Nuclear Astrophysics

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Lecture – 28
Carbon, Neon, Oxygen, Silicon Burning

Welcome to 28th lecture of Nuclear Astrophysics. Can you recollect quickly what I discussed in the previous lecture? Survival of carbon 12 nucleus. Before that, I discussed the creation of carbon 12. These two topics were discussed after I had covered the PP Chain and CNO Cycle. It makes sense if we remember these fundamental and very important things regularly.

Nuclear astrophysics, which is the union of nuclear physics and astrophysics, is a subject which helps us in two-fold. Number one: how to calculate the energy produced from the stars including the sun. We need to understand the nuclear reactions for energy produced at a different stages of stars evolution stellar evolution. That is where nuclear astrophysics comes into picture.

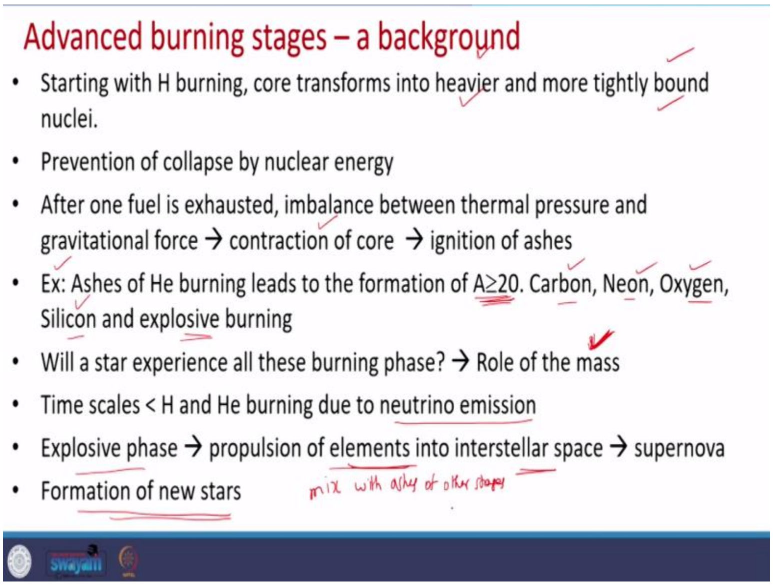
Number two is synthesis of elements. In the universe, you see so many elements, isotopes and isobars around you and majority of the nuclides can be found in the star. So, it is the hub of the elements. It is like cooking the nuclides inside a star.

In the topics that we are discussing, like PP Chain, CNO Cycle, creation, and survival of carbon 12, we see the energy produced because of some reactions at certain stage, but mostly we are covering the synthesis part. What kind of nucleus is produced because of which type of nuclear reaction that. So, in recap of the survival of carbon 12, we have seen how nuclear reactions should happen so that the ratio of carbon to oxygen should be maintained. i.e., 0.6.

And then how the helium burning phases are blocked because of some reasons and what are the perspectives of helium burning. these are the things which I have discussed in the previous lecture.

In today’s lecture, I am going to cover a few more stages during the stellar evolution which covers many types of nuclides, how they are synthesized. I will discuss how this carbon burning leads to the synthesis of different nuclides. I am discussing the advanced stages in the burning during stellar evolution. Of course, I have not yet crossed the iron peak. Thus, I have not yet crossed the discussions on synthesis of elements beyond iron. So, I am discussing only below iron peak, if you consider the binding energy curve.

In the advanced burning stages of the stellar evolution, after hydrogen and helium burning, what are the burning stages that come into picture? These are carbon burning neon burning, oxygen burning and silicon burning. These are four types of burning stages that I am going to cover in today's lecture. In the previous chapters we have discussed thermonuclear reactions in the interior of a star that starts with hydrogen burning and energy keeps on being produced. Once hydrogen is exhausted, whatever process are taking place, they are leading to the formation of elements which are more tightly bound when compared to the hydrogen and also heavier elements. The burning of these heavier elements emits energy, which we call as nuclear energy. So, there has to be a balance between the nuclear energy and the gravitational energy, so that evolution of star goes on smoothly. The moment there is any imbalance, the star will completely contract and go to a white dwarf stage or it will go to the explosion stage like supernova. These are two extremes that I am going to discuss in today's lecture.



