Astrophysics & Cosmology
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Lecture - 17
Stellar Physics II

Welcome, we have seen that the sun is continuously emitting radiation and the energy that the sun obtains from the gravitational contraction is not sufficient to provide enough energy to support this radiation for a period of around 10 billion years or at least 4 and half billion years which we know is the lifetime of the solar system. So the question then arises what is the source of energy of the sun?

And today we are going to discuss this question what is the source of sun's energy? And I have told you that this source is hydrogen burning.

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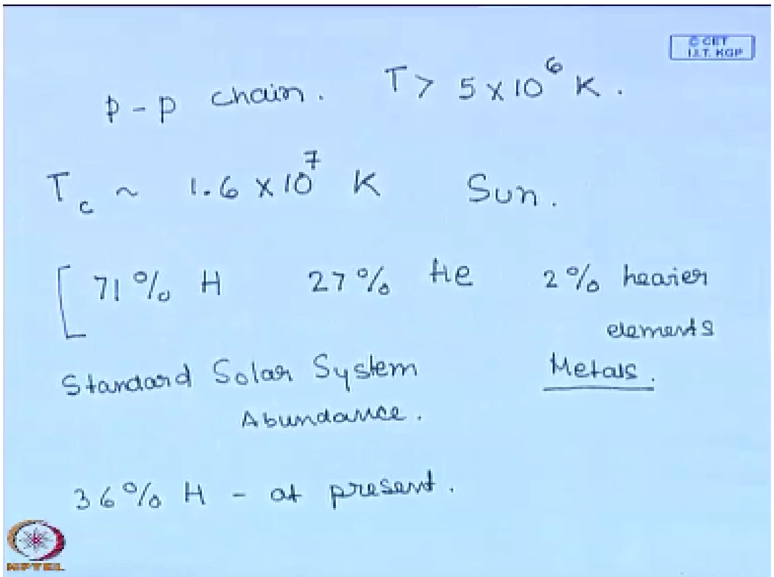

The main process is called pp chain proton-proton chain and in this process protons are converted. So hydrogen is converted into helium through the pp chain proton-proton chain and this process becomes effective at temperature > 5 million Kelvin. And the temperature at the core of the sun is around is 1.6*10 to the power 7 Kelvin for the sun. So we expect this mechanism to be functional in the core of the sun.

The core of the sun the solar constitution at the beginning we know that it is 71% hydrogen, 27% helium, 2% heavier elements which in astrophysics is known as metals are known as metals. So anything heavier than hydrogen and helium we refer to as metals and this is the standard solar abundance. This is what is referred to as the standard solar system abundance. So this is the abundance of elements that we have in the solar system.

And this is the abundance of elements that the sun started out with, but at present the constant burning of hydrogen, the constant through the pp chain, the constant conversion of hydrogen into helium has modified this. So the present abundance is quite different and at present the abundance is around 36% so at present it is around 36% hydrogen at the present.

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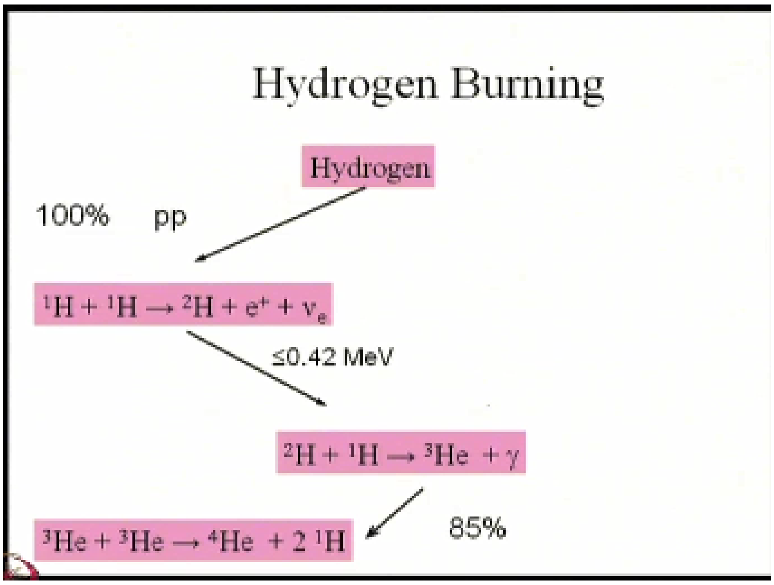

Now the pp chain has several possible pathways. There are a variety of pathways different paths through which the pp chain can finally convert hydrogen into helium and we shall start off by discussing the most probable pathway. So this diagram here shows you the most probable pathway in the pp chain. So you should bear in mind that there are other pathways possible this is only the most probable pathways.

So in this the first step you start with hydrogen and bear in mind that the entire gas inside the sun is ionized. So you have essentially got protons and electrons free. So you start off with protons and 2 protons they collide with each other. We have discussed how this happens essentially you require tunneling. So the 2 protons collide with each other and they form some short live intermediate state unstable intermediate state.

That intermediate state decays and as a consequence of the decay you get this isotope of hydrogen which is called deuteron. So 2 protons produce deuteron. So this is 2H. This is a hydrogen isotope which has got 1 proton, 1 neutron. So you form 1 deuteron nucleus and there are 2 other products which are other particles that are produced in this nuclear reaction. So you have this particle E+ so this is 2H.

