Nuclear Astrophysics
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Module – 05
Lecture – 23
pp Chain

Welcome back students, we are in process of understanding the fundamental nuclear reaction in the universe which is responsible for the evolution of stars and production of elements that is p + p reaction. Let me quickly summarize the previous lecture.

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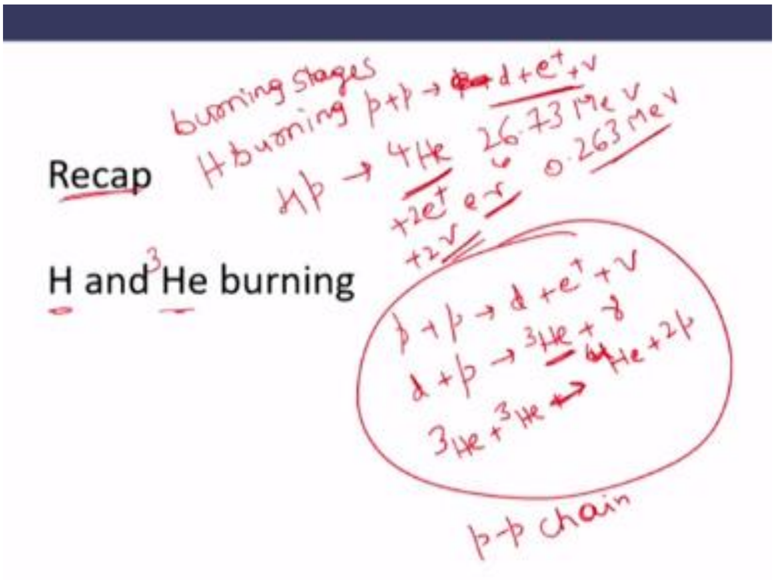

Recap

H and ^{3}He burning

burning stages

H burning $p + p \rightarrow d + e^+ + \nu$

$4p \rightarrow {}^4He + 2e^+ + 2\nu$ 26.73 MeV

e^- 0.263 MeV

$p + p \rightarrow d + e^+ + \nu$

$d + p \rightarrow {}^3He + \gamma$

${}^3He + {}^3He \rightarrow {}^4He + 2p$

p-p chain

In the previous lecture, I have given some pictorial information about the burning stages and then hydrogen burning. As part of that, I have shown you why p + p should go to deuteron + positron + neutrino. Why not ^{2}He or ^{3}Li? Because of the high unstability, so, with those reasons, we have concluded that the fusion of 4 protons into ^{4}He whose overall Q-value is 26.73 MeV.

And, the effective is 26.2 MeV. So, I have calculated the effective energy produced in the fusion of 4 protons into ^{4}He. And, by taking some realistic values of the luminosity of the Sun and mass of the Sun, we have seen that Sun is a middle aged star.

But, remember, that requires the fact that the burning is taking place at the center of the Sun where about 10% of hydrogen is there. And, we have done some calculations in the previous lecture. Let us see some more features of this p + p reaction and then also the burning of deuterium and the burning of helium if time permits. But, mainly, we will see the burning of deuterium.

I mean burning of hydrogen and then burning of deuterium and then burning of ^{3}He because deuterium and ^{3}He are produced in this p + p reaction. So, when I say here helium burning here I am talking about the mass number 3. Please remember, initial reaction is p + p. It gives deuterium + proton + neutrino. And then, this deuterium is interacting with another proton through electromagnetic force which gives ^{3}He + gamma ray.

And, ^{3}He produced in another reaction reacts with ^{3}He produced in this reaction to produce ^{4}He and 2 protns. So, this is basically pp chain. And, this is basically pp-I chain. Then, we have pp-II and pp-III also. That I will discuss in the next lecture. Maybe if time is not possible.

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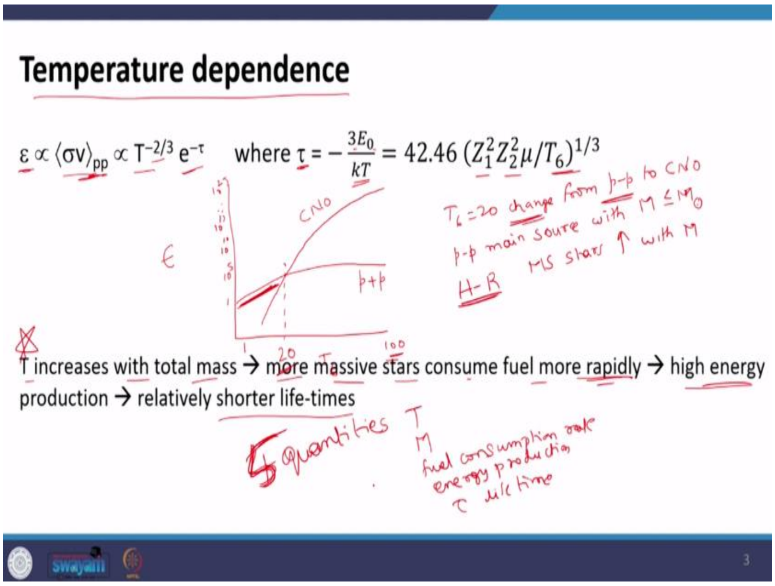

