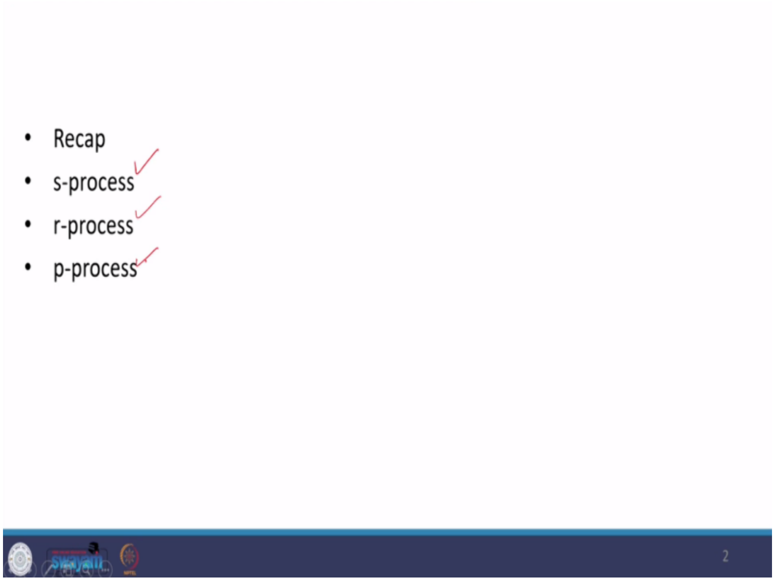
Nuclear Astrophysics
Prof. Anil Kumar Gourishetty
Department of Physics
Indian Institute of Technology – Roorkee

Lecture – 30
S, R and P-Process

Welcome students. I have been discussing the salient features of nucleosynthesis beyond iron peak. In the last class, I have discussed how the abundance curve is supporting the idea of neutron capture cross section as the responsible process for the synthesis of elements except very few nuclides which we call as p nuclides. It is the neutron induced reaction which is giving rise to the synthesis of elements beyond iron.

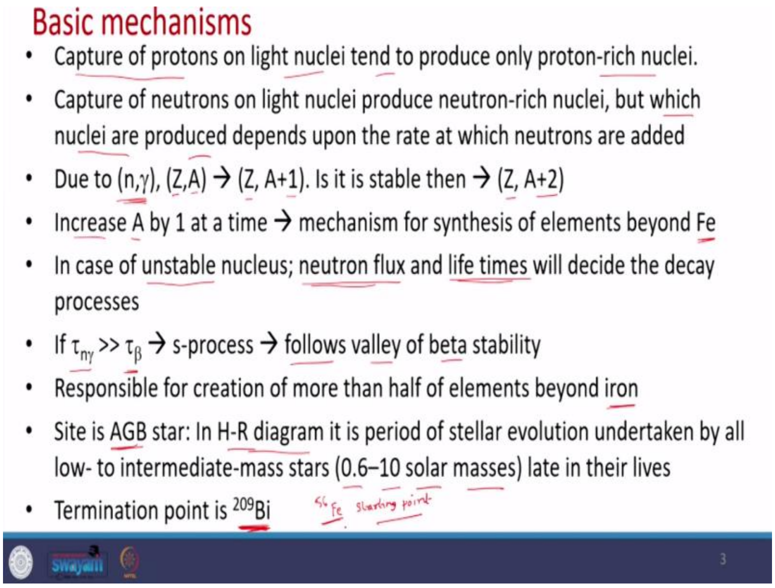
Now it is the time to go forward to discuss the various processes which are responsible for the synthesis of elements as part of neutron induced reaction.



- Recap
- s-process ✓
- r-process ✓
- p-process ✓

So, as part of this, I will discuss s-process, then r-process and then p-process in today's lecture. I am going to discuss the salient features of these three processes which take place after the iron peak elements nucleosynthesis. What is the basic mechanism underlying all these s, r and p processes? Remember, we are discussing about the neutron induced reactions.

So, I will be focusing on s and r process which comes under the category of neutron induced reactions.



