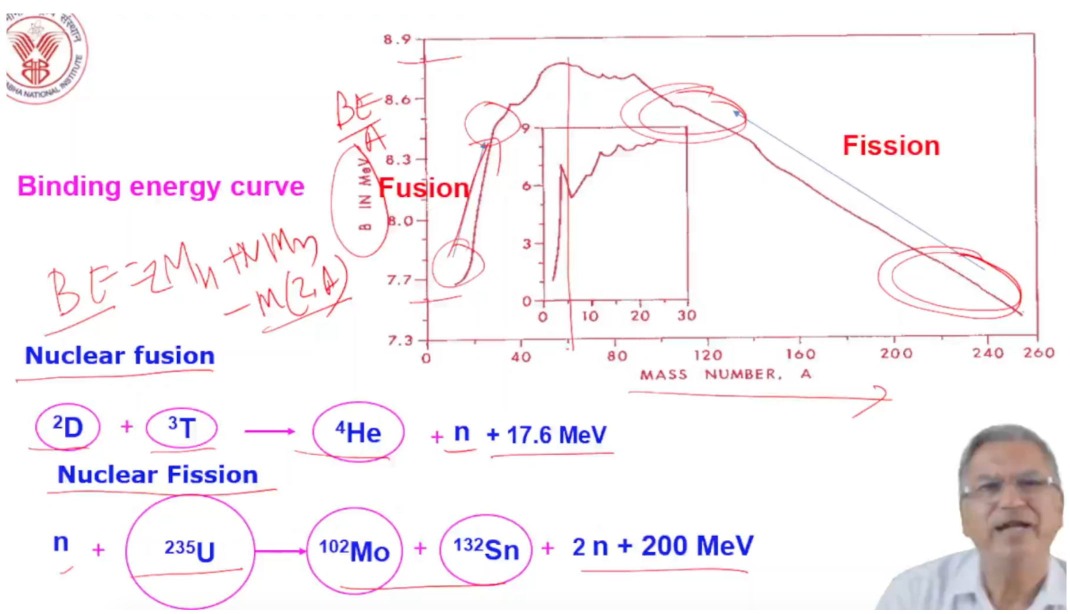
Lecture-14, module-1

In the previous lecture, we discussed about the mechanism of different types of nuclear reactions like elastic scattering, inelastic scattering, direct reactions and most importantly the compound nuclear reactions. Today we will discuss another type of reaction that is nuclear fission which also undergoes through compound nuclear formation only. But nuclear fission and nuclear fusion particularly the fission reactions you know utilized for production of energy that itself is a subject so I thought I will discuss them in more details. So today I will talk about nuclear fission and nuclear fusion reactions.



So nuclear fission and fusion can be explained using the binding energy curve. What I have here is the binding energy per nucleon that is called the average binding energy as a function of mass number of the nuclei.

And so you are familiar with this graph, the binding energy per nucleon is in the range of 7 to 8 MeV per nucleon. And if you see the fine structure, the binding energy per nucleon increases up to mass 60 it increases and goes up to almost 8.8 MeV per nucleon and subsequently for higher masses the binding energy per nucleon decreases.

Now if you recall the relationship between binding energy and masses, so binding energy was equal to $ZM_H + NM_n - M(Z,A)$. So higher the binding energy, lower is the mass. So that we can tell from here that nuclei which are around heavier side of the actinides, their binding energies are low, so their masses are high. In terms of mass numbers, you must have seen the mass defect can be positive or negative. If mass defect is positive that means the masses are higher, binding energies are low. If mass defect is negative that means the binding energies are high.

So now in nuclear fission what is happening, you split a heavy nucleus to lighter fragments. Also in the process the binding energy per nucleon is increasing that means masses are decreasing, so there will be energy released. So this process will be exo-ergic. When you split a heavy nucleus of lower binding energy to two heavy nuclei of higher binding energy per nucleon, then energy is released. That is what is nuclear fission.

And in nuclear fusion reaction, you are fusing the lighter nuclei like deuterium, tritium and forming heavier nuclei. Again, you are going from reactants of lower binding energy per nucleon to the products of higher binding energy per nucleon. So any process in which you go from low binding energy per nucleon to high binding energy per nucleon will be exo-ergic and such reactions, nuclear fission and fusion can be explained on the basis of the average binding energy curve. So what happens in nuclear fusion, light nuclei like deuterium+ deuterium or deuterium + tritium and so on, fuse together to form a heavier nucleus, relatively heavier nucleus like helium, plus a neutron is emitted and they have very high Q value.