Advanced burning stages – a background

- Starting with H burning, core transforms into heavier and more tightly bound nuclei.
- Prevention of collapse by nuclear energy
- After one fuel is exhausted, imbalance between thermal pressure and gravitational force → contraction of core → ignition of ashes
- Ex: Ashes of He burning leads to the formation of A≥20. Carbon, Neon, Oxygen, Silicon and explosive burning
- Will a star experience all these burning phase? → Role of the mass
- Time scales < H and He burning due to neutrino emission
- Explosive phase → propulsion of elements into interstellar space → supernova
- Formation of new stars

mix with ashes of other stages

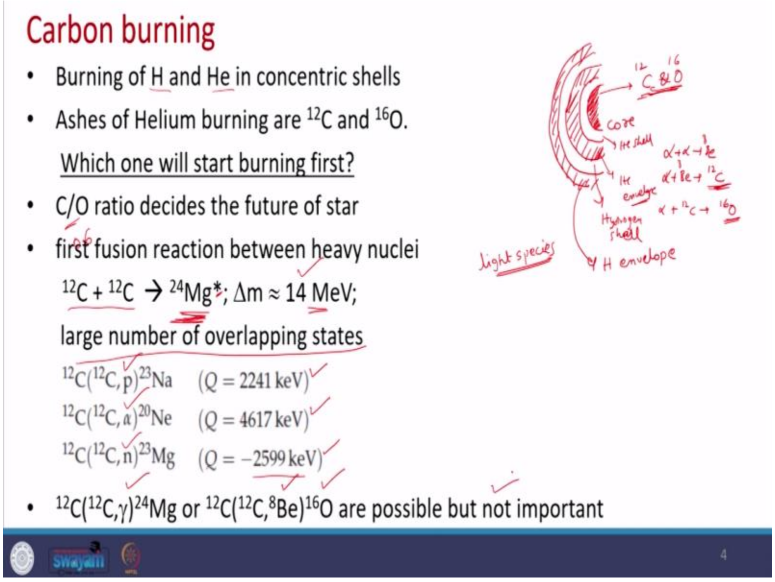
Let me give you a brief background of advanced burning stages in the star. Starting with the hydrogen burning, the star's core transforms into heavier and more tightly bound nuclei. The energy produced in the nuclear reactions will help the star not to collapse against the gravitational effect. Now, starting from the hydrogen, what will happen after one fuel is exhausted?

There will be an imbalance between the thermal pressure and the gravitational force, because the temperature is not yet enough to ignite the other things. As a result, contraction of the stars core will start. The contraction of the core leads to the increase in density and temperature. The contraction of stars core will help in igniting the ashes of previous burning stage. For example, ashes of helium burning leads to the formation of nuclides whose mass numbers are greater than 20. You will find the elements carbon, neon, oxygen, silicon after this helium burning. We can also discuss this explosive burning. Now, there is an interesting question. When I say burning of carbon, burning of neon, burning of oxygen and burning of silicon, they are happening in every star. All those burning phases maybe happening or may not be happening. What will tell us whether any particular burning phase is happening within the star?

It is the mass of the star. You can realize the importance of temperature in terms of energy, Gamow peak width and Gamow peak centroid. In the same manner, you can also realize the impact of mass in explaining whether all these burning stages will happen inside the star or not. I will explain it very soon.

What is the time scale of all these burning stages? Are these shorter than hydrogen burning or longer? Of course, we can easily expect they are shorter than the hydrogen, helium burning because of larger loss due to the neutrino emission. As you go towards carbon, neon, oxygen, silicon, the number of neutrons emitted is very high. Because of this, the timescales of these burning stages are shorter than the previous stages.

What will happen in the explosive phase? Whatever heavier elements are formed, they are propelled in the interstellar space, which we call as supernova. They will mix with ashes of other stages, giving rise to formation of new stars.
This is how stellar evolution takes place and how supernova helps in formation of new stars. So, I have given you some overview of advanced burning stages.



Carbon burning

- Burning of H and He in concentric shells
- Ashes of Helium burning are ^{12}C and ^{16}O.