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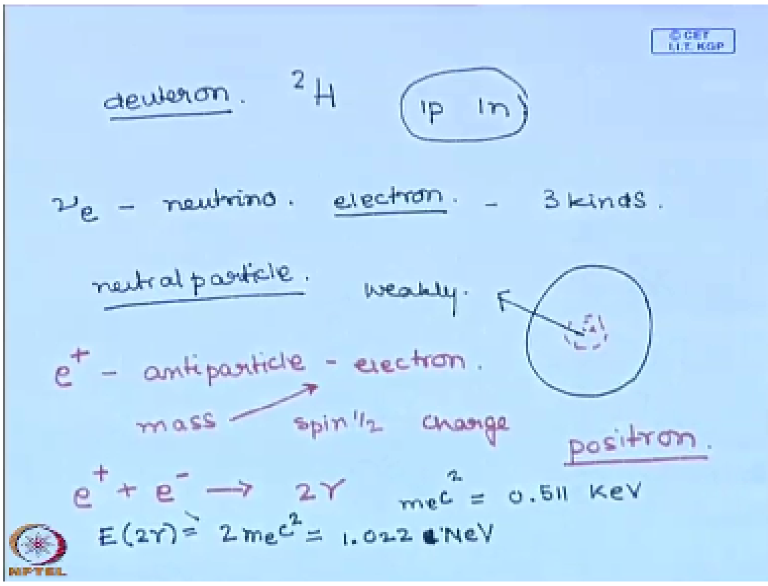

Then you have this particle which is denoted by e+ okay I shall come to this e+ later. You produce this is a positron and you produce a neutrino. So you have this nu e this is a neutrino and this particle is an electron neutrino. There are 3 different kinds of neutrinos, neutrino species which are possible. It is now known that there are 3 different species of neutrinos which are possible and for each different kind of neutrino you also have its associated anti-particles.

So you have 3 kinds. You can have a mu neutrino a tau neutrino or an electron neutrino. And in this reaction there is an electron neutrino that is produced and the neutrino is the neutral particle which interacts weakly with the rest of the material it interacts also through the weak interaction. So the neutrino in all probability just escapes from the interior of the sun and just passes through the entire sun and comes out.

So the energy that is there in the neutrino the energy in the neutrino is somewhere below 0.42 meV mega electron volts and the neutrino which is produced at the core of the sun. So the entire reaction is taking place at the core of the sun somewhere in this region and the neutrino does not interact. It is a very weakly interacting particles. So in all probability the neutrino just comes out.

So the energy which is there in the neutrino is lost. It is not transferred through the rest of the material of the sun. So there is 1 neutrino produced an electron neutrino and the neutrino when it is produced it just goes out of the sun carrying away whatever energy it has and the energy in the neutrino is < 0.42 MeV. It could have spread in value this is the highest value it could have.

So that is one of the products of this reaction of the first reaction in the pp chain where 2 protons combine to give you a deuteron. The other product is a positron. So let me also go through this. So the other product is e+. This is the anti-particle corresponding to an electron. So it has the same mass and it is the spin half particle exactly opposite charge. So it has the same mass. So it mass is that of the electron.

Spin is half and charge is positive exactly opposite that of the electron. And this particle when it is produced it propagates and it interacts with the electrons which are there in the interior of the sun it is ionized inside. This particle is called a positron. It interacts with the material outside it and if encounters an electron and interacts with it then the 2 of them can annihilates and the result will be 2 photons.

And the entire energy in these 2 particles is converted into the energy of these 2 photons. So whatever rest mass is there in these 2 particles and whatever kinetic energy they have is all converted into the energy of these 2 photons, 2 photons are produced. Now the rest mass of electron and positron we know this number. So the rest mass ME C square is 0.511 KeV. The kinetic energy of the typical electron inside is around 1 KeV at 10 to the power 7 Kelvin.

I have told you the temperature inside is around 10 to the power 7 Kelvin. So the kinetic energy of the electron there is around 1 Kelvin which is negligible compared to this. So it really does not contribute. The positron that is produced may have some kinetic energy. So the 2 photons that are produced is roughly > at least 2 ME C square and it is > or =. It is roughly of this order it is 1.022 electron K is MeV.

So these are gamma rays 2 gamma ray are produced and so these particles that are produced these gamma rays. So the positron gets converted into a gamma ray and this gamma ray that is produced basically will again interact with the material inside and transfer whatever energy is there to the material inside it will not escape we have seen that already that the mean free path is extremely small so this photon that is produced inside will transfer all its energy to the material inside.

Similarly, the deuteron atom also if it has any excess kinetic energy it will be distributed amongst the material inside. So energy gets transferred to the material inside in this process.

