Nuclear Physics Fundamentals and Application

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Lecture - 35
Nuclear Fission Reactor

So, we discussed the basic reactions in neutron induced fission of uranium. Natural uranium has 2 isotopes; uranium 235 and 238; little bit of uranium 233 also. And, we saw how a neutron when gets into uranium 235. It can induce almost instantaneous fission in the time scale of 10 to the power minus 15, 16 seconds. And, we call it fissile material 235 uranium is a fissile material. It can fission on absorbing thermal neutron low-energy neutron. The other component uranium 238 which is much larger abundance in natural uranium that is not fissile. If you put neutron into it most likely low-energy neutrons will not create a fission in it.

So, today we will be talking about general features or basic basics of nuclear fission reactors which are used for power generation from nuclear fission. All over the world including India large number of fission reactors are operating; in which one produces power from this nuclear fission and uses it for various purposes. Before going into that description of typical fission reactor let me little bit discuss more about the reactions of neutron with uranium. We have already seen the nuclear reactions with uranium 235 and 238 cross-sections. How much is the cross-section of this induced fission? So, that is one thing we will be doing.

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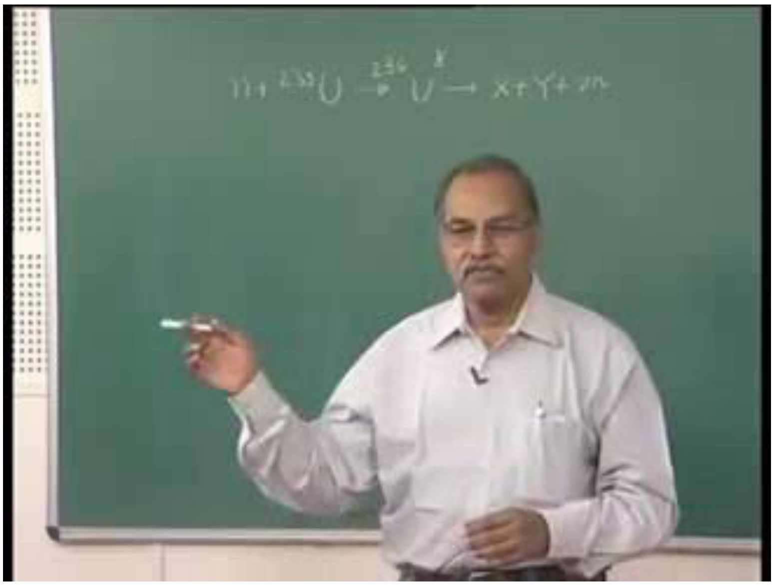

So, neutron and then uranium 235 this goes to uranium 236 in excited state and that fission in 2 parts. So, the cross-section and then plus energy and some neutrons and so on. So, the cross-section for probability for this reaction depends very strongly on energy of this incoming neutron. At almost 0 energy, when it comes you know that the excitation energy is higher than the activation energy of that fission barrier and it takes place. And, as you increase the energy of this incident neutron, the excitation energy is more than the q value. And, one may expect that since the energy is much higher than the activation energy; the fission cross-section will increase the fission, probability will increase but that is not the case with uranium 235.

As you increase the kinetic energy of neutron, the fission cross-section goes down; this is a typical 1 by v phenomena. We call it 1 by v dependence of cross-section on speed of this low-energy neutron qualitatively. You can think of if speed is low, it gets more time to interact with the nucleus and more probably to get absorbed into it. If it is a higher speed, then it will just cross through and the absorption cross-section will be low and so on whatever. So, let me show you how this fission cross-section changes with the incident neutron energy. So, that will be on the power point slide.

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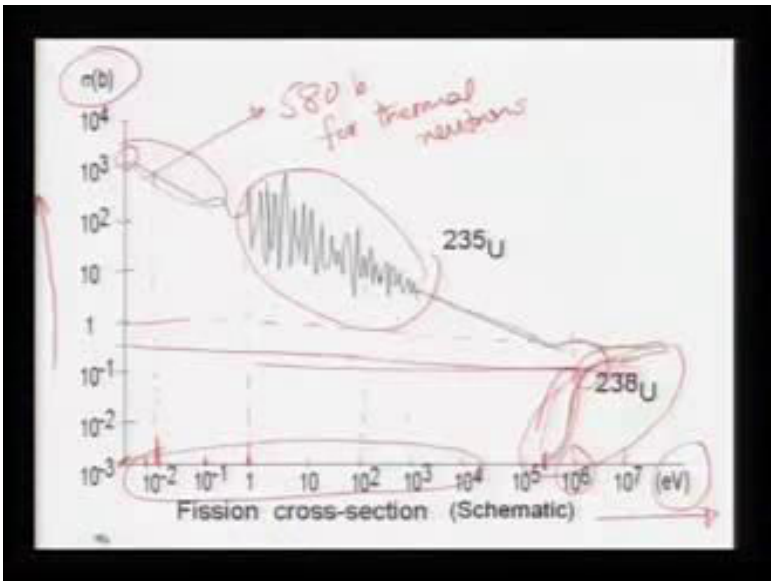

So, this diagram is in front of you; it is schematic diagrams drawn do not take it very seriously; these are not experimental data but this is the trend. So, this is uranium 235 and the vertical side here is the cross-section sigma in barn. You know barn 1 barn is 10 to the power of minus 28 centimeter square. This is reaction probability is or reaction mechanism decides this and the this probability is measured in terms of these cross-sections. So, this is the cross-section. And, the horizontal side is the energy kinetic energy of neutron in electron volts; both these access are logarithmic. So, you have 10 to the power minus 2 here, 10 to the power minus 1 here, then 10 to the power 0 here, then 10 power 1; that is 10, this is 100, this is all in electron volts.

