# Nuclear Astrophysics

**Prof. Anil Kumar Gourishetty**
**Department of Physics**
**Indian Institute of Technology – Roorkee**

**Module - 02**
**Lecture – 06**

## Evidences of Nucleosynthesis-III and Mass Gaps

Welcome students, to today's lecture in the course of Nuclear Astrophysics. Today is the sixth lecture in this course. I hope you got some idea about the objectives of this course of Nuclear Astrophysics. What did we discuss in the previous lecture? Let me provide a brief summary. The evidences for the nucleosynthesis in stars that is what I discussed in the last class. What are the evidences I have discussed? The discovery of $^{99}$Tc.

The spectrum of Tc in the recorded spectrum when some of the lines was designated as Tc it had given strong evidence that nuclear reactions are still taking place. Why so much importance to the discovery of Tc which has changed the way researchers looked at the evolution of universe because no isotope of Tc is stable. All isotopes of Tc are unstable.

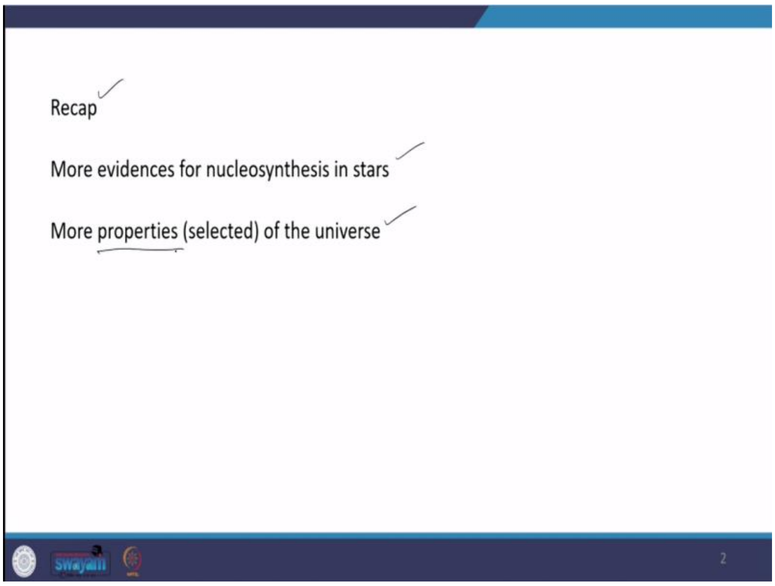
So, if the elements were produced much, much earlier than the half-life which is of the order of $10^5$ or $10^6$ years which is nothing in front of cosmological time scales, even now in the present times we are able to detect them. The half-life is $10^5$ years so before 1 lakh year this element must have been produced, it is a very small amount of time tough.

So, that shows that the synthesis of elements is continuous process within the stars. Another discovery is of $^{26}$Al and its decay scheme was discussed in detail in the previous lecture. The discovery of gamma line from Al has also provided strong evidence that synthesis of nuclei is a continuous process within the stars. In today's lecture let me provide some more interesting evidences for nucleosynthesis. After that I will discuss a few more selected general properties of the universe. So, what was the first general property I have been discussing? Elemental abundance curve.

As part of that elemental abundance curve I have covered the content related to evidence of nucleosynthesis and after all these elements like $^{26}$Al, $^{99}$Tc discovery which provided a strong support to the nucleosynthesis in stars, the general features of elemental abundance curve we have seen, but there are some more selected general properties of the universe.

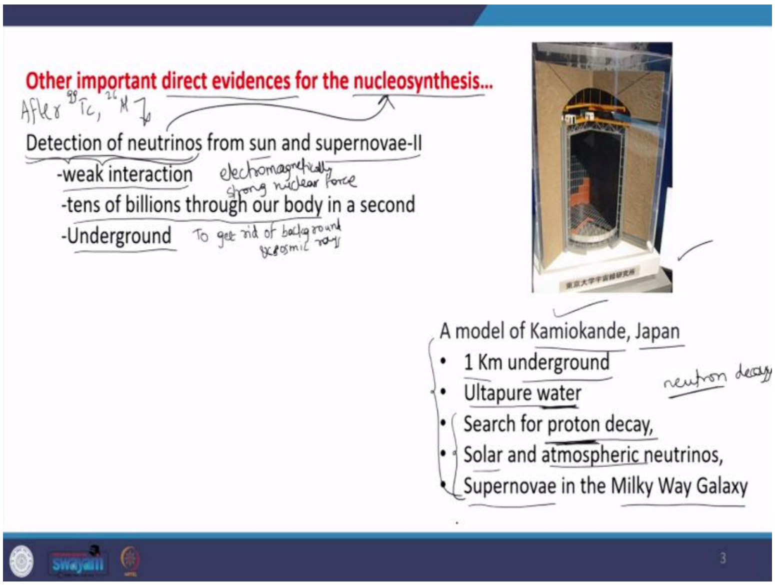
What are those? I will discuss in today’s lecture, but before that some more evidences for nucleosynthesis in stars.

