Fundamentals of Nuclear Power Generation

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Lecture – 05
Artificial radioactivity and neutron-nucleus interactions

Hello friends, welcome back to our MOOCS course on the fundamentals of the nuclear power generation. And today we are into the third lecture of our second module where we are discussing about this is very interesting topic of radioactivity and nuclear reactions.

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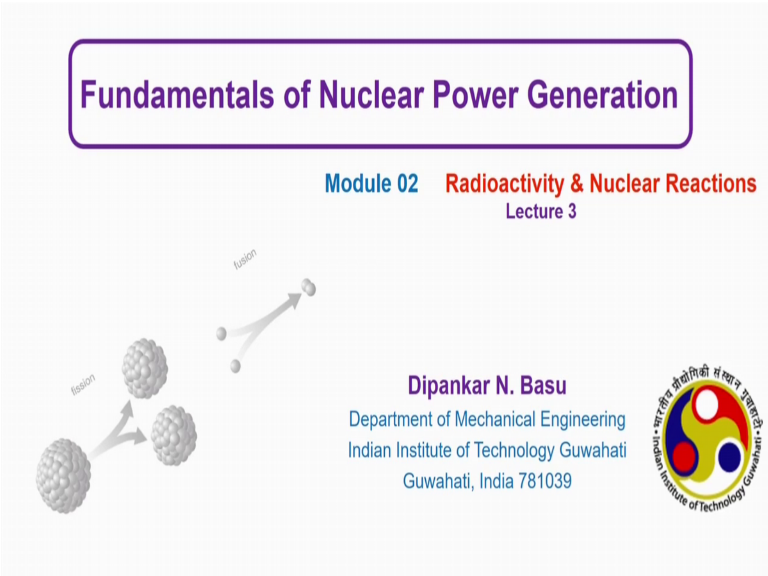

We have already gone through two lectures on this topic of radioactivity and almost all the fundamentals associated with has been introduced to you. Like, if we quickly revisit our earlier two lectures; the topic of radioactivity was introduced.

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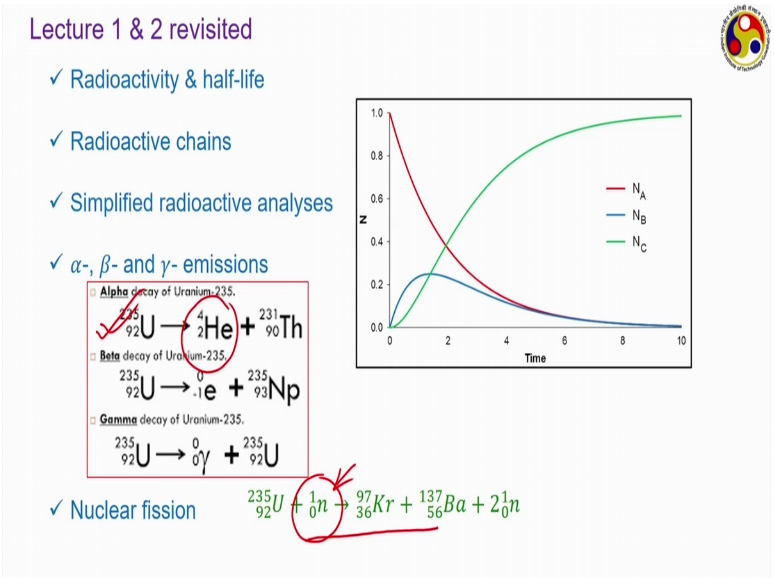

Which we have defined as the spontaneous disintegration experience by an unstable nucleus because of this disintegration, generally a nucleus gets converted to some other nucleus a process which we have named transmutation. And also such kind of reactions are generally accompanied by emission of several kind of particles or energy photons.

And the radioactive materials or radioisotopes can be characterized by several parameters it with the decay constant, mean life, but half life is the most important one of them which you were introduced to you and we have already had a detailed discussion about half life; the ways to measure half life, how half life varies about a wide range starting from a few seconds to a few billion years to a certain particles.

And also quite often the product of such radioactive disintegration leads to a daughter isotope which itself is radioactive in nature, leading to the formation of radioactive chains. For certain materials, the chain can be quite long involving 8 and 12 isotopes and such chain keeps on continuing till the appearance of some kind of stable isotope, which is actually not radioactive in nature.

Quite often that is found to be an isotope of lead, when you are talking about disintegration of some heavy isotopes like uranium or thorium or plutonium. Using the concept of half life etcetera, we also had a few calculations like we took a simple 3 parameter radioactive chain or radioactive chain will holding just three nucleus and did the analysis using their exponential rate of decay and the relation between their half life or the decay constant and we now know how to estimate several associated parameters like at a particular time instant what can be the number of nucleus of any particular species at what rate all these three elements in this example they keeps on decaying.

And something like that several cases related to do this was also studied. And then we also discussed about particularly in our second lecture, we focused more on different types of radioactive decay reactions which generally involves emission of alpha and beta particles and also gamma rays. Alpha emissions as we have already discussed is generally associated with some heavy nucleus something having an atomic number greater than 80, where as beta plus or beta minus emissions are common to any nucleus and whether it will be a electron emission or is or a positron emission that generally depends on the ratio of proton to neutron numbers present in the nucleus.

And gamma emission is common to any kind of such reactions, whenever we have a nucleus which is having energy higher than it is ground state, it always tries to eject some kind of energy in the form of gamma photon and go back to the ground state. Several examples of each of these kinds are also discussed and like we have also seen a particular isotope can undergo all this three kinds of decays or any kind of decay depending upon certain conditions.

Like this particular example of uranium 235 isotope which can exhibit alpha, beta or gamma decay; depending upon certain conditions. We have to discuss about this conditions in today's lecture and also the topic of nuclear fission which can also be an example of radioactivity or radioactive decay; that was mentioned as one of the examples towards the end of our second lecture, where we know that when an uranium isotope is hit by a neutron that leads to the splitting of this uranium isotope; leading to the formation of too much lighter isotopes and quite often that is accompanied by release of 1, 2 or 3 neutrons or may be even more.

But there is one big difference with this particular reaction and we say this one. You can see in both cases, our target nucleus is uranium 235, but in this particular one it is more spontaneous reaction; that is the uranium 235 under certain condition is getting splitted or getting converted to a thorium isotope and ejecting one particular helium isotope which is basically the alpha particle.

However, in the fission reaction, we have this particular element present on the left hand side of this equation or this reaction. Here basically this reaction does not look to be spontaneous in nature; rather the uranium isotope needs to be excited one is to be entice into this reaction; by virtue of using this neutron.

And therefore, it violates the very basic definition of radioactivity which is started, which is spontaneous in nature. It does not look to be a spontaneous reaction rather more like an induced or forced reaction and that is what is the topic of our today's discussion.

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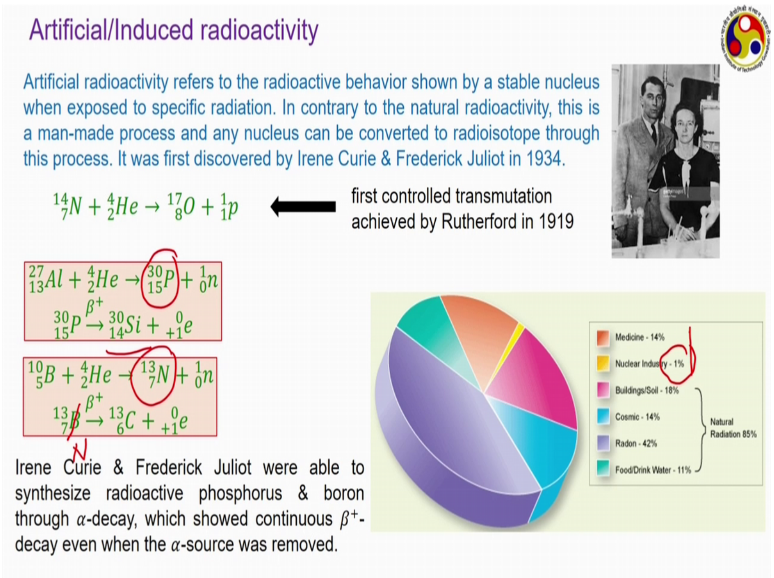

Which is artificial or induced radioactivity, whereas the natural radioactivity concerns unstable isotopes which by itself goes for radioactive disintegration; artificial radioactivity is concerned about some nucleus which is generally stable; which is stable in nature, but that is being exposed to certain kind of radiation maybe alpha radiation or maybe gamma radiation or something else.