Temperature dependence

$\varepsilon \propto \langle \sigma v \rangle_{pp} \propto T^{-2/3} e^{-\tau}$ where $\tau = -\frac{3E_0}{kT} = 42.46\,(Z_1^2 Z_2^2 \mu / T_6)^{1/3}$

$T_6 = 20$ change from p-p to CNO

p-p main soure with $M \leq M_\odot$

H-R MS stars ↑ with M

T increases with total mass → more massive stars consume fuel more rapidly → high energy production → relatively shorter life-times

5 quantities T

M

fuel consumption rate

energy production

τ life time

So, as I said, now, it is time to understand the dependence of temperature on the reaction rate when p + p are involved. Earlier, if you remember while discussing the non-resonant reactions, I have shown you that energy produced in this non-resonant reaction is proportional to the reaction rate. And, this is proportional to $T^{-2/3}$ $e^{-\tau}$ where $\tau = -\frac{3E_0}{kT} = 42.46\,(Z_1^2 Z_2^2 \mu / T_6)^{1/3}$.

So, this is a formula we know where the reaction rate is related to the temperature. So, if we try to see the dependence of energy on the temperature, we can draw like this, quite interesting diagram (refer to the above slide). So, this is the energy produced. And, this is the temperature starting from say 1 to 100.

So, one can say that the energy produced in this p + p reaction when temperature T_6 is changing from 1 to 100. Whereas, if you see another reaction set which is responsible for the production of ^{4}He that is CNO cycle whose details I will discuss very soon. You can see that up to $T_6 = 20$ it is the p + p reaction which is playing important role for the energy production.

So, at $T_6 = 20$, the change is taking place from pp chain to CNO. pp chain involves 4 protons overall. And, we can say that pp is main source for Sun and stars with mass less than or equal to mass of the Sun mainly. And, in HR diagram, if you remember, the temperature of main sequence stars increase with mass. So, based on this, we can say that the temperature increases with total mass. That is quite natural to understand.

That means more massive stars consume fuel more rapidly. The mass is more the fuel consumption is happening with better rate that leads to higher energy production. However, this kind of stars will have shorter lifetimes. So, this should highlight the relation between temperature and fuel consumption rate, energy production and lifetime. 4 quantities are involved here.

In this statement, 4 quantities are there. Number 1, temperature; number 2, mass; and, number 3, fuel consumption rate; number 4, energy production. I mean, actually, 5 quantities energy production and lifetime. So, how these 5 quantities are related to each other? We can understand from this dependence of reaction rate on the energy production and keeping in mind the value of masses from the HR diagram or mass luminosity relation.

So, that is a reason initially I have spent some time on the relation between mass luminosity temperature and spectral color in terms of HR diagram. So, understanding of HR Diagram plays very important role to know different features of nuclear burning stages. Let us continue.

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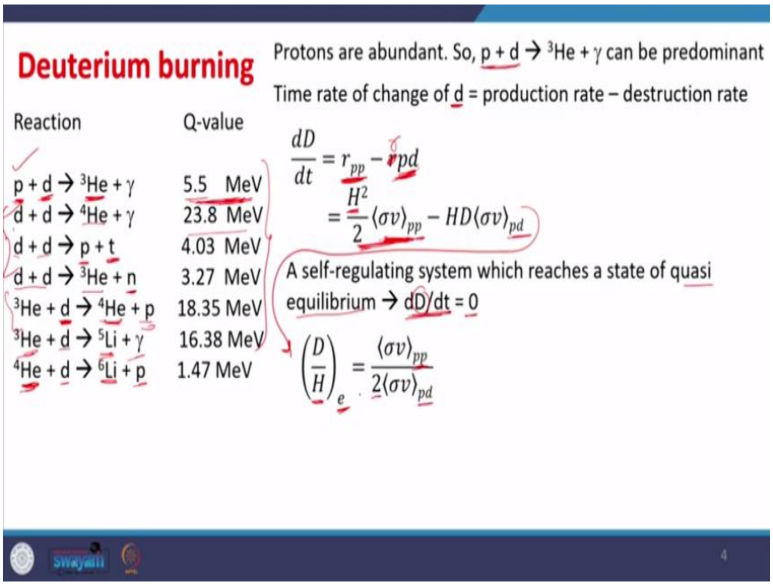

Deuterium burning

Reaction	Q-value
$p + d \rightarrow {}^{3}He + \gamma$	5.5 MeV
$d + d \rightarrow {}^{4}He + \gamma$	23.8 MeV
$d + d \rightarrow p + t$	4.03 MeV
$d + d \rightarrow {}^{3}He + n$	3.27 MeV
${}^{3}He + d \rightarrow {}^{4}He + p$	18.35 MeV
${}^{3}He + d \rightarrow {}^{5}Li + \gamma$	16.38 MeV
${}^{4}He + d \rightarrow {}^{6}Li + p$	1.47 MeV