**(Refer Slide Time: 04:04)**




So, I had discussed in the last class the discovery of Al and Tc and more evidence for nucleosynthesis in stars I have to discuss. When I say more properties what are the first property I have discussed. Elemental abundance curve and these are the properties which are relevant for Nuclear Astrophysics mainly.

**(Refer Slide Time: 04:33)**




What are the other important direct evidences for nucleosynthesis, which is the formation of nuclides because of the reaction between two nuclei which is happening continuously within the stars? What is the third evidence after $^{99}$Tc, $^{26}$Al, the third evidence is detection of neutrinos, which were observed the site is either sun or mainly supernovae.

Neutrinos from other parts of the universe have not yet been absorbed in a majority way. So, what are neutrinos and how they were detected? They were coming either from sun or supernovae. How the detection of neutrino is linked with the nucleosynthesis we have to understand this.

See neutrinos are particles which does not interact by electromagnetically or strong nuclear force, so it is extremely difficult to detect. Gamma rays do not have charge and mass, but they are electromagnetic in nature.

They undergo either photoelectric effect or Compton scattering or pair production mostly. So, gamma rays can be detected if you use a material, interacting with which this probability for photoelectric effect, Compton scattering and pair production is present in a large manner. Those materials processing large probability for these three processes or one of these three processes can be used for the detection of gamma rays.

The outcome of these three processes is mainly electron. In the photoelectric effect gamma rays knock out mainly K shell electron which is just near to the nucleus and this electron becomes a free electron, which is playing role in the detection of gamma ray. In Compton scattering there also some of the energy of the gamma rays get transferred to the loosely bound electron and that has become free which is undergoing scattering with some angle and gamma rays undergoing scattering with some angle and electron is undergoing some recoil. One detects this electron. Then in pair production gamma ray is depositing its energy in the presence of nuclear field then that energy is getting converted into electron and positron pair production.

So, this electron with negative charge is becoming the reason for the detection of gamma whereas electron with positive charge that is positron will have a deal with the electron in its surroundings and it undergoes annihilation. So, because of annihilation again two photons are coming out and these photons will again undergo either photoelectric or Compton, of course not pair production because 511 keV is much less than the pair production required energy.

So, this is how gamma rays are detected. What about alpha particles? They have mass, they have charge and they undergo Coulombic interaction, so, excitation, ionization take place. Beta rays are electrons, protons irrespective of their charge they have mass and some charge either negative or positive. So, the presence of mass and charge allows the charger particles like electron, protons, alpha particles and heavy ions to get detected by a Coulombic interaction. I hope all of you remember the basics of beta decay.

So, when I say beta decay it could be either beta minus or beta plus and when one proton gets converted into neutron or one neutron gets converted into proton what will happen either negatron that is electron with negative charge or positron that means electron with positive charge will be emitted. Along with that you are very well aware that neutrinos are also emitted in beta decay.

These neutrinos they are the by-products of large number of nuclear processes within the stars. Neutrinos also do not have any mass, they do not have any charge, of course lot of research is going on regarding its mass and charge. Right now at this stage you can assume that it has no charge and mass, at this stage it is sufficient to understand.

And they cannot undergo electromagnetic interaction like gamma because gamma also does not have any electronic charge and mass. So, neutrinos because of their inability to participate in electromagnetic or Coulombic interaction it is extremely difficult to detect them.

When neutrinos are emitted they cannot deposit their energy within the star like alpha particles or neutrons or protons, electrons. Whatever Nuclear radiation is emitted as part of the nuclear process they can always deposit some energy, but neutrinos cannot. It is very difficult to interact with the matter so they can easily escape from the star without any resistance.