$^{2}\text{D} + {}^{2}\text{D} \;\square\; {}^{3}\text{He} + \text{n} + 2.45\ \text{MeV}$

$^{2}\text{D} + {}^{3}\text{T} \;\square\; {}^{4}\text{He} + \text{n} + 17.6\ \text{MeV}$

So the 17.6 MeV energy is released which is primarily going to the neutrons. So neutron will in fact have 14 MeV energy and the rest will go to helium. So there are different types of reactions where isotopes of hydrogen fue together to form heavier elements like helium and so on and in the process, lot of energy is released.

Then in nuclear fission, the heavy nucleus captures a neutron. So ^{235}U a neutron, become ^{236}U and which then splits into two fragments and there are many such pairs.

$\text{n} + {}^{235}\text{U} \;\square\; {}^{142}\text{Ba} + {}^{92}\text{Kr} + 2\ {}^{1}\text{n} + \sim 200\ \text{MeV}$

It is not, it is just one of the examples of a pair of fission fragments but there are many, many such, many hundreds of such fragments are found, binary fragments and in the process again, sometimes two, sometimes three neutrons are emitted and a large amount of energy is emitted as the kinetic energy of fission fragments and other particles are emitted in the fission process. So both these reactions, large amount of energy is released and we will discuss shortly how to compare energy production from these two processes.

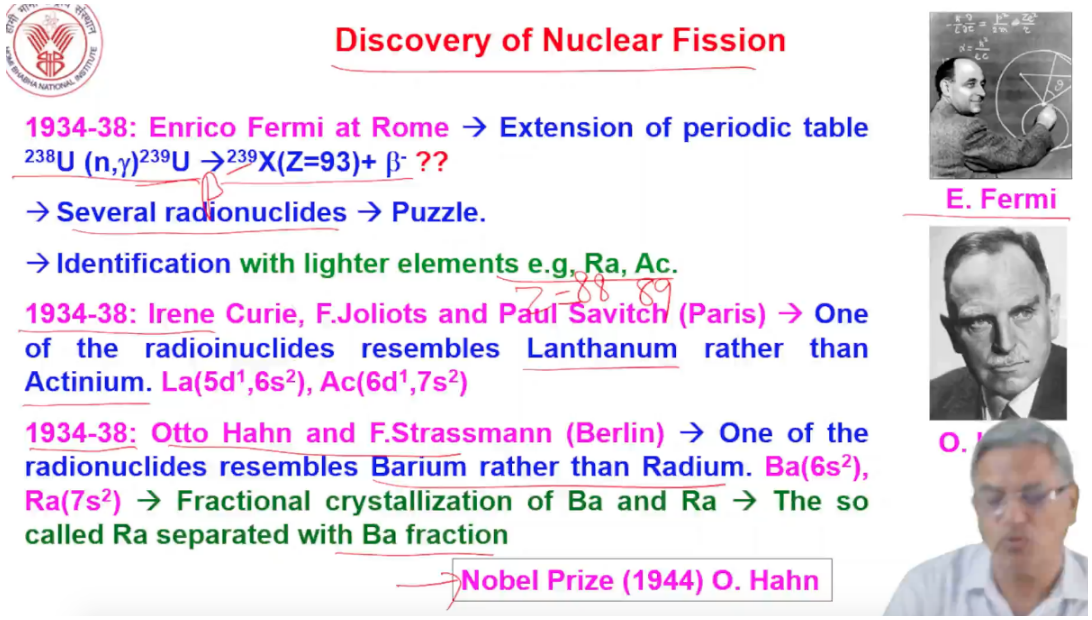
Comparison of Nuclear Fission and fusion

Nuclear Fission	Nuclear Fusion
Energy released 200/236 = 0.8 MeV /amu	Energy released 17.6/5 = 3.5 MeV/ amu
Can be induced by low energy particles	Induced by charged particles V_C > 10keV = 10^8 K
Radioactive fission products	Massive amount of tritium and neutrons
Power from fission reactors: a reality	Fusion reactor: yet to be realised

So comparison of nuclear fission and fusion particularly with regard to tapping this energy to produce power. So nuclear fission and nuclear fusion if you see in terms of the energy released per nucleon in nuclear fission, let us say Uranium-235 plus neutron, so you have 236 uranium, there are 236 nucleons and 200 MeV is energy released. So per nucleon 200/236 around 0.8 MeV per nucleon or per atomic mass unit energy is released. Compared to that in nuclear fusion reaction, take the case of D-T fusion. In D-T fusion 17.6 is the Q value of the reaction and 5 nucleons are involved, ^{2}D and ^{3}T. So 3.5 MeV is released per atomic mass unit. So you can see compared to nuclear fission, fusion has much more energy per gram or per nucleon of the target material. So it is having a positive point with regard to energy released per unit mass.

