Nuclear Physics Fundamentals and Application
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Lecture - 41
Nucleosynthesis of elements in Stars

Previous lecture, we talked about what is going on inside the core of the sun, how nuclear fusion is taking place, and how hydrogen is being converted into helium.

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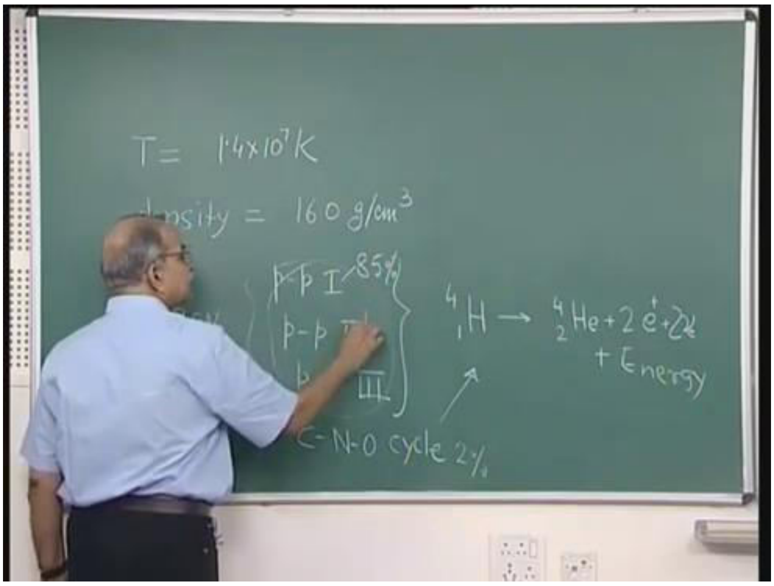

So, we saw that the temperatures are about 1.4 into 10 to the power 7 K and so at these temperatures in the core, and the density is also very high, density of that hydrogen core around 160 grams per centimeter cube. And corresponding pressure and which that the reactions p p I, then p p II, p p III main reactions, and the result of all this is that 4 hydrogen nuclei get converted into 4 helium nucleus, and you have 2 positrons and these nucleons formed and plus energy of course.

Same is the case with C N O cycle same final result, this happens around say 2 percent of the time, and this happens about 98 percent of the times and of this is 85 percent, this is almost 15 percent and this is 0.1 percent. The neutrino is which come out of these reactions, these neutrinos have different energies in different cycles p p I, p p II, p p III C N O etcetera. And these neutrinos in fact, give us and almost live update of what is going on inside the core of the sun, with an 8 minutes of delay.

Because, the photons that are created or energy that is created in fusion, that takes long long time to come to the surface, and get emitted to the earth and other surrounding space. But, neutrinos which are produced in these fusion reactions, they almost without interacting with the material, they come out with almost the same speed as the speed of light. And therefore, by studying these neutrinos, we know the details of these fusion reactions.

Now, today's topic is making of newer elements inside these stars, here helium is being made from hydrogen, so one element is getting converted into another element. And in the sun itself if we see apart from this hydrogen and helium, we have a varieties of other elements, some 64 other elements have been detected. And if we look for the whole universe, in the whole universe you have some 100 odd elements some 94 elements or so, stable elements that we know in periodic table.

And if we think of the stable nuclei, there are about 300 of them stable nuclei starting from this hydrogen, helium, then carbon, nitrogen, oxygen everything boron everything, so many nuclei this iron and silicon and zirconium and everything. So, where these nuclei were formed for the first time that is known as nucleosynthesis, and turns out that you can think of two parts.

One part where the is called big bang nucleosynthesis, the universe is now almost certain that it has started from a big explosion from a point, entire universe, the entire energy, the entire matter everything was first confined into point. And then some explosion took place some 15 billion years ago, which is known as big bang, and that is supposedly the beginning of universe, the beginning of spaces time, no space, no time existed before this event that is how people describe this.

And from there from the big bang that after the explosion universes started expanding, so within first few minutes lots of complex events took place, and this protons and neutrons and neutrinos and photons and these things were created initial the temperature is very high. So, that no bound system can be thought of, so at those temperatures it was all quarks and other things, but when the temperature came down, then these quarks got into the bound states making protons, making neutrons.

And there are so many theories and speculation and calculations to describe those early part, that early part of just after the big bang. But, within few minutes this situation was such, the temperature were such that bound systems could exist number 1, number 2 protons could combine into somewhat heavier nuclei, like deuteron and from there helium 3, and from there helium 4 and so on.

But, within minutes the temperature fell down, because of this expansion, so that the nucleosynthesis, the nuclear fusion making of heavier nuclei from lighter nuclei that process could not be sustained anymore and that ends the big bang nucleosynthesis, so what was the composition of the universe after that. Now, our theories, our calculations have are showing that the mostly it was by weight about 75 percent of hydrogen, and 25 percent of helium 74.0 something, and 24.0 something else, so on.