Basic mechanisms

- Capture of protons on light nuclei tend to produce only proton-rich nuclei.
- Capture of neutrons on light nuclei produce neutron-rich nuclei, but which nuclei are produced depends upon the rate at which neutrons are added
- Due to (n,γ), $(Z,A) \rightarrow (Z, A+1)$. Is it is stable then → $(Z, A+2)$
- Increase A by 1 at a time → mechanism for synthesis of elements beyond Fe
- In case of unstable nucleus; neutron flux and life times will decide the decay processes
- If $\tau_{n\gamma} >> \tau_{\beta}$ → s-process → follows valley of beta stability
- Responsible for creation of more than half of elements beyond iron
- Site is AGB star: In H-R diagram it is period of stellar evolution undertaken by all low- to intermediate-mass stars (0.6–10 solar masses) late in their lives
- Termination point is ^{209}Bi ^{56}Fe starting point

Capture of protons on light nuclei tend to produce only proton rich nuclei. In the same way, capture of neutrons on light nuclei produced neutron rich nuclei. Which nuclei are produced, depends on the rate with which the neutrons are added.

Due to the most widely occurring neutron induced reaction (n,γ), a nucleus having atomic number Z and mass number A is transformed (Z, A + 1). Now the question is whether this nucleus, having atomic number Z and A + 1, is stable or not. If it is stable, then it will capture another neutron and it will transform into A + 2. This means there is an increment in mass number by one at a time. This is the mechanism for synthesis of elements beyond iron.

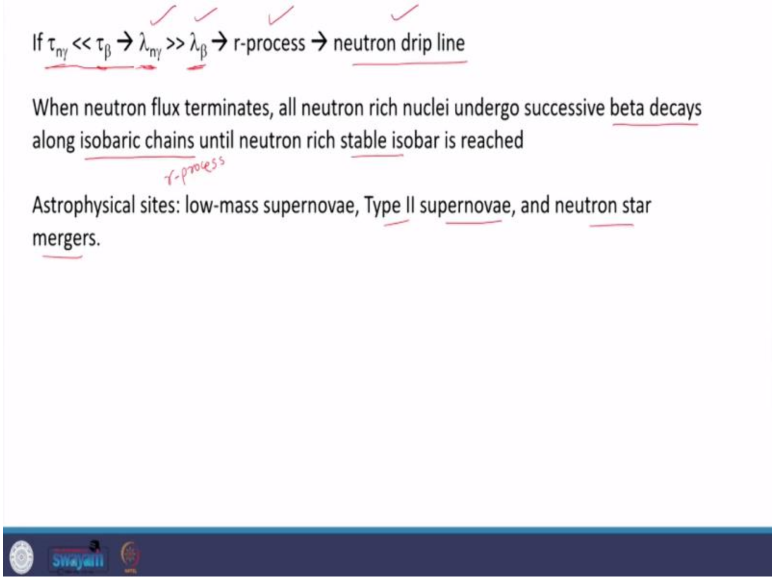
If the nucleus formed because of the neutron capture is unstable, it has to undergo decay. Whether this decay will be same in all types of situations or not?

The processes which are happening after the formation of unstable nucleus, are controlled by two important parameters. These two quantities are neutron flux, i.e., the flux with which neutrons are emitted within the star; and the life time of the unstable nuclei. These two parameters play very important role in deciding whether the process is s-process or r-process. We will write abundance evolution equation corresponding to these two processes and see what interesting features people have observed experimentally.

If the lifetime corresponding to the neutron capture reaction is greater than lifetime of the beta decay, we call this as s-process and it follows valley of beta stability. This s process is responsible for creation of more than half of the elements beyond iron. The astrophysical site of this s-process is AGB star. Please recollect the HR diagram that I have discussed in the initial stage. In HR diagram, it is the period of stellar evolution undertaken by all low to intermediate mass stars. It is about 0.6 to 10 times the solar mass. ^{56}Fe acts as a seed nucleus, which will initiate this s-process.

Iron 56 is the starting point and it goes on up to the Bismuth 209. Beyond Bismuth 209, whenever any unstable nucleus is formed, the decay is not by a specific process. It is not beta minus decay, as the separation energy is available for alpha particle.

So, because of the emission of alpha particles from the unstable nuclei beyond Bismuth 209, we can consider the termination point of the s-process as Bismuth 209.



If $\tau_{n\gamma} << \tau_{\beta} \rightarrow \lambda_{n\gamma} >> \lambda_{\beta} \rightarrow$ r-process → neutron drip line

When neutron flux terminates, all neutron rich nuclei undergo successive beta decays along isobaric chains until neutron rich stable isobar is reached

r-process

Astrophysical sites: low-mass supernovae, Type II supernovae, and neutron star mergers.