Now, so that is the plus point of fusion but in the case of fission, the fission can be induced by neutrons, neutral particles or low energy particles. But in the case of fusion, as we are using the charged particles, it requires them to cross the Coulomb barrier and if you recollect that 1 eV corresponds to 10^4 K, then for 10 KeV almost 100 million K temperature is required. So that is the disadvantage.

Nuclear fission gives rise to a large amount of radioactive fission products, some of which are very, very long lived. And nuclear fusion also produces tritium and neutrons but we don't have a long lived radioactive isotope produced in nuclear fusion. In the case of nuclear fission, the electricity production had been already realised, it is being produced for a long, time. So it's a reality. Whereas the power from the fusion reactor is yet to become a reality.



So we will discuss both these aspects in the subsequent presentation. But before that, let's me try to go down the memory lane wherein how historically the fission process came into being. So you know in 1932 James Chardewick discovered neutron and it was soon realized that neutron can be captured by nuclei and when a neutron is captured by a nucleus, you get by n,γ a higher isotope of that element, which is invariably β- active. And β- decay essentially gives you the next higher element.

So Enrico Fermi at Rome very soon realized the importance of this particular concept of producing higher element using n,γ reaction. And he had in his mind how to extend the periodic table. At that time, the highest element known was uranium, atomic number 92. And so if uranium 238 captures a neutron, then we get ^{239}U, which may undergo β- decay to give you element 93. So with that objective, he in fact started experiments to irradiate uranium- 238 with neutrons and look for the radioactivity of the products that are formed. But Enrico Fermi was a physicist and he did have one or two chemistry people in his group. So what they found that this particular reaction instead of a particular one isotope having one half-life, they found several isotopes. So there will be a lot of half-lives and at that time, they did not have the gamma spectrometry set up by which one can distinguish between different isotopes. One has to do the chemistry to separate different isotopes and count for the beta activity.

So they were not in the position to solve this puzzle. What is the reason for or which are the isotopes that are produced when you bombard with ^{238}U with neutrons. But they had an idea that if you, if element 93 is produced, it might decay by alpha. So that will become 91. That is, protactinium and again, it can go further decay by alpha to elements radium, actinium. Radium is 88 and Actinium is 89. So these elements would be produced by the alpha decay of the element 93 and other elements. But they were not in a position to do any meaningful radiochemical separation to identify these radioisotopes.

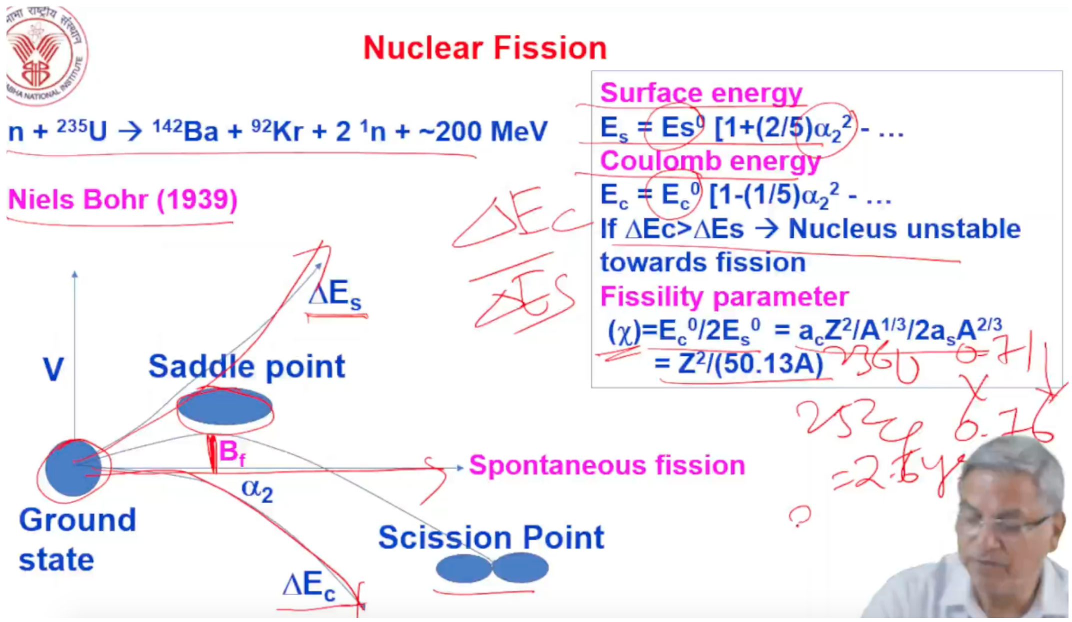
So then the established chemistry groups in Europe, in France, Irene Curie, Frederick Joliot and Paul Savitch started the experiments on bombardment of thorium and uranium with neutrons. And they were experts in doing radiochemical separations. So they were trying to separate actinium for which they used lanthanum as a carrier because chemically they are similar. Lanthanum is a homolog of actinium. And so when they did the radiochemistry, they found some of the activities got concentrated with the lanthanum fraction. And so actually they have seen lanthanum as fission product, but they did not do an unambiguous chemistry to establish this as lanthanum. They were thinking it is actinium.