Protons are abundant. So, $p + d \rightarrow {}^{3}He + \gamma$ can be predominant

Time rate of change of d = production rate – destruction rate

$$\frac{dD}{dt} = r_{pp} - \overset{\sigma}{r}pd$$

$$= \frac{H^2}{2}\langle\sigma v\rangle_{pp} - HD\langle\sigma v\rangle_{pd}$$

A self-regulating system which reaches a state of quasi equilibrium → dD/dt = 0

$$\left(\frac{D}{H}\right)_e = \frac{\langle\sigma v\rangle_{pp}}{2\langle\sigma v\rangle_{pd}}$$

Once p + p the first reaction in pp chain is giving rise to deuterium + positron + neutrino whose Q-value is 1.44 MeV including the annihilation energy. Now, it is time to understand the deuterium. Deuterium is produced. It has to be destroyed. The production of deuterium is because of this reaction. What about the destruction? Let me show you some reactions which are important for the destruction of the deuterium.

So, the reaction and corresponding Q-value let me inform you here. The reaction which is well known as part of pp chain. That is whatever deuterium is produced will interact with another proton to give rise to the ^{3}He and gamma ray. The Q-value is about 5.5 MeV. What does it mean my dear? If you measure this reaction of proton and deuterium, then you can detect gamma rays.

The gamma rays energy will be 5.5 MeV around it. And then, the deuterium can also be destroyed by reacting with deuterium produced in another p + p reaction. So, then, this deuterium can be destroyed by this reaction where ^{4}He is produced Q-value is 23.8 MeV. And, the reaction between deuterium and deuterium can also lead to proton and tritium. The deuterium can also be destroyed with the same reaction of d + d producing ^{3}He.

But, giving rise to neutron, this is also possible. Another possibility is when p + d is giving rise to ^{3}He, that ^{3}He can react with the deuterium I mean overall whatever deuterium is present they can undergo reaction with either proton or deuterium or ^{3}He. These are the available nuclides which gives rise to alpha particle and proton. So, these are some of the possible reactions for destruction of the deuterium.

The production of the deuterium is because of p + p. That is clear to us. Another reaction which is possible is deuterium by reacting with ^{3}He it does not give you alpha particle + proton, but it may give ^{5}Li and gamma. All these are remember exothermic reactions. And one more reaction, deuterium can also interact with the alpha particle, ^{4}He which is outcome of a fusion of 4 protons and to give rise to ^{6}Li and proton. This also is exothermic reaction.

So, remember, in all this, which is more probable? The question is which is more possible more probable? See, in this, because protons are abundant when compared to other nucleus naturally we can say that the predominant reaction is p + d only because when compared to proton no other element is more abundant. So, it is time to understand the time rate of change of deuterium.

So, it means production rate minus destruction rate. Production rate is reaction rate is r_{pp}. Destruction rate, this I should write as r_{pd}. Production rate is because of p + p reaction. Now, this one can write in terms of atoms as H^2 because identicalness is there.

And, $\frac{H2}{2}\langle\sigma v\rangle_{pp}$ is the expression for total reaction rate. And, you know the relation between reaction rate per particle pair and a total reaction rate in terms of number density. Please write down for both p + p and also p + d. Now, $\frac{dD}{dt} = rpp - rpd = \frac{H2}{2}\langle\sigma v\rangle pp - HD\langle\sigma v\rangle pd$ represents a self-regulating system and which reaches a state of quasi equilibrium kind of thing which means that dD/dt = 0.

See the capital D and small d they are not very much different. Only thing is that from nucleus to atom state I have represented. Now, from this, one can say dD/dt = 0. This expression gives rise to this expression, $\left(\frac{D}{H}\right)_e = \frac{\langle\sigma v\rangle pp}{2\langle\sigma v\rangle pd}$. The ratio of deuterium and hydrogen at equilibrium depends on the reaction rates were 2 is in the denominator.

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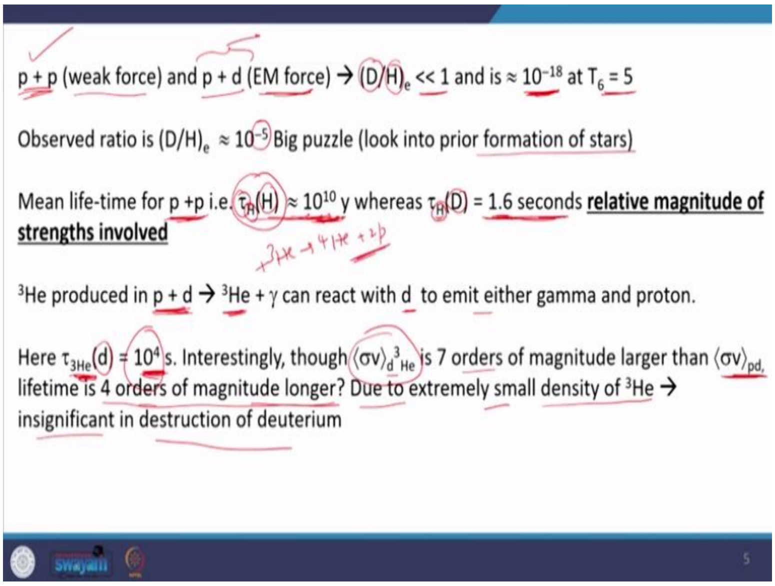

