Nuclear Astrophysics

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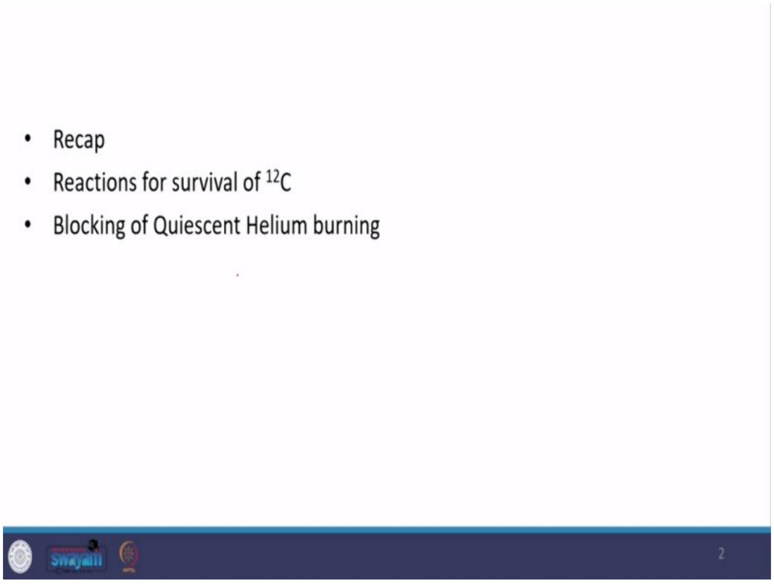
Lecture – 27
Survival of ^{12}C

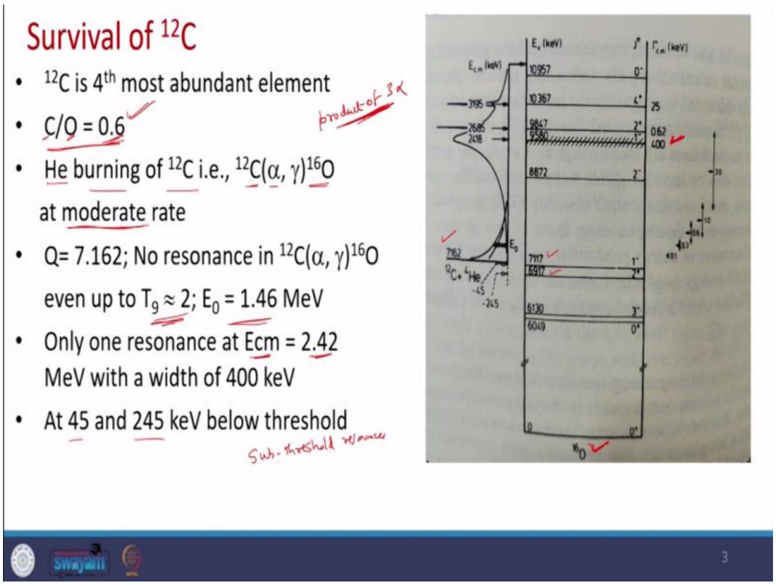
Hello students. In the last lecture I have discussed creation of Carbon-12 and we have seen how beautifully Carbon-12 is created because of a two-step process, called as triple alpha process. Let me summarize the previous lecture quickly. In the triple alpha process, which is a two-step process, initially beryllium 8 is formed and by reaction between beryllium 8 and alpha, we have Carbon-12. It is the resonance state within the Carbon-12, because of which the rate of reaction is inconsistent with the ratio. In today's lecture I will share some of the salient features of survival of Carbon-12.



So, in last lecture we have discussed creation of Carbon-12 and in today's lecture, survival of Carbon-12, what are the nuclear reactions which play important role in the survival of Carbon-12 and then blocking of quiescent helium burning.

In the helium burning, we have seen in the core of the star, it is a red giant basically. And we have discussed in the basics of helium burning why we call it as red giant already.

And there is a stage when this helium burning phase, the quiescent helium burning stage blockings. We will discuss in today's lecture, what is the reason for it and then what are the other important helium burning processes or reactions that and finally I will summarize the helium burning by putting some perspectives on helium burning reactions.



Remember how the stability gaps at masses A =5 and A = 8 were bridged by the triple alpha reactions and it was clear that Carbon-12 is formed within the star. Carbon-12 is fourth most abundant element in the universe. We have to understand how it survives.

