Nuclear physics Fundamentals and Application
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Lecture - 40
Fusion reaction in stars and stellar neutrinos

So, in the previous lecture I discussed what kind of efforts are being made to create a nuclear fusion reactor in which some isotope of hydrogen will be fused to make heavier nuclei and energy will be produced. This effort is being going on for last 6 decades or so internationally, and still we have not been able to come to a situation where at least the energy which we give to this plasma for heating at least that much should be recovered through this fusion. The best we have achieved so far it is a 60 percent of the input energy that comes as the output.

Of course we are very hopeful coming decades maybe we will be able to create a nuclear fission reactor, but it has been a very difficult task. But just in front of our eyes 8 minutes away from us we have a fantastic nuclear fusion reactor, and that is our sun where so the last 4.5 billion years hydrogen is being fused into helium and energy is being produced, and that energy is responsible for our survival all live form on the earth. So, what goes on inside the sun? How that plasma is confined in that volume for such a long time? What kind of reactions are taking place? What are their rates and so on? So, these are the some of the questions that we will be discussing in this lecture. So, physics of the sun or physics of fusion inside the sun. So, let me show you the basic data on sun that I have put on this power point. So, go to your screens.

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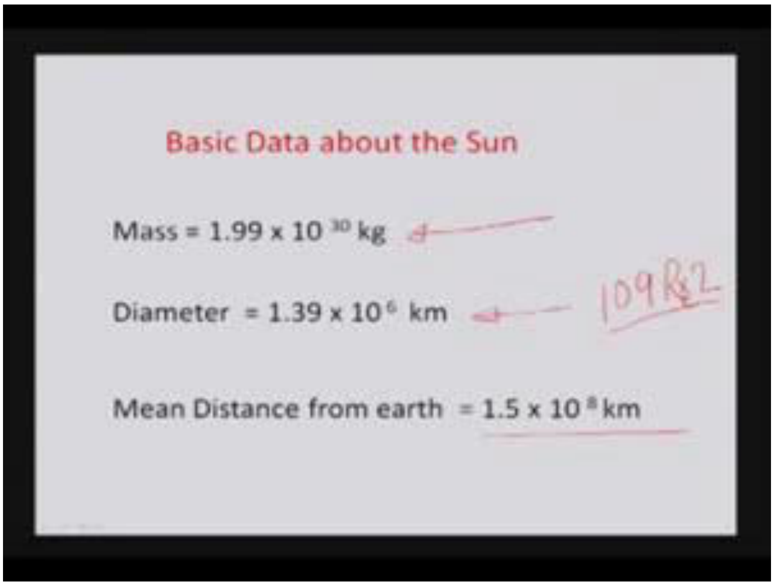

Now, basic data about the sun as you can see here mass is about 2 into 10 to the power 30 kilograms, in compression earth's mass is 6 into 10 to the power 24 kilograms. Then diameter is 1.39 into 10 to the power 6 kilometer which is 109 approximately, 109 times diameter of the earth, 109 is ((Refer Time: 03:10)) close to 108. Suppose to be a very good number in our Indian culture. Then mean distance from earth is 1.5 into 10 to the power 8 kilometers, so there are some of the distances mass.

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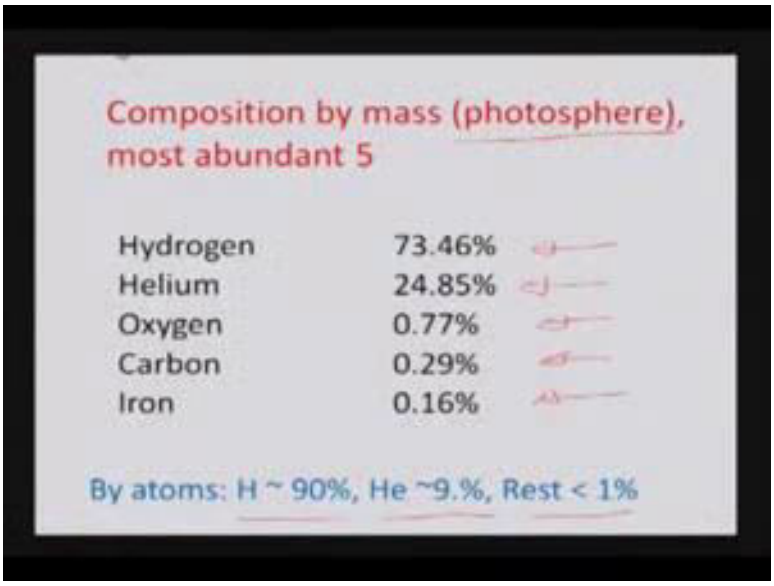

Then, composition by mass, composition of the sun as you know it is all gaseous mass. So, what are the elements in that? And that we I am talking of photosphere; I will talk what photosphere is, it is that outer layer of the sun that we that is visible from earth during day time. So, that is known as photosphere about 500, 400 and 500 thick. So, there the composition is given here 73.46 percent hydrogen, helium 24.85; then oxygen and carbon and iron and many more. So, these are the most abundant 5. If I go by atoms then the number of hydrogen atoms will be more than 90 percent and helium is about 9 percent and rest is about 1 percent.