And in the rest 1 percent you had this little bit of lithium, little bit of perhaps boron and so on, that is all after that nothing, so nothing beyond a equal to 7 lithium was synthesized there, and that makes what we called p module composition of the universe. So, the matter was in this form hydrogen and helium almost went to 75 percent, 25 percent by weight, and trace amount of 1 or 2 other material that is the composition of the universe as such, this is first few minutes.

And then from there onwards till now 15 billion years, this primary material which is there in the space at places they condensing galaxies in galaxies, in stars and in stars nucleus fusion takes place. And all those other elements they are formed inside this is starts just as hydrogen is fusing into helium, so there are so many stars some 100's of billions of galaxies, and 100's of billions of stars in the galaxy. So, and these stars are of various sizes and depending on the size some particular nuclei could be synthesized inside the core of that.

So, first let us look at the total abundance of different nuclei in the universe, so look at your screen I will show you an abundance graph, the different nuclei and there abundance.

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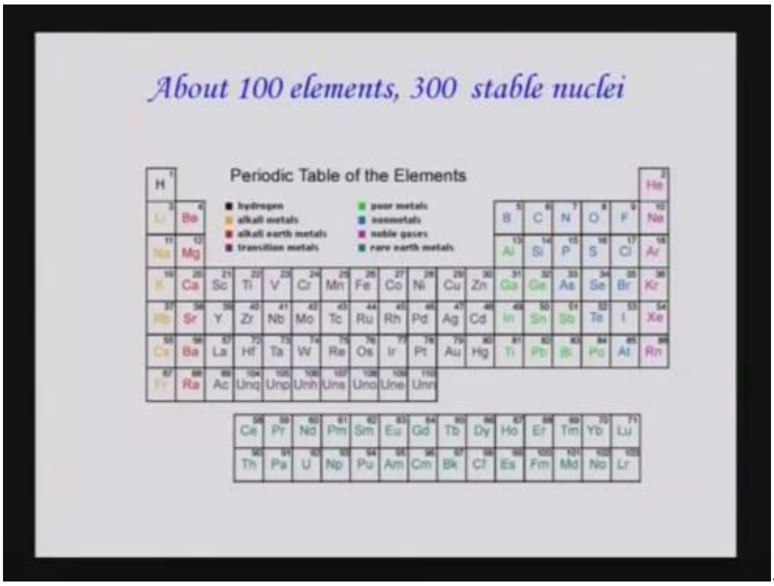

So, on your screen you have this periodic table, which shows that there are so many elements, each element has a different z and corresponding n for each z you can have more than one stable nuclei isotopes, so around 300 of stable nuclei.

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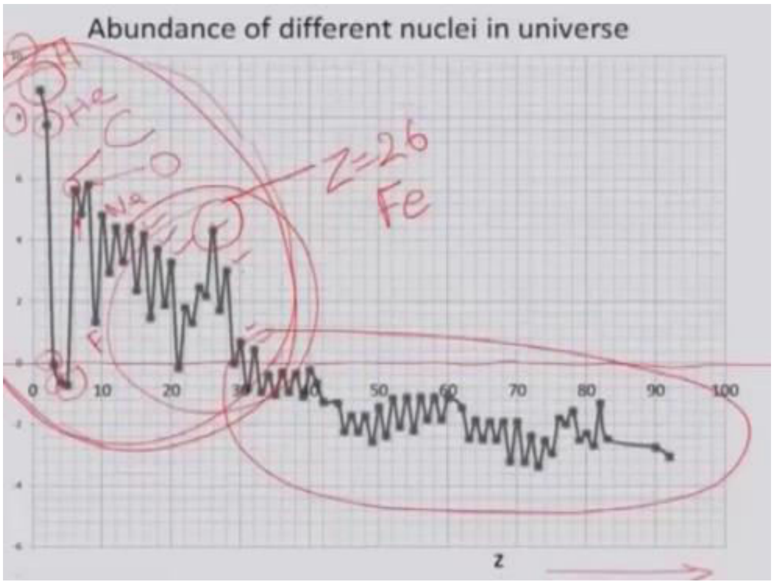

And this is abundance diagram, so you can see that the most abundant element is here and that is hydrogen, remember when you read 8 here it is 10 to the power 8, if it is 10, it is 10 to the power 10 and so on, so is log scale and on this side it is z. What is the next, the next is helium, this is helium z is equal to 2 and after that what is next is this, this is carbon, this was helium, this was hydrogen and this is carbon.

