Fundamentals of Nuclear Power Generation

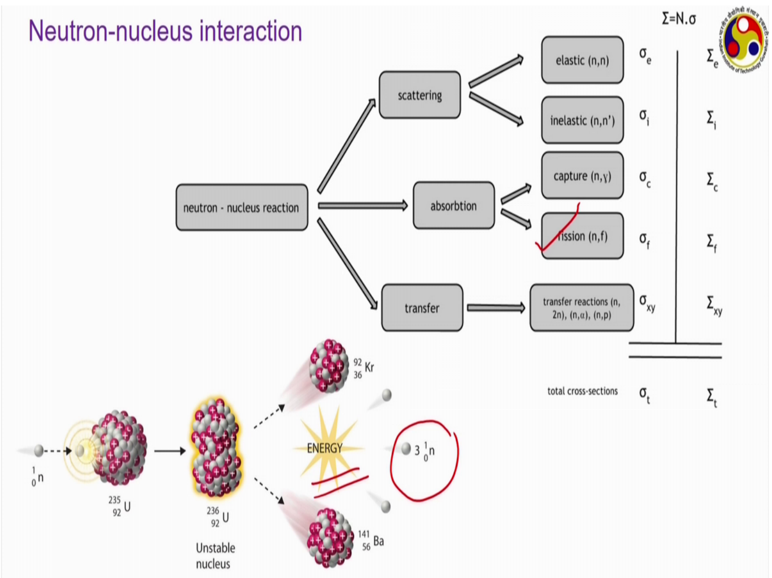
Dr. Dipankar N. Basu
Department of Mechanical Engineering
Indian Institute of Technology, Guwahati

Module – 03
Nuclear Fission
Lecture – 07
Fission & role of neutron energy

Hello friends, welcome back to our MOOCs course on the fundamentals of nuclear power generation and today we are going to start a very interesting portion and a very important module of our course which is the topic of nuclear fission. We have already studied the fundamentals of nuclear power generation in the previous 2 modules where you got introduced to the concepts of binding energy and we have discussed about actually how mass can get converted to energy to give a huge amount of energy production because of a very small amount of mass defect.

We have also discussed about the topic of radioactivity in our second module and there we have seen that this is one particular figure which was also presented a during the second module that is whenever there is an interaction between a particle and a nucleus.

(Refer Slide Time: 01:30)



We can have different kinds of interaction while we can initiate any such interaction by hitting the nucleus with several possible particles of sufficiently large energy, but the neutron is generally the most preferred choice and therefore we are discussing all these interactions in terms of neutrons only, but all these discussions are equally true if we can use some other particle to produce similar kind of effects, but generally it is universal to use neutron as the initiating a particle.

And therefore, we are keeping our discussion restricted to neutrons only now when we have already learned that whenever there is a neutron nucleus interaction, we can have 3 types of possibilities one is scattering where the neutron and nucleus remains separately, but because of their collision there is will be transfer of momentum and kinetic energy from the neutron to the nucleus and we can have an elastic and in elastic version of the same in case of elastic collision both kinetic energy and momentum are conserved, whereas, in case of inelastic collision the momentum is conserved.

But kinetic energy is not conserved for the system because a good amount of energy may get released in the form of photons inelastic collision is particularly relevant for neutrons having extremely high energy level the second kind of interaction is the absorption which is actually of our interest in the second module.

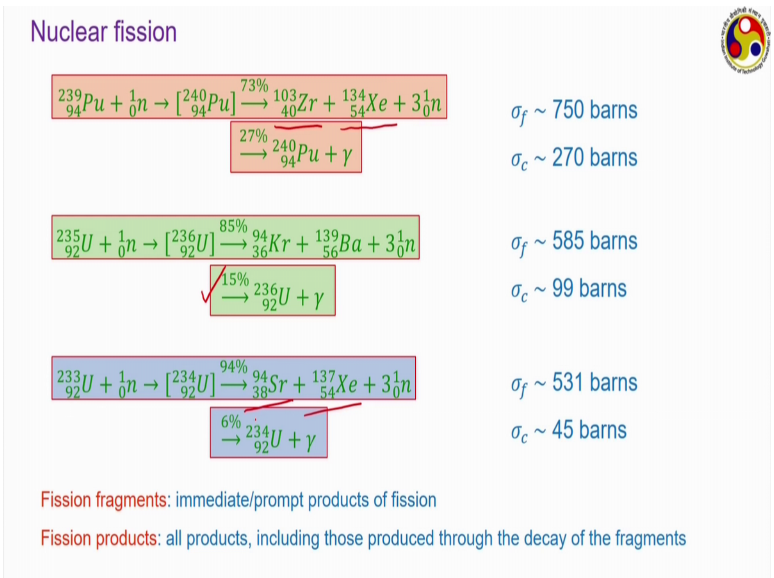
In this case the neutron goes inside the nucleus and then either it may remain inside the nucleus because of a radiative capture sometimes also called non fission capture and to and it produces just another isotope of the same parent nucleus, but the other possible option or other possible following step subsequent state for the absorption is the fission where after absorbing the neutron the parent nucleus or the newly formed nucleus is generally very excited to having high energy content and accordingly it can get splitted into 2 components.

So, which is what we are going to discuss here and there is also third kind of interaction possible which is transferred where neutron gets absorbed to the particle, but also leads to the production of several other kinds of particles like alpha particles protons or maybe neutrons as well and the possibilities or probabilities of having any such kind of interaction having any particular interaction when one particular neutron strikes a nucleus is given in terms of the cross sections and corresponding to each possible kinds of interactions we can have one cross section definition summation of all of them gives the total cross section.

So, as we have already studied see if our interest is to know what is the probability of fission occurring when a nucleus of known energy strikes a known nucleus when a neutron of known energy strikes a known nucleus that we can calculate considering sigma f divided by a sigma total that is a fission cross section divided by the total cross section of the same nucleus similarly we can also calculate the probability of any such other kind of interactions and here as we are focusing primarily on this fission reaction.

So, this is one example here one neutron strikes a nucleus like in this example is a uranium 235 the neutron is consumed or absorbed inside the nucleus forming uranium 236 which is generally an unstable nucleus and also having a very high amount of energy content. So, it get can get splitted into 2 daughter isotopes which is also associated generally with release of several number of neutrons like 3 in this particular situation. And also huge amount of energy because the mass of all these products like in this case we have products in the form of krypton 92, barium 141 and also 3 neutrons. The combined mass of all these 5 components together is generally found to be less than that of uranium 236 which is the parent in the second step of reaction. So, corresponding mass defect gets converted to energy.

(Refer Slide Time: 05:30)



Let us first start with a few examples of fission like first one corresponds to plutonium one third 239 which observes a neutron produce plutonium 240 and extremely unstable nucleus which gets through a fission reaction to produce zirconium 103 and xenon 134 plus 3 neutrons, but that is not the only possible way plutonium 240 can decay because it happens only 73 percent of the total possible situations, but for remaining 270 sorry remaining 27 percent cases plutonium 240 remains as it is rather.

