Nuclear fusion

B.S.Tomar

Homi Bhabha National Institute

Lecture-14, module-2

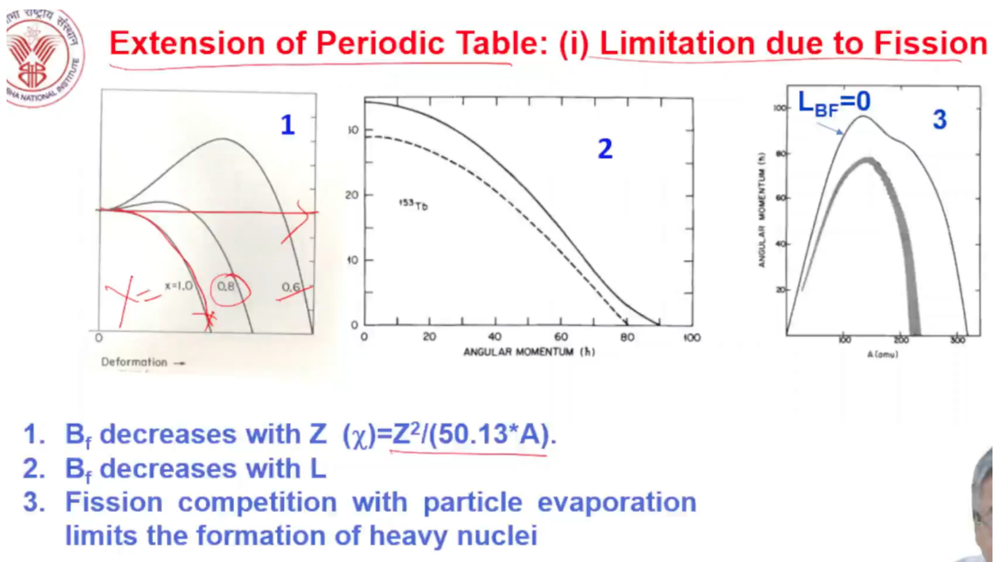
Hello everyone. In this lecture, I will discuss the nuclear fusion process from the point of view of two aspects.

Nuclear Fusion

1. **Extension of periodic table**
2. **Power from Nuclear Fusion**

One is the extension of periodic table, that means essentially synthesis of heavy elements. I will not give too much details, but explain the concepts behind what are the limitations in extension of periodic table, but that also involves a nuclear fusion process. And second is what are the research or what is the work going on producing electricity from nuclear fusion process. So first let us discuss the extension of periodic table.

You know that the elements up to 92 were available till 1930s. And after the discovery of nuclear fission, the attempts were made to synthesize heavier elements in the reactor, plutonium by (n, γ) reaction followed by beta minus decay and with the accelerators producing heavy ions, then by fusion reaction also heavy elements were being synthesized. And by this time, elements up to 118 have been discovered, majority of them, in fact, beyond element 100, most of the elements have been synthesized by nuclear fusion, fusion of heavy projectiles with the heavy targets. And so, but there is a limitation.



There are some inherent limitations in extending the periodic table that I try to explain in this particular presentation. So the limitation due to fission, as I discussed in the previous module that fissility parameter. If you have a fissility parameter χ= 0.6, that will correspond to a mass number of around 100 or so. You can see from here, Z^2/ (50.13×A), you can calculate. So these nuclei are stable towards fission. They will not undergo fission. Whereas if you see χ = 0.8, so this comes to around Californium or Einsteinium, Fermium, generally close to 100.

And these nuclei will have the fission barrier of the order of even around close to one MeV or so. So this is the spontaneous fission happening. They are having very short half-lives because they have a high fission probability. But if the facility parameter is one, then there is no fission barrier. You can see here, there is no fission barrier for this nucleus. And so you cannot produce these nuclei. The moment they are formed; they will undergo fission. For them, the fission barrier is 0. So that is the limitation because of this instability towards fission of this heavy nuclei, it is very difficult to extend the periodic table.