And under the specific radiation; it is able to show some kind of radioactive behaviour that is if the isotope is kept as it is never expected to undergo any kind of radioactive decay. But only on the certain conditions that is one that is exposed to certain kind of radioactive emissions or some kind of radiations that shows the radio activity. This is definitely a man made process, a very much artificial process.

And it is a very important concept to have because if we can identify exactly for which kind of radiation, any given nucleus will show a radioactivity then basically we can convert any isotope to something else or I can say that any natural isotope can be converted to a radioisotope; only by subjecting it to some kind of suitable radiation. This artificial radioactivity was first discovered by Irene Curie; that is the daughter of Mary and Marie Curie who was working along with her husband Fredrin Juliet; may Irene Curie is quite oftened also known as a Irene Frederick.

Juliet Curie they jointly identified or reported this concept of in artificial radioactivity in the year of 1934, which led to a Nobel prize very soon. Now probably the first reported artificial radioactivity incident was by Rutherford in 1919; when we bombarded nitrogen of 14 isotope that is a natural isotope nitrogen with alpha rays and that led to the ejection of proton. This particular experimental result was used to establish the presence of proton.

And the topic of artificial radioactivity was not introduced by that time later that came only in 1934 by the work of Irene Curie and Frederick Juliet, when they showed this particular reaction that is they bombarded alf aluminium 27; the natural isotope of aluminium with alpha particle and lead to the formation of this particular one; that is phosphorus.

Phosphorus 30 that was the first incident of phosphorus 30 appearing (Refer Time: 08:33), but in conquer to the Rutherford experiment where oxygen seventeen was formed; this phosphorus 30 actually showed positron decay and getting converted to Si 30 that is silicon 30; that means, this phosphorus isotope act after being formed for aluminium to the process of transmutation that showed radioactive behavior.

Similar incident was also observed for boron 10, which after being bombarded by helium was converted to nitrogen 13 and that nitrogen 13; I think I have a typing error here this should not be boron, this should be nitrogen this nitrogen 13 went through a radioactive decay which leads to the ejection of a positron or a beta plus element and gets converted to carbon 13.

And more interestingly this synthesis of phosphorus and boron and their radioactive nature does not depend of on the availability of this a alpha particle source. Rather once we have this phosphorus 30 of boron; nitrogen 13 available to us, once we have this phosphorus 30 nitrogen available to us even after removing the source of alpha particle they kept on ejecting the positron.

That means, they kept on showing the radioactive behaviour; that means, the Irene Curie and Frederick Julia able to form two new radioactive isotopes, which was phosphorus 30 and nitrogen 13 and that is what was termed as the artificial radioactivity. This has immense importance not only in the field of nuclear power generation, but in several other fields like a here just if a pie chart is shown about different kinds of radioactive reaction.

Radiation that we can experience in nature where almost 85 percent transformer natural sources such as our buildings and soils which can contribute 80 percent and the food and drink that we have. And also very much natural sources such as cosmic radiation coming from the outer space and radon; there are several rocksgen found to be emitting radon which is a strong radioactive element.

But a good contribution is also coming from these artificial sources like the medicinal fields, which nuclear medicine particular uses this phenomenon of artificial radioactivity is a lot. And of course, the nuclear industry it is very interesting that while there is huge hue and cry about the emissions that we receive from nuclear power plants etcetera; actually the nuclear industries contribute only 1 percent out of the total global radiation that we actually experience.

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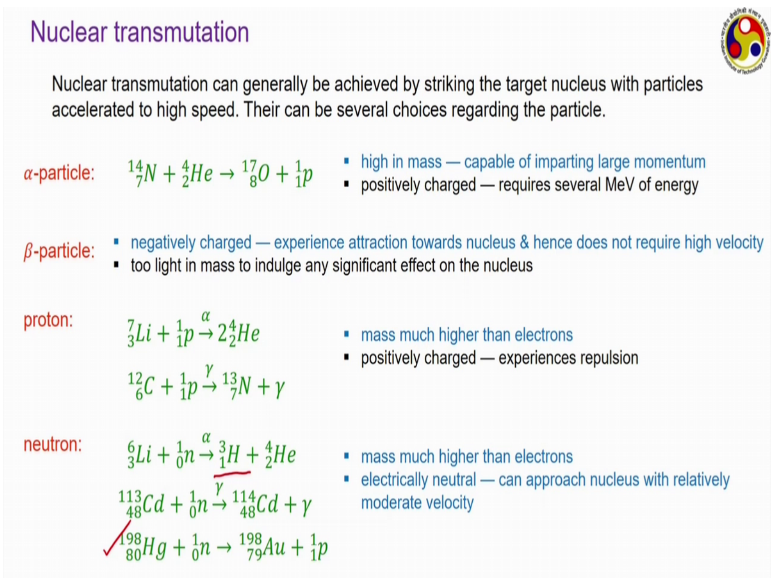

Now, continuing this topic of artificial radioactivity; now we know that to have artificial transportation of any nucleus, we need to strike that by some kind of particles which has to be accelerated to at high speed. Like the examples of the alpha particles in the previous slides, but there actually not only alpha particle; we can use different kinds of particles.

While alpha particle was the first one this particular example which was the buy experiment from Rutherford. But alpha particles has it is own issues, it is advantages it is high in mass therefore, it is available to carry a huge amount of moment and once it strikes a nucleus that is of course, expected to cause a good amount of damage to the nucleus or there is very likely to cause a splitting.

However, the problem for alpha particle is they are positively charged. Alpha particles have two protons and two neutrons and therefore, they have two units of positive charge and nucleus is also positively charged. Therefore, when the alpha particle approaches a nucleus, it experiences very very strong nuclear electrostatic force electrostatic repulsion force.

And therefore, we need to excite this alpha particle to very high energy level or I can say we need to input several mega electron volt of energy into the alpha particle to make it reach to the nucleus. Electrons or beta particles they can also be used, but their advantages they are negatively charged; therefore, they actually experiences electrostatic attraction towards the nucleus and does not require very high velocity.

But problem is that they are very very light in terms of mass, if you remember the mass of electron is at least four orders lower than that of a single proton or a neutron. And therefore, that is not expected to cause too much damage to the nucleus after a collision. Proton can be an example proton has one unit of mass; so, it is much heavy 1 unit of mass com or a very close to one any of mass.

And therefore, it is very much expected to cause certain amount of damage because of the collision. At least much larger compared to the electron, but again similar to the alpha particles proton is also positively charged and therefore, it will also experience similar amount of repulsion force. And there neutron comes into picture; neutron has a several advantages, firstly, it is mass is quite similar to proton; if it is slightly larger than proton.

And therefore, it can definitely import good amount of momentum and it is also electrically a neutral. Therefore, we do not need to provide as much energy as a proton requires rather with much moderate energy level or with much moderate energy velocity, it can approach a nucleus. Incidentally, it will actually experience some kind of electrostatic attraction like what we get (Refer Time: 14:24) in a charged particle and a neutral one.