And in between helium and carbon z is equal to 3, lithium is here, z is equal to 4 beryllium is here, z is equal to 5 boron is here, so they have very small concentrations in the universe, and after that you have carbon. After carbon it will be nitrogen here, after nitrogen it will be oxygen here, after oxygen it will be nines of fluorine here and so on neon here, so increase z in steps of 1 and you get this diagram.

There are several things which I should point out looking at this diagram, one is hydrogen is by far most abundant material, and even today after so many 15 billions of years of stars making newer elements, it is composition, it is weight, it is weight percent still remains very close to 75.

And next is helium that also remains very close to that 25, so all these 15 billion years are of synthesis of helium and other elements has given only a very very minute change in the composition of the universe, what it was just 3 minutes after or 4 minutes after or few minutes after this big bang, so that is 1. Hydrogen and helium are still almost 99 percent of the universe is hydrogen and helium, another thing I would point out of this oscillations is the points you are saying or in steps of z is equal to 1.

So, as you increase z in steps of 1, you can see the abundance goes up and down, then up and then down, then up and then down. So, all the even z materials this helium and then carbon and then oxygen and then neon and then magnesium and then silicon, all these even z materials are here, they are here. So, even z materials have a higher abundance then the next odd z material, so this going up and down this oscillation that is one thing which you can identify from this.

The other thing you can identify somewhere here ((Refer Time: 13:07)), this z is equal to 26 and that is iron, 56 iron z is equal to 26 n is equal to 30, here after this helium and hydrogen and carbon oxygen etcetera, in this vicinity this has highest abundance. And once you look at the elements which are away from this iron z is equal to 30 onwards, this abundance is much much smaller than the first part. So, you can see this has two different parts, this whole diagram you can see abundance wise if this is the 0 line, 0 line means remember it is a log scale.

So, all this part is less than that 0 line, and all this part is more than 0 line, so somewhere it is iron nickel that region where a is 56, and around that if some kind of a dividing line, below that abundance is high, more than that abundance suddenly drops. So, that is one another observation you can see, and in general as you increase this if you go towards heavier and heavier, heavier nuclei. You can see that abundance gradually goes down I can show the expanded version of this abundant diagram for a lighter elements and that is on this next slide and that is here.

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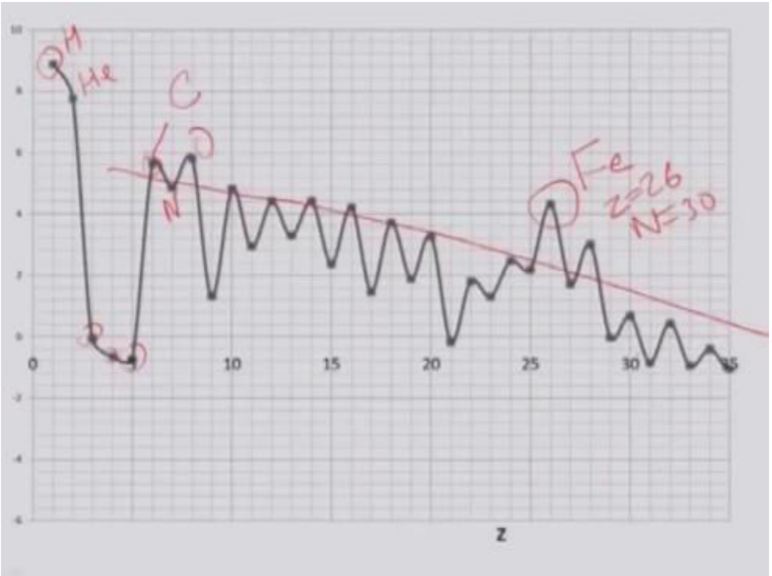

So, here you can see more clearly what happens in that first part of it hydrogen is here, and then you have helium and so on, this is lithium, then beryllium, then boron here this is carbon, this is then nitrogen and this is oxygen and so on, this will be fluorine. So, this way you can look at this diagram, and see how apart from the initial things hydrogen, and helium, and very low abundance of this lithium, beryllium and boron, this have some special meanings.

And after that in general you can see that as your going towards heavier things the abundance is going down, the fluctuations you can see going up and down, and here is that iron part z is equal to 26, N is equal to 30 that is somewhere here, and then after the sudden drop all these things you can see from here. So, let me come to the board, so that was the kind of abundance that was displayed on this graph, how scientists know about that they have all varieties of spectroscopy, all varieties of radiation that is coming from different portion of the space that they analyze.

And from that they derive all this information, and once this information is there then the theories, the models are built up. So, let us first look at this hydrogen and helium 74 percent of 75 percent roughly of hydrogen, and 25 percent of helium as I said most of it was synthesized most of this was formed during that big bang period, within few minutes of that. And after that only small changes are there, carbon the third most abundant material is carbon, and carbon is you know is very, very important for life.