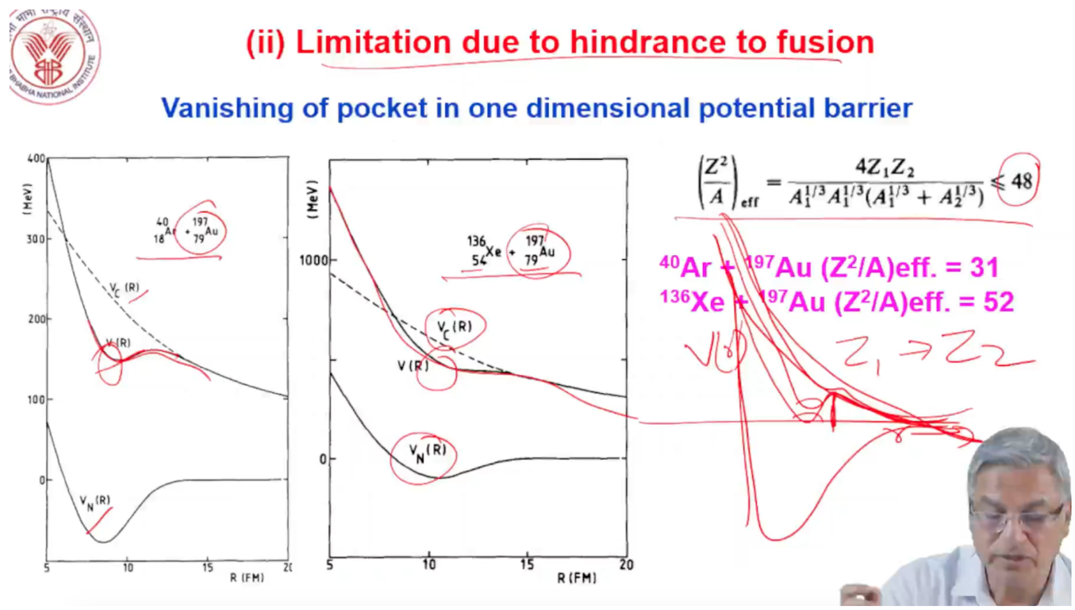
Another aspect, so the fission barrier decreases with the increasing atomic number. And you can see how the fissility parameter is changing for different nuclei, you can calculate from here. So let us say Z^2/ (50.13×A), let us say 200 mass number. So let us take 100 square upon 200*50, so it will become 10,000. So that means 10,000 upon 10,000, that is equal to 1. So a nucleus of mass number 200 will have one facility, so it will not survive. But if you make it 250, so it will become 125,000, we will put 12,500, then it will be close to 0.8. The fissility will be close to 0.8. And so it will have some fission barrier and therefore it can survive fission.

Another aspect is the angular momentum. Angular momentum is adding to disruption of the nucleus, like Coulombic repulsion. The Coulombic repulsion is trying to separate the protons away and that is the factor which accelerates fission. Another thing is angular momentum. So in a heavy ion reaction, when you bring in a heavy ion, it will bring in angular momentum. And the angular momentum will try to destabilize the nucleus. So because of that, there is one more term, apart from surface energy. So if you recall the expression, if you recall this one, for surface energy, Coulomb energy, the angular momentum term also will be destabilizing the nucleus. So the net result of surface energy, centrifugal energy, and the Coulomb energy will dictate the fission barrier. And so because of this, for the same nucleus, if you have higher angular momentum, fission barrier will decrease.

What I am showing here is you increase the angular momentum from 0 to 20, 40, 60, 80 h cross. For this nucleus, ^{153}Tb, the fission barrier for zero spin was around, this is 35 or so, 35 MeV. And it is going down to close to, let us say, 5 MeV at angular momentum of 70 or so. So you can see sharply declining fission barrier with increasing angular momentum. So in heavy ion reactions, invariably you will have higher angular momentum.

And so they will be more unstable towards fission. What I have shown here is the profile locus of the angular momentum and mass number for nuclei having fission barrier zero. The angular momentum for which fission barrier become zero, we can see here for a mass number around 150, it can accommodate about 90 ħ of angular momentum. But for a nucleus of mass 300, it cannot accommodate even 5 ħ. So that means what? The fission barrier for the angular momentum for which fission barrier become zero, it is increasing and then it starts decreasing. So when you go to heavier elements close to 300, they will have nearly zero fission barrier. So that's why you will find that their survival become very difficult. And so that puts a limit on extending the periodic table.

The third is the competition with particle evaporation limits the formation of heavy nuclear. So fission competes with the particle evaporation and therefore that puts a limitation on the survival of the heavy nucleus. So there are different ways to reduce the particle evaporation by using what we call it the cold fusion. That means you produce a compound nucleus which have very low excitation energy. There are different ways, but we will not go into details of those processes. I just wanted to give you a feel that what are the limitations in extending the periodic table.