The ratio of carbon to oxygen is less than 1, i.e., 0.6. That is the reason why oxygen is the third most abundant, after hydrogen and helium and. I am not going to discuss how people have measured it.

But I am discussing how nuclear reactions have to proceed, with what rate it has to proceed so that this ratio should be maintained. The helium burning of carbon, i.e., the alpha reacting with Carbon-12 gives rise to oxygen 16 and the ratio of carbon to oxygen is 0.6. Whether it has to proceed through a low rate, moderate rate or high rate? How to know that?

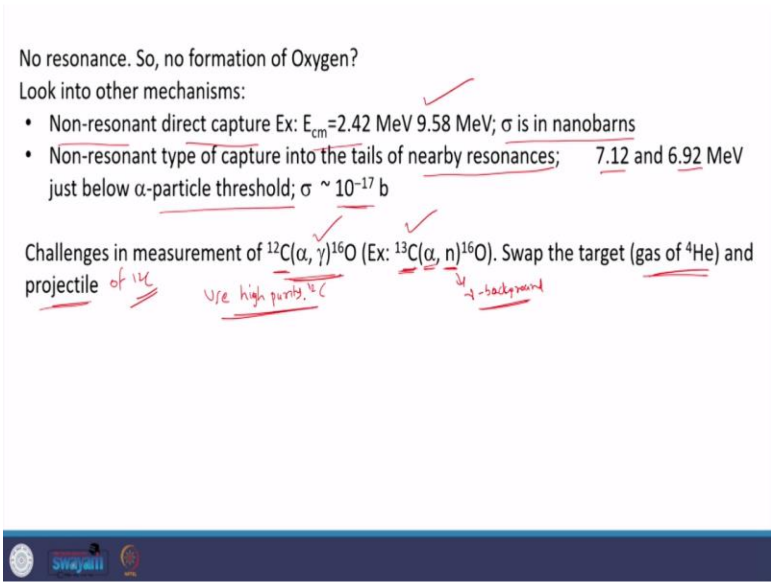
It is very clear that carbon is formed within the stars in the universe. Majority of the abundance of carbon is the direct product of triple alpha reaction. So, it is sensible. It is logical to assume that if Carbon-12 is the direct product of triple alpha process, then the rate with which this alpha plus Carbon-12 has to proceed, should be moderate. If it evaporates quickly, then it is difficult to manage this ratio and we know the rate with which triple alpha process takes place in the star.

Now, let us see the level scheme of oxygen 16. Why oxygen 16? Because when we say the C by O ratio is 0.6, it is the oxygen which is formed because of the reaction between Carbon-12 and alpha particle.

Is there any resonance state in oxygen 16, like alpha plus beryllium? Let us see. 7162 is the alpha particle threshold in this reaction of alpha plus Carbon-12. Near 7162, we have two energies: 717 and 6917. They are below the alpha threshold. There is no resonance above the threshold, even up to the 2 gigakelvin. The centroid of the Gamow peak comes out to be 1.46 if you do the calculation at this temperature. What does that mean? That Oxygen is not formed? If there is a resonance near the particle threshold, like in the case of Carbon-12, then the rate with which this alpha plus Carbon-12 proceeds will be very high. But it is not happening here. There is no resonance to fasten the resonance.

So does it mean oxygen is not formed? No, oxygen is being formed. How can we say that? Because it is the most third abundant element in the universe. So, when there is no resonance because of which oxygen 16 cannot be formed through resonance for higher rate of the reaction, but at the same time oxygen is the third most abundant element in the universe, what kind of mechanism is happening inside this alpha plus Carbon-12?

It could be some other mechanism. One has to look into it. What are those? We will discuss. Now, oxygen 16 at center of mass energy 2.42 MeV and with a width of 400 keV in this level diagram, there is one resonance. Now just below the threshold, like 45 keV and 245 keV, you have 7117 and 6917 keV. So, there are two levels just below the threshold and we can say that there are sub threshold resonances. We call them as sub threshold resonances.