p + p (weak force) and p + d (EM force) → $(D/H)_e$ << 1 and is ≈ 10^{-18} at $T_6 = 5$

Observed ratio is $(D/H)_e \approx 10^{-5}$ Big puzzle (look into prior formation of stars)

Mean life-time for p +p i.e. $\tau_H(H) \approx 10^{10}$ y whereas $\tau_H(D)$ = 1.6 seconds **relative magnitude of strengths involved**

$+ {}^3He \rightarrow {}^4He + 2p$

^3He produced in p + d → $^3He + \gamma$ can react with d to emit either gamma and proton.

Here $\tau_{3He}(d) = 10^4$ s. Interestingly, though $\langle \sigma v \rangle_{d\,^3He}$ is 7 orders of magnitude larger than $\langle \sigma v \rangle_{pd}$, lifetime is 4 orders of magnitude longer? Due to extremely small density of ^3He → insignificant in destruction of deuterium

Now, let us see some more features of this D/H ratio. See, p + p reaction is not via electromagnetic or nuclear interaction. It is via weak force whereas p + d is because of EM force. Why I am discussing this reaection? Because it is the reaction which is responsible for the production of deuterium and this is responsible for the destruction of the deuterium. And, we are trying to understand the overall mechanism of the detail deuterium production and destruction.

And, considering the strength of these 2 forces, naturally, weak force when you take the production, it is very less. So, the D/H is much less than 1. Why? This is a weak force and, the other is the electromagnetic force which is stronger. So, the ratio will be less than 1 only. That is what I have written here. And, it is of the order of 10^{-18}. It is much less than 1.

If you take in terms of reaction rate, the ratio is 10^{-18} at T_6 is equal to 5. Now, the interesting feature is that observed D/H ratio is 10^{-5}. If you measure the reaction rates individually for p + p, of course which is not possible to measure experimentally theoretical one. And then, p + d reaction rate can be measured. There is no problem because it is via electromagnetic interaction.

It was about 10^{-18}. Whereas, observed D/H ratio if you take the abundance, it is 10^{-5}. Why so huge difference? This is one of the interesting puzzles in nuclear astrophysics on which work is going on. So, one has to look into the production of deuterium prior to the formation of stars. We have to go before the formation of stars stage so that whether deuterium is available at that time.

Otherwise, observed deuterium why it is so high. Now, let us see, what is the lifetime of this p + p reaction? As we discussed earlier, it is about 10^{10} years. Lifetime of hydrogen while reacting with another hydrogen is about 10^{10} years whereas lifetime of deuterium while reacting with hydrogen. Why not others?

Because we have seen hydrogen is abundant. So, other reactions are not very important. It is just 1.6 seconds. See 10^{10} years and 1.6 seconds. This is just nothing this highlights the importance of relative magnitudes of the interaction mechanisms p + p is proceeding through weak interaction and p + d which is reason for the destruction of deuterium is proceeding through electromagnetic interaction.

And, lifetimes are 10^{10} years and 1.6 seconds. So, the relative magnitude of strengths involved shows this you know reflects the difference in this lifetimes. Now, once ^{3}He is produced in p + d, it can react with deuterium to emit either gamma or a proton. Now, after this deuterium, I am discussing about the ^{3}He. Now, this deuterium if it reacts with ^{3}He, earlier I have discussed deuterium with proton.

Now, if we discuss it interacts with the ^{3}He, then it comes out that the lifetime is about 10^4 seconds. Now, please listen to me carefully though the reaction rate between ^{3}He and deuterium is 7 orders of magnitude larger than this pd reaction. pd reaction lifetime is 1.6 seconds and ^{3}He + d reaction is 10^4 seconds, so, about 7 orders of magnitude larger.

However, lifetime as expected it is not much lower whereas it is 4 orders of magnitude longer. I repeat when the deuterium is undergoing destruction via different mechanisms, we have concluded that let us take the only one reaction that is deuterium is undergoing destruction by reacting with proton. And, we have seen its lifetime is 1.6 seconds. Just for the sake of convenience, I am taking another reaction.

Deuterium is reacting with ^{3}He. The reaction rate is 7 orders of magnitude larger. The lifetime is 4 orders of magnitude longer, 10^4. So, due to this extremely small density of ^{3}He, we can see that the lifetime is 4 orders of magnitude longer though reaction rate is 7 orders of magnitude longer than the pd reaction.