So, this is 1 kilo electron volt, then 10 kilo electron volt, 100 kilo electron volt, this is 1 mega electron volt and this is 10 mega electron volt and so on. So, this is horizontal axis is in logarithmic scale and that is in electron volts. The vertical scale cross-section is also in logarithmic scale this is 1. So, this is 1 barn, and this is 10 barn, and this is 100 barn, this is 1000 barn, this is 10000 barn and so on. This is 0.1, this is 10 to the power minus 2 and this is 10 to the power minus 3 and so on. So, at almost 0 energy 10 to the power minus 3 electron volts here, this origin in this drawing is 10 to the power minus 3 electron volt. Here the cross-section is about 1000 barn any standard this is a very high cross-section. And, as you increase the energy of the neutron this cross-section decreases, you can see this cross-section decreases and thermal neutrons at room temperature the kinetic energy will be something like 0.025 volts.

So, that is 2 into 10 to the power minus 2 that will be somewhere here. So, this is the thermal energy range. So, here if you ask what is the cross-section, that cross-section turns out to be about something like 600 barn or 580 barn; this is for thermal electron. Thermal neutrons means where the kinetic energy is of this neutron is about say 0.025 electron volt corresponding to thermal motion at room temperature. So this is something of the order of 600 barn or so and then it decreases.

Now, from 1 e v to 100 d e v this range. This range this will be around 1 electron volt and this will be around, say this is here it is this is 100 e v here. So, little more say 1 k e v this is the range; in which you see lots of line going up and line going down these are in fact resonances. So, the cross section suddenly increases and suddenly decreases. So, this the region where you have resonances overall the cross section is decreasing and but there are some fluctuations here. And, then again here you do not distinguish those though separate resonance peaks perhaps they are all merged together and you get a almost smooth variation.

Here is 10 to the power 6 that is 1mega electron volt. This is also important number 1 mega electron volts, 2 mega electron volts because the neutrons that are produced in a fission reaction the prompt neutrons; they are of this energy something like 2 mega electron volt energy. Similarly, the beta decay process also gives neutrons delayed neutron; they are delayed neutron, they are the energies also large in mega electron volts. So, you have energies like this and at these neutron energies the cross section for fission in uranium 235 is somewhere here which will be around 1 barn.

So, from thermal energies to mega electron volt energies the cross section decreases 3 orders of magnitude. Here at thermal energy it was some somewhere around 600 barns are like that whereas, in mega electron volt it drops to 1 barn or so. So, a fraction of 600, 700 down as you compare these 2 energies that is about uranium 235. Now, look at uranium 238. As you know in uranium 238 and the activation energy is larger and the q value of that reaction is smaller. The q value is only 4.8 mega electron volt; whereas, the activation energy is something like 6.6 m e v or so.

So, at thermal energies neutrons will not induce fission in uranium 238 and that is you can see the diagram here. This is uranium 238 and it is it is appreciable only after this 100 k e v or so. Before this thermal energy range or k e v range 10 kilo electron volts and

100 e v; at all these places the cross section for fission is almost 0 for uranium 238. When it approaches that 1 m e v point then the cross section starts building up. And, the you know that is the barrier penetration region. So, as the neutron energy increases the barrier width to be penetrated becomes smaller.

And, therefore the barrier penetration probability becomes larger and hence the cross section increases rapidly. So, this is that region where cross section is increasing rapidly from very low values to somewhat higher values. And, then once this it reaches somewhere around 1.4 mega electron volts. So, that the fission barrier that activation energy and the here q value plus then neutron energy they become equal or almost equal; after that you do not have to penetrate the barrier. And, therefore it just goes. So, that is this range; this is 10 power 710 m e v, we do not interested in this region.

So, 2 m e v, 1 m e v, 2 m e v the cross section is here and that is less than 1, less than 1 barn, there is a less than 1 barn. The fission cross section will be little less than 1 barn if you have fast neutrons to induce this fission. So, that is about the fission cross sections. Now, apart from fission cross sections this uranium 235 and uranium 238 they can also absorb neutrons and still not fission. So, that is the mechanism we had talked earlier. It is radioactive capture most prominent non fission mechanism is radioactive capture.

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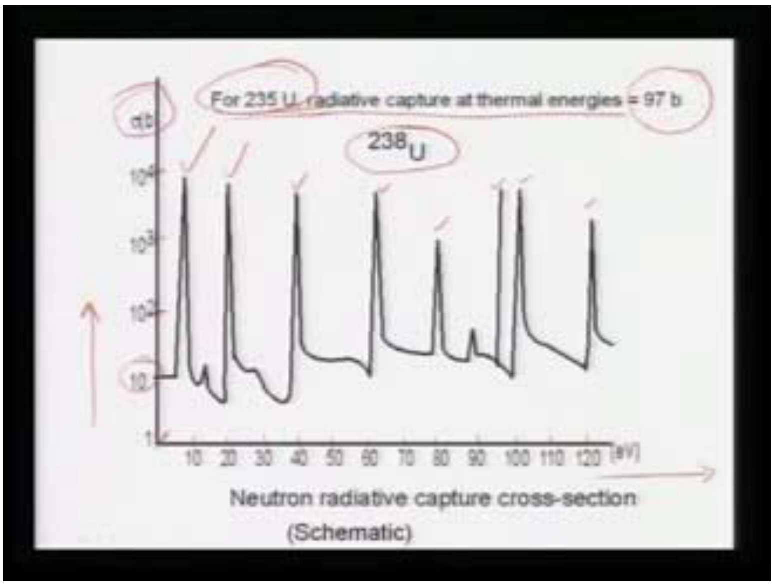

Now, you see this diagram. This diagram again it is schematic is not experimental data as such it is only shows the type of variation it has. Here, what we are showing is neutron radiative capture cross section. And, that is this diagram is for uranium 238; on the vertical side we have cross section sigma again in barn logarithmic scale. So, 1 and then here 10, then here 10 power 2 that is 100 barns, this is 1000 barns, this is 10000 barns and so on. So, this is the kind of scale and on the horizontal side you have once again neutron energies. And, this time it is not logarithmic it is 10 electron volt here, then 20 electron volt, 30 electron volt, 40 electron volt and so on say linear scale and this is 120 here. And, what are these cross section for? These cross section is for a neutron getting absorbed into uranium 238 but not creating fission of course at these energies 10 electron volt or 50 electron volt or 100 electron volt.