  Which one will start burning first?
- C/O ratio decides the future of star
- first fusion reaction between heavy nuclei

  $^{12}C + ^{12}C \rightarrow ^{24}Mg^*$; $\Delta m \approx 14$ MeV;

  large number of overlapping states

  $^{12}C(^{12}C,p)^{23}Na \quad (Q = 2241\ keV)$

  $^{12}C(^{12}C,\alpha)^{20}Ne \quad (Q = 4617\ keV)$

  $^{12}C(^{12}C,n)^{23}Mg \quad (Q = -2599\ keV)$
- $^{12}C(^{12}C,\gamma)^{24}Mg$ or $^{12}C(^{12}C,^{8}Be)^{16}O$ are possible but not important

Let us start with the carbon burning. Why only with carbon burning? Why not others? Very simple to imagine. When the burning of the hydrogen and helium is over, what will happen? I am drawing the cross-sectional view of star evolution. This can be considered as carbon and then oxygen, they are occurring within the core of the star.

Where this carbon and oxygen have come from? When helium is exhausted, what are the ashes of the helium burning? We have seen alpha plus alpha gives beryllium and alpha plus beryllium give rise to carbon 12. Now, in the helium burning stage, whenever carbon is formed, there are plenty of alpha particles which reacts with carbon to give rise to oxygen 16.

Once helium is exhausted, you have carbon and oxygen in the core. That is why I have written carbon and oxygen in the core. Around this core, you can see a shell of helium. This is called as helium shell. Around this shell, there is a open envelope surrounding the helium shell. This is called as helium envelope. Around the helium, there is hydrogen.

Once hydrogen and helium are exhausted within the core of the star, do not think that they are completely gone. They are around the core. Once hydrogen is exhausted and helium is there within the core, we were discussing about the hydrogen burning in the shell around the helium core.

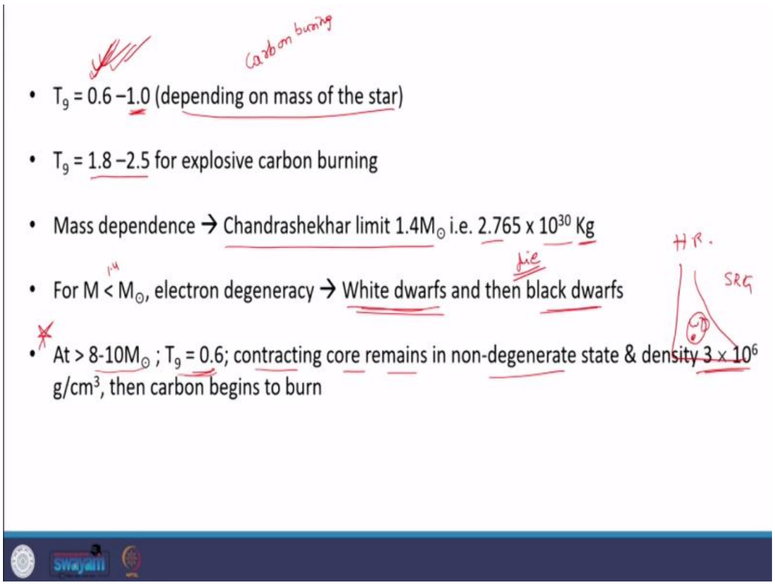
Similarly, once helium gets exhausted, there are carbon and oxygen in the core as the ashes of helium burning. Around the core, you have helium shell. As it expands, you can always expect helium envelope. Around the helium, you always have the hydrogen shell. And then you have the hydrogen envelope. So, the outermost dashed region in the figure is hydrogen envelope.

So, burning of hydrogen and helium continues around the core, within which we have carbon and oxygen. Now a question comes into our mind: both carbon 12 and oxygen 16 are available but which one will burn with faster rate. Which one has to considered as next stage of the burning phase? If we consider the reaction between carbon-carbon, carbon-oxygen or oxygen-oxygen and do a calculation, Coulomb barrier will be less for the carbon 12. So, it is a carbon burning which comes first, before the oxygen burning. C / O ratio decides the future of the star. Interestingly, the first fusion between heavy nuclei in the stellar evolution is here with us, i.e., C + C. Only light species were involved until now.