I hope you are able to understand what I am trying to say because of the extremely low availability of ^{3}He lifetime is much longer. And, that is the reason it is insignificant in the destruction of deuterium. So, because in this previous reaction the dominant reaction is p + d which is giving rise to ^{3}He. And, this ^{3}He is reacting with another ^{3}He to produce ^{4}He + 2p completing the chain.

The time has come to understand the mechanism of destruction of ^{3}He. With that we can complete the pp-I chain. Let us see.

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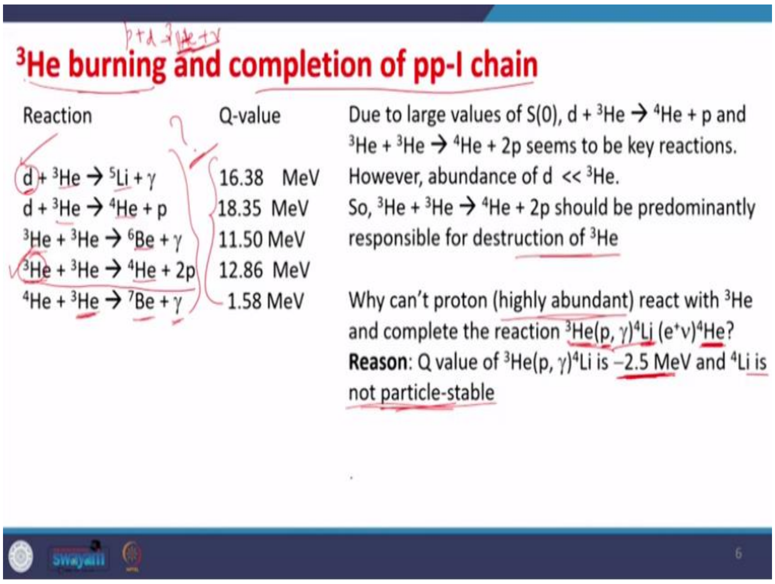

$p + d \rightarrow {}^{3}He + \gamma$

^{3}He burning and completion of pp-I chain

Reaction	Q-value
$d + {}^{3}He \rightarrow {}^{5}Li + \gamma$	16.38 MeV
$d + {}^{3}He \rightarrow {}^{4}He + p$	18.35 MeV
${}^{3}He + {}^{3}He \rightarrow {}^{6}Be + \gamma$	11.50 MeV
${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$	12.86 MeV
${}^{4}He + {}^{3}He \rightarrow {}^{7}Be + \gamma$	1.58 MeV

Due to large values of S(0), $d + {}^{3}He \rightarrow {}^{4}He + p$ and ${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$ seems to be key reactions.
However, abundance of d << ^{3}He.
So, ${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$ should be predominantly responsible for destruction of ^{3}He

Why can't proton (highly abundant) react with ^{3}He and complete the reaction ${}^{3}He(p, \gamma){}^{4}Li\,(e^{+}\nu){}^{4}He$?
Reason: Q value of ${}^{3}He(p, \gamma){}^{4}Li$ is –2.5 MeV and ^{4}Li is not particle-stable

So, the ^{3}He burning and completion of pp-I chain, so, when I say burning of ^{3}He, how it is produced? Please remember p + d giving rise to ^{3}He. This is the production rate. This is a production mechanism. Now, once ^{3}He is produced, in how many ways it can be destroyed? It can undergo destruction by reacting with another deuterium and giving rise to ^{5}Li or ^{4}He.

Or, this ^{3}He can react with ^{3}He again to produce either ^{6}Be or ^{4}He or because in 4 protons fusion ^{3}He He is the end product. That end product ^{4}He it can react with ^{3}He. With that, ^{3}He can undergo destruction giving rise to ^{7}Be and gamma. Remember, all these are exothermic reactions. Now, the question is, which reaction is important and why?

Remember, one has to see the extrapolated astrophysical S-factor values and that shows that ^{3}He + d has large value and also ^{3}He + ^{3}He producing these 2 protons, which is the last reaction in the pp-I chain. These two seems to be key reactions. However, abundance of deuterium is much less compared to ^{3}He. See, directly we are not saying that ^{3}He is produced. So, to produce ^{4}He, it can react with another ^{3}He.

But, why only that reaction? Why not other reactions? For that, those reactions have to be measured. One has to see the S-factor values and extrapolate to zero energy. That gives us an idea which reaction is important and why it is important. Now, because the abundance of deuterium is much less than the abundance of ^{3}He, we can say that the 2nd key reaction that is ^{3}He + ^{3}He is the predominant one in the destruction of ^{3}He nucleus.

So, this is responsible for the destruction of ^{3}He. Now, you can always ask, why cannot proton which is highly abundant, now, I am saying because deuterium is less abundant when compared to ^{3}He the original topic that is destruction of ^{3}He should happen through reaction with ^{3}He only. But, what about protons? Anyway, they are highly abundant. So, ^{3}He should undergo destruction by reacting with proton. What is the problem?