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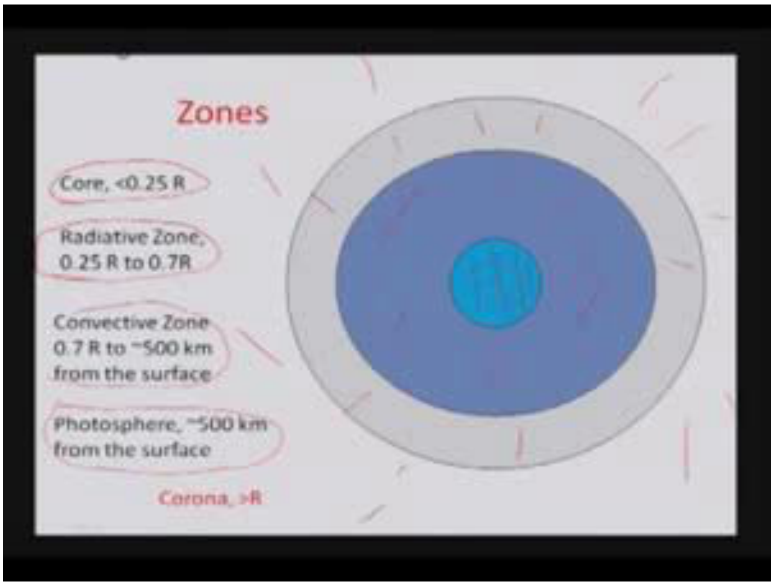

Now, sun the whole mass of the sun which is very nearly spherical; almost in all directions you have the same radius. So, that you can visualize as composed of 3 different zones; one is core which is say up to 0.25 of the radius. So, the central the central here, this is core and most your fusion is taking place inside core up to 0.2 or 0.225 of the radius so that is core. And then the next is this radiative zone. This part is surrounding the core this part is called radiative zone that goes from 0.25r 2.7r. So, this part is radiative zone. I will just talk why this is called radiative and all that? And next is convective. So, this is convictive this is known as convective zone 0.7 r to almost the surface. So, that is known as convective zone and the surface itself and surface would mean something like 400, 500 kilometers that is known as photosphere.

So, you have convective zone and after that you have this photosphere. And beyond photosphere also you have some mass which is not visible from here; the densities are too low though temperature are high those are corona and another things. I will be mostly concentrating on what is going on inside this core. Now, the fusion takes place in the core, energy is produced inside this core fusion energy and that energy gets transported to the surface. And the temperature in the core is 1.5 into 10 to the power 7 Kelvin approximately and that is were of course, that will also vary as you go towards the outer regions of the core; the temperature will be low. But mostly the temperature is around that 1.5 into 10 to the power 7 Kelvin. So, here the it takes place fusion takes place. Now, this energy as it moves outward towards the sun surface there are various phenomena taking place.

So, there the roll of this radiative zone and convective zone. So, initially in the radiative zone you have these photons are emitted and where they very quickly absorbed within few millimeter or so. And then again reemitted; again they go ahead again they are absorbed. So, this way it radiates reradiates absorbs and energy moves a in forward direction. So, that is forward means towards the outer layers. So, that is why it is radiative zone. So, that happens up 2.7 r; in the convective zone it is convection. Convection you are all familiar in school days you have learned what is convection? When you put some water or some liquid on a stove then the lower portion gets heated. And then that lower portion of this material, of this liquid that rises up. And from that upper portion the colder mass that comes down you call them convection currents. And that is how the heat is transferred from one place to the other place.

So, in this convective zone which is 0.7 r too almost the surface that is the heat or the energy is transported in this manner. So, to the masses the three hydrogen helium which is there that mass is they move they make convection current. And take heat from these inner regions to outer regions. And the last 500 kilometer or 400 kilometers photosphere that is what is visible it is transparent to the radiation. So, photons is straight away come from there to the earth; and that is what we known as know as sun light.

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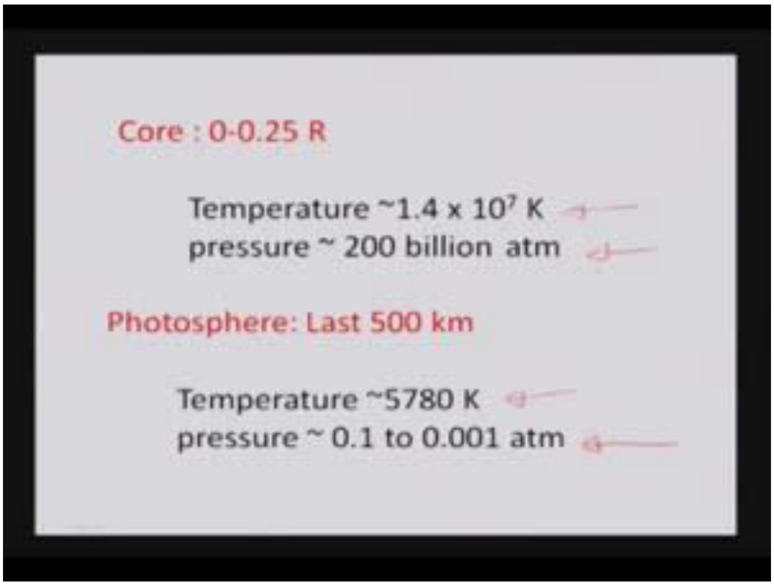

So, in the core the temperature as I said is around 1.5 or 1.4 into 10 power 7 Kelvin. And the pressure of the gas there that is very high temperature is also very high and the pressure is also very high. The density of that gas there is say 160 time the density of water and the normal conditions. So, say 160 grams per centimeter cube. So, that is a kind of density of that gas. And if you calculate the pressure; the pressure at that density you can use p v equal to n r t and pressure will come out to be almost 200 billion atmospheric pressure. So, at that pressure and temperature that gas is confined. And naturally it will all be plasma; all the electrons will be away. And from hydrogen if the electrons are away you have protons. Say you have a mass composed of protons and electrons which is that plasma there helium is of course also there.