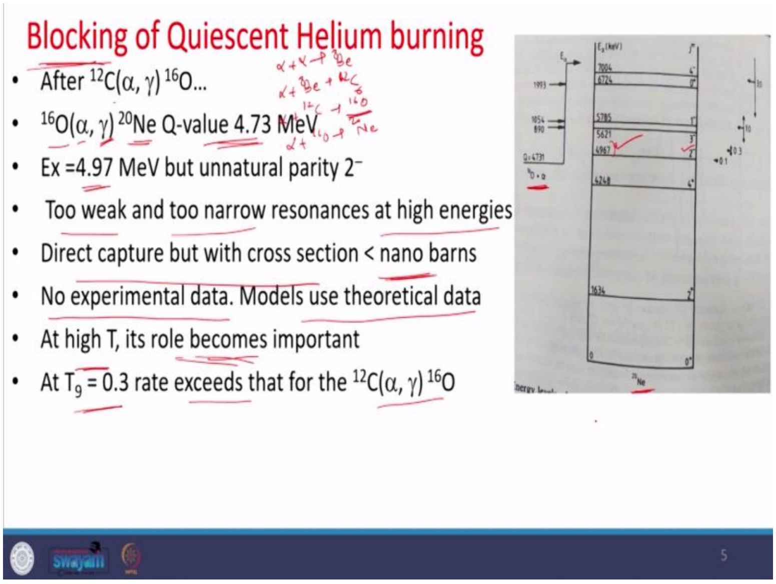


Let us look into the other mechanisms. One is non-resonant direct capture. For example, at center of mass energy 2.42 MeV, you have the state at 9.58 MeV in the oxygen 16, σ is in nanobarn. It is very difficult to measure. But once oxygen is excited to this state, transition can happen during de-excitation through sub threshold resonances.

So, second possibility is non resonant type of capture into the tail of nearby resonances. When I say nearby resonances what does it mean? 7.12 and 6.92 MeV just below the alpha particle threshold. The problem is that the cross section of this is expected to be around 10^{-17} b, which is just impossible to measure. There are challenges in the measurements of $^{12}C(\alpha,\gamma)^{16}O$. What are those challenges?

When you take any target, in general, it also contains carbon 13. When alpha particle reacts with carbon 13, it is giving rise to the production of neutrons. These neutrons will induce some gamma background, which is higher than gamma background of $^{12}C(\alpha,\gamma)^{16}O$ reaction. Neutron induced background is one of the big problems in executing measurement of alpha plus Carbon-12.

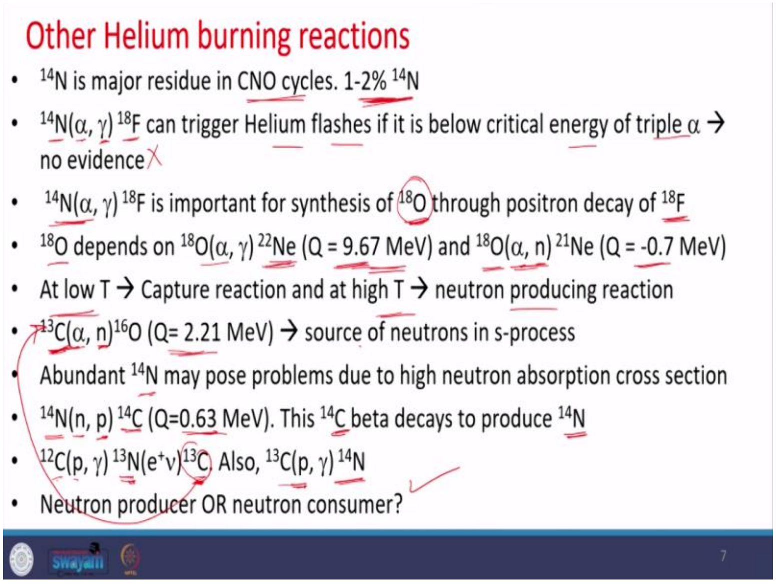
One way to circumvent this problem is swapping the target and the projectile. It means, instead of using alpha in the particle accelerator as a projectile, take gas of helium and then use Carbon-12 as projectile. Another way is using high purity Carbon-12, i.e., highly enriched Carbon-12. Using these two ways, one can perform this experiment.