It ejects or it loses its energy in the form of gamma emission and comes to the ground state. So, whenever the neutron strikes if you can 239 and gets absorbed; firstly, here we are talking solely about the absorption reaction that is the scattering and transfer reactions are eliminated. So, whenever we are writing an equation as some nucleus plus a neutron.

You are talking only about the absorption reaction; that means, neutron is going inside to form another isotope of the same parent in this case plutonium 240 which is one neutron more compared to plutonium 239. Now plutonium 240 after that is getting formed each can have 2 kinds of hits one is the fission which is the first one and in this particular example it happens 73 percent of total about 73 percent of the total possible cases, but for the remaining 4 6 cases, it will only go through a gamma emission.

That means, it is actually a non fission capture the other part of that absorption reaction fission is absorbed by the nucleus, but there is sorry neutron is absorbed by the nucleus, but there is no fission it just produces another isotope of the same and whatever amount of energy extra energy that has come with the neutron there gets rejected in the form of gamma emission. Now how can we calculate these percentages we already know of the corresponding cross sections and that idea can be used like for plutonium 239.

Corresponding with thermal neutrons, that is neutrons which are having energy of approximately 0.025 electron volt. Its fission cross section is 750 bonds and the capture cross section that is non fission capture cross section is approximately 270 bonds. So, if we try to calculate the possibility of a fission reaction here, then it is sigma if or let me write properly it is a sigma f divided by total absorption cross section that is sigma f divided by sigma c and this will come approximate to be equal to this 73 percent.

So, just by a knowing the values of this fission and absorption non fission capture cross sections we can get the idea about what are the possible percentages of having a fission reaction and having a non fission capture reaction after neutron has got absorbed another example with uranium 235 here, here absorption and neutron first produces and 236 and it can either go through a non fission capture like in the second case which happens about 15 percent of the total times to remain as uranium 236 other is the fission reaction like here it is producing krypton 94 and barium 139.

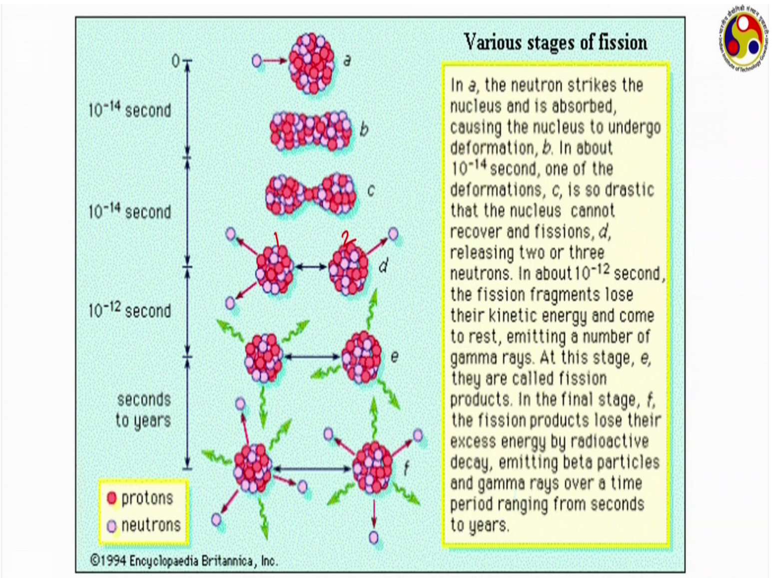
So, we know for thermal neutrons or cross sections for fission for uranium 235, is 585 and for capture, it is 99 bonds. Correspondingly, we get this, percentages a third set of examples. Now with uranium 233, another very popular isotope used in nuclear reactors it after capturing the neutron uranium 234 and almost all uranium 234 isotopes can go through fission reaction is a very high percentage of 94 percent because corresponding fission cross section is extremely high compared to the capture cross section only if about 6 percent cases. We can see that uranium 234 can eject gamma rays and come back to a ground state.

So, there are possibilities of having both fission reaction and non fission capture after the neutron gets absorbed and we can get the ideas just by knowing the values of this cross sections here I would like to introduce 2 terms one is fission fragments other is fission products fission fragments refers to the immediate products of the fission like.

Say if you focus on the first reaction involving plutonium here these 0 1 0 3 and Xe 134. These are the fission fragments because these 2 are produced immediately from the fission reaction. Similarly, for the last example involving uranium 233, this SR 94 and xenon 137, these are the fission fragments, but there are several other kinds of products like we can see for all these cases, we have neutrons getting emitted and also all these products of fission like in the last example this strontium 194 and xenon 137 both of them generally a strongly radioactive. So, after the fission reaction they keep on decaying a following their own decay constant there by producing several new isotopes and also releasing several other particles like alpha particles or more neutrons or maybe electrons etcetera combining all those things what we get that is called the fission products.

So, fission products definitely involve the fission fragments plus all the products of the decay of the fission fragments plus neutrons and any other particle that may get emitted during this fission reaction if we look further into exactly how a fission reaction happens, it is a step by step of figures shown here.

(Refer Slide Time: 11:27)



In the first case, one nucleus is being struck by your neutron and that is getting absorbed the neutron is getting absorbed in the second case which is shown by this b here in this b. Now because the neutron is having a good amount of energy it is able to excite the newly formed nucleus to a higher energy level and because of that excitation this nuclear starts to deform you can see; it is taking a dumbbell kind of shape in the third case the deformation is even more drastic. It is just about to get split because you can think or just check out the focus or the thickness here it is about to speak it is almost similar to how our human body cells or any live cell gets the divided into 2 components just quite.

Similarly it is this dumbbell shape produced during step b that is now even more stronger and the 2 components are almost separated from each other which happens in the step d in the step d they will get separate into 2 components this is our component number one. This is our component number 2 which we have already termed as fission fragments plus we can also see there are release of neutrons there are 3 neutrons shown in this figure and also in the previous slide we have seen the examples in all those 3 examples 3 neutrons are emitted.

But actually 3 is not a constant number the emissions that are happening a number of neutrons that gets emitted that may vary from anything from 1 to 7 also I would like to just briefly go back to the previous slide where we have seen these examples, I must mention here these are just one possible way the fission can happen let us take the second uranium 235, once uranium 235 absorbs a neutron to produce uranium 236 then it is not possible to predict the next step; that means, the out of this 2 step reaction the first step is always the same uranium 235 absorbing neutron to produce 236.