At that time, Otto Hahn in same time period at Berlin was studying again the same reaction uranium bombardment of neutrons. And again, they were focusing on radium. Radium could be one of the alpha decay products of higher elements. And that time they were using barium as a carrier to precipitate out radium. So they got the activity of radium with barium, but they wanted to make sure whether it is radium or barium. So what they did, they used radium-226 as a tracer to follow the path of radium and then did the chemistry. To separate barium and radium is a very very tough task. So they did fractional crystallization of the barium and radium fractions. And they found that whatever they were calling as radium actually was barium. Thus they could unambiguously confirm the the bombardment of uranium by neutron gives barium isotopes not radium.

Because they have used radium-226 as a tracer, and activity got separated with the barium fraction not with the ^{226}Ra. This was a landmark discovery in December 1938 by Otto Hahn and Strassman. In fact, there is an excellent story behind this. There were old colleagues, namely, Lisa Meitner. Lisa Meitner was working with Otto Hahn and she had to leave Europe because of this Nazi movement.

And later on in the United States, she actually gave the theory of nuclear fission. So anyway, the Nobel Prize for the discovery of nuclear fission went to Otto Hahn in 1944. And the theory behind nuclear fission then was given by Neils Bohr in 1939. Very nice paper in physical Review published by Neils Bohr. It can be even explain the spontaneous fission which we will discuss shortly or a capture of a neutron by heavy nucleus like you know ^{235}U giving rise to two fission fragments plus neutron and large amount of energy.

If you recall my discussion during the liquid drop model, from the energetics point of view, the liquid drop model can explain the occurrence of fission by competition between surface energy and Coulomb energy of a nucleus which is deforming.



So this is a diagram to explain nuclear fission. We have a nucleus as a liquid drop. So the liquid drop model will predict that the nucleus remains spherical in its ground state because the surface energy will try to be minimized and the surface energy of a sphere is minimum compared to the deformed nuclei. So the surface energy term tries to minimize energy in the form of a spherical nucleus.