So, the neutrinos coming out from different part of the universe, when researcher tried to detect them using some experimental set up what is it that I show you. So, detection of neutrinos when it is possible what does it mean? Nuclear processes are happening and neutrinos detector they also have given enough evidence are not going into the details because the objective of the lecture in this Nuclear Astrophysics is to give you some kind of overview regarding the evidence of Nuclear synthesis.

Though in later part of the course I will discuss some detailed physics aspects of the course. So, for time being it is sufficient to believe because enough research has been done in this regard. Neutrinos were detected on Earth using some experimental facilities and because neutrinos were detected we can say confidently that nuclear processes are happening continuously in the stars and different parts of the universe though it is weakly interacting.

Remember neutrinos are the byproducts of the nuclear process. Now maybe you are aware of this every second tens of billions of neutrinos are passing through our body, we do not have clue. Through my body neutrons are passing, I do not have any kind of feeling that neutrons are passing through me because it hardly interacts with the matter.

So, many neutrinos are reaching Earth every second and even through our body in every second tens of billions of neutrinos are passing. That is the reason. The detection of neutrinos, as they cannot be detected so easily, the facilities are mainly below the Earth. So, the underground facilities are used to detect the neutrinos to get rid of background and cosmic rays.

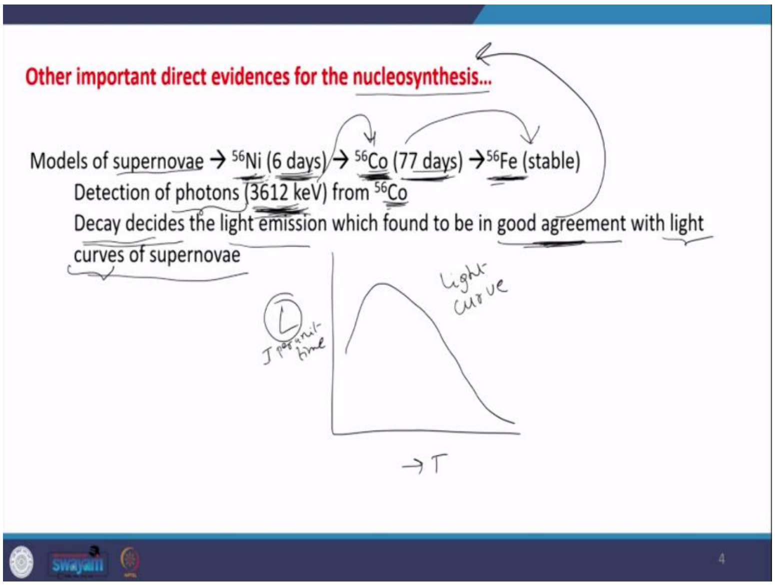
It is very difficult to separate the contribution of the background from the contribution of neutrinos. So, it is essential to go to a region where background is almost zero. So, either you prepare or you design a laboratory within a big hole within big hill and setup a laboratory there because this hill will protect the facility from the background and cosmic rays or you go to the underground.

So, this is how neutrinos can be detected if we acquire the data for long time. Now this is one of the important facilities across the world which is Kamiokande in Japan. It is 1 km underground. The detection medium is ultra pure water. To increase the probability of detecting the neutrino one has to go for very high quality detection medium that is water. Why only water, all those things I have not discussed because that is not the purpose of this lecture.

The purpose of the slide is to show you how neutrinos have played an important role in establishing the fact that nuclear processes are still taking place. The purpose of this Kamiokande facility in Japan is not only to detect the neutrinos, but also to look for decay of proton. Neutron decay is well known. Its half-life is of the order of minutes and free neutron can decay giving us to proton.

But for free proton it is almost stable. So, if you want to understand the decay of proton and the neutrino coming out from proton we need to use this kind of facility. This facility is also designed to detect the neutrinos from sun and the atmosphere, not only that it keeps an eye on the supernovae in the milky way galaxy. So, this particular facility of Kamiokande in Japan is working to meet these three objectives: the studies of proton decay, the studies of neutrinos from sun and atmosphere and the properties of the supernovae. So, I took the liberty of discussing one important facility for the neutrino detection. More details can be found in the website of this facility.

**(Refer Slide Time: 16:31)**




Now, let me go for another important direct evidence for nucleosynthesis, after that I will stop discussion on evidence for nucleosynthesis. So, till now how many evidences I have discussed? Number one Tc discovery, number two $^{26}$Al number three detection of neutrinos which is very difficult to detect. The fourth evidence which is the last one it looks like this.