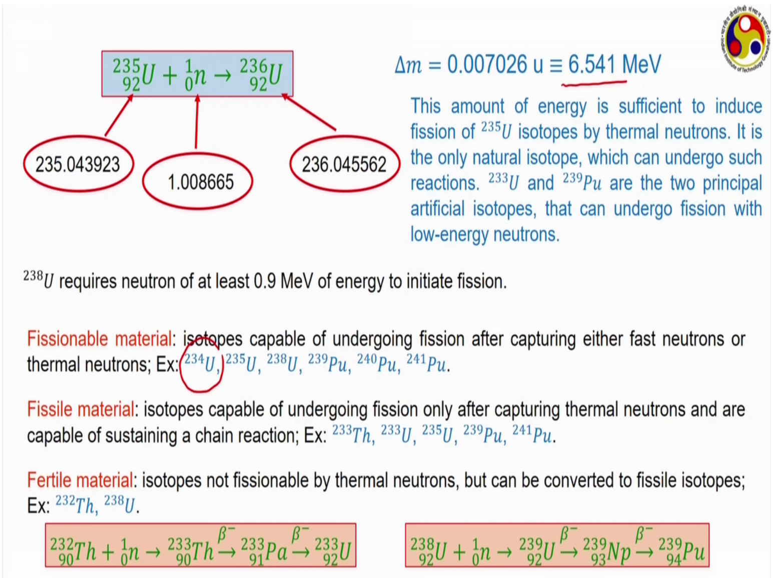
But the second step there are infinite possibilities it is only one possible options to have krypton 94 and barium 139, but it can produce any number or any types of fission fragments and also any number of neutrons the number of neutrons can vary from 1 to 7 with approximately the average is being 2.5. So, it is not possible to say exactly which fission reaction or exactly what we are going to get as efficient fragments. But it is for sure that the newly formed the intermediate nucleus is going to get deformed into 2 components and also will be releasing several neutrons number of neutrons can vary from 1 to 7.

Now just take a look at the extreme left of this figure what are the time scales that is involved the step from a to b to c to d, this total thing is happening within a time span of just 2 into 10 to the minus 14 seconds that is this is an extremely small time scale that we are talking about within which this entire phenomenon of one parent nucleus being struck by neutron and getting splitted into 2 components that happens and next the step e that is not precisely the fission reaction rather that is related to the later part or the decay of the fission fragments in will the fission fragments are radioactive. So, they go through their own decay which is shown here you can see both the fission fragments are getting decayed and the nature of the decay has no relation.

With the fission reaction the nature of the decay depends solely upon this fission fragments and on this fission fragments decay keeps on continuing till I; both of them reaches some kind of stable nucleus. So, the decay process of this fission fragments that depends on the half life of the fission fragments themselves and accordingly that can take a time span of seconds to a few years or maybe a few hundred years also, but invariably that we finish when both of them lead to some kind of stable isotopes and the fission product the term that we have introduced earlier that is primarily added to that decaying products that we are getting from the or decay or radiative disintegration of all these fission fragments.

So, primarily the decay of the fission fragments involves gamma emission and beta emission.

(Refer Slide Time: 16:23)



So, that their energy is lost in the form of gamma emission and also there is transmutation because of the beta decay we shall be seeing that very shortly. Now let us take this example of uranium 235 absorbing one neutron to produce a young 236, these are the rest masses for all 3 of them uranium 235 he is having 235.043923 and similarly value is given for uranium 236 if we calculate the corresponding mass defect the rest mass of urine 236 is found to be lower than the combined rest mass of uranium 235 plus neutron and that is having a value of mass different value of about 0.007 MeV which corresponds to 6.541 MeV.

This amount of energy is sufficient to induce the fission reaction that we have just seen particul and whatever we are talking about that is because of thermal neutrons that is the neutron which is having very very small amount of energy. So, we have not at all considered the energy level of the neutron if we are making this reaction happens with an high energy neutron then of course, that add energy of the neutron also kinetic energy of magnetron.

Also will get added with this value, but unfortunately uranium 235 remains the only natural isotope which represents this kind of behavior; that means, while there are infinite number of natural isotopes presents in the universe uranium 235 is the only one that can experience fission reaction when it is being struck by a thermal neutron and if you remember in our module 1, I have made given some percentages of all these isotopes presents in the nature uranium while uranium is present in a good quantity.

But uranium 235 is only about 0.7 percent of a natural uranium core or ore as therefore, it is present in a very small quantity and that is the only isotope that can go through a fission reaction, but there are several artificial isotopes that can be produced and out of this uranium 233 and 239 are 2 principal artificial isotopes that can also undergo fission when being struck by low energy neutrons. So, the fission reactions are any thermal reactor what do you mean by thermal reactor I hope you remember thermal reactor is something which works on thermal neutrons that is its working principle is based upon the thermal neutrons are not fast neutrons.

So, for thermal reactors we can you primarily use these 3 isotopes as the main fuel to have the fission reaction one is uranium 235 which is available in nature other 2 are uranium 233 and p plutonium 239 both of them needs to be produced artificially there are several other isotopes which may undergo fission reaction, but not when is struck by thermal isotope rather it requires much higher energy level to undergo fission reaction and that energy can be supplied only through the kinetic energy of neutron say for example, uranium 238 can undergo fission only when it is being struck by a neutron of approximately 1 MeV of energy. So, there are several we can clearly see we can have at least 2 types of isotopes in nature one like uranium 235 which can undergo fission just through the thermal neutrons.

Whereas there are examples in uranium 238 which requires high energy neutrons something at the level of fast neutrons to initiate the fission sis accordingly all material available or in related to the nuclear power generation can be divided into 3 categories first is the fissionable material fissionable refers to isotopes which are capable of undergoing fission after capturing either fast neutron or thermal neutron or maybe both isotopes which are capable of undergoing fission reaction when that is being struck by a neutron of any energy level either fast or thermal that we call fiza element fissionable material. So, this example that we have just discussed uranium 235, 233 plutonium, 239 uranium, 238 all of them are fissionable materials; however, the issue is that uranium 235 can undergo fission only by a thermal neutron, but uranium 238 cant.

So, while both of them are fissionable material, but only one is a fissile material which refers to an isotope which is capable of undergoing fission only after capturing a thermal neutron and also that is capable of sustaining a chain reaction and that is uranium 233, uranium 235, plutonium 239, plutonium 241, thorium 233, all are fissile materials you remember 233 is only the natural one, but others are all artificial. So, when we strike any of these isotopes with the thermal neutron.

It can lead to a fission reaction and also we shall be seeing later on what we chain reaction means, but for the moment you just keep in mind that a fissile material or to identify something as a fissile material you need to have 2 conditions satisfied number one the isotopes should initiate fission reaction when being struck by a thermal neutron that is it does not depend upon the energy of the neutron to initiate a fission reaction and secondly, after the fission reaction happens it is capable of sustaining a chain reaction like the example of uranium 230 that was given earlier it is a not a fissile material from both counts it continued a fission reaction with thermal neutron rather it requires only fast neutron to initiate fission.