Now, what if the lifetime of the neutron capture reaction is less than the lifetime of the beta decay? So, if the time between the capture of successive neutron induced reactions is less than the life time of the beta decay or the decay constant of the (n,γ) reaction is greater than the decay constant of beta decay, i.e.,

$\tau_{n\gamma} \ll \tau_{\beta} \rightarrow \lambda_{n\gamma} \gg \lambda_{\beta}$

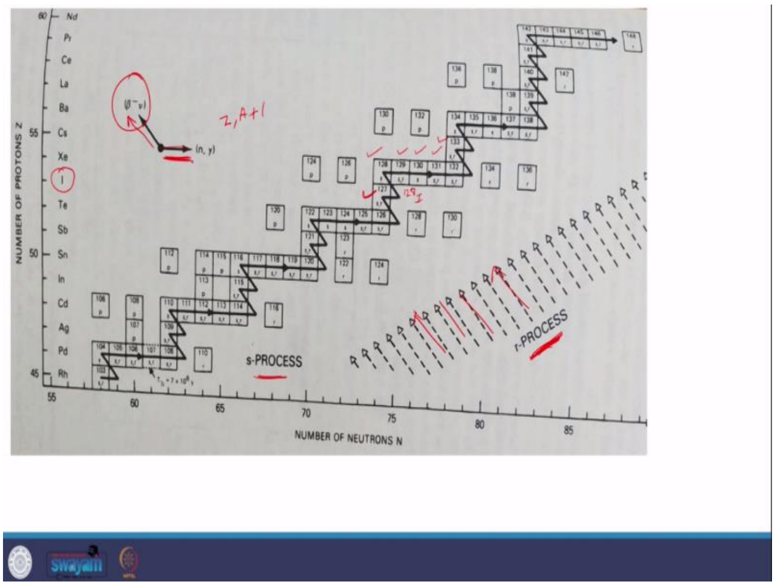
there would not be time available for the unstable nucleus to undergo decay. If neutron flux is more, unstable nucleus will not get enough time to undergo decay even though it is unstable. Most of the unstable nuclei will capture the neutron before they undergo decay because enough neutrons are available because of the high neutron flux.

Because they are taking place at the high temperature region, i.e., beyond one gigakelvin, we call this process as r-process. It absorbs the neutrons continuously until the flux is over.

The limit to which this process takes place is neutron drip line. The r-process goes towards the neutron drip line whereas s-process lies close to the stability curve.

When neutron flux terminates, all neutron rich nuclei undergo successive beta decays. This successive beta decay will stop only when an unstable nucleus becomes stable nucleus. These stable nuclei which are produced because of the successive beta decay starting from the neutron drip line, are called as r-nuclei and this process is called as r-process.

Astrophysical sites for the r-process is low mass supernova, type 2 supernovae and neutron star mergers.



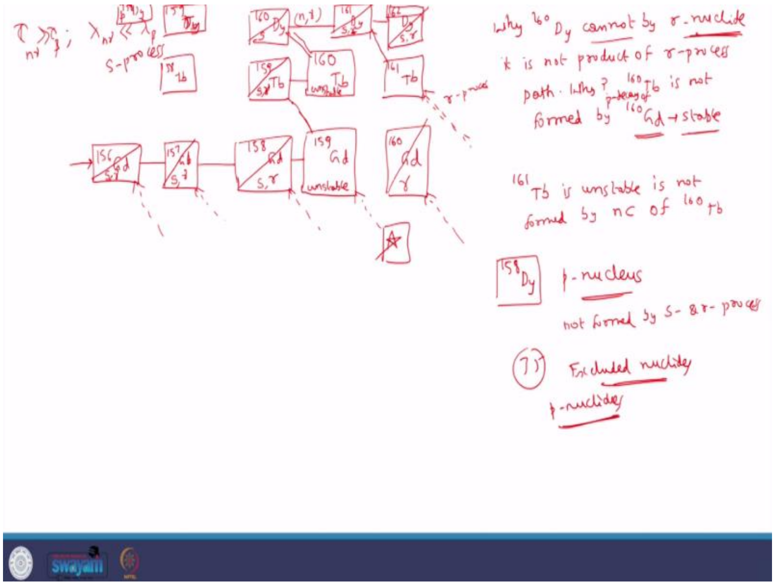
So, in this diagram, try to have a look where is r-process and where is the s-process. S-process is close to the stability curve and r-process is near the neutron drip line. Let us take an example of Iridium. If its stable isotope is 127. When neutrons are available it becomes 128. It is unstable and undergoes beta minus and when it undergoes beta minus, you will observe Xenon-128.