So, all this carbon that has come only through this is stellar nucleus synthesis, the nuclear fusion inside different stars only their carbon can be formed. Because, during the big bang situation was not at all allowing formation of carbon, now formation of carbon itself is a very interesting thing. Because, helium is there, hydrogen is there and the temperatures are high, hydrogen is converting into helium that is in our sun and many more stars, and beyond that what happens.

Once this hydrogen core gets largely converted into helium, so that there is no more hydrogen to burn or to fuse into helium, after that the fusion reaction inside that core stops for a while that will happen in our sun some 5 billion years from now. When the hydrogen supply add in the core will be exhausted, and the temperatures are not very high.

So, that helium's can fused together, then the fusion will stop for a while and this core will starts shrinking why because, of gravitation, at present also the gravitation is there, when the hydrogen is converting into helium that time also the gravitation is there, which is trying to collapse the core that trying to shrink the core. But, then the pressure due to this energy production, the outward pressure, outward forces that are the pressure gradient which is there.

Because, of this energy production, which is going towards outwards that balances this gravitational attraction and is known of hydrostatic equilibrium. Once this fusion stops in the core and no more energy is produced, then the gravitation takes over and then the core shrinks, as the core shrinks the gravitational potential energy is converted into thermal energy, and the temperature rises.

And at a certain stage the temperature rises to a value where, helium can fuse why do you need higher temperature for a helium fusion because, of coulomb barrier hydrogen hydrogen z 1 z 2 is 1 helium helium z 1 z 2 will be 4. So, you need higher temperatures, and when those temperatures are attained then helium fusion starts are can start, now helium fusion is again a very interesting thing.

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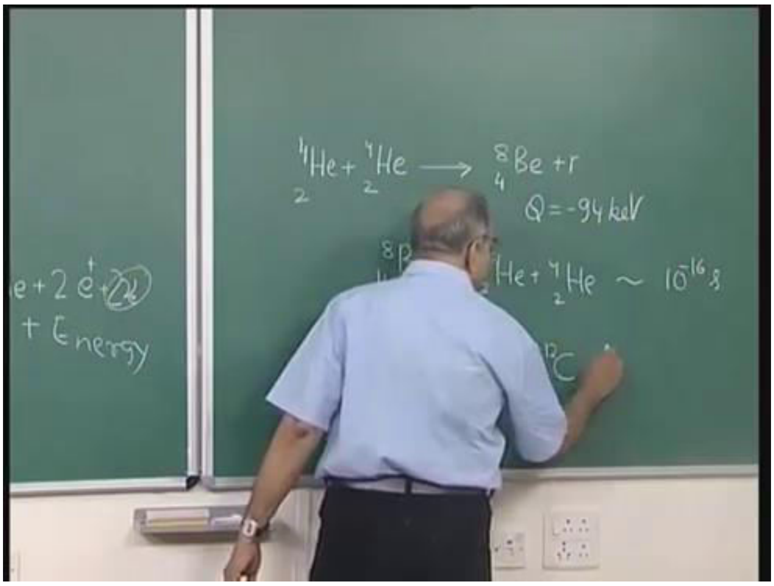

Because, if 2 helium nuclei 2 alpha particles 4 H e plus 4 H e, if they fuse if nuclear fusion takes place between these two, what product do you expect you expect 8 beryllium 4 plus gamma etcetera. Now, this is very, very unlikely because, beryllium 8 is not a stable particle, if you look at the Q value, the Q value is negative minus 94 kilo electron volts. And therefore, as soon as this 8 beryllium forms it decays into 4 H e 2 plus 4 H e 2 and the time scales are something like 10 to the power minus 16 seconds.

So, that is why you do not have 8 beryllium nucleus is not a stable nucleus, so almost immediately 10 to the power minus 16 minus 17 seconds at that time scale, it converts back into 4 H e plus 4 H e. And remember you do not gain energy by this fusion because, helium 4 is an extra ordinarily stable particle, the binding energy per nucleon is very high here. And so even though you are going towards higher mass value, you are not gaining anything into energy, so this reaction is very, very less probable.

And if this reaction does not take place then nothing else will take place because, it has to start from here. So, this was the puzzle, this is also known as this bottleneck this bottleneck, so this was the puzzle, but then people realize scientist realize that at these high temperatures even if this beryllium is unstable and it will decay back into 2 alpha particles.

But, at these high temperatures there could be some thermal equilibrium between 2 alpha particles and 8 beryllium, at higher temperature the higher energy levels are also populated alright e to the powers minus capital E by k t that kind of distribution. And since if the densities are very high, and this 8 beryllium forms for even a tiny period 10 to the power minus 16 or minus 17 seconds, if the helium concentration around is very high, and the temperatures are high.

