Fundamentals of Nuclear Power Generation
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Module – 09
Nuclear Fusion
Lecture – 23

Hydrogen fusion reactions.

Hello everyone, a very welcome back for all of you in the 9th module or in the 9th week of this course on Fundamentals of Nuclear Power Generation, where we are going to discuss about something completely new more or less completely independent of whatever we have discussed till now which is nuclear fusion from the very beginning of this course or rather I should say in the very first module of this course. You were introduced to two kinds of nuclear reaction one is nuclear fission and other is nuclear fusion and as you already know the term nuclear fission refers to breaking of one heavy nucleus into two lighter counterparts and also some small fragments like this.

And in this course. So, far we have discussed only about nuclear fusion.

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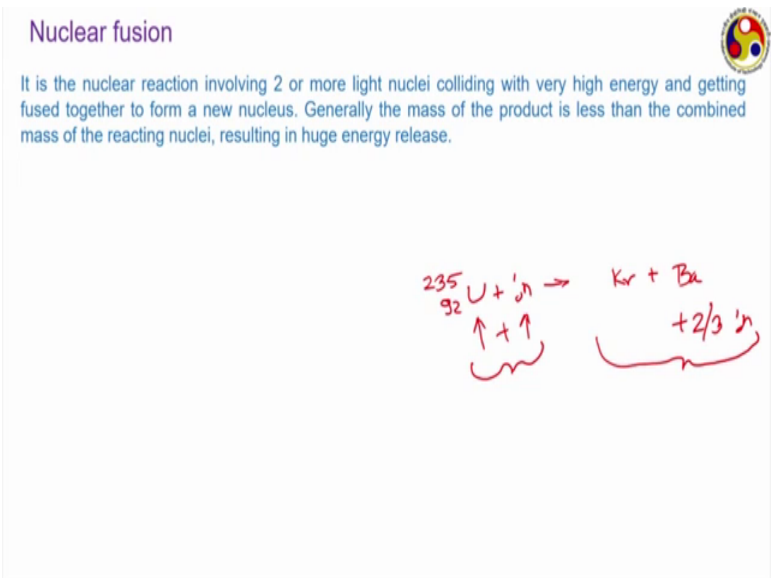

Because, that is the technology which we have somehow mastered as we have already seen we have gone through several generations of nuclear reactors all of them are working on nuclear fission and we have also discussed about thermal fission and fast fission among and different associated factors about that and we have discussed. So, much about nuclear fission like starting from you can say from module number 2 to module number 8, we have talked only about nuclear fission simply because; that is something that we have completely in our control or more or less in our control and that is the one which is the source of all commercial nuclear power generation at the moment.

100 percent of all the nuclear power plants that we have throughout the world they are based on nuclear fission only, but nuclear fission or I should rather I should say nuclear fusion I also getting confuse with the term, because we rarely use the term fusion. While talking about nuclear power generation rather we stick to nuclear fission only, but whenever you are talking about nuclear fusion; that is the another extreme here like in case of nuclear fission we are having a heavy nucleus getting broken into smaller counterparts here it is the opposite 1 or 2 or more light nucleus or lighter nucleus they are getting fused together to produce a heavier counterpart like.

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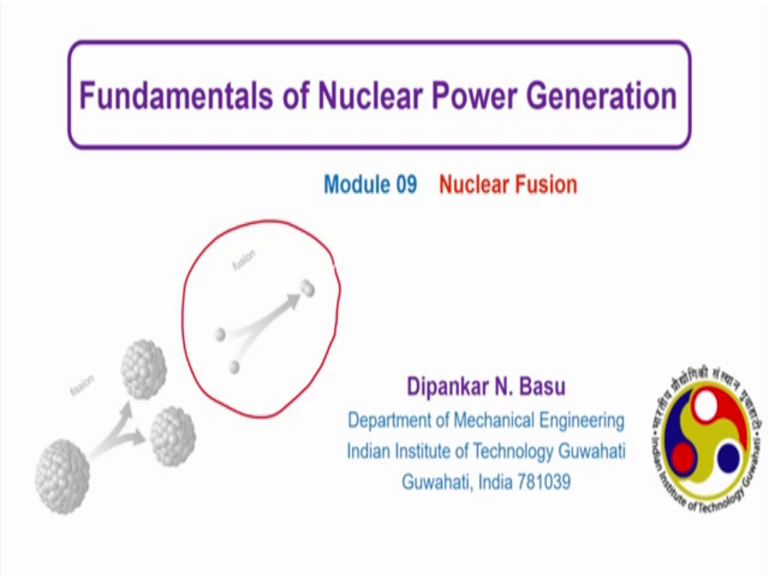

From the very first beginning very beginning of this course, I am using this particular template and always you have seen these two pictures.

This is the fusion this is the fission that we are talking about from the beginning here this heavy nucleus is getting broken into two smaller fission fragments and also generally associated with some neutron release and of course, production of energy, but whenever we are talking about a fusion this is the situation that we have despite having this on the very first slide of all the modules or all the lectures I have never talked about this one the simple reason for that is the technology of nuclear fusion whatever may be the potential it has that is still not something in our control.

Several things or several aspects of this technology is still unknown lots of still required lots of technological improvements are required to reach the situation; where we can realize a fusion based reactor and we can use fusion for commercial power production, that is why; the discussion on fusion is be limited only through this particular module which will be spanning over two lectures, but I must also mention that fusion is something that is having immense potential like I have mentioned earlier based upon the present energy requirement of the world.

While the conventional fossil fuels like coal or petroleum and natural gases can survive something like 45 years at the most nuclear fission technology based upon uranium 235 uranium is also something harness from the mines and therefore, it is stock is also limited and that is why; the stock of uranium that we have at the moment considering the present global energy demand it can survive something like 70-80 years at the most.

In the previous module we have discussed about the breeding technology, we can use fertile isotopes to get converted to fissile isotope by the virtue of breeding and thereby you can use fertile nuclei like uranium 238 or thorium 238 to produce uranium 2 or rather plutonium 239 and thori[um]- uranium 232. I am again getting confused we can use the breeding technology to produce plutonium 239 from uranium 238 and uranium 233 from thorium 232 which offers an immense potential and if we can completely master the breeding technology that probably will be solving all the energy needs for next 25 to 30, 000 years which is a very very wrong period we are talking about.

Coming to fusion again I repeat everything about fusion is still not in our control, but if we can master the fusion technology somehow maybe in next 50 or 100 years to come then that will be sufficient to solve all energy requirements of the world for something like three million years; that is the potential of this technology and; that is why; we are going to have a discussion about fusion as well. So, coming back to fusion you already know that two or more lighter nuclei getting combined they colliding with each other with a very high energy and thereby they are getting fused together to form a heavier nucleus.

Sometimes maybe one heavy nucleus and some other light components like proton or neutron. Generally, the mass of the product is found to be lesser than the combined mass of the initial reactant nuclei. Thereby providing the mass defect which is the source of the energy that we can get during fusion reaction quite similar to fission like, in case of fission we are having like a common fission reaction we can write something like this 92 U 235; last one neutron they are they will produce there are several kinds of possibilities, but most common isotopes. We are we generally get there is a krypton and a barium some of the isotopes of krypton and barium and 2 or 3 neutrons.