And, if you look at the outer surface of the sun which is visible from earth during day time that temperature there is around 5780. So, this is gradient from about 15 million Kelvin to 5000 Kelvin and so on. And pressure of this gas at this in this photosphere that is also very low; the pressure is about say 0.1 to 0.001 atmosphere; lower pressure as you go in the outward layer of this photosphere. So, that is the kind of composition.

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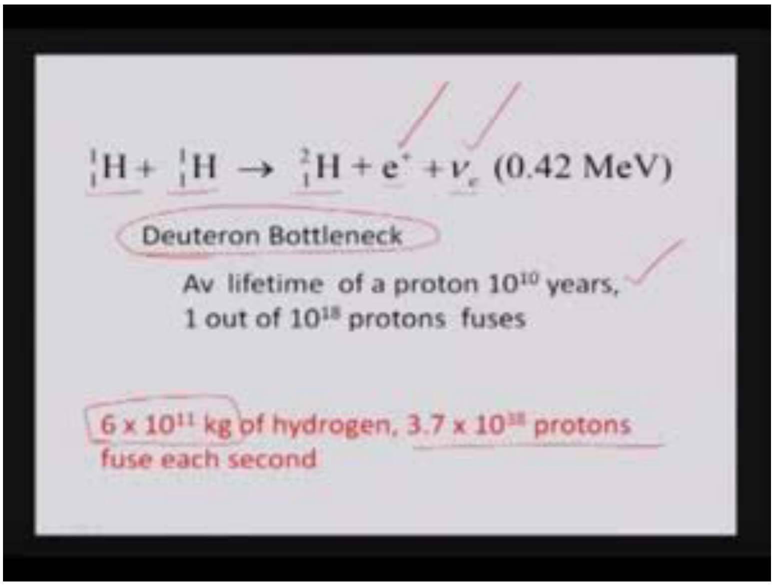

Now, let us come to the fusion; the reaction that is taking place inside the sun. Essentially all fusion events have to start with of fusion of 2 protons. You have large number of protons moving with thermal velocities at that temperature and occasionally 2 protons will come close enough. So, that they interact through this transpose and then combine. When they combine what will happen? Now, of 2 nucleons the only stable nucleus is deuteron. You do not have any di proton, you do not have nucleus of 2 protons or you do not have a nucleus of 2 neutrons; the only nucleus that exist with 2 nucleons is deuteron that is 1 proton and 1 neutron.

So, if these 2 protons are to combine and make 1 nucleus; that nucleus has to be a proton and a neutron. That means, 1 of these 2 protons have to convert itself into neutron simultaneously the 2 protons are fusing to make a bigger nucleus of 2 nucleus. And simultaneously 1 of these 2 protons must convert itself into a neutron. And once proton converts into a neutron you also have a positron created and a neutrino created. So, you have a proton plus proton and that will give you a deuteron and then this positron and then this neutrino. So, 2 process taking together occurring together. One is governed by strong forces; proton and proton they have to interact through strong forces to get into 1 nucleus. And for that typical nuclears time scales are some 10 to the power minus 20 second or so. So, that the time scale in which this reaction will take place.

And, the other part proton converting into neutron that is governed by weak interactions. We have talked about these things little bit a during our beta decay chapter. When proton converts into neutron or neutron converts into proton that is governed by those weak interactions. And they are really weak the time scales you can estimate by saying a lifetime of a free neutron. A free neutron decaying into proton and electron and antineutrino the lifetime is around 14 minutes or so. So, if you convert in seconds it will be something like 800 seconds. So, that is kind of time scale for these weak interaction driven beta decays. But here we are demanding that this must occur during that 10 to the power minus 20 seconds. And therefore the probability of this reaction is very low.

The first step 2 protons fusing into a deuteron and it production of positron and neutrino; that first step is very slow. Because of this demand that this weak interaction driven beta decay must occur together with this fusing of these 2 protons. And it is therefore known as deuteron bottleneck; it is known as deuteron bottleneck. And the probability of this reaction is so small that average lifetime of a proton in that situation lifetime of proton does not I am talking of proton decay or anything. The proton how much it should be the how much time it should be there before another proton comes and makes it a deuteron? So, that lifetime is around 10 to the power 2 years or 1 out of 10 to the power 18 protons will fused extremely low probability.

But still since the total number of proton present it so large. That even at this low probability some 6 into 10 to the power 11 kilogram of hydrogen or 3.7 into 10 to the power 38 protons fuse every second inside the core of the sun. So, that the first to step of this and that makes a deuteron; this first step makes deuteron. What happens after that? As soon as the deuteron is formed and so many protons are there around.

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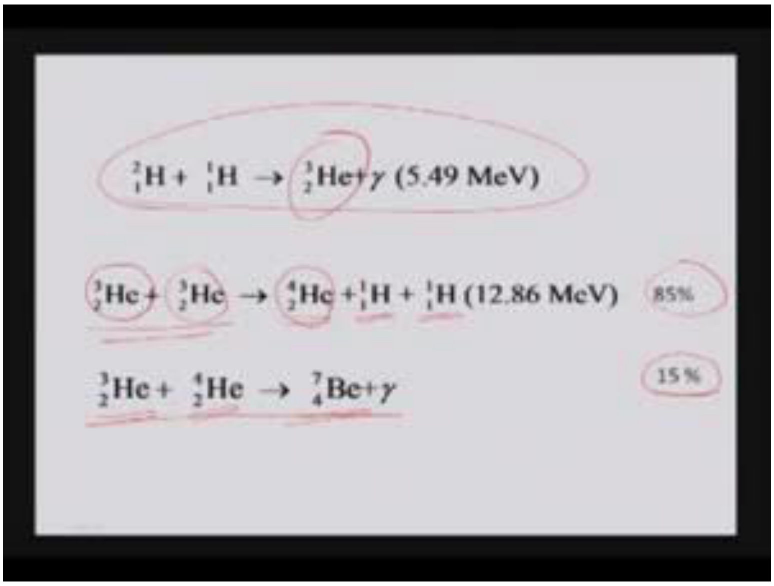