Then it is possible that before it decays it has formed and then a before it decays, it needs another alpha particle, another helium nucleus and that makes 12 carbon, it will go into or plus gamma it can be 12 carbon plus gamma. So, if the concentration of this helium nuclei around is very high, then it is possible then you one can calculate the probabilities that before it is decays into 2 alpha particles it combines with the helium, another helium nucleus and makes 12 carbon, 12 carbon in a stable, the ground state 12 carbon as such is stable.

But, then when it combine what it forms is carbon 12 in an excited state because, if you just calculate based on this reaction it turns out that the high abundance of carbon one cannot explain. So, that high percent is that high concentration of carbon in universe will not come out according to the theories of fusion and the theories of physics, if we just think that whenever this helium combines with this it will make carbon.

Because, the production rate will be much small, and to understand how that high concentration of carbon is coming great scientist hoyle proposed or predicted that this carbon 12 must have an excited state with energy is close to this 3 alpha energies. So, that the q value matches, and there is a resonance in reaction, you remember resonance in reactions if the initial constituents in a reaction nuclear reactions, and the final product in the reaction there is a level. So, that the energy matched, then the probabilities of that reaction enhance many, many orders higher.

So, it was the suggestion from hoyle that this carbon must have an excited state, and this reaction leads to that excited state through resonance. So, that the probabilities are high, and that is why we get that much of carbon and the calculations was that this energy should be and that energy should be somewhere around 7.3 M e V or, so this is for carbon 12 energy. That should be an energy level somewhere around this value, so that a resonance can take place, so that the cross sections can go very high and therefore, carbon can be produced in large quantities.

This was in 1954 and then experimental search began at Caltech, and in 1957 foulard and the group found experimentally in laboratory that s carbon 12 has an excited state. So, this weather prediction and then 3 years this was 1954 and 1957 experimentally found experimental verification foulard and group, somewhere around 7.65 M e V close to that.

So, the resonance reaction takes place and the probabilities are high, but then the actual level if one calculate what is the total mass energy of this 3 alpha particles 3 helium nuclei the starting material. And what is the final rest mass energy plus this excitation energy final energy of this carbon 12 in the excited state, one find that it is slightly higher the energy of this carbons excited state is the total energy, including the rest mass energy it is slightly higher than the energy of 3 alpha particle.

And therefore, spontaneously over it would like to decay back into 3 alpha particles, but then there is a competing process. And the competing process that excited carbon 12 emits a gamma photon and comes to the ground state, and that probability is a 4 parts in 10,000. If that happens 4 parts in 10,000 rest of the time it goes into 3 alpha particles, but even if does decay through this gamma emission, then it comes to 12 carbon in ground state with energy very stable and much, much lower than this 3 alpha particles and you gain energy.

So, all that carbon that we have today on earth, in solar system and in the universe was created through this process alpha 2 alpha particles going into 8 beryllium. And before that 8 beryllium decays another alpha particle combining with it to give excited state carbon. And that excited state carbon with this small probability of coming down to ground state, the entire carbon that exits had been produced in this particular fashion. So, that is how during this helium fusion state carbon is produced our sun will do this, but it will do it some 5 billion years from now.

But, many of the stars had done it during this 15 billion years of lifetime of universe, and are doing it still. So, that is this helium fusion what happens if the helium supply in the core is exhausted, once again the nuclear fusion will stop, once again the core will start contracting, and temperature increasing for our sun or other stars of similar masses or somewhat greater masses also, the total mass is not enough to give energy is gravitational potential or energy is converting into thermal energies.

And to give large enough temperature for this carbon core to go for fusion, this helium after this helium burning phase, helium fusion phase you have mostly carbon, and some oxygen also.

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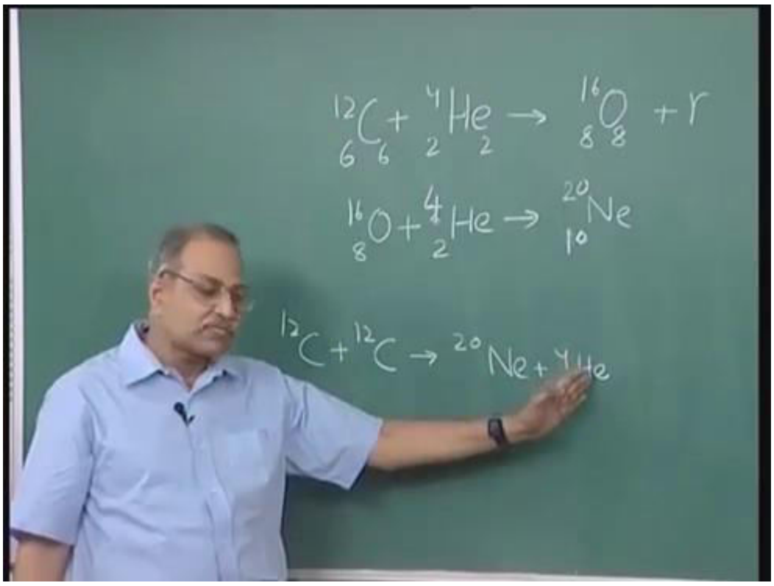