It will anyway, it will not create fission in uranium 238 because of the activation energy because of the barrier height; but the neutron can still get absorbed into it. And, not only it can get absorbed into it; it has a large resonances in this region. That means, the uranium 238 energy levels are there. So that these 10 electron volt neutrons or 40 electron volt neutrons; they have a just sufficient energy to excited this uranium 238 and that particular level. And, hence the reaction probability increases very rapidly the usual resonance. So, you see that from thermal energies or say 1 electron volt to say 120 electron volt or 150 electron volt. You have very large resonances look at the heights of the peaks that we are showing here very large resonances.

The cross section is approaching 10000 barns few 1000 barns from any standard, it is a very very high cross section. And, this probability of absorbing neutrons in this energy range by uranium 238 is extremely high. So, these resonances are to be kept in mind. In contrast if you think of uranium 235 the low energy neutrons can induce fission. We have seen the fission cross section of uranium 235 lower the energy larger the fission cross section. But here also in competition to fission after absorption of neutron in uranium 235 gamma rays maybe emitted. And, once gamma rays are emitted and energy of this uranium 236 that is formed is lowered. So that the barrier becomes important and the it has to penetrate the barrier the this fission may not take place.

And, if further gamma ray energies take it to the ground state of uranium 236 then it is permanently uranium 230s. Permanently means? Whatever its own lifetime of alpha emission so that is it. Now, the radiative capture cross section at thermal energies by uranium 235 is about 97 barns. And, it gradually decreases just like that fission cross section alright you have seen the fission cross section that decreases. Similarly, the radiative capture cross section also decreases. Here it is starts at about 1000 barns and they are the absorption radiative capture absorption that starts at say 100 barns 97 barns. And, then that also decrease that also goes through the resonances and so on.

So, the magnitudes or the of these 2 events that should be remembered; 97 barn is the cross section for absorption of neutrons in uranium 235 at thermal energies followed by gamma ray emissions not followed by fission. Whereas, the cross section for absorption of neutrons in uranium 235 at thermal energies followed by fission that cross section is about 600 barns. And, both these cross section decreases as you increase the neutron kinetic energy. And, for uranium 238 the cross section for fission starts around 1 m e v or so before that the there is almost no fission. But the absorption is there radiative capture absorption is there, neutron getting absorbed in uranium 238 followed by gamma ray emission is there. And, the cross sections for the that in the range 1 electron volt to some 100 electron volts. There are so many resonances and at these resonances the cross section goes to few 1000 of barns.

So, that is to be kept in mind and then there are other processes also like elastic scattering and inelastic scattering. And, neutron which goes to a uranium 235 or uranium 238 they it can just gets scattered elastically or in elastically. For inelastic scattering there will be some threshold because inelastic scattering in some kinetic energy goes into internal excitations. That means, it takes the nucleus to its one of its excited state to some energy goes into the nucleus. And, the total kinetic energy available to these interacting particles becomes slower. So, that excitation that that gives you threshold, so any neutron of any energy will not show up inelastic scattering. For uranium 235 this threshold is 14 kilo electron volt and for uranium 238 that is 44 kilo electron volts. So, for neutrons greater than these threshold they can in elastically scattered from these uranium nuclei.

And, elastic scattering can always take place. There are cross sections for that normally less than 10 barns also between 1 barn to 10 barn for this elastic and non inelastic scattering. So, these are the process that goes on. Now, a typical fission reactor. So, that is now a general knowledge what a typical fission reactor it is what are the components and so on? But still let me tell those typical words again look at the diagram.

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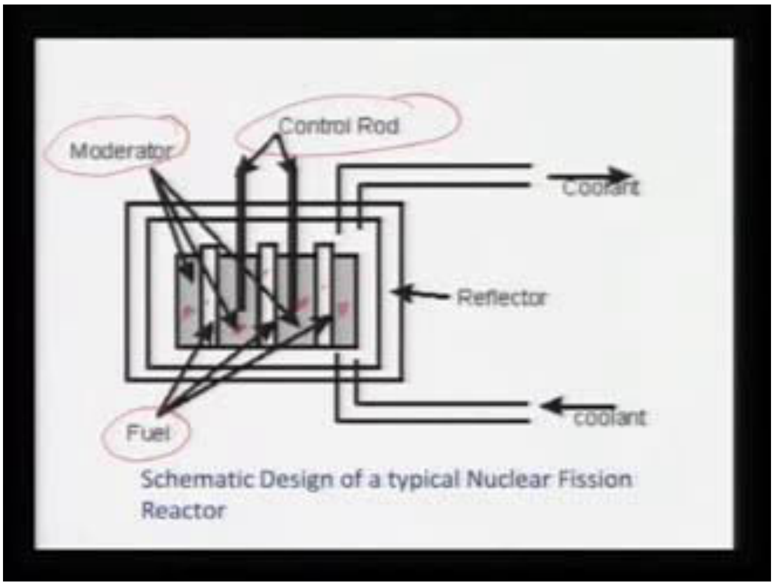

So, this is again a schematic design of a typical nuclear fission reactor. And, I am only showing the core where this nuclear reactions are taking place there is a lot outside this. And, that react design is by any means it is a very very complex thing but right at the core weather nuclear reactions are taking place what are the things? So, you have first is you have a fuel rods. So, these are the fuel rods I am showing these are white things here these are the fuel rods; that white things are I am showing. So, what are these fuel rods? So, let me describe little bit on that. Fuel is nuclear fuel that means the uranium which will be most of the reactors involved are based on this uranium.

So, that uranium which fission which gives energy that is fuel but in what form it is placed in the reactor? The uranium is first mind from the rocks and then the uranium that other rock part is to be separated and uranium part is to be extracted from that. So, some chemical bleaching or something is done to get that uranium compounds out of that rock. And, then these uranium compounds are further processed.