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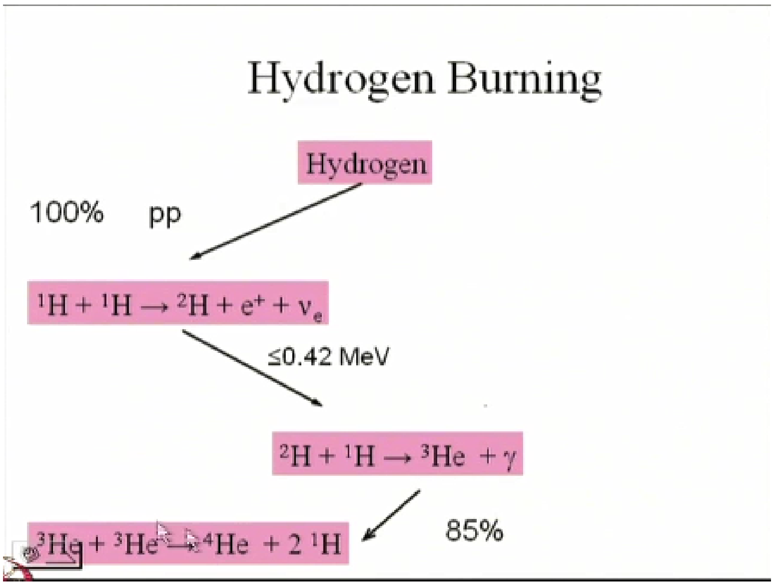

The next stage in this reaction in the chain of reaction. So in the next stage what happens in the next stage this deuteron again collides with another proton. This is hydrogen ion. So this deuteron nucleus again collides with another proton. And as a consequence of this reaction helium is produce an isotope of helium an unstable isotope helium 3 is produced not the most lowest energy one, but isotope with the higher energy helium 3 is produced.

And there is a photon also produced in this reaction. So more energy is released in this reaction and the energy in the photon is transferred to the material inside. So we have produced helium 3 and in the third stage of the reaction what happens is that 2 helium 3 nuclei. So you have one such thing being produced and again the same thing suppose another helium 3 is produced.

So 2 helium 3 nuclei they will collide and these 2 helium 3 nuclei will collide to form a helium 4 nucleus and 2 more protons are released. So this is the most probable chain of reaction in the pp chain. There are other pathways which we shall some of which we shall discuss, but this is the most probable pathway in the pp chain. So let us briefly discuss what is happening? So we have let us just look at this again.

So we have 2 such reactions taking place. So in each of these reactions 2 hydrogen atoms they combine and produce deuteron. Deuteron then produce helium 3 and then you have helium 4 forming. So let us just make a brief summary of what is the N product of this entire chain of reaction. So the N product the final outcome of this entire chain of reaction is that you have 2 hydrogen atoms and then you have 3 hydrogen atoms so 3 protons. So 3 hydrogen atoms and then you require 2 of these reactions.

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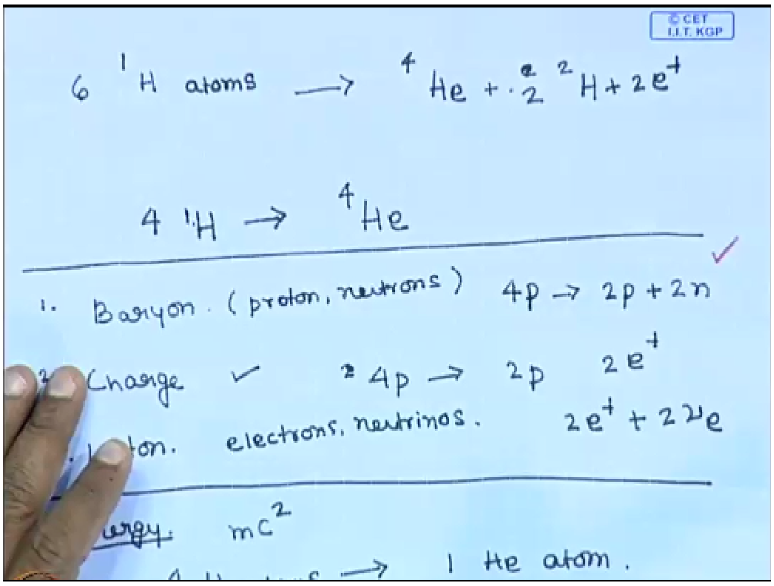

So 6 hydrogen atoms it is only the nuclei which participate in the reaction, but the electron is there. The whole sun as in whole is neutral. So 6 hydrogen atoms to start with and at the end you have 1 helium 4. So these are each one 4 helium and you have 2 hydrogen atoms in addition to this. So you have 2 times 2 hydrogen atom. This is the overall effect. So if you want to really think of the overall effect 4 protons or 4 hydrogen atom, 4 protons get converted into 1 helium 4 that is what happened 4 protons get converted into 1 helium 4.

2 hydrogen atoms here and here you can just forget about this. Okay they are just intermediate. Now any reaction we know any such nuclear reaction or any reaction for that matter is governed by certain conservation laws. So let us see what the conservation laws are here and how they are being actually how the reaction that we have been discussing are quite in keeping with these conversation laws.

So the relevant conservation laws over here let me write it down. So there are 4 relevant conservation laws. The first one is the conservations of Baryon number and Baryons we mean protons neutrons these as Baryons. So let us see if this is conserved. So to start with we have 4 protons. So here we have 4 protons. So we have 4 protons and it goes to 2 protons + 2 neutrons. The helium 4 has 2 protons and 2 neutrons. So we see that the Baryon numbers is conserved.