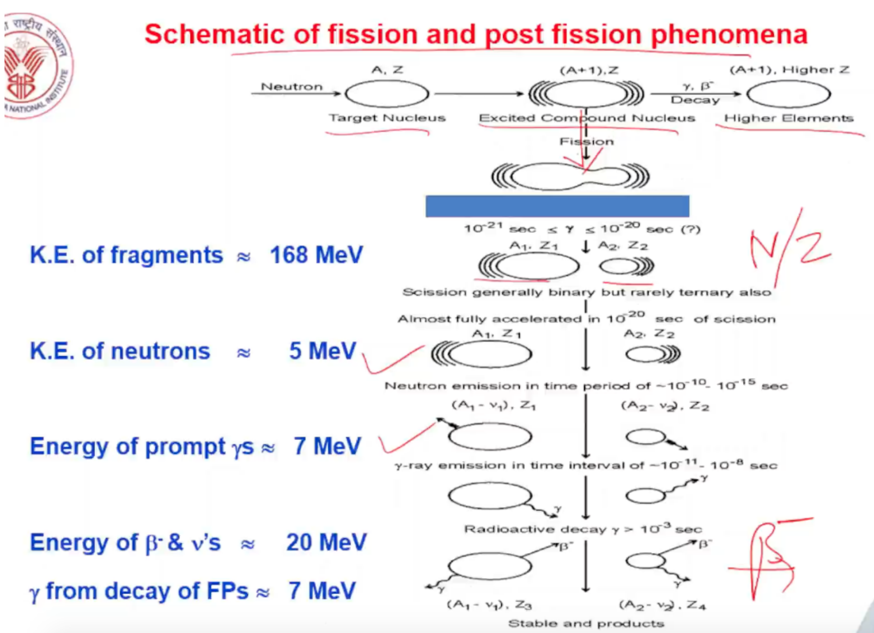
Now you know that fission is taking place, so the nucleus has to deform. The x-axis is the degree of deformation. This is symmetrical deformation α_2. So when the nucleus is deforming the surface energy is going to increase E_s and the Coulomb energy is going to decrease because now the protons are little bit apart from each other. So $Z_1Z_2\ e^2/d$. So further apart the protons, less is the Coulomb repulsion. So depending upon the nuclei the ΔE_s and ΔE_c, the change in the surface energy and Coulomb energy, then it will decide whether it can go fission or not. So the deformation energy, surface energy of a deforming nucleus in terms of the deformation parameter, this is the surface energy of a sphere that is $a_sA^{2/3}$ and this is the column energy of a sphere, $a_cZ^2/A^{1/3}$. So the change in surface energy and Coulomb energy will dictate whether the nucleus can undergo fission or not. So if you will see the ratio $\Delta E_c\ /\Delta E_s$ at this point when the nucleus becomes committed to fission that can be written as in terms of $E_c^0\ /2E_s^0$. So basically you take

$E_s = E_s^0\ [1+(2/5)\ \alpha_2^2]$ and $E_c = E_c^0\ [1-(1/5)\ \alpha_2^2]$

$\Delta Es = Es - Es^0$ and $\Delta Ec = Ec - Ec^0$

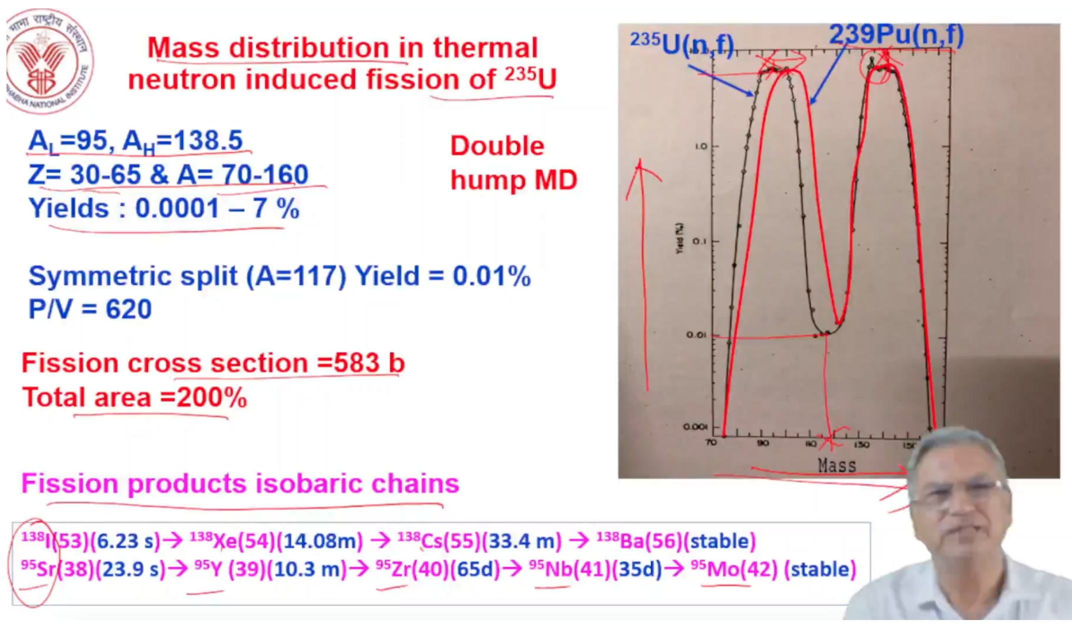
and take the ratio of $\Delta Ec/\Delta Es$ and it is $E_c^0/\ 2E_s^0$ and that becomes equal to $a_cZ^2/A^{1/3}/2a_sA^{2/3}$ which you can write in terms of $Z^2/50.13$ A. This is called the fissility parameter (X). The fissility of the nucleus is dictated by this term. So higher the value of this fissility parameter, higher the fissionabiity of this nucleus.