So, if we combine the mass of this uranium 235 and the mass of one neutron; whatever combined figure we get; that is generally larger than the combined mass of these products which leads to the mass defect and as we know 1 amu of mass defect is equivalent to 931 MeV of energy. So, we get a large amount of energy and by now you definitely know that one fission of uranium 235 nucleus generally leads to release of something like 200 MeV of energy to be more accurate something like 207 to 210 MeV of energy.

Then, what about fusion?

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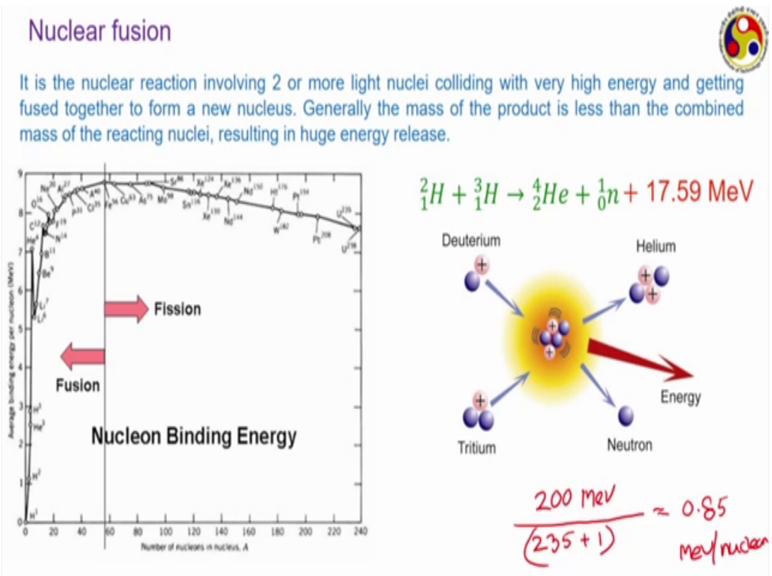

This is the diagram which determines what kind of nuclear reaction that we have got again something that we discussed in the very first module based upon the binding energy per nucleon we get a criterion that when the mass number of nucleus is greater than something like 60 it partition fission whereas, when it is smaller it participates in fusion; because higher the binding energy per nucleon more stable is the nucleus and the largest value of binding energy per nucleon is obtained in this in this particular range of mass number which corresponds to iron or nickel or cobalt those group of elements which are having mass number around the 60.

All isotopes which are having mass number a bit away from that zone they always try to participate in some kind of nuclear reaction by virtue of which it can attain this particular zone. And, so whenever you are talking about an isotope which is on this particular side something like uranium, plutonium, etcetera. They do participate in reaction because of which their mass number decreases or they go through some kind of transmutation because of which the mass number of the resultant nucleus decreases like in the example of fission that we have just seen uranium 235 getting broken into two isotopes whose mass number will be somewhere in the range of a 120, 130 or 140.

So, those cases it is we are talking about a transmutation of a nucleus which is somewhere in this zone to couple of fission fragments. In this particular zone which is definitely much closer to that zone of mass number of 60 and as you can clearly see from the graph the binding energy per nucleon of the fission products is definitely larger than the parent uranium 235, but when you are talking about fusion we are on this side of the curve where the mass number is very low.

And therefore, it is not possible for the nucleus to get broken into even lighter components, because if it gets separated into lighter components it is mass number will decrease even further and thereby taking it further away from that is zone of largest binding energy per nucleon therefore, the most likely reaction that they can have is to combine into or rather is to combine with each other and produce a heavier nuclei like you can see this is deuterium and this is tritium.

So, both of them are having a very low mass number 2 for deuterium 3 for tritium and from the graph you can see their binding energy per nucleon is also very low, but if they can somehow combine with each other to produce any suitable isotope; then what can be the result; the one product can be like this say this is one typical fusion reaction where 1 deuterium is combining with a tritium to produce a helium and also releasing 1 neutron and of course, as the combined mass of this helium 4 and neutron is generally found to be less than the combined mass of the deuterium and tritium corresponding mass defect gets converted to this energy release.

But, now coming back to the diagram we have already marked deuterium and tritium. And now this is the product helium and as you can clearly see the while the binding energy per nucleon of a deuterium is something like one and that for tritium is something like 3 MeV that for helium 4 is quite close to 7 MeV. So, it definite increase in the binding energy per nucleon and hence this helium 4 definitely is a more stable isotope compared to both deuterium and tritium.

Similarly, any nucleus which is somewhere in this zone, it can participate in fusion reaction mainly in an effort to go closer to this that is whatever result in the isotope we are going to have because of a fusion reaction that is expected to have a higher mass number and the closer it is to that value of mass number of 60 the most stable it will be from fusion reaction point of view. Now, writing this equation 1 H 2 plus 1 H 3 will be equal to 2 H 4 plus the neutron plus energy and how much about 17.6 MeV of energy; that is just by combining 1 deuterium and 1 tritium a nucleus into fission fusion reaction we are getting about 17.6 MeV of energy.

Now, you may think about, what is the big deal; like fission of a one uranium gives us about 200 MeVs of energy or slightly higher than 200 MeVs of energy and here we are talking about only something like 17.6, but just combine this particular energy yield with the corresponding mass of the reactant. In case of a fission reaction let us say 200 MeV of energy is released, because of the fission of 1 uranium 235, then how much is the mass involved there; or forget about mass just consider total number of nucleons involved there, because nucleons means we are talking about protons and neutrons and we can say both of them are having mass very close to 1 amu.

So, further moment just approximate the mass of both proton and neutron to be one amu then total mass of the reactants will be equal to 235 for the uranium plus 1 for the neutron. So, 200 by 236 which will be I am approximately it will be something in the range of 0.85. So, we are getting 0.85 MeV of energy per nucleon of reactants. Now put that into perspective with the; present fusion reaction, here we are getting 17 sorry we are getting 17.6 MeV of energy and how much is the number of nucleons it is 2 for deuterium and 3 for tritium. So, total 5.

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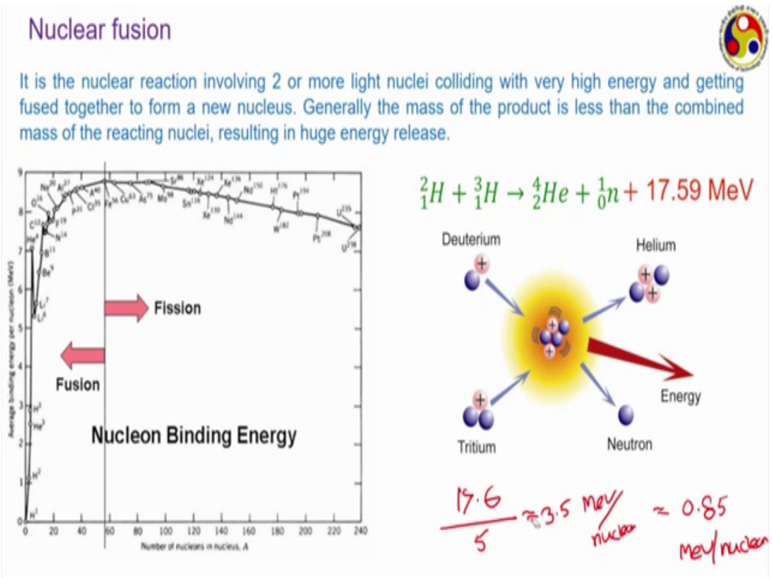

So, total or the result of that is approximately 3.5 MeV of energy per nucleon. So, let me erase everything else and just combine the just compare the 2 numbers for every nucleon involvement into the reaction while we are getting only about 0.85 MeV of energy in case of a fission reaction conventional. Fission reaction a very common fusion reaction is getting a giving a number something like 3.5. So, at least about 4 times or maybe more than 4 times and; that is the biggest advantage that we have with fusion reaction.