What is the compound nucleus formed when carbon reacts with carbon? It is magnesium 24 in the excited state. If you do the mass difference calculation, it comes out to be around 14 MeV. You can see the level of excitation within the magnesium. So, we can easily expect large number of overlapping states, because the excitation energy is 14 MeV. The reaction of carbon plus carbon proceeds through these large number of overlapping states of magnesium. What are the possibilities?

It can either emit proton along with 23 sodium or it can emit alpha along with neon 20 or it can emit neutron along with magnesium 23. So, we are getting lighter species again, like proton, alpha and neutron. Corresponding Q values are shown here. We need to supply 2.6 MeV (-ve Q value) to C + C so that neutrons are emitted.

Two more reactions are possible. Number one may be a radiative capture. Carbon 12 capturing carbon 12, giving rise to ^{24}Mg in very high excited state and emitting gammas during de-excitation. Number two can be that magnesium 24 breaks up into beryllium 8 and oxygen 16. So, 5 reactions are possible. Out of them 3 reactions emit lighter species and 2 reactions emit gamma and beryllium 8. The last two are not of very importance in the energy production, but they can give us an idea about the synthesis of different nuclides.



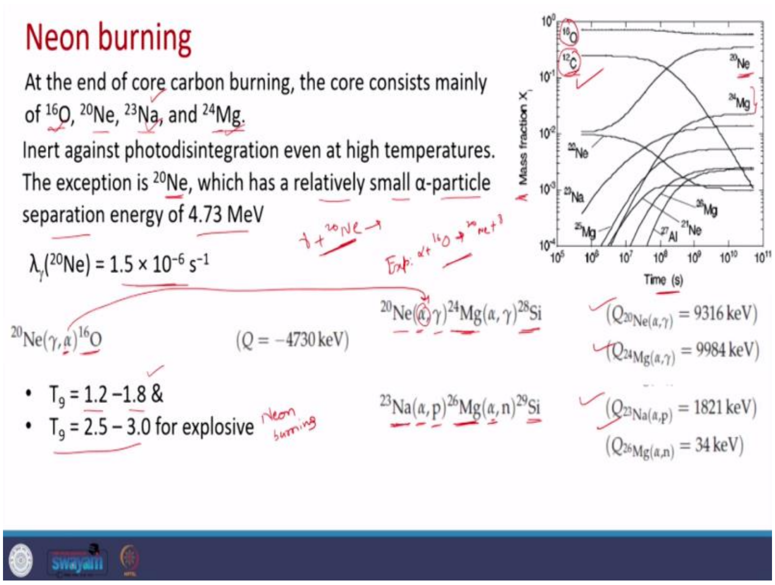
- $T_9 = 0.6 - 1.0$ (depending on mass of the star)
- $T_9 = 1.8 - 2.5$ for explosive carbon burning
- Mass dependence → Chandrashekhar limit $1.4 M_\odot$ i.e. 2.765×10^{30} Kg
- For $M < M_\odot$, electron degeneracy → White dwarfs and then black dwarfs
- At $> 8\text{-}10 M_\odot$; $T_9 = 0.6$; contracting core remains in non-degenerate state & density 3×10^6 g/cm^3, then carbon begins to burn

Depending on the mass of the star, please understand the temperature region over which this carbon burning take place. It is 0.621 gigakelvin. If you remember, during the triple alpha process when we discussed the Hoyle state, it was T_8.

And the explosive carbon burning can happen in the temperature region of 1.8-2.5 gigakelvin. You might be aware of a very important quantity, Chandrashekhar limit. Chandrashekhar limit says that, if mass of the star is less than 1.4 times that of mass of Sun, i.e., 2.7×10^{30} Kg, then the central core does not have enough temperature to ignite the carbon. If the mass of the star is less than 1.4 times of the mass of the sun, no matter what temperature is available within the central core, it is not sufficient to ignite the carbon. The contraction of the core continues, and density will increase. No carbon burning takes place now, but the contraction of the core leads to the increase in density and the thermal energy produced will radiate away from the core. When majority of the thermal energy is radiated away from the central core, the electron degeneracy which is a quantum mechanical phenomenon will exert pressure to balance the gravitational collapse. The star becomes stable. This state of the star is called as white dwarfs. We have used this word when we discussed the HR diagram. Once white dwarf is formed, eventually it cools down and dies as black dwarfs.