Once you have this carbon helium is converting into carbon a lot of helium and carbon is being formed, and that time you can have these kinds of relation, reaction this carbon and helium nuclei are present there, so that will make 16 oxygen 6 here and 2 here. So, 16 oxygen plus gamma, and 16 oxygen can combined with 2 and 4 helium, and that can give you 8 here 2 here, so neon.

So, these kinds of reactions can take place depending on what is the temperature, and what in the concentration and so on. So, during this helium burning phase mostly it will be carbon, but some oxygen, some neon can also get produced, once this helium supply is over and you have largely the carbon core or carbon oxygen core. Then once again depending on how much is the mass it can contract to give a temperature large enough, so that this carbon oxygen start fusing or if the mass is not large as it is the case with our sun, and many more stars in the universe the this fusion is almost off.

So, if the fusion is off then that is all you have carbon, you have synthesized carbon, you have synthesized oxygen and little bit of neon perhaps and it is over. But, we do how very heavy elements and they are formed in stars which were much more massive, and these elements are still being formed in stars which are much more massive. In those stars what happens, in those stars this core contracts this carbon core carbon oxygen core contracts temperature become high.

And at a certain stage this carbon nuclei start fusing, when carbon nuclei start fusing what can they produce several things, one is that 12 carbon plus 12 carbon can go for 20 neon plus 4 H e it can also go for 24 magnesium. But, since alpha particle helium nucleus is very stable it is binding energy per nucleon is very large, so this reaction is more probable, so this. And important thing is that you again get this helium nucleus through this reaction, helium was already consumed and you had only carbon core or oxygen core, carbon oxygen core.

But, now fresh helium is being produced and when fresh helium produce is produce it starts combining with that. So, all that reaction will keep on going oxygen and so on, so with oxygen it will go for neon with neon it will go for magnesium, so these kinds of reactions will go on. And this process will keep on going once this carbon core that fuel is exhausted, outside layers other things are going on, if it is carbon core which is giving fusion here, outside that you will have helium layer which will be fusing.

And after that you will have hydrogen layer which will be fusing and after that you have colder hydrogen. So, that will be the structure, and this structure more and more layers will formed in the mass of the total star is high, at the end of it you have something like 28 silicon core. So, all this carbonates etcetera this process will go on from 16 you will go to 20 to 24 and 24 to 28 that is 28 silicon.

And now the coulomb barrier is very fusion is becoming more and more difficult, but fortunately the same alpha production of alpha and absorption of alpha that process can still go on. If you want to fuse 228 silicon n plus 28 silicon is very, very difficult, but that 28 silicon and so many gamma photons are there. So, even that those gamma photons can disintegrate this 28 silicon, and create alpha particle.

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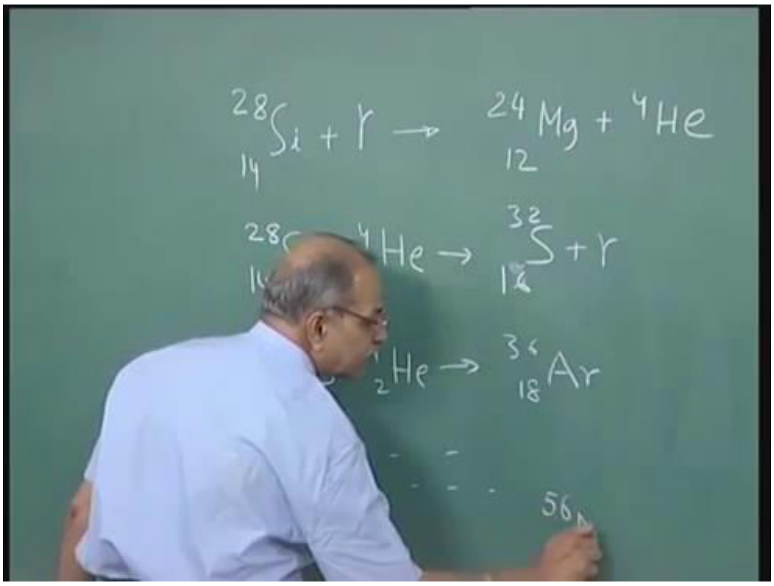

So, at those high temperatures 28 silicon, and gamma lot meaning gamma photons are there we have radiation. So, it can disintegrate 24 M g and plus 4 H e, this is 12 and this is 14, and once this 4 H e is there that can combined with 28 silicon, remember we have a lot of 28 silicon in the core. So, one nucleus combines gives you 1 helium nucleus, and this helium nucleus combined with another silicon which is present there, so 4 H e this will give you sulphur 32 S.