That is the amount of energy yield that we are getting per unit mass of the reactants is significantly larger compared to what we get in case of fission and that is the first big advantage.

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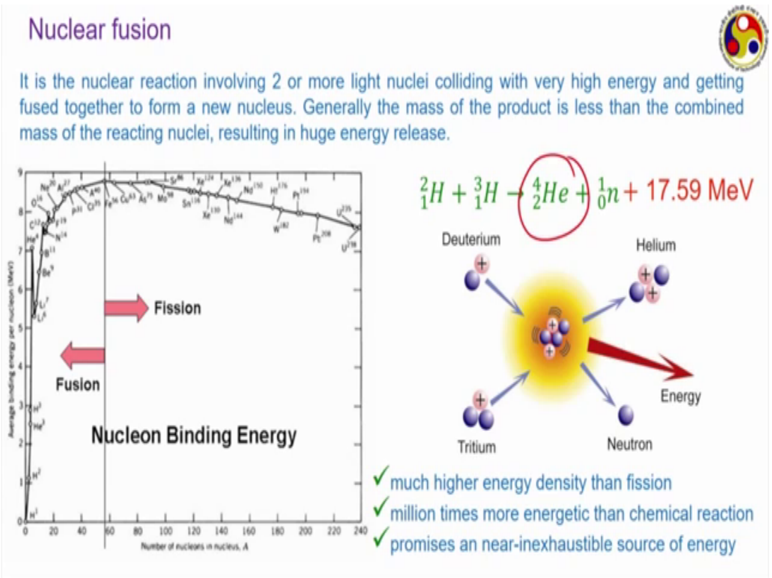

To have a fission reaction we are getting a much higher energy density; that is energy yield per unit mass of the reactants must higher energy density. We can get in fusion compared to fission also it is million times more energy take than chemical reaction means that is a somehow true for fission also the amount of energy yield, that we have we can get from a nuclear reaction. We this we should not compare that with chemical reaction at all in one of the earlier modules I have shown one calculation where we have found that the amount of energy released during nuclear reaction can be 10 to the power 7 to 10 to the power 6 times larger than compared to an equivalent chemical reaction.

So, fusio[n]- in case of fission the gap even increases more and also the biggest advantage of fusion it promises an near inexhaustible source of energy. Now compare that with fission in case of fission we are breaking the uranium 235 plutonium 230 to much lighter isotope and once a uranium or a plutonium nucleus participates in fission reaction, then we cannot get that back unless you doing some kind of breeding reaction rather the number of such kind of nucleus present in the universe that may decrease.

But, in case of fusion reaction and also I have to mention that the stock of uranium and plutonium is quite limited, but put that in a perspective fusion here we are using two isotopes of hydrogen and hydrogen is abundant and also can be produced through several chemical processes and also as you will be finding later on lithium is 1 of the source of deuterium. Generally, is the most common fuel like uranium is the most common fuel for fission deuterium is the most common fuel that is used in case of fusion and the most likely source of deuterium is lithium at least for industrial processes, we use lithium to produce deuterium and throughout the world or throughout the earth we have a very large stock of lithium available.

And hence from that point of view we can say that the fuels that we generally use in case of fusion reaction are near infinite at least from present use point of view and hence fusion can be an option of energy production for a very very long period of time like I have mentioned it can be something in the range of three millions.

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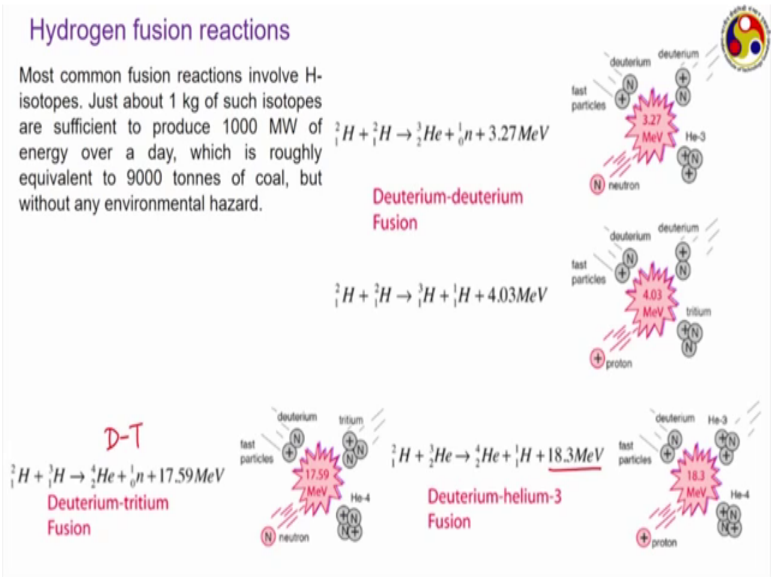

So, now, you go to see if what other kinds of fusion reaction you can have generally fusion deuterium is the most common material that used in case of fusion and it can interact with other deuterium or tritium isotopes just to put in context with chemical reaction which I have mentioned to produce or to run a 100 megawatt power station. Using coal based fuel over one day we generally have to spend something like 9,000 to 10,000 tonnes of coal and that is you are talking about good quality coal if the coal quality reduces; that is if the calorific value of the coal goes down then we have to supply even larger amount of coal that is to produce 1,000 megawatt of power throughout a day.

And the same amount of energy we can get from fusion reaction just by using a 1 kg of total deuterium and tritium just compare these two numbers. We are talking about 1 kg of reactants here and 9,000 tons of reactants on the other side and also what is the end product of that reaction? In case of a hydrogen, sorry; in case of coal based reaction we get several products which are environmental which can cause environmental hazards like carbon dioxide of course, is there and also we can have carbon monoxide we can have nox if the coal contain sulfur we can have sox that is sulfur di or sulfur trioxides etcetera all of them are environmentally polluting particle.

But what we are getting for the fusion reaction just go back to the previous slide here your product is helium which is the inert gas which actually has a quite a bit of use in different heat transfer application as a coolant, but it is definitely environment friendly or it does not have any kind of environmental engrossment and hence it this fusion reaction quite similar to nuclear fission it is a completely clean in a form of energy from environmental pollution point of view. In fact, it is sometimes said that the amount of lithium that we commonly have in common lithium ion battery lithium and battery which we use in our computers.

Just in one computer the amount of lithium we use in a lithium ion battery if we use that amount of lithium and just a few buckets of water something like 1 bath towel water that will be sufficient to provide 500 megawatt of energy over a long period of time. So, just think about we are talking about lithium contained in a single lithium ion battery and just a bit of water. So, you can immediately get an idea about the magnitude of energy that we can get from some from those materials.

Now, what are the possible reactions we can have deuterium can combine it itself, like in a common deuterium base reactor we can have a deuterium come reacting with itself and there are two kinds of fusion reaction possible which are involving only deuteriums the first one involves or produces 2 He 3 1 isotope of helium plus neutron and also it gives 3.27 MeV of energy.