So, this deuteron and proton they will interact and they will fuse strong interaction only no weak interaction coming in. So, quickly it will happen almost in the deuteron find some proton to combine. And then this 3 helium this will be form and of course some gamma will be emitted. Now, what happens after that? After this 3 He what this 3 helium will do? This helium will not be able to combine with 1 more proton because then it will become 4 lithium. 4 lithium will not exist with 3 protons and 1 neutron it will not exist. So, it will combine with the protons; combining with deuteron is most unlikely because as soon as deuteron is formed it is converted into 3 He. So, 3 He finding another deuteron there itself is much less likely.

So, what is the fate of this 3 He; one is this. It has to wait for another 3 He to appear on the scene. 1 3 helium nucleus is formed and then it is wondering thermal motion here there and some other 3 He is formed. And then these 2 nuclei of helium with total number 3; 2 protons and 1 neutron they combine together. And that reaction gives you an alpha particle a helium nucleus and plus 2 protons. And 80 percent of the time this 3 He follows this path; the helium which is created with 2 protons and 1 neutron 84 percent of times it goes through this path and make this helium. What is the other 15 percent? The other 15 percent is that this helium combines with the regular helium 4 He alpha particle; which is already there the in sun this 4 He is already there say 20 percent by mass I said it in the photosphere. And in core it will be even more because for 4.5 billion years hydrogen is being converted into this 4 He.

So, in core you do have this 4 helium nuclei insufficient number and significant numbers as so of this 3 He combines with this 4 He making 7 beryllium. So, that is the there is a another route which happens 15 percent of time 2 helium, 3 helium they combining that happens 85 percent of time. So, if I start with 2 protons fusing making deuteron. Deuteron combining with a proton making 3 He combining with 3 He; another 3 He making an alpha particle. And 2 protons that makes 1 full cycle, 1 full chain which is known as pp 1 chain.

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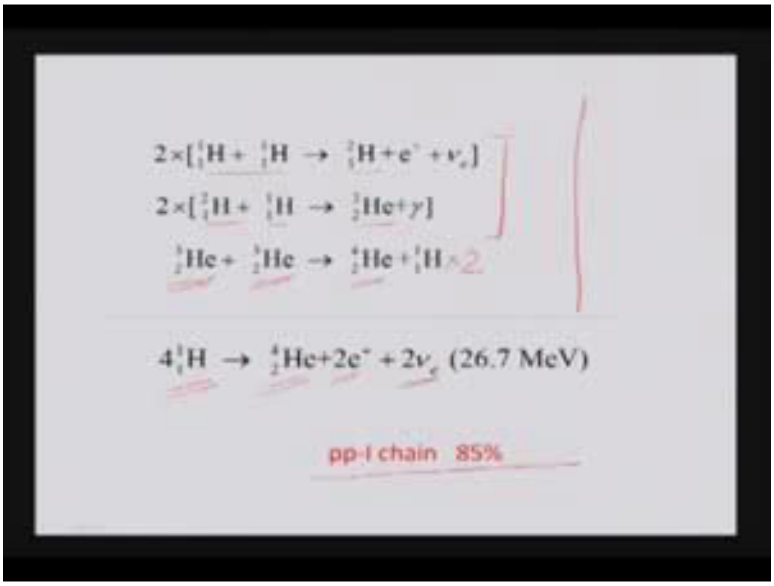

So, here it is 2 protons combining to deuteron and deuteron combining to a proton giving 3 He 2 and 2 such reactions to take place. So, that I have 2 nuclei 3 He 2 here and 3 He 2 here and that makes this helium and plus 2 protons. And then even you combine all these things together you get 4 protons making an alpha particle and 2 positrons and 2 neutrinos. So, this is known as pp 1 chain. And if this 3 helium nucleus combines with 4 helium nucleus that another 15 percent. Then what happens?

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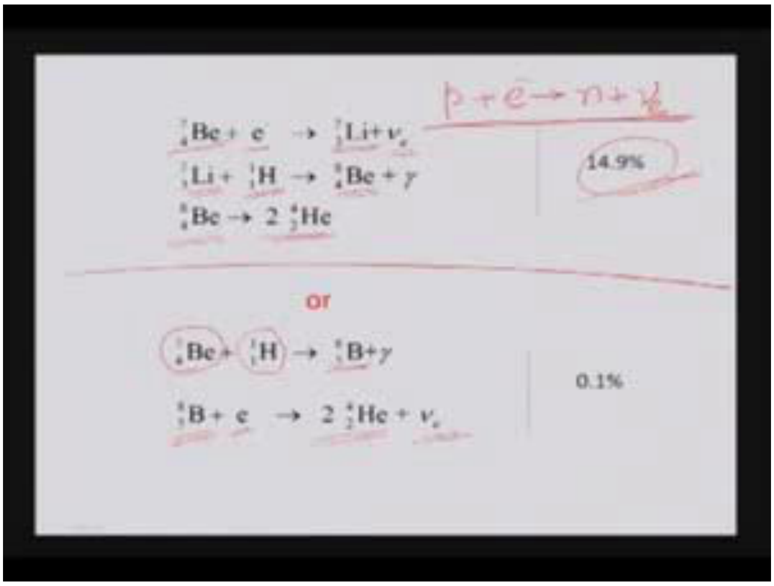

Again, you have 2 different possibilities; 1 possibility is that this 7 beryllium 4; remember this 7 beryllium 4 is coming; when 3 H e combines with 4 He. From there you get this 7 beryllium that 15 percent probability that combines with electron are also there it is plasma. So, electrons are also there. So, that combines with electron and then it is one of the protons and this electron here that is giving you a neutron and this antineutrino. So, you can have this reaction a proton and an electron giving you an neutron and neutrino; usual beta decay you remember proton going to neutron, positron and neutrino. So, from you can bring that positron from the right side to left side and you will get this reaction. So, a proton and this electron they combine to make a neutron. So, 7 beryllium becomes 7 lithium and a neutrino is created. And this 7 lithium then combines with a proton and that gives 8 beryllium which is also a very unstable nucleus; which will be quickly break into 2 alpha particles.