And. Secondly, it cannot sustain a chain reaction also and the reasons we shall be discussing later on, but there is a third category of particles who are elements which are fertile elements fertile elements are not fissionable by thermal neutrons that is when that being struck by thermal neutrons, they cannot undergo fission, but after capturing a thermal neutron they can get converted to a fissile neutron or fissile a fissile isotopes rather that is fertile and fissile had 2 kinds of materials fertile refers to after capturing a thermal neutron it initiates fission and sustains that through a chain reaction fertile on contrary it is not able to initiate a fission reaction after capturing a thermal neutron, but it can get transmuted to a thermal neutron.

Like this example of thorium 232 when it captures a thorium 232, it gets converted rhodium 233 which can undergo 2 steps of beta decay to produce uranium 233 which is a fissile material therefore, thorium 232 is called a fertile material it cannot as undergo fission by on its own, it is actually a fertile material because it cannot undergo fission by on its own.

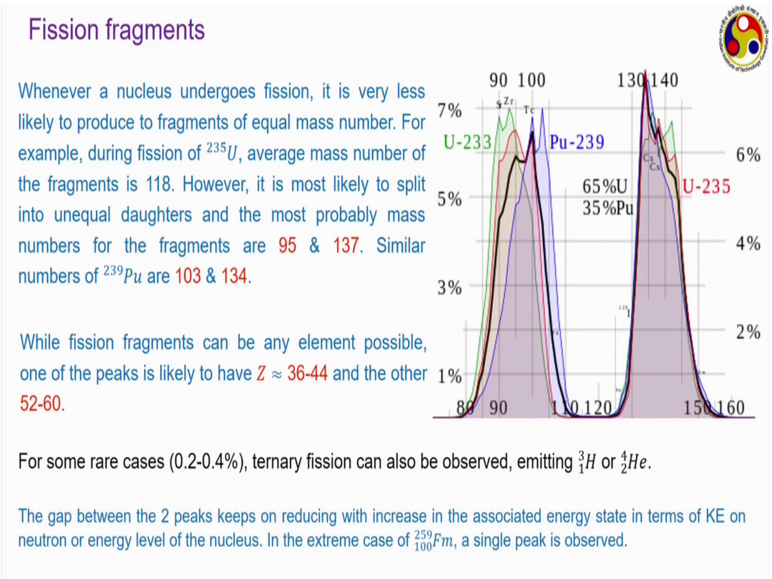
But by capturing thermal neutron it can lead to the formation of uranium 233 which is the fissile material and that is why you are calling it fertile another example of uranium 238 which we have identified as a fissionable material, but not a fissile material it can also capture a neutron thermal neutron that is to produce uranium 239 which again goes through 2 steps of beta decay to produce plutonium 239 which is a very strongly fissile material actually the all the fissile material that we are discussing here like uranium 233, 235 plutonium 239 this is the one probably the strongest one.

And generally not used for commercial power generation rather kept separately as wear grade materials that is for producing weapons nuclear weapons that is. So, i repeat we can have 3 types of isotopes from nuclear reactions point of you fission reaction points point of view one is fissionable; fissionable isotope can undergo fission by capturing either thermal neutron or fast neutrons second is fissile which can undergo fission only by capturing a thermal neutron and hence and also capable of sustaining the chain reaction.

So, all fissile materials are fissionable, but all fissionable materials may not be fissile because there may be examples which cannot initiate fission a thermal neutron rather require fast neutrons something like uranium 238 and fertile material is the third category the isotopes which cannot undergo fission by capturing thermal neutrons, but can get transmuted to some kind of fissile neutrons fissile materials there can be examples of fissionable material, which are not fissile and not fertile as well like the example of uranium 234 uranium 234 after capturing one neutron goes to uranium 235, which actually cannot undergo fission because of reasons we shall be discussing later on.

But that is one example of something or you can it is actually uranium 235 is a slightly debated you better can take the it is better to stick to uranium 234. Now later we shall be coming back to this later on it is a fissionable material, but it is not fissile neither fertile. Now come to fission fragments.

(Refer Slide Time: 26:03)



As I have mentioned because of fission reaction, we have 2 fission fragments that gets produced, but there can be from the same combination of neutron and nucleus we can have different kinds of fission fragments produced and actually it is more like a probabilistic phenomena that which by which we can predict what can be the types of fission fragments that gets produced that is while we cannot predict exactly what fission fragments. We are going to get but we can predict what is the most likely fission fragments here the concentration of fission fragments as shown during the fission of on different 3 different isotopes.

Let us follow the red lines which corresponds to uranium 235 you can see the 2 fission fragments that we get they are never having equal mass number rather it is generally always true for any kind of fission reaction both the fission fragments have significantly different mass number like say for uranium 235, once it captures you a neutron it converts to uranium 236. So, we can expect that there will be 2 fission fragments having a mass number of 118, but that is not true while the average mass number for both the fragments remains to be 118, but invariably we will find one fission fragments have a mass number in the range of eighty to hundred 10 while the other is having in the range of 120 to 150 and the most probable one being somewhere here which is approximately 95 and other is somewhere here which is approximately 137.

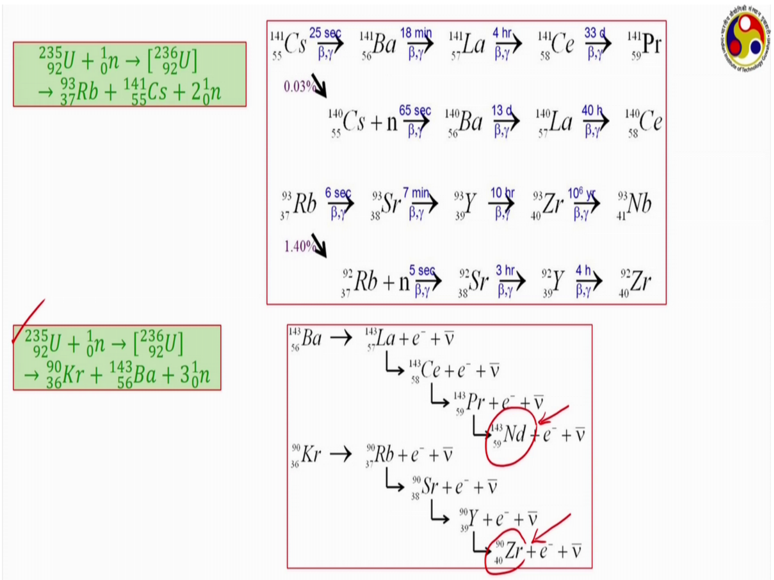
Similarly for other isotopes, we can get other numbers while the range may of this model is the same one between 80 to 110, other between 120 to 150, 60 or 150 slightly above 150, but the most likely fission fragments for plutonium 239 will be having mass number of 103 and 134. Now similar, if we focus on the atomic number, then it is likely that the most probably fission fragments one will be having atomic number in the range of 36 to 44 and other in the range of 52 to 60 and these figures shown here includes a very large database of nuclear reactions involving all these 3 fuels and so we can almost take these numbers for granted like for uranium the most likely fission fragments will be having mass number of 95 and 137 and for plutonium 239 in the range of 103 and 134. There can be very some very very rare cases a 0.2 to 0.4 percent where we can have a ternary fission that mean along with the these 2; there can be a third fission fragments which is invariably an alpha particle or maybe a tritium.