So we can put a tick mark here. Let us see next. Next let us look at the charge. The charge has to be conserved. So the conservation of charge. So here we have 4 protons which have 4 positive charges. Here we have only 2 protons and 2 neutrons so there is an deficit of 2 positive charges, but these 2 positive charge we know are being carried away by the 2 positrons.

So we have 2 positrons also being produced which are carrying away. So this is also conserved. So 2 protons we have 4 protons and we have 2 protons and 2 positrons. So the charge is also conserved. Then we have the lepton number. So lepton number is associated with the electrons neutrinos etcetera and the anti-particle have a lepton number of -1 the particle has a lepton number of +1 that is the convention.

So let us analyze this reaction. So to start with if you take the protons there are no leptons associated with it. And you finally produce protons neutrinos you also produce 2 positrons which have got negative lepton number, but you also produce the neutrinos. So you produce 2 positrons and you produce 2 electron neutrinos which balance the lepton number. This is an anti-particle which has lepton number -1.

So this is -2 and this has a lepton number +2 so these 2 get balanced. So Baryon number charge and lepton number these are all being conserved in these reactions. You also have the conservation of energy. So you have to bear in mind that when a particle is at rest it has rest mass energy MC square. So any particle at rest has rest mass energy MC square. In addition, it can have more energy if it is moving. Now the total energy is conserved.

Now in this reaction so if you start off with particles which have more rest mass then the N product the difference in rest mass gets converted into the energy which is released to the sun that is the source of energy in this reaction. And in this process one has to also be a little careful and take the electrons into account. So essentially one has to look at the energy difference between 4 hydrogen atoms and the N product is one helium atom that is the energy which is released in this process.

The difference in energy is released actually either in the form of kinetic energy of the N products or through some other particles which carry away the energy and we shall come back to this energy later today. So this covers the main chain of reaction in the pp chain.

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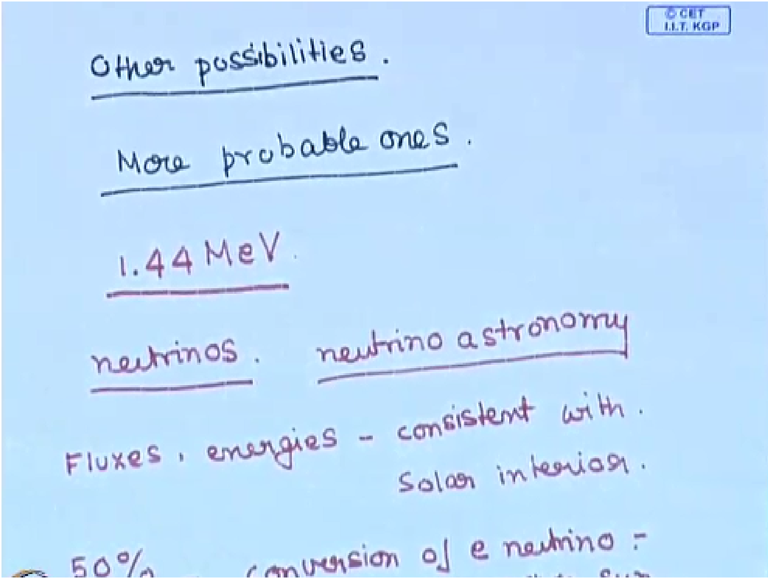

But there are other possibilities. So this is the most probable possibility. There are not one or 2 other possibilities there are many other possibilities. So here we shall only be discussing some of the more probable ones. So the most probable ones we have already discussed. So we will amongst the lesser probable ones we shall be discussing the ones which have still somewhat more probable.

There are many more which are extremely improbable which we shall not be discussing at all. So let me now show you. So there is right at the beginning you want to produce this helium 3. So there is another pathway by which you can produce helium 3 and this pathway is shown over here and this is the PEP chain. So you can go from here to here either through the PEP chain which involves the collision of 2 protons or there is less likely possibility where you have 2 protons and an electron.

So they combine and they combine to produce again the deuteron plus just the neutrino there is no positron here. And there is a neutrino produced in this reaction. The energy of the neutrino is 1.44 MeV and this 1.44 MeV you see the neutrino here has a much lower energy as compared to the neutrino in this. So this 1.44 MeV is easier to detect from the earth. The neutrino we have seen will just come straight out. The neutrino as I have told you will not interact much it will just come straight out.

So we can actually probe these neutrinos from the earth if you have neutrino detectors you can probe these neutrinos from the earth and this 1.44 MeV neutrino high energy neutrino so it is easier to detect the higher energy neutrinos. So this is amenable to easier detection on the earth. So this chain though it is not important for the production of helium 4 or the energy releasing the sun.

It is important if you want to look at the detection of neutrinos and the percentage shown over here essentially tells you what fractions of the helium 4 is produced by this path and what fraction is produced by this path. So you can see that extremely small fraction is produced by this path when you compare to this. So both of these paths give rise to the deuteron and then the deuteron again there are several paths which can occur from here.

So 85% of the helium is produced by the reaction where the helium 3. So this is common to all of them, but 85% of the helium is produced by the mechanism where 2 helium 3 combine to form helium 4 with the release of 2 protons okay 85% of the helium 4 is produced this way, but there are other pathways so let me show you these other pathways. So we are starting from here where you already have helium 3 produced.