Now, what if the temperature is high? I am ignoring the region between 1.4 to 8 MeV times of the mass of the sun because I am more focused on carbon burning.

When temperature of the star in the core is 0.6 gigakelvin and the mass is more than 8 to 10 times that of mass of the sun, then the contracting core remains in non-degenerate state. And if the density is, say, 3×10^6 g/cm^3, then whatever temperature is available within the core, it is enough to ignite the carbon for burning. So, it is very important to know the numbers regarding temperature, density and mass corresponding to the carbon burning.



Neon burning

At the end of core carbon burning, the core consists mainly of ^{16}O, ^{20}Ne, ^{23}Na, and ^{24}Mg.

Inert against photodisintegration even at high temperatures.

The exception is ^{20}Ne, which has a relatively small α-particle separation energy of 4.73 MeV

$\lambda_\gamma(^{20}Ne) = 1.5 \times 10^{-6}\ s^{-1}$

$\gamma + {}^{20}Ne \rightarrow$

Exp: $\alpha + {}^{16}O \rightarrow {}^{20}Ne + \gamma$

$^{20}Ne(\gamma,\alpha)^{16}O$ $(Q = -4730\ keV)$

$^{20}Ne(\alpha,\gamma)^{24}Mg(\alpha,\gamma)^{28}Si$ $(Q_{^{20}Ne(\alpha,\gamma)} = 9316\ keV)$ $(Q_{^{24}Mg(\alpha,\gamma)} = 9984\ keV)$

$^{23}Na(\alpha,p)^{26}Mg(\alpha,n)^{29}Si$ $(Q_{^{23}Na(\alpha,p)} = 1821\ keV)$ $(Q_{^{26}Mg(\alpha,n)} = 34\ keV)$

- $T_9 = 1.2 - 1.8$ &
- $T_9 = 2.5 - 3.0$ for explosive

Neon burning

Let us go to the next stage. You might be expecting that oxygen burning should start, because we have only oxygen, after carbon. Where did this neon come from? We will see. If we plot mass fraction abundance versus time, we see oxygen 16 is there on top. It is the third most abundant element in the universe and fourth most abundant element is carbon.

Oxygen16 is above Neon 20. At the end of core carbon burning, hydrogen is gone, helium is gone, and ash of helium is carbon, oxygen. Because of the Coulomb barrier considerations, we saw carbon has to go next.

The ashes of carbon burning are oxygen 16, neon 20, sodium 23, magnesium 24. They are inert against the photodisintegration, even at high temperatures. Now the temperature scale is going higher. At these temperatures, either photodisintegration has to be initiated or capture of lighter particles has to happen. Although, oxygen 16, sodium 23 and magnesium 24 are inert against the photodisintegration even at high temperatures, neon 20 is an exception. It has a relatively small alpha particle separation energy of 4.73 MeV. All the remaining have more alpha particle separation energies. So, neon comes into picture before oxygen for the burning.

When reaction between gamma neon 20 happens, various possibilities are there. Neon 20 reaches the excited state. How can you find out the decay constant for decay to ground state from this excited state? Experimentally, it is very difficult to carry out this reaction.

But we can simply go for reverse reaction and then apply the reciprocity theorem. It will give you the decay constant of the neon 20. In the following reverse reaction

$$^{20}\text{Ne}(\gamma,\alpha)^{16}\text{O} \quad (Q = -4730 \text{ keV})$$

alpha particle is very easy to obtain in the particle accelerator.

The decay constant is found out to be 1.5×10^{-6} s^{-1}. Another possibility is that neon reacts with alpha. Initially, after absorbing gamma, alpha is emitted. This alpha particle can react with neon 20, giving rise to gamma as ejectile; and magnesium 24.Alpha particles are still available and they can react with magnesium 24, giving rise to silicon 28.

$$^{20}\text{Ne}(\alpha,\gamma)^{24}\text{Mg}(\alpha,\gamma)^{28}\text{Si} \qquad (Q \text{ for } ^{20}\text{Ne}(\alpha,\gamma) = 9316 \text{ keV})$$