Xenon-128, being stable, will capture a neutron to give Xenon-129. Because it is stable, it will capture one neutron and give rise to Xenon-130. It is again stable. So it captures neutron and gives Xenon-131. It captures neutron because it is stable. In this s-process, decay constant of beta is higher than the decay constant of (n,γ). So. it will undergo beta decay and give rise to Caesium-133. Caesium-133 is stable. From now onwards, when I say stable nucleus, it may not be exactly stable, but the half life is so long that it is okay to consider that nucleus as a stable nucleus. Those nuclides, which are not perfectly stable, also participate in the s process because there is enough time available for the nucleus to undergo beta minus decay. This path which I have explained from I-127 to Caesium-133 is called s-path.

So, these nuclides are designated by s for sure. I-127, Xenon 128, 129, 130, 131, 132 and Caesium-133 are all designated with s, because they are able to capture the neutrons emitted by other reactions.

We can see the arrow representation. Horizontal arrow denotes (n,γ) reaction. And if it undergoes beta minus decay, then it is left tilted arrow mark and a new nucleus can be expected. So, this is how one can denote the s process to in one chart.

When the nuclides undergo successive neutron capture and once they are extremely rich in terms of neutrons, they will undergo successive beta minus along isobaric chain and you can see the left tilted arrow marks. They will reach to a stable state and those stable nuclides are called r nuclides. There are few nuclides which can be produced because of both processes and there are nuclides which can be produced only because of s and there are few nuclides which can be produced only due to r processes. Accordingly, the designation of nucleus is presented in this chart of nuclides. Let me take a part of this chart of nuclides for better understanding of s and r process.



Why 160 Dy cannot by r-nuclide
it is not product of r-process path. Why? 160 Tb is not formed by β-decay of 160 Gd → stable

161 Tb is unstable is not formed by nc of 160 Tb

158 Dy p-nucleus
not formed by s- & r- process

(7?) Excluded nuclides
p-nuclides

I am considering Gadolinium-156. It has extremely high neutron capture cross sections for which it is preferred as thermal neutron scintillators nowadays and a lot of research work is going on Gadolinium based detectors.

This ^{156}Gd is produced because of some reactions. The diagonal line denotes that it is stable. Because it is stable, it will capture one neutron and produce ^{157}Gd. Because it is stable, it produces ^{158}Gd. Because it is stable, it produces ^{159}Gd. ^{159}Gd is not stable. Therefore, no diagonal line. So, it undergoes beta minus decay, to the left tiled arrow. This leads to the formation of ^{159}Tb. This is stable. So, it can absorb one neutron and give rise to ^{160}Tb. Because it is unstable, it will undergo beta decay and give rise to Dysprosium-160. Dysprosium-160 is stable. The stable nuclei are denoted as s, because they are formed due to s-process.

Now, because this ^{156}Gd can be a product of successive beta decays along isobaric chains, I can denote this nucleus. Similarly, ^{157,158,159}Gd. When the successive beta decay by isobaric chain happens, it can cross this ^{159}Gd also. So, because ^{159}Gd can undergo beta decay by an s path and also by a r-path, Terbium 159 also can be designated using r. So, 159 Terbium is formed because of the decay of Gd-159 and this Gd-159 is produced because of the beta minus decay of some previous nucleus. Because Terbium 159 is the product of this successive beta minus decay we can also denote this 159 Terbium as r nucleus.

Terbium-160 is unstable, so neither s or r can be used. I will not use the symbol r for Dysprosium-160. Why? I will explain soon. Whereas, I can use symbol r for Dysprosium 161 and 162. Now let me draw something else. After this ^{159}Gd, I am not drawing any line between ^{159}Gd and ^{160}Gd. Remember, ^{160}Gd is the stable nucleus.