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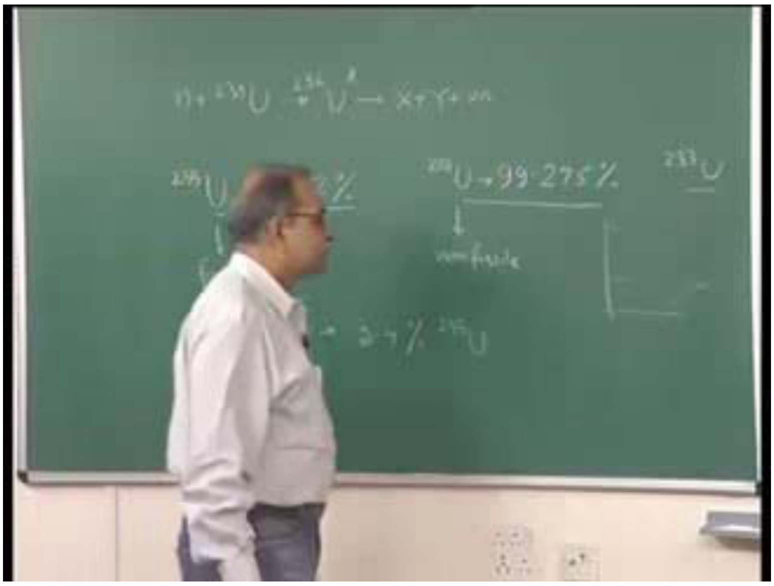

And, sometimes or most of the times it has to be enriched because in natural uranium as you know the uranium 235 is about 0.72 percent and uranium 238 is almost the rest 99.28, I can write if I neglect that third digit or 275 like that. And, then the rest is other things uranium 233 and so on. There is a present story it will depend on time although the time scales will be millions of the years. But because they there these are the alpha active things they will change, so the concentration of uranium 235 and concentration of uranium 238 that will change as a function of time. But not with the time scale of few months or few years or few decades in the time scales will be in 10000 years or million years or things like that but presently this is the composition.

So, and as you know this is a fissile material, this is non fissile slow neutrons will cause fission here and only fast neutrons can do fission here is lot of it. But and even if I go with fast neutron fission the cross section of fission is very low. That we have seen that uranium 238 line starts from here and then goes like this and it is still less than 1 barn. Whereas, the uranium 235 cross section at thermal energies is very large about 600 barns and so on. So, most of the fission that people depend upon in a fission reactor is from this uranium. But then with this small concentration the design is more difficult, the size of the reactor will become very large; although there are some reactors operating with this natural uranium.

So, normally what people do? People enrich it and generally it is enriched to something like 3 percent or 3 to 4 percent in uranium 235. And, how is that enriching done? Once you have from the or you have separated out that uranium compound which has uranium in the form of uranium 235 and uranium 238, so to enrich that part people make a gas out of it something like some fluoride or something and in the gaseous form. And, then it is taken through some kind of a mesh or so.

So, that diffusion can take place. And, the diffusion the rate of diffusion that depends on the mass of that diffusing gas molecules. And, so depending on we depend on the mass difference this is u 235 and that is u 238. So, that masses of those molecules will be different and the diffusion rates will be different. And, that is how some of this can be separated out. So, some mechanism or you can centrifuge these things. So, that because of the mass difference in centrifuge things will be separated. So, some uranium 238 is to be extracted out is to be removed. If you want to go from 0.7 percent to 3 percent or 4 percent how much uranium 238 you will have to remove? That number comes out to be around 80 percent or so.

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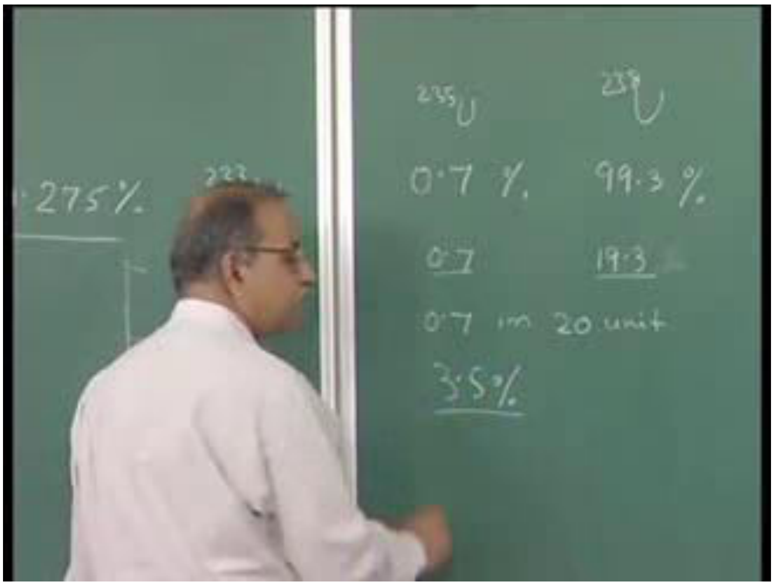

If you have initial concentration 0.7 percent here and 99.3 percent here this is uranium 238 and this is uranium 235 that compound form. So, if you remove 80 percent of it. So, you start with say 100 units and 80 units of uranium 238 you remove. Then, what you will get here is if you remove 80 from here it will be something like 19.3 percent here or whatever is left is 19.3 units and here it will be 0.7 units. So, if you remove 80 percent of uranium 238 species you get this composition. And, how much is percentage of this? This total is 20 and out of this 20.7 is here.