So, this is where it is interesting thing. Look at here. See, because the highly abundant proton can react with the ^{3}He, it will give ^{4}Li but it is highly unstable. It undergoes positron decay. And, it can give rise to ^{4}He. No problem because ^{4}He can be produced by this process also. However, the Q-value of this reaction is negative, -2.5 MeV and ^{4}Li is not particle stable. It is full of nuclear reactions.

Initially, I told you to understand the features of astrophysics and astronomy, the role of nuclear physics comes into picture in terms of nuclear reactions. And, as we are discussing the different burning stages, what are the various types of nuclear reactions coming into picture? So, that is where you need to be clear. Which reaction is exothermic and endothermic?

What reaction is possible to lead to the production of which kind of element? So, this whole story it has to be clear to you. So, go step by step and try to see, which reaction is possible and why? And, which another reaction is not possible and why? So, this is how you can develop interest in terms of understanding this course with the help of nuclear reactions. I hope it is clear to you.

When I say that p + ^{3}He giving rise to ^{4}Li is not possible though at the end we are able to see ^{4}He. It is basically endothermic reaction my dear. And, ^{4}Li is not particle stable. So, that is the reason proton cannot react with ^{3}He and complete the reaction to produce ^{4}He. So, overall, we are in the framework of ^{4}He production from the fusion of 4 protons overall.

Now, let us see the time rate of change of ^{3}He production rate minus destruction rate.

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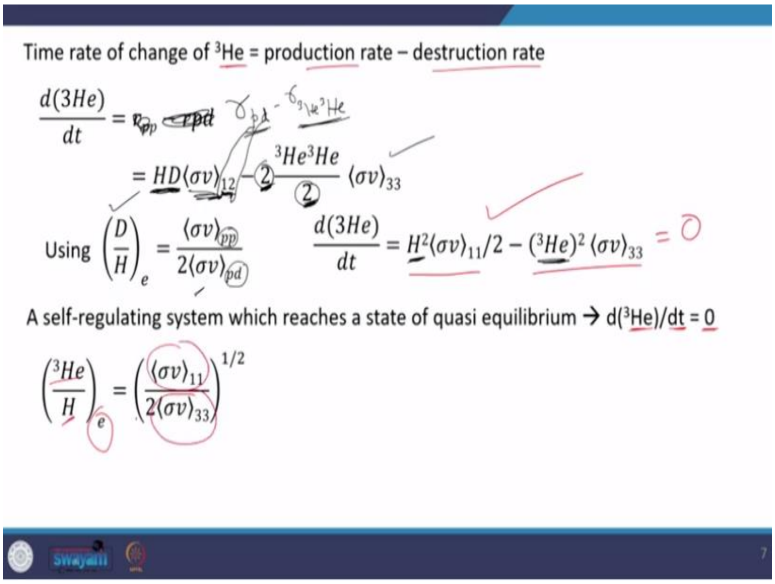

Time rate of change of ^{3}He = production rate – destruction rate

$$\frac{d(3He)}{dt} = \cancel{r_{pp}} - \cancel{r_{pd}} \quad r_{pd} - r_{^3He^3He}$$

$$= HD\langle\sigma v\rangle_{12} - ② \frac{^3He^3He}{②} \langle\sigma v\rangle_{33}$$

Using $\left(\frac{D}{H}\right)_e = \frac{\langle\sigma v\rangle_{pp}}{2\langle\sigma v\rangle_{pd}}$ $\quad \frac{d(3He)}{dt} = H^2\langle\sigma v\rangle_{11}/2 - (^3He)^2\langle\sigma v\rangle_{33} = 0$

A self-regulating system which reaches a state of quasi equilibrium → d(^{3}He)/dt = 0

$$\left(\frac{^3He}{H}\right)_e = \left(\frac{\langle\sigma v\rangle_{11}}{2\langle\sigma v\rangle_{33}}\right)^{1/2}$$

Production rate is because of p + p reaction and earlier I have written this equation. So, basically the production rate minus destruction rate is,

$$\frac{d(3He)}{dt} = r_{pd} - r_{3_{He}3_{He}} = HD\langle\sigma v\rangle 12 - 2\frac{3He3He}{2}\langle\sigma v\rangle 33$$

So, instead of p and d and ^{3}He, I am using the mass numbers in the subscript. Please be careful, this transition from symbols to numbers. And, you know, why 2 in the numerator? Why 2 in the denominator? See, 2 ^{3}He nuclei are involved. That is why in the production of ^{4}He, two ^{3}He nuclei are involved.

That is the reason I am using 2 and because of the identicalness, I am using 2 in the denominator. I hope it is clear to you why 2 is there in the numerator and 2 is there in the denominator. Now, we know that earlier we have established $\left(\frac{D}{H}\right)_e = \frac{\langle\sigma v\rangle pp}{2\langle\sigma v\rangle pd}$.