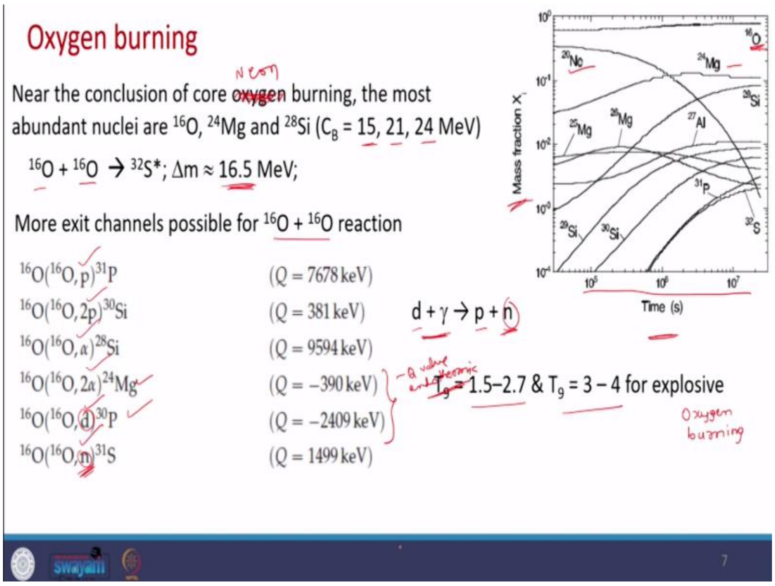
$$(Q \text{ for } ^{24}\text{Mg}(\alpha,\gamma) = 9984 \text{ keV})$$

There is another possibility. ^{23}Na is one of the ashes of carbon burning. When ^{23}Na absorbs alpha particle, magnesium 26 is formed and proton is emitted and once again when alpha reacts with this magnesium 26, we have silicon 29.

$$^{23}\text{Na}(\alpha,p)^{26}\text{Mg}(\alpha,n)^{29}\text{Si} \qquad (Q \text{ for } ^{23}\text{Na}(\alpha,p) = 1821 \text{ keV})$$

$$(Q \text{ for } ^{26}\text{Mg}(\alpha,n) = 34 \text{ keV})$$

For neon burning, the temperature region is 1.2 to 1.8 gigakelvin and 2.5 to 3 gigakelvin for explosive neon burning. So, we have reached slowly to around 2 gigakelvin for neon and 1 gigakelvin for carbon burning.



Oxygen burning

Near the conclusion of core ~~oxygen~~ Neon burning, the most abundant nuclei are ^{16}O, ^{24}Mg and ^{28}Si (C_B = 15, 21, 24 MeV)

$^{16}O + ^{16}O \rightarrow ^{32}S^*$; $\Delta m \approx 16.5$ MeV;

More exit channels possible for $^{16}O + ^{16}O$ reaction

$^{16}O(^{16}O,p)^{31}P$ $(Q = 7678 \text{ keV})$

$^{16}O(^{16}O,2p)^{30}Si$ $(Q = 381 \text{ keV})$

$^{16}O(^{16}O,\alpha)^{28}Si$ $(Q = 9594 \text{ keV})$

$^{16}O(^{16}O,2\alpha)^{24}Mg$ $(Q = -390 \text{ keV})$

$^{16}O(^{16}O,d)^{30}P$ $(Q = -2409 \text{ keV})$

$^{16}O(^{16}O,n)^{31}S$ $(Q = 1499 \text{ keV})$

–Q value endothermic

$d + \gamma \rightarrow p + n$

T_9 = 1.5–2.7 & T_9 = 3 – 4 for explosive

Oxygen burning

Now, after neon is over, we have oxygen into picture. Same kind of diagram is shown here, mass fraction versus time. See the timescales. This diagram is not exactly the previous one.