So this is the pathway which we have discussed 85% of the helium 4 is produced this way, but there is another pathway here and in this pathway. Okay let me first discuss this pathway. In this pathway, the helium 3 collides with 1 proton straight away to produce helium 4 and in this reaction one positron is released and there is a neutrino released with again high energy 18.8 MeV.

Okay, but this reaction the very small fraction of the total helium is produced in this path very small fraction. So we have discussed this path and this path there is a third path. In the third path, the helium 3 which was there collides with the helium 4 which is already existing and in this collision you form 7 beryllium and photon is released. So 15% of the total helium is produced through this pathway.

Now having reached here there again are 2 paths and the bulk of the reaction in this path occur in this way. So here the beryllium 7 collides with an electron to form lithium 7. It captures an electron to form lithium 7 with the release of 1 electron neutrino and the energy of this neutrino could be either of these 2 values. And then this lithium 7 could again collide with the proton to form 2 helium 4 nuclei.

And in this path the bulk of the helium is produced this way, but again here there is another possibility again a very small fraction goes into this path. Here the beryllium collides with the proton to form Boron 8 and this 8 Boron then becomes beryllium with the emission of a positron and the neutrino this is beta decay and this beryllium then give rise to 2 helium 4 and there are neutrinos emitted in this and these neutrinos the energies are given over there.

So there are a variety of pathways by which hydrogen goes into helium I have told you the most dominant pathway in the pp chain, but then there are these alternatives also which involve beryllium Boron etcetera and there are neutrinos produced in these pathways. And now there is a branch of astronomy called neutrino astronomy very important branch. So the astronomy that we have been discussing till now is all based on the study of electromagnetic radiation from sources, but one could also study neutrinos.

Now this has been possible only in the recent past where you studied neutrinos coming from distant astronomical sources and the sun is the most strongest source nearest and strongest source nearest to us. So much of neutrino astronomy is studying solar neutrinos. So the neutrino astronomy allows you to directly probe the interior of the sun as it is now. The neutrinos are produced in the interior of the sun.

So neutrino astronomy allows you to probe directly the interior of the sun as it is now. The photons produced inside we have seen take around 20,000 years to come out they diffuse out. But the neutrinos they do not interact much they are weakly interacting particles so they come straight out and neutrino astronomy let you probe directly to the core of the sun where the solar where these reactions are going on.

And the fluxes and energies are roughly consistent with our idea of the solar interior which we have just outline the reactions and a long standing 50% deficit. So there was a 50% deficit long standing. This was a big problem in solar neutrino the study of solar neutrino that the neutrino flux was found to be 50% smaller than what is predicted by these calculations. So if you can calculate the rate at which you expect these reactions to produce neutrino it was found that the measured fluxes of 50% less.

This is now understood to be a result of the conversion of electron neutrino to other types. So there are the mu and tau neutrino. So the 50% deficit is now understood to be because of the conversion of electron neutrinos to other type of neutrinos during its propagation inside the sun and most of the neutrino detectors are sensitive to the electron neutrino. So they were missing out the neutrinos.

Because they were being converted into other type into the mu or tau neutrino. So this is also now understood. So I have told you about the main chain of reaction that takes place in the sun where 2 protons collide to form helium.

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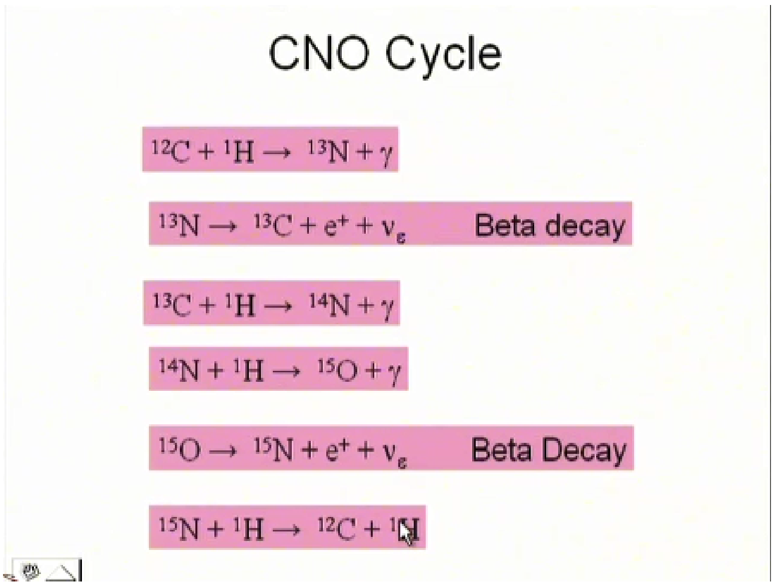

But there is another possibility which is another possible mechanism for the nuclear reaction let me also go through that. That is called the CNO cycle. CNO because this reaction chain of reaction involves carbon, nitrogen and oxygen. So I have told you that the sun has 2% heavy metals so that 2% includes carbon, nitrogen and oxygen. So there is another reaction pathway where the proton can combine with these carbon, nitrogen and oxygen to produce helium.

So let us go through that also. So in this CNO cycle what happens? You start off with carbon 12 colliding with one proton and this produces nitrogen 13 and the photon. Now this nitrogen 13 then does beta decay and in this beta decay it produces carbon 13 and the positron and the neutrino. Now the carbon 13 then collides with the proton to produce nitrogen 14 and photon.