When researchers try to model the supernovae the models predicted that during the explosion stage of star $^{56}$Ni is ejected. The ejection of $^{56}$Ni whose half-life is say 6 days and which is radioactive leads to the formation of $^{56}$Co. Now I am not discussing how people have measure this half-life of this nickel, all those things the details will be discussed later. Its half-life is also 77 days, not like years or light years and this $^{56}$Co is again radioactive. So, it tries to achieve the stable status and by forming Fe finally the stability is reached. $^{56}$Fe is very stable.

So, what is so important about this evidence? $^{56}$Co is decaying to $^{56}$Fe and because of this transformation from $^{56}$Co to $^{56}$Fe, a gamma ray is emitted whose energy is 3,612 KeV. This decay decides the emission of light which is found to be in good agreement with the light curve of the supernovae. I am using a word light curve. So, basically when you draw luminosity what is luminosity my dear energy emitted per unit time joules per unit time if you take some kind of unit for luminosity then normally it looks like this, this is called as light curve.

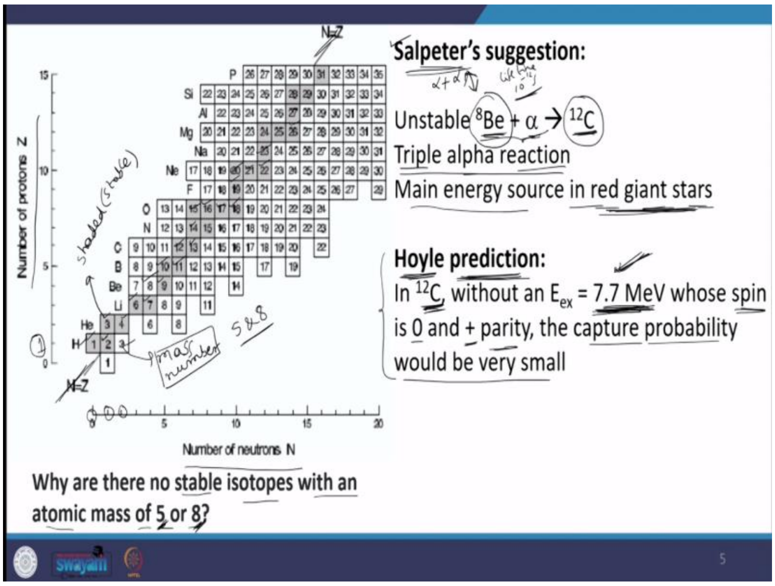
I am drawing one approximate light curve. People have plotted theoretically and calculated this kind of light curve then it required the presence of decay from nickel to cobalt, cobalt to iron. See the good agreement between the light curve calculated from theory and light curve measured. That good agreement provides a strong evidence that nucleosynthesis is continuous process in the stars.

I hope it is bit clear to you. By saying that a good agreement between the light curve calculated for supernovae using theoretical models and measurements and whatever concepts are included in the theoretical predictions that is decay of $^{56}Ni$ to $^{56}Co$ and $^{56}Co$ is giving 3.6 MeV gamma and then it is reaching to $^{56}Fe$, it provides a strong evidence that nucleosynthesis is continuous process within the star.

So, with this let me close the discussion on evidences for nucleosynthesis. So, how many evidences I have discussed in lecture? Discovery of Tc, discovery of $^{26}Al$.

Neutrinos is the third evidence, fourth one is the gamma ray whose energy is 3.6 MeV emitted by $^{56}Co$. It means the formation of $^{56}Co$ is still taking place, that means synthesis of elements is going on continuously within the stars. So, I hope you got enough idea about the evidences for nucleosynthesis. As part of discussion on selected general properties of the universe I have started discussing elemental abundance curve and how the curve looks like, what are the important features of this curve. Then I discussed this list of evidences for nucleosynthesis. So, one property of the universe is over.

**(Refer Slide Time: 23:15)**




Before discussing the second property I want to discuss one more important thing in the course. Please try to understand this and the detailed discussion on this particular topic will come after several lectures. Detailed mathematics will be done at that time. Right now because I am discussing the elemental abundance curve and discovery of various elements, let me try to discuss one of the most fascinating concepts in the field of Nuclear Astrophysics. In this slide in this diagram number of protons on y axis. Number of neutrons on x axis you can see N = Z curve it is a straight line this is a straight line fine and can you see hydrogen 1, 2, 3 number of protons and number of neutrons is on x axis, the boxes contain mass number.