Similarly, it is also possible to have a deuterium fusion to produce tritium conventionally this particular reaction like we use H to denote hydrogen which is the common hydrogen quite frequently we write this equation as D plus D where D refers to deuterium is equal to T plus H T refers to tritium and H refers to common hydrogen isotope the tritium or proton. So, in this lecture we are quite frequently; we are going to use quite frequently the symbol D to denote deuterium and T to denote tritium.

So, deuterium and deuterium can combine with itself or with another deuterium nucleus. We have two kinds of possibilities in one case we are having helium 3 and neutron. In the other case we are having tritium and proton it is also possible for the deuterium to react with the tritium particularly if we fill one reactor with only deuterium then initial two reactions will be this two only, but by virtue of this two reactions whatever the second reaction.

So, you have an tritium production and now the deuterium can react with the tritium also to produce this helium and that gives us 17.59 MeV of energy this particular one like the previous two as there only deuteriums are whatever in reaction they are often called D-D reaction whereas, this is commonly known as the D-T reaction; because here deuterium and tritium are participating together.

And there can be another possibility the ones the D-D reaction produces this two he three that can also react with deuterium to produce 2 He 4 plus proton and releasing even higher amount of energy 18.3 MeV of energy this 4 type of reactions are quite common in any deuterium power fusion reactor.

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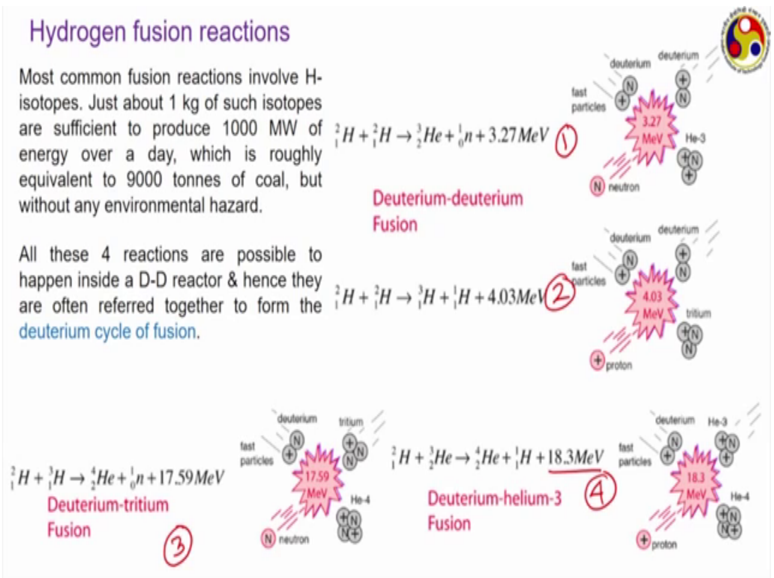

And all these reactions can simultaneously happen, because as I have just mentioned initially; when the reactor is contain only deuterium we are going to have only reaction 1 and 2 while we are talking about this is at 1 and this is 2 both are D-D reaction.

But, once we have the products from reaction 1 and 2 available reaction one giving you helium 3 and reaction 2 giving you tritium, then we can also have this reaction 3 which is a D-T reaction involving deuterium and tritium and the equation number 4 which involves deuterium plus helium 3. So, all these four reactions occasionally are put together to get something known as a deuterium cycle of fusion to get that we just need to add those 4 equations together to get this.

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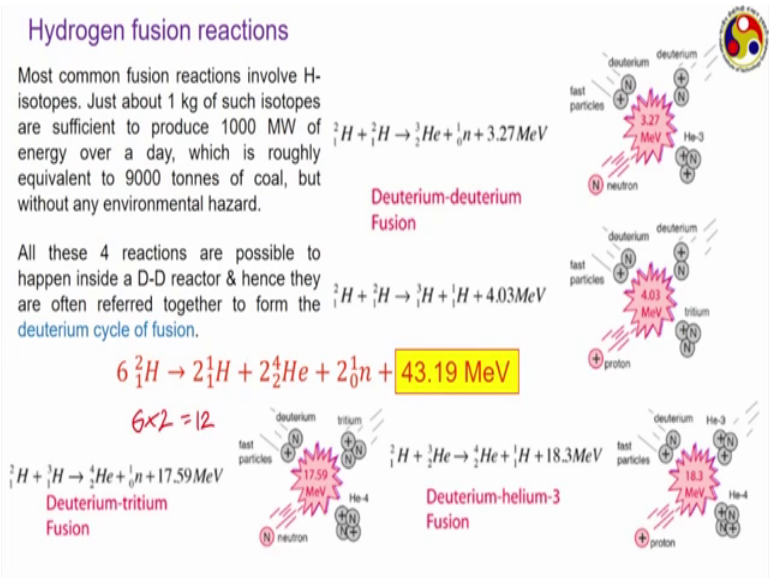

Final form where we can see that there are 6 neutrons, sorry; 6 nucleus of deuterium participating to produce 2 protons and 2 helium nucleus helium 4 the common nucleus plus 2 nitrogen; as well plus if we combine all the energy yield 43.19 MeV of energy which is really a huge amount of energy.

If you consider the total number of nucleons participating in this reaction is only 6 into 2; that is 12; only 12 nucleon nucleons are participating in this reaction giving an ultimate yield or 43.19 MeV which is something about just; what we calculated; earlier about 3.5 MeV of energy per nucleon participation which is definitely much more than what we get in case of a fission reaction going forward.

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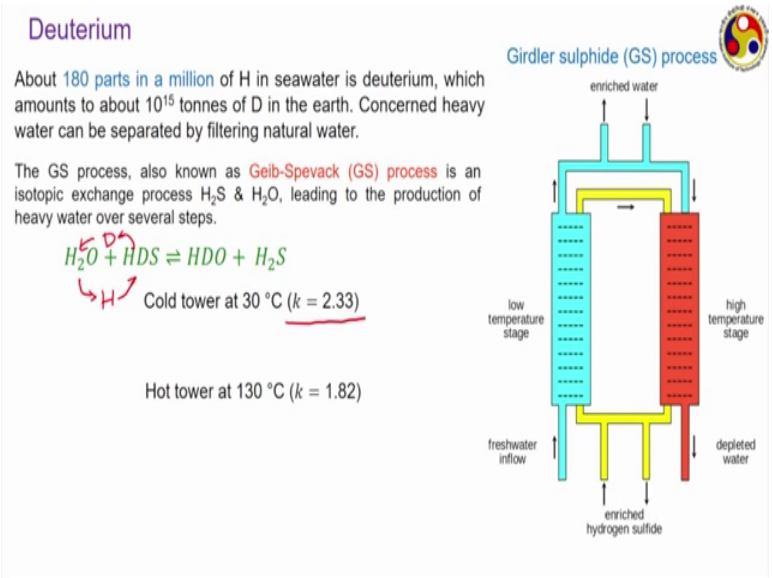

Deuterium as I have mention is the most common fuel that we use in fusionic reactors and deuterium is naturally available in the ocean that is in the seawater.

Generally, every million parts of seawater or I should say the hydrogen part of seawater for every 1 million of that hydrogen part about 180 to 190 part is heavy water or deuterium. So, the seawater that we get in the earth about 180 ppm of; that is heavy water that is the concerned hydrogen nucleus is actually a deuterium this amounts to something like 10 to the power 15 tonnes of deuterium in the earth which generally is sufficient to run to get all sorts of those projections of 3 million years.