Now let us compare the 3 lines that are shown here the green line corresponds to uranium 233 the rate corresponds to uranium 235 and the blue line corresponds to plutonium 239, if you observe carefully the gap between the most probable mass number for uranium 233 is something between here to here it is a large gap, but if we compare that with plutonium the gap is something only a range of like this or if I write properly you will get it is something like this the most likely fission fragments for plutonium 239.

One is somewhere here other is likely to be somewhere here and definitely they are much closer compared to what we get for uranium 233 if you follow uranium 235 one is somewhere here other is somewhere here. So, the distance between the most likely mass number for uranium 239, 235 fission is larger than plutonium 239, but definitely smaller than uranium 233.

So, what can we conclude from here we can clearly see as the mass number of the fissile material or fissile nucleus is increasing then the difference between most likely mass number for the fission fragments that keeps on reducing and that is an important observation I repeat as the mass number of the fissile nucleus keeps on increasing generally, its energy level also keeps on increasing accordingly the distance between the most likely the mass numbers of the most likely fission fragments that also keeps on decreasing in an extreme case of fm 100 fm one 259 which is an artificial isotope. We generally get only a single peak that is it is likely to produce 2 fission fragments having equal mass number; that means, as the mass number or energy level for the fissile nucleus is increasing the both the fission fragments are there are larger chances of having 2 equal or identical fission fragments.

(Refer Slide Time: 31:27)



Now, let us focus on the fission fragments it was mentioned that fission fragments can be strongly radiative in nature here.

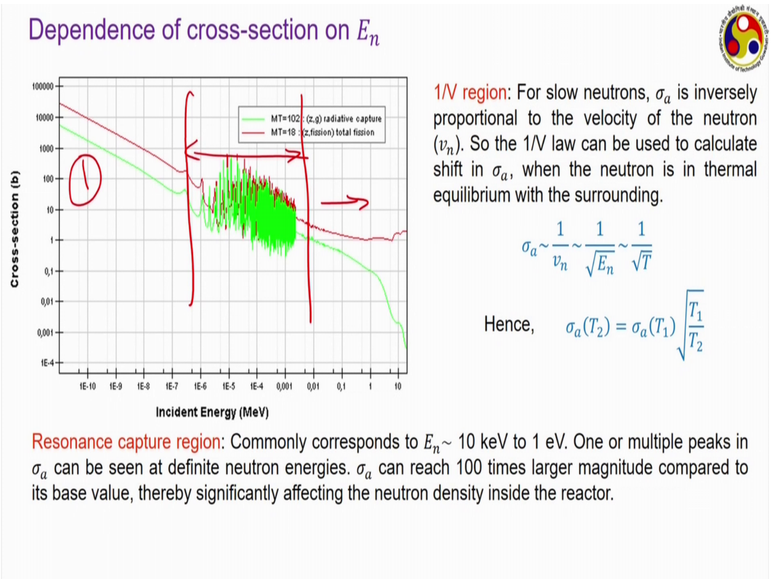
One example is shown for uranium 235 fission which is producing rubidium and cesium or rubidium 93 and cesium 141 both of them are strongly radioactive some possible decays are shown cesium can go through as you can count there are 4 steps of beta decay it can go through from cesium to barium to la to Ce finally, leading to pr and all these steps of beta decay they are also accompanied by gamma emission in some very small cases of point 0 3 percent cesium 141 can first get converted to a cesium one forty and then finally, going through 3 steps of decay to reach Ce 140 for rubidium again we can see there are 4 steps of beta decay to produce nb 93 as the final product whereas, in certain situation it can under also undergo a different route to lead to zirconium 92 here.

So, just forget the alternate or less likely or decaying option for the fission fragments if we just consider the first line for both cases that is this line for cesium and this line for rubidium then while because of the fission of uranium 235 we are getting a rubidium 93 and cesium 141 as the fission fragments its fission products will include several other possible into isotopes and it is most likely the final one.

Will be this one and this one and also there will be several electrons produced like in the first case there are for beta decays and also same in the second case. So, there will be eight electrons produced and also eight gamma photons plus 2 nitrogen, sorry, 2 neutrons that has produced originally; that means, the fission fragments while it is restricted only to 2 isotopes the decay of the fission fragments leads to a good basket of the fission products another example of uranium fission which is leading to the formation of krypton ninety and barium 1 for 3 both of them are radioactive again you can see that is going through 3 steps or rather 4 steps of beta decay in also it is producing electrons and new anti neutrinos and possibly also gamma emission similarly krypton is also undergoing 4 steps of beta decays to finally, producing 0 90 that is while this particular fission reaction is having krypton and barium.

As the fission products, but once the complete decay of all the products are done then we are likely to get this one and this one and also several electrons and neutrons and also large amount of energy as the fission products also one point I must add here because of the decay of all this fission fragments, we are also getting some amount of energy; that means, the amount of energy that we get from the fission reaction itself will also get a significant amount of addition from this decay of the fission products and this total together can be a substantial amount we shall be seeing the numbers later on now it is it was seen that thermal neutrons can produce fission for certain elements, but there are other elements which cannot have fission with thermal neutrons.

(Refer Slide Time: 35:14)



Rather they give or they can go through fission reaction only when they struck by a fast neutrons that is because the cross sections any cross section like the fission cross section or capture cross section or maybe scattering cross section all of them depends strongly on the kinetic energy of the neutron here the corresponding variation is shown for uranium 235, you can clearly see as the neutron energy keeps on increasing energy level of the neutron from extremely low level to mega electron volt level. The corresponding cross section values are also reducing rather there are 3 clear zones we can identify one zone as this one; one zone as this one and add another zone as this particular one.

And there are 3 distinct behaviors of the cross section variation with an energy can be seen the first zone which is this particular one for corresponding to the slow neutrons that is a corresponding slow neutron that is called the one by v region you can see here this cross section is reducing almost linearly with the kinetic energy and it has been observed that this absorption cross section is nearly inversely proportional to the velocity of the neutron and accordingly we can use this one by v relation to calculate the energy level of any thermal neutron like say exam say here sigma a is inversely proportional to the velocity. So, we can always say that is inversely proportional to the root of En.

En being the kinetic energy and hence as the kinetic energy of thermal neutron can be directly related to the temperature of the surrounding we can also write this to be inversely proportional to the square root of temperature absolute temperature that is and using this we can say suppose we are having we know the data corresp; of absorption cross section for a certain temperature T 1, then the system changes its temperature goes to some temperature T 2.