And that is why neutron is the most preferred kind of particle which you use for this nuclear transmutation or I should say artificial transmutation of nucleus. Like quite of a examples are shown here lithium 6 isotope being struck by neutron leads to alpha decay, leading to the formation of hydrogen 3 or tritium; cadmium also can absorb one nitrogen leading to formation of another isotope cadmium and this particular reaction which you have discussed earlier also.

Mercury; nucleus has being struck by nitrogen leading to the formation of gold nucleus also rejection of 1 proton. So, neutron is the most preferred particle which we generally used for artificial transmutation.

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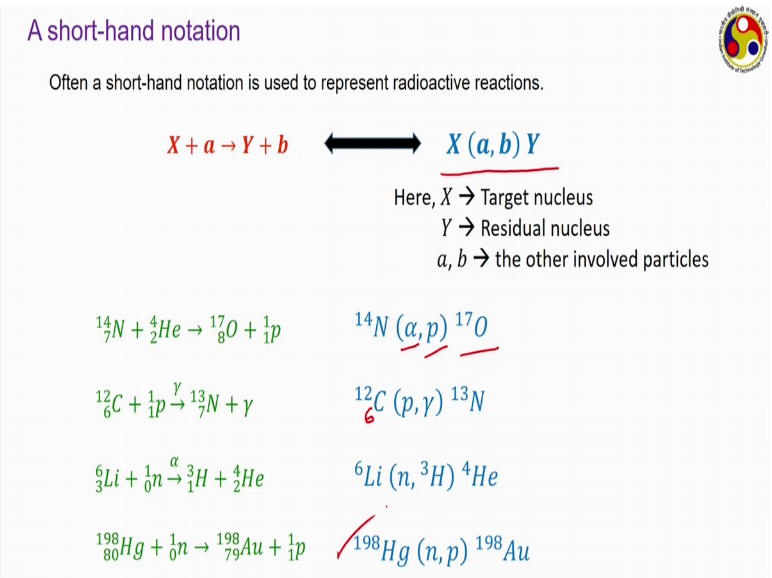

Now a shorthand notation which we often use in this particular field, like suppose we are having a reaction involving a parent nucleus X which is being struck by some particle small a and leading to formation of a daughter nucleus Y and also some kind of particle or say energy b. Then we often represent that by a formation like this, where X the target nucleus or the parent nucleus, Y is the daughter nucleus and a and b are the other involved particles; which actually can be energy like gamma in a photon also.

Say this particular example here nitrogen 14 is the parent isotope. So, that is the X oxygen 18 is the daughter isotopes; so, that is the Y. And here on the left hand side; we have alpha particles, so a is alpha particle and we have proton on the other sites; so b is proton. Let us see this particular example, here C 12 is the parent isotope and N 13 is the daughter isotope. We have proton on the left hand side and gamma photon on the right hand side.

Here you can see we are writing only the mass number of nitrogen or carbon or any such nucleus. Of course, you can always include their atomic number also like you can always put this 6 here to indicate the atomic number of carbon or this we can indicate for other articles also. But generally, the symbol of any particular element itself indicates is atomic number and therefore, sometimes just for the ease of representation, we often eliminate the atomic number. Like whenever we are mentioning the symbol N; we know that is nitrogen and that isotope has 7 number of protons in it is nucleus. So, that does not need a separate mention; this we can give a few other example.

Also like the last one we have mercury 198 as the parent and gold 198 as the daughter; if we have nitrogen as the element which is causing this reaction and photon is being ejected. So, corresponding shorthand notation is this particular one.

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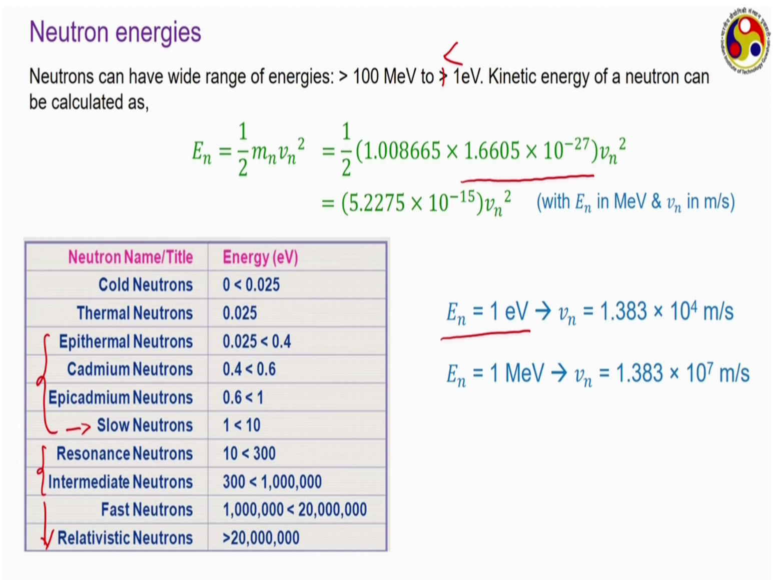

Now we know that nitrogen need some kind of energy to approach the nucleus and also to have enough momentum to cause some kind of transportation process. And this energy level of nitrogen can vary widely like; it can be greater than 100 milli volt to it is wrong, it can be actually much less than 1 electron volt as well; 100 mega electron volts a billion electron volts where as it can be as small as much less than 1 electron volt as well.

Kinetic energy of the neutron can be calculated the common formula that is half m v square, where here m n refers to the mass of the neutron and v n is the velocity. Now putting the values of the mass of the neutron, you know it is 1.008665 mev multiplied by the conversion factor between mev and kilogram, we approach to this where we have E n represented in mega electron volt and velocity in the metre per second. So, as per the website of IAEA that is the International Atomic Energy Authority, we have this kind of classifications for neutrons depending upon their kinetic energy level.

Of course, all these are not important rather we can club several of them together; say for example, this slow neutron refers to as per IAEA guidelines refers to electrons having energy between 1 to 10 electron volt. But generally this entire group we shall be calling as a slow neutrons that is any neutron having energy less than 10 electron volt, we can call as slow neutrons. Whereas, anything having energy greater than 1; mega electron volt can be called first neutrons and something in between called the intermediate that is from 10 electron volt to something like 10 to the power of 5 or 10 to the power 6 electron volts.

So, basically we are classifying electrons into three categories slow, intermediate and fast. And each of these values definitely can be associated with very large amount of energy release and large amount of velocity as well. Like for example, let us take a very small energy level E n equal to 1 electron volt; if you put it back to the other formula then that gives the velocity level of the order of 10 to the power 4 meter per second.

Whereas if you are talking about something of the order of 1 mega electron volt of kinetic energy for a neutron, the neutron must have velocity of the order of 10 to the power of 7 meter per second. So, we are talking about extremely large velocity levels just to give a small amount of energy to a neutron. There is another term that is of our interest that is the thermal neutron.

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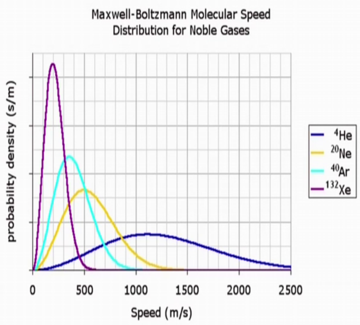
Thermal neutrons

Lowest possible energy for a neutron is the one that puts it in thermal equilibrium with the surrounding molecules. Such a thermalized neutron will also follow the Maxwell-Boltzmann velocity distribution. Accordingly,

$$E_n = \frac{1}{2} m_n v_n^2 = kT$$

$$\Rightarrow v_n = \left[\frac{2kT}{m_n}\right]^{0.5} = (128.369)\,T^{0.5}$$

(in m/s)



Temperature (°C)	E_n (in eV)	v_n (in m/s)
20	0.0253	2197.89
260	0.0459	2964.05
537.8	0.0699	3655.59
1000	0.1097	4580.36

Nuclear reactors operating primarily with thermal neutrons are called thermal reactors, whereas those depending mostly on fast neutrons are termed fast reactors.