Concerned heavy water can be separated by filtering this natural water these girdler sulfide process is one of the most common processes of separating the heavy water from seawater this particular device is also known as Geib-Spevack process; because or based upon the name of the two scientists; who independently proposed this same procedure more or less of the same time this facilitates an isotopic exchange between hydrogen sulfide and water leading to the production of heavy water over several steps of processing to mention the working principle in a very a brief manner the a freshwater that is fresh sea water is supplied through this blue channel.

Actually you can see the procedure or this device involves two different chambers: the blue chamber the blue tower is known as the cold tower which is maintained at 30 degree Celsius whereas, the reddish color tower is maintain at 130 degree Celsius and the reaction that goes through or ok. Before coming to the reaction here fresh water is supplied to the blue channel tower; that is the cold tower through which it flows at low temperature whereas, enriched hydrogen sulfide is also supplied parallel to that both these two fluids that is the seawater and hydrogen sulfide flow parallely through both the two reactors.

And while coming in close proximity with each other they participating this particular reaction here D refers to deuterium H refers to hydrogen and the term HDO refers the a heavy water where the out of the 2 molecules or I should say out of the 2 atoms of hydrogen 1 is deuterium and other is a common hydrogen. Similarly, HDS refers to just a molecule of a H 2 S only, but here instead of having 2 hydrogen nucleus we are having 1 hydrogen and 1 deuterium nucleus.

So, this is the isotropic exchange that happens in such a procedure; when it passes through the cold tower the corresponding equilibrium constant is higher than what we get in case of the hot tower; because the equilibrium constant for this particular reaction reduces with increase in temperature. Now a higher value of the equilibrium constant at a low temperature, that is while passing to the cold tower refers the forward reaction will be more prominent therefore, the deuterium which is bound inside this hydrogen sulfide that gets transferred to this H 2 O or you can see this way the H 2 O and HDS they exchange 1 hydrogen and 1 deuterium with each other with the hydrogen from here going to this and the deuterium from here going to this resulting in HDO plus H 2 S.

However when we go to the hot tower there the equilibrium constant is lower facilitating the reverse reaction a reverse reaction refers the deuterium from HDO.

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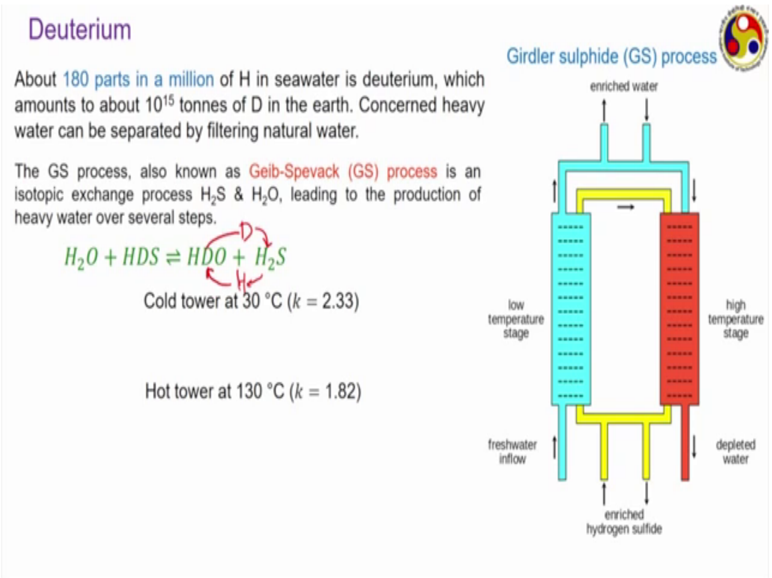

Now goes back to H 2 S and the hydrogen from H 2 S goes back to this HDO to form H 2 O. So, while passing through the cold tower the fraction of deuterium present in the water that increases while passing through the hot tower that decreases this you can also say to be an enrichment of a water from heavy water point of view here enrich in refers the fraction of deuterium is increasing in water.

So, pass the one pass of seawater through this will cause every small increase in the total deuterium concentration or total heavy water concentration in the sample once there itself is not sufficient we need to go for multiple number of steps and that is why the enriched water which we are getting.

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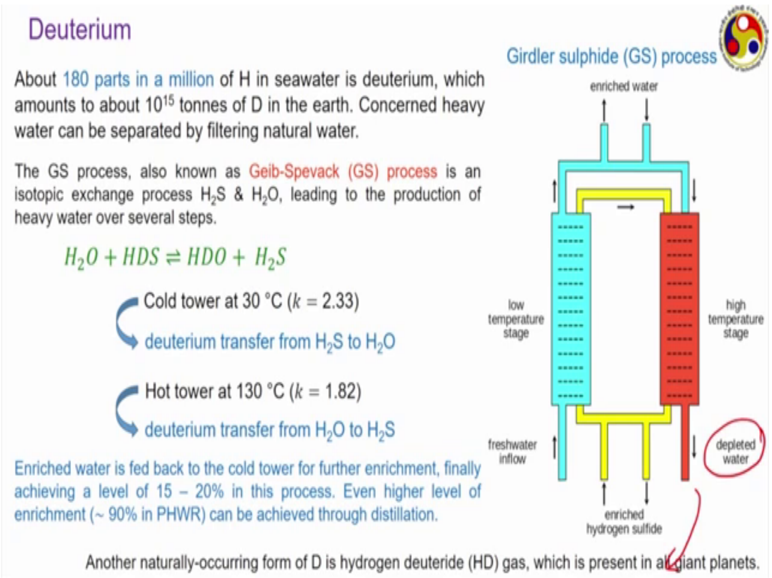

Here from the as the output from this cold reactor quite often is supplied back here or may be supplied to another reactor; which is placed in a cascaded position and we get repeated we get repeated enrichment. Similarly, this depleted water depleted here refers to the water which has transferred the deuterium to hydrogen sulfide thereby it is deuterium concentration has reduced.

It is fed back to a lower level processor this way we generally have several processors put in series and the always the principle being the enriched water collect from one reactor is a fed back to the same reactor or occasionally to another reactor to the downstream side of another reactor which may be placed somewhere here. And the depleted water that is coming out from the hot chamber or hot tower that is fed to a lower side or on an upstream reactor. So, the principle is because of the higher equilibrium constant value at the low temperature of cold water deuterium transfer some H 2 S to H 2 O whereas, in the hot tower, because of lower value of the equilibrium constant deuterium transfers from H 2 O to H 2 S.

This total procedure can give you something in the range of 15 to 20 percent in deuterium or heavy water concentration as a final output that is of course, after using a several cascaded systems where both the enriched water and depleted whatever are fed to suitable processing steps, but in a nuclear reactors we occasionally read much need much higher level of enrichment and for that purpose we go to the distillation process by virtue of which we can reach something in the range of 85 to 90 or even higher percentage of heavy water which are used in PHWR or other heavy water based machines.

Another naturally occurring form of a deuterium is hydrogen deuteride gas which is present in all giant planets like Jupiter, Saturn or Neptune , but that is beyond the scope of present discussion if you are interested you can go to net and search about this one in the earth atmosphere the amount of hydrogen deuteride is negligible, but it is definitely significant in several other planets tritium in contrary.