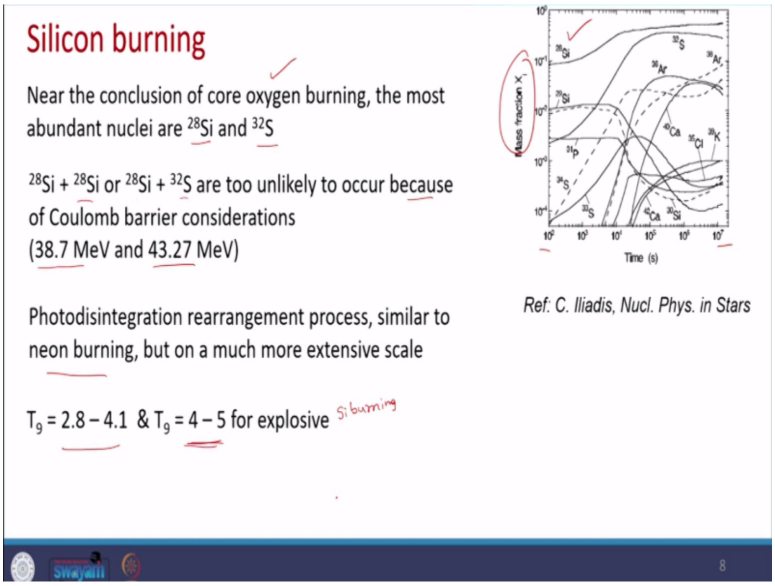
Near the conclusion of core neon burning, the most abundant nuclei are ^{16}O, ^{24}Mg and ^{28}Si. The corresponding Coulomb barrier values are like 15, 21 and 24 MeV respectively. Now the fusion oxygen and oxygen should give rise to sulfur 32 in the excited state.
As in the case of previous neon and carbon burning, the mass difference is also high, i.e., 16.5 MeV. So, you can expect large number of overlapping energy levels and the reactions proceeds through these overlapping energy levels. When you have more excitation energy, you can always expect more exit channels for this $^{16}O + ^{16}O$. Let me quickly give you a list of the reaction possible.

It can give a proton; two protons; one alpha; two alphas; deuteron; and neutron. You can see two negative Q values, i.e., endothermic reactions. When a deuteron is emitted, it can react with gamma giving rise to proton and neutron.

So many possibilities are there for emission of neutrons. I am discussing about neutrons suddenly because neutrons are responsible for the synthesis of elements beyond iron. No more charged particles. Almost all elements are synthesized beyond iron because of neutron as probes, if you want to study in the laboratory. So, it is neutron induced reactions which are responsible for the synthesis of elements beyond iron.
so from where these neutrons are coming.

So, the last reaction in this slide is one of the reactions through which neutrons are emitted. Not only that, when deuterium and gamma react with each other, then also you get neutrons. What are the temperature scales? It is 1.5 to 2.7 gigakelvin; and 3 to 4 gigakelvin for explosive oxygen burning.

We are done with carbon, neon and oxygen burning. Now the last burning stage remains, i.e., silicon burning.



Silicon burning

Near the conclusion of core oxygen burning, the most abundant nuclei are ^{28}Si and ^{32}S

^{28}Si + ^{28}Si or ^{28}Si + ^{32}S are too unlikely to occur because of Coulomb barrier considerations (38.7 MeV and 43.27 MeV)

Photodisintegration rearrangement process, similar to neon burning, but on a much more extensive scale

$T_9 = 2.8 - 4.1$ & $T_9 = 4 - 5$ for explosive Si burning

Ref: C. Iliadis, Nucl. Phys. in Stars

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The time scale here starts from $10^2 - 10^7$ seconds and silicon 28 is the most abundant material in these time scales. Silicon 28 and sulfur 32 are the ashes of core oxygen burning. Silicon 22 will burn first because of the Coulomb barrier considerations.

Let us see some of the numbers regarding silicon burning.
^{28}Si + ^{28}Si or ^{28}Si + ^{32}S are too unlikely to occur because of the Coulomb barrier considerations. They occur very rarely because the Coulomb barrier for these two reactions are 38.7 MeV and 43.27 MeV respectively.

Here also, one can expect photodisintegration rearrangement process at this high temperature, similar to neon burning, but on a much more extensive scale.
The burning of silicon takes place at about 4 gigakelvins and the explosive silicon burning takes place between 4 to 5 gigakelvin.

So, in today's lecture, I have discussed a general background of advanced burning stages within the star: carbon burning, then neon burning, then oxygen burning and finally silicon burning. After this silicon burning, different types of nuclear reactions take place, finally leading to the formation of most stable nuclides, i.e., nuclides around iron peak.

In the next lecture, we will see how elements are formed because of the neutrons when synthesis of elements beyond iron is considered. Thank you so much for your attention.