Thermal neutron refers to the neutron which has been thermalized with respect to it is surrounding like whenever we have a neutron that is in thermal equilibrium with the surrounding nucleus; it is of course, is in it is lowest possible energy level. Now under general condition; any thermalized neutrons similar to any gas molecules follows the Maxwell Boltzmann velocity distribution like the one showed here; on the right hand side for several noble gases.

So, accordingly we can say that when a neutron, which has been thermalized it is energy will be equal to k into T, where k is the Boltzman constant and T is the absolute temperature of the surrounding. And comparing this, we can derive that v n is equal to this 128.369 into root over of absolute temperature, where v is in metre per second and T is in Kelvin.

So, depending upon the temperature of the surrounding; a thermalized neutron can have several velocity level. Say, if we are talking about a surrounding temperature of 20 degree Celsius; corresponding energy for a thermal neutron is just 0.25 electron volt, but that corresponds to something about 20 to 100 metre per second of velocity. As the temperature keeps on increasing; corresponding energy level and velocity of a thermal neutron both keeps on increasing.

Commonly the term thermal neutron, we associate with electrons which are thermalized with a 20 degree celsius surrounding and having an energy level of 0.0253 electron volt.

So, these values we shall be using from now onwards for a themalized neutrons; thermal neutrons have; of course, it is a kind of slow neutron because like we have discussed earlier, whenever you are having a neutron having energy less than 10 electron volt; we are calling that slow neutron.

But thermal neutron that is this particular energy level has it is own significance which we shall be coming or discussing later on. Now, but one important concept I must mention here the nuclear reactors can commonly be classified based on two categories depending on what kind of neutrons they are using to get this artificial transmutation; when they are using thermal react neutrons we call them thermal reactors whereas when they given mostly on the first neutrons that is high velocity neutrons, we call them fast reactors.

Thermal new reactors are the most common one or most prevailing one that you can find throughout the wall. And whenever you heard this term thermal, you can safely can say that they are using neutrons which are thermalized with respect to a surrounding and most likely is having a energy level of 0.0253 electron volt.

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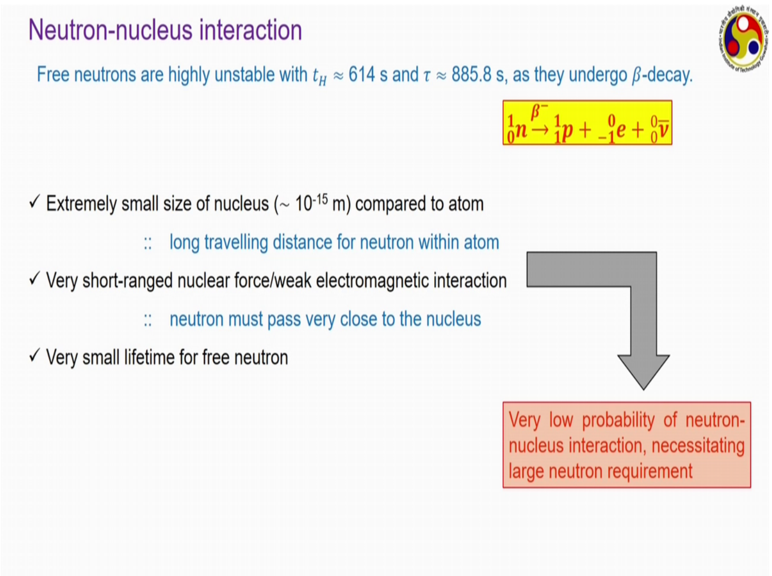

Now, a neutron can interact with a nucleus during artificial transmutation in several possible ways, but quite a few other factors to consider here. Firstly, we have mentioned while you discuss about half life; a free neutron is also highly unstable one.

When you are talking about a neutron bound inside a stable nucleus, that is very much stable; what if free neutron is very much unstable and it has a very (Refer Time: 23:40) half life of just about 614 seconds and giving a mean life of just 885.8 seconds; slightly less than 15 minutes; that means, if we allow a few neutron to travel through any particular isotope, this very likely that we give an average period of 15 minutes; it will be it will be suffering some kind of radioactive decay of it is own.

And it generally undergoes a beta decay leading to the formation of a proton; 1 electron and neutrinos. So, we must put such kind of arrangements so that the neutron is able to interact with the nucleus or able to strike the nucleus, before this 15 minute period of time; before it is own disintegration starts. So, using a neutron is also has it is own issues; firstly, the size of the nucleus is extremely small, compared to the atom that is it is of the order of 10 to the power minus 15 or minus 14 metre only.

That means the neutron needs to travel very very long distance through the within the atom before it can collide with the nucleus. And there is every possibility as the most of the part inside an atom is the void, there is every possibility that the neutron may not at all collide with the nucleus that are just passed through. In fact, if we send a group of neutrons towards a particular nucleus very very few of them will be able to interact with the nucleus; with others just passing with on (Refer Time: 25:09).

Another issue is that the neutron being electrically neutral there is not experiencing any kind of force towards the nucleus; the corresponding nuclear force or electron that we introduction is actually with very very weak. And therefore, the neutron must be very very close to the nucleus to have any kind of introduction. And third like we mentioned that the top, the lifetime of neutron is very small means whatever we want to do that should be done within an average period of 15 minute, otherwise a neutron will separate own radioactive decay.

So, this 3 factor combines to say that the probability of neutron nucleus interaction is very very low. And hence to get any particular kind of neutron nucleus interaction done, we need to send large number of neutrons, because most of them will not be having any kind of interaction at all that we just passing through the target material without any changes in it is properties or in it is quanti; parameter values.

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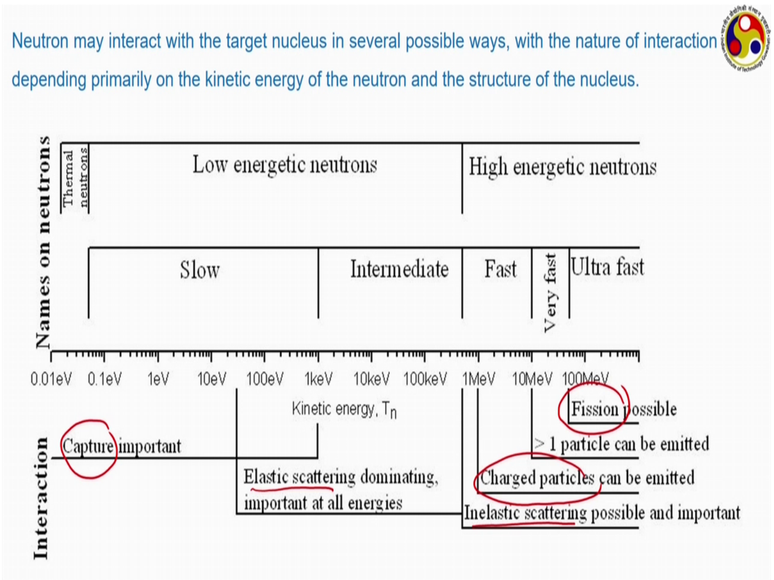

Now, there are several kinds of nucleus, neutron nucleus interaction possible as I mentioned earlier. And exactly what kind of interaction can takes place in a given situation that depends upon both the energy level of the neutron and also the structure of the nucleus. The energy level we have already discussed, we can have thermal, slow intermediate or first neutrons.