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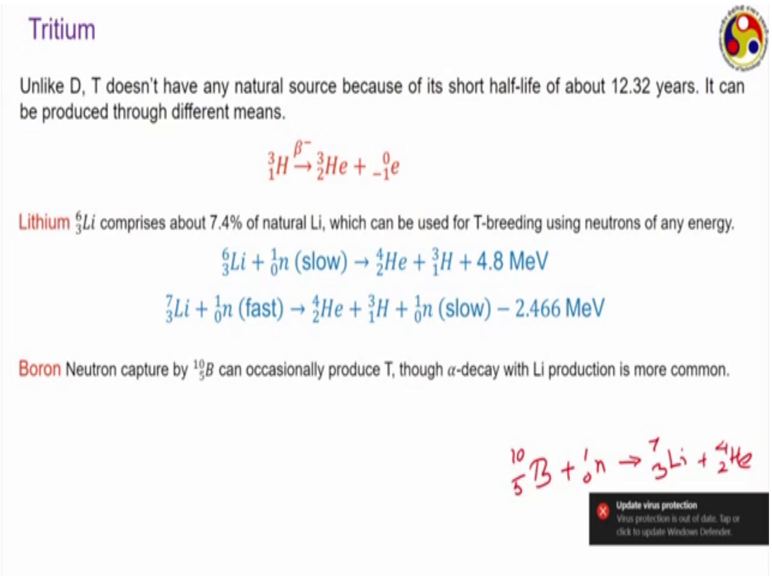

To deuterium does not have any kind of natural source tritium has a quite short half life of about 12.32 years whereas, a deuterium can participate in only a neutron capture reaction to produce a tritium a tritium generally participates through participates in a beta decay reaction to produce helium 3 a and an electron and that happens with a half life of something like 12.3 years that is the reason tritium cannot be produce and store for long duration rather as soon as the tritium is available it is better to utilize that.

Just like in a fusion reaction there are several sources of tritium and the first source is lithium of course, lithium generally has a two common isotopes while lithium 7 comprises the majority of that lithium 6 also comprises about 7 percent or 7.4 percent of natural lithium. This one can be used for a tritium breeding using neutrons of any energy this is the reaction that goes on by striking the lithium 6 with any neutron it is slow neutron. Generally, we can produce helium and tritium and also it is an exothermic reaction releasing 4.8 MeV of energy.

But, when the same lithium is stuck by a fast neutron it produces helium and tritium again and also one neutron and this reaction is an endothermic one absorbing 2.466 MeV of energy; I just correct one here this reaction we are talking about is actually lithium 7 mixture by a fast neutron. So, while lithium 6 can be used to breed tritium using new neutrons of any energy and that is not very easy to do with a lithium 7, because we need neutrons of very high energy level.

Another source of a tritium can be boron or neutron capture by boron. While the most common reaction the boron ten undergoes after capturing a neutron is this one when it captures the neutron generally it goes through a alpha decay. So, alpha decay means it will produce a 2 He 4 plus you now should be a very comfortable with this kind of reaction. So, whenever you are having an alpha decay then the result should be a reduction of a 2 in the atomic number. So, atomic number goes down to 3 which corresponds to lithium and what should be the mass number helium is having a total mass of 4 a mass number of 4.

So, this 1 should be equal to 7, there is a natural isotope of lithium this is a most common reaction that we generally get when a boron 10 captures neutron, but there are also possibilities though fractional perce[ntage]- or the corresponding percentage probably is quite small, but it is still possible that boron can also produce tritium by a reaction like this.

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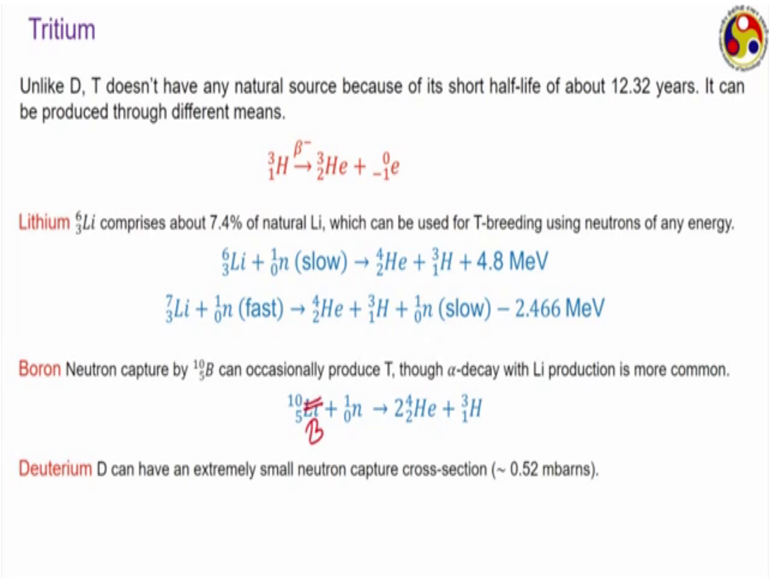

Where it should not be lithium, sorry; this should not be lithium it is actually boron 10. So, boron 10 capturing neutron and produce 2 helium isotopes plus 1 tritium; then deuterium has an extremely small neutron absorption cross section or something like 0.5 to mill points. When it does that it produced tritium, but it is interest important that deuterium has a very small neutron capture cross section, because can you guess where we can make use of this small neutron capture cross section or a deuterium is very very unlikely to capturing neutrons. So, where can we make use of this I am sure you are guessing it correctly that is in the modulating property or heavy water we kept on saying is an excellent moderator, because of this extremely small neutron capture cross section of deuterium.

In fact, the neutron capture cross section of common oxygen isotope that is o 16; that is even smaller and that is why; D 2 o which involves deuterium and if it involves also common oxygen 6, then that will virtually have a negligible neutron capture cross section, but still it has very small capture cross section. So, for a long period of time if you are considering this reaction then there will be some amount off a tritium formation and hence even in case of heavy water moderated reactor occasionally maybe once in a year we need to replenish and separate the tritium from the reactor.

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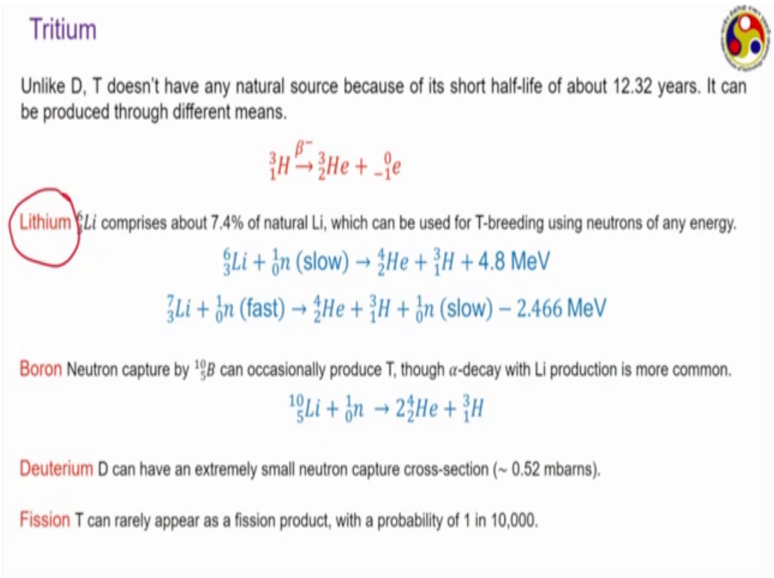

There is another possibility extremely unlikely, but in certain fission reaction those fission which generally gives a tertiary products that is along with two fission fragments there will be a third fission fragments also there we may get a tritium production as well, but again I repeat it is very very unlikely the probability being just 1 in 10,000. So, these are the ways tritium can be produced, but the most preferred way industry is the lithium using a lithium 6 to form a blanket around the fusion reactors generate the whatever fission reactors we have they are covered by a blanket of lithium 6 or lithium 7.