So, this is 1 possibility and the probability of that is say 14.9 percent within that 15 percent. So, 14.9 percent probability is that helium will combine with helium 3 will combine with helium 4 making beryllium 7; and then combining with electron and then combining with proton and so on. So, that whole process 14.9 percent. The other possibility this 7 beryllium that is formed that first combines with a proton and that gives me 8 boron, 1 proton goes here. So, proton number becomes 5 and it is 8 boron. And that 8 boron that combines with electron and that gives me 2 alpha particles and a neutrino;

the probability of this event is 0.1 percent. How do we say this much probability and that much probability?

This is all from calculations computer calculations; we have something which we are receiving from sun; some information, some date we are receiving from sun the light. How much light is coming? What is the composition of that light? What is the wavelength distribution all these things are there? And from these we make this solar model; what must have been going on inside. And we know all the nuclear physics of this fusion. So, combining all these things solar models are created, calculations are made and from there we know that these are the things.

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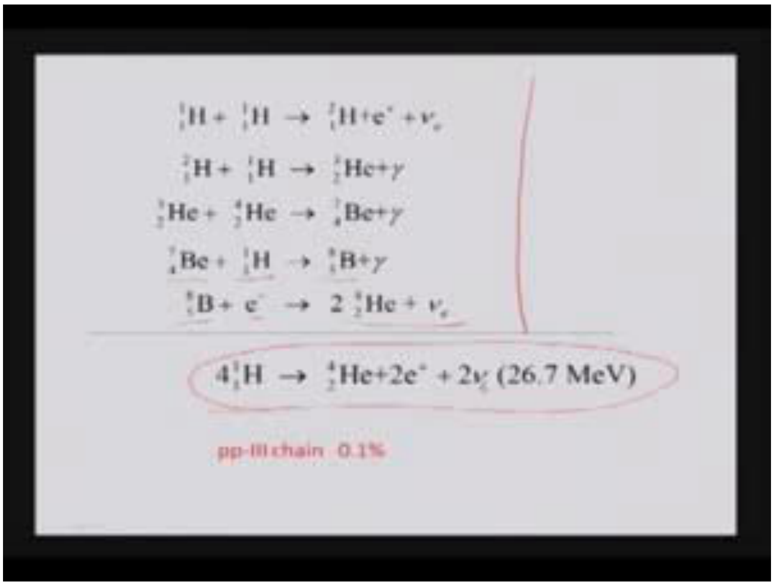

So, that 14.9 percent thing I have collected at one place; starting with proton and proton making deuteron. And that making 3 He; 3 He combining with 4 He that combining with this electron. And finally that combining with this proton and end result is the same. End result 4 proton making helium nucleus and 2 positrons, 2 neutrino; that end result is the same as what we had considered in pp 1 chain. Now, this whole process is known as pp 2 chain. And that 0.1 percent thing where this 7 beryllium is first combining with the proton. So, that is that also I have collected at one place. And so here it is that 7 beryllium combines with a proton giving 8 boron. And that 8 boron combining with this electron making alpha particle and neutrino.

End result is once again same; 4 proton going to a helium 2 positrons and neutrino. This is known as pp 3 chain. There is one more process by which energy is liberated, fusion takes place; 4 protons combined to hydrogen and that is known as carbon nitrogen oxygen cycle c n o cycle not much important for sun. But for heavier stars that c n o is important in sun also about 2 percent of energy is created through that c n o cycle. What is that c n o cycle?

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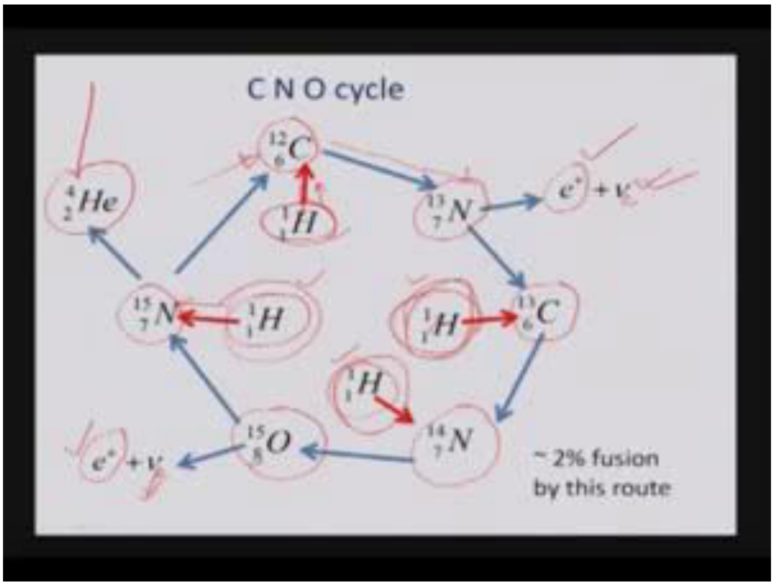

If in this gas, if in this core you already have some carbon nucleus carbon 12. So, if you will be have some carbon there then this c n o cycle can take place temperatures meter are slightly higher. And therefore this process is only 2 percent or less than 2 in the sun at that temperature. But see what is the process? 1 proton going into this carbon combining, fusing what does it make? It makes this 13 nitrogen. So, proton going into carbon already you had 6 protons; 1 more proton going making 7 protons. So, that is why it is nitrogen and total nucleon number capital a was 12; 1 proton going in so that becomes 13. So, it is this 13 nitrogen.