So the nucleus is undergoing deformation. So the shapes of the nucleus like this is called the saddle point like a transition state in chemical reaction and once a nucleus is able to reach the saddle point then it becomes committed to fission and when the two fragments are about to separate that is why that point is called the scission point. So ground state, saddle point and scission point these are the three stages of the fissioning nucleus. So the fissility of the nuclei if you see that like for example for ^{236}U, it will be X= 0.71, Z^2 /(A*50.13). So that nucleus if you see the spontaneous fission half-life will be very very high 10^{14}, 10^{15} years. You go to Californium-252, X is 0.76. For ^{236}U X will be 0.71. So slight increase in the fissility parameter from 0.71 to 76 the half-life is 2.6 years that is average half-life and half-life for spontaneous fission is 85 years, $t_{1/2}$ for fission of ^{252}Cf. So slight increase in the fissility parameter leads to a drastic reduction in the spontaneous fission half-life.



So this is the schematic of the phenomena that occur during the fission and the post-fission phenomena. A neutron is captured by the target nucleus and you have ^{236}U which is excited. It can undergo beta minus decay to become the higher element or it can undergo fission. So in the fission the compound nucleus will undergo deformation. So these are the saddle point and scission point.

And then because of the columbic repulsion between two fragments you will have two fragments, a heavy fragment and the lighter fragment. And then this so I am showing here binary fission because two fragments are formed. There could also be ternary fission also three fragments are formed. Then this fission fragments are highly neutron rich they have very high N/Z. So because of the high N/Z they have excess neutrons they emit neutrons. The binary energy of neutron is very small. So first they emit 2 to 3 fission neutrons per fission. Then if the neutron is not possible then you have the gamma rays, the neutrons, gamma rays and then by gamma from gamma ray emission they become fission products. The fission fragments by emission of neutrons and gamma rays become fission products and the fission products will undergo β- decay and in the gamma ray emission also to end up with the stable end product. So this is the journey of the fission process from neutron capture by the heavier nucleus to fission products and ultimately a lot of energy is emitted in the form of fragment kinetic energy, the energy of neutron from the gamma rays, energy of beta minus and neutrinos and the gamma decay after beta decay there will be gamma decay from the fission products. So this is how the energy is distributed in different forms a total that 200 MeV energy or little bit more than that you will find it is distributed in different forms here.



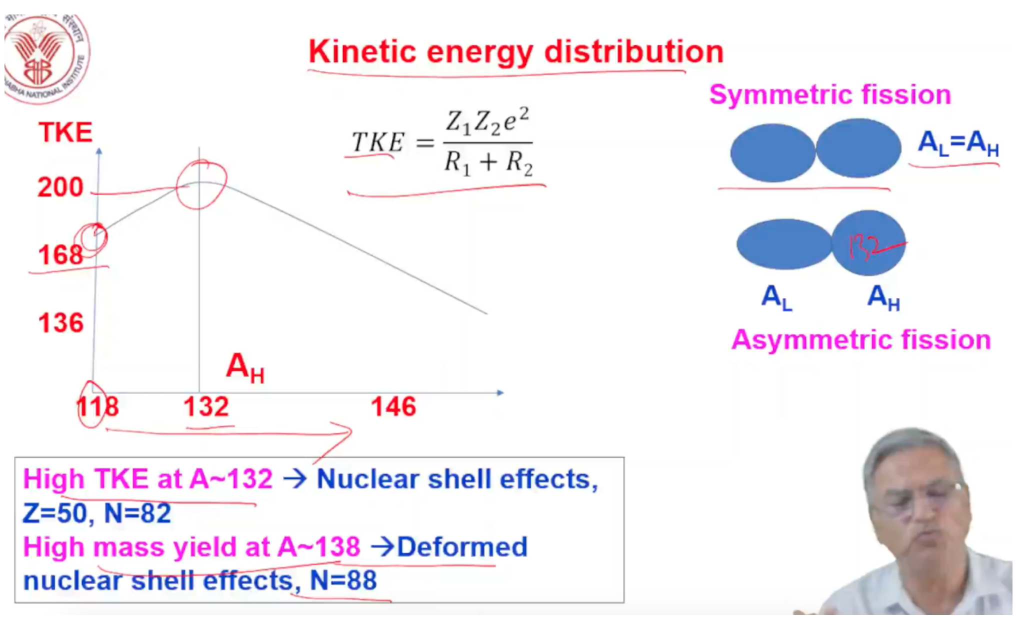
Now let us go little bit much deeper into the different aspects of nuclear fission. I will explain two processes, two observations one is the mass distribution, second is the kinetic distribution. So mass distribution means as a function of mass how the yield is varying. If you see from the liquid drop model point of view the liquid drop model will predict a nucleus splitting into two equal halves that is having the highest energy to be released. But what happens in this particular case of ^{235}U you will find that we have a double hump mass distribution that means the asymmetric fission is more probable, 117 is here, 117 mass is equal to the splitting of the nucleus into two equal halves but that has got a very low yield.