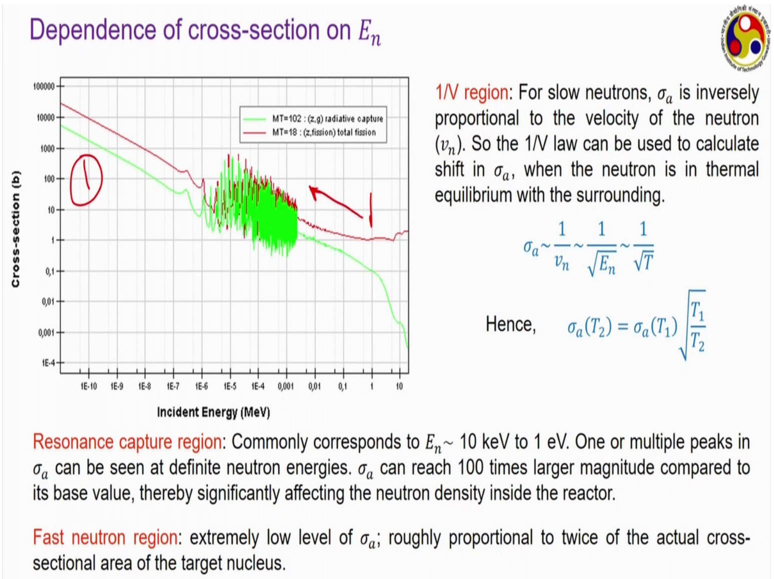
So, if you want to know the absorption cross section corresponding to the thermal neutrons at this particular temperature we can always calculate using this sigma a at T 2 will be equal to sigma at f T 1 into root over T 1 by T 2. So, these is a very straightforward relationship and for all as all thermal reactors operate in this particular slow neutron zones. So, we can easily use these numbers or these relations for calculation of the cross section absorption cross section the second one is quite interesting which is called the resonance capture zones you can see there are lots of peaks or undulations in the profile this is commonly observed between the energy level of 10 electron oh sorry one electron volt to 10 kV; KeV.

There are multiple peaks actually there are certain elements like indium which can have just a single peak, but inevitably uranium 235 or 238 or other fissile or fertile materials can have large number of peaks there. So, at certain energy levels the cross section of the neutron is quite high where as certain other energy levels it can be quite low.

In fact, for elements like uranium 238 the absorption cross section at this peak can be 100 times more than the base values and therefore, it can significantly affect the neutron density inside the reactor we in nuclear reactor most commonly we find the neutron available as fast neutron level somewhere here and to convert that to thermal neutron we have to go through some kind of process during which its kinetic energy will be reducing and it will be going in this direction.

So, while going through this direction it has to pass through this resonance capture region and if when it is passing through a resonance capture region at that certain energy level when this cross sections are high there is a every chance that the neutrons will get absorbed by the fuel itself and this is a non fission capture reaction sometimes also called the resonance capture reaction and therefore, it is better to be avoided actually we cannot avoid this, but it is always attempt is always made to pass through this region as quickly as possible.

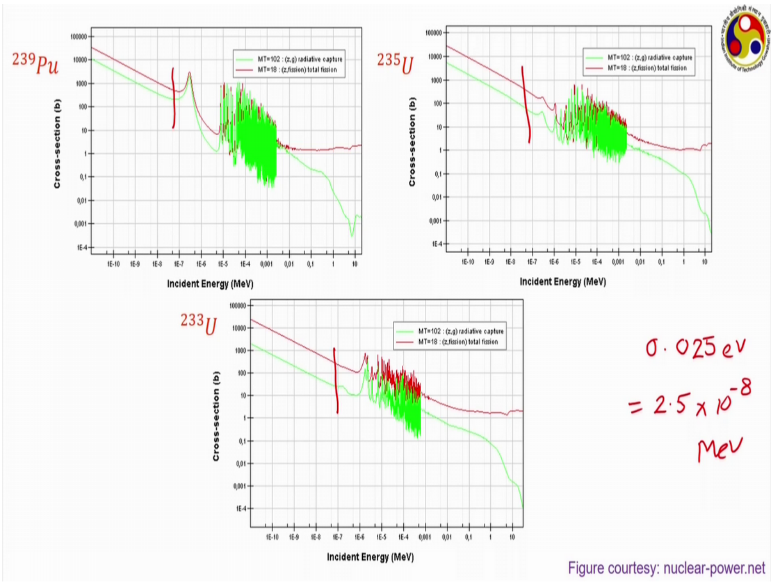
(Refer Slide Time: 39:42)



So, that the loss in the number of neutrons is not very significant and the third region is the first neutron region first neutron refers to in a neutron energy greater than one electron volt during sorry 10 keV or 0.01 mega electron volt.

So, in this region it is generally not very important for power generation point of view, but generally it is found to be the that the cross section is roughly proportional to twice of the actual cross section area of the target nucleus here we are talking about the actual cross section or physical cross section not the cross section from nuclear point of view. So, the variation of cross section with kinetic energy can have 3 cleared zones we have the one by v relation applicable for the slow neutron or thermal neutron level then we can have a resonance capture zone where there are several peaks of cross section and then they are the of there is the fast neutron region which is not very commonly used or considered for analyzing a thermal reactors.

(Refer Slide Time: 40:44)

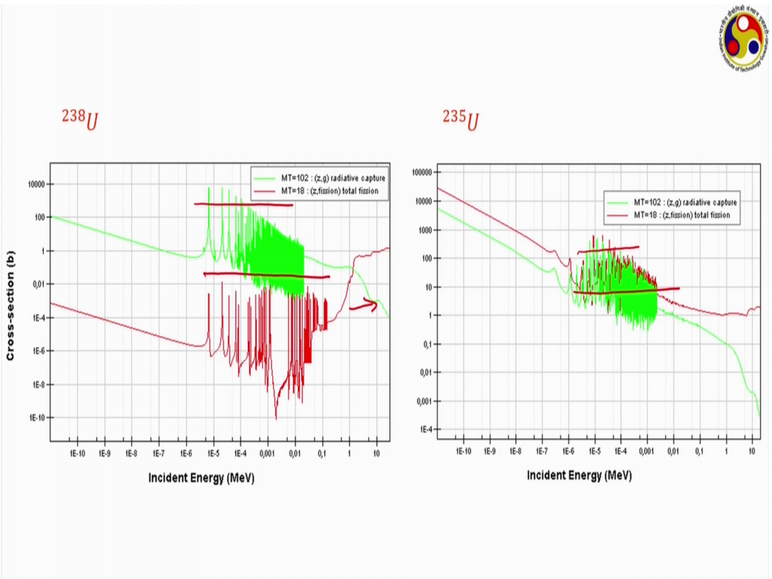


These are the figures for 3 different fissile material that we are discussing you can see; suppose, for thermal neutron is having an energy level of points 025 electron volt. So, 0.025 electron volt is equal to 2.5 into 10 to the power minus 8 MeV.