Now, this 13 nitrogen that beta plus decays it gives of this positron and this neutrino; and that this proton becomes neutron. So, it again becomes carbon; from 7 protons it becomes 6 protons because 1 proton becomes neutron. But that 13 remains 13; 1 proton becoming neutron that 13 mass number 13 remains 13. And therefore you get 13 carbon nucleus. To this 13 carbon nucleus 1 more proton goes and combines and then it will again make nitrogen; 6 protons are there 1 proton going on 7 protons. So, that will make nitrogen but now the total mass number will be 14. So, you get this 14 n. And this 14 n combines with another proton here and what will it make? It will make 15 oxygen and 15 oxygen will be beta plus decay. And when it beta plus decays it will give this positron, it will give this neutrino and it will give this 15 nitrogen. So, 1 proton in this oxygen 8 that is being converted into neutron. So, you are getting 7 protons and 8 neutrons and so you have 15 nitrogen. And on this 15 nitrogen when yet another proton goes and hits and fuses then you get an alpha particle and this carbon back. So, we started with carbon 12 nucleus; total mass number 12 and after this whole cycle we created that carbon 12 once again back.

So, carbon is not consumed, nitrogen is created and it is consumed; oxygen is created and it is consumed. So, nothing changes in carbon, nitrogen, oxygen composition. So, essentially when I combine all these things once again the total net result is that 4 protons are being consumed. You can see here the red arrow here 1 proton; 1 proton going here, then 1 proton going here this arrow than 1 proton going here and 1 proton going here. So, 1, 2, 3 and 4; 4 protons are being consumed. And what are output? One area that is alpha particle, that is helium nucleus then you have 1 positron here, 1 positron here, 1 neutrino here and 1 neutrino here. So, it is once again is the same end result 4 protons are being consumed; 1 helium nucleus is formed, 2 positrons are formed and 2 neutrino are formed. So, that is known as carbon nitrogen oxygen cycle. So, that is how the fusion takes place in the sun.

Now, a very interesting question is that we have done all these calculations, computer calculations, models solar models by which we say that if this the scenario. If energy is being produced by fusion of protons into helium yes this much sun energy I should get at the earth or this should be the wavelength, composition all these things fine. But what is the direct evidence of that? This model fits very well with the of kind of energy we are getting it is good. So, this model is able to explain our observations. But then is there direct evidence is can there will be a separate mechanism different mechanism; which can also give me these results, which can also give me these many joules per centimeter square or per meter square. And which can also give me the same wavelength distribution and all that. How do I know?

That it is because of the fusion that we are getting this energy. The energy that we are getting in the form of sunlight; that is not coming from the fusion. Remember fusion takes place inside the core and from there it goes through the radiative zone and then convective zone and then it comes to photosphere. And the photosphere which is transparent electromagnetic waves. The photons from the photosphere they cross the layer and come to the earth. And passing from core to this photosphere this process may take million years or many 10s of 1000s of years. So, what we are receiving is only remotely connected to the fusion in inside that core; in the radiative region when the photons are absorbed and then remitted and then again absorbed and again remitted at different energies, different frequency and so on. So, what finally comes to photosphere is very different from what was produced inside the core.

And, also since if it takes them 1 million years. So, not only the nature of that radiation is different what has started because of those temperatures and those energies. And what we are receiving here a are visible and ultraviolet and infrared. So, the nature is different. And apart from that not only the nature is different; apart from that what we are getting and its origin if I find it was 1 million year ago. So, today if I am getting these many joules per centimeter square that is related to the event in the court which took place 1 million year ago. As of today how do I even if I understand that it must have been chosen otherwise I will not get this much of energy?

So, how I know that the fusion is still going on in the earth, on in the core? Because in the fusion is in the fusion stops today. We will come to know about it only 1 million year after because it takes that much time. So, what we are getting today was there was created in the core 1 million year ago. Now, direct experimental evidence that comes through those neutrino those 2 neutrinos in all these cycles you so pp 1, pp 2, c n o and all that that two neutrino were created. And those neutrinos we have talked about neutrinos once again in our during our beta decay discussions. These neutrinos very weekly interact with matter. And that is why billions and billions neutrinos keep falling on our bodies and going through our bodies.

And, we just do not notice anything the entire diameter of the earth they cross. And the probability is extremely low; out of many billions 1 neutrino perhaps will interact with the whole mass of the earth. So, these neutrinos which are created in the core during the fusion they directly escape from the core go through all those radiative convective photosphere zone; and come to the earth almost at the velocity of light. Till last decay we thought that they are really moving at the velocity of light. But now we know that maybe they have a very slight mass and velocity is not exactly see the velocity of light in vacuum. I am slightly smaller but still around 8 minutes. So, those neutrinos they escape from the core and they come to earth; they go to in all directions of course they come to the earth.

And, if we trap those neutrinos, if we can study those neutrinos and we have done that; we have it was a very heroic effort of experimentalists. They had trap those neutrinos, they had absorbed that neutrinos and that gives a direct information of what is going on inside the core. So, let us look at the energies of those neutrinos because when we do experiments on the earth to detects these neutrino; and we have to make lots of calculations once again. How this neutrino will interact with the detector material? So, energy of the neutrino is also an important parameter. And we see what kinds of energy distribution of these neutrinos are there?