Yield means you know out of 100 fissions how many times the particular pair is formed. So this is a fission yield curve where total area will be 200 percent because 100 fissions are taking place you will have 200 fission products. And the cross section for this reaction for $^{235}U(n,f)$ for thermal neutron is 583 barns which is very very high. And the average mass of lighter and the heavier fission products are 95 and 138. And the atomic numbers will be varying from 36 to 65 and mass number from 70 to 160.

Yields are varying from maximum yield about 7 percent minimum 0.001 percent. Very interesting thing I will tell you here that if you see the ^{239}Pu fission then the heavier mass peak remains constant and to conserve the mass the lighter mass is shifted to heavier mass. Lighter fission product mass is shifted to higher side and it tells about the mechanism of the fission process. That means that the heavier side has got some fission products which have a very stable configuration and so their yields are higher and to compensate for the total mass lighter mass peak shifts.

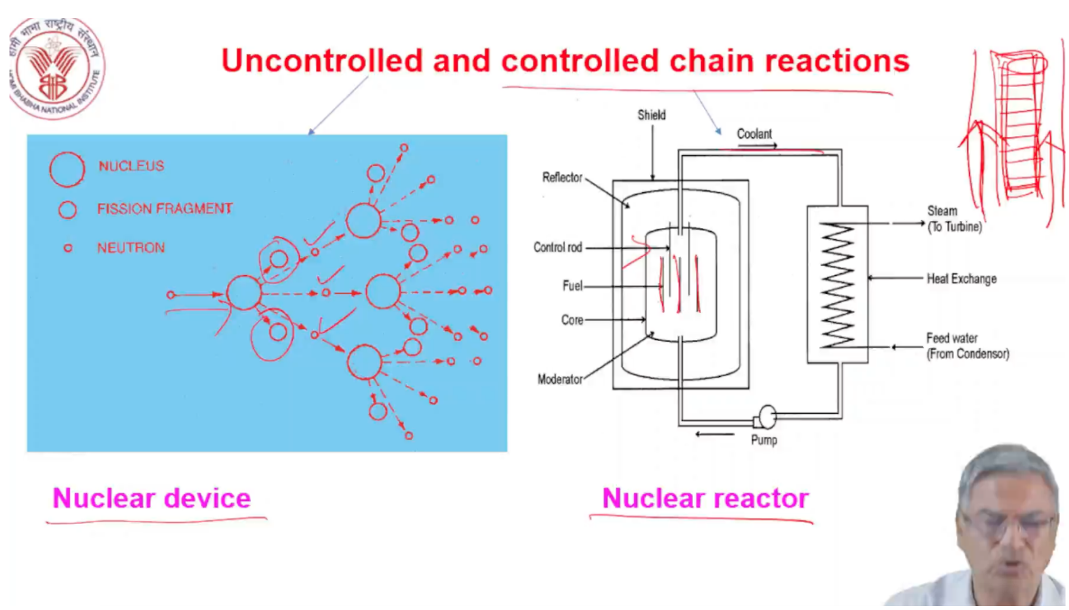
So now for each mass, this axis is a mass number. For each mass number there is a chain of isobars like if you take this pair is formed $Z_1 + Z_2 = 92$ here iodine and strontium. You will find that there will be a chain of isobars. So ^{138}I will undergo beta minus decay to xenon, to cesium, to barium and so on. So ultimately it becomes stable. Similarly, ^{95}Sr undergoes beta minus decay to yttrium, zirconium, niobium and finally stable.

So whatever pair of fission products are formed in one fission process they will start undergoing beta minus decay and you can see the half-lives are increasing. The ones which are very much away from stability have got shorter half-lives and by the chain of beta minus decay all of them will come to stability. So that takes time. The half-lives are increasing. Some of the fission products have very, very long half-lives, almost billions of years' half-life.