Here do not go into the numbers that are shown in this table, just look at the different kinds of reactions that I have mentioned. One possible reaction is the capture reaction also can be called an absorption reaction which is more likely for slow neutrons. Whereas, we can also have elastic scattering, we can have inelastic scattering; very very suitable for fast or ultra fast neutrons.

We can have some charged particle emission and of course, the fission reactions. These are different kinds of interactions that we can have between one neutron and a nucleus. And for a given neutron nucleus combination, exactly which kind of interaction will takes place; that depends on both, depends on the energy level of the neutron and also the precise nature of that particular nucleus.

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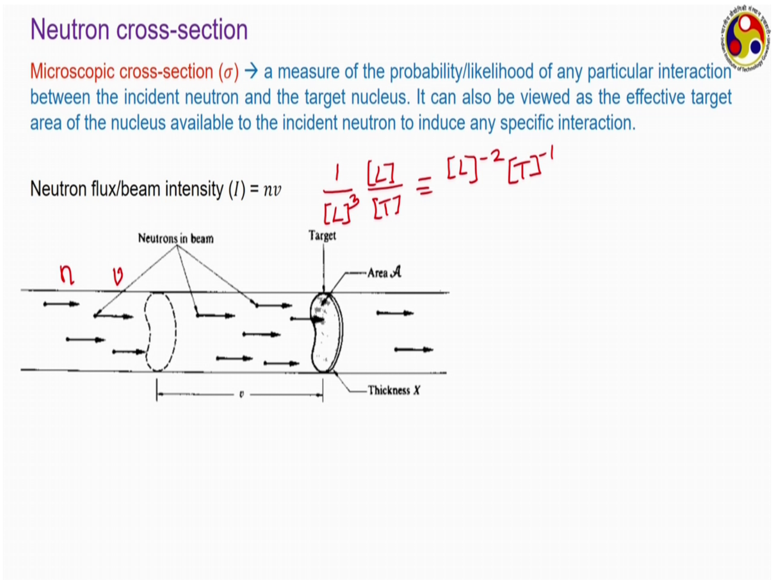

And while the energy level of the neutron; we have already discussed the property of the nucleus that is very relevant here it is called a neutron cross section; which is represented by the small sigma later. It is actually measure of the probability or likelihood of any particular interaction between the incident neutron and the target nucleus. That is when a neutron collides with a nucleus, what is the probable of having either of the five types of interaction that we have discussed in the previous slide; that is given by this microscopic cross section.

As we can have five different kind of phenomena's; maybe a few more so, there has to be a certain finite probability associated with each of them, which is given by this cross section. We can also view this one as the effective target area of the nucleus available to the incident neutron to induce any particular interaction. Like say, if you are interested to know what is the probability of the fission?

We can say that out of the entire surface area of the nucleus only a part is exposed for the fission reaction. And if the neutrons strikes that part, then only the fission reaction will happen. Actually that does not happen; this the way that I am explaining, but you can visualize this way that the entire surface area of the nucleus is divided into different components. And if the neutrons strikes in a particular component, then only that particular interaction is possible others are not likely.

And so, that probability is given by microscopic cross section; let us say we have a tube within which we are having some kind of target area, having an area A and thickness of X and a neutron are passing through this particular channel and is expected to strike this target area. All the neutrons are having the same velocity v and the number density of the neutrons that is travelling through this is given by small n.

So, small n represents the number of neutrons travelling in this beam permit volume and small v is the velocity of the neutrons. Here we are assuming that all neutrons are moving in the same velocity. Then the product of these two quantities; that is n into v is called a neutron flux or beam intensity.

So, what will be the unit of this intensity? Of course, small n has a dimension of it is number of neutrons per unit volume and so it is having a dimension of L cube and v is velocity. So, it is having a dimension of length by time which gives the dimension of the intensity to be L to the power minus 2; T to the power minus 1, that is we can say it represents the number of neutrons passing through some unit area per unit time or the rate of neutron passing through some kind of unit area.

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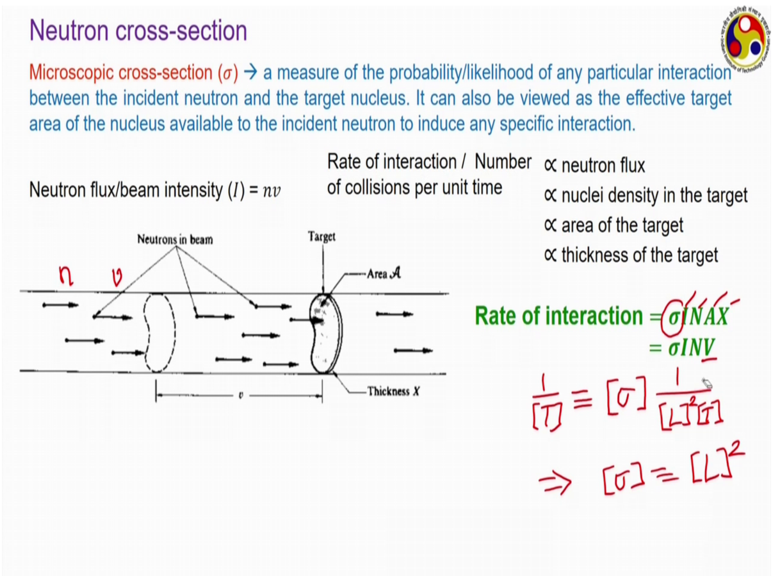

Now, the interaction between the neutrons and some nucleus available in the target area that definitely is proportional to this neutron flux, because higher the neutron flux, more is the number of neutrons participating in the interaction and so larger is the possibility of any interaction, it is definitely proportional to the nuclei density in the target. More the number of nucleus present in the target, more will be the number of interactions.

This is also proportional to the target area, as the neutrons are hitting the area of the surface; so, larger surface is always like to give larger interactions and it is also proportional to the thickness of the target, because the neutrons will be passing through this target area and larger the thickness it is more likely to face some kind of nucleus during this passage.

Whereas, a very thin target may allow you a free entry for the neutrons through it; so it is also proportional to the thickness of this target. See, if you combine all this 4, then the rate of interaction can be given to be proportional to I; which is the neutrons flux or the beam intensity, N is the nuclei density; that is number of nucleus per unit volume of the target, A is the cross section area, X is the thickness; which are already shown in the figure.

And, we can combine A into X into V, which is the volume of the target material or target element and sigma is the constant of proportionality which we are calling as this neutron cross section. So, neutron cross section, then can we visualize this way as the constant of proportionality as well or we can also say if we are talking about then the; a nuclear beam of unit intensity and number of the nuclear nucleus density is also 1 in the target; then the rate of interaction per unit volume of the target is equal to the neutrons cross section or the microscopic cross section.

Then, what will be the dimension of this. As we have already, what is should be the dimension of the interaction? Let us see first dimension of interaction is number of interaction per unit time. So, it is dimension is one upon T; we are looking to get the dimension of the sigma. So, I as we have already seen has a dimension of number of neutrons per unit area per unit time and n is the number of nucleus per unit volume multiplied by the volume next is dimension less.

So, accordingly the dimension of sigma what it should be? It has to be sorry; it has to be length square only, that means, the microscopic cross section has a dimension of area only and that is actually reason we call it a cross section because commonly the term cross section refers to the area and also we are seeing this particular constant of proportionality sigma is having a dimension of l n square.