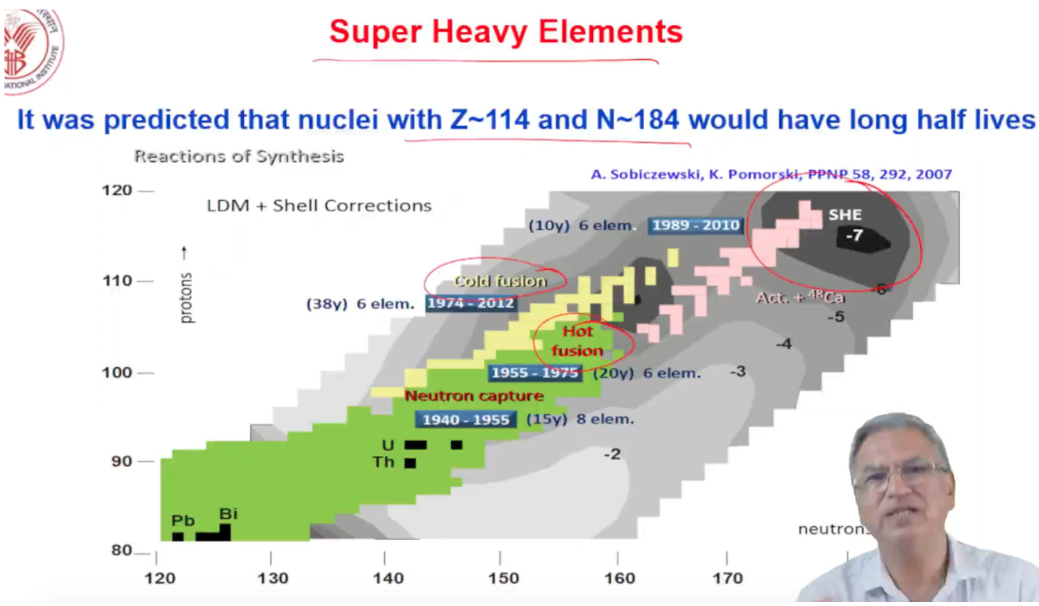
Another thing is to entrance to fusion. There are other limitations that when two nuclei come together, then there are other factors which hinder fusion of nuclei. So if you recall the previous lecture, I have shown in the compound nucleus mechanism that suppose a nucleus is coming close to another nucleus, Z_1, Z_2. So this is the R versus the potential. And this is nuclear potential is like this. The Coulomb potential is like this.

$$\left(\frac{Z^2}{A}\right)_{eff} = \frac{4Z_1Z_2}{A_1^{\frac{1}{3}}A_1^{\frac{1}{3}}(A_1^{\frac{1}{3}}+A_2^{\frac{1}{3}})} \leq 48$$

And the sum total of that will be, so this is the fusion barrier. There is a pocket being formed. Once you bring in angular momentum, then angular momentum also is a repulsive barrier. And so that will reduce the pocket. So the fission barrier will decrease for higher angular momentum. In fusion of heavier nuclei the pocket will vanish. This is what I have tried to show here that for $^{40}Ar + ^{197}Au$ $(Z^2/A)_{eff} = 31$, the nuclear potential and the Coulomb potential will give rise to this pocket. This is the pocket in the fusion barrier. For heavier projectile like $^{40}Xe + ^{197}Au$ $(Z^2/A)_{eff} = 52$, target is same, but the projectile is now increased. You will see here that the Coulomb barrier is here, nuclear potential is here and the fusion profile has become very shallow.

That means this pocket starts vanishing. And once this pocket starts vanishing, the compound nucleus formation becomes difficult. So the two nuclei cannot come close enough to fuse and form a mononucleus called compound nucleus. So you can see here 54 + 79. If you want to go to heavier elements, you have to have heavier projectiles trying to fuse with each other, so the nuclear physics community is trying to study what are the factors that will limit the formation of heavier elements. So there is an effective fissility parameter, they call $(Z^2/A)_{eff}$. That if it is less than 48, so again, it is nothing but, it's like a Coulombic energy of a dinuclear system. If it is less than 48, then you may be having a pocket. If it is more than 48, then you may not have the pocket. So you can see here for $^{40}Ar + ^{197}Au$ is 31, for $^{40}Xe + ^{197}Au$ it is 52.