And similarly this 32 S 16 this 32 S will combine with 4 H e 2, and that will give 36 argonne and so on. So, this process can go on, and ultimately what you get is 56 nickel just keep on adding alpha particles, alpha particles are continuously produced there and consumed there. So, you get this 56 nickel and then this beta decays in fact, twice once it will go to cobalt, and then it will go to iron 28 here, 27 here and 26 here, and this is that most stable nucleus.

So, if these size of the star is quite large, so that it can reach to this position to this state, then this 56 iron can be produced as the end product kind of end product, nickel some nickel some iron and so on. And after that once for all the nuclear fusion as stopped in the star, so up to this iron nickel state which is the first part on that abundant diagram. So, that is created in this fashion, now this is the main process of nuclear fusion in the stars, and all these elements which are there they have even z.

And therefore, the concentration the abundance of this even z elements are higher than the odd z elements in their neighborhood. Because, this is the main process with which the elements are being produced, new nuclei are being produced, then how that those odd z nuclei are produced, they are produced in some kind of stray reactions that take place here and there. So, I will show you on the screen what kind of reactions take when you have these main things are going on in the site once in a while some other reactions take place giving you an odd value of z look at your screen.

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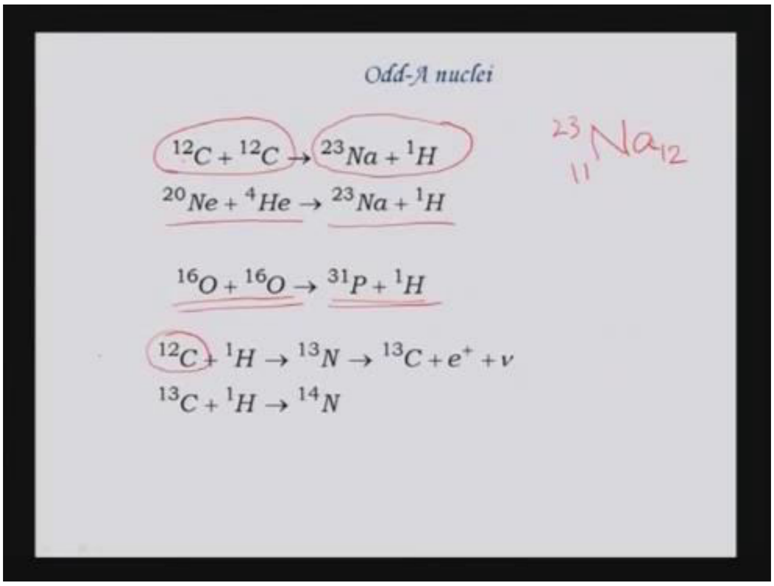

So, can see here this carbon plus carbon, normally it should be go for 24 magnesium, but it does go sometimes 23 sodium plus proton. So, 23 sodium z is equal to 23 sodium is z is equal to 11 and this is 12 a constituent of our common site is produced in this fashion, similarly 20 neon plus 4 H e that gives 23 sodium once again and then plus a proton. Here 16 O plus 16 O 32 sulphur is the normal thing which you can expect, but you also have 31 phosphorous plus this proton.

So, this way this phosphorous is produced, 12 carbon this is right in the helium burning phase 12 carbon are even in hydrogen burning phase, if you have the c n o cycle going on this 12 carbon taking 1 proton going to 13 this nitrogen, and that decaying to 13 carbon, and then that combining with proton to give you 14 nitrogen. So, in some of the reactions sometimes once in a while these odd z elements are also formed and therefore, their abundance is quite low.

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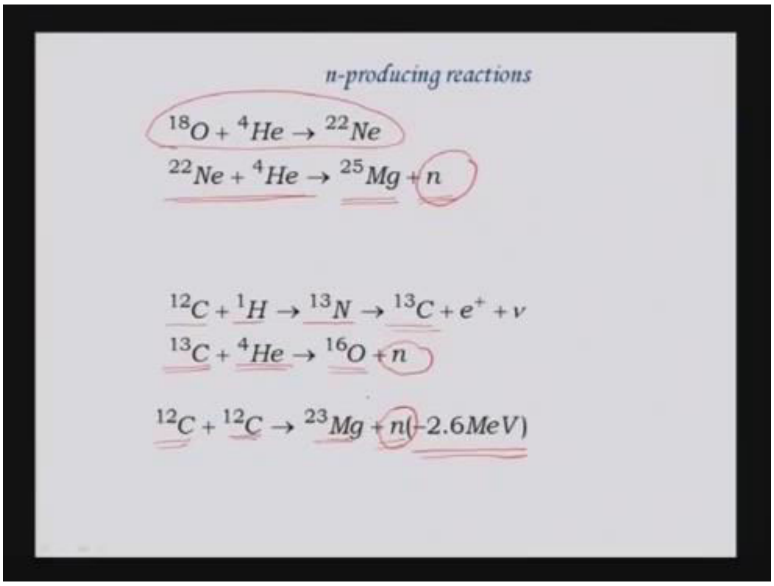