See here, I am transforming the equation of this $\frac{d(3He)}{dt}$ in terms of $\frac{D}{H}$. And, I am converting finally in terms of only hydrogen and ^{3}He no deuterium here. So, one can come up with this expression, $\frac{d(3He)}{dt} = H^2\langle\sigma v\rangle_{11}/2 - (3_{He})^2\langle\sigma v\rangle_{33}$. Now, as I discussed earlier while talking about the time rate of change of deuterium, this equation represents a self-regulating system which reaches a state of quasi equilibrium.

That is d(^{3}He)/dt = 0. That gives rise to the ratio of ^{3}He and hydrogen at equilibrium, $\left(\frac{^3He}{H}\right)_e = \left(\frac{\langle\sigma v\rangle_{11}}{2\langle\sigma v\rangle_{33}}\right)^{1/2}$. And, this is basically decided by the reaction rate of p + p and the reaction rate of ^{3}He and ^{3}He.

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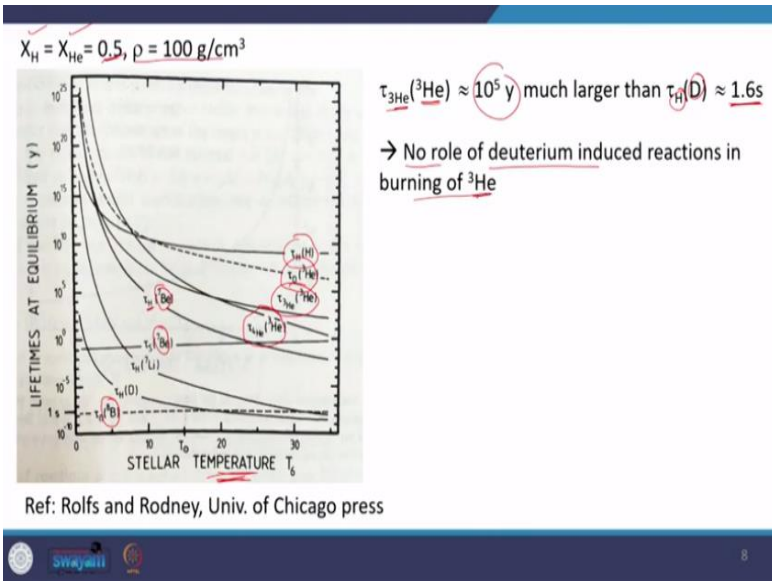

$X_H = X_{He} = 0.5$, $\rho = 100$ g/cm^3

$\tau_{3He}(^3He) \approx 10^5$ y much larger than $\tau_H(D) \approx 1.6$s

→ No role of deuterium induced reactions in burning of ^{3}He

Ref: Rolfs and Rodney, Univ. of Chicago press

Now, let me show you an interesting diagram by considering the mass fraction of hydrogen and helium as 0.5, the density as 100 g/cm^3. I am showing you the variation of lifetimes at equilibrium versus temperature. Please understand. τ_p(p) is the lifetime of the proton against proton, τ_d(^{3}He) is the lifetime of ^{3}He against deuterium. τ_{3He}(^{3}He) is the lifetime of ^{3}He against ^{3}He. And, τ_{4He}(^{3}He) is a lifetime of ^{3}He against ^{4}He.

Similarly, you can see the decay lifetimes when ^{8}B is undergoing decay and ^{7}Be which is undergoing decay. That is the reason it is almost a straight line the lifetime. And, what is the lifetime of ^{7}Be when it undergoes destruction with proton? So, we have considered different lifetimes of different kinds of reactions at different temperatures.

Now, the point which is of our interest from this diagram is the lifetime of ^{3}He against the destruction of ^{3}He is about 10^5 years whereas the lifetime of a deuterium against proton earlier I have shown you it is 1.6 seconds. What does it mean? There is no role of deuterium in these reactions in burning of ^{3}He. So, though initially I have said deuterium abundance is less when compared to ^{3}He. It is the ^{3}He + ^{3}He which is playing predominant role in the destruction of ^{3}He. In terms of lifetime, we can understand that the lifetime of ^{3}He against ^{3}He is 10^5 years whereas against deuterium is about just 1.6 seconds. So, in the destruction of ^{3}He, there is no role of deuterium. So, what all these things tries to convey us?

In the production and destruction of a specific nucleus, what are the nuclides which are playing important role? And, why they are playing important role? So, this is what I am trying to explain you by showing the reaction rate equations for deuterium and for the ^{3}He. So, I hope it is clear to you from this diagram.