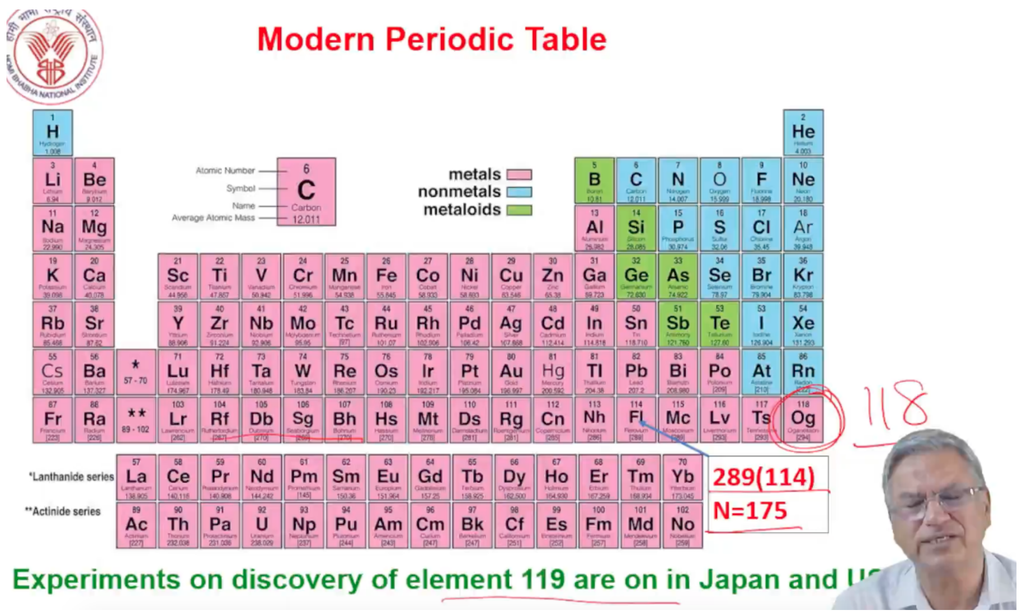
So that is how, this is one of the limitations in fusion of projectile and target to achieve synthesis of heavier elements. So the nuclear chemistry fraternity has been engaged in synthesizing heavier elements. There are predictions based on shell model calculations that nuclei having atomic number 114 and neutron number 184 are expected to have long half-lives. That is what is called super heavy elements. The super heavy elements around this region ma



y have a long half-life.

So people have tried to in fact separate them from the natural resources, from the earth's crust, from wherever there is a large deposits of uranium, thorium, people have tried to separate some elements resembling their lighter homologs. But so far there has been no success in the process. People have been trying to synthesize them by fusion reactions. So as I was mentioning, hot fusion, you take lighter projectile and heavier target nuclei or cold fusion, you take heavier projectile and not so heavier targets. So by cold fusion reaction, you will try to produce a compound nucleus which is not very hot in terms of excitation energy.

And so by these processes, people have tried to synthesize heavy elements. And because of that, the half-lives are very short, but still attempts are going on to synthesize heavier elements.



So you can see here, the periodic table has been extended to mass 118. And these experiments take a very, very long time. In fact, even to synthesize elements, these elements, Rutherfordium, Dubnium, Seaborgium, for which the chemistry has been also studied, element 104, 105 and 106, lot of chemistry has been studied.

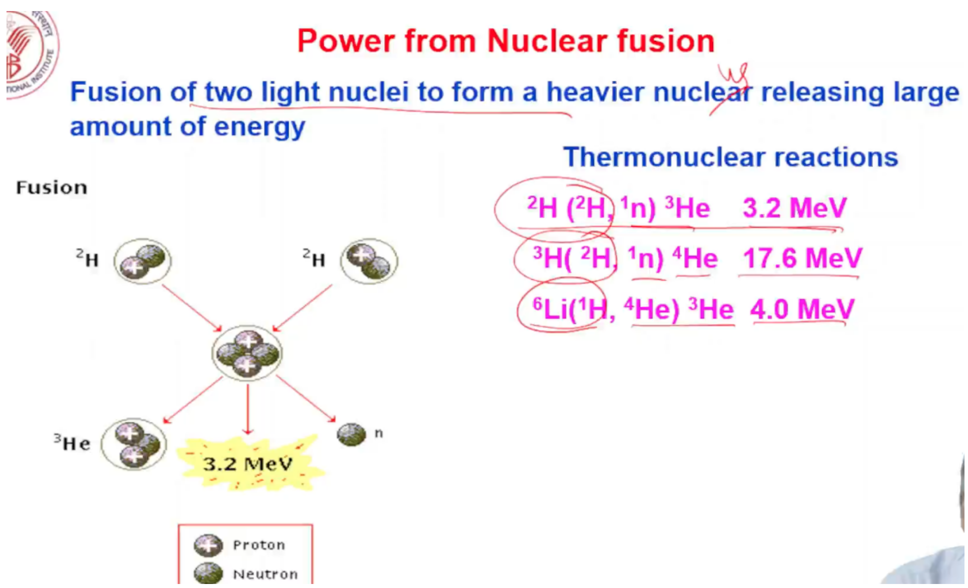
Even there, the production rates are one atom per hour or so. As you go to higher and higher, like this highest elements, production rate may be one atom per month or so. You can see here the kind of experiments people are doing. And then they have to get an unambiguous signature of that, it is that Z and A. So the atomic number, the mass number of that particular isotope has to be established to claim that they have discovered a particular, their new element.