Both can be there and the neutrons which are produced; because of the reaction which can involve both the lithium 6 and lithium which can interact with both lithium 6 and lithium 7 like as this already shown lithium 6 requires fast neutrons, but lithiums; sorry, lithium 7 requires fast neutrons, but lithium 6 can be activated by neutrons of any energy and. So, whenever in the neutron leaks out of the core they are able to capture the neutron if it is a fast neutron then it will be captured by both lithium 6 and 7 and they will participate in this reaction to produce tritium.

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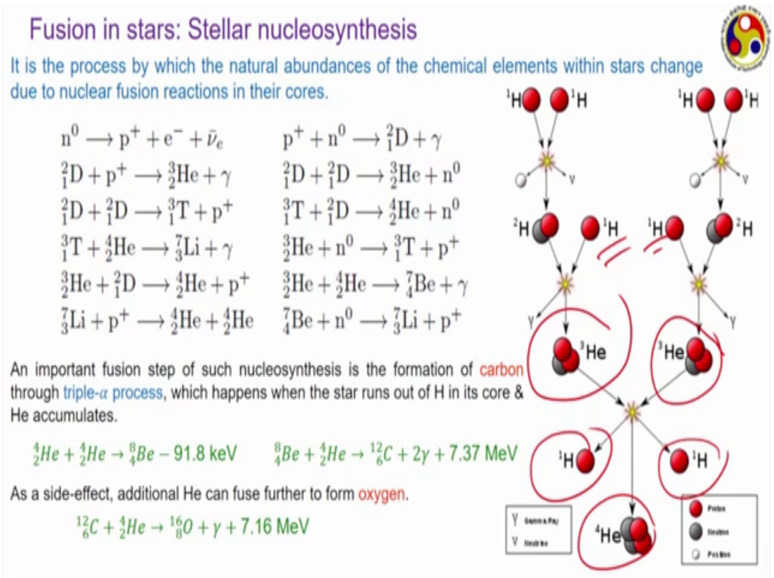

And now fusioning starts it is the fusion; that is the it is the fusion is the process by virtue of which this entire universe has been produced has been created, because all the stars under stellar nucleosynthesis or I should say they are undergoing the stellar nucleosynthesis. Since the very beginning of their birth because of this a nucleosynthesis process, the natural abundance of some chemical elements which are already there in a star that that can get chemically con sorry I should not say chemically that can get converted to some other nucleus.

This is one example like if initially considered that the body of the star contained only proton then these 2 protons can combine together to form a deuterium the deuterium can combine with another proton to form helium 3 and this helium 3 can participate in another helium 3 with another way to produce helium 4 and also another 2 protons. So, we started with proton and we started with four protons rather and also added two more the final product being helium 4. This particular process is called nucleosynthesis and only happens in stars or those kinds of extraterrestrial bodies we call it stellar nucleosynthesis.

These are some further example like a neutron getting broken into a proton and then electron. Similarly proton and neutron combine in together to form deuterium and then it goes on it can lead to the formation of much heavier isotopes or I should not say much heavier, but heavier compared to a single proton we can have lithium we can have beryllium and this way as the reaction goes on continuously heavier isotopes starts with to appear and a very important stage of such fission step or such nucleosynthesis state is the formation of carbon through triple-alpha process the triple-alpha process refers to reaction between three different helium 4 isotopes.

This particular reaction becomes more prominent when the hydrogen straw of the is about to expire and helium accumulation has happened inside the reactor in that case 2 helium isotopes can react with each other to produce a beryllium which is also endo thermic and there we absorbing 91 a keV of energy and then this beryllium reacts with another helium isotope to produce 6 C 12 and it is extremely exothermic. So, to produce 7.37 MeV of energy as a Be proton of this reaction we can also have oxygen where this 6 C 12 the carbon can react with another helium to produce 8 o 16 which is also radioactive reaction or which is also an exothermic reaction.

Because it is giving you 7.16 in a MeV of energy allowed to it.

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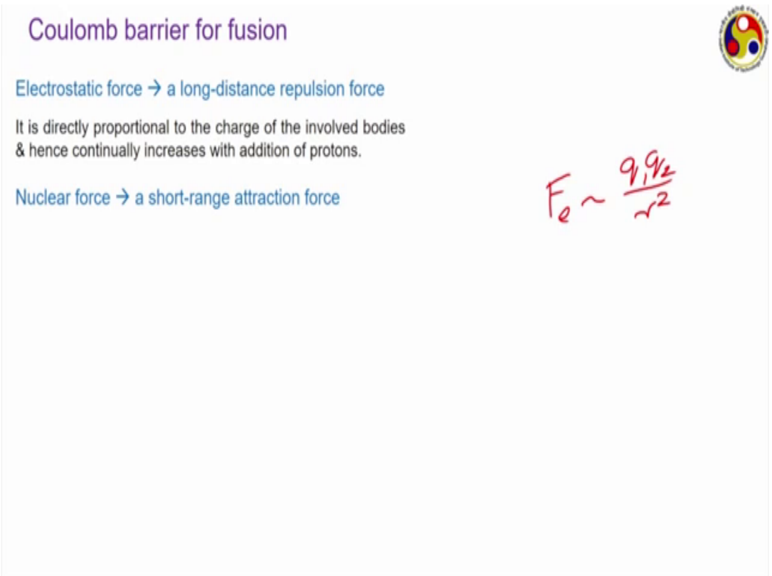

But the fusion reaction of course, we now know that tritium and deuterium are the two most common fuel that we use for fusion reaction, but to make that happen or to make such a reaction happen we need to bring these two nucleus close to each other and while doing that these are the two forces that the particles experience one is the electrostatic repulsion force which is a long distance repulsion force and other is the. So, called nuclear force which is; generally a short range attraction force.

Now the nuclear sorry electrostatic force is directly proportional to the charge on the individual particles and also inversely proportional to their distance, because if we use the coulombs law of electrostatics we know that it can be written as F is equal to q 1, q 2 by r square, where q 1 and q 2 are the electrical charge for both the part involved particles and r is the distance between them nuclear force; however, is a short range attraction force this is the.

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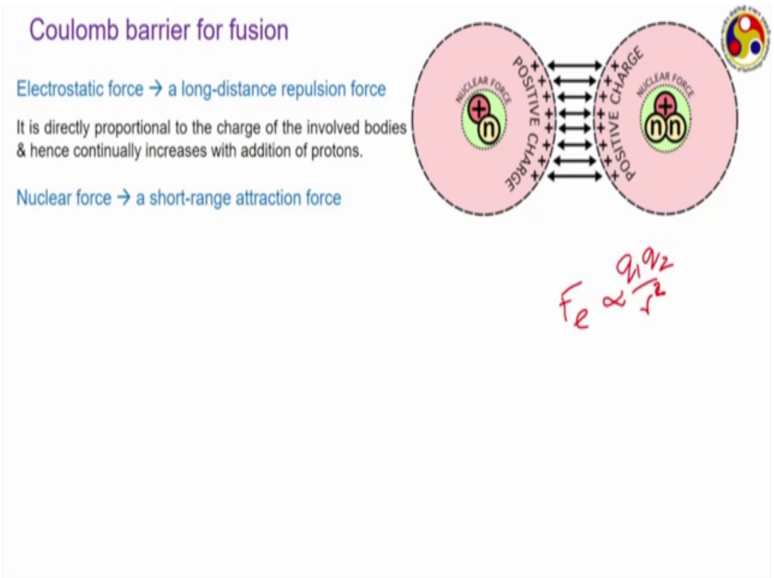

Electrostatic force and as we are talking about reaction between one deuterium nucleus and one tritium nucleus both of them are electrically positive because deuterium contains one proton. So, is tritium?