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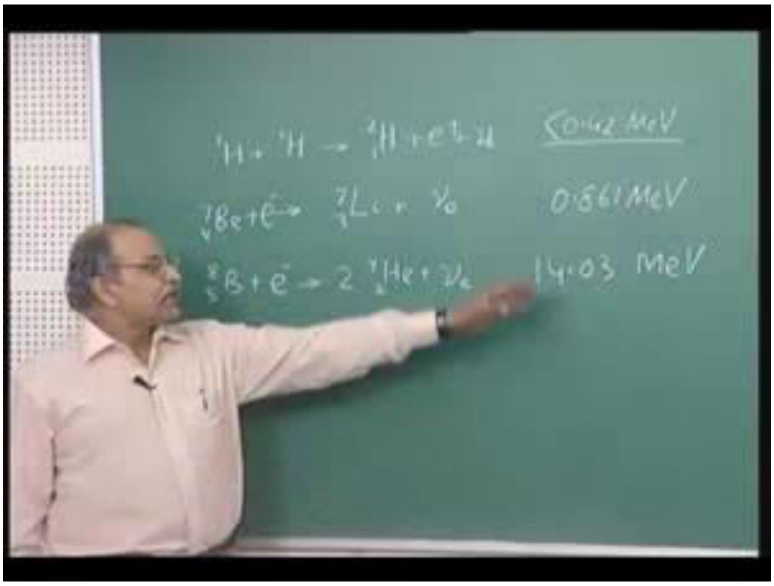

So, if you think of pp 1 chain this neutrinos is produced when this 2 protons combine to make deuteron and the stage this neutrino is produced. If you look at pp 2 chain where 7 beryllium combines with electron and that produces this neutrino here. And in pp 3 you have this 8 boron that combines with electron and that produces this nu e. Here, the energy is 0.42 M e v and has it is shared between this positron and this neutrino. The neutrino energy will vary from 0 to 0.42 M e v; a continuous spectrum of energy that it will show up. And the maximum will be 0.42 m e v that is how the whole concept of neutrino was started in beta decays. Those beta particles where having continuous spectrum of energy and people were not able to understand how come the q value can be calculated accurately? And these beta particles are having energy less than q values. And that to it can vary from 0 to that maximum of q value that is how poly proposed existence of this neutrino.

So, both this positron and this neutrino they will have continuous energy distribution because the total should be given by this 0.42 M e v; barring some recoil energy that might have small energy that might have taken by this 2 H. So, it is a continuous variation. So, that energy is safe less than 0.42 but here in these 2 cases nothing like that whatever is the q value that q value just shared by a very small tiny fraction of recoil maybe here. But almost everything is taken away by this neutrino. So, these neutrino are mono energetic and the energy is 0.861 M e v. And similarly here also this nu e that will take away all the energy that is made available through this reaction and that is 14.03 or so M e v. So, the range are different 0.42 m e v and less that is coming from here. And then 0.861 M e v sharp mono energetic from here pp 2 and 14.03 M e v this.

Now, how people measure it? The first measurement of neutrino rather antineutrino was made long back 1956; but some 26 years after this neutrino thing was conceived. And that was the nuclear reactors. You know in nuclear reactors the fission fragments are neutron rich. And once so the fission fragments are form they beta minus decay neutrons get converted into proton.

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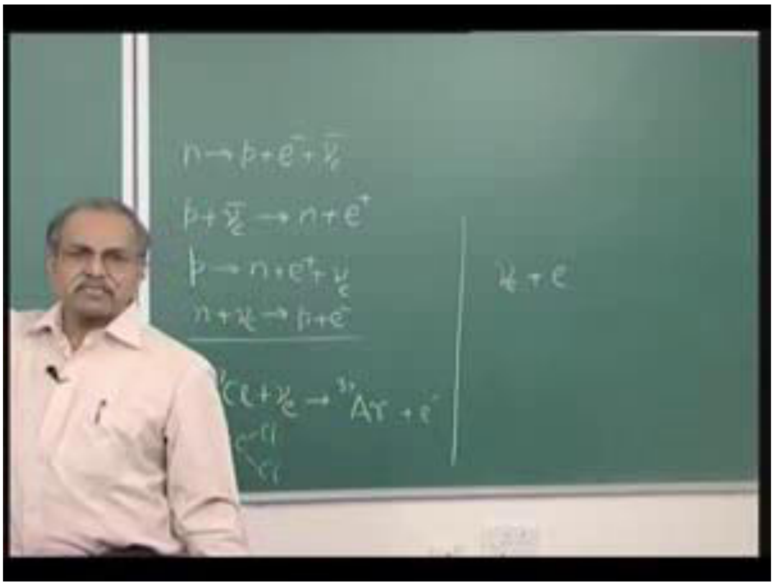

And, in that case when neutron get converted into proton you have electron and antineutrino. So, this rinus group a group that ((Refer Time 40:34)) once minus they made the first experiments to measure these antineutrinos. The thing was coupled with nuclear reactors were neutrino flux was coming. So, if you want to convert this it will be p plus nu e bar be that will give you n and plus e plus. So, these antineutrinos will react with protons to give this reaction. So, the experiment was to have lots of liquid with free protons.

And, this neutrino flux falling on that and vocationally a neutrino depending on what is the reaction cross-section? Once say while a neutrino will attach one of the protons and this reaction will take place. And this positron will be created; one the positron will be created it will move in that material in that liquid and will find some electron. And then they will annihilate and 2 gamma photons of energy around 511 kilo electron volts will be generated. And that can be measured by centiliters in that detector volume. So, that is one; another thing is that this neutron is also produced. And this neutron can be made to get absorbed in some kind of material.