So what they do actually, when this heavy element isotope is produced, they will undergo alpha decay and the alpha decay energies are monitored for the lower daughter products, the alpha decay energies are known. And so that is how they correlate that this daughter is growing from this parent. So this is the atomic number and mass number of this particular heavy isotope. So element up to 118. So the super heavy element as we are calling Z-114 and N=184 is close to that region that people have achieved, but the half-lives are not long enough.

Half-lives are very short. They are in millisecond, microsecond range. So still people may be searching for the super heavy elements with long half-lives, but the experiments in accelerators to synthesize elements beyond 118, they are now going on, they are planned in Japan and USA. Now in fact, the different countries actually are pooling their resources to plan such mega experiments to synthesize heavy elements.

So to conclude the part of nuclear fusion in producing heavy elements, I would like to say that there are experiments going on using nuclear fusion reactions, wherein you try to understand what are the factors that limit the extension of periodic table. People have tried to produce heavy nuclei by hot fusion reaction or cold fusion reaction. This cold fusion is not the type of cold fusion which were in between it came in the news that fusion of hydrogen isotopes to give neutron. This is a fusion of heavy nuclei, but to give lower excitation energy to compound nucleus. So you want to survive the fission. So you produce compound nucleus with low excitation energy so that it can survive fission.

Now I will come to the next part, how to produce power from nuclear fusion and what is the status as of now.



So the fusion of two light nuclei to form a heavy nuclear nucleus to release large amount of energy is similar to fission process and fission process has been already realized to produce electricity because we can control the reactor very easily. But in the case of nuclear fusion process that still is yet to become a reality. So let us discuss this nuclear fusion, the fusion of lighter isotopes. So here we have the different types of nuclear fusion reaction. Fusion of deuterium plus deuterium giving rise to helium-3 and neutron, the Q value is 3.2 MeV. Fusion of deuterium and tritium to give rise to helium plus neutron, Q value is 17.6 MeV and fusion of lithium with hydrogen give rise to helium-3 and helium-4, Q value is 4 MeV. Now as you know that these are all charged particles. So if you want to fuse the charged particles, you need to cross the coulomb barrier and so there are different channels which people are trying to explore for achieving a nuclear fusion process which you can sustain. I will discuss this soon what are the problems in sustaining a fusion reaction.

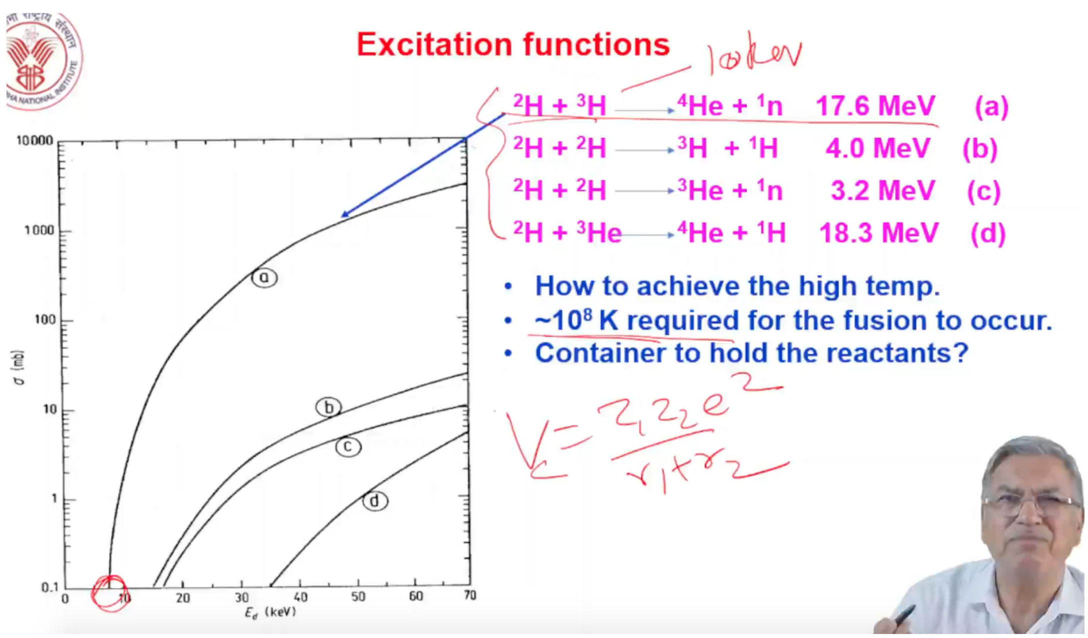
So this is a simple deuterium plus deuterium fusion reaction.