So, 0.7 in 20 units. So, 5 times of this 3.5 percent, to get this 3 percent or 4 percent of enrichment you have to almost remove 80 percent it of that uranium 238 part. So, that is how it is enriched. And, once again it is then converted into solid oxide powders and then pallets are made. Those pallets are stacked one over other in some thin zirconium alloy tube to make one long unit of that. And, such tubes are then clustered together several tubes and that makes one unit which we call fuel rod. So, it has this enriched uranium or natural uranium if you want to work with that. And, that is shown here look at your diagram once again the these white things that with your red dots on your screen. These I am schematically showing those fuel rods which are constructed the way we have said. And, then these rods are separated from each other and the space in between is filled with something called moderator. So, these grey things here these are moderators. These all schematic diagram do not think that if you go to a reactor it will look like this geometrically.

So, these are moderators. Now, what is moderator? So, once again let us talk about moderator. So, what we had seen that the cross-section for fission decreases 3orders of magnitude. If the neutron energy is goes up from thermal neutron to mega electron neutron. And, in a fission reactor the neutrons which are used to ignite these fissions they come from the fission events themselves. The neutrons are not supplied from outside for each fission event. So, once fission starts we call it chain reaction. Once fission starts each fission produces few neutrons. And, those neutrons are used to trigger further fissions all these are known to almost everyone.

So, but then these neutrons which are produced in fission events they are produced at much higher energies; mega electron volt energy some somewhere around 2 mega electron volt energies. And, at these energies the fission cross-section is much lower is about a 1 barn or even less than that uranium 238 also can fission. And, these energies but there also the cross-section is much smaller is less than 1 barn and uranium 235 also the cross-section is much smaller. So, to utilize that large cross-section at lower neutron energies is what we do is we thermalize these neutrons. These fast neutrons which are producing fission events they are there kinetic energy is reduced.

And, how the kinetic energy is reduced? Kinetic energy of the neutrons can be reduced by scattering processes. So, neutron is the if you look in terms of nuclei if you think then after proton neutron is the lightest one. So, any material you take carbon or beryllium or any material you take neutron will be the lighter one with one exception with protons. And, there also the masses are almost equal almost a very slight difference between proton. So, you can treat them as equal mass. So, if neutron collides with some other material and elastically scatters then some kinetic energy will be reduced. You can make a simple calculations for head-on collisions.

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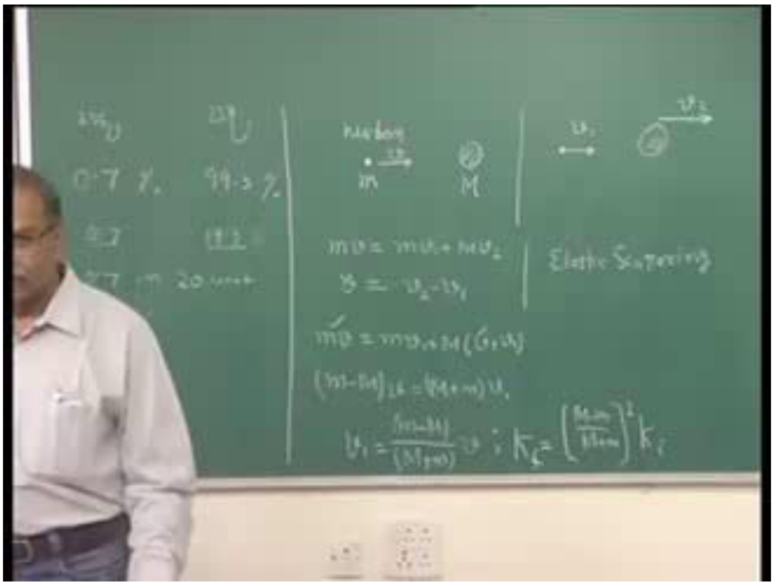

If you have this small m is for neutron let us say and it is going with some kinetic energy some speed. And, then you have another nucleus here with mass capital M at rest and this neutron goes and hits this. Then, what happens? If it is all elastic collisions no internal excitations and so on, you can do a simple calculation if this after the collision if this goes with a velocity v 1 the and if this goes with a velocity v 2. The separation will increase. In fact since neutron is supposedly lighter one and this other mass capital M the other nucleus with which it is colliding that mass is largest. So, neutron will in fact come back to this v 1 will should turn out to be negative literacy. So, the momentum conservation will be m v is equal to m v 1 plus capital m v 2.

And, then if it is the elastic collision then kinetic energy before the event is equal to kinetic energy after the event. And, that will leads to the equation that velocity of separation is equal to velocity of approach. So, velocity of approach here is v and velocity of separation here is v 2 minus v 1. So, v should be equal to v 2 minus v 1. So, this is for elastic scattering. So, from here you can get this v 1; we are interested in v one that v 2 is find whatever material we had kept for lowering down the energy of neutron the moderator materials. So, that material we do not we have not interested. What happens to this velocity and how this gets it is distributed into that material? But the neutrons which is interacting with that v 1. So, eliminate v 2 from here. So, m v is equal to small m v 1 plus capital m v 2 and v 2 is v plus v 1. So, v plus v 1 and collect v 1 on one side and other things on the other side. So, m minus capital m into v, so I have taken this term I have taken this term is equal to m plus m times v 1. And, hence v 1 is equal to small m minus capital m and divided by small m plus capital m and into v.

So, as expected if capital m is larger than small m this v 1 is negative. If a lighter particle collides head-on with heavier particular this lighter particular rebounds it comes back. So, v 1 is negative and if they are if with small m is larger than capital m then of course this v 1 will be positive. So, kinetic energy you can write kinetic energy off neutron marked the total system kinetic energy of neutron after the event final kinetic energy will be half small m into v 1 square. And, kinetic energy of the neutron before the event is half small m into v square. So, this kinetic energy final will be just m minus m by m plus m square times kinetic energy is reduced.

Kinetic energy of the neutron only it is elastic collision. So, kinetic energy of neutron and that other particle with which it is colliding that will remain same; that will that is not going to change it is all elastic scattering, but then the kinetic energy of the neutron itself in which we are interested. So, that kinetic energy is reduced by this factor m minus m by m plus m square. Now, I am squaring so that minus does not matter.