Now let us see whether quiescent helium burning continues without any problem. No, there is some problem because of which we observe blocking of quiescent helium burning. Ideally, we expect in the helium burning, alpha plus alpha giving rise to beryllium, alpha plus beryllium giving rise to Carbon-12, alpha plus Carbon-12 giving rise to 16 oxygen and alpha plus 16 oxygen give rise to neon 20. But things are not so easy. The reactions do not proceed like this because of some problem, that I am going to discuss in the slide. If you see the reaction of alpha plus oxygen 16, the compound nucleus formed is neon 20 and it always emits gamma during de-excitation. Q value for this reaction is quite low. It is 4.73. Fortunately, there is a state at 4.97 in the neon 20. Naturally we expect some kind of reaction resonance reaction so that we can get high rate resonant reaction, but unfortunately, due to unnatural parity of 2^-, the reaction does not proceed through this channel. Remaining levels are two way weak and too narrow at high energies for the resonances. This is another problem.

The remaining possibility is direct capture of alpha by oxygen 16 with cross section less than nanobarns, again difficult to measure. So, there is no experimental data as of now. Stellar network calculations depend on the inputs from the theoretical data. I am not going into the details of this reaction because I am trying to give some framework to understand how the blocking of quiescent helium burning is happening.

However, as temperature goes up, the oxygen plus alpha reaction plays very important role at high temperature. For example, when you go to 0.3 gigakelvin, the rate of reaction exceeds even that of the alpha plus Carbon-12. This kind of reaction can happen only at very high temperature, in very massive stars. So, blocking of quiescent helium burning is happening because of properties of the energy levels in neon 20.



Continuing discussion on what are the other possible reactions that are happening in the helium burning, one of the major residue in CNO cycle is nitrogen 14. In the helium burning phase, 1% to 2% of nitrogen 14 is always present. It also plays some role in the synthesis of elements. For example, helium with nitrogen 14 gives rise to ^{18}F, giving rise to some gamma ray also.

People expected that it can trigger some kind of helium flashes, if it is below the critical energy required for the triple alpha process. But, as of now there is no evidence. However, this reaction of alpha plus nitrogen 14 is very important for the synthesis of oxygen 18, through the positron decay of ^{18}F. We are discussing this nitrogen plus alpha reaction because the purpose of nuclear astrophysics is also to understand synthesis of various nuclides.

Fate of this oxygen 18 depends on $^{18}O(\alpha,\gamma)^{22}Ne$ reaction whose Q value is 9.67 MeV, because alpha particles are always available. In addition to that, alpha can also emit neutrons by reacting with oxygen 18, i.e., $^{18}O(\alpha,n)^{21}Ne$ (Q = -0.7 MeV). This is one of the sources for the neutrons. Now, at low temperature, capture reaction is dominating. and at high temperature, neutron producing reaction is dominating.

One of the important sources of neutrons in this stars, which play role in the synthesis of elements beyond iron, is $^{13}C(\alpha,n)^{16}O$ (Q=2.21 MeV). Where has carbon 13 come from? When Carbon-12 reacts with some kind of lighter particles, we can get this carbon 13. And when it reacts with the alpha particle, it is a source of neutrons in the s-process.

Coming back to the ^{14}N, abundant ^{14}N may pose problems because of the high neutron absorption cross section. When it absorbs the neutron, carbon 14 is emitted and it emits a proton and whose Q value is very less.

$^{14}N(n,p)^{14}C$ (0.63 MeV)

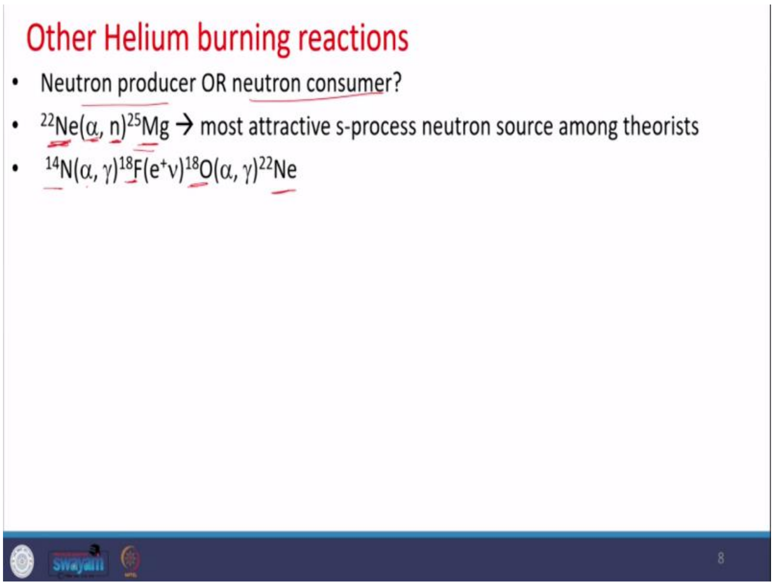
This carbon 14 undergoes beta decay to produce nitrogen 14 and this nitrogen 14 can absorb the neutrons again.