In this diagram we can see the shaded boxes denote stable isotopes. For example hydrogen and deuterium, they are stable, tritium is not. $^{3}$He, $^{4}$He and Li with mass number 6 and 7 are stable, but not 8 and 9, that is why they are not shaded. $^{7,8}$Be are not shaded so they are unstable, only $^{9}$Be is stable that is why the box is shaded. What is so special about it? You can see stable isotopes with all mass numbers 1, 2, 3, 4, 6, 7. Where is 5? 8 is also missing. Then 9, 10, 11, 12, 13, 14, 15, 16, 17, 18….. are there.

Stable isotopes with mass numbers 5 and 8 are not visible here. How nucleosynthesis could have been proceed without the existence of stable isotope with mass number 5 and 8 that was a mystery for long time to the researchers. Synthesis of elements is happening one after the other. It is not like suddenly mass number 10 is giving rise to mass number 50.

It is a step by step process. Now let me discuss some salient features of this diagram. Why are there no stable isotopes with mass number of 5 or 8 that is a question. Why there is no stable isotope with mass number 5 and 8? Researcher has suggested $\alpha$+$\alpha$ when give rise to $^{8}$Be which is highly unstable its life time is very low, 10– 12 sec.

Immediately it undergoes decay into two $\alpha$. But Salpeter suggested there is always some probability for this $^{8}$Be to react with another $\alpha$ particle even though it has very less life time.

Of course you can ask on one hand I am saying half-life of $^{8}$Be is extremely less, at the same time I am saying it can also react with alpha particle, where is the time available? Time is available provided the transit times between the two alpha particles is lesser than the life time of the $^{8}$Be and when huge number of alpha particles are there in the star before $^{8}$Be undergoes a decay this alpha particle can react with $^{8}$Be giving rise to stable element $^{12}$C.

How it is addressing my question why there are mass numbers 5 and 8? So, $^{8}$Be+ $\alpha$ giving rise to $^{12}$C. That is why this is called as triple alpha reaction, even though it is triple alpha reaction it is basically two step process. Number one $\alpha + \alpha$ is giving rise to $^{8}$Be number two $^{8}$Be plus $\alpha$ is giving rise to $^{12}$C.

Now this reaction has been proved to be main energy source in red giant stars. What are the red giant stars? I will discuss very soon wait for some time. Then researcher Hoyle predicted for which he won the noble price, that the probability for alpha to react with $^{8}$Be will be very less and the resultant abundance of $^{12}$C is not matching with the observed abundance.

I repeat whatever probability of the reaction people have assumed is not sufficient to reproduce the abundance of the $^{12}$C then Hoyle has predicted the rate of triple alpha reaction should be high, only then the calculated abundance can match with the observed abundance. For this to happen he said that in $^{12}$C there has to be a energy level whose energy is 7.7 MeV that also the spin should be 0 and parity should be positive.

No what is this spin and parity? As I said in one of the previous lecture it is helpful to understand the course if you know the concept of shell model. If you are not aware of it, it is not very difficult to understand please go through the textbooks. So, liquid drop model you might be aware of whatever disadvantages in the liquid drop model are there they have been addressed mostly using shell model.

And if you know shell model it is not a difficult thing for you to understand the concept of spin and parity for each level of the nucleus. So, Hoyle has predicted that in $^{12}C$ if there is no 7.7 MeV state then the probability for the capture will be extremely small and it is not possible to match the calculated abundance with the observed abundance. So, because of the prediction of Hoyle later it was experimentally confirmed that yes indeed energy level whose range is 7.7 MeV exists in the decay scheme of $^{12}C$.

It is not very easy to determine the energy level of 7.7 MeV in $^{12}C$. So, this slide tells us the synthesis of elements having stable and unstable isotopes in nature and what are the corresponding mass numbers because I have discussed Tc, $^{26}Al$, Ni, Co and Fe. I thought I should give some flavor about the triple alpha reaction which is the energy source for one particular type of stars that is red giant star.

So, hope you have understood how the bypass in nucleosynthesis could take place at mass numbers 5 and 8. Even though there is no stable isotope having mass number 5 and 8, $^{12}C$ could be formed because of the tripe alpha reaction. More details will be discussed in coming lectures. Thank you very much for your patience.