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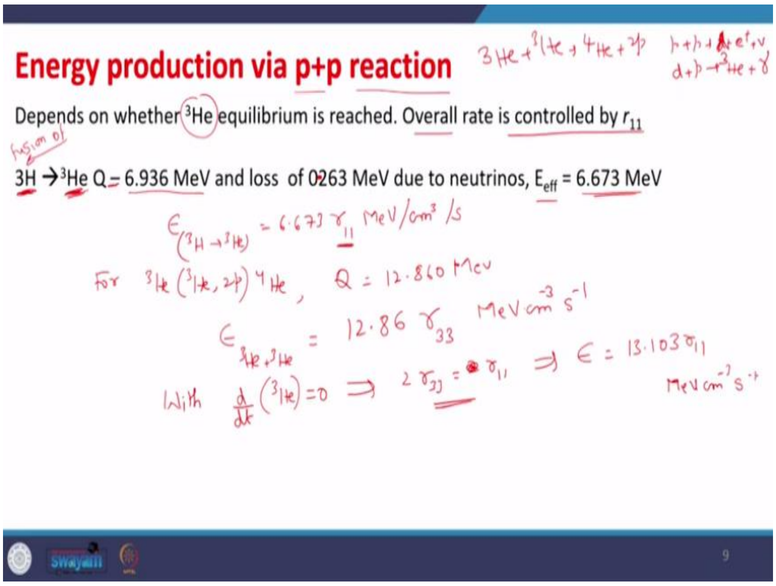

Energy production via p+p reaction

$^3He + ^3He \rightarrow ^4He + 2p$

$p + p \rightarrow d + e^+ + \nu$

$d + p \rightarrow ^3He + \gamma$

Depends on whether ^{3}He equilibrium is reached. Overall rate is controlled by r_{11}

fusion of

$3H \rightarrow {}^3He$ Q = 6.936 MeV and loss of 0263 MeV due to neutrinos, E_{eff} = 6.673 MeV

$$\epsilon_{(^3H \rightarrow ^3He)} = 6.673\, r_{11} \text{ MeV/cm}^3\text{/s}$$

For $^3He(^3He, 2p)^4He$, $Q = 12.860$ MeV

$$\epsilon_{^3He + ^3He} = 12.86\, r_{33} \text{ MeV cm}^{-3} \text{s}^{-1}$$

With $\frac{d}{dt}(^3He) = 0 \Rightarrow 2 r_{33} = r_{11} \Rightarrow \epsilon = 13.103\, r_{11}$ MeV cm^{-3} s^{-1}

Now, another question which is of our interest is, what is the total energy produced via p + p reaction? Remember, the energy production via p + p reaction depends on whether ^{3}He equilibrium is reached or not because it is the ^{3}He + ^{3}He which is giving rise to ^{4}He + 2p. And, it was clear that overall rate is always controlled by the p + p reaction only because of its weak interaction and slow consumption.

Now, please remember, instead of going to 4 protons I am stopping with only the fusion of 3 protons giving rise to ^{3}He. Is not it? How? 2 protons giving rise to deuterium + positron + neutrino. So, 2 protons are over another proton reacting with deuterium giving rise to ^{3}He. So, overall 3 protons when they undergo fusion to give rise to ^{3}He, the Q value involved is 6.936 MeV.

Please remember, it is 0.263 MeV neutrinos on average. Earlier, I have shown you. The loss of neutrinos energy is 0.263. So, overall, the effective energy is 6.673 MeV. So, with this, one can understand the energy produced in the stars via p + p reaction. How? See, the energy is when 3 protons are giving rise ^{3}He; this is 6.673 MeV.

So, this is the energy produced in the reaction when the total reaction is controlled by the p + p reaction only. Either, you can write r_{11} or r_{pp}. That is up to you. Whereas, for ^{3}He reaction, in the next step, when overall 4 protons are involved, energy released is 12.860 MeV in this reaction. So, the energy production is when ^{3}He + ^{3}He is happening, it is basically 12.86 MeV the reaction between ^{3}He and ^{3}He, so, MeV per centimeter cube and per second.

So, in the reaction model calculations normally there are several steps which I am ignoring here. So, it is sufficient to understand that at equilibrium when $d(^3He)/dt = 0$, we can show that $2r_{33} = r_{11}$ which gives rise to, already this we have discussed in the previous slide. The energy produced is 13.103 r_{11} MeV cm^{-3} s^{-1}.

So, to summarize today’s lecture, I have discussed more salient features of p + p reaction. In particular, when p and p produces deuterium, in how many ways deuterium is undergoing destruction? And, what is the predominant way of destruction? And with that, how to understand the lifetimes of the destruction mechanisms? And, when p + d is giving rise to ^{3}He, in how many ways ^{3}He is undergoing destruction?

And finally, the rate of production and the rate of destruction of ^{3}He has given some information about the reaction rates and the ratio of ^{3}He quantity and hydrogen quantity. Finally, the energy produced via this p + p reaction which we are calling as fundamental nuclear reaction. It is about 13 MeV multiplied by r_{11}. So, overall the reaction rate is decided by the proton + proton reaction.

And, the overall reaction rate for proton + proton reaction multiply with the r_{13} gives you energy produced because of this particular reaction. So, in the next class, I will discuss some more types of pp chains. See you soon. Thank you so much for your attention, see you.