We can see the production source of carbon 13 as follows.

$^{12}C(p,\gamma)^{13}N(e^{+},\nu)^{13}C$. Also, $^{13}C(p,\gamma)^{14}N$

The question is: is this nitrogen 14 helping in the production of neutrons or in the absorption of neutrons?

So, before postulating any reaction to be major source of neutrons, we have to check whether it is leading to huge absorption of neutrons also or not?



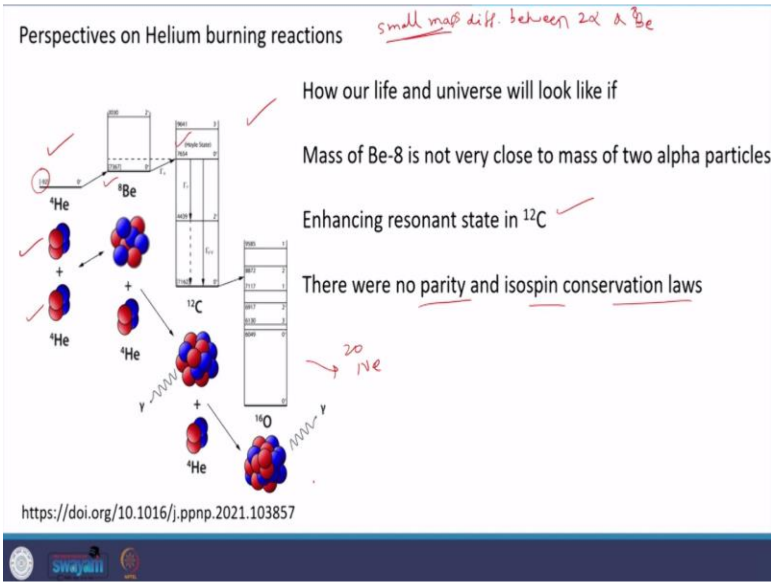
Neon 22, once it is formed while helium burning is still going on, we can get neutron and ^{25}Mg after it reacts with alpha, i.e., $^{22}Ne(\alpha,n)^{25}Mg$. This is most attractive s-process neutron source among theorists.

Where is this neon 22 forming?

When nitrogen 14 reacts with alpha, fluorine 18 is formed and during positron decay, it is emitting oxygen 18. This oxygen 18, if it captures alpha particle, emits neon 22.

$$^{14}N(\alpha,\gamma)^{18}F(e^{+},\nu)^{18}O(\alpha,\gamma)^{22}Ne$$

This is how different process are happening after the Carbon-12 formation and so many reactions are possible within the helium core while the Carbon-12 is surviving. Now, let me put some perspectives on helium burning reactions.



This is a beautiful diagram where it is shown that alpha plus alpha give rise to beryllium 8. There is very small mass difference between two alpha particles and beryllium 8, simple 922 keV. This is one of the major reasons why Carbon-12 is created. What is the problem if the energy difference is more. There is a big problem, because the Hoyle state resonance probability will be less.

So, the small mass difference between two alpha particles and beryllium 8; and the occurrence of Hoyle state in the Carbon-12 are the two main features of synthesis of elements Carbon-12 and oxygen 16. If we see deviation from any of these two, it is very difficult to continue the synthesis of elements. So, you can imagine how our life and universe will look like, if mass of beryllium 8 is not very close to the mass of two alpha particles.

The parity and isospin conservation laws followed by energy levels in the neon after this oxygen 16, because of which blocking of quiescent helium burning is taking place. So, these three reasons: very close difference between the beryllium 8 mass and two alpha particles, the happening of resonance state, and the properties of the energy levels which are playing important role in blocking the helium burning, are important perspectives of the helium burning reactions. With this, let me end the topic of Survival of Carbon-12. Thank you very much.