Now, you can see if you want quicker thermalisation this kinetic energy to be reduced in few number of collisions. What should be that case? This factor should be as small as possible and that will happen if this capital m is closer to small m. If it is just equal then you have see it become 0 in one collision head-on collision remember. If you have 2 equal mass objects colliding head on and one then the velocities are interchanged. If they are equal mass particles in elastic collision in 1 dimension is just interchange but that is in 1 dimension. So, here it will not be 1 dimension but is still gives you an idea that lighter is the mass of that moderator material which is used to reduce kinetic energy of neutrons; that reduction process will be more efficient.

Now, in lighter things what you can take lightest one is proton hydrogen? So, you can put water in it reactors are developed with water as moderator. So, these fast neutrons if they come to these water neutrons collide with protons of hydrogen and then they thermalised very fast. But then there are some problems with water or with hydrogen with protons this water if you think of this most efficient way.

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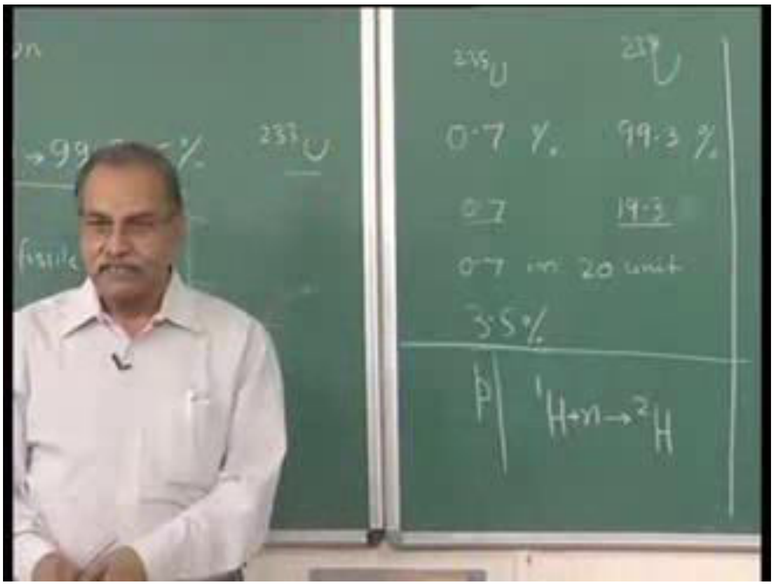

So, that the proton is there and this neutron collides with proton. And, almost in one single collision if it is head-on it gives of its kinetic energy to that water molecule to this p. But then you have this reaction that 1 h and plus neutron that goes to 2 h deuteron. And, this reaction has sizable probability. So, if you put water there and think that this neutron will go hit and will transfer kinetic energy it will. But in some of the cases and the number of such cases may be significant this neutron can just go and stick to that proton and make deuteron.

So, it is all together lost from the chain. So, that moderator material all this consideration should be there this should not absorb the neutron; at the same time it should reproduce the kinetic energy. So, this is about the moderation. And, why we need moderation outside that fuel rod? This is because as you decrease the energy of the neutron from mega electron volt to thermal energies to perfectly utilize that large cross-sections. It has to go through that region of 1 electron volt to 100 electron volt also. In that region if it is in the same vicinity of uranium 238. That means, the fuel rod the neutrons are slowed down right in the fuel rods itself; there also there will be scattering and the neutrons will slow down.

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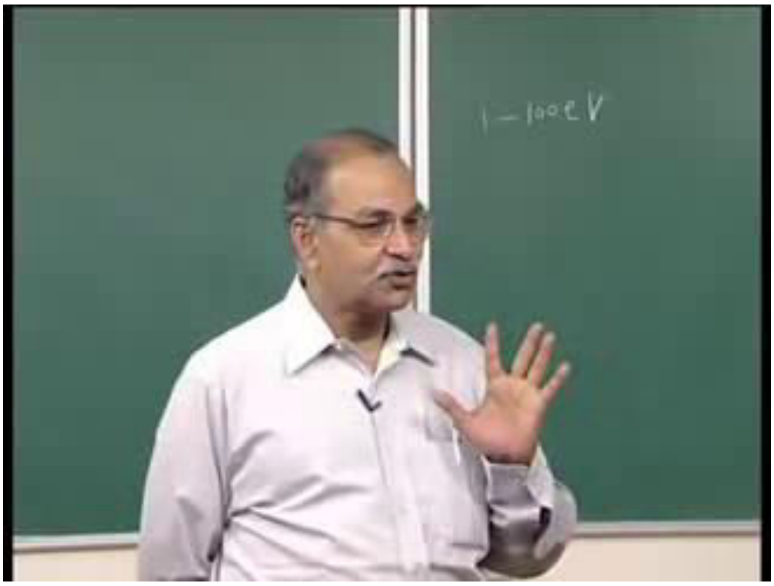

But then as it passes through that region say 1 to 100 e v during the slowdown from mega electron volts to thermal energies. Thermal energy is 0.025 electron volt or so 1 by 50 electron volts or even less. So, it has to pass through this. And, you had already seen that the radiative capture cross-section for this neutron plus uranium 238 reaction is very larger around 10000 barns or so. If these slower neutrons in the energy range 1e v to 100 e v are in that fuel rod where uranium 238 is there even if it enrich it by uranium 235 by 3 percent, 7 percent is still uranium 238. So, all these neutrons are likely to get absorbed in that uranium 238 and get captured because it just gives off gamma rays and comes to ground state.

So, these neutrons are lost for further fissions. So, that is why the design is such that the fast neutrons once they are produced in that fuel rod quickly they should come out of the rod. And, then in that moderator area between the rods you have all this moderator whatever water or carbon graphite or beryllium or heavy water or whatever that moderator material. The choice of moderator material has to be made it has to be a low z material, easily available, cost-effective at the same time it should be have lower cross-section for any nuclear reaction that absorbs neutrons. So, all those considerations are there but whatever is the moderator material the scattering of neutron takes place from these moderator material. And, then the kinetic energy is decreased to thermal energies before going into a rod. And, no one will ((Refer Time: 41:56)).