$^{2}D + ^{2}D$ □ $^{3}He + 1n + 3.2$ MeV

Like that you will have deuterium plus tritium.

$^{2}D + ^{3}T$ □ 4He + n + 17.6 MeV

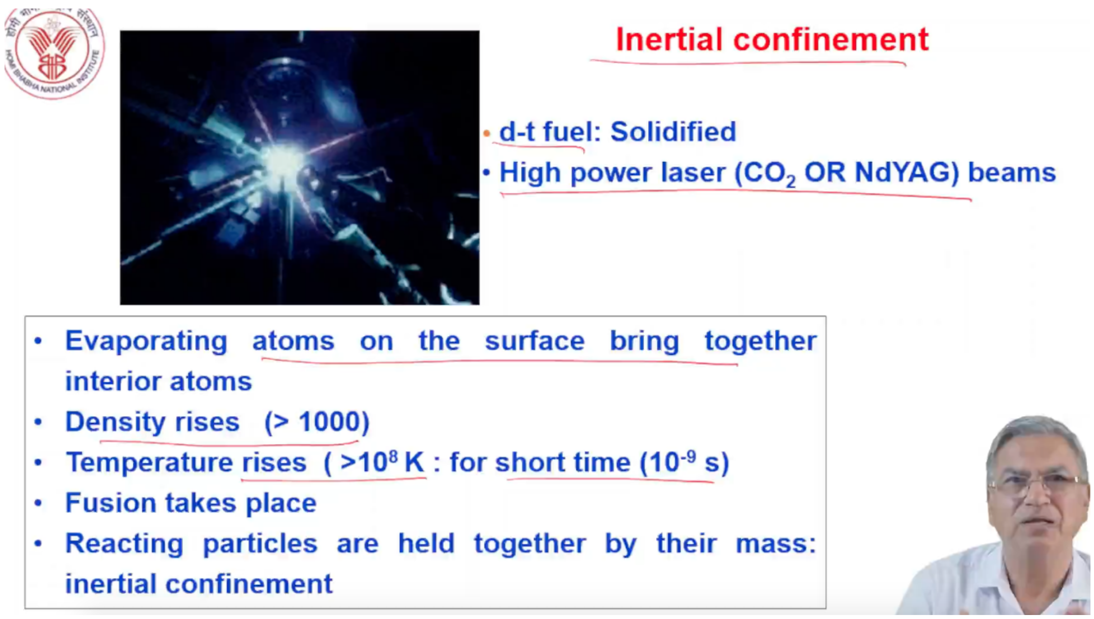
So let us see what are the problems in achieving a fusion reaction. As I was mentioning these reactions, different fusion reactions of lighter isotopes of hydrogen, the one which is having deuterium plus tritium having the lowest threshold that means the coulomb barrier.



So in coulomb barrier you know already $Z_1Z_2e^2/(r_1+r_2)$. So for deuterium plus tritium, the coulomb barrier is about 10 keV. So the coulomb barrier for this will be 10 keV and if you translate this 10 keV into temperature it becomes 10^8 K. So it's like a threshold reaction, threshold energy. So if you want to induce fusion of deuterium and tritium you require to achieve a temperature of 10^8 K.