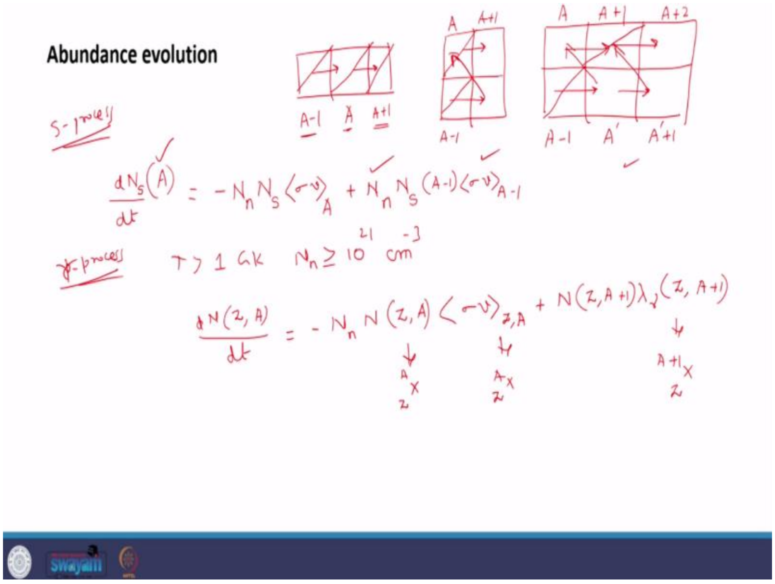
This Gadolinium-160 is formed because of the beta decay as part of the r process. So, I am designating this Gd-160 as r only. I am not using s here because, even though Gadolinium 160 is the stable nucleus, it is not formed because of the s process. For Gd-160 to be formed as part of s process, Gd-159 has to capture neutron, but Gd-159 is a unstable nucleus.

Gd-160 is the stable nucleus so it cannot undergo decay to give rise to Tb-160. Since Tb-160 cannot be formed from Gd-160, Dysprosium-160, which is formed from Terbium-160, cannot be designated as r nucleus. This is the reason why160 Dysprosium cannot be r nuclide, as it is not product of r process path.

Similarly, let me discuss one more nucleus, that is ^{161}Tb. This is also part of r process. This is unstable, but this unstable nucleus is not formed by neutron capture of Terbium-160. That is the reason when Terbium 161 undergoes beta minus decay and Dysprosium-161 is formed from this path, Dysprosium-161 cannot be designated as s. But when it goes to 160 Dysprosium from Terbium 160 and then it captures the neutron, we get 161 Dysprosium. So, Dysprosium 161 can be designated with r because it is formed by Tb 161 and Tb 161 can be formed because of r process. So, with this it must be clear to you how nuclides can be designated either with s or with r.

Let me include two more nuclides, ^{158}Tb and ^{159}Dy. Just before ^{159}Dy, there is one nucleus ^{158}Dy. This is neither s nor r, it is p nucleus. How are such nuclides formed?

There are around 35 such nuclides and Cameron, in his famous paper published in 1957, has given a name “excluded nuclides”. Later, we named it as p nuclides. They are considered a little bit neutron deficient. This p nuclides do not contribute much to the energy production in the stars, but play important role regarding synthesis of elements.



Abundance evolution

s-process

$$\frac{dN_s(A)}{dt} = -N_n N_s \langle \sigma v \rangle_A + N_n N_s (A-1) \langle \sigma v \rangle_{A-1}$$

r-process $T > 1$ GK $N_n \geq 10^{21}$ cm^{-3}

$$\frac{dN(Z,A)}{dt} = -N_n \underset{\substack{\downarrow \\ {}^{A}_{Z}X}}{N(Z,A)} \underset{\substack{\downarrow \\ {}^{A}_{Z}X}}{\langle \sigma v \rangle_{Z,A}} + N(Z,A+1)\underset{\substack{\downarrow \\ {}^{A+1}_{Z}X}}{\lambda_\gamma (Z,A+1)}$$

The abundance evolution of the nuclide formed in s-process:

Consider few blocks like a nucleus, which is stable, having mass number A – 1. It gives rise to nucleus with mass number A by capturing neutron. Again, this new nucleus captures a neutron which gives rise to nucleus with mass number A + 1.

This can be drawn in a different way also. On the right figure, A – 1 is stable. So it can undergo neutron capture giving rise to an unstable nucleus. So, I am not drawing any diagonal one. It can go to a stable one with mass number A. Because it is stable it can capture a neutron giving rise to A + 1.