So, all this all random phenomena, so in that fuel rod a fast neutron is created of course there will be probability that it remains in the rod but then it is a fast neutron it is moving with high speeds. So, most likely it will leave the rod early if the rod is not too thick. So, it will leave the rod and get into the moderator in the moderator with some scattering events it with thermalize. And, then it will still wander here and there. And, then in this random wandering sometime it will get into the fuel rod that thermalized neutron.

So, the geometry is to be very nicely designed. So, that after thermalisation it gets good chance to get into the fuel at the same time before thermalisation; when it is in the range of few electron volt energies that time we should not be able to get into the fuel rod. So, that geometry has to be designed taking into account all kinds of statistics and all kinds of theories of probabilities and random walks and this and that, so that most of the time the fast neutron as it is created in efficient event in the fuel rod comes out in the moderator. And, then remains in the moderator area till it is thermalized, till it crosses that danger zone of 100 e v to 1 e v and comes below that.

And, then once it comes below that and once it is kinetic energy is almost the thermal kinetic energy. Then, you should get a sufficiently good chance to get into one or the other fuel rod. So, all these design has to be made. So, that is why the moderator is needed. Now, in the diagram once again look at your screen those reactor designs. The other thing you can see here are these control rods. We will talk about that little later but why this control rods are there? But these are rods of materials like cadmium which absorbed neutron with high probabilities. So, these rods are there to absorb the neutrons. And, if you find if the operators find that these nuclear reaction is going faster then what it is designed for these rods are inserted deeper into the into this core.

So, that they start absorbing some neutrons and the rate of fission goes down that is it. And, then you have this reflector outside this is your reaction core in which you have moderator and the fuel. And, then outside here this is some kind of envelope which reflects the neutrons; if neutrons try to get out of this reactor core some of them will be reflected back that is here. Then the heat that is generated here if that heat is to be used to produce electricity energy purposes, then that heat is to be taken out some kind of coolant goes into this reactor core gets heated because of the heat generated in fission. And, that heat is taken away from some other channel and then used to drive turbine and this and that. So, these are this is the typical design.

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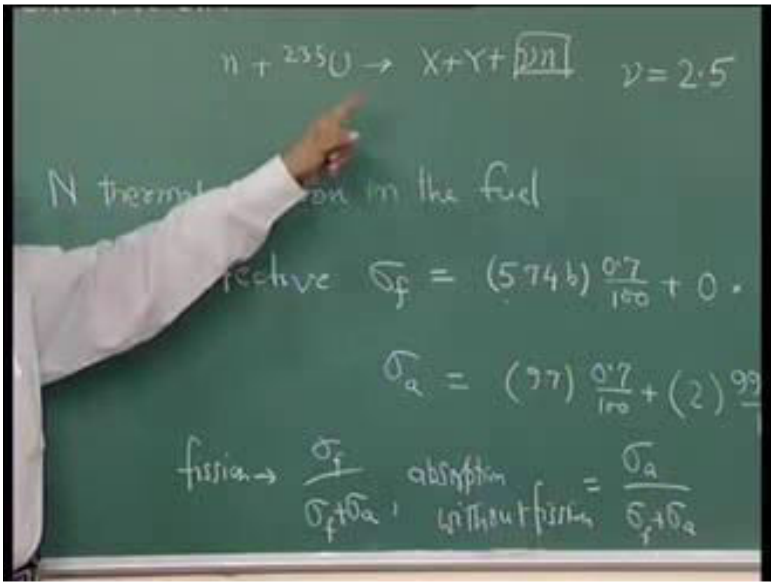

Now, let us look at what we call four factor formula whole idea of this fission reactor is that once it starts it is self sustained. Once fission reaction starts that fission reaction produces more neutrons and those neutrons themselves produce more fissions and more neutrons. And, it goes on as long as you want. So, that is the thing it is known as chain reaction. And, that is that is because as you know this neutron plus 235 uranium that goes to uranium 236. And, then finally x plus y and then you have these neutrons. So, with 1 neutron you get these neutrons and on the average for uranium 235 this nu is something like 2.5 or 2.45. So, on the average 2.5 neutrons are produced and these are of course fast neutrons they have to be moderated and all that.

And, what controlled fission reaction will be that out of this 2.5 one is used to trigger the next fission. So, every 2.5 one should be able to produce new fission. If it is more than 1 then you are lost the it will just explode. If it is less than1 then it will die this will not sustain. So, these reaction will stop it has to be just made at 1. So, what are the processes where this 2.5 reduces to 1 or whatever is the number? So, at certain stage let us say at certain time you have n thermal neutrons in the fuel. So, at a certain time say you have these n thermal neutrons already thermalized in the moderator. And, then these neutrons have reached fuel rods to make fission.

So, this is one time instant or one time level. Now, what happens to these n thermal neutrons? The first is in the fuel these are all thermal neutrons. So, they have high probability of fission in uranium 238, 235 but then they can also get radiative capture. They can undergo this radiative capture reaction in uranium 238 as well as in uranium 235 both. In uranium 235 also if 600 barn is the cross-section for fission 97 barn is the cross-section for radiative capture. And, uranium 238 there is no cross-section 0 cross-section almost 0 cross-section per fission. But then there is a some cross-section for this radiative capture we are talking of thermalized neutron. So, that resonances are out of questions. Those resonances are beyond 1 electron volt but even this lower thing although it is not going through those resonances some cross-section is therefore, that non-fission kind of. So, you talk of effective cross-section for fission; effective also because you have both the species.

So, average on the average what is the fission cross-section per nucleus that is there? And, that will be say for this is let us say 570 or 574 barns for uranium 235 but then that is only 0.7 or if it is enriched 3 percent. So, say 0.7 percent and then you have that is all 0 for that uranium that uranium 238. Whereas sigma a if you see that will be 97 here, 0.7 here and then you will have some cross-section there some 2, 3 barns whatever some three barns or so. So, that is there and then you have 99.78 by 100 and the fraction sigma f by sigma f plus sigma a. This by this fraction it is reduced because the fraction which fissions that only give you nu times n.