Another property of this fission process is the kinetic energy distribution. So I mentioned that kinetic energy of fission fragment is 168 MeV. So the total energy about 200 MeV. So what happens when the two fragments are separating? This is what I have shown at the scission point. If it is equal fragment, both fragments are equal, that is what symmetric fission, that is the mass numbers are same. So when they separate out, $Z_1Z_2e^2/d$, this much kinetic energy is released.

Similarly it could be an asymmetric pair, one light and one heavy and then it could be slightly different. So normally from the spherical fragments you would find that symmetric splitting will give you higher kinetic energy. If you see from Z_1 Z_2, Z_1 equal to Z_2, this kinetic energy is maximum. But if you see the actual observation as a function of mass number of heavier mass product, this is the symmetric splitting, 118, 236 by 2. So what was found experimentally that the total kinetic energy is lower for a symmetric splitting compared to the asymmetric splitting where it is 200. So for mass number 132, the total kinetic energy is higher. Again it cannot be explained on the basis of liquid-drop model. And so the higher kinetic energy at 132 was explained due to the shell effects. If you recall the shell effects, those nuclei which have magic number of nucleons, have spherical shape. And so if this heavier mass is at 132, this is spherical and once the nuclei are spherical, the kinetic energy will increase. Another observation that in the previous slide I showed you that the mass number 138 is constant for different fissile nuclei, 235 or 239. And that again 138 mass having highest yield was attributed to a deformed magic number, deformed neutron shell. So these are the kind of explanations, experimental observations of double hump mass distribution and total kinetic energy can be explained in terms of the nuclear shell effects. So ultimately when fission takes place, a neutron is captured by the heavy nucleus and in the process, you have two fission fragments and there could be two or three neutrons produced.



Now this fission reaction, if it left uncontrolled, it leads to a device, nuclear device atom bomb which you can call because these neutrons can subsequently induce fission in many more ^{235}U nuclei. And therefore, it becomes a chain reaction. If you do not control, it means you do not suppress the neutrons, this multiplying neutrons will lead to an explosive device and the whole thing will explode in a very short span of time. That is the concept behind the nuclear device. But the same thing if you control the reaction in such a way that for every neutron that is absorbed by a nucleus, one neutron is left to propagate the chain, then it becomes a controlled chain reaction.

So in the controlled chain reaction, normally when neutrons are produced, they will be captured by structural materials, they may escape from the device. So you may not have even one neutron left to sustain the reaction. So you have to have that reactor designed in such a way that at least one neutron is there available to sustain the chain reaction. That is the concept behind a nuclear reactor. The nuclear reactor you have, the fuel, the fuel is in the form of pellets like uranium oxide, and which is now, so this is the fuel tube inside which you put the fuel pellets. So you have a fuel tube, inside the pellets are filled and you can cap it. So these lines are like this. And then you have the outside the fuel, there is a pressure tube, the coolant is flowing to take away the energy of the fission. So this coolant is flowing through this reactor, the pressure tubes, and then this heat, it will form steam, there is a heat exchanger, heat exchanger will then take the steam to turbine and you can run the turbine with the steam. So the whole process of fission ultimately leading to generation of steam and then that steam running a turbine is a concept behind a nuclear reactor. So you require the clad in between to keep the fuels intact, you know, you have a cladding material, encasing of the fuel, then there is a coolant flowing through the coolant channels. So outside the cladded fuel, you have another angular pipe through which the coolant will flow. The coolant could be heavy water or light water, fast reactor it will be sodium. And then you have the moderator also to thermalize the neutron because thermal neutrons are more reactive than fast neutrons. So you need to reduce the energy of neutron, make them thermal so that you have more fission reaction.

And again to control the reaction so that the reactor does not go out of control, there are control rods. So the control rod will maintain the neutron economy in such a way that there is no inadvertent rise in the neutron number at any point of time. In fact, as a function of time also you will find the neutron economy will change and the control rods are adjusted so that the reactor remains as critical. So all this, the entire thing basically becomes the concept behind a nuclear reactor. So fission has been tapped to produce electricity, whereas and the nuclear device based on fission also reality as all of you know.

So the nuclear fission has been tapped for nuclear power production. In the next lecture, I will discuss about nuclear fusion, how it can be used for or what is the status behind the taping of fusion energy for electricity. Thank you.