So, both of them contains one positive charge and hence there will be a strong electrostatic force that acts between them and as that force as I have just erased from the slide as they come closer to each other or the distance between their centers keeps on decreasing that is that r keeps on decreasing electrostatic force that is that Fe is inversely proportional to r square and it is directly proportional to q 1, q 2. So, as the r keeps on decreasing Fe keeps on increasing here q 1 and q 2 both are of a equal amplitude because that corresponds to positive one unit of positive charge.

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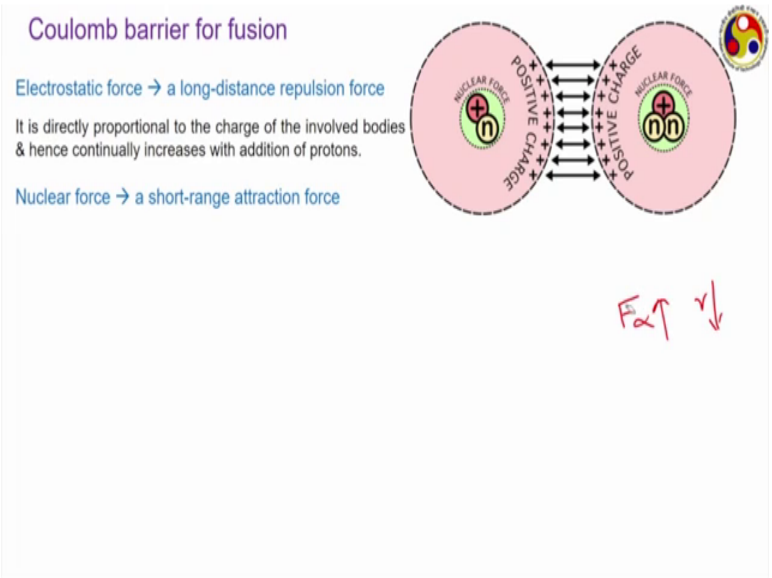

Therefore, Fe keeps on increasing as r keeps on decreasing.

Then, how we can keep this toward me how we can take this to nucleus in contact with each other the answer lies with the nuclear force nuclear force.

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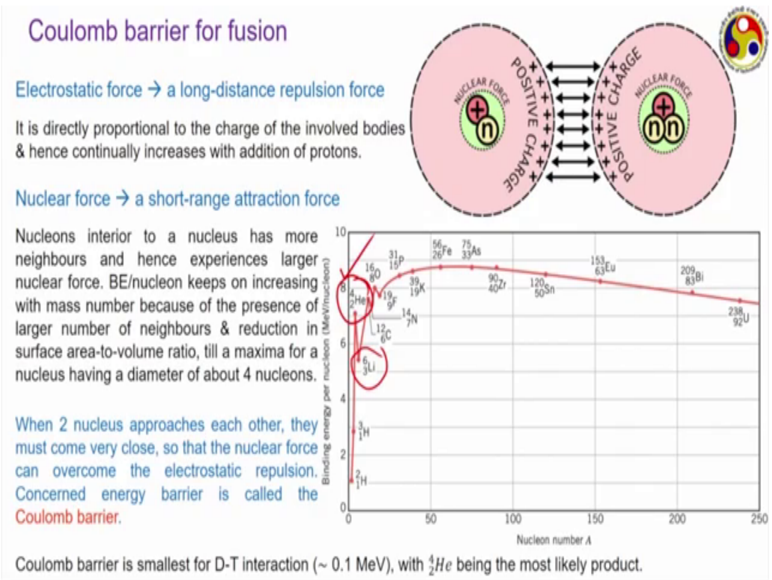

Is something that acts between the nucleons and more number of neighbors nucleon has the larger will be the nuclear force between these 2, but it is a very very short range force therefore, the nuclear force and nuclear experiences generally is from the influence of only it is nearest neighbors and not from those which are a bit away from this.

Binding energy per nucleon keeps on increasing with the mass number, because of the presence of large number of neighbors as the number of neighbors keeps on increasing every nucleon; particularly those which are in the interior side keeps on experiencing larger amount of nuclear force and also the surface area to volume ratio keeps on increasing I should say keeps on decreasing as the volume keeps on increasing correspondingly surface area to volume ratio keeps on decreasing and therefore, there will be even lesser possibility of having any kind of interaction.

Thankfully there is a maximum of binding energy per nucleon which is related to the mass number and it is found that around a mass number of sixty which we have mentioned earlier also it reaches a maximum that mass number of sixty corresponding size of the nucleus generally is quite similar to combining four nucleons together and hence any nucleus like this deuterium tritium which are much lighter than that binding energy of sixty or their effective radius is less than this 4 nucleon range they should come very close to each other to experience any kind of nuclear force.

Now, this is a particular chart the same diagram which I have shown earlier also that I am reproducing, but in a slightly different way here you can see binding energy per nucleon is very low for deuterium and tritium and as we go on like for elements like carbon oxygen or fluorine it keeps on increasing and attains at a maximum, but one big aberration that you can find here this 1 this helium 4 the binding energy per nucleon for helium 4 is greater than the next heavier isotope which is lithium 6 which is definitely an aberration the answer to this one can be given from quantum mechanics point of view, but I do not want to go there for the moment just consider that helium 4 has a higher binding energy per nucleon compare to it is neighboring nucleus and the result is it is very very stable from nuclear point of view.

So, when to approve a new when a 2 nucleus approaches each other they must come very close. So, that the nuclear force can overcome it is repulsion and corresponding energy barrier which the nucleon or this deuterium and tritium nucleus has to overcome it is known as the coulomb barrier. Coulomb barrier is smallest for deuterium tritium interaction a something like 0.1 MeV one reason being they are small binding energy per nucleon, but 2 He 4 is the most likely product of such a reaction, because this high binding energy per nucleon for this 2 energy per neutron.

So, in order to facilitate the fusion process we must overcome this coulomb barrier and then only the particles or this deuterium and tritium nucleus will be able to come close to each other come within the zone of effect or within the zone of action of this nuclear force and then only we can have a proper fusion reaction. So, this lecture I will keep up to this point only in the next one I shall be starting with discussing the option of overcoming this coulomb barrier and then discussing some further aspects of fusion reaction.

But, what to summarize the absorption that we have in this lecture is you are introduced to the topic of fusion. We now know that fusion refers to two lighter nuclei combining with each other to produce a heavier nuclei; which is to heavier nucleus which is having a higher value of binding energy per nucleon. And hence from nuclear point of view more stable we have also seen there are different kinds of nuclear reaction that we can have involving deuterium particularly deuterium is a most common fuel in fusion reaction and it can participate in four kind of fusion reaction. We have discussed about the sources of deuterium and tritium and then your interest in this topic of coulomb barrier which is the from technological point of view the most important term that we have to consider while developing a fusion reactor. So, that is it for this lecture.

Thank you very much.