So, from the figure it should be somewhere here and you can see here this red line corresponds to the fission cross section and green line corresponds to the capture cross section you can see here the fission cross section for uranium 235 is quite high a few hundreds generally about 600; the value was given in one of the earlier slide whereas, the capture cross section is in the range of tens. Now, it is less than 100 at least similarly, if we compare that with plutonium corresponding with the same level plutonium somewhere here. Here also the fission cross is quite similar maybe slightly higher and the capture cross section is also a bit high whereas, in case of uranium 233, you can clearly see there is a while in case of plutonium that gap between these 2 is not very large of course, it is a logarithmic scale you have to be careful the vertical scale here is logarithmic.

So, small gap still can corresponds to a large difference in the actual values, but uranium 233 is having a significant difference between the capture and fission cross section and if we think about the thermal neutron part somewhere here then of course, the capture cross section is extremely small compared to the fission cross section.

(Refer Slide Time: 42:26)



Now if we compare between one fissile and one fertile nucleus uranium 235 and uranium 238 very interesting for uranium 238 is that the capture cross section is much larger compared to the fission cross section almost throughout apart from very high energy level that is when we are talking about energy level of one MeV or more that is fast or ultra fast neutrons, but below that the capture cross section is significantly higher than the fission cross section like if we think about say the thermal neutrons which will be somewhere here or maybe slightly more towards right here the capture sorry the fission cross section is of the order of 10 to the minus 5 only. So, that is you can take it virtually to be 0 whereas, the capture cross section is greater than 1.

So, capture is the most likely to phenomena which is, but in case of even 235 as we have already seen the fission lines is above sufficient cross section is always greater almost at any energy level fission cross section is greater than the capture cross section and also just compare the resonance peaks that we are getting between the 2 materials like if you is in the resonance zone say if we take this as the base level which is approximately 10 bonds then the largest peak that we are getting these are more or less at this level.

So, about 10 to twenty times larger peaks can be obtained now you compare that in case of fission now sorry in case of uranium 238 here if we take the base level to be something here that is of the order of 0.01 the peaks can be much much larger a few hundreds. So, there can be 10 to the power 3 times increase in the fission cross section at those peaks and hence uranium 238 exhibits a very strong resonance absorption behavior and in any thermal reactor.

(Refer Slide Time: 44:44)

	Thermal neutron			Fast neutron		
	Scattering	Capture	Fission	Scattering	Capture	Fission
H-1	20	0.2	-	4	0.00004	-
H-2	4	0.0003	-	3	0.000007	-
C-12	5	0.002	-	2	0.00001	-
Zr-90	5	0.006	-	5	0.006	-
Fe-56	10	2	-	20	0.003	-
Cr-52	3	0.5	-	3	0.002	-
Ni-58	20	3	-	3	0.008	-
O-16	4	0.0001	-	3	0.00000003	-
B-10	2	200	-	2	0.4	-
Cd-113	100	30	-	4	0.05	-
Xe-135	400	2,000,000	-	5	0.0008	-
In-115	2	100	-	4	0.02	-
U-235	10	99	583	4	0.09	1
U-238	9	2	0.00002	5	0.07	0.3
Pu-239	8	269	748	5	0.05	2

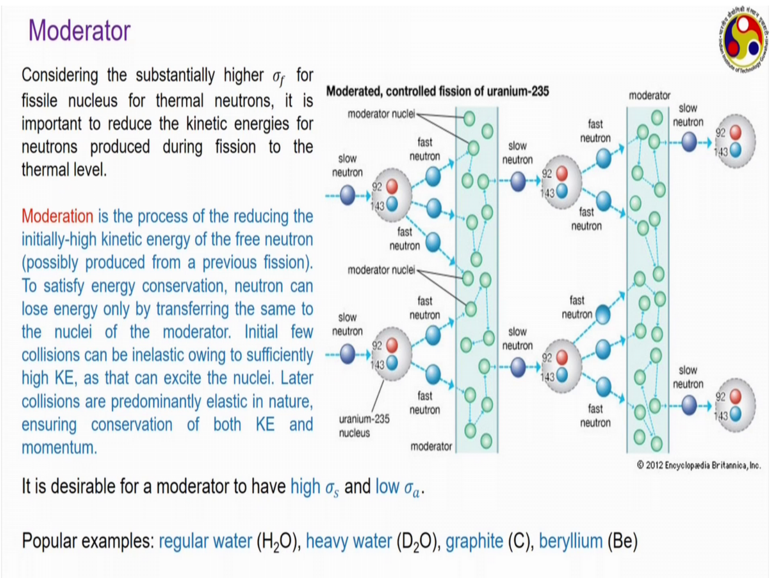
If we are using natural uranium as fuel which has more than 99 percent of uranium 238, there is every chance that a good number of neutrons may get absorbed by the uranium 238 while passing through this resonance capture zone some numbers just to focus on the previous points that I have mentioning just focus on the uranium 235 and 238 here even a 4 thermal neutron uranium 235 is having a fission cross section of 583 and capture cross section of about 100.

Whereas, the fission cross section is negligible for uranium 238 and it is a very capture cross section is also quite small there are certain materials like say xenon is a extremely large capture cross section. So, that can actually act as a poison in the reactor which will eat up all the neutrons available there by completely stopping any possible fission reaction another thing you see for all these materials there is no fission cross section ale applicable or that is their fission cross there will be no possibility of fission reaction for any of them. So, they are not even fissile materials as well.

Now, if you come to the fast neutrons for uranium 235 the fission cross section is just one, it was 583 here, it is just one here capture cross section has also see a found similar amount or similar level of decay, but uranium 2 thirty it actually has an increase in its fission cross section that is still quite small, but significantly larger compared to its value corresponding to the thermal neutrons. So, uranium 238 can undergo some amount of fission through fast neutrons, but the corresponding cross section value being quite low that probability is also quite small. So, now, we know that it is important to convert a fast neutron to the thermal neutron level as the fissile materials particularly like uranium 233 or 235 or plutonium 239 has much higher values of fission cross section or absorption cross section of corresponding to the thermal neutron correspond to the fast neutrons their cross section values are extremely small as we have just seen in the previous slide.

For the example of uranium 235, we are talking about a difference of 583 and one.

(Refer Slide Time: 46:50)



So, we must reduce the neutron energy to the thermal energy level and then only we can have a significant amount of fission inside a reactor and corresponding process is called moderation. Moderation is a process of reducing the high kinetic energy of free neutrons and the con get it converted to the thermal neutron this is one schematic representation say generally neutrons the chain this we shall be coming back during chain reaction of also, but as we have seen whenever a fissile nucleus undergoes a fission there are neutrons that is giving produce and those neutrons are generally fast neutrons because they will carry a significant amount of energy released during this reaction. So, like in this case these are the 3 neutrons that just got produced because of the previous fission as their fast neutrons.