So, from these n neutrons what I am looking for from this capital n thermal neutrons; when they fission how many new neutrons will be created? So, not all these capital n will go through fission this fraction because this sigma a is for absorption without fission. So, this fraction only this fraction this is you can call it total cross-section. So, out of total only this is going for fission and rest is going for absorption. So, this is for fission and this is for non fission absorption; absorption without fission that is sigma a. That fraction will be sigma a by sigma f plus sigma. So, do not multiply by just 2.5 it is not n into that nu but it is n into nu into this part. And, that is written as eta.

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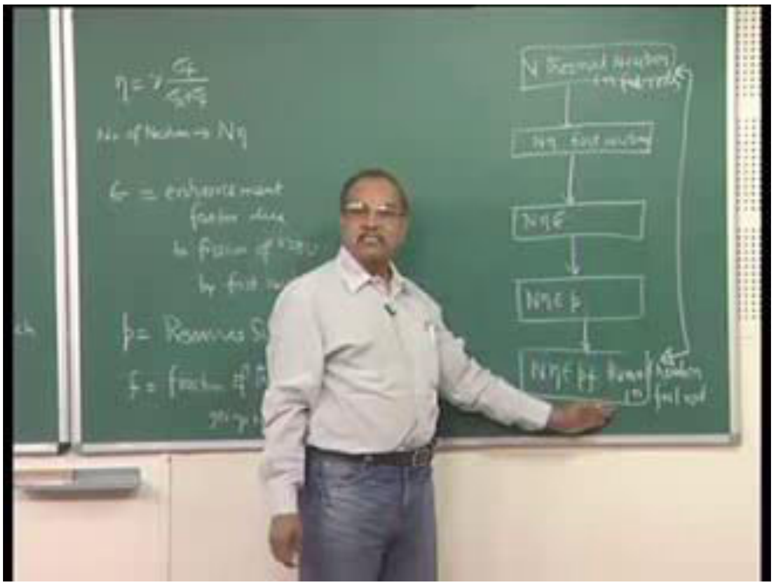

Eta is nu times sigma f sigma a plus sigma f and number of neutrons when this fission take place will become n times eta. So, you had n thermal neutrons and from this n thermal neutrons what you get is n times eta fast neutrons. So, you get this n times eta. And, what are the typical values of eta? If it is natural uranium this eta will be somewhere 1.3 or so for 3 percent enriched this will rise and this will be something like 1.8. So, that is the factor. So, ((Refer Time 53:22)) from 2.5 by that remember uranium 238 is in large quantity. So, it brings down this number drastically.

Now, these are fast neutrons. These fast neutrons are supposed to come out of this fuel rods as soon as possible. So, that they get into the moderator but it is all random phenomena, it is all statistical phenomena. So, before coming to that moderator; some of these neutrons can interact with the uranium 238 which is there and produce what you call fast fission. Fission of uranium 238 is possible at these energies. These neutrons which are produced fast neutrons they are at something like 2 mega electron volts or so. And, the fission cross-section becomes considerably it is still below 1 barn. But after 1m e v or so that cross-section becomes significant. So, some of these fast neutrons can induce uranium 238 fission before they come out of in fact they do not come out of the fuel rod; they get absorbed and they create fission. If they create fission once again you will have enhancement in neutron.

So, out of that capital n into eta most of them come out in the moderator that is how the geometry is designed. But some of them which create fission in uranium 238 and do not come out in moderator; they because of that the number of neutron will be enhanced. So, that is written by one more factor and that is epsilon. So, epsilon. So, what that epsilon? This is the enhancement factor due to fission of uranium 238 by fast neutrons. Now, you have n into eta into epsilon. So, this many fast neutrons are there and they come to the moderator. Then, in the moderator they are suppose to thermalize but then some of them even if they are in moderator they are randomly moving here and there. And, you have a fuel rod here; you have a fuel rod here although the geometry is designed, so that most of the time they will not see a fuel rod before getting into thermal energies.

But it is all random phenomena apart of them, a small fraction of them can always go to that fuel rod surface. And, interact which that uranium 235 while still in that dangerous 1 electron volt 100 electron volt range. So, not all of them will be thermalized. So, that the resonance that absorption resonance survival from that. So, there will be a factor how many of them survive? So, typically some 90 percent, 95 percent survive but still 5 percent, 10 percent neutrons do get trapped into that resonances region. So, that is p. So, resonance survival factor you can call it. Now, you have n eta epsilon and p. So, these many have survived that uranium 238 non-fission absorption in 1 to 100 electron volt energy range.

And, they are thermalized but even if they are all thermalized not all of them will be able to get into the fuel rods. Because after all there are some small cross-sections where the moderator material or the other surrounding material that is there can absorb this neutron. So, the part of thermal neutrons which are able to get into the fuel rods. So, that is written as f. So, f is the fraction of thermalized neutrons going in the fuel rods. So, that is here and then you get this n eta epsilon p f. So, these where the thermal n thermal neutrons in the fuel rod and then here you get fast neutrons this is in the fuel rod. Then, here it is epsilon enhancement factor; fast neutrons enhance the things then the part of it goes into the moderator and survives that resonance peak that is here. And, finally the fraction f goes into the fuel rod, and so here once again these are thermal neutrons in the fuel rod same as this. So, this is 1generation. In 1generation this n thermal neutrons in the fuel rod has become n into eta into epsilon into p into f thermal neutrons in the fuel rods. So, in 1 generation capital n has become this.

So, it is changed by a factor k infinity we I will I will tell next lecture what is this k infinity? It is eta times epsilon times p times f. So, in 1 generation the number of thermal neutrons ready to fission in fuel rod that changes by this factor. And, this is known as 4 factor formulae for obvious reasons. There are 4 factors; 1, 2, 3, 4. So, this is known as 4 factor formulae.