There are some very important reactions which I will show here, here you have 18 oxygen plus 4 H e giving 22 neon. And this 22 neon when combined with an alpha particle it gives 25 magnesium plus neutron, why this is important, this is important because, this reaction is producing a neutron. We will see that this neutron plays very, very important role in nucleosynthesis, similarly here this carbon plus proton gives 13 nitrogen that decays into 13 carbon.

And that 13 carbon if that combines with 4 helium that gives 16 oxygen plus neutron, similarly here this 12 C plus 12 C can also give you 23 M g plus neutron of course, this is energy consuming it is energetically not favorable. So, minus 2.6 M e V, so the initial energies are lower and the final energy is rest mass energies are larger, but then at high temperature it is possible, at high temperature it is possible this reaction, so neutron is produced here alright.

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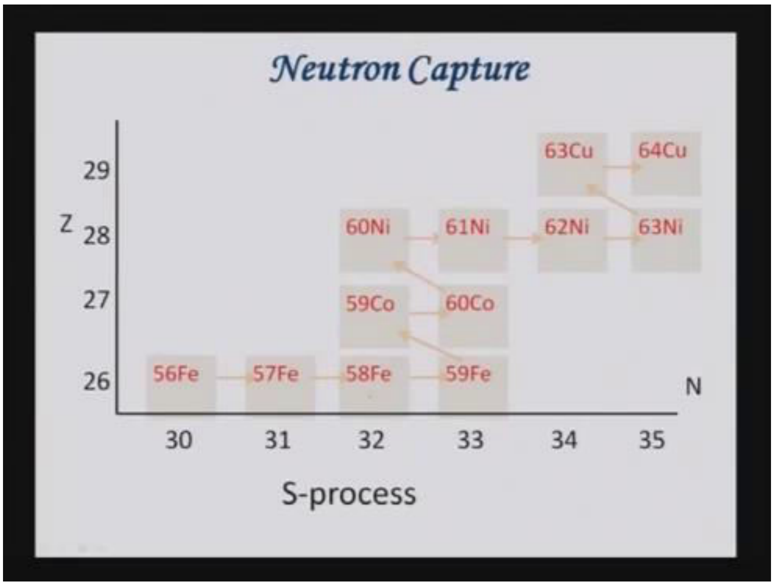

So, these are some of the once a wide type of reactions which give me more elements, more neutrons sometimes they produce neutrons, sometimes they produced these odd a nuclei and so on. Now, this sequence or this process which I described that explains me the formation of nuclei with that a value less than 56, less than equal to 56 or around that up to their iron nickel thing from hydrogen helium to this iron nickel that we can understand through this nuclear fusion going inside the core of a star.

But, then will in the periodic table we have many more elements beyond this 56 iron, 56 iron is only in 3D in the periodic table that 3D block in that period 4'th period you have iron and after that you have, so many element you have whole 4D block and 5D block and then rare earth and actinide, transuanium and so on. How are those elements formed, how are those nuclei formed, they cannot take place through this kind of fusion.

Because, if you remember your binding energy per nucleon versus capital E diagram it is highest at this 56 iron nickel region and after that it falls. So, nucleus fusion will not create all those things, how is that done that is done by a process which we called neutron capture process. Once you have certain stable nuclei, and if you have neutrons present, then these neutrons get can into the nuclei and form a somewhat higher heavier nucleus it is in fact, when neutron gets captured you do not produce a new element, you only produce a new isotope.

But, total mass number capital A that increases, so this can be one process, but then you do not need that coulomb barrier penetration. So, the best part of this neutron capture is that you do not need that coulomb barrier because, neutron itself is a charge less particle, and then it can just go and sneak there. So, if you have a regular supply of neutrons, then these neutrons can get absorbed into the existing nuclei to give you heavier elements, and that is why these neutrons are important on the screen I showed you that there are certain reaction which produce neutrons.

Now, these reactions are important because, in the early stages they are they are produced neutrons, and these neutrons at the later stages can sneak into those nuclei to give you heavier and heavier and heavier nuclei. So, I will stop here, and next lecture we will elaborate more on this neutron capture process, and synthesis of elements synthesis of nuclei heavier than that iron nickel region.