So, they must pass through something called a moderator a moderator works on the principle of elastic scattering that we have discussed earlier during elastic scattering the neutron collides with the nucleus and exchanges kinetic energy and momentum thereby it loses his own energy and transfers a bit or a good part to the corresponding nucleus. So, while passing through the nucleus the sorry passing through the moderator the neutron can undergo repeated collisions repeated elastic scattering and finally, coming out as a slow neutron here the slow neutron of course, will offer much larger fission cross section.

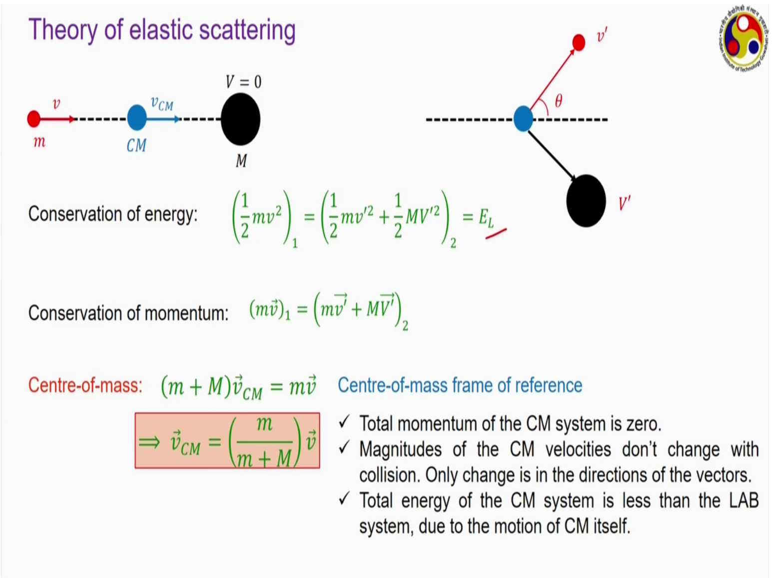
So, that will lead to another fission reaction this way a moderator helps in fission reaction because suppose if this fast neutron is allowed to strike another nucleus corresponding cross section being very low there is a very less chance of having a fission reaction, but as we are using the moderator the slow neutrons will offer continued rate of fission another thing when these fast neutrons initially strike the moderator nucleus there extremely high energy level may lead to inelastic collision passing.

Some amount of excitation energy the corresponding nucleus, but after 2 or 3 such collisions the most of the next collision steps are elastic in nature. So, collision for a good performance from the moderator it must have a high value of scattering cross section and also it is important that it has a low absorption cross section because if the moderator which here itself is absorbing neutron then there will be no neutron left to induce the next step of fission therefore, it is desirable that a moderator material should have very high signal scattering cross section and extremely low preferably 0 absorption cross section.

Some common choices are regular water heavy water heavy water refers to the water where the hydrogen is actually a deuterium. So, heavy water and regular water both are very good moderator graphite can also be used beryllium also has found some applications as moderator whereas, certain hydrocarbons has also been proposed recently the reason of choosing these particles or choosing these materials we shall be seeing very very shortly.

Now another term I would like to clarify here as we use the term heavy water to signify water molecules which contains deuterium quite occasionally that one light water is used to indicate normal water, but we shall be using term regular water because light is not a proper terminology.

(Refer Slide Time: 50:34)



So, we comes to the theory of elastic scattering here we are taking one nucleus of mass capital M which is initially at velocity at 0 velocity the black one here is a nucleus and the red one is a neutron having a mass of small m and coming with a velocity v it is approaching the nucleus with the velocity V, once the collision happens, then it transfers a part of its kinetic energy to the nucleus. So, both of them can get scattered in 2 different directions here theta is the angle by which the neutron gets scattered from its initial line of motion and similarly v prime is also getting scattered by some other angle.

So, as this being realistic scattering both energy and kinetic energy and momentum will be conserved conservation of energy can accordingly written as before collision here one refers to the state before or state before collision to after collision before collision the nucleus is stationary. So, only kinetic energy is associated with the neutron.

So, half MV square represents the kinetic energy of the neutron after collision both are moving. So, this is the kinetic energy of the this for the neutron this for the nucleus here small v prime and capital V prime represents the velocity magnitudes of neutron and nucleus respectively after the collision process and let us say E L is the energy magnitude of this particular energy next is the conservation of momentum again initially the nucleus is stationary.

So, entire momentum is coming from the neutron and after that both of them are moving this is a vector addition because momentum is a vector quantity next we define a term called center of mass we can easily analyze this from this conservation of energy and conservation of momentum point of view, but it is and by taking our laboratory or wherever this experiment is going on as the frame of reference that is why it is often called the lab scale and that is why this l subscript we are using energy at the lab scale, but whenever you are talking about such kind of 2 particle collision it is better to go for a center of mass approach center of mass is defined as and hypothetical body of mass which is having the same amount of mass as the initial system that is it is this mass is the combined mass of the neutron and nucleus and also it is carrying the same amount of momentum as the entire system.

So, the total mass of the body is small m plus capital M and if v cm represents velocity then as I have mentioned the total mass will be equal to the total mass of the system and total momentum will be equal to the total momentum of the system now before collision total momentum is small m into v that is the momentum carried by the neutron and as that remains constant. So, this will be the total momentum of these center of mass here this blue ball shows a center of mass which is moving with a velocity v cm now. So, v CM can be represented in terms of the velocity of the neutron center of mass; mass approach has certain advantages and certain characteristics here total if we can or the center of taking centre of mass as the frame of reference.

We can gain certain advantages once we know the velocity and mass of the center of mass then we can calculate the velocity and momentum for both neutron and nucleus with respect to that and that is by taking the centre of mass as a new frame of reference and the advantage that we are going to get the total momentum of the center of mass system will remain 0 both before and after collision magnitude of the center of mass velocities will not change because of the collision, but there will be only change in the direction that is the direction of velocity vectors.

So, will change, but no change in magnitude and third is total energy of the center of mass system will be less than the lab scale system due to the motion of the center of mass itself. So, we shall be next discussing about the theory of elastic collision by converting this lab scale system to a center of mass system.

But as we are running short of time today we shall be starting that in the next class onwards where or next lecture where we shall be deriving the mathematical expression starting from the kinetic energy conservation and momentum energy conservation according to the center of mass frame of reference we shall be deriving the expressions for velocities of the neutron and nucleus after collision and we shall be seeing how much reduction in the kinetic energy of the neutron that is possible and accordingly we shall be we shall be setting up some criterion of choosing the moderator material.

So, thanks for your attention today hope to see you in the next lecture.