So, in that original experiment it was cadmium chloride mixed in that fluid, in that liquid. So, cadmium is a very good absorber of for neutron you know that. So, this neutron which is created that gets absorbed in to cadmium. And takes this higher isotope of cadmium to excited state. And when that the excites to its ground the state. It gives of a gamma ray of energy about 9 mega electron volts and area should be related. So, appearance of 2 gamma photons of 511 k ev and within microseconds; few microseconds a appearance of 9 M ev gamma. That will give the signal that yes a neutrino has come and interacted. And that is how the first antineutrino where measured.

In case of solo neutrinos it will be different because we do not have antineutrinos; we have neutrinos. And if you look at that reaction p going to n e plus nu from here you can write and n plus nu is p plus e minus. So, this is used for a solo neutrino detection; Davis experiment the famous Davis experiment started in 1964. And first results came in 1968; they using this kind of reaction some chlorine 37 chlorine in cleaning fluids double c2 cl 4; 100 of tons of that will be needed.

So, this fluid in this liquid they and they the whole thing has to be protected from cosmic rays and radiation coming from there. So, this detector was created some 1500 meters below the ground in some kind of a mine in South Dakota. And there they were looking for these reactions. So, this and neutron will into proton. So, that will make 37 argon and plus electron and all that. So, the idea was to search for argon start with the this cleaning fluid this c 2 c l 4. And then wait for some time and after some time somehow separate try to separate argon from there. And see if the argon is there that will give the signal that yes neutrino has been detected. So, it was about say 1 or 2 events in whole day because neutrinos interact so weekly with the material; that with the kind of solo neutrino flux that we are getting the kind of detector they made.

It was expected that some few neutrinos will come in the whole day but years of data collection did established that neutrino are coming from sun. And they are neutrinos not antineutrinos they interact with these neutrons to make protons all this things. But then the number of neutrino was which we are detected was only about one-third of what the solar model calculation. And what the Davis the experimental set up of Davis that calculation all this all this probability reaction cross-section and all that. What was expected number? And what was the observed number? The observed number was only one-third of that, after that several more experiments were done that gallium based detector; where gallium will absorb this neutrino; and will make germanium that was there. Then this camu cande and super camu cande where the scheme was different. They were looking for just scattering of neutrinos from electron just scattering.

So, high energy neutrino comes hits an electron and gets scattered and electron also gets velocity. And electron can get such a larger velocity that would be more than the velocity of light in that medium. And then serenco radiation will be emitted which can be detected and from there this neutrino will be absorbed; that was the scheme there. So, highly pure water detectors were made. And though from those water detectors they try to measure this was sensitive to the lower energy neutrinos also. In the Davis experiment the cross-section sector etc it was dominated by the high energy neutrinos.

So, pp 1 chain those neutron where almost not being counted there but in this experiment the pp 1 neutrinos where also captured. So, here from this experiment the result was that about 60 percent of expected numbers of neutrinos were absorbed. So, consistently all right is of experiments which were then of course not many; they were showing that be the neutrinos which we observed here is less than about half of or about one third of what is expected. If the if we understand what is going on inside the sun. If we understand how this neutrino are interacting in our material? If both this theories are correct; if the experiments are done very carefully the data are analyzed very carefully. Then some neutrinos are missing. And this missing neutrino this problem solar neutrino problem remained there were about 30 years also 3 decades also. And then finally this s n o sudbury neutrino observatory they made experiments; where all these neutrinos were observed.

And, there they could distinguish between what we call electron neutrino and 2 other types of neutrino; muon neutrino and tau neutrino. I am not talk much about that but you know 3 kinds of leptons are they are electron, muon and tau. And associated with each you have corresponding types of neutrinos entry neutrinos. What we had been talking so far; what is being produced in the sun is only electron neutrino. But there are other neutrinos to. And when the other neutrinos can also hit electrons, can scatter electrons, can break nucleus in this s n o experiment you had heavy water was used. So, neutrons where there.

So, these neutrons can hit the neutron and break the neutron and proton apart. So, varieties of reactions where possible. It is scattering with electrons was there an electron neutrino doing this kind of reaction; which we have written on the board that was also possible. And the other neutrino tau and muon neutrino they can also break the neutron giving you proton and neutron. That neutron can get absorbed into some material and the signal from there can also be obtained. So, they could calculate how many electrons neutrinos are coming? And how many total neutrinos are coming? So, that means if you my detector is only sensitive to electron neutrino then I will be detecting this. But if and it is sensitive to the other neutrino; and we are finding a total count which is more than this electron neutrino count tau neutrino and muon neutrinos are also coming.

But they are not produce in the sun because in the sun it is proton going into neutron and so on. These are all they will only give electron neutrino. So, from where this tau neutrino and muon neutrino are coming? And the when the data are combined the total neutrino that are observed in s n o experiment; that total matches very well with the number of electrons neutrino which has been calculated to be there from the sun. So that means, during transit from these sun to the earth. These some of these electron neutrino as changed they are flavor; during this transit some of these electron neutrino had converted themselves into tau neutrino and muon neutrino.

And, that is why the detectors that we are only detecting electron neutrinos they were finding less number of neutrons. This is known as neutrino oscillation. And this the sudbury experiment was announced, results were announced, very conclusively only in 2001. So, it is 1 decay ago into 2001 that this neutrino oscillation has been established; and the problem of missing neutrino which were there for 30 years what was reserved. So, that is all about this is fusion inside the sun energy production inside the sun. Our next lecture will be how new elements are produced in a star; in general all kinds of which we call nucleosynthesis.