Nitrogen 14 then collides with the proton to give you oxygen 15 under photon.

Oxygen 15 then again does the beta decay it becomes nitrogen 15+ a positron and a neutrino. The nitrogen 15 then collides with the high proton to give back carbon 12 sorry this has been type wrong this should be helium 4. So this 16 so this should be helium 4 not hydrogen. So there is one helium 4.

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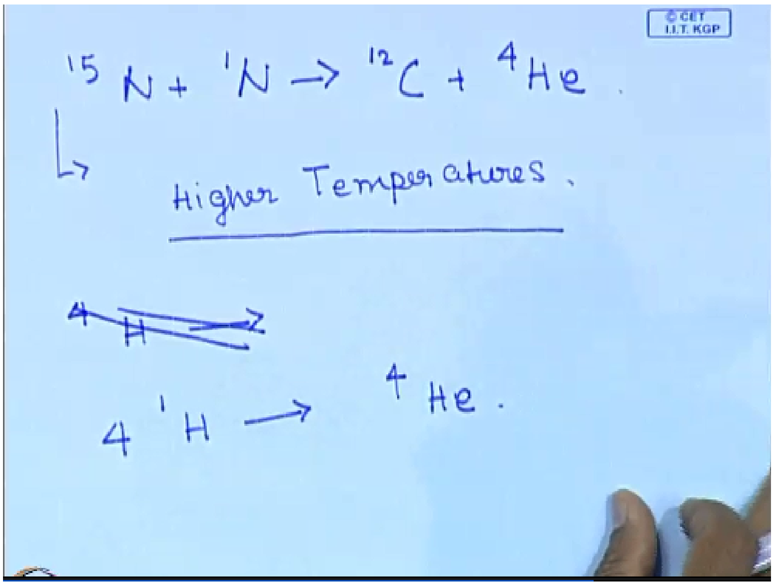

So the last reaction should read 15 nitrogen+ 1 proton this goes to carbon 12 + 4 helium. So please make this correction that is the last reaction in this chain. So the net effect you see is that you start with 4 protons and you produce helium 4. Carbon, nitrogen and oxygen they basically act like some kind of catalyst. They are required for the reactions, but at the end you are back with where you started as far as these are concerned whether the carbon is concerned.

And you end up producing helium from 4 hydrogen atoms. So you have this reaction and this reaction is more effective at higher temperature. We shall come back to this issue. So this is more effective at higher temperature. And stars which are more massive than the sun have higher temperature inside. So CNO cycle is more important if you go to more massive stars.

Stars which are more massive than the sun whereas the pp chain is more important for low mass stars like the sun or even lower masses. So there are these 2 possibilities and if you go to high mass stars. Stars which are considerably heavier than the sun then you have more of the CNO cycle less of the pp chain whereas in stars like the sun you have more of the pp chain less of the CNO cycle.

So in both of these reactions you have 4 hydrogen, 4 proton, you have 4 protons 4 hydrogen atoms going into sorry let me write it correctly so you have 4 hydrogen atoms going into helium 4. So let us see how much energy is released in one such reaction. So we have to look at the difference in masses between this.

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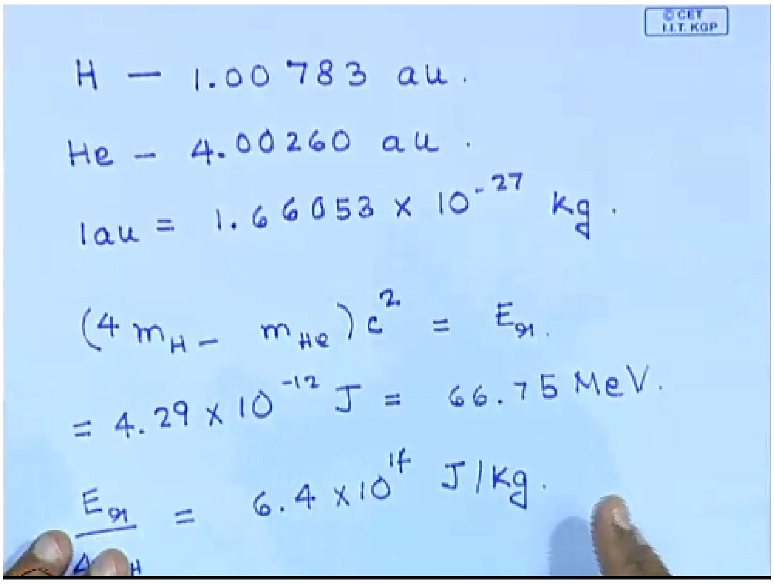

So 1 hydrogen atom has a mass 1.00783 atomic units whereas 1 helium 4 has mass 4.00260 atomic units. One atomic unit is 1.66053*10 to the power -27 kg. So what we have to do is we have to calculate 4 MH –M helium*C square. Like 4 times the mass of a hydrogen atom – the mass of helium and you can see that there is a considerable difference between these 2. This is the energy which is transferred to the material is the sun which is released in this reaction not necessarily transferred.