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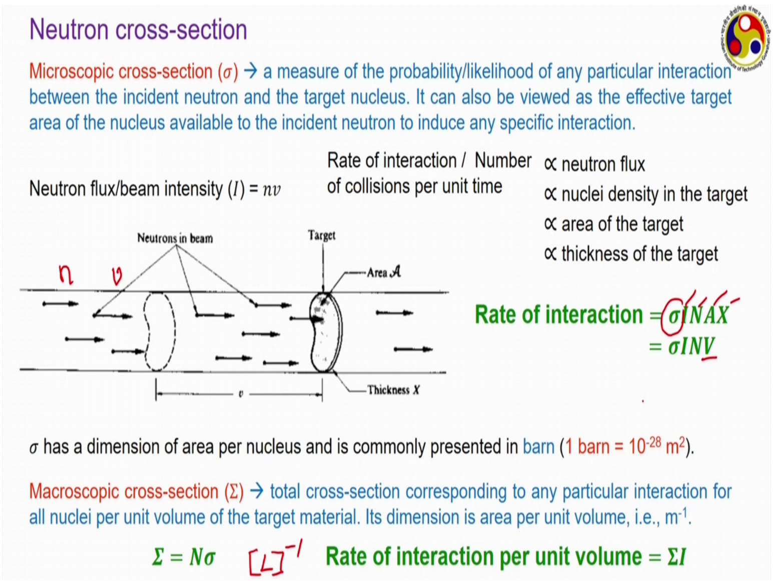

So, it is dimension is also area per unit nucleus and commonly it is represented by something called bond, with 1 bond is 10 to the power minus 28 meter square. Bond is generally a very, very small unit, so quite often we have to go for multipliers of this one. There is another term that is called microscopic cross section, which is actually the total cross section corresponding to any particular interaction for all nucleus present per unit volume of the target nucleus.

So, we are talking about microscopic cross section given by capital sigma as the product of the microscopic cross section into the number of nucleus present per unit volume of the target that is N into sigma, then what should be this dimension sigma as a dimension of length square and N will be having dimension of L to the power minus 3 as you are talking about nucleus per unit volume. So, the dimension of this capital sigma should be L to the power minus 1 or length inverse.

So, truly speaking, it is not a proper dimension of the cross section, but still we, it is conventionally called a microscopic cross section and accordingly comparing the previous equation rate of interaction per unit volume can be written as sigma into I, that is the macroscopic cross section multiplied by the neutron density and this is the equation of our interest, because here the rate of interaction can be represent in terms of 2 quantities 1 is the sigma that is the nature of the target nucleus and other is I which is a property of the beam, which is coming to or which is being incident on the target.

Now, but there can be different kinds of interactions as I have mentioned earlier and each interaction has it is own probability. Therefore, corresponding to each such interaction, we can define 1 cross section; like, we have mentioned about the captured reaction or fission reactions. A particular neutron nucleus combination can have finite probability for all this happening at a given instant of time and so we need to define this cross section corresponding to each such interactions, before you do that let us check out all the possible interactions.

The first one is radioactive capture, which is generally a characteristic of slow neutron interaction.

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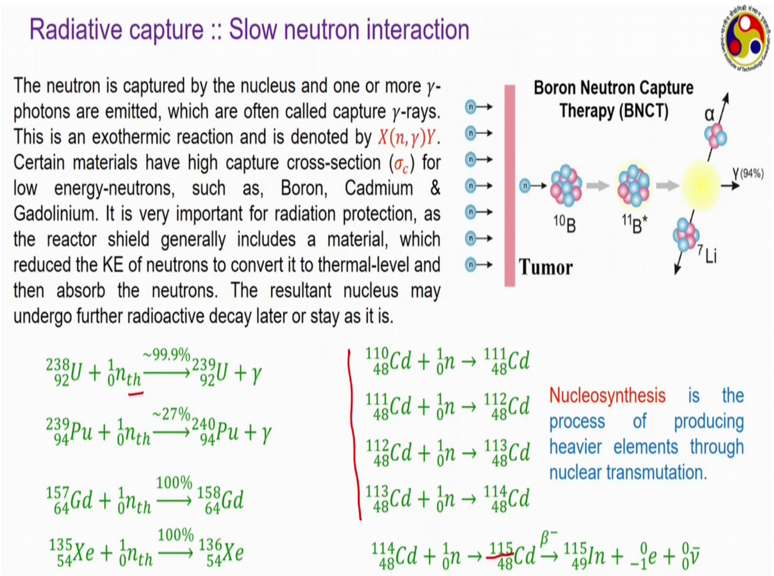

Here, the neutron is captured by a nucleus and leading to the formation of 1 excited nucleus like, in this particular diagram is shown we a boron tin isotope, which is absorbing 1 neutron, leading to the formation of a boron 11 isotope and that is of very high energy and in that new isotope can go back to it is ground state by ejecting gamma photons. So, this reaction is always a exo thermic one and it is generally denoted by as per our previous notation n gamma, where n is the incident neutron and gamma is the product of this and X one I why are of course, the dot parent and the daughter isotope respectively.

Here, the symbols small c is generally used to indicate the capture cross section at low neutron energies certain materials can have very, very high capture cross section and they are very, very important from radiation protection or for radiation shield building point of view. Materials such as boron, cadmium or gadolinium, they have very high capture cross section for slow energy neutrons. I have to mention here that, say any particular cross section, so the capture cross section that we are talking about here for a given nucleus, the capture cross section also varies with the energy of the neutron, that is as that energy of the neutron changes it is probability of being captured by the same nucleus that also keeps on changing and generally the capture cross section for a nucleus is higher for low energy neutron.

Particularly for this elements like boron or cadmium, they have very high capture cross section for low energy neutrons and therefore, in radiation shield building point of view, we quite often would like to reduce the kinetic energy of a fast neutron to much lower level and then exposed to some cadmium or boron layer.So, that it can get captured there leading to the formation of some other isotope of cadmium or boron, but the neutron will not be allowed to go outside.

Of course, the neutron sorry the after getting the neutron absorption done, this new nucleus itself can undergoes certain kind of decay like the one shown here; this boron 11 isotope can go alpha decay leading to the formation of lithium 7, actually this is a very, very important medical application diagram that I am showing, which is called the boron neutron capture therapy or BNCT in short, which is a very popular technology for tumor or cancer treatments, where they use this radiation capture or radiative neutron capture. There can be other examples like, uranium 238 absorbing a thermal neutron, here this t h substitute refers to thermal, that is we are talking about a neutron which has been thermalized with respect to surrounding and is having an energy of just 0.25 electron volt.

So, when such a neutron strikes a uranium 238 isotope, there is nearly 100 percent probability that it will be captured there leading to the formation of uranium 239 and gamma emission. Similarly, a thermalized neutron when it strikes to plutonium 239 leads to plutonium 240 formation, but corresponding probabilities only 27 percent. We can have certain other reactions also like, gadolinium that was mentioned, when it receives on thermal neutron it immediately absorption there is 100 percent probability of that, so for xenon 135. Another important application or issue is a very natural phenomenon of such kind of radioactive capture is the nucleosynthesis.

Nucleosythesis is the process of producing heavier elements through nuclear transmutation. Basically, when this universe was formed, we had only sub atomic particles like proton and neutrons and as the universe start to cool down the temperature kept on reducing and this neutrons and protons kept on combining each to form much heavier isotopes and that particular process is called this nucleosynthesis and this radioactive capture of neutron is a very important part of that like one is shown here is series of radioactive capture by cadmium, cadmium 110 can absorb, neutron forming cadmium 111, then 112, 113 and 114 all of them are stable isotope, but when cadmium 114 absorb 1 neutron to form cadmium 115, then that is actually unstable.

So, it undergoes a beta decay and the chain stops there, but this particular process of forming a contentious or in a chain heavier isotopes is called the nucleosynthesis and that is the principle mechanism of forming any kind of heavy nucleus, something heavier than iron in particular.