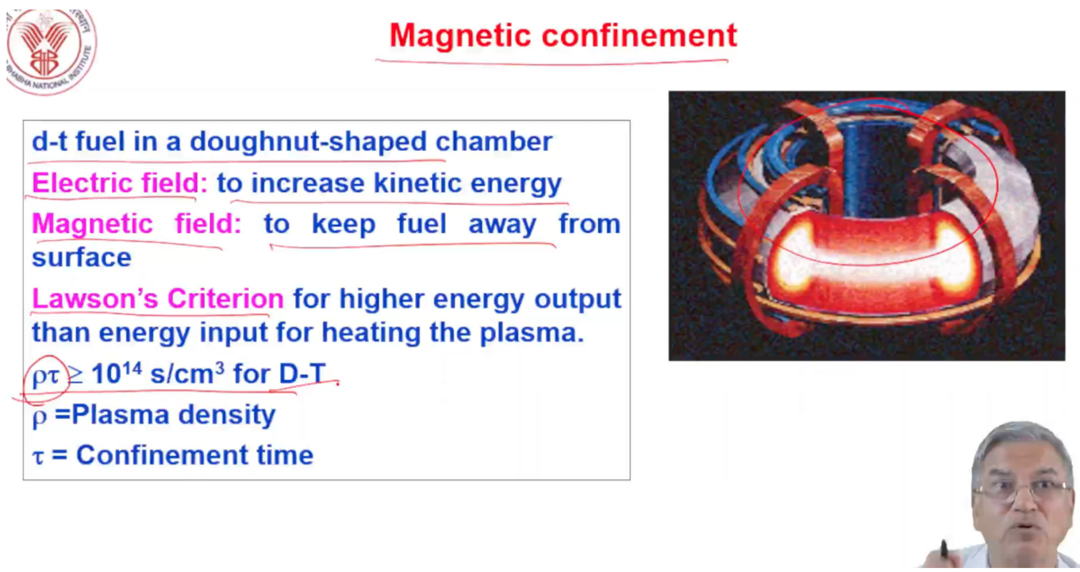
Now you can imagine unlike in the case of neutron induced fission where you didn't have this problem because thermal neutron can induce fission. But for charged particles you require to have very high temperatures and then if you have to achieve high temperature what kind of container you will have to hold reactants at such a high temperature. So the storage materials, storage vessels how to achieve at this temperature the matter will be in the form of a plasma. So you have to contain the plasma in a container. All these are the limitations for achieving a fusion reaction.

But now there have been attempts going on for last many many years, several decades have been spent and there are mainly two types of approaches people have followed. One is the inertial confinement. So what is that you are trying to confine? The deuterium tritium plasma. The deuterium tritium they have to fuse together and you require a temperature of 10^8 K. So how do you contain this plasma? So the one approach is called inertial confinement.



By inertial confinement you mean that by virtue of their mass you can confine the solid fuel in a very small volume and but you have to also have a high temperature. So you achieve high temperature by bombarding them with high power laser beams, CO_2 or NdYAG laser beams and you take a solidified fuel. So when the laser beams are bombarded on the solidified fuel it will ablate the surface atoms outside and this ablating atoms now will give a recoil to the core and their density will increase. So you contain the core of the solidified fuel by ablating the surface atoms using a laser beam. So the evaporating atoms on the surface bring together the interior atoms by the recoil of the ablating atoms and that will lead to a rise in the density of the core and in the process the temperatures can go beyond 10^8 K but then it may not sustain for a long time.

So there is in fact a Lawson's criterion which I will discuss very shortly. So for a very short time you can achieve very high temperature and during that time the fusion can take place. So in the process of inertial confinement the reacting particles like deuterium and tritium are held together by virtue of their mass and that is why it's called the inertial confinement. So this inertial confinement by using the laser beams to ablate the outer surface layer to increase the density of the core the experiments are going on but it has not been as successful as the next experiment of magnetic confinement.



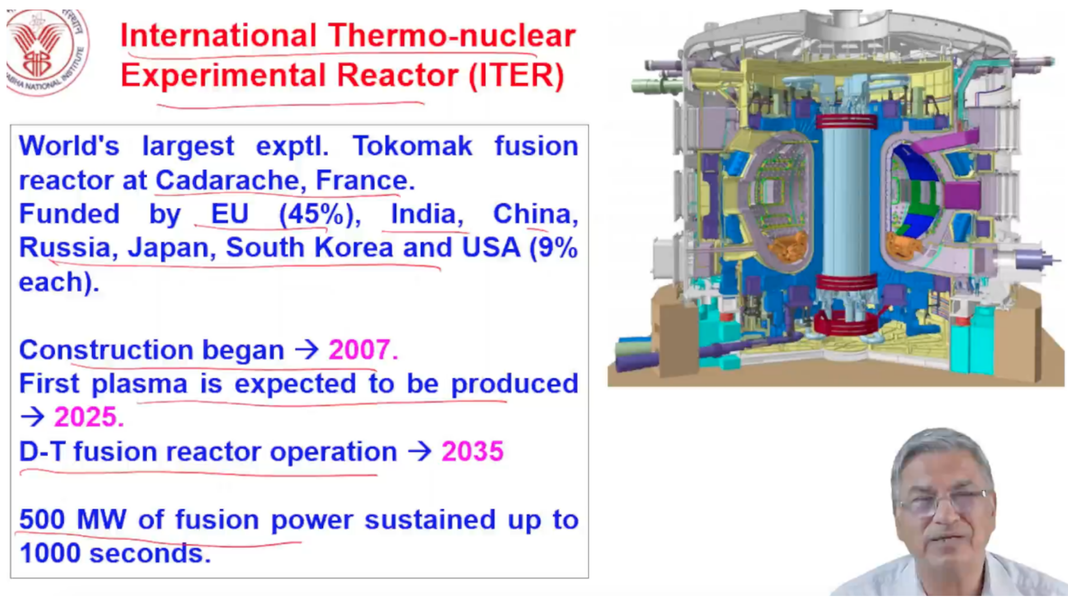
In the magnetic confinement again you take the deuterium tritium fuel in the shape of a doughnut and in the central portion of this doughnut the plasma can rotate, move and confine a avoid the plasma touching the container walls using the electric and magnetic fields that is called as the Tokomak system where the electric field will accelerate the particles it will increase the energy of the reacting particles and the magnetic field will keep the fuel away from the surface.