The part in the neutrino is just lost. The rest of it is transferred to the sun. They also transfer the energy to the sun. But positrons are produced in this. So the energy difference is essentially part of that goes into positrons. So that mass again get annihilated and converted into radiation which is transferred to the sun. At the end you do not have this positron hanging around.

So all the energy in the positron has been converted into the energy of the sun. The electron also get annihilated in that process. One of the electrons is the hydrogen atom. Finally, you start off with 4 electrons you are left only with 2 electrons. So all of that has gone into this.

They are all converted into all of this mass is converted into energy and if you put in the values. I have given you the values here then this comes out to be 4.29*10 to the power -12 joules that is the energy released in one such.

So 4 hydrogen atoms get converted into one helium then this is the energy that is released you can calculate it yourself putting it these values and this is also = 6.75 MeV. Now the quantity which is more interesting is the fraction of the mass that get converted into energy. So let us look at this so we want to calculate this is the energy that is released and divided by the mass of 4 hydrogen atoms.

So this is the ratio of the energy that is released to the mass that you started with and this comes out to be 6.4*10 to the power 14 joules per kg. So if you take 1 kg of hydrogen and put the entire 1 kg through the pp chain or the CNO cycle you will produce 6.4*10 to the power 14 joules of energy. It is an enormous amount of energy and just if you just make an estimate 10 grams of hydrogen are sufficient to provide all the fuel that an individual living in an advanced country.

In India, our fuel consumption is extremely small, but 10 grams of hydrogen is adequate to produce all the energy that an individual living in a developed country requires in his entire lifetime okay just 10 grams of hydrogen. So you will appreciate how efficient this nuclear fusion is as a source of energy. So if you could have controlled fusion on earth which has not yet been possible, but if it could be achieved then a very small amount of hydrogen would be enough, adequate to provide the energy requirement of the entire arrangement.

What is the sun is now doing? Sun is now providing us the energy, but we are able to tap only a small fraction of it. So this is the energy that is released by 1 such. So per kg if I can take 1 kg and put it through this reaction this is the energy that will be released.

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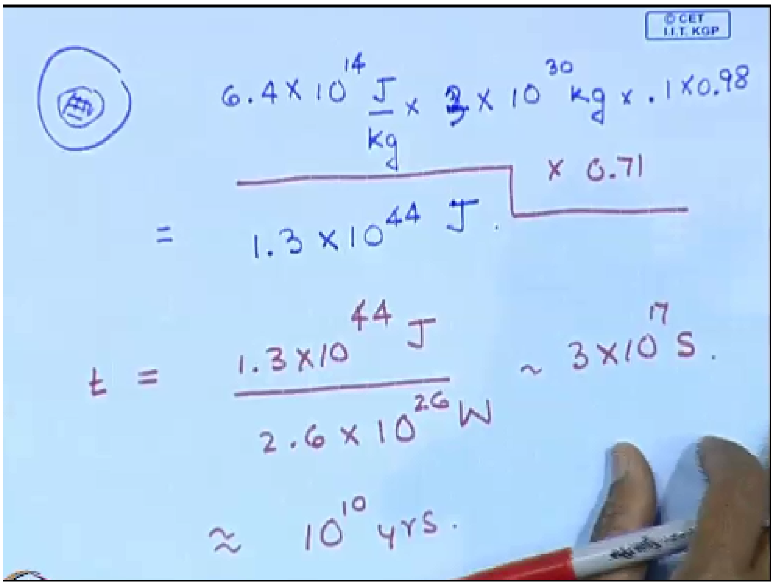

Now let us estimate the total energy that will be released by the sun okay total energy that will be released by the sun. So to do this estimate. So we know the mass of the sun so this is the sun we know the mass of the sun. And but only a small part of the energy is actually going to be burned into hydrogen. So we will assume that 10% in the score gets converted into hydrogen the outer parts do not participate in this reaction.

So the mass of the sun. If I can take 1 kg let us start off this way if I take 1 kg and I will get 6.4*10 to the power 14 joules/kg. The mass of the sun is 3*10 to the power 30 kg. And then 10% so *0.1 and 2% of the energy is lost in the form of neutrinos. So we take another factor of .0.98. This should be 3*10 to the power 30 kg which will give us these many joules that is the joules of energy available.

So what have we done this is the energy that will be released if we can burn 1 kg of hydrogen the mass of the sun is 3*10 to the power 30 and 10% of that in the center is going to get converted into helium and 98% of that is going to get transferred to the sun. There is another factor which I should include and that is the factor of 0.71 because 71% only is hydrogen the rest is helium.

So we have the starting ratio of hydrogen and hydrogen abundance into the mass, into the fraction that can actually get converted into helium the fraction of the center. The fraction of the energy that is transferred into the energy that is transferred for every kilo converted for every kilo. And this if you combine all of these factors you will get 1.3*10 to the power 44 joules.

Now we can now estimate the lifetime of the sun how long do we expect the sun to last. So this will be 1.3*10 to the power 44 joules/ 2.6*10 to the power 26 volts which comes out to be of the order of 3*10 to the power 17 seconds which is of the order of 10 to the power 10 years and which is more than the known age of the solar system 4.5 billion years. So the nuclear fusion the conversion of hydrogen to helium has adequate energy to power the sun for something like 10 billion years.