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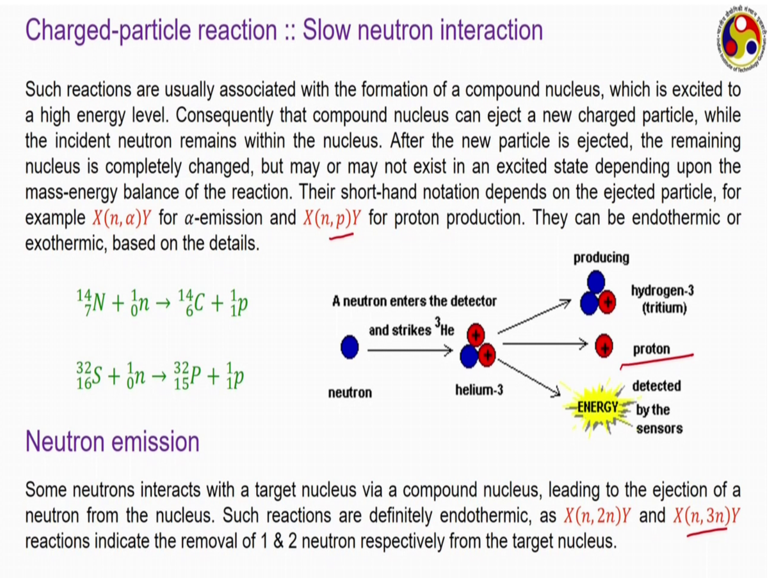

Another, possible kind of interaction is the charged particle reaction. When a compound nucleus or a nucleus absorbs a nitrogen forming a compound nucleus, that is generally at a high energy level and quite often it can it eject 1 charged particle such as alpha particle or proton in very, very rare situations, the neutron is remains inside the original nucleus, but the a new particle that comes out, leads to the development of a new isotopes which can be a an excited state or can be back to the gamma back to the ground level because of gamma radiation.

These kind of reactions can be endothermic or exothermic based on the details, like couple of examples I am showing here, the nitrogen 14 isotope absorbing 1 neutron leaving the emission of one proton, same for sulphur 32 leading to the emission of a proton and neutron detector is an instrument which is used to identify the presence of neutron, that works on similar principle that is when a neutron strikes an helium three isotope it leads to the emission of 1 proton and forms tritium or hydrogen 3 and also energy, the proton can generally be sensed by some kind of sensor and that indicates the presence of neutron in the original sample.

So, this is one kind of examples or practical application of this charged particle reaction, but generally this charged particle reaction is a process, that is associated more with heavier particle collusion and not that much with neutrons. Another similar examples can be neutron emission, where thus a single neutron strikes a nucleus leading to the ejection of more than 1 that is may be 2 or 3 kinds of neutrons. So, which is associated with chain reactions as well, but similar to the charged particle reaction neutron emission is also is more associated with some heavier particle collisions.

Short hand notation of this depends on what is the output product? When proton is the 1 that is ejected we use a p here, whereas, suppose the product contains 3 neutrons, then we shall be having this n comma 3 n kind of representation. So, all this 3 that we have introduced so far radioactive captured, charged particle reaction and neutron emission they all are characteristics of slow neutron interaction.

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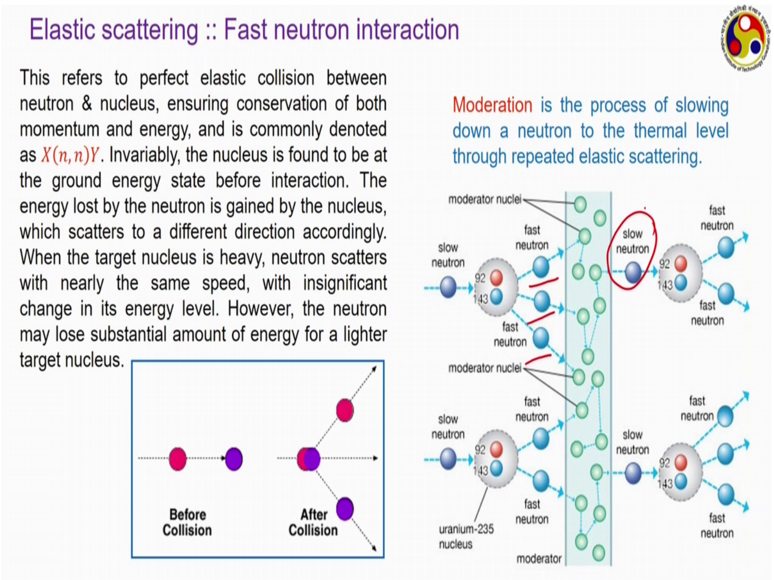

For fast neutron, we have something called elastic scattering. Here, the neutron is coming with a high velocity because they are fast neutron and they are striking a nucleus which most often will be at the ground level only and invariably stationary a leading to some kind of elastic collision; elastic collision means something where both kinetic energy and momentum remains conserved, something like the collision of billiade balls or something like on the carom board, when one; when we strike one particular coin with another one, then we get virtually elastic scattering that is what happens here.

So, the neutron will be losing some part of energy, which will be transferred to the nucleus, accordingly the nucleus will be moving to certain direction, but the important point is I repeat both kinetic energy and neutron will be conserved here. This particular process is more used for reducing the kinetic energy of the neutron, like I have mentioned while radiate reading additive capture, that generally radioactive capture cross section is high for s slow neutrons.

So, when you have a, fast neutrons available somehow we have to reduce the kinetic energy and elastic scattering is the most preferred choice. If we can use the suitably characterized nucleus, then the neutron can lose significantly large amount of energy in a single collision or sometimes we may require multiple elastic collisions also.

This particular process actually is called moderation; that is moderation is a process of slowing down a neutron generally from fast neutron level to the thermal neutron level through repeated elastic scattering. How much collisions will be required? That depends upon, again the nature of the nucleus; we shall be discussing more about this elastic scattering and corresponding calculation about how many reactions or how many interactions will be required for a given nucleus in the next module, but this is typically how a moderator works, when a slow neutrons strikes 1 uranium 140 sorry, uranium 235 isotope it leads to the fission reaction and during the fission reaction we may have several fast neutrons formation like we can see three here. All these fast neutrons passes through something called a moderator.

Moderator is some kind of element, which is having high elastic scattering cross section. So, when the fast neutron passes through the moderator it loses a significant part of this kinetic energy, invariably coming out as slow neutron and they are freeze ready to go for some kind of further reactions.

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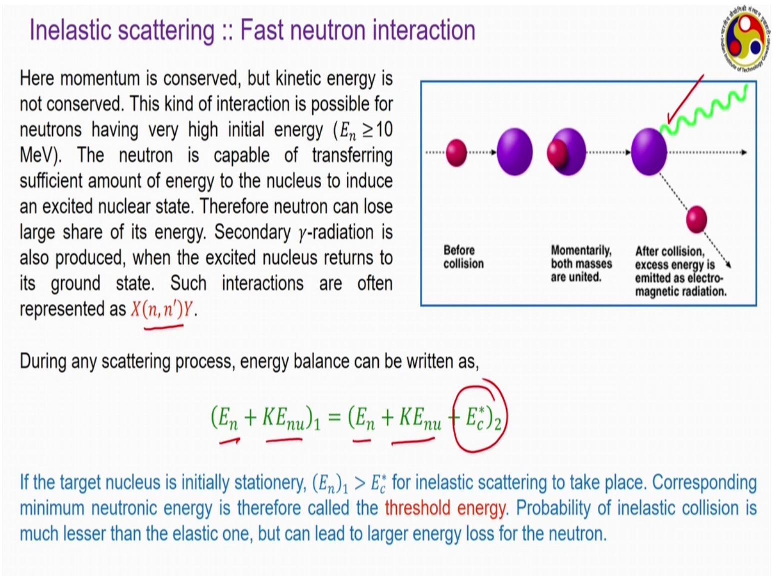

Another possibility is the inelastic scattering, which again is a characteristic of a first neutron, actually that happens to very, very fast neutrons something which is having energy greater than 10 MeV. I forgot something there, as in leaving elastic scattering it is 1 neutron that is coming for the reaction and again going as it is. So, it is often represented as it is n comma n, where as inelastic scattering we represent n comma n prime, this prime just indicates is an inelastic scattering. During inelastic scattering as you can see from the diagram, the neutron and nucleus for a very, very short duration combines to form a temporary neutron or temporary nucleus and then both of them goes to some other direction, but ejecting a good amount of energy.