So you have to adjust the electric field and the magnetic field to have the plasma and when they are fusing they should not touch the container walls. So the magnetic confinement strategy has been working and there have been several attempts to generate the Tokomak type of reactor worldwide.

One of the conditions to achieve to sustain a fusion reactor is called the Lawson's criterion. The Lawson's criterion essentially emphasizes how to achieve a plasma density beyond certain number for a reasonably long confinement time. So we have to confine the plasma for a reasonable length of time. So this criterion is

$\rho x \tau > 10^{14}$ seconds/cm^3

ρ is the plasma density and τ is the confinement time. If you have to have higher energy output than the energy input being given to heat the plasma to a temperature 10^8 K. then the product of plasma density and confinement time should be more than 10^{14} second per cc for the deuterium tritium system. For deuterium deuterium we need 10^{16} second per cc. So D-T is the system which has a lower threshold so the lowest temperatures required for this fusion reaction. So this is the confinement. So overall attempt is to increase the confinement time and the plasma density. So these are the two efforts are being made to have Lawson's criterion. If you can have a high plasma density and high confinement time nothing like that.



So let us see what is the current status for producing electricity from fusion reactor. Since this is a very costly affair to build a reactor which we still do not know when it will work. But there has been an international effort called ITER, International thermonuclear experimental reactor in which almost the majority of the countries which have interest and have come together and they have proposed a fusion reactor at Cadreache, south of France. So this is the world's largest experimental tokamak fusion reactor which is being built.

It is funded by European Union largely and India, China, Russia, Japan, South Korea and USA contributing 9% each. So every country you know whoever has a stake in the fusion power they want to contribute in this and the construction of this fusion reactor began in 2007. This is 2022. So already 15 years have passed and the first plasma from this fusion reactor is expected to be produced by 2025.

In fact, India has contributed a great deal in cash and kind. In fact the cryostat for this reactor was built in our country and many universities in the country are also participating. We have Institute of plasma research in Gandhinagar. They are the leading agency in the country to contribute in the plasma research in the fusion reactor. So this fusion reactor based on deuterium tritium fusion is expected to start operation by 2035 and this reactor is expected to have a power of 500 megawatts which will be sustained up to 1000 seconds.

So you can see here that even this is a very meager target. What do you do for after 1000 seconds? but this is such a challenge. It's a really big challenge. So this kind of mega projects if you can sustain, if the such a high power of fusion power for 1000 seconds, it will open up gates for the sustaining. Actually materializing, realizing the electricity from the fusion in the times to come. So this is the one area where there is a lot of scope for research for students in the country. There are many universities are also contributing in this fusion research and the Department of Atomic Energy is also contributing in a big way both in terms of producing the materials, the different systems and that of course the government of India is contributing by way of funding.

So what I wanted to share with you today that while the nuclear fission has been already utilized for producing electricity in our nuclear reactors, the nuclear fusion is yet to be realized for producing electricity but maybe you young students will see one day that we are producing electricity from the fusion power and so it is a challenge for all the students to participate in such big mega projects those who are in the field of nuclear chemistry or nuclear physics or in fact many engineering students, mechanical engineers, all types of disciplines are involved in producing this kind of a facility. So I will stop here and the next I will take in the next lecture the production of radioisotopes in different types of nuclear reactions. Thank you very much.