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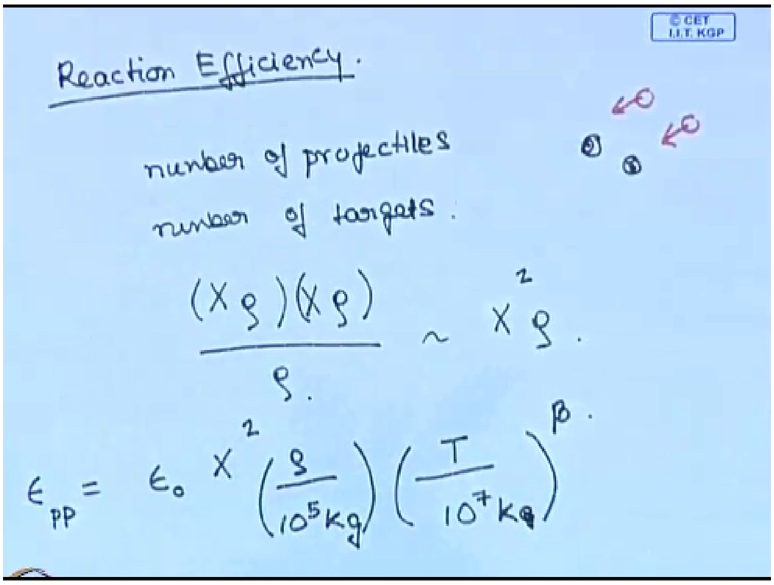

Finally, let us now look at the energy that is released. So the rate the energy release rate, the reaction efficiency or the energy release rate. Now the rate at which energy is released in this reaction that depends on the number of projectiles for any reaction it depends on the number of projectile. So we have these particles the way we think of it we have these particles and there are some other particles incident on them.

So it depends on the number of incident particles and it also depends on the number of targets. So in this case the number of projectiles is the hydrogen abundance for the pp chain let us say. It is a hydrogen abundance into the density of hydrogen and the number of targets is also the hydrogen abundance into the density of hydrogen. So it is proportional to X square rho square.

And if I ask what is the rate at which energy is released per kg of the hydrogen then I have to divide by the density of per kg of the star material then I have to divide by the density so then this is the dependence. So we can quantify the energy release rate in this way that is how it is normally done. So this tell you the rate at which energy is released per kg of the material and it depends on the hydrogen abundance square there is a constant over here roughly constant.

A number which is roughly constant for the temperate range of our interest and it depends on the density at the center of the star and it depends at the temperature at the center of the star in units of 10 to the power 7 Kelvin density in units of 10 to the power 5 kg temperature to the power beta. So temperature dependence is not linear it is sum to the power beta. I have told you that the temperature dependence is a very sensitive dependence on temperature.

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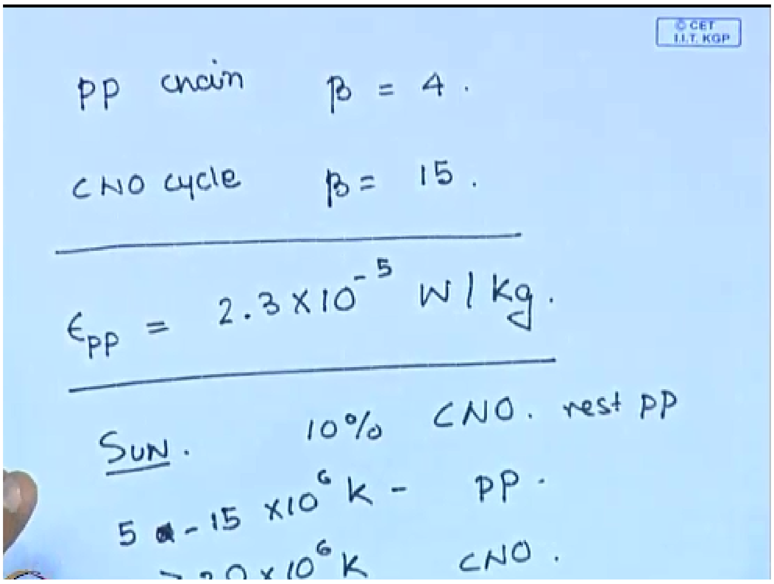

And for the pp chain beta is known to have a value around 4 and for the CNO cycle beta is known to have a value around 15. So the CNO cycle has a very strong dependence. The efficiency of the CNO cycle or the rate at which the energy is released through the CNO cycle has a very strong dependence on the temperature and it become much more effective at higher temperature.

For the sun the value the energy release per the rate at which so this has a value watt per kg. These are for the parameter of the sun which I have already told you in the values. The temperature inside the sun, the density inside the sun etcetera. For the sun 10% of the burning is through the CNO cycle the rest is through the pp chain, but for more massive stars the CNO cycle is much more effective.

And this is where the pp chain is effective and this is dominated entirely by the pp chain and if you have these temperatures it is the CNO cycle. So in more massive stars where the temperature is higher the CNO cycle is much more dominant. So let us bring today's discussion to a close over here. In today's class we learnt essentially the reactions that are responsible for producing the energy in the core of the sun.

And I told you that there are several pathways through which this reaction can take place and I also discuss what is the most dominant pathway that is taking place in the center of the sun.