So, momentum and kinetic energy, while both of them gets conserved during an elastic collision process. In this particular process, energy is not conserved as we can see here; if we write an energy balance for any scattering process here 1 refers to the here state before collision. So, before collision total energy available is the energy for the neutron which is here and the kinetic energy for the nucleus if anything at all available, where as the total energy available after the interaction is done is again the kinetic energy of the neutron and the nucleus, but some amount of energy which may get released during the process which sometimes called excitation energy.

When we are having an elastic scattering, then there is no energy released both momentum and kinetic energy are perfectly conserved, but in inelastic scattering while momentum is conserved, kinetic energy is not conserved, because we may have this amount of energy emission, that is we may have a non 0 value of this E c star. So, the neutron must have energy greater than this E c star then only an in elastic scattering is possible, otherwise it will be going through an elastic scattering process only.

This amount of energy that is E c star is often called threshold energy because the neutron must possess this amount of energy to undergo an inelastic scattering, while inelastic scattering is much clear; much rarer compared to the elastic scattering, but it is a process during which much larger amount of energy can get lost, but as we have mentioned earlier it requires neutrons of very, very high energy and the final kind of introduction is the fission.

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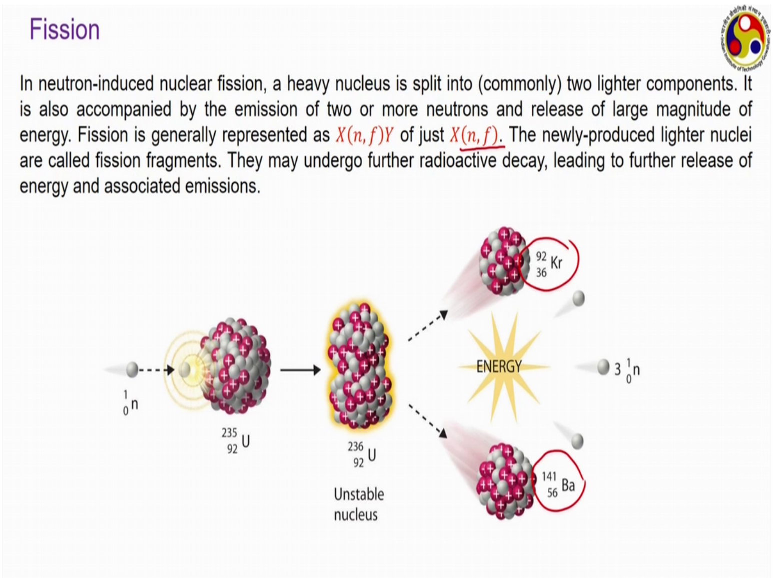

During the fission reaction, the neutrons strikes 1 nucleus and splits it into 2 components both of which are much lighter and that is also generally associated with the emission of two or more neutrons and large amount of energy released. A fission is often represented as this kind of symbol n f, just to indicate that a neutron is coming and leading to the fission reaction.

These, new elements or nuclear respond like in this example we have, 1 K r 92 and barium 141, they are called fission fragments. This fission fragments also can be radioactive in nature, they may go for further radioactive decay such as alpha or beta decay or just gamma emission to go back to the ground state, there by leading to some further energy production later on.

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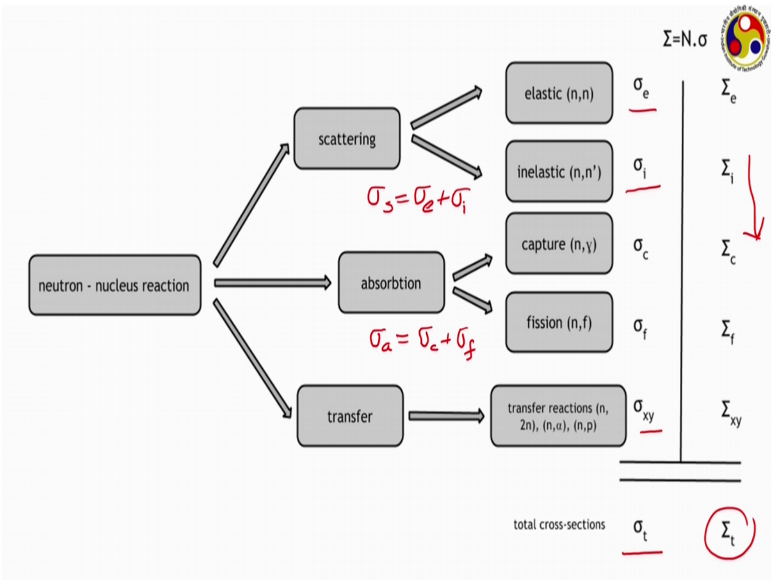

Fission, we shall be again discussing detail in the next module, but just to combine all this interactions, we principally can have 3 groups of interaction, first is scattering, which is associated with first neutrons, we can have elastic scattering or inelastic scattering. Elastic scattering is represented corresponding cross section is given as sigma e and sigma i represents the inelastic scattering, absorption again can be of 2 types, whether neutron goes inside the nucleus before doing something else, one can be the capture where the neutrons stays inside the nucleus and leading to the formation of another isotope of the parent nucleus, other can be the fission where the newly formed compound nucleus gets broken or splitted into 2 components.

So, they come under this category of absorption and capture and fission, sometimes we also can define a sigma a, which is the absorption cross section which is nothing but the combined probability of this captured and fission capture and fission reaction, whereas sometimes not commonly what sometimes a common scattering cross section is also defined, which is a again a summation of the elastic and the inelastic probabilities and finally, is the transfer which combines all other possible, like the neutron emission charge particle ejection system etcetera, here this xy just represent this symbol, depending upon what kind of specific reaction taking place, we can use suitable subscript.

Now, all this 5 kinds of cross sections together gives the total cross section sigma t of a nucleus. Therefore, for any given neutron energy a nucleus at a particular instant of time can have non 0 values for all the 5. So, exactly which particular kind of interaction will takes place that depends upon which one is more probable that is which one is higher, but generally we what we find is that, the values of all this cross sections vary strongly with the kinetic energy of the neutron itself and while at certain energy levels say the capture cross section is more dominant at certain other energy levels the fission 1 may be more dominant and at are certain other energy levels particularly for fast neutrons, the elastic scattering 1 may be the most dominant one and so we can safely conclude about which is the most provable one.

Each of these microscopic cross sections can be multiplied by the total number of nucleus per unit volume present in the sample to get their corresponding macroscopic versions and again by combining all these macroscopic cross sections we get the total macroscopic cross section of the sample. So, cross section is a property of the nucleus and we now know that depending upon the energy level of the neutron the cross section of a nucleus also varies.

We shall be discussing more about, how they vary or how any particular say capture or fission cross section varies with the neutron energy during the next module, but here the topic of radio activity we should keep up to this, where we have discussed about the natural radio activity in the previous two lectures and today we have discussed about the artificial radio activity, which we can now say that is being governed by 2 particular factors 1 is the kinetic energy of the neutron and other is the corresponding cross section of the nucleus.

So, depending upon their combinations, we can have different kinds of interactions possible, as we shall be seeing in the 3rd module. This is the end of today's lecture, in the 4th lecture of this 2nd module, we shall be discussing about how to solve a few relevant numerical problems associated with the radio activity.

Thanks for the day.