There is another possibility. A stable nucleus with mass number A – 1, can capture neutron giving rise to an unstable nucleus designated by A'. It undergoes beta minus and gives rise to nucleus with mass number A. By capturing neutron, it can go to A+1 and because it is stable, it goes to another nucleus whose mass number is A + 2. This unstable A', because of the neutron flux, it can always capture a neutron and go to mass number A + 1. Depending on the flux availability, if it undergoes beta minus, then A + 1 also can be formed. Considering this process let me write down the abundance evolution of s-process.

$\frac{dN_s(A)}{dt} = -N_n N_s < \sigma v >_A + N_n N_s (A-1) < \sigma v >_{A-1}$, where

dN = nuclides formed as part of s-process;

N_n = number density of neutrons;

N_s = number density of s-nuclides;

$< \sigma v >$ = the reaction rate per particle pair.

So, this is how one can write the abundance evolution for the s process.

Now, how to write about the r-process abundance evolution regarding the r process?

When $T > 1$ GK and $N_n \geq 10^{21}$ cm^{-3},

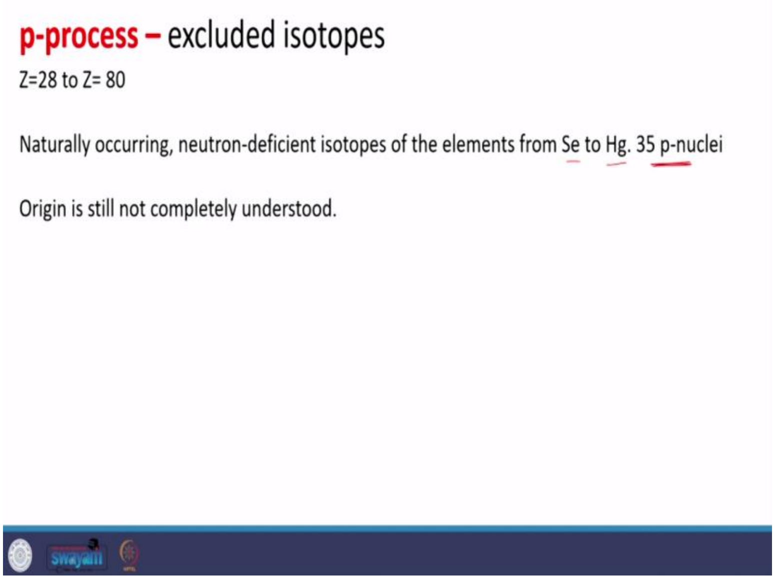
$$\frac{dN(Z,A)}{dt} = -N_n N(Z,A) < \sigma v >_{Z,A} + N(Z,A+1)\lambda_{\gamma}(Z,A+1)$$, where

N(Z,A) = number density of nucleus having atomic number Z and mass number A;

$< \sigma v >$ = capture reaction rate per particle pair;

$\lambda_{\gamma}(Z,A+1)$ = photo dis-integration constant of nucleus having mass number A+1.

This is how one can express the abundance evolution of s-process and r-process mathematically.



p-process – excluded isotopes

Z=28 to Z= 80

Naturally occurring, neutron-deficient isotopes of the elements from Se to Hg. 35 p-nuclei

Origin is still not completely understood.

Finally, let me finish this class by giving a very brief information about the p process. As I said, they are called as excluded isotopes by Cameron. So, it has been seen, those nuclides which are not formed because of s and r process, they are lying between 28 and 60 in terms of atomic number and naturally occurring neutron deficient isotopes of these elements range from selenium to mercury. There are around 35 p nuclei. The origin of p nuclei is not still understood and many individuals theoretically and many groups experimentally are actively working to understand the origin of p nuclei using world class facilities. As of now, according to available information, the astrophysical site of this p nuclei is type 2 supernova. They are very rare in terms of number. They are not very much important from the point of energy production, but they are important in terms of synthesis of isotopes. The abundance is about 10 to 1,000 times less than the nuclides corresponding to s and r process.

To summarize today’s lecture, I have covered salient features of s process r process mainly and little bit about p process. Two important parameters we have to remember while understanding the synthesis of elements beyond iron and that is the role of neutron flux and life time of the unstable nuclei. These two will decide whether a nucleus is formed by s path or it is formed among r path.

In the next lecture, we will see experimental aspects of these neutron induced reactions in addition to some general considerations of experimental aspects of nuclear